Multi-Channel Routing Protocols for Wireless Body Area Networks

by

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STATEMENT OF CANDIDATE

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me.

In addition, I certify that all information sources and literature used are indicated in the thesis.

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Sobia Omer

I dedicate this thesis to my husband Omer and my children who supported me all the time with their love and pray.

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ABSTRACT

Wearable sensors connected through Wireless Body Area Networks (WBANs) have emerged as a promising enabling technology for many healthcare applications in recent years. A WBAN utilises wearable sensors on the human body to route information between a sensor and a central control unit (CCU) which can be connected to remote stations for further analysis. The routing schemes used in WBANs face challenges due to limited energy and excessive traffic overhead constraints. Most routing protocols for WBANs use a single-channel which limits network performance in terms of interference among links, throughput, end-to-end delay, and congestion. As opposed to single-channel communication, multiple channels increase the number of paths that can be active simultaneously between nodes and increase bandwidth capacity with reduced inter and intra-channel interference. Multi-channel routing protocols can overcome many of the limitations mentioned above for single-channel routing protocols improving traffic congestion, energy consumption, network lifetime, and link stability. However, several challenges still need to be solved when utilising multiple channels, such as channel selection methods for multiple routes and optimising routing metric.

In this thesis, various multi-channel routing protocols have been proposed for WBANs to improve the performance over traditional single-channel protocols commonly used in WBANs. Firstly, the thesis develops multi-channel versions of existing routing protocols, such as single-path, single-channel AODV (Ad-hoc

On-demand Distance Vector) and REL (Routing based on Remaining Energy and Link quality indicator) to overcome bottlenecks at intermediate nodes. Secondly, new performance metrics are proposed such as a channel-diversity metric named Weighted Multi-Channel Hop-Count (WMHC) and a lexical composite metric named Dual-CHannel REL (DCHREL) for route selection combining hop count, link quality, and nodes residual energy. Lastly, channel selection methods based on Link Quality Estimators (LQEs) such as Link Quality Indicator (LQI) and Received Signal Strength Indicator (RSSI) for static as well as mobile nodes are proposed, which outperform random channel selection in WBANs with a small number of channels.

The implementation of the proposed multi-channel routing protocols was carried out in the OMNet++ based Castalia. Simulation results show that the multi-channel routing protocols with the LQE based channel selection at network layer outperform their corresponding single-channel protocols. Similarly, it is shown that the multi-channel routing protocols with the LQE based channel selection efficiently utilise multiple channels to reduce the number of retransmissions needed for route establishment and data forwarding. Moreover, significant improvements in network performance are observed in terms of packet delivery with less control overhead, routing stability in the presence of link fluctuations caused by mobility, and less co-channel interference with balanced and low energy consumption.

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Chapter 1

Introduction

Contents

1.1 Thesis Motivation

There will be more than double population (954,600 Australians) aged 85 and over in next 20 years according to Australian Bureau of Statistics (ABS) [1] who would require more affordable, permanent and continuous healthcare. A developing field in the health monitoring market is that of wearable sensors or on-body sensors. Healthcare becomes more proactive and affordable if these wearable devices become the fundamental technology in continuous physiological health monitoring. These devices assist in monitoring vital physiological signs and provide feedback to help maintain an optimal health status. The communication part of this system requires efficient mechanisms to send data from one device to another or the Central Control Unit (CCU). New developments in medical science bring together new trends of pre-emptive health care which gives rise to the era of Wireless Body-Area Networks (WBANs). One of the most prominent approaches to building wearable health-monitoring systems utilises emerging multi-channel WBANs. The recent research in the WBAN is mainly focused on making its communication more reliable, energy efficient, secure, to better use system resources such as energy, and bandwidth, and to increase the throughput.

To design a WBAN system, there are many areas under investigation such as communication protocols, power-management techniques, and data-dissemination protocols. These have been designed explicitly for WBANs where efficient data delivery and energy awareness is an important design issue. Considering the limited bandwidth available and accommodating the demand for high data rates is a significant task which requires substantive and efficient technology that can alleviate performance issues while dealing with various frequency channels. The transmission bandwidth requirement of a typical WBAN is of the order of 1.2 MHz [2]. In comparison to other networks such as Mobile Ad-hoc Networks (MANETs) and Wireless Sensor Networks (WSNs), the bandwidth available to

WBANs is limited and is likely to be shared with other same-band-sharing devices. Moreover, it is subject to physical-layer attributes such as fading, interference, and attenuation due to the specific characteristics of the human body, so the protocol's amount of network control information, known as control overhead, should be limited.

This thesis focuses on the design of multi-channel routing protocols based on the Ad-hoc On-Demand Distance Vector (AODV) over a dual radio for WBANs to improve the communication performance, namely energy efficiency, less control traffic, high throughput and better channel-selection metrics. The reason for selecting AODV for the multi-channel routing protocol is that AODV does not require periodic global advertisements [3]; the demand on available bandwidth is less than for other on-demand reactive protocols such as Dynamic Source Routing (DSR). Moreover, all the intermediate nodes in an active path update their routing tables, making sure of maximum utilisation of the bandwidth. This feature makes it favourable for WBANs.

1.2 Wireless Body-Area Networks

WBANs are a special type of WSN having the following requirements as shown in Table 1.1. A WBAN is a collection of low-power wireless sensor nodes, miniaturised sensors that monitor physiological signs and respond accordingly. The information collected from the different nodes is then sent to the central processing unit or Central Coordinator Unit (CCU), which is connected to remote stations for further analysis. The CCU sends the data to the hospital, ambulance or a concerned doctor.

Traditional WSNs do not hold the particular challenges such as heterogeneous nodes (regarding available energy or computing power) many-to-many communication and mobility associated with the human body in WBANs [4] [5]. The human body constitutes a complex core environment that reacts to and interacts with its external environments.

The human body had different challenges than those faced by WSNs such as smaller scale and required different frequency and its type of monitoring. The demand for reliability increases when the monitoring of medical data is required. If a WBAN is integrated into a telemedicine arrangement, these systems can help alert concerned personnel (i.e. Physicians or Paramedics), when any critical physiological variations occur. For example, they can be employed as a part of a diagnostic practice such as an optimal maintenance of a chronic condition, radiological procedures such as X-rays or an administered recovery from a surgical procedure or critical event, to monitor observance to treatment-recommendations (e.g. conventional heart device), or to monitor the effects of medication therapy in terminally-ill patients.

1.2.1 IEEE 802.15.6 Standard

The IEEE 802.15.6 standard (released in 2012), was implemented to develop a communication model for low-power devices. The wireless communication between sensors is based on IEEE standards such as the commonly used ZigBee 802.15.4 [6] or 802.15.6 [7]. The IEEE 802.15 Task Group 6 (TG6) communication standard was released in 2012 for low-power devices including the Physical layer and Medium Access Control (MAC) components. The 802.15.6 standard supports three different PHYsical (PHY) layers: Narrow-Band (NB), Ultra-Wide-band (UWB) and Human Body Communication (HBC) as shown in Table 1.1. The body surface or the external nodes (on-body) can use a range of frequencies available for WBANs, whereas implanted sensors can only use the Medical Implant Communications system (MICS), the band. To date, most WBANs have utilised a single wireless channel for communication that can be either the NB, UWB or HBC band. The NB band further divides into the MICS and ISM (Industrial Scientific and Medical) bands.

Table 1.1: WBAN Requirements

Data rate	up-to about 2 Mbps
Range	0.01 to 2 meters
Power Consumption	1-10 mW
Frequency Bands	400 MHz, 800 MHz, 900 MHz, 2.4 GHz
PHY Layers	NB, UWB, HBC

A medical-care system is one of the essential application scenarios for WBANs as described in the IEEE 802.15.6 standard [7]. This standard is developed explicitly for WBANs or medical devices such as pacemakers, implantable cardioverter defibrillators, spinal actuators, continuous glucose monitoring, insulin pumps, a deep-brain stimulator. The architecture is depicted in Figure 1.1, where the on-body WBAN resides on the body of the patient. For example in a medical scenario [8], a glucose monitoring device (a sensor node) is attached to a diabetic patient on his or her body to monitor his/her blood sugar levels. Due to the decrease in optimum blood sugar level, a glucose monitoring device will alarm the patient. In that way attached or implanted medical devices can help immobile or elderly patients to keep track of their physiological symptoms even without going to the hospital.

1.3 WBAN Requirements

The primary requirements for WBAN are reliability, robustness, wearability, interoperability, real-time data acquisition [9] and if further analysed more critically shown in Table 1.1: including data rate, the range of the sensor nodes' communication, maximum power consumed by the nodes, the frequency bands and PHY layers.

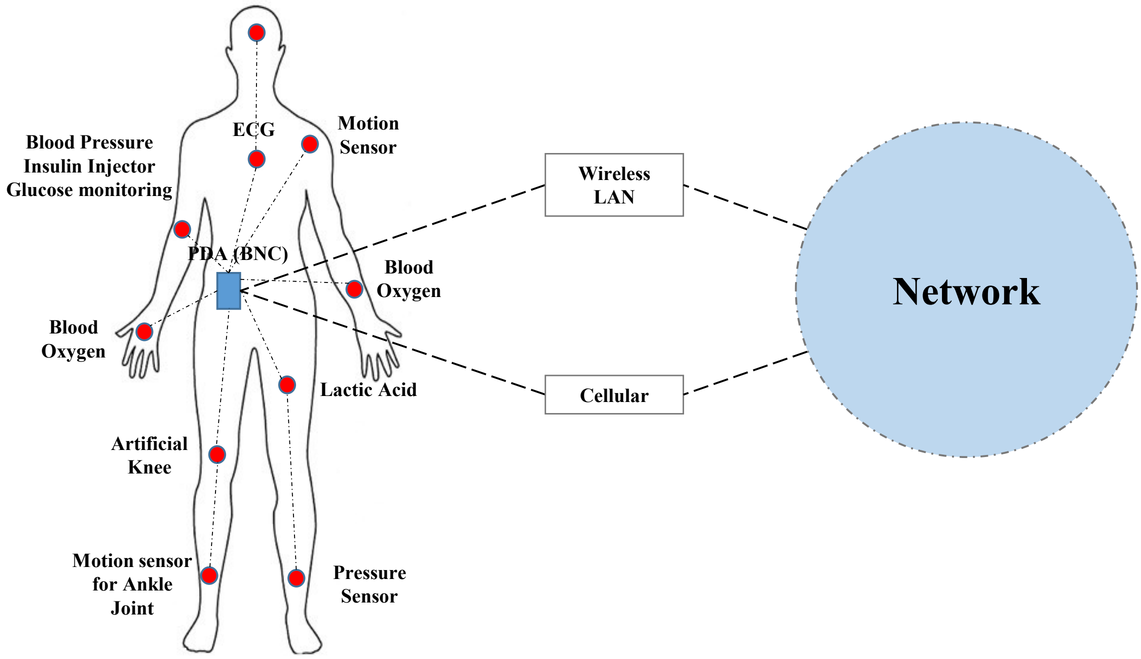


Figure 1.1: On-body wearable sensors wirelessly communicate with wearable personal device (PDA) to relay sensor data to hospital or physicians

WBANs are typically connected with remote monitoring systems. Therefore, these systems need to maintain a high level of reliability and a low level of latency [10]. The communication protocols in a WBAN should consider the number of physical environments because the networks are configured on the body. First, because of the physical properties, the WBAN can easily cause free-space attenuation (fading), noise and interference compared to free-space networks; thus, the bandwidth is variable and limited. Second, devices attached to the body are movable owing to various body motions. Given the characteristics described above, there is a need for routing protocols for WBANs. Less work has been done in the area of routing protocols for WBANs as compared to other related networks such as Wireless Mesh Networks (WMNs) and WSNs.

In WBANs, some functional requirements including network life extension, data reliability, optimal use of channel bandwidth, energy efficiency need to be included when designing any communication protocol. The energy consumption depends on many factors like the frequency and amount of forwarding network traffic, how distant it is from the sink and node activity. However, the broad applications of WBANs in medical scenarios are severely hindered by the concerns on reliable data transmission on a limited channel bandwidth, and the short lifespan of the network because of the higher energy consumption by the devices [11].

As far as routing is concerned, in single-channel networks, protocols use just one shared channel to communicate. A packet broadcast on the shared communication channel is received by all the neighbours of the transmitter. They have to contest with the extended-hop neighbouring nodes, leading to a high collision likelihood as the traffic load increases [12]. However, in a multi-channel network, no collisions will be caused by such simultaneous transmissions as long as they work on different channels. Moreover, if multiple channels are within the same network, it significantly increases the maximum bandwidth utilisation of sensor nodes [13]. Therefore, compared to single-channel communication, sending multiple copies of the information over multiple channels increases the probability of successful transmission of information within a neighbourhood, and hence improves the network capacity. If a wireless network assigns different channels to different nodes in a concurrent transmission, it is called a multi-channel routing protocol. The use of multiple channels gives rise to communications on different frequency bands using different channels. Moreover, it also improves the overall network capacity [14]. Using multiple channels has also shown the ability to improve the network throughput dramatically [13].

There has been an increasing interest in multi-channel communication for WBANs to improve robustness, connectivity, and performance through the development of core enabling technologies such as antennas, radio system architectures and simple protocols for link data transfer. Examples of these include the following: [15] developed a multi-channel EEG recording to enable precise brainwave measurement of fish. This is the most recent development in multi-channel WBANs. [16] developed a dual-band node (using 433/868 MHz) with the aim of relieving the effects of congestion and catastrophe on reliability and QoS. [17] developed a wireless device that used an alternative HBC link if the primary RF link (ISM) became unreliable or blocked. [18] developed a dual-band device that used UWB for data transmission and NB communications to receive control signals to avoid the complexity of a UWB receiver in a small WBAN device. As far as routing is concerned, the routing protocols developed for the WBANs have mostly concentrated on MAC layer issues.

1.4 Routing Issues and Challenges in WBAN Routing Protocols

The design of an efficient routing protocol for a WBAN requires unique properties and specific characteristics. The following sub-section presents the details of routing issues and challenges. These include network topology and topological partitioning, energy consumption (scarce energy resources), variable data rates, QoS and reliability, heterogeneous environment, and path loss.

One of the main issues in Routing protocols is that they aim at constructing routes with a more extended lifetime to deliver data efficiently. However, the in-between nodes or next-hop nodes need to rebroadcast more requests to discover more stable routes, leading to a higher routing overhead, e.g. the rate of sending messages such as Route Requests (RREQs), Route Replies (RREPs), and Acknowledgements (Acks) will increase. Moreover, broadcasting is the most basic way to transmit data from one source node to all the others in all wireless networks such as WBANs, WSNs and WMNs, yet the traffic broadcast overhead can be a vital element limiting the improvement of system performance, particularly in single-channel networks.

Routing in most of the existing Ad-hoc network protocols, e.g. DSR, and AODV depend on flooding RREQs between the source and a destination or forwarder nodes and selecting the minimum-hop-path after that. But, this typically results in a large number of redundant transmissions if link breakage propagates between nodes, which could be costly for resource-reserved nodes such as those in a WBAN [19].

The routing challenges [20] in a WBAN are shown below.

1. Topology: The network topology is one of the leading issues in WBANs. It is concerned with the performance of overall system features, such as routing protocols, traffic load, latency, power consumption, and node robustness. The conventional network topologies are bus, ring, star, and mesh. Bus and ring topologies are not suitable for the complicated human body because of their small scale. The star topology is commonly used in WBANs, where all sensor nodes directly communicate with the sink node. This type of topology has the main disadvantage such of energy limitations. Due to this factor, the sensor nodes are located on different parts and are unable to build connections [21]. However, the mesh topology is suitable for multi-hop networks, based on its superior performance. This reduces the path loss and has a well-distributed network, in which each node requires less energy to communicate with each other [22]. If a multi-hop topology works with a single-channel protocol, it leads to a high degree of contention between nodes. Multi-hop and multi-channel routing protocols may contribute to the reduction of overall interference [23].

2. Limited Resources: WBANs have limited resources such as short communication range, limited energy, storage capacity and low bandwidth. Thus, routing protocols should be able to handle these constraints by exploiting multiple channels.

3. Interference: A WBAN interference can be categorised into two types: Inter and Intra-WBAN interference. In the Intra-WBAN interference, it occurs between sen-

sor nodes within one WBAN whereas, inter-WBAN interference occurs among different WBANs functioning in the same frequency band, and this type of interference should be minimised or mitigated to ensure signal quality in WBANs [13]. There are more chances of collisions and packet loss if interference is present. There must be a way to recognise the nodes which are not in communication range.

4. Mobility: A WBAN is dynamic. The dynamic nature of a network also decreases the network lifetime. To handle a mobility challenge efficiently, efficient multi-channel routing protocols are required to maintain connectivity between the nodes [24]. The protocols might be single-hop, multi-hop and also cluster-based communication depending on the network size. Continuous monitoring of link conditions is necessary to maintain connectivity and to increase the network lifetime and decrease the energy consumption.

1.4.1 Challenges of Single-channel Routing Protocols

When sensor nodes are set up in a human body, single-channel routing protocols may be performance-poor due to a higher consumption of the limited bandwidth [25]. Due to limited or inadequate energy resources of WBAN sensor nodes, essential design objectives for WBANs comprise of minimising the total energy consumption within the network, minimising the overhead of control messages, or balancing energy usage among the sensor nodes to avoid disconnected links in the networks.

With the strict energy constraints in WBANs, the energy consumed for data transmission, route establishment and maintenance should be kept as low as possible. Many researchers have worked on controlling the transmission power of the radio, but that has been done on the physical and MAC layers using multi-channel and on multi-channel MAC only. The energy consumption of the sensor nodes comes from data collection, processing, and transmission. In common sensor applications in WBANs, the radio communication consumes most of the energy during this process [26]. As far as communication is concerned, there is also a substantial amount of energy wasted in different states such as collision, control-packet overhead, overhearing, passive listening, and interference, that are useful from the routing point of view [27].

The two main classes of multi-channel energy efficient techniques can be classified as overhead reduction and energy-efficient techniques. These techniques emphasise on the least number of control packets should be propagated within the network to enable data transmissions successfully. In protocol overhead reduction technique, the routing protocol is made efficient by reducing the routing overhead in the form of periodic message exchanges. These exchanges are the primary source of communication overhead in WBANs. However, energy-efficient routing protocols should be designed by maximising the network lifetime, minimising the energy consumption, limiting unnecessary end-to-end transmissions and avoiding low-energy nodes. Cross-layering (sharing information between two layers) is also used to optimise network resources while meeting application requirements [28]. Optimised flooding can be used to avoid unnecessary retransmissions.

1.5 Research Questions

1. Why are single-channel routing protocols insufficient for the next-generation networks such as WBANs ?

   In a single-channel environment, a minimum number of transmissions depends on finding the least number of next-hop or forwarding nodes. If a routing protocol follows a single path and a single channel, it will not get more forwarding nodes for the data transmission. Moreover, nodes lying on a single path will share the same channel, again and again, leading to contention and increased back-off. Flooding is a commonly used procedure in WBANs for route discovery (RREQ) and route establishment (RREP) or sending link-connectivity messages (HELLO). Therefore, it is considered as an expensive operation to carry out for the energy-limited sensors in WBANs. The proposed protocols in this thesis aim to increase protocol efficiency by reducing the routing overhead by using multiple channels. Periodic message exchanges are sources of overhead in WBANs. The optimised flooding technique is used to avoid unnecessary retransmissions.

2. Is there a need to devise new performance routing metrics for the multi-channel routing protocols ?

   The answer is Yes! In a traditional routing strategy, minimum-hop is the primary metric for selecting the next hop. Some sensor nodes have a high probability to be chosen as a relay [29]. The minimum-hop-count selection does not ensure energy efficiency and reliable data transmission in a multi-channel network [30]. The network protocols should be able to deliver data efficiently and effectively using optimised routing metrics for the channel diversity, with less interference between nodes and channels. To fully support the multi-channel operation of the routing protocols along with appropriate routing metrics are needed for a WBAN, and are proposed in this thesis in later chapters.

3. How does channel selection impact the performance of a multi-channel routing protocol ?

   When the channel quality varies over time, and the varying parameters in the Physical layer result in instabilities of link quality. The link-quality variations can make one channel (out of many available) less favourable to be chosen again for future communication between the nodes. Thus channel selection has to be coupled with both link-quality metrics and routing for maximising throughput and minimising link-quality fluctuations in static and mobile scenarios. When the multi-channel operation is considered, the above problem becomes even more complicated. The performance using multiple channels depends on how those channels are selected. The overall number of successful packet receptions increases, if the number of channels increases [31]. Single-channel communication fundamentally drops more packets due to channel conflict between source and destination. Multiple channels usage may reduce the packet drops between the source and destination and ensures more favourable packet reception.

4. How will multi-channel routing protocols help with mobile nodes ?

   Mobility is a critical factor because of the body movement in WBANs. When the mobile node moves, the link quality changes over time which interfere with the data transmission [32]. To handle fluctuations more efficiently and promptly, one of the proposed multi-channel routing protocols in this thesis supports mobility in WBANs. It shows that a multi-channel protocol can better handle link-quality fluctuations than the single-channel protocol, and achieves better routing stability using LQEs (Link Quality Estimators).

In this thesis, all of the questions listed above motivated us while working with the single-channel environment. Moreover, the new multi-channel routing protocols proposed in this thesis help in gaining network performance regarding energy consumption, traffic overhead, latency and throughput. To the author's knowledge, this is the first research work that has evaluated multi-channel routing protocols for WBANs. The offerings of this thesis are given in Section 1.7.

1.6 Multi-Channel Routing Protocols for WBANs

The performance of multi-channel wireless networks can be considerably improved by using multiple channels as compared with single-channel communications. Multiple channels can reduce the interference present between different channels as presented by one of the proposed protocols [33]. In a WBAN, sensor nodes are strictly energy restrained, and hot spots would die from much forwarding of the control messages. These nodes are usually around the central node or CCU, and loss of their coordination would degrade the overall performance. The simplicity of use of on-body sensors leads protocol designers to think about the careful design of energy efficiency because of the small form factor that contains the battery and antenna.

1.6.1 Advantages of Multi-channel Routing Protocols

It is concluded in [34] that, despite the suitability of IEEE 802.15.6 for a WBAN, a successful network-layer protocol design should be combined with investigations of multiple channels. A summary of the advantages of using multi-channel routing protocols in WBANs in a broader sense are listed below:

- Multi-channel routing protocols utilise the available bandwidth in a better way and as a result, may perform favourably in medical applications demanding high data rates. Nodes can operate on different non-overlapped channels to avoid interference if they exist within each others transmission range. Also, sensor nodes around the human body carry various sensors to collect different data, and early energy depletion of specific nodes would undermine the function of the WBAN system.

- Multi-channel routing protocols use a variety of channel-selection schemes for achieving the desired level of link quality and simultaneously maximise the utilisation of the limited bandwidth. The resources at the MAC layer are supposed to be variable. They can vary due to channel quality variations and change parameters in the PHY layer. Such variations result in fluctuations of link quality. Thus channel selection is coupled with both link quality metrics and routing. If we consider the multi-channel operation, the channel selection process becomes more complicated. This cooperative optimisation between routing and associated channel allocation becomes one of the most challenging problems for a cross-layer design (MAC/Routing). This thesis brings the concept of multi-channel utilisation into the routing layer. However, the data transmission required for successful and error-free communication depends mostly on the availability and quality of the channel between the communicating nodes.

- Mobility is a key factor in a WBAN design. Sensor nodes can be relatively static or move about. Moreover, in case of mobile users, one sensor node moves relative to another sensor node. This requires mobility support. The WBAN nodes connected to the same person move together and in the same direction. This causes the distance between devices, levels of interference and multi-path effects and results in channel conditions to change between NLOS, LOS, and partial LOS. Multipath routing protocols use multiple routes to achieve load balancing and robustness against routes failures. When the nodes move, this changes the distance between nodes and the sink which affects the energy consumption of nodes, network lifetime and throughput [35]. Specialised protocols for WBANs are therefore needed. The node mobility also affects the variations of the channel on which the transmission is taking place.

In this thesis, multi-channel routing protocols are developed and evaluated. The dual-band hardware implementation of sensor nodes, as discussed in Section 2.3 provides a power-efficient WBAN communication system that can be used in wireless body communication applications that require various data-transmission capabilities [36]. Right frequency bands should be chosen to reduce interference and thus increase the coexistence possibility of individual sensor nodes with other sensors or network devices [37].

1.7 Thesis Contributions

A multi-channel WBAN architecture requires joint channel assignment and topology discovery, for an efficient routing protocol. Thus, the focus of this thesis is on the unexplored and possibly promising feature of multi-channel assignment and its incorporation with routing.

To solve all of the aforementioned problems, routing protocols based on multi-channel multi-path strategies are proposed in this thesis. The principle of the multi-channel routing protocol is to establish several paths between a source node and a destination node using multiple channels from the available bands and optimise the route selection strategy according to the channel conditions and remaining energy of the possible next-hop nodes. This thesis investigates reactive routing protocols in dual-channel WBANs, mainly focusing on joint routing with channel selection strategies based on different metrics.

The principal contributions of this thesis are as follows:

- **A Multi-Channel AODV routing protocol based on RSSI channel selection for WBANs (MC-AoRSS)** We propose a multi-channel AODV routing protocol based on RSSI (Received Signal Strength Indicator) channel selection for all static nodes. This protocol uses RSSI values to select the new route by its having the highest RSSI values out of the two on-body sensor nodes. Simulation results demonstrate that the proposed scheme is able to achieve a significant reduction in the number of control packets and the network stability over single-channel AODV. This work is presented in Chapter 3.

- **A Multi-Channel AODV routing protocol based on LQI channel selection with mobile nodes for WBANs (MC-AoLQM)** We Propose a multi-channel AODV routing protocol based on Link Quality Indicator (LQI) channel selection for all static nodes as well as one mobile node, and this is compared to RSSI and random channel selection. This protocol uses the RSSI and LQI values to select the new route by this node's having the highest LQI values out of the two on-body sensor nodes. Simulation results demonstrate that the proposed scheme can also achieve a significant reduction in the number of control packets and the network stability over single-channel AODV. This work is presented in Chapter 4.

- **A Multi-Channel AODV routing protocol based on Weighted Metric Hop Count for WBANs (MC-AoWMHC)** We Propose a multi-channel AODV routing protocol based on a channel-diverse metric Weighted Metric Hop Count (WMHC). Simulation results have shown that WMHC is a simple and effective method of reducing interference and improving the throughput of WBANs. This work is presented in Chapter 5.

- **A Multi-Channel routing protocol based on Remaining Energy and Link quality for WBANs (MC-REL)** We Propose a multi-channel lexical routing protocol based on the composite routing metric (remaining energy of all nodes in a path and weak link quality indicator and hop count) called MC-REL. This protocol is built on the number of hops, the link-quality indicator values of the physical link, and the remaining energy of all nodes in a path to construct a lexical routing protocol. Simulation results show that it is an energy-efficient routing protocol for achieving high throughput paths with fair and minimal energy consumption as compared to previous work on multi-channel and single-channel routing protocols. This work is presented in Chapter 6.

1.8 Thesis Outline

This thesis is organised as follows. This chapter introduced the basic concepts of WBANs and its structure, the main requirements and constraints, the research background of single as well as dual-channel nodes, and the energy efficiency challenges in a WBAN. A short introduction to the general IEEE 802.15.6 protocol is outlined in this chapter. Chapter 2 explains the single-channel routing protocol limitations and the benefits of using multi-channel routing protocols in WBANs, and illustrates the related research. Chapter 3 formally introduces the multi-channel reactive routing protocol and analyses the working of a multi-channel AODV routing protocol and channel selection based on RSSI with no mobility in effect. Chapter 4 demonstrates an extension of the multi-channel routing protocol with one node mobile, and the effectiveness of mobility in minimisation the energy consumption and control message overhead. Chapter 5 introduces a channel diverse-path metric into the multi-channel routing protocol, which is a simple and effective way to reduce the interference and improve throughput. Chapter 6 introduces a new multi-channel routing protocol based on lexical routing with a composite metric (hop count, remaining energy of the path and link-quality indicator values). Finally, future development of the WBAN, conclusions and further work are addressed in Chapter 7.

1.9 List of Publications

1. S. Omer, R. Vesilo, E. Dutkiewicz, and Q. Zhang, "A dual-channel routing protocol for Wireless Body Area Networks," in *Proceedings of the 10th EAI International Conference on Body Area Networks.* ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Sep. 2015, pp. 240–246.

   This work is presented at 3.

2. S. Omer, R. Vesilo, E. Dutkiewicz, and Q. Zhang, "An LQI based dual-channel routing protocol for Wireless Body Area Networks," in *International Telecommunication Networks and Applications Conference (ITNAC)*, Nov. 2015, pp. 320–325.

   This work is presented at 4.

3. S. Omer and R. Vesilo, "A channel diversity path metric for dual channel Wireless Body Area networks," in *26th International Telecommunication Networks and Applications Conference (ITNAC)*. IEEE, 2016, pp. 32–37.

   This work is presented in 5.

4. S. Omer and R. Vesilo, "A Dual Channel Routing Protocol Based on Energy and Link Quality Indicator in Wireless Body Area Networks," *2016 International Telecommunication Networks and Applications Conference*, Nov. 2016.

   This work is presented at 6.

1.10 Work to be submitted

1. S. Omer and R. Vesilo, "Wireless Body Area Networks - Enabling Technologies and Emerging Applications," *2018 Chapter - InTech Open*

Chapter 2

Literature Review

Contents

This chapter analyses the literature on multi-channel routing protocols related to Wireless Body Area Networks (WBANs). A comprehensive literature review of the existing routing protocols for WBANs during the last decade is presented in this Chapter. It also offers a critical exploration of the reactive routing protocols with the proposed multi-channel routing protocols. In Section 2.1, a brief overview of the WBAN is presented, including the main requirements for WBAN devices and their applications in wireless body communications. In Section 2.2, sub-layers of the WBAN will be discussed. Section 2.3 provides the background on dual-band WBAN technology. In Section 2.4 various mechanisms of channel quality measurement are analysed for providing effective communication in a WBAN. Section 2.5 discusses routing protocols for WBANs and the need for multi-channel routing protocols and their metrics in WBANs. Section 2.6 gives the detailed description of a reactive routing protocol named AODV and after that Section 2.7 discusses the challenges for single-channel routing protocols. Then Section 2.8 concentrates on the existing work related to multi-channel routing protocols and their applications. Section 2.11 concludes the summary of this chapter.

2.1 WBAN Overview

A WBAN is one of the sub-type of Wireless Sensor Network (WSN) [38], in which low-powered, resource-constrained and miniaturised devices (sensors) and actuators are placed in, on or around the human body. These sensor nodes collect information and send it to the central processing unit to provide continuous health monitoring (e.g. disease management devices) and real-time feedback to the user (e.g. independent aged person) or medical personnel (e.g. paramedics and specialists).

These in-body (internally) or on-body (externally) sensors are used to measure physiological parameters of the human body, e.g. the wireless capsule for endoscopy, X-rays, blood pressure monitoring. The actuators, on the other hand, take concrete actions concerning the data (measurements) they receive from the sensors. A wireless communication channel connects the sensors in a WBAN. The primary utility of these sensor nodes [1] is to unobtrusively sample dynamically changing vital signs and symptoms and transfer the critical data to a personal server such as PDA through a WBAN implemented using ZigBee 802.15.4. These sensors can be used for medical monitoring and intervention to support improved patient management in the clinic, at home and out of the home. This improves patient convenience, mobility, and outcomes at lower cost.

Types of Sensor

Fundamentally, wireless body communications are generally located: on-body, where sensors are attached to the human body and communicate with one or more sensors located off-body; off-body, a number of sensors are located on the body and communicate with each other; in-body e.g an in-body blood glucose level sensing device can wirelessly trigger an insulin pump to inject a required dose of insulin, thereby acting as an artificial pancreas [39], the some or all of the sensors are implanted inside the human body. The on-body sensors provide easy patient mobility, comfort, and scalability. The on-body medical applications such as monitoring of patient vitals, e.g. electrocardiogram (ECG), blood pressure, body temperature and saturation of peripheral oxygen (SpO2), etc. listed in Table 2.1 are used for communication between the on-body WBAN. The standard terminology is discussed in [40].

[1] The term node refers to both sensor and actuator node

Table 2.1: Types of Sensor in WBANs

Sensor	Energy	Bit Error Rate (BER)	Latency	Duty Cycle	Topology	Data rate
Accelerometer	Low	10^{-10}	≤ 250 ms	$\leq 1\%$	Star	High
Temperature	–	10^{-10}	≤ 250 ms	$\leq 1\%$	p2p	High
Blood Glucose	Very low	10^{-10}	≤ 250 ms	$\leq 1\%$	Star	Low
Blood Pressure	High	10^{-10}	≤ 250 ms	$\leq 1\%$	Star	High

Differences between WSN and WBAN

Different techniques and protocols from the WSN can be used to implement communication between the sensors. WBANs are a subset of general WSNs, and they share many common challenges, though a lot of differences exists between them concerning extreme reliability requirements, extreme energy efficiency, exclusive designs of the bio-sensor nodes, bio-channel complexity, security, human-body shadowing and mobility issues [41] - [42]. However, due to the typical properties of a WBAN such as size, reliability, low power consumption, and wearability, current protocols aimed for these WSNs are not always appropriate for a WBAN.

A summary of the differences between WSNs and WBANs is given in Table 2.2. The WBAN node has limited energy available to process and communicate the information. The WSN node also has a limited energy source available, but it can be easily replaceable when depleted which increases the maintenance cost. WBANs also provide greater mobility regarding gathering information on-the-move without affecting day-to-day activities and transferring the physiological data to the concerned person or system. WBANs are related to Mobile Ad-hoc Networks (MANETS) in a way that the mobile nodes need to reorganise themselves, whereas the speed and the number of nodes may usually differ, i.e. the only small number of nodes (10-15) are present in WBANs. Thus routing protocols in MANETs can be employed but due to human body movements that change network topology frequently makes less favourable for WBANs.

Parameter	**WSNs**	**WBANs**
Scale	variety of environments (m/km)	Body vicinity (m/cm)
Node Numbers	heterogeneous nodes	fewer normally 6 up to 256, heterogeneous limited body
Node Tasks	dedicated tasks	one node performs multiple tasks
Topology	fixed or static	more recurrent changes due to movement (one-hop star, extended-star (possibly 2 hops), bidirectional links)
Data Rate	homogeneous	Heterogeneous
Node lifetime	long lifetime	small battery capacity
Impact of data loss	tolerated	unaffordable
Wireless Technology	802.11.4	low power

Table 2.2: Differences between WSNs and WBANs

The standardisation of WBAN (802.15.6) [7] enables new applications and thus new possible markets for WBANs. On the other hand, their design is affected by several issues that call for new paradigms and protocols. Unlike WSNs, in WBANs the communication channels are heavily attenuated and shadowed by the human body [43]. According to [44], the WBAN communication design phase must consider several significant requirements such as energy-management policy, energy-efficient design, point-to-point and link reliability, robustness, scalability support, interoperability, self-organisation, security, and mobility support. While WBANs have many advantages, their disadvantages range from poor reliability because of mobility to unreliable Quality of Service (QoS) [45]. To help overcome these performance issues, this thesis presents multi-channel routing protocols to make them less susceptible to the limited energy crisis, reduced latency, and throughput.

2.1.1 IEEE 802.15.6 Channel Models

A wireless channel has a defining characteristic of variations of the channel strength over time and frequency. The variations can be divided into small-scale or large-scale fading described below.

- *Large-scale fading* is due to path loss of the signal which depends on distance and shadowing effect by large objects such as buildings and hills. This kind of fading occurs as the mobile nodes move through a distance of the order of the cell size and are typically frequency independent.
- *Small-scale fading*, due to the useful and destructive interference of the multiple signal paths between the transmitter and receiver. This type of fading happens on a spatial scale of the order of the carrier-wavelength and is frequency dependent [46].

At channel bandwidths typical of Narrow-Band (NB) WBAN systems, the radio channel has been shown to be mainly slow and flat-fading, with an insignificant amount of inter-symbol interference from multi-path effects. On-body NB-RF signal transmission in an anechoic compartment without any movement or posture change is mainly by creeping waves above the body surface and LOS (Line-Of-Sight) transmission if it exists. Position change causes small-scale fading as waves interact with irregular body structures and inhomogeneous dielectric structures. Fading conditions can result in a bad network performance regarding node energy and throughput. Small-scale multipath fading is more relevant to the design of reliable and efficient communication systems such as routing protocols. The channel quality varies over multiple time-scales. On a slow scale, the channel varies due to large-scale fading effects. At a fast scale, channel varies due to multipath effects [46] as shown in Figure 2.1.

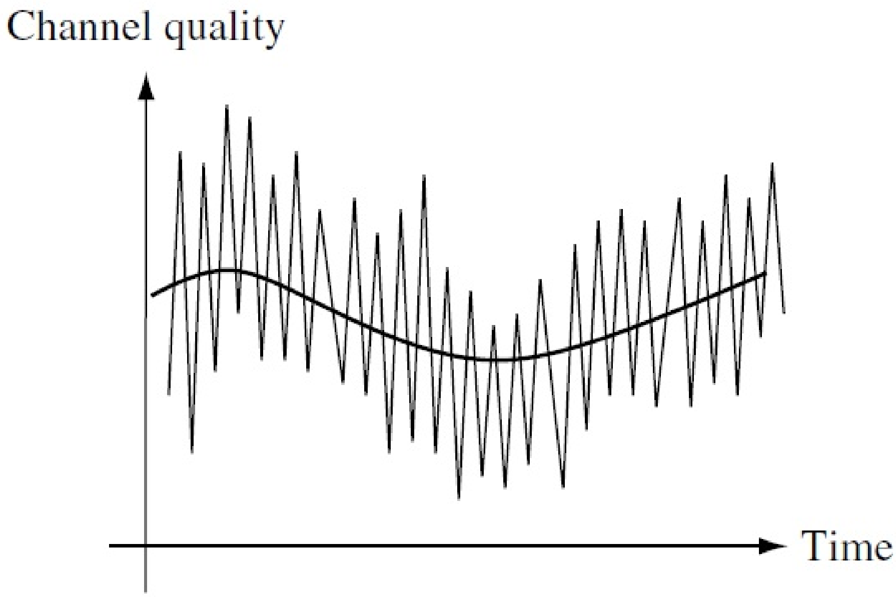


Figure 2.1: Channel quality variations

With the recent interest in multi-band devices for WBANs such as multi-band antennas and transceivers, efficient utilisation of multiple bands requires an equally valid routing protocol.

2.1.2 Propagation Scenarios and Models

The sensor nodes attached to the human body follow the 802.15.6 standard. In this standard, different scenarios for sensor nodes are provided. These scenarios are determined based on the location of the communicating nodes (i.e. implant (in-body), body surface (on-body) and external (off-body)). Depending on the chosen scenario the frequency band and channel model are determined. A list of scenarios can be identified in which IEEE 802.15.6 devices are operating, as listed in Table 2.3. The scenarios are grouped into classes that can be represented by the same Channel Models (CM). These channel models provide the basic distance-based path loss static models without any time-varying effects and correlation features.

Table 2.3: List of scenarios and their descriptions

Scenario	Location of Nodes	Frequency Band	Channel Model
S1	Implant to Implant	402-405 MHz	CM-1
S2	Implant to Body Surface	402-405 MHz	CM-2
S3	Implant to External	402-405 MHz	CM-2
S4	Body Surface to Body Surface (LOS)	402-405 MHz	CM3-A
S5	Body Surface to Body Surface (NLOS)	402-405 MHz	CM3-B

The IEEE 802.15.6 standard [7] defines some different scenarios for wireless communication. Channel models for these various scenarios are given in [47] and [48] and include: CM1 (implant-to-implant), CM2 (implant-to-surface or external), CM3 (body-surface to body-surface or external). [47] gives an overview of these models which are based on probability distribution functions (pdf) whose parameter values have been calculated by measurements and physical modelling.

In the empirically based model, the body is divided into regions called cells using similar concepts to the Virtual Coordinate System [49]. In this system, there are more than one nodes in each cell. The path-loss is given for each source to destination cell pair. When a transmission occurs from one cell to another, the actual signal-loss is calculated which is the sum of the cell-to-cell path loss and a fading-loss. This value is determined by a random look up from a look-up table whose values have been calculated from different measurement studies. The work by [50] and [51] challenges a number of assumptions used in wireless channel modelling [52].

2.1.3 Narrow-Band 2.4 GHz

The 2.4 GHz band is selected for the simulations in this thesis. It is freely available, and most practical existing enabling technologies for WBANs works in this band [53]. These models are proposed in the standard for on-body to on-body surface scenarios and derived from measurement campaigns in an anechoic compartment or hospital-room environment, focusing on the NB models termed as CM3-A and CM3-B (detailed in [50]). The CM3-A channel model is used in this thesis, that works from the on-body to on-body surface for the 2.4 GHz band using the S4 scenario (LOS) as shown in Table 2.3.

A number of assumptions used in channel modelling are challenged in [50] and [52]. In particular, they show that posture changes of human bodies can cause temporal correlations and that many of the WBAN probability models [47] - [54] are inaccurate. They propose a more empirically based model, and this has been included in Castalia which will be discussed in Chapter 3 in detail. Castalia also includes a mobility model that supports simple movements of nodes and involves a recalculation of node positions and path losses, which will be discussed in Chapter 4.

2.2 Sub-Layers of WBAN

In a WBAN, three layers play a significant role in sensing precise readings of patient health and transmitting accurate information to medical servers, namely the PHYsical layer (PHY), the MAC layer (MAC) and the network or routing layer. The PHY layer is concerned with signal transmissions, antennas, and radios. The MAC layer has the responsibility to manage data rates, whereas the network layer or routing layer has a role to search for an optimal and metric-evaluated route from source to destination. There are many design and research issues in channel selection, the number of antennas and radios, that must be resolved to enable efficient and flawless communication in the WBAN as discussed in [55].

2.2.1 Physical Layer

Frequency band selection is one of the most important contributions of the PHY layer in WBANs. The radio spectrum includes many frequency bands, but most of them are already occupied as defined in The International Table of Frequency Allocations in Article 5 of the Radio Regulations (Volume 1) (RR nos 5.138 and 5.150) [56] produced by International Telecommunication Union (ITU). The frequency bands will be discussed in more detail in Section 2.3.

The *IEEE 802.15.6* standard specifies three different physical layers: Human Body Communication (HBC), NB and Ultra-Wide Band (UWB). The PHY layer of IEEE 802.15.6 performs following tasks: Clear Channel Assessment (CCA) for CSMA-CA within the current channel, data transmission and its reception, activation, and deactivation of the radio transceiver. The selection of the PHY layer depends on the type of the application such as medical or non-medical. It also depends on the position of nodes, i.e. in, on and off-body sensor nodes. The PHY layer offers a method for transforming a Physical Layer Service Data Unit (PSDU) into a Physical-layer Protocol Data Unit (PPDU). The NB-PHY layer provides specific functions such as the activation and the deactivation of the nodes, data transmission and reception of the channel. The NB is responsible for the CCA within the current channel that is transmitting the signal.

2.2.2 MAC Layer

MAC is a layer 2 of the Open Systems Interconnection (OSI) model also known as sub-layer of the data-link layer. The MAC sub-layer is responsible for a variety of functions including addressing, assigning multiple channels to different nodes and channel access control mechanisms. For multiple nodes in a network to communicate through the shared medium, the MAC sub-layer provides the channel access control scheme known as mul-

Table 2.4: Features of Wireless Technologies for Short-range Data Communications

	Frequency Band	**Data Rate**	**Range**	**Standard**	**Transmission power**
Blue-tooth	2.4 GHz	up to 1 Mbps	1-100 m	802.15.1, WPAN	1-100 mW
ZigBee	2.4 GHz Worldwide, 868/915Eur/US	up to 250 kbps	0-10 m	802.15.4, WPAN	1-100 mW
Wi-Fi	2.4 GHz, 5 GHz	up to 400 Mbps	300 m	IEEE 802.11 (b/g/n)	250-100 mW
6LoWPAN	2.4 GHz	250 kbps	up to 30 m	802.1.5.4/$IETF$	10 mW

tiple access protocol. The MAC protocols, in the case of a WBAN, should be selected in such a way that it consumes the lowest possible power. For short-range wireless communications such as WSN and WBAN, MAC protocols often use Time Division Multiple Access (TDMA) or Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for fair access of the shared medium [39].

Typically, some sensor nodes and one coordinator are organised to constitute a WBAN. A hub or single coordinator (SINK) controls the entire operation of a WBAN. In a single WBAN, there is only one SINK who is either directly connected to all the nodes through star topology (one-hop or two-hop extended star) as depicted in Figure 2.2 to exchange the frames via a forwarder or relay node. The maximum numbers of nodes in a WBAN are limited to 'mMaxBANSize' which makes it inherently small-scaled for different applications.

In a single-channel network, load balancing is sometimes used to balance resources such as energy consumption across nodes or to improve the performance of the wireless network. However, load balancing in the similar neighbourhood is not always essential in single-channel networks for maximising the capacity of the wireless network. Although a comprehensive overview of a dual-band WBAN architecture is proposed in [57] - [58],

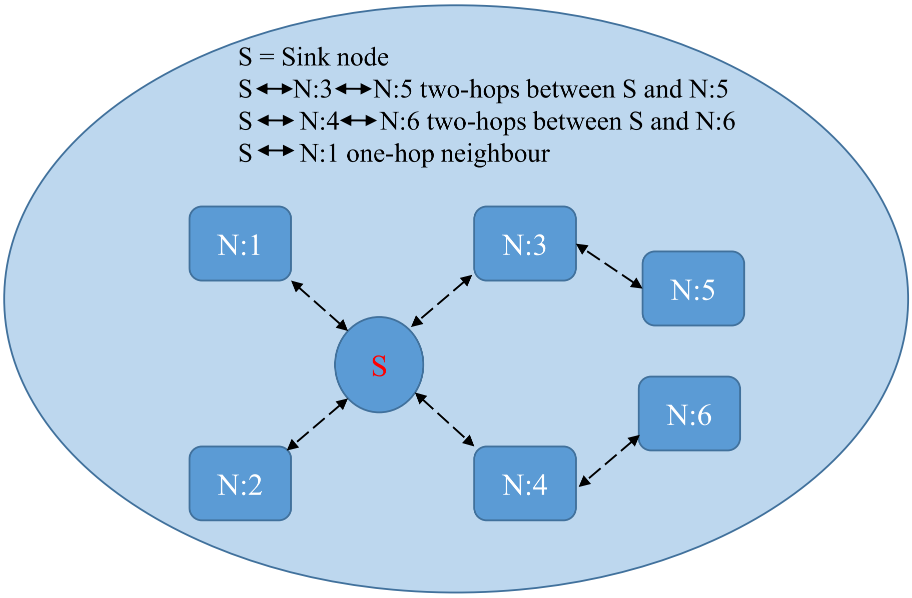


Figure 2.2: Network Topology - Extended Two-hop

and this shows that little or no work has been done on multi-channel routing protocols for the WBAN. Thus, there is a need for a customised routing protocol for multi-channel networks.

The primary requirements of a MAC protocol for a WBAN are reliability, a flexible transmission mechanism, and high channel efficiency [59]. Contention-based and Schedule-based MAC protocols are the two broad categories mainly used in WBANs [38]. In the first one, Contention-based MAC protocols such as ALOHA and CSMA/CA, nodes compete to access the channel, e.g. before transmission. In the second one, nodes access the channel in a synchronised manner using time slots, e.g. via TDMA. The TDMA-based MAC protocol guarantees the real-time life-critical data. However, regarding regular monitoring of patient data at home or in the hospital, such as blood pressure and body temperature readings, the energy and lifetime of a sensor node can be saved with the help of low-duty-cycle CSMA/CA operation.

Contention-based MAC protocols have better scalability with no need to establish infrastructure. However, TDMA-based MAC protocols avoid collisions and reduce energy wastage by explicitly assigning specific time slots to sensor nodes and keeping sensor nodes asleep on other occasions. This kind of scheme is not easy to apply in networks whose structure frequently changes, e.g. WBAN (body mobility). Furthermore, the necessity of synchronisation deteriorates the performance of a TDMA network by introducing a significant overhead.

The CSMA/CA scheme is used in the simulations of this thesis. The CSMAprotocol offers lower delay and reliable transmission of packets in small networks like a WBAN [60]. These protocols can be extended to achieve solutions better suited for multi-channel architectures. The advantages of these protocols are scalability, adaptability to network changes (human body mobility) and no time-synchronisation constraint. The network operates in a multi-hop manner where each link transmits data using the $CSMA$ protocol.

2.2.3 Network Layer

Routing protocols for WBANs are reviewed in [38], [61] - [62], the authors, classify routing protocols into five categories: thermal-aware, cluster-based, cross-layer, QoS aware, and delay-tolerant-aware routing protocols. Finally, particular emphasis is given in [63] and [64] to routing protocols and the cross-layer approach to improving the performance of reactive and proactive protocols. Some of the common objectives in a WBAN are to achieve maximum throughput, minimum delay, and to maximise the network lifetime by controlling the primary sources of energy waste, i.e. collision, idle listening, overhearing, and control-packet overhead. In WSNs, the deployment of sensor nodes (hundreds to thousands in number) covers vast terrain, offering a substantial degree of redundancy, and uses multi-hop for communications. As opposed to WSNs, the WBANs cover an area limited to the body and offered no redundancy, involving only two hops (extended star). Data has to be collected and send it to SINK reliably under unique characteristics such as specific Absorption Ration (SAR) and frequently varying channel conditions [65].

2.3 Dual-band WBAN Technology

To date, most WBANs utilise a single wireless band for communication that can be either NB including the MICS (Medical Implant Communications system) or ISM (Industrial Scientific and Medical) bands, UWB (Ultra-Wide-Band) and HBC (Human Body Communications) band. The ISM band is a freely available portion of the radio spectrum internationally reserved for industrial, scientific and medical purposes other than communications as shown in Figure 2.3. However, there has been a growing interest in multi-channel communication for WBANs to increase the available network capacity, and for interference reduction among neighbouring nodes, energy efficiency, reliability, robustness, connectivity, network throughput, and performance.

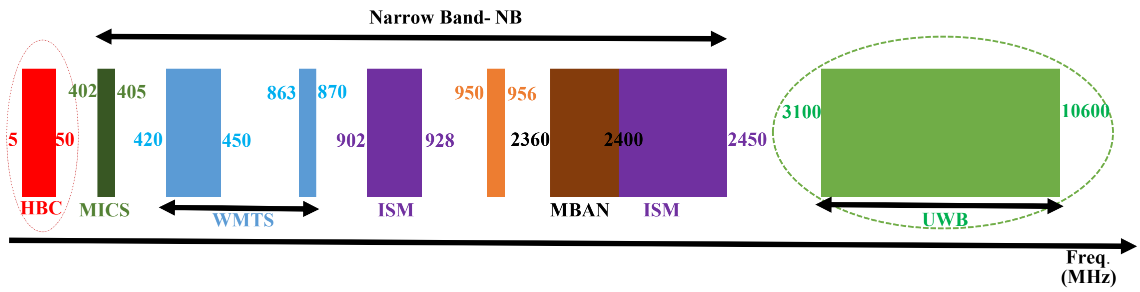


Figure 2.3: Frequency Bands

The Dual-band WBAN sensor node outperforms other single-band sensor nodes regarding variable data rates, categorised as critical or non-critical data and less power consumption [57]. The dual-band also improves and extends the lifetime of a sensor node [58].

2.3.1 Wireless Communication Protocols for WBANs

The leading characteristics of existing standard wireless communication protocols that could be used for WBANs are: Wi-Fi (IEEE 802.11N), Bluetooth (IEEE 802.15.1), Bluetooth Low Energy (BLE), ZigBee (IEEE 802.15.4), ZigBee PRO, and Body Area Network (IEEE 802.15.6) as shown in Table 2.5.

1. Wi-Fi [66] operates in the 2.4 GHz and 5 GHz radio bands. Due to the interference with another type of equipment and high level of energy consumption, sharing the same frequency range, it becomes less suitable for use in small WBAN sensors around the human body.

2. Bluetooth [67] operates at 2.4 GHz, and has been designed for high-data-rate networks such as WSNs, and large battery capacity, which does not match the WBAN requirements as discussed in Chapter 1.

3. The IEEE 802.15.4 [6] is the most widely implemented point-to-point communication standard for low-rate wireless personal area networks. The standard defines robust radio PHY and MAC Layers. The protocol operates in the following frequency bands: 2.4 GHz, and 3.1–10.6 GHz. At 2.4 GHz, the capacity of the band is 250 kbps, at 915 MHz its 40 kbps, and at 868 MHz its 20 kbps. The communication range of some modern devices is 50 m for indoor, and 500 m for an outdoor.

4. On the other hand, BLE [68] provides ultra-low power consumption but, it is not yet supported by many devices such as CC2420. This is built on the traditional and established IEEE 802.15.4 standard for a packet-based wireless transport. It was developed to provide low-power wireless connectivity for a wide range of network monitoring and control applications. It is an open standard operated by ZigBee Alliance [6].

Table 2.5: Features of Wireless Technologies for WBAN

Technology	Frequency	Network Topology	Data Rate	Coverage	Modulation
Bluetooth HS	2.4 GHz and 5 GHz	Star	3-24 Mbps	$\leq$ 10m	GFSK
Bluetooth LE	2.4 GHz	Star	1 Mbps	$\leq$ 10m	GFSK
ZigBee	2.4 GHz	Star, Mesh, Cluster, Tree	20, 40, 250 kbps	$\leq$ 10m	QPSK, BPSK, ASK
Zarlink	402-405, 433-434 MHz	P-to-P	200-800 kbps	2 m	2 FSK, 4 FSK
Narrowband	2.4, 2.4835 GHz	Star	1 Mbps	$\leq$ 6 m	GMSK
ANT	2.4 GHz	Mesh	1 Mbps	$\leq$ 30 m	BFSK, FSK
Rubee	131 kHz	P-to-P	9.6-10 kbps	$\leq$ 30m	ASK, BPSK
RFID	860-960 MHz	P-to-P	10-100 kbps	$\leq$ 100 m	FSK, PSK, ASK
NFC	13.56 MHz	P-to-P	106, 212, 424 kbps	$\leq$ 20 m	ASK
Ultra Wideband (UWB)	3.1-10.6 GHz	Star	110-480 Mbps	$\leq$ 10 m	OFDM, DSUWB, BPSK, QPSK
Sensium	868, 915 MHz	Star	50 kbps	1-5 m	BFSK

2.3.2 Dual-Channel Enabling Technologies for WBANs

Most research to date on multi-channel WBANs has an emphasis on developing the core supporting technologies such as radio system architectures, antennas and simple protocols for link data transfer. The dual-band sensors are presented in [16] - [18] and [69] - [70]. Examples include the following: [16] developed a 433/868 MHz dual-band node with the aim of easing the effects of congestion and failure on reliability and QoS. [17] developed a wireless device that used an alternative HBC link if the main RF link (ISM) became unreliable or blocked; [18] developed a dual-band device that used UWB for data transmission and NB communications to receive control signals to avoid the complexity of a UWB receiver in a small WBAN device. [69] developed an on-body repeater for implant (MICS) to external communication (2.4 GHz). Antennas to be integrated on-body are crucial in catering for various future 802.15.6 wireless standards [70]. The main barrier to implementing these antennas is usually the degraded performance when operating in the proximity of a human body, e.g. the reduced or smaller bandwidth available for the WBAN. Large-bandwidth or multi-band behaviour is needed in multi-application wireless devices for effective on-body sensor communication. Dual-band antenna designs for WBAN applications have been reported by [71], [72] and [73].

WBANs may interact with the Internet and other existing wireless technologies like WSNs, Wireless Local Area Networks (WLANs), ZigBee (CC2420 ZigBee Ready) and Bluetooth 802.15.4. As shown in Table 2.4, those operate in the 2.45 GHz unlicensed ISM band. Hence they create interference issues with each other [74]. Moreover, a multi-channel characteristic would be more desirable, especially when catering to the requirements of multi-channel WLAN operations such as mobile devices to operate on multiple frequencies. In addition to the 2.45 GHz band, many WBAN antennas need to operate in the 5 GHz WLAN band to enable seamless on-body and off-body communication.

The IEEE 802.11 Wi-Fi frequency band comprises many non-overlapping channels that can be allied together in multi-radio to improve the general overall connectivity and efficiency in a WBAN. This kind of mechanism can increase the data rate if the multimedia information is required to analyse a patient's medical condition. Multi-radio, multi-channel availability can also improve the overall end-to-end throughput of WBANs. However, designing effective mechanisms to select channels dynamically is a critical issue that requires attention. Most of the current WBAN systems tend to use commercially available Wireless Personal Area Network (WPAN) platforms such as ZigBee and Bluetooth with the sensor nodes of a WBAN system.

The protocols developed in this thesis are based on market-standard devices and are currently in use in healthcare environments. All of them can operate on the unlicensed 2.4 GHz Industrial, Scientific, and Medical frequency band. Bluetooth and ZigBee are wireless communication technologies used in relatively short-distance environments, whereas Wi-Fi is used for longer distances. Nonetheless, with a mesh topology, a ZigBee network can cover a wide area. ZigBee is the slowest (250 kbps), compared with Bluetooth (1–3 Mbps), BLE (1 Mbps), or Wi-Fi (600 Mbps), but ZigBee's speed is sufficient for monitoring medical sensors.

2.4 Channel Quality

In WBANs, the network formed is either located on the human body or very close to it. Usually, sensors are attached with a fabric-patch or located on a wrist-band. From a channel quality viewpoint, the placement of nodes on the body as well as the path to other nodes have a high impact on the channel quality. In a human body, a direct LOS path with two nodes is impossible, as tissues will absorb the signal and more path loss will occur. The channel quality for WBANs is the major challenge as it limits the possible solutions in finding an optimal route between the source and destination. The accurate measurement of wireless link-quality is essential to dealing with link-quality fluctuations in WBANs. As a multi-channel WBAN system has to determine the best-quality channel among multiple available channels, it requires information on the quality of each channel.

Channel quality can be assessed passively (using actual data transmissions) or actively (using probe packets sent by nodes). The procedure is defined as the probe packets add additional overhead to the routing protocol in estimating link quality. This is shown in Figure 2.4.

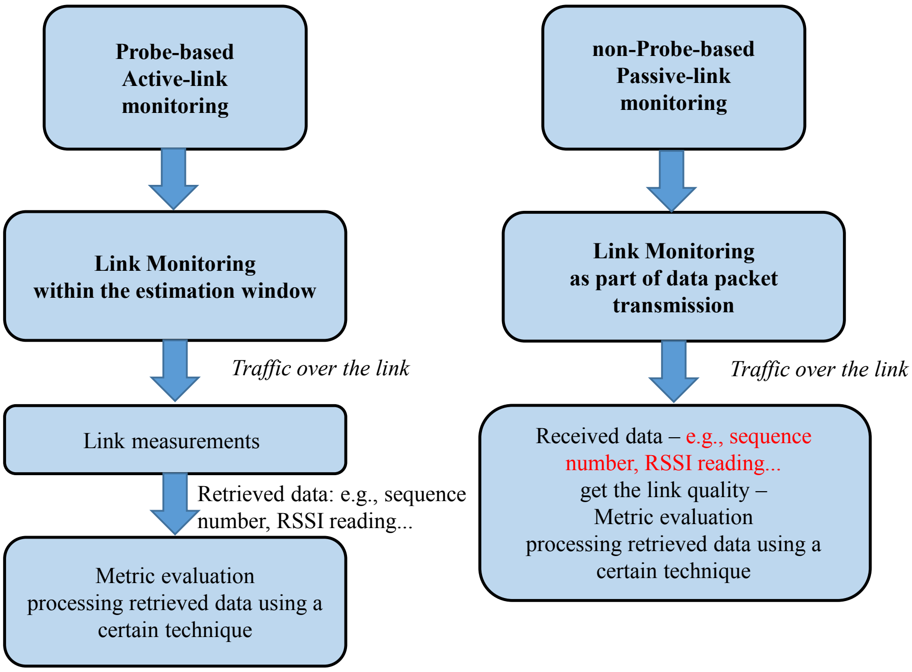


Figure 2.4: Link quality Estimation Methods

Probe-based Channel Quality Measurement

Probe-based channel quality measurement is also known as active link monitoring. The Probe packets are transmitted at a (sufficiently) low frequency, interspersed between data packets. The receiver returned the RSSI values of the probe packets in aggregated form to the coordinator, possibly piggy-backed on the data packets and called a feedback mechanism. As the human body moves, it changes the network layout as well as the network traffic.

Non-Probe based Channel Quality Measurement

Non-Probe based channel quality measurement is also known as passive link measurement. As the name suggests, it exploits existing traffic without incurring additional communication overhead, but instead link quality is measured as part of packet transmission. Passive link monitoring has been widely used in low-power wireless networks such as WSNs and WBANs due to energy-efficiency compared to active link monitoring [75].

Similarly, [76] uses node energy and an Expected number of Transmissions (ETX)-based channel-quality assessment metric for communication. Though this metric is considered reliable for shorter hops, it may still need probe packets that are considered as an expensive operation for a wireless network. Additionally, it only measures channel quality instantaneously. It does not consider the past channel-quality and stability assessment for measuring the accumulative or overall channel quality estimation.

2.4.1 Channel Selection

The analysis of channel selection in WBANs and related networks is still a challenging area of research which is covered in this thesis.

[77] - [78] do not differentiate between good and bad links. On the other hand, there are some multi-channel protocols in WSNs such as Efficient multi-channel MAC protocol (EM-MAC), Decentralised Optimisation for Multi-channel Random Access (DOMRA) [79], Multi-radio Multi-channel Opportunistic Cooperative Routing algorithm (MMOCR) [80], Distributed Routing and Channel Selection scheme (DRCS) [76], and Regret Matching based Channel Assignment algorithm (RMCA) [81] - [82] employ MAC-based mech-

anisms for measuring channel quality.

The Multi-Radio Multi-Channel Opportunistic Cooperative Routing (MMOCR) [80] based on opportunistic forwarding on a channel with the least interference. Each node uses the Cumulative Interference Strength (CIS) as a metric to quantify different channel conditions.

In fact, for routing-protocol performance, it is imperative that the channel selection strategy should be efficient because without dynamic channel selection a routing protocol cannot perform well. Moreover, this process is often based on the metric of characterising channel quality. Thus, in this section, the primary focus will be on a detailed discussion on channel selection strategies proposed for WBANs. There are different goals of channel selection strategies which include maximising throughput and minimising link quality fluctuations in static and mobility scenarios. One important goal is routing, in which the goal of the channel selection strategy is to assign channels in order to fulfil routing requirements. In a WBAN, routing requirements for channel selection include low intra-flow interference between channels, high bandwidth utilisation and maximum connectivity.

In the EM-MAC algorithm, channel quality ranking is maintained through the Clear Channel Assessment (CCA) and mainly focused on instantaneous channel quality measurements. When an interfered channel is encountered by a node, it is marked as black-listed and cannot be used until the end of the session. In this algorithm, previous or past channel quality for the previous links was not considered, which makes it less suitable for mobile nodes in WBANs.

Taking into account link-quality indicators in the establishment of routes is an essential feature for efficient use of network resources such as energy and goodput. Joint estimation of link quality and choice of useful metrics are substantial problems for network-protocol designers. To facilitate the efficient link-quality measurement in a route selection, nodes label every outgoing packet with a sequence number (one-hop), independent of packet type

(RREQ, RREP etc.). Nodes keep track of these one-hop sequence numbers in packets received from each of their neighbours. When there is any sequence number gap identified at a receiver indicates that packet was sent but not received. Each node acquires the downstream knowledge from each of its neighbours efficiently by storing the number of packets received out of the last packets sent. Bi-directional link quality is considered to be the minimum quality value in each direction between a pair of nodes. Nodes would share their local quality statistics with each of their neighbours if they wanted to identify bi-directional quality. This data could be transmitted in a new periodic message. However, to avoid consuming additional bandwidth, these statistics are piggybacked onto the HELLO messages that are already periodically broadcast from each node for the neighbour discovery. When a node receives a quality list from a neighbour, it supplements its local quality statistics for that neighbour with the neighbour's perception of the quality of the link.

2.4.2 Link Quality in WBANs

Poor link quality may lead to poor performance of a WBAN system. If the good links are not selected, nodes in a WBAN still tries to send data on the links that are below a link-quality threshold value. This degrades the network performance. Transmitting data through poor-quality links leads to re-transmission, which severely affects the energy efficiency and reliability [83]. Therefore, a good channel quality measurement scheme is required to maintain adequate network performance. Additionally, irregular link failure increases the communication and computational load on each body sensor [84].

2.4.3 Link Quality Metrics

In this section, a brief presentation of a set of core routing metrics that were examined by empirical studies to capture low-power link characteristics is given:

- Received Signal Strength Indicator (RSSI) is the signal strength of the received packet. When there are no transmissions, the register gives the noise floor.

- Link Quality Indicator (LQI) is measured based on the first eight symbols of the received or incoming packet.

- Packet Reception Ratio (PRR) is computed as the ratio of the number of successfully received packets to the number of transmitted packets. PER (Packet Error Ratio) is a similar metric to the PRR , which is calculated as $1 - PRR$.

- Signal-to-Noise-Ratio (SNR) – It is typically provided by the difference in decibels between the pure RSSI - without noise and the noise floor.

There are two types of link-quality assessment methods existed: software-based and hardware-based methods. The first method mainly uses PRR as a metric. The benefit of using PRR as a metric in the route selection procedure is that it can give an accurate estimation of a link. This protocol [85] established a relationship model between PRR and distance. The link quality can be obtained by this model if the distance is known. However, it is not sensitive enough for link quality status because it needs a time-period to count data packet reception, and also the communication overhead will be increased because the network needs to maintain many probe packets to calculate PRR.

A hardware-based assessment method is widely used in recent years, which uses the value of the sample which is obtained from the hardware of the radio transceiver directly without additional calculation, i.e. LQI [86], RSSI [87], or SNR. The advantage of this method is that, when the link-quality changes, it reacts quickly as compared to the software-based calculations. Based on the signal strength and the detected SNR, an LQI can be calculated which represents the energy and quality of the received data frame. Each packet's LQI is defined as correlation value of the first eight symbols of the received frame.

LQI values are typically between 110 and 50 and correspond to the maximum and minimum quality frames respectively; the higher the values are, the better the channel is. These let a given node calculate the RSSI, LQI or SNR of packets within the node's communication range to estimate the link quality needed for channel assessment [88]. Their advantage is that these estimators do not require any additional computation [89]. In the Castalia simulator, it is implemented as a worst-case SNR. RSSI represents the signal strength observed at the receiver's antenna during packet reception.

The LQI has good correlation with PRR, and thus it gives a better estimate of link-quality over time [88]. Similarly, as the LQI is not a fixed quantity, even though the distance between the nodes is unchanged (in case of static topology); it varies over time due to fading. The causes for fading are multipath reflections from the obstacles present in the surroundings and interference from other sources. Hence the LQI is the vital metric to decide the next hop, and it should be calculated dynamically.

If the link quality is included in the route selection process, several methods are proposed with several QoS metrics including bandwidth, delay, packet delivery ratio and BER. The route selection process should take into account the link quality of a channel. However, most methods proposed for link-quality estimation and best-path selection are not appropriate for the rapid topology changes of a WBAN [90]. The link quality can also be estimated through RSSI measurement [91]. However, the RSSI values are difficult to obtain, especially when a collision happens. The benefits of CSMA/CA mechanism for WBANs [92] is to allow to use RSSI values for high-quality channel selection.

2.5 Routing Protocols

Routing protocols are categorised into proactive, reactive, and hybrid protocols as shown in Figure 2.5.

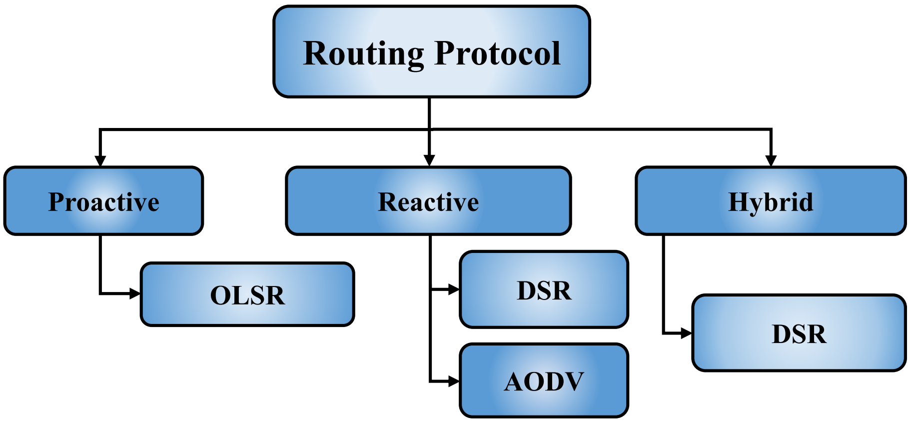


Figure 2.5: Classification of Routing Protocols for WBAN

This Section introduces a general overview of routing protocols for the WBAN. The routing protocols play a significant role in defining the path between source and destination. Several factors affect the performance of the routing protocols such as flooding, network scalability and link capacity. Propagation of a packet from a source node to other nodes in the network is a standard operation in an Ad-hoc network. Flooding is the most straightforward broadcast protocol: each node rebroadcasts the message once and discards duplicates.

2.5.1 Proactive Routing Protocol

For proactive routing protocols (i.e. DSDV and OLSR), every single node stores information in the form of tables, and when any change occurs in the network topology, they need to update these tables. Each node exchanges topology information so that they have route information at any time when required. This protocol is considered as low-latency protocol but may result in much higher overhead due to the frequent routing updates between the nodes.

Proactive routing protocols endeavour to maintain the routing information of all nodes in the network in the form of routing tables even before it is needed. For proactive routing protocols, the latency delay is low as the routing path is only established when communication is required. The routing overhead of proactive routing protocols is higher because the route updates need to span all nodes when links break due to mobility.

One of the main disadvantages of proactive routing protocols in a WBAN is that they require a constant bandwidth and cause a processing overhead to maintain the routing information up-to-date. This overhead increases when the total number of nodes increases and with mobility, since the updates have to be more frequent to maintain accurate routing information.

2.5.2 Cross Layered Routing Protocols

When the MAC and Network layers cooperate with each other to achieve higher performance, it is termed as cross-layer routing protocol [25]. Many researchers and protocol designers are attracted due to its applicability in WSNs. In order to implement it in a WBAN, different cross-layered routing protocols have been proposed [63], [76], [93] - [94].

The Wireless Autonomous Spanning Tree Protocol (WASP) routing protocol [93], increases the packet delivery ratio and decreases the energy consumption as well as the end-to-end delay. However, it does not consider the link quality and two-way communication (bi-directional). Moreover, it does not support mobility. Hence, it cannot be used for dynamic sensor network applications [95].

Cascading Information Retrieval By Controlling Access To Dynamic Slot Assignment (CICADA) [63] is an improved version of WASP. Unlike WASP, It reduces the energy consumption of the sensor nodes by putting them to sleep for enough time. However, it does not support traffic from the SINK to the nodes, which is a primary requirement of the star and extended star or multi-hop WBANs.

Time-Zone Coordinated Sleeping Scheduling (TICOSS) [94] is a cross-layered routing protocol which is designed to improve IEEE 802.15.4 network performance in terms of energy consumption, PDR, and Packet Delivery Delay (PDD) or PLR but sadly it increases the latency.

The Multi-radio Multi-channel Opportunistic Cooperative Routing algorithm (MMOCR) [80] relies on opportunistic forwarding on a channel with the least interference. Each node uses the Cumulative Interference Strength (CIS) as a metric to quantify different channel conditions.

2.5.3 Energy-Aware Routing protocols

In most applications of WBANs, it is not practical to replace batteries over several years; for example, a glucose monitor or a pacemaker is supposed to last for at least five years or longer. Therefore, energy-aware approaches have to be devised to keep nodes working correctly over the required time duration of the batteries. Energy-saving strategies should support uniform energy drain, focusing on balancing energy consumption among all the nodes comprising the network lifetime [38]. The network lifetime is the time between the moment the entire single WBAN is turned ON and the time that the first node runs out of power or energy. Therefore besides the issues above, several causes of energy waste have been identified in WSNs such as collision, overhearing, passive-listening, over-emitting, control-packet overhead and traffic fluctuations. Overhearing is a term used when the node receives packets that are not intended for that particular node. Control-packet overhead occurs when nodes add too many control headers to the payload, and over-emitting means that many retransmissions are required to make a packet reach its destination.

A number of energy-aware routing protocols [96], [97] are proposed on single-channel sensor networks. Unfortunately, like single-channel WSNs, energy wastage due to overhearing [98] from other sensors is a critical factor in single-channel WBANs [99].

There are two categories of energy-aware protocols in WSNs: collision-aware protocols and load-balancing protocols [100]. In collision-aware protocols, when one node is sending data on one channel then the other nodes which are not on the route must be aware that a data transmission is going on and should not interfere. On the other hand, in load-balancing protocols the emphasis is on sharing the resources among all the other nodes, so the pressure does not build upon a single path alone, creating premature energy depletion.

A careful trade-off between communication (i.e. data transmission and reception) and computation is crucial for optimal system design. In addition to decreasing the high demands on the communication channel, the reduced and fair communication requirements save on total energy expenditure and consequently increase battery life. Longer battery life can only be achieved if the communication system in the routing protocol, does not put an extra load on the system design. Also, on-body sensor nodes having longer battery life, low and fair communication loads may benefit patients for constant long-term monitoring for a diagnostic process. These systems will help in achieving optimal treatment of a prolonged condition or can be monitored during the recovery time after the acute event, or surgical procedure, e.g. during knee-replacement rehabilitation.

A balanced energy utilisation in an energy constrained network is the primary challenge in low-power WBANs. Non-uniform energy consumption decreases the network lifetime and QoS, hence it affects the service provider as well as the customer. To improve the energy utilisation, the factors that affect the energy efficiency need to analysed and rectified. The significant factors that influence energy efficiency in IoT healthcare applications are uneven data traffic, the energy hole problem, multiple data re-transmission, and delay.

2.5.4 Reactive Routing Protocols

In reactive or on-demand routing protocols, i.e. AODV, Dynamic Source Routing (DSR), a route is discovered when it is required. In the reactive routing protocols where nodes need to identify the neighbour nodes and $sink/coordinator$ in the network, the connection is established by flooding control packets in the network, which consumes a significant amount of energy.

AODV and DSR are reactive routing protocols that use flooding by changing the Time-To-Live (TTL) value of the broadcast packet to limit propagation in the network. The flooding approach has a high overhead for the multi-path routing protocol (involving broadcast packets and a MAC layer access). Although DSR is a reactive (on-demand) routing protocol, a significant problem is its non-uniform packet size, so an intermediate node may not be able to forward packets of information correctly [101]. The main difference between AODV and DSR is that an RREQ carries the destination address in AODV, whereas in DSR full routing information is usually carried by the RREQ; this infers that AODV has potentially less routing overhead that DSR. Another difference is that RREP carries the destination address and a sequence number in AODV, while DSR carries the address of every subsequent node along the route. Therefore AODV resolves the problem of potential overhead found in DSR.

[102] states that the routing overhead of reactive protocols is lower than the routing overhead of proactive protocols because only the existing routes need to be re-established during a link break. But with multiple channels, delays during route construction could be reduced by sending multiple copies of the data on to different channels. Reactive protocols tend to decrease the control-traffic messages overhead. In reactive protocols, there is no need for distribution of information, as they consume bandwidth when they transfer data from a source to its destination. A WBAN using the unlicensed ISM band can have a limited bandwidth, so the interference could be reduced by assigning different channels to different links, improving the efficiency of the bandwidth usage.

Single-channel Reactive Routing Protocols

Due to the rigorous requirements of WBANs, i.e. low energy consumption, longer network lifetime and low latency, an energy-efficient routing protocol is needed to address these issues. In a single channel, when the same channel is used over many hops, there can be increased interference between links which reduces capacity.

Three common routing techniques exist in WBANs, namely single hop, multi-hop, and cluster-based. In multi-hop routing, data between the source node and the destination node are transmitted via relay nodes. These relay nodes are called the next hops. Different algorithms take into account either the coverage distance or the residual energy of a node as the deciding parameter in the next hop selection. The residual-energy parameter balances the energy consumption among the sensor nodes [103].

2.6 Ad-hoc On Demand Distance - Vector Routing Protocol – AODV

The AODV is an on-demand routing protocol which was initially proposed in RFC 3965 [3]. AODV is a standard destination-based reactive routing protocol. The attractiveness of AODV is due to the fact that it has a distinct structure and low complexity which makes it appropriate to be used by WBANs, where processing and memory resources are reduced [59]. In AODV, routes are discovered on-demand by using pairs of Route Request (RREQ) and Route Reply (RREP) messages, which decreases overhead. Though, the route selection procedure is only carried out created on the minimal number of hops, which is not considered suitable for ensuring energy efficiency and reliable data transmission in WBANs. Two routing schemes are available in WBANs, namely mesh and tree routing. The mesh routing scheme is analogous to the AODV routing algorithm. In AODV, RREQ is sent by the source node to all of its neighbour nodes. The RREQ carries the destination address, and this indicates that AODV has possibly less routing overhead. At AODV, RREP transmits the destination IP address and sequence number, so AODV resolves the problem of potential control traffic overhead. A sensor node consecutively broadcasts an RREQ message on the network, when it wants to send data to the target node. When the transitional node receives the RREQ message, it creates a reverse RREP to the destination sensor node and then checks for a valid path to the destination node in the routing table; it will broadcast an RREQ message in the network if it does not have a valid path. These require periodic updates, which causes network overhead.

A node disseminates an RREQ when it determines that it needs a route to a destination and does not have one available (Send src no-active). This can happen if the destination is previously unknown to the node, or if a previously valid route to the destination expires or is marked as invalid. Before broadcasting the RREQ, the originating node buffers the RREQ ID and the Originator IP address (its own address) of the RREQ (buff push src no-active) for $PATH\_DISCOVERY\_TIME$. In this way, when the node receives the packet again from its neighbours, it will not reprocess and re-forward the packet.

In route discovery process, when a source node wants to send data to a destination node but does not have a route to the destination it broadcast the RREQ by incrementing the RREQ ID and the Destination Sequence Number (DestSeqNum). Intermediate node receives RREQ and sends RREP if it has active route available for destination otherwise it broadcast the RREQ again. An RREQ packet travels entirely in the network, intermediate node receives the packet and adds node address in Routing Table (RT) from which it has received for reversed route (RevRoute) if it does not has a route. Intermediate node or destination node can send an RREP. If the intermediate node has a route to destination (Recv in-active), then it generates RREP and sends it to source node using the reverse route with the new sequence number in a unicast manner (Send Inter RREQ no-active). After receiving a route reply, intermediate nodes establish a forward route to the destination. If the intermediate node has an active route to the destination (SrcActive), the destination sequence number (DestSeqNum) within the node's existing RT entry for the destination is valid and greater than or equal to the DestSeqNum of the RREQ. The intermediate node additionally updates its RT entry for the node originating the RREQ by inserting the next hop towards the destination for the (RevRoute) entry.

Every intermediate node increments the hop-count value by one (HopCount + 1) in the RREQ. The new route is established when a node has a higher sequence number than the sequence number in the RREQ message. The RevRoute is maintained to send back the RREP to the originator of RREQ by maintaining the precursor list for the next-hop from which a node receives an RREQ packet. Every intermediate node, when it receives an RREQ, updates its DestSeqNum if required. It reads the ID of the node from which it receives the RREQ from the RREQ packet and updates it with its own before forwarding it towards the destination. An RREP message is unicast back to the source node over the RevRoute. The source-to-destination route is established when the source node receives the RREP message (Recv dest). If the source receives more than one RREP message, then the RREP message with the higher sequence number is used.

Traditionally, an optimal route is selected based on the distance or the number of hops (Hop Count) between nodes. To ensure the loop freedom sequence numbers are used at the destination. Every node in AODV maintains an RT, but AODV does not maintain the entire route to the destination. Each node only maintains the next-hop information, as this reduces the processing and storage overhead for maintaining routes. A node updates the routing table when it receives a control packet; the routing table will be checked for the existence of entry for that destination [3]. If no matching entry for that destination is found (Recv in-active), a new table entry will be created. If the routing table record for the destination is present, then the sequence number for that destination will be updated.

The control packet updates the SeqNum for that destination if the packet has a SeqNum higher than the DestSeqNum in the RT table. A new route to the destination is found either when the RREQ reaches the destination or when an intermediate node has a fresh enough route to the destination.

The node's RT table make a note of the route it has taken in the past. When the route is not used for a long time, then that route is deleted from the RT table of that node, and this is referred to as the node lifetime. When the destination node receives the RREQ, it generates an RREP. If some route replies are established at the source, then the route with the shortest hop-count is selected. In that case, when the intermediate node fails to forward the packet to the next hop or destination for any reason, it generates a RERR message [3]. When a link breakage in an active route is detected, a RERR message is used to inform other nodes of the loss of the link. When a link breakage is detected, routes to destinations that become unreachable are invalidated. The RERR broadcast mechanism ensures that all sources using the failed link receive the RERR packet, which is also generated when a node is unable to forward a data packet for route unavailability. Every node keeps a "precursor list", containing the IP address for each neighbour that is likely to use it as the next hop towards each destination; this is known as the link breakage reporting mechanism. The source node initiates the route discovery procedure again for the destination when it receives the RERR.

To maintain the local connectivity among neighbour nodes, HELLO Messages are sent with the (Time-to-Live) TTL value set to 1. Every node that is part of an active route should send HELLO messages to ensure local connectivity. If a node does not send a HELLO message or any other packet for $ALLOWED\_HELLO\_LOSS \times HELLO\_INTERVAL$ milliseconds, the neighbouring node will consider that the link to that node is lost. HELLO, packets are sent only when the neighbouring nodes are not sending any packets.

The advantage in AODV routing is that it provides an easy way to get changes in the link situation, but the node may experience substantial delays during route construction and consume more bandwidth as the network size increases. The routing protocols generate small packets, called routing packets, to keep up-to-date information about the network routes. In AODV routing protocols, HELLO packets are used to check whether the neighbour node is active or not. The routing packets do not carry any data packets. Both routing and data packets have to share the same network bandwidth most of the time and hence routing packets are considered to be an overhead in the network. This overhead is called routing overhead. A suitable routing protocol should incur a small routing overhead to the network.

2.7 Challenges for Single-channel Routing Protocols in WBANs

The single wireless channel is mathematically modelled as a pseudo-differential operator. For a network operating on a single-channel, a route is established when each participating node in the route knows the next-hop towards the destination node. However, in a multi-channel network, each node needs to know on which available channel it is transmitting packets along a route until it reaches the next-hop node along with a next-hop channel and eventually the destination.

In the wireless medium, all nodes operate over a common communication channel, due to the broadcast nature of each node. They have to compete with the neighbouring nodes within extended hops, leading to a high collision probability as the traffic load increases [12]. The single-channel for the data transmission increases the number of interferences such as intra-channel interference and data retransmissions [34]. There are several approaches to relieving the data retransmission, interference, and collision problems, such as using directional antennas and employing multiple channels.

The above research studies into multipath routing concentrate on network measurements as path selection metrics when considering static nodes. But in case of mobile nodes in a WBAN, multipath ring routing gives channel diversity but often ignores spatial diversity, and path reliability could suffer as a result.

Current multipath routing protocols [104] - [105] focus on multi-radio and multi-channel, where an intermediate node has to provide improved metrics for path selection and also to address channel assignments and to switch. One possible direction is to combine channel diversity into path selection algorithms [106]. The multipath routing incurs more energy consumption than the single path routing and also suffers from route coupling problem [107]. In a WSNs, routes are considered heavily coupled if transmission on one route directly impedes the qualities of that of the other known as route coupling. Route coupling can be alleviated by making changes at the routing or physical/link layers, such as using multiple channels, or directional antennae.

In the single-channel WBANs, energy wastage due to overhearing from other sensors, collision, control-packet overhead and idle-listening are the critical factors [108], [109] - [110]. It has been observed that multi-path routing has to be used in concert with multi-channel design to improve end-to-end throughput. Existing WSN hardware, such as MICAz and Telos, uses CC2420 radio, which provides multiple channels that can help in reducing the over-hearing problem. CC2420 radio is used in evaluating the routing protocols.

Most of the proposed multipath protocols, like Ad-hoc On-demand Multipath Distance Vector routing (AOMDV) [111], and SMR (Lee and Gerla, 2001), are based on an original single-path version (AODV [112] or DSR [113]). These protocols are reactive routing protocols. In fact, reactive multipath routing protocols improve network performance (load balancing, delay, and energy efficiency). [114] and [115] show that the probability of finding a route between two nodes using a single frequency is significantly lower than the likelihood of finding a route hopping between different channels.

2.7.1 Single-channel Routing Metrics in non-WBANs

A Routing Metric is the deterministic cost value used by the sensor node to determine the best path to the destination node. Routing metrics have a significant impact on the performance of multi-hop networks such as WSNs and WBANs. There are several routing metrics widely used in single-channel routing protocols to determine the best route to the destination. This sub-section will discuss the single-channel metrics used in WSNs and WBANs. Surveys of routing protocols on the basis of different routing metrics are given by [116] - [62]. The analysis of different routing metrics has been discussed in [117] and covers routing metrics such as network delay, bandwidth, path length, load balancing, reliability, energy, and communication cost and so forth.

Hop Count

The hop-count metric has been used to decide the shortest path and has been widely used in existing protocols such as AODV [3], DSR [118], and DSDV [119]. An advantage of the hop count is that it generates minimal overhead in routing packets and that it does not require learning processes to acquire link quality information. However, factors such as interference, transmission rate, link quality and packet loss ratio are not considered. As a result, reliance on a hop count may result in poor performance in some network environments. Since the hop-count metric prefers fewer long hops over several shorter hops, the increased transmission power may be needed by nodes, resulting in increased interference.

ETX

The ETX metric [115] for a link is defined as the expected number of transmissions required to deliver a packet successfully over that link. The performance of ETX becomes low in case of single-channel routing because it neither distinguishes links with different bandwidths nor considers data-packet sizes.

ETT

To include the bandwidth and different link transmission rates, an Expected Transmission Time (ETT) [54] is proposed, which is an improvement over ETX. It is basically an ETX adjusted value to give the expected time to transmit a data packet. However, similar to ETX, the problem of ETT is that it still does not adequately capture the inter and intra-flow interference in the network. For example, ETT may choose a path that only uses one channel, even supposing a path with more differentiated channels has less intra-flow interference where higher throughput exists than using a single channel.

In this thesis, simulation results confirm that the multipath, multi-channel AODV protocol provides better end-to-end delay values and better routing stability with less data loss and good throughput.

2.8 Multi-channel Routing Protocols for WBANs

The principle of the multi-channel routing protocol is to establish several paths between the source node and destination node using multiple channels from the available bands. Multi-channel based communication protocols can improve network throughput and the quality of communication services. The multi-channel WSN is an emerging technology with varied applicability in different fields of life, e.g. sports, medicine, science, engineering, civil and environment control. To support multi-channel communication in a

WBAN network of devices, including a Body Network Controller (BNC), requires the development of multi-channel routing protocols and MAC protocols.

Multi-channel based communication protocols improve the network throughput and the quality of communication services. Many solutions [77] and [120] present multi-channel designs implemented at the MAC or the link layer, which is not sufficient for efficiently utilising multiple channels. [77] proposed a multi-channel allocation strategy which is based on dynamic route allocation algorithm, which reduced data delay and increased the throughputs. Multi-channel routing protocols have been used previously in other kinds of networks such as WMNs and ad-hoc wireless networks. The most recent survey of multi-channel routing protocols in WSNs can be found in [121].

As far as radios are concerned, a multi-channel WBAN device may use a single or multiple radios. The sensor device may also have a single or multiple antennas. A simple device architecture is to use multiple radios with each radio having its antenna, as this avoids the complexity of switching between radios. This approach is employed in this thesis because it is the easiest way to include multiple channels into a simulation model. Although in practice, there is an additional effort regarding cost and size involved with multiple radios and antennas. Separate MAC modules for each band are used to avoid the difficulty of two nodes trying to find a common channel for sending and receiving data – It is called the rendezvous problem. This thesis presents new multi-channel routing protocols specifically designed to exploit multiple channels in WBANs.

As discussed earlier, the routing protocols developed for WSNs are not well suited for WBANs, because of the performance of the routing protocols; the throughput and packet delivery ratio (PDR) degrades as shown in [45]. Specialised routing protocols are needed for WBANs to meet the stringent requirements of WBANs, e.g. throughput, battery lifetime. The proposed routing protocol in this chapter aims to introduce the benefits of multi-channel utilisation in the routing protocol for the WBAN. The multiple channels are used to enable parallel transmissions and hence allow fast data gathering at the sink while reducing collisions [122]. It is necessary for a routing protocol to ensure that routes are carefully distributed in the network to get the benefits of multiple channels [123].

In [124] a multi-channel version of AODV called CA-AODV has been proposed. In this protocol, the source node randomly picks a channel from the set of all available channels, if it does not have a channel yet to transmit. Any node that receives an RREQ packet selects a channel that none of its former k-hop neighbours had chosen. The RREQ message conveyed the node-ids and channel numbers that its n preceding nodes were using. This method of channel selection might be practical in WMNs that have many channels available, but in WBANs there are usually only a small number of channels available so that the approach is less practical.

In [125] a review of multi-channel MAC protocols has been presented and proposed a multi-channel MAC protocol called MMAC. They compared parallel-rendezvous, dedicated-control-channel and split-phase multi-channel MAC protocols. It is mentioned that a switching penalty could be a significant factor in multi-channel MAC protocols that use frequency hopping. At times routing functions have been combined with MAC channel functions, such as in opportunistic routing. The disadvantage of this scheme is the long time it takes to assign channels to the new nodes. Opportunistic routing was extended to the multi-channel case in [126].

2.8.1 Multi-channel Routing Metrics in non-WBANs

In multi-channel, multi-hop wireless network environments, most routing metrics use key network components such as the number of hops, link quality and capacity, isotonicity, channel diversity and so on. Surveys of routing protocols for WBANS are given by [61] and [127]. Multi-channel based communication protocols can further improve network throughput and the quality of communication services.

The analysis of different routing metrics have been discussed in [115] - [116] and [128] that cover routing constraints such as bandwidth, network delay, path length, load balancing, reliability, energy, communication cost and so forth. The isotonicity reflects the ability of a routing metric to compute minimum-weight, loop-free paths.

In [113] and [129], routing protocols are proposed for multi-hop WSNs that typically preferred shortest-hop routes and do not incorporate load balancing. In particular, the proposed routing protocol in this thesis is developed to satisfy the requirements of network lifetime extension by minimising the energy requirements, which is the core operating requirement of WBANs.

Similarly, [96] have utilised the node energy, and an Expected number of Transmissions (ETX) based channel-quality assessment metric which was considered best for performing future communication. Although this metric is reliable, it may require probing packets and, consequently, is costly to carry out.

[130] presented a new routing metric for multi-radio, multi-hop wireless mesh networks and multi-channel networks called Weighted Cumulative ETT (WCETT) which allocates weights to individual links built on the ETT of a packet over that link which uses the same channel. As a result, the WCETT of a route with hops can be the sum of the ETTs of all the hops along with that path. The WCETT metric is designed to trade-off channel diversity against the delay. The WCETT metric is one that has been developed for multi-channel networks to increase channel diversity and is based on the ETX and ETT metrics. WCETT is proposed as an enhancement to ETX that uses only the loss rate but not the link bandwidth. WCETT also supports mobility which makes it very productive for the WBANs in terms link stability [131].

By capturing interference between the neighbouring nodes using the same channel and overcoming the non-isotonic problem, Metric of Interference and Channel switching (MIC) [132] proposed which improves the WCETT. However, MIC does not measure interference dynamically, with the implication that alterations to the interference level over time due to signal strength indication and traffic load may not be captured accurately.

Similarly, a multi-channel protocol is proposed [30] where each sensor node maintains a utility function and the performance matrix is based on the past information that helps to predict future flows/network topology and expected actions of neighbouring nodes. Channels are assigned accordingly. In this protocol, future channel assignments are based on predictions about the past-knowledge of flows only. However, it does not consider current channel quality assessment. In this thesis, the interaction between the physical and routing layers are exploited.

2.8.2 Advantages of using Multi-Channel Routing Protocols in WBANs

Most research to date on the WBAN routing protocols has been for single-channel communications. To obtain the most out of these research studies and to support WBAN applications over a full WBAN network of devices, requires the development of routing protocols that are personalised towards multi-channel operation. In this thesis, the focus is on the extension of the single-channel routing protocols to the multi-channel routing protocols. To our knowledge, this thesis is one of the first studies to investigate multi-channel routing protocols for WBANs. Using a single channel may result in interference and bring channel collision and energy inefficiency [92]. The traditional routing protocols for a multi-hop wireless network, such as the AODV routing protocol and the Dynamic Source Routing (DSR) protocol, can be used in multi-channel networks, but do not get optimal performance [130]. These routing protocols typically select shortest-hop routes, in which the channel diversity, interface switching cost, and interference along a path are ignored. Thus a multi-channel routing protocol is needed [133] for WBANs. The routing protocol must perform channel assignment as well as route discovery and maintenance.

The provision of multi-channel also allows more concurrent transmissions and thus enhances the network capacity. As in [120], a single transceiver per node is considered better for a dense network as in MANETs. Different scenarios were considered. In the first setup, every node has a single transceiver and broadcasts the routing information over all channels. After gathering the route information, a sender node switches to the destination node's channel and start sending packets. This assumes that every node has at least one neighbour for every channel. This case is not applicable for a WBAN, as these networks are considered to be sparse networks because of the limited number of nodes and short communication range [134]. In the second setup, there are nodes with multiple radios that can act as relays and forward packets from one channel to another. This scheme requires enough nodes with multiple radios to establish routes between any pair of nodes in the network.

The problem of routing in multi-channel WBANs targets the creation and the maintenance of wireless multi-hop paths among various nodes by deciding both the next hop and the available channels to be used on each link of the path. Such a problem exhibits similarities with routing in multi-channel, multi-hop WBAN networks such as ad-hoc and mesh networks [114].

Channel Diversity

The use of the same channel by the consecutive hops of a path may result in significant co-channel interference and a reduction of the overall throughput. Channel diversity is a kind of performance gain compared to a single-channel scenario, produced by assigning different channels to different links within a path so that they can be active simultaneously. The extent to which this can be achieved can be expressed as channel diversity [135]. The multi-interface feature is utilised by considering the channel diversity of the routing path. Obviously, channel diversity is only relevant for multi-radio networks, subsequently, in single-radio networks, all interfaces are required to operate on the same channel to guarantee connectivity [136] - [137].

Interference Mitigation

In wireless networks, several protocols estimate link quality in order to enhance the performance of the network. Though, a defined categorisation of wireless links in realistic networks is a challenging issue, since the links may experience frequent channel variations and exhibits involved interference between neighbouring nodes. There are two types of interference exists in a network such as inter-flow interference and intra-flow interference. The intra-flow is the same flow, but between different hops whereas, the inter-flow interference exists between different neighbouring nodes in the network.

Using multiple channels helps in reducing interference between the nodes and channels, and thus improving the network communication. Current WSN hardware such as MICAz [138] and Teleosb that uses CC2420 provides multiple channels (16 channels - 5 MHz spacing in between the centre frequencies) that can help in reducing the overhearing problem to conserve energy. However, designing mechanisms to select channels for a multi-channel WBAN routing protocol dynamically is a critical issue that requires attention. Interference between parallel transmissions can cause severe performance degradation in WSNs. While the multiple channels available in WSN technology such as IEEE 802.15.4 can be exploited to lessen interference, channel allocation can have a significant impact on the performance of multi-channel communication.

Interference mitigation is a primary concern for a dual-band sensor-node design [57], as opposed to the current multi-channel routing protocols in WSNs that mainly target reduced interference. An exciting action was taken by the Federal Communications Commission (FCC) on May 2012 to allocate 40 MHz of spectrum from 2.36-2.40 GHz on a secondary basis for a new Medical Body Area Network (MBAN) licensed service. This will be an efficient way to mitigate the interference experienced by devices working in the adjacent ISM unlicensed band.

One of the primary objectives of this dissertation is to enhance the throughput of the network and the network lifetime through efficient route and channel selection and interference reduction. The interference between sensor nodes increases the phenomena of collisions/retransmissions or routing overhead, which demand an extra energy consumption causing premature failure of some nodes

2.8.3 Multi-channel MAC Protocols

The MAC protocols in WBANs should be selected in such a way that it consumes the lowest possible power. A multi-channel protocol not only needs to select a path in between different nodes and eliminate the need for retransmissions, but it also needs to select the most appropriate channel or radio on the path.

A multi-channel system can be built in four different ways: Single transceiver on a single radio, multiple transceivers on a single radio, multiple radios each with a single transceiver and multiple radios each with multiple transceivers. Routing metrics developed for multi-radio WBANs may not be applicable for single-radio multi-channel WBANs.

The standard WBAN employs a star topology over a single channel using a MAC protocol based on contention. However, this may lead to energy inefficiency and high data latency, because many nodes may want to concurrently send data to a sink node on that one channel with one radio transceiver [139]. In a single-radio multi-hop environment, co-channel interference reduces the capacity of a single-radio multi-hop wireless network [130].

[78] shows that duty cycling can be supported in energy-efficient routing protocols by reducing idle listening and overhearing, two of the most substantial causes of unnecessary

energy consumption in WSNs. Idle listening refers to a node listening to a wireless channel when there is nothing on the channel to receive, and overhearing relates to a node hearing packets not intended for this node. Usage of multiple orthogonal channels alleviates the overhearing problem [109].

Multi-channel MAC Single Transceiver

The most significant problem in using multiple channels is that current hardware devices such as CC2420 have only one radio transceiver. A single-NIC architecture limits the whole wireless network to operate in one single channel. The wireless multi-hop networks, in which each node is equipped with a single radio interface and all radio interfaces work on the same frequency channel, often suffer low channel utilisation and poor system throughput due to transmission or reception happens on one channel at a time, even though nodes can switch channels very quickly, i.e. $(80\mu/s)$. Therefore, in future work, we will choose to enable cross-channel communication by equipping each node with multiple 802.15.6 commodity NICs each operating on a different channel. Cross-channel communication is possible between two nodes when either node has a channel-switching capability or has multiple NICs and each node tuned to operate on a separate channel. Channel switching requires fine-grained synchronisation between nodes as to when any node will transmit/receive over a particular channel. Such fine-grained synchronisation is challenging to achieve without modifying 802.15.6 MAC.

The capacity of multi-hop wireless networks can be increased by using multiple Radio Frequency (RF) channels simultaneously for packet transmission. The capacity increased even further because of the reduction of PLR due to inter and intra-flow interference. However, this approach presents new glitches. For example, a node cannot operate on multiple channels at the same time having only one RF transceiver. Hence, devices with only one transceiver are required that can switch from one channel to another within a short period of time. Deafness occurs if two nodes cannot communicate with each other because they operate on different channels. However, this problem can be resolved when the transmitter and receiver are tuned to different channels [140] - [23].

Multi-Channel, Extremely Opportunistic Routing (MCExOR) [23] is an opportunistic routing protocol that operates with one RF transceiver per device . This multi-channel, single-transceiver solution solves "deafness" for the single RF transceiver devices and allows both flow and node channel assignment.

Multi-channel MAC protocols are required to increase system throughput and to reduce signal interference among interfering nodes [141]. The multi-channel MAC protocols are divided into two classes depending on the number of transceivers: having one transceiver or multiple transceivers (≥ 2). The performance of having two transceivers is better than that of having one due to the ability to receive and transmit packets simultaneously, and the capacity to receive multiple packets; however, this is accomplished at the expense of higher hardware complexity and cost.

Conversely, our proposed solutions are designed to be practical and to run smoothly on existing low-cost ZigBee devices such as CC2420, which have only one transceiver. Therefore, our MAC approach falls in the first class; for this reason, in the following, multi-channel MAC protocols using only one transceiver are used in this thesis.

2.9 Weak Aspects of Multi Channel Routing Protocols

Multi-channel routing protocols raise new challenges or make existing ones more complex. The use of multiple channels allows parallel transmission without risk of interference, and therefore increases the number of paths that can be active simultaneously. A potential source of interference in dual-channel WBANs could be caused by the network load on all the sensor nodes [25]. The sensor nodes should keep track of the network load capacity and avoid the highly congested routes. Other problems with multichannel communication include:

1. Multi-channel deaf node: A transmitter wrongly considers a destination node to be unreachable because it does not get any response to its requests. This occurs when the destination node is tuned to another channel when the transmitter is trying to communicate with it.

2. Multi-channel hidden node: In a single channel condition, the hidden node problem may occur in a configuration with at least three nodes, where at least two nodes are out of each other's radio range. In a multichannel environment, the hidden node problem occurs when the node misses an RTS/CTS exchanged on one channel while listening on another, causing the hidden terminal problem despite the use of RTS/CTS signaling.

3. Internal and External interference: Due to the broadcast nature of the wireless medium, the performance of a multichannel wireless network is drastically limited by interferences due to concurrent transmissions on the same or adjacent channels in the same network.

4. Stability of links: Radio links in WBANs are often unpredictable. Indeed, their quality fluctuates over time and space. Therefore, selecting high quality links is essential for data delivery. While the problem of links stability exists in single channel WBANs, it is more challenging in multichannel WBANs.

2.10 Benchmarks

A benchmarking listing is required to experimentally evaluate and compare the behaviour of various multichannel routing protocols. The development of benchmarking methodologies is essential to support the required underlying comparison and selection processes according to trade-off factors exhibited by eligible multichannel routing protocols, such as performance and energy consumption. Nevertheless, by the time being, there is a lack of benchmarks in the domain of the routing protocols used in WBANS.

The following benchmarks in the domain of WBANs can be basically classified into the following categories:

- Timeliness, encompasses the measures that indicate the time required in order to deploy a communication, e.g., end-to-end delay, round trip time, jitter, etc
- Throughput, which gathers those measures used to identify the traffic transmitted or received in the communication, e.g., number of packets received, goodput, packet loss, etc.
- Quality of Service (QOS), which groups those measures used to assess the correctness of established communications, e.g., nodes density, link quality, out-of-order packets received, etc.
- Resources consumption, such as bandwidth consumption, that gathers those measures addressed at measuring the expenditure of resources required to establish a communication, e.g., routing protocol overhead, packet size, duplicated packets rate, etc. Energy. It gathers those measures addressed at measuring the expenditure of energy required to establish a communication, e.g., power, voltage, energy consumption, etc.

2.11 Chapter Summary

This Chapter presented a brief overview of WBANs, the 802.15.6 standard and the importance of multi-channel routing in WBANs. The first section introduced the importance of using innovative dual-band technology in WBANs. The next section then reviewed the routing protocols used for WBANs for single and multi-channel WBANs. Also, challenges were discussed when considering the implementation of existing non-WBAN (i.e. WSNs and MANETs) communication protocols into a WBAN. This Chapter also presented the solutions for the best channel and route selection in multi-channel, multi-hop WBANs. The multichannel extension of Castalia was thoroughly described in this Chapter. After that, it then discussed that the single-channel metrics for multi-channel WSNs are not compatible with multi-channel WBANs. Parameters such as throughput, energy consumption, end-to-end delay, packet delivery ratio, network resource balancing and routing overhead were also discussed for a single as well as multi-channel WBANs.

Chapter 3

A Multi-channel Routing Protocol based on RSSI Channel Selection for Wireless Body Area Networks

Contents

3.1 Introduction

A Wireless Body-Area Network (WBAN) constitutes a network of on-body sensors attached to a human body. The placement of on-body nodes as well as the paths to other nodes or the collector node (Sink) has a significant impact on the channel quality. From a channel quality perspective, this has severe implications for finding an optimal route that delivers packets efficiently as well as consumes less energy. A direct Line-Of-Sight (LOS) path with two nodes is impossible, as bodily tissues will absorb the signals and more path loss will occur. Single-channel routing protocols use a single wireless channel between the source and the destination or the intermediate nodes [142]. This sharing causes contention and aggravates packet loss, which could decrease the Packet Delivery Ratio (PDR). The channel quality for WBANs is a major challenge for wireless networks as it restricts possible solutions. Because of the miniature design, the energy consumption will have to be very limited. Routing protocols for WBANs suffer from the poor-channel-quality paths available in the network.

The benefits of multi-channel operation appear to come from the capacity to reduce the number of nodes trying to communicate with each other, leading to fewer control messages being sent and better convergence. The main distinctive feature for multi-channel protocols is the ability to support different communications channels. Some nodes may have access to more than one physical medium, or a node may be allowed to change the channel during a routing operation. In this chapter, a multi-channel version of the Ad-hoc On-Demand Distance Vector (AODV) routing protocol [3] is developed and implemented in Castalia [143].

A key aspect of the proposed protocol in this chapter is that it is a multi-hop, multi-path, multi-channel routing protocol for WBANs. This protocol also emphasises the development of channel selection algorithms that choose which channel to be used between two nodes. The hop-count metric was used to determine the best route. The protocol was tested using simulation over two channels in the ISM 2.4 GHz band (2.400-2.485 GHz).

The multi-channel AODV protocol with Link Quality Estimators (LQE) based channel selection is compared against a Multi-Channel AODV based on Random channel selection (MC-AoRand) and the single-path Single-Channel AODV (SC-AODV). The simulation experiments show that in terms of packet delivery Multi-Channel AODV based on RSSI (MC-AoRSS) performs equally with SC-AODV but with a lower overhead of AODV control packets, better routing stability and slightly better energy per bit efficiency. In this chapter, the primary motivation is on better channel selection methods and routing stability assessment for the dual-channel routing protocol in WBANs. The dual-channel AODV helps in reducing the number of nodes trying to communicate with each other, leads to a fewer number of control messages being sent, and achieves better routing convergence.

The rest of the chapter is structured as follows. Section 3.2 discusses related work in a detailed manner and defines the motivation of the research. Section 3.3 explains the operation of the multi-channel routing protocol and Section 3.4 explains the underlying system model. Section 3.5 gives a detailed discussion on the implementation of the routing protocol using Castalia. Section 3.7 explains the architecture of the Communication Module and how it can be modified for multiple channels. Section 3.8 explains the multi-channel modification for the routing protocol. Then Section 3.9 discusses the performance evaluations of the proposed protocol. And finally, Section 3.11 draws the conclusions.

3.2 Background and Motivation

The objective of this chapter is to develop a multi-channel routing protocol that aims to perform joint channel-quality assessment and selection to achieve less control-traffic overhead, better routing stability, and energy efficiency in WBANs.

Multi-channel routing protocols have been used in other kinds of network such as Wireless Mesh Networks (WMNs) and Mobile Ad-hoc Networks (MANETs) such as [78], [80], [124], [125], [144], [145].

An Efficient Multi-channel MAC (EM-MAC) protocol [78] was proposed. A node in EM-MAC independently collects channel-condition information, as a by-product of regular transceiving operations, without extra energy consumption. EM-MAC does not send probing packets to determine the channel condition because such a proactive channel-condition measurement approach increases the node energy consumption and network traffic. The proposed protocol in this chapter has assumed that no probe packets will be used to determine the channel quality, to save expensive resources such as energy consumption in EM-MAC.

The Distributed Routing and Channel Selection (DRCS) protocol [80] is a joint channel-selection and quality-aware routing scheme for multi-channel WSNs to improve the battery life and increase the network lifetime. In this scheme, improvement of the battery life is made by reducing the energy consumption resulting from overhearing neighbouring nodes, and also by dynamically balancing the individual battery life among nodes.

A multi-channel version of AODV, called Congestion Adaptive-AODV (CA-AODV) [124] was proposed. In this protocol, if the source node does not have a channel yet it randomly picks up a channel from the set of all available channels for that node. Any node that receives a Route Request (RREQ) packet selects a channel that none of its former k-hop neighbours has selected. The RREQ message conveyed the node-ids and channel numbers that its k previous nodes were using. This channel selection procedure may be practical in WMNs. WMNs have many channels available, but in WBANS there is usually a small number of channels available, so this makes that approach less practical here.

In [125] a multi-hop routing protocol was developed to function over an Ad-hoc 802.11

Wi-Fi network with nodes equipped with multiple 802.11 NICs with the aim of improving performance when deployed in a WMN. A distributed channel-allocation algorithm was developed, that uses only local traffic load information.

[145] Multi-Channel Extremely Opportunistic Routing (McExOR) selects the optimal candidate forwarders under a given channel assignment in a single-radio and multi-channel WMN. The channel selection and assignment was not considered, and this technique is only suitable for a single-radio network.

3.3 Multi-Channel AODV Protocol based on RSSI Channel Selection (MC-AoRSS)

The proposed MC-AoRSS protocol is designed to be a source-initiated multi-channel on-demand routing protocol, similar to AODV. It is extended to the multi-channel case. The single-channel AODV has already been discussed in Chapter 2. In this section, the extensions made for multi-channel AODV will be discussed. The first section is to estimate link quality using RSSI values which are readily available from the Castalia simulator [143].

The proposed algorithm in this chapter MC-AoRSS is based on a multi-channel AODV routing protocol, so it uses the same control messages as AODV [3], such as RREQ, RREP, RERR, and Route Reply Acknowledgement (RREP-ACK) with a multi-channel modification in mind.

3.3.1 Message Formats

This sub-section below describes the message formats of the control packets used.

Table 3.1: Modified RREQ Format

Type	J	R	G	U	Reserved	Hop Count
RREQ ID						
Destination Sequence number						
RSSI						
Incoming Channel						
Outgoing Channel						

Route Request Packet Format

The RREQ packet in MC-AoRSS contains the extra fields RSSI, Incoming Channel and Outgoing Channel, and it specifies on which channel RREQ has to be forwarded, keeps track of the RSSI value of the last 8 received packets, and records the average RSSI value.

Route Reply Format

The RREP packet in MC-AoRSS also contains RSSI values required by the next-hop node for sending data to the node currently handling the RREP and vice versa.

Route Error and Route Acknowledgement Format

The RERR and RREP-ACK packets in MC-AoRSS have the same format as in RREP.

Routing Table Entries

MC-AoRSS has a slightly modified routing table with one new entry named nextHopChannel (channel for the next hop) which specifies the selected channel based on the RSSI values required to send a packet from the current node to the next hop. A number of modifications were made to extend single-path, single-channel AODV to make it a multi-path, multi-channel routing protocol.

1. The first modification in MC-AoRSS is to incorporate channel selection so that, when a node has a packet to send to a given destination and needs to send an RREQ message, it first selects a channel over which to broadcast the RREQ message.
2. The second modification is developing a neighbour table for selecting the best RSSI containing neighbours for the next-hop.
3. The third modification is to modify the Medium Access Layer (MAC)-layer for the cross-layer information from the Radio layer and includes in the routing table entries for a given destination, the next-hop-channel along with the address of the next-hop node.

3.3.2 Channel Selection

When an RREQ packet is received by the destination node, it needs to select a channel for the route. The AODV is extended to multi-channel AODV by adding a channel selection procedure and next-hop-channel information into the routing table. Separate RREQ timers are used for each channel. The channel selection comprises two methods DCHRand and DCHRSSI:

Randomised Channel Selection (DCHRand)

In a randomised channel selection, a node selects randomly one of the free channels available. The main advantage of this approach is that no global view of the network is required.

AODV with the Multi-RREP (AODV-MR) protocol [146] is a multi-route reply-based AODV routing protocol. In this protocol, the routes are formed using a random channel selection instead of the optimal channel. As a result, links frequently get saturated and suffer from interference. The interference among channels essentially causes the routes to break-off prematurely, thereby causing new route discoveries. These route discoveries increase the routing overhead to 90% for each data packet transmission. Moreover, the increased flooding of unwanted control packets leads to higher energy consumption.

On the other hand, optimal channel selection using LQE, i.e. RSSI and Link Quality Indicator (LQI), improves the channel selection process as in EM-MAC [78]. In this proposed protocol, the dual-channel node independently collects the channel-condition information, as a by-product of regular transceiving operations, without extra energy consumption.

RSSI-based Channel Selection (DCHRSSI)

Instead of choosing a channel randomly, the observed link-quality information could be taken into account to select a channel. In RSSI-based channel selection, the RSSI values are recorded for all the channels on which the node receives incoming packets. New RSSI values overwrite previous values. Each channel also has a max_{time} parameter that specifies the maximum amount of time that an RSSI value is maintained for the channel. When a channel is to be selected using the RSSI method a test is first done to determine that each channel has received an RSSI value that was no older than a maximum allowed time call max_{time}. This is done to ensure that stale values of RSSI are not used.

If all channels (two channels in this case) have valid RSSI values (If all RSSI values are not stale), then the channel with the most substantial RSSI value is selected. As the incoming messages are received, the Radio module determines RSSI values, and this information is passed up through the MAC module to the Routing module which records the current value of each, and the time the latest value was received. The implementation of this module is described later in Section 3.6. If one or more RSSI values are out of date, then a channel is selected at random as an alternative.

3.3.3 Route Discovery

(a) When a node has packets to send, it initiates a route discovery by broadcasting a Route Request(RREQ) packet via multi-channel broadcast [3]. In a multi-channel network, nodes may stay in different channels [25]. Thus, the RREQ packet must be broadcast on all channels, as opposed to one channel in a single-channel protocol. The number of RREQ packets transmitted is at most kn, where k is the number of channels, and n is the number of nodes in the network. For a single-channel routing protocol which uses flooding for route discovery, the overhead is at most n [25]. The route discovery process is initiated by a source node, which broadcasts an RREQ packet over all channels. Each new route discovery initiated by a node uses a unique sequence number which is included in all RREQ packets. The modified RREQ format is shown in Table 3.1.

Suppose node S wants to send packets to node D with two channels. Also, suppose that source node N=3 was initially on channel 1. Then, S broadcasts RREQ in all channels, one by one in a round-robin manner. More specifically, S broadcasts RREQ on channel 1, switches to channel 2, broadcasts RREQ on channel 2, and so on. The RREQ packet sent over a channel i at a node S contains the channel index i, as well as the RSSI values of using channel i at node X, as shown in Figure 3.1.

Each RREQ contains an ID; the source and the destination nodes, channel and sequence numbers together with a hop count and control flags. In the route entry, all fields except channel, RSSI, and LQI are also in AODV. The channel field specifies the channel that the next hop node is listening on. So the node has to transmit a packet on the channel indicated in the channel field to reach the next-hop. The RSSI field is the average correlation value for the first eight symbols which are appended to each received frame (the received RSSI value).

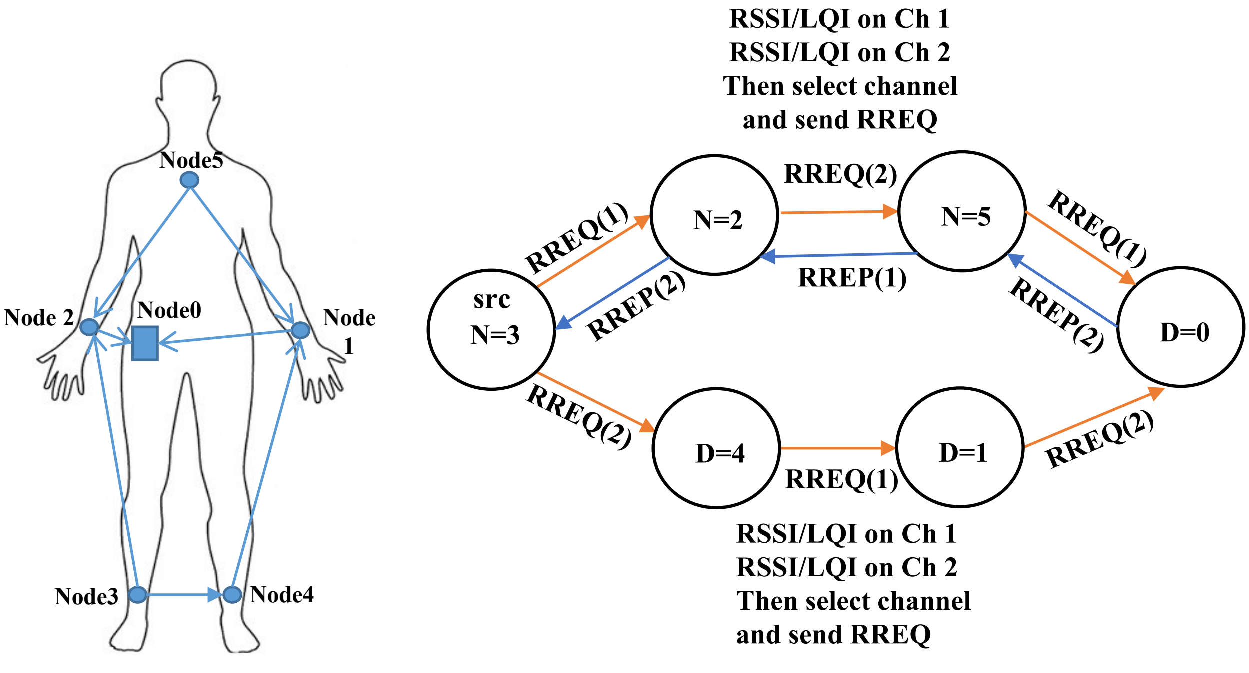


Figure 3.1: Route Discovery Procedure

Note that during the route-request process, nodes keep switching channels. Therefore, a deafness problem may occur temporarily.

(b) When an AODV source node N has application data to send to an AODV destination node D if N is an active route to D, it just begins sending the application data using AODV DATA packets to the next-hop node using the next-hop channel in its routing table. If it does not have an active route to D, it re-initiates a route-discovery process by broadcasting an RREQ message on all channels for that destination. When that RREQ message is received at an intermediate node, a next hop entry back towards the source is created in the intermediate node's routing table using the immediate source of the RREQ message as the next-hop back towards the source.

(c) When an RREQ message is received the next selected node address and incoming channel are stored as the next-hop node address and the next-hop channel back to the source in the routing table. There is a function named UpdateNeighbourTable that updates the RSSI values along with the new sequence number. The UpdateNeighbourTable function updates quantities from the local Radio when a packet is received.

(d) Later, when the intermediate nodes receive the matching RREP, RREP is sent back to the source node by using the next-hop address and a next-hop channel. Also, the next source address and incoming channel of the RREP message are stored as the next-hop address and next-hop channel for forwarding packets and messages to the destination. Later, when a route has been established, all DATA packets are unicast using the next-hop address and next-hop channel information stored in the routing table.

AODV retransmits RREQ messages if an RREP message has not been received in a given time. The RREQ retransmission queue is modified such that the selected channel an RREQ was transmitted from was stored with a message so that the RREQ message could be retransmitted on the same channel as previously. For HELLO messages each channel is managed separately, and each channel has its own HELLO expiry and refreshes timers as shown in Figure 3.2. With RSSI, when a node sets up a reverse path to the source node, it needs to know to which channel the next-hop node is listening. In order to provide this information back to the node, a node includes its operating channel (the channel which the node was on before broadcasting the packet) in the RREQ packet. This channel information (Chann) is used by the nodes that received the RREQ packet to establish a reverse path to the source node. Finally, RREQ packet reaches the destination. Then node D selects the channel which is to be used for the flow. The channel selection mechanism is explained earlier. After selecting a channel, node D sends an RREP to node S using the reverse path.

3.3.4 Route Maintenance

Hello, messages are used to detect and monitor links to neighbours. When Hello messages are used, each active node periodically broadcasts a Hello-Message on all channels (e.g. Hello(chann) chann = 1..n) that all its neighbours receive. Because nodes periodically send Hello messages, if a node fails to receive several Hello-messages from a neighbour within a ExpireHello timer Expire(Ch) , a link break is detected. If the data is being delivered and a link break is detected, a Route Error is sent to the source of the data in a hop-by-hop way on the same channel. When the source node S receives the RERR packet, it invalidates the route and re-initiates route discovery if necessary [147].

If the current receiving node has not received this RREQ before and it is not the destination node, and it does not have a current route to the destination, it rebroadcasts the RREQ message and refreshes Refresh(ch). When a node receives RREP messages, it regularly broadcasts HELLO messages so that its neighbour nodes are aware of the node's continued presence. There are separate timers for all channels available as shown in Figure 3.2.

3.3.5 Data Forwarding

As the RREP propagates back towards the source, each intermediate node creates a next-hop entry with a next-hop channel number in the routing table towards the destination using the immediate source and next-hop channel of the RREP message. When the initial source receives the RREP message, it records the next hop to the destination in its routing table, thus stating that there is an active route to the destination. Then it responds to the RREP message with an RREP-ACK message that is sent to the destination, and it begins sending data to the destination using DATA packets. Each time a node receives an RREP message, the node updates its routing table with the next-hop channel if the

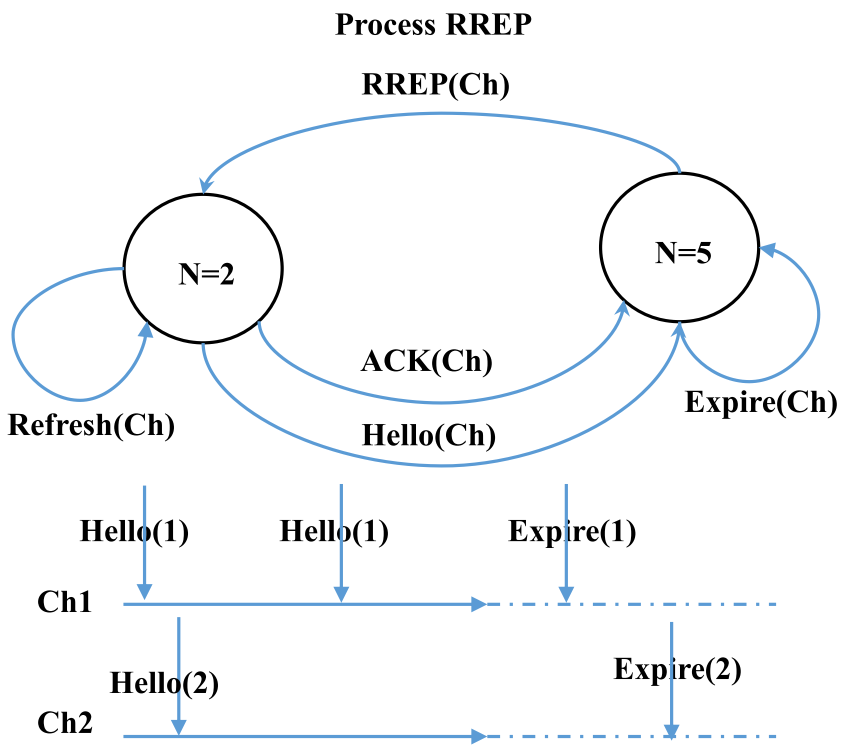


Figure 3.2: HELLO Messages

RREP message indicates that a route with fewer hop counts to the destination has been found. As data start flowing from the source node to the destination, each node along the route updates the timers $ROUTE\_UPDATE\_TIMEOUT$ associated with the routes to the source and destination. If a route has not used for some period, a node cannot be sure whether the route is still valid. A route expiry-timer times out and the node removes the route from its routing table.

If the receiving node is the destination or it already has an active route to the destination node, it generates an RREP message that is unicast in a hop-by-hop fashion back to the source node using the previously stored next-hop node and next-hop channel information in the node's routing table. An intermediate node responding in such a way reduces the number of control messages sent in the network.

3.4 Dual-Channel WBAN System Model

The WBAN system model consists of K dual-channel nodes as shown in Figure 3.3. Each node has two antennas with each antenna supporting broadcast communication over a separate frequency channel to other nodes.

3.4.1 Dual-channel Sensor Node Structure

The structure of a dual-channel node that is implemented for the dual-channel routing protocol is shown in Figure 3.3. It consists of Application, Communication and a Resource Manager modules. The Application module is the source and sink of all application data transmitted and sends sensor data (source) to the sink BNC (Body Network Controller). The Communication module supports the transmission of data between nodes. It consists of one Routing Module, two independent MAC modules and two Radio modules. The Routing module implements the multi-channel AODV protocol developed in this chapter.

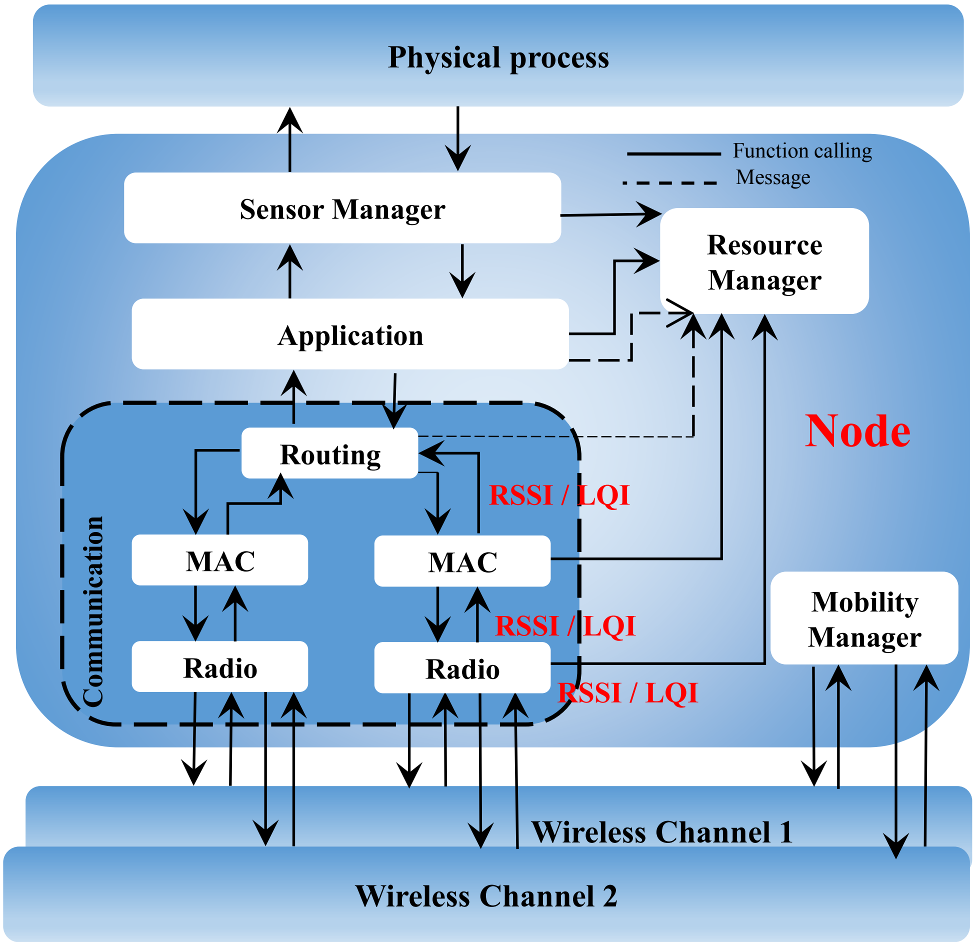


Figure 3.3: Dual-Channel Castalia Node Structure

As shown in Figure 3.3, the Communication module is composed of three functional modules, i.e. Routing, dual MAC and dual Radio modules. The MAC modules each contain an instance of a single band MAC protocol. Each of the two radios is a single-band radio with a separate wireless connection to isolate two Wireless Channel modules. The Radio module not only transmits and receives signals but also accepts signals whose signal strength is above the radio receiver sensitivity. It also provides RSSI (Receive Signal Strength Indicator) and LQI information about channels to higher-layer modules. Each Wireless module operates on a different frequency channel and is responsible for broadcasting wireless signals to other nodes.

The implementation of multi-channel routing protocols was done in Castalia, as detailed in the next Section

3.5 Castalia - Simulator

3.5.1 Overview

Castalia is used for developing and implementing multi-channel routing protocols in this thesis. Castalia is a discrete event simulator for WSNs and WBANs. It is written in C++ language and based on the popular simulation platform OMNeT++ [148] which is a general network simulator with a modular and simple implementation. OMNeT++ version 4.4 and Castalia version 3.4 running in a Linux operating-system environment were used in this thesis. Castalia developed by National ICT Australia (NICTA) in 2010 and is released under an Academic Public Licence (APL). Also, users and developers can receive support from a dedicated forum [149]. Castalia is highly parametric which makes it suitable for simulating a wide range of applications in different platforms. One of the main advantages of Castalia is the realistic modelling of wireless and radio channels, resulting in a realistic node behaviour and primarily interacting with the wireless medium. This feature makes Castalia an attractive option for researchers who wants to test their protocols.

The decision about which simulator fits better was made based on these reasons:

- Advanced ***Channel Model*** based on empirically measured data
  - Model defines a map of path loss, not simply connections between nodes
  - Complex model for temporal variation of path loss
  - Fully supports mobility of the nodes
  - Interference is handled as RSSI, not as separate feature

- Advanced ***Radio Model*** based on real radios for low-power communication
  - Probability of reception based on the Signal-to-Interference-and-Noise-Ratio (SINR), packet size, modulation type. Custom modulation allowed by defining Signal-to-Noise Ratio (SNR) and Bit-Error-Rate (BER) curve.
  - Complex model for temporal variation of path loss
  - Multiple TX power levels with individual node variations allowed
  - Flexible carrier sensing (polling-based and interrupt-based).
- ***Routing and MAC protocols*** are available (ByPassRouting and Multipath Ring Routing) thus allowing the user to enhance its functionalities, and create and import new modules.
- Designed for ***adaptation and expansion***, As the intention is to develop a multi-channel architecture inside the simulator, new complex and simple modules and their interfaces are easy to include.

With the base simulator chosen, the next step is to define the requirements that the multi-channel simulator needs to satisfy and the single-channel Castalia does not fulfil.

- Multiple frequencies, channels and modulations implementations: An essential characteristic is to bring the possibility of changing communication parameters such as multiple frequency bands, multiple communication channels or modulations.
- Routing protocols have not been enhanced. By default, only a ByPassRouting module was added to the simulator which bypasses routing module. They are prepared to accept any routing or application implemented by researchers in order to validate their specific implementations.

- The Radio module processes the incoming messages from the wireless channel and detects interference among them. Also, this module manages radio parameters such as carrier frequency, bandwidth, bit rate or modulation type.

The multi-channel simulator can use all these features to create more realistic scenarios in WBANs. For that purpose, the original Castalia implementation will be discussed first, and then, in Section 3.8, improvements and modifications will be discussed to provide multiple channel capabilities to the simulator.

3.6 Castalia Architecture

Castalia treats a wireless sensor network as a collection of sensor nodes as shown in Figure 3.4. In Castalia, nodes are not directly connected to each other but instead communicate through Wireless Channel and Physical Process modules. The Wireless Channel is responsible for delivering the messages. Also, it models the path losses. A Physical Process module implements the physical events which provide the simulator with the ability to model environmental-sensor acquisition data.

Modules communicate with messages that may contain arbitrary data, in addition to the usual attributes such as a time stamp. Simple modules usually send messages via gates, but it is also likely to send them directly to their destination modules. These gates are the input and output interfaces of modules: messages are sent through output gates and arrive through input gates [143].

3.6.1 Sensor Node Structure

Each Castalia sensor node consists of five modules including Sensor Manager, Application, Communication, Resource Manager and Mobility Manager modules. The Communication module is a composite, or compound, a module which consists of three sub-modules

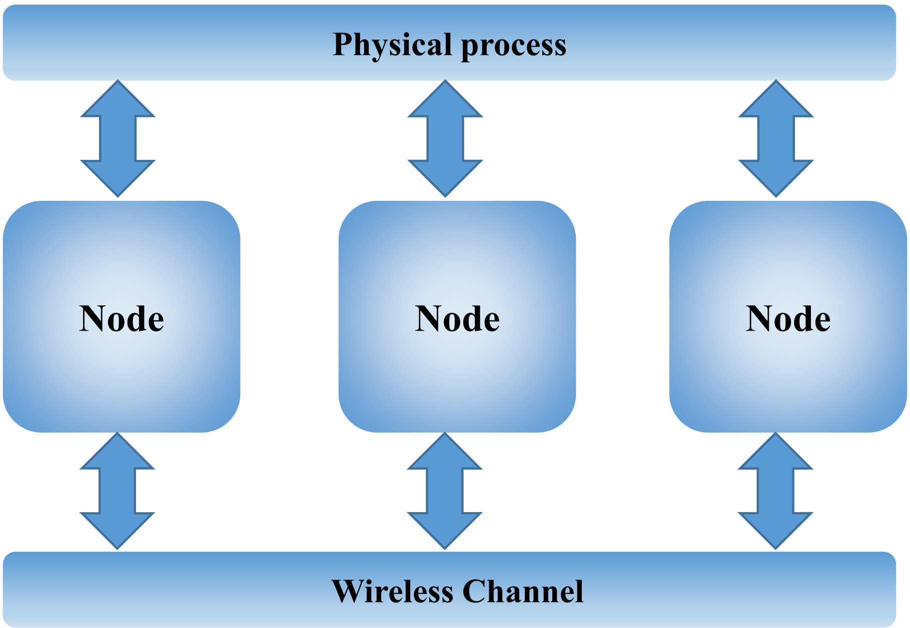


Figure 3.4: Overview of a Castalia Sensor Network

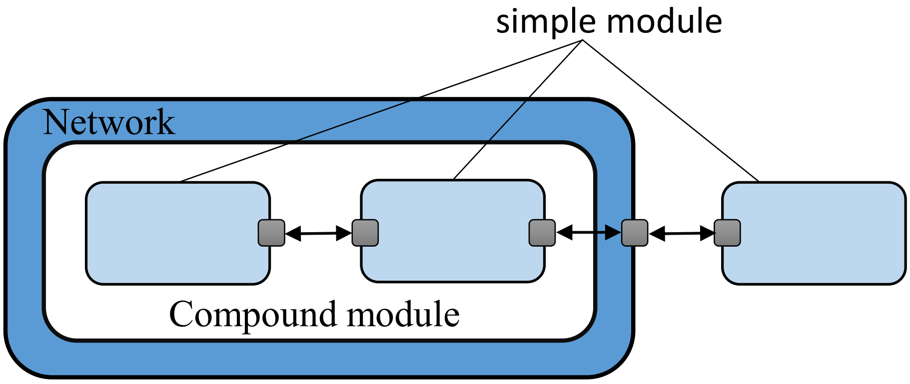


Figure 3.5: Castalia Implementation for Compound Modules

including Routing, MAC and Radio as shown in Figure 3.6 and as will be discussed in more detail later in the Section 3.7.

The Sensors Manager module implements the actual sensing devices on the node and is responsible for collecting data from the environment through the available Physical Processes. Then it alerts sense data to include the distortion due to realistic sensing devices. Finally, data can be provided to an application running on the

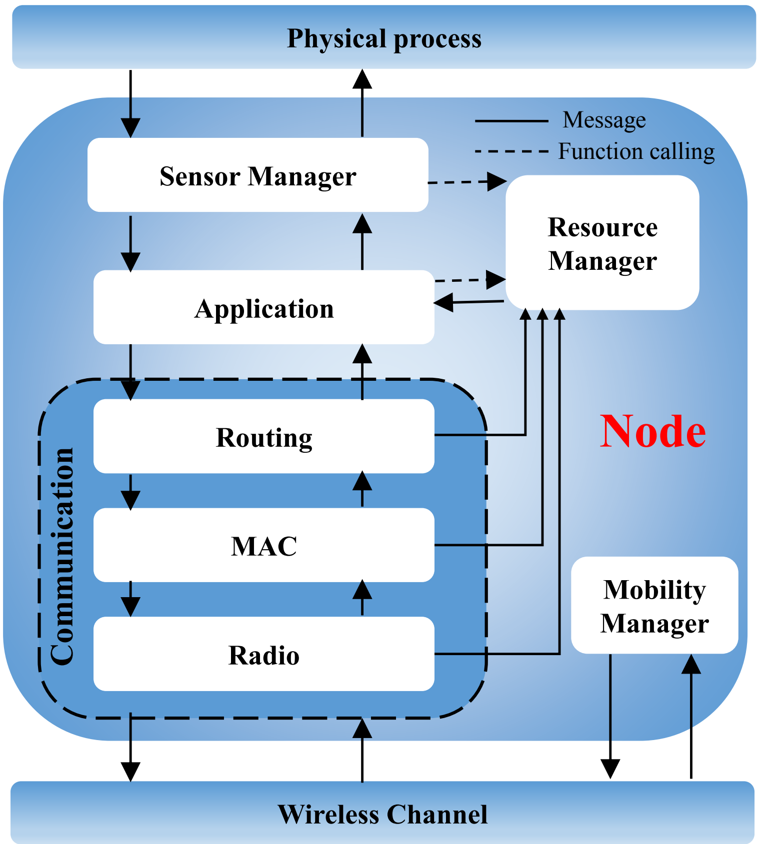


Figure 3.6: Interior Structure of the Single-channel Castalia Node

sensor node. A Sensor Manager establishes a one-to-one correspondence between each sensor and the Physical Process module when there are complex interactions.

The Application module represents the application software running on the sensor node. This layer is responsible for receiving sensed data from the Sensors Manager module, processing the data according to the application specifications, and dealing with packets' forwarding and reception. Castalia provides a number of simple although effective applications, aimed at testing its main features, and making the user familiar with the simulation framework, such as *"Throughput test"*, *"Value propagation test"* and *"'Value Reporting test"'*. The throughput Test application is configured to send data from all other nodes to the sink node.

The Resource Manager module is solely responsible for the battery status (energy spent by the node), CPU state, and memory of each node. To do that, modules that implement hardware devices (i.e. the Radio and the Sensors Manager modules) notifies how much power they have drawn to the Resource Manager. Then the consumed energy is calculated both periodically, and each time a variation of power occurs. Also, the Resource Manager module owns node-specific information such as the clock drift and the baseline power consumption, i.e. the minimum power that the node consumes. Castalia supports a linear energy-consumption model. The computation of energy consumption is the primary task for the Resource Manager. Every single module's setting specifies the amount of energy used by the sensor node.

The Mobility Manager module deals with how sensor nodes move through the simulated space. It keeps track of each node location over time and makes such information available to other modules of the same node through a function call. Also, it is responsible for periodically notifying the current node position to the wireless channel. Its operation is described in more detail in Section 4.5.

3.6.2 Wireless Channel Modelling

The wireless channel is a difficult medium to model, especially when taking into account mobile nodes, a changing environment (e.g. in the WBAN case: the body posture is changing). The central aspect of wireless channel modelling is the estimation of the average path loss between any two nodes. Using an accurate channel model is an important issue in order to have a realistic environment model and meaningful results. To do so, Castalia bases its path-loss model on two components: the average path loss and the temporal variation model.

The average path loss (PL(in dB)) is given by the log-normal shadowing model [143] given by the equation.3.1.

$$PL\,(d) = PL\,(d_0) + 10 * \eta * log(d/d_0) + X_\sigma \tag{3.1}$$

where d is the distance between the receiver and transmitter in metres, $PL\,(d_0)$ is the known path loss at a reference distance, $X\sigma$ is a random-Gaussian-mean variable with zero mean and standard deviation, and η is the path loss coefficient. This formula returns path loss in dB as the function of the distance between two nodes. A probability density function (pdf) consists of the component of the path loss due to temporal variations to get the new values of mobility.

Although the two traffic directions are typically treated as independent links, the Wireless Channel model returns an average path loss for both directions. Castalia adds and subtracts a separate Gaussian zero-mean random variable with a specified standard deviation, whose value is supposed to be small (1:0). By doing so, it is possible to control the correlation between the two traffic directions.

Furthermore, the Wireless Channel model provided by Castalia takes into account the presence of mobile sensor nodes within the network. Thus, information about the path losses between points in space must be kept, rather than between actual nodes. To do that, Castalia organises the simulated space as a collection of discrete cells. Then path losses from each cell to each other cell are computed. If only static nodes are considered, each one of them is treated as a special cell, as is discussed in more detail in Section 4.5.

Average-Path-Loss Modelling

A critical aspect of the Wireless Channel modelling is to estimate the average path loss between two nodes or, in general, two points in space. The close-to-reality path loss model presented in Castalia is a result of explicitly setting their path loss map in Castalia and not following the log-normal shadowing model that is generally used for simulations of WSNs. A log-normal shadowing model is suitable for a WSN because the distance between two nodes could be the order of a hundred metres, but in WBANs the distance between two nodes could be 2-3 metres. In that case, the log-normal shadowing model is not correct if the correlation between the two directions of a link needs to be captured.

If the two directions are treated as independent links, the variance will be much more significant than the one experienced in reality. For this reason, as discussed in the previous section, Castalia uses the model to return an average path loss for both directions of a link and then adds and subtracts a separate Gaussian zero-mean random variable with standard deviation. However, with mobile nodes, the average path loss would not be enough for modelling the Wireless channel. More details about temporal-variation modelling and interaction between the wireless channel and nodes' radio can be found in the following subsection. In Castalia, the average path loss between any specific pair of nodes remains fixed, and it provides the option of endowing it with an instantaneous/temporal component.

Temporal-Variation Modelling

Estimation of the average path loss between any two nodes is the central aspect of wireless channel modelling in a WBAN. The current version of Castalia computes the instantaneous path loss of a link as the sum of the mean path loss between the two nodes and the temporal variation at that moment. At NICTA, experimental test-beds were created to capture hundreds of thousands of measurements to define a path-loss map to develop realistic models. In this case, the pathlossMap files that are generated from experimental measurements implicitly integrate human body mobility such as walking on a treadmill, since each one relates to a particular posture and body type.

During the channel initialisation phase, the average-path-loss (spatial variation of the wireless channel) is defined in the pathlossMap file, which is based on those real on-body measurements that were taken by the NICTA. On the other hand, the temporal variation of the Wireless Channel (i.e. Chann1 and Chann 2 to Chann n) is defined in another file named TemporalModel.txt. The Wireless Channel model in Castalia was enhanced with the average-path-loss measures derived experimentally for this thesis.

Due to the rapidly changing environment in a WBAN, the small-scale fading can be modelled theoretically. Since the actual path loss may differ very significantly from the average path loss during the time, a *probability density function (pdf)* is produced to deal with this problem, and it is defined from the last observed value of the path loss and from the time that has passed since then. Castalia records that last simulated path-loss value and the time elapsed since that value was computed, then it will generate a pdf. The pdf cannot be produced dynamically from the actual model, but it has to come from experimental measurements [143] provided by NICTA. Castalia provides configuration of extension ini for such pdf descriptions, but it is intended for the WBANs. The sum of the pre-computed average path loss and temporal variation is used to calculate the actual path loss.

3.7 Communication Module

The actual communication stack of sensor nodes is comprised of three sub-modules – Routing, MAC, and Radio. Figure 3.7 shows a Castalia modules list in a hierarchical structure.

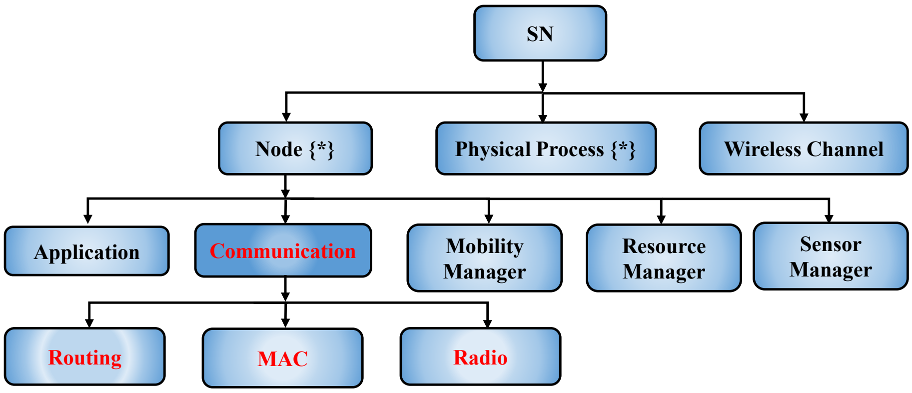


Figure 3.7: Castalia Module Hierarchy

3.7.1 Routing

The Routing module in Castalia receives less attention than the other communication modules such as MAC and Physical-layer modules. There are a few necessary routing protocols implemented and released with Castalia. However, due to the Castalia support group's [149] efforts, a few more single-channel, single-path routing protocols were also implemented such as AODV [150], REL [151] and a multi-path routing protocol Collection Tree Protocol (CTP) [152], but they are not included in the official Castalia distribution. As has already been discussed in Chapter 1, that in a single-channel environment, nodes lying on a single path will share the same channel, again and again, leading to contention and back-off.

If the network layer is considered, Castalia provides two necessary routing protocols, *bypassRouting* and *multipathRingsRouting*. BypassRouting does not implement any actual routing protocol for any network but instead passes on messages to the upper layer. On the other hand, multipathRingsRouting (MPR) is a ring formation protocol, which defines a sink node as a collector and organises connected network nodes in different levels. During the setup phase, each node receives a level number or a ring number without any specific parent. More specifically, the sink node starts the setup phase by transmitting a setup packet with its level no. 0. Upon receiving such packet, a node adds 1 to the level and broadcasts it to other nodes. This process goes on until all connected nodes have a level number. To send a packet from a source node to the sink node, a source sensor node broadcasts the packet, including its level number. Then any node with smaller level number rebroadcasts the packet. This process ends when the sink receives the packet. MPR allows multiple paths for data transmission between the sensor node and the sink.

This routing protocol ensures data reliability as far as any one of the available paths is reliable. However, in WBANs, link quality fluctuations compromise the reliability of any path. Unnecessary traffic is created at every transmission, as all nodes are forwarding the same packet towards the sink during the setup phase. The excessive forwarding leads to a collision, and as a result, the network might be easily congested, and its performance can be severely affected. In particular, nodes have no information on the energy levels of their neighbouring nodes. Flooding towards the sink can lead to higher overall energy consumption. Summing up, it is observed that MPR is not a good option for critical-energy systems such as WBANs.

A multi-channel routing protocol can be designed by combining an existing single-channel routing protocol with a new routing metric by considering multi-channel effects [95].

3.7.2 MAC

The MAC protocol is an integral part of the node's behaviour. This section presents three MAC modules, i.e. TunableMAC (TMAC), IEEE 802.15.4, and BaselineBANMac.

The **802.15.4 MAC** module implements the core functionality of the MAC part of the IEEE 802.15.4 standard, but some features are not implemented in Castalia, which makes it less practical for multi-channel routing protocol implementation for WBANs.

The **Baseline BAN MAC** module is an implementation of the IEEE 802.15.6 standard in BAN MAC. Since the polling mechanism is out of the scope of this thesis, and readers are referred to [153].

Tunable MAC is a duty-cycled MAC, which reflects the behaviour of a simple CSMA/CA MAC protocol, and does not support acknowledgements and RTS/CTS control packets. It also exposes many parameters to the user and the application for tuning. The experiments with CSMA-CA (Carrier Sense Multiple Access With Collision Avoidance) also provide values influencing carrier sensing [92].

TMAC is a contention-based MAC which employs a CSMA mechanism for transmissions. It can be tuned in terms of its persistence and backing-off policies. Another primary function of TMAC is to duty-cycle the radio since the nodes are not aligned with their sleeping schedules. An appropriate train of beacons is diffused before each data transmission to wake up potential receivers. It also provides several other parameterised functions such as retransmissions, probabilistic transmission, and randomised TX offsets. In the protocol implementation, to save energy in WBANs, TMAC is used for its energy-saving properties in WBANs.

3.7.3 The Radio

The Radio module makes an effort to reproduce the behaviour and features of real low-power radios. The Radio model simulates the conversion of bits to signals and vice versa. The Radio model gives the complete state transition for the radio, allowing multiple transmission power levels.

Three radios are already defined in Castalia distribution: CC2420, CC1000 by Texas Instruments, and BANRadio which describes the Narrow-band radio proposed in the IEEE 802.15 Task Group 6 documents [143]. The Radio model operates with event messages received from the Wireless Channel. Messages indicate either the start or the end of a transmission. The start-transmission message carries information about the signal's ID, RSSI, modulation technique, carrier frequency, and encoding method. The ending signal takes only the ID of the signal. Therefore, the transmission of a packet has a duration (i.e. the transmission time), and it is not a single event in the simulator. As a result, signals from multiple sources are interfering and overlapping with each other. Whenever a transmission-start or end-message is received by the Wireless Channel (i.e. at every signal change), Castalia calculates the SINR of every signal and based on modulation type, and radio parameters, the bit error rates on every signal are computed.

Finally, whether a packet is received or not at the receiver end, is based on encoding and bit errors during the total time of packet transmission. When the radio is on the RX (Receiving) mode or the listening mode, it integrates the total received power over some Radio symbols. The result of this integration is the RSSI value which can be accessed from the MAC layer. The function of how to retrieve an RSSI value is described in detail in Section 3.8.1. The RSSI is compared with a programmable threshold to determine if the channel is clear or not.

Castalia supports five modulation schemes: Frequency-Shift Keying (FSK), Phase-Shift Keying (PSK), Differential Quadrature Phase Shift Keying (DiffQPSK), Differential Binary-Phase-Shift Keying (DiffBPSK), and Ideal modulation (which enables disk-model). Castalia also calculates fine-grain interference (dynamically changing during packet reception) and the calculation of real bit errors in a packet [143].

Reception and Interference Calculation

The signals are calculated at Wireless Channel as part of the simulator and then provided to the Radio module for processing. This module (in fact representing a single wireless node) has a list of the incoming signals at any time. When the signal is received without any other signals at the same time (according to the parameters defining the start and the end time of the current signal), the SNR is calculated based on the noise floor and the

RSSI. Given the modulation scheme, the data rate, and length of the packet/signal, the number of bit errors per packet is calculated based on the SNR. The success of reception [143] is determined based on the encoding and BEP. The interference is calculated if other signals are received at the same time. All of the received signals are just added up together with the noise floor to establish the SINR.

There are three different models that define the interference between nodes. In the first model, `NO_COLLISION`, as the name states, there is no collision happening at all. The second model, which is known as `ADDITIVE_INTERFERENCE`, always produces a collision at the receiver end, but only if that receiving node receives two or more signals (even though some of them have minimal strength) at the same time. The last model `COMPLEX_INTERFERENCE`, it considers the strongest signal of them all and adds all weaker signals as noise, then based on the Signal-to-Interference-Ratio (SIR), the signal is considered received or ignored. In that case, the success depends on the SINR and the parameters of the simulated radio [143].

3.8 Castalia Multi-Channel Architecture

To implement multi-channel functionality in Castalia, the internal structure of the single-channel model is modified as shown in Figure 3.8. Figure 3.9 shows the new simulator structure. The single channel code has been modified as slightly as possible to introduce the least changes to third-party applications and module implementations.

In a multi-channel system, the sensor nodes can communicate with each other through multiple Wireless Channels (i.e. Wireless Channel 1 and Wireless Channel 2 in Figure 3.9). In the new multi-channel model, the Communication module is comprised of multiple MACs (MAC1 and MAC2), Radios (Radio1 and Radio2) and a Routing module which can be configured with different parameters that allow simulating multiple interfaces in

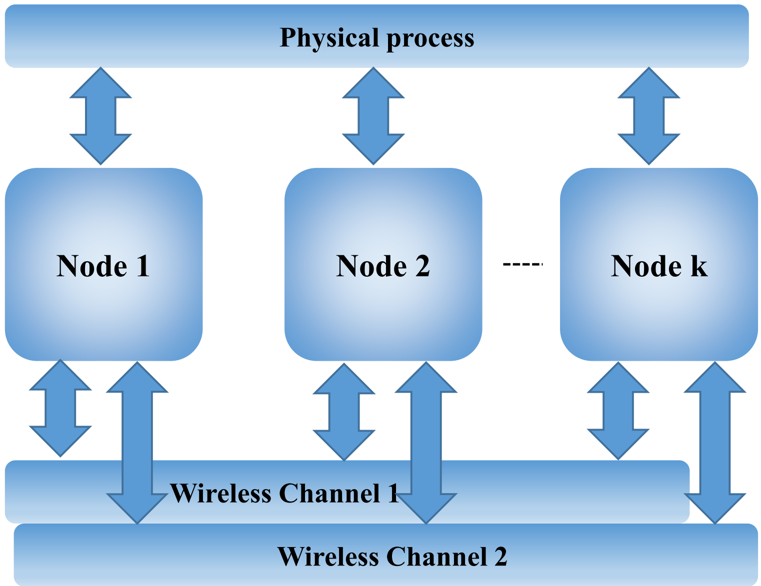


Figure 3.8: Overview of a Multi-Channel Sensor Network

a wireless node. Every interface is connected to the application module and also with multiple Wireless Channels.

The dual-channel node has two MAC modules one for each Radio module. The two MAC modules, MAC1 and MAC2, each contain an instance of a single-band MAC protocol module. Each of the two radios is a single-band radio with a separate wireless connection to separate Wireless channel modules. Each Wireless channel module operates on a different frequency channel. It is responsible for delivering wireless signals to other nodes. In the Castalia simulator, the Wireless Channel module implements a channel model to determine the received signal levels. Also, some changes in the resource manager are made to add several parameters necessary to monitor the energy usage of each node.

For developing a multi-channel extension to the single-channel node, various input and output gates are used, such as input from Resource Manager to MAC1, and MAC2. Likewise, input gates needed to be attached from the Resource Manager to Radio1 and Radio2. Since all the elements are developed as Castalia modules, they communicate and access each other via the OMNeT++ message system. The architecture of the implemen-

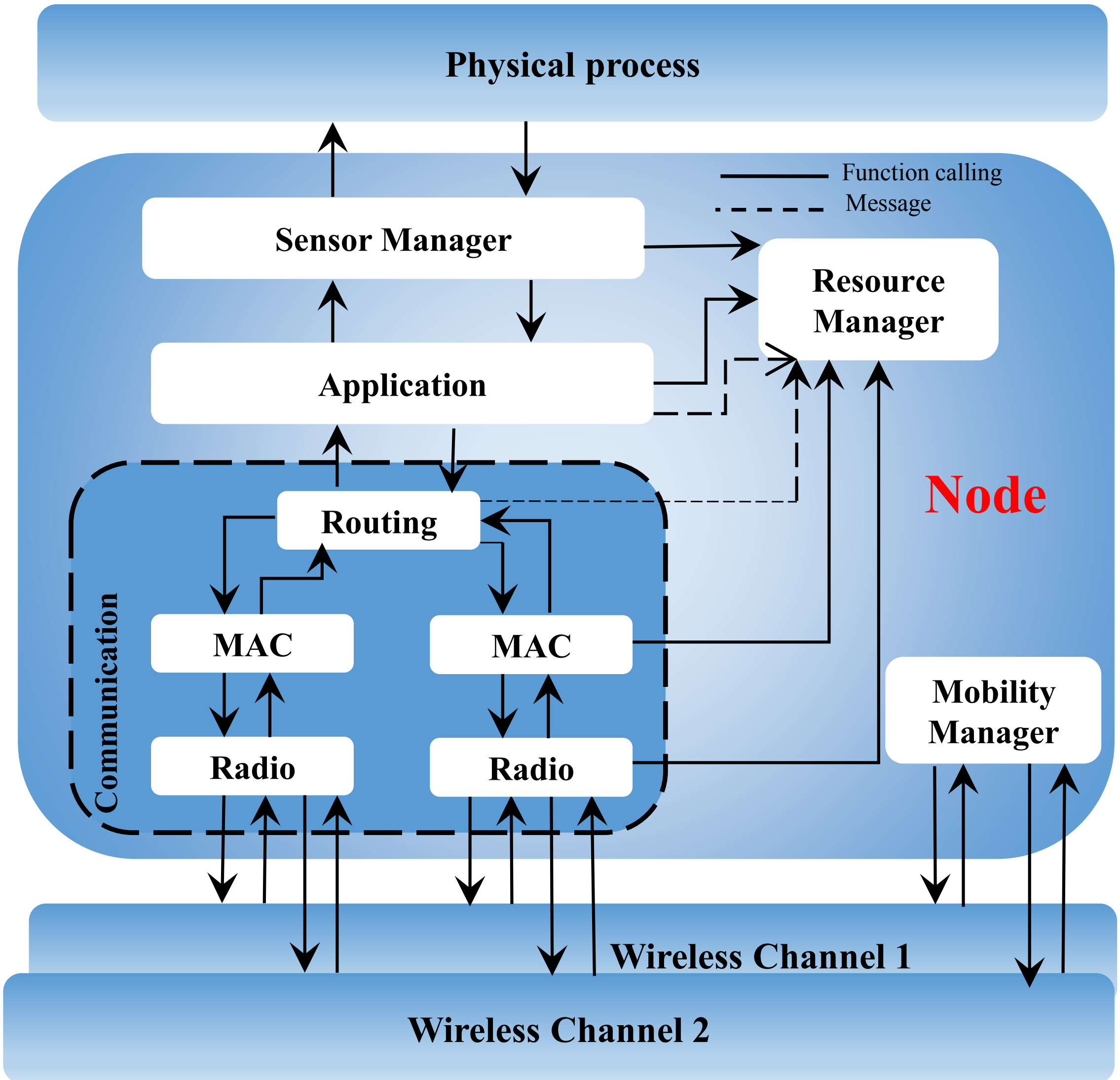


Figure 3.9: Interior Structure of Dual-Channel Node Structure

tation is described in Figure 3.10. The interfaces between two modules allow messages to pass from one module to another and are implemented as shown below.

```
fromApplicationModule --> Routing.fromCommunicationModule;
Routing.toCommunicationModule --> toApplicationModule;
Routing.toMac1Module --> MAC.fromNetworkModule;
MAC.toNetworkModule --> Routing.fromMac1Module;
Routing.toMac2Module --> MAC2.fromNetworkModule;
```

```
MAC2.toNetworkModule --> Routing.fromMac2Module;
```

7

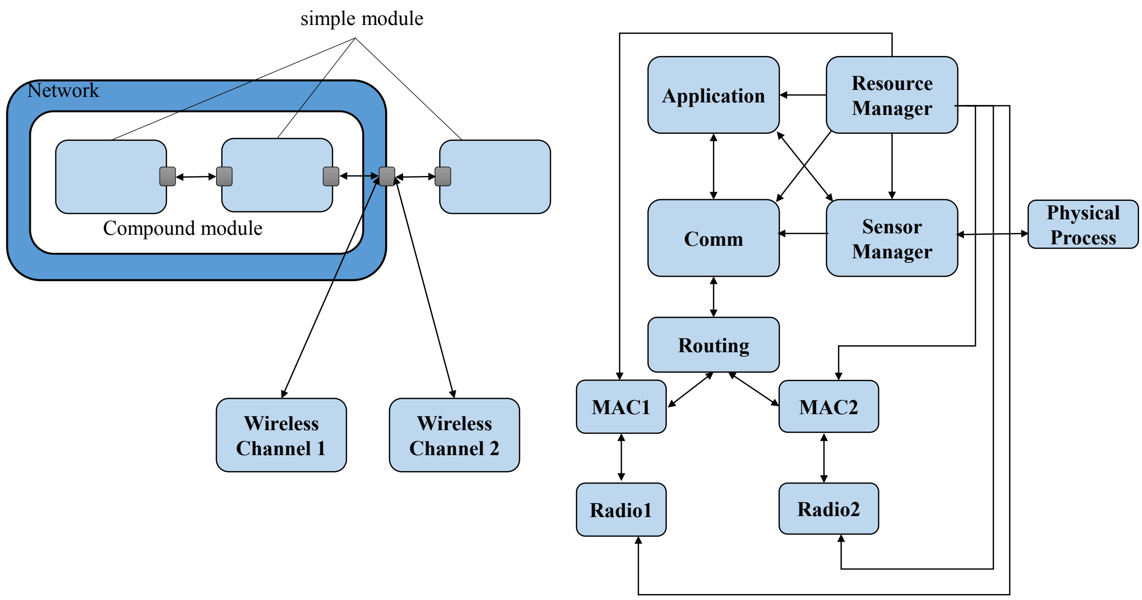


Figure 3.10: Castalia Implementation for Dual Channel

Also, even if nodes could use some of the different MAC layers, none of these MACs implements different channels. Depending on the interface, it would have a different channel bandwidth, different first and last frequencies available and a different number of available channels. By combining multiple channels and multiple interfaces, the scenarios are very realistic.

In this new proposed system model, some changes have also been performed to the Resource Manager module to add the possibility to control the energy consumption of the added modules (radio interfaces or new modules). For example, a Resource Manager is used to find the remaining energy of the nodes and pass this on to the Routing module.

Each multi-channel routing protocol developed in this thesis is presented in separate chapters. These variations transform Castalia into a simulator capable of running multi-channel routing algorithms, although it still lacks any of the synchronisation needed in multi-channel protocols which are we will be remedying in the extension of this thesis.

3.8.1 WBAN MAC Layer Protocol

A Castalia-provided TMAC protocol can be used that operates typically over a single band using a single-radio. A single-channel medium-access protocol, e.g. Synchronised-MAC (S-MAC), does not perform well because of the multi-channel hidden-terminal problem [154]. In the proposed dual-channel system of this thesis, two TMAC modules are set up, one for each frequency channel. The utilisation of multiple channels enables multiple transmissions on different bands or same band having different channels, thereby improving the overall network throughput. TMAC is designed for broadcast communications and does not include acknowledgements and RTS and CTS control packets. It is a contention-based protocol utilising the CSMA (Carrier Sense Multiple Access) mechanisms for transmissions as suggested in IEEE 802.15.6, whereby a node obtains a contended allocation if it needs to transmit in the uplink [13]. The advantages of a contention-based MAC protocol are its simplicity, infrastructure-free Ad-hoc feature and excellent adaptability to traffic fluctuations, especially for low loads. It is tunable in the sense that the persistence and back-off policies can be adjusted. TMAC can be configured to transmit trains of beacon packets to support wakeup and duty-cycle management. In duty cycling, each sensor node alternates between active and sleeping states, while turning their radio on only periodically. That percentage of time in which a node is awake is known as the node's duty cycle. The two packet types used by TMAC are DATA for data transfer and BEACON for beacon broadcasting.

The modified structure for the information exchange between MAC and Radio to get RSSI values in the Routing layer is shown previously. As the physical and MAC layers are closer to each other in their protocol stack roles, many cross-layer schemes have adopted both layers as part of a jointly optimised scheme to deliver improvements to traditional protocols. In the proposed protocol, the Radio and MAC information is exchanged based on the structure macRadioInfoExchange as shown below.

```
struct{
  MacRadioInfoExchange_type macRadioInfoExchange;
  int source;
  int destination;
  unsigned int sequenceNumber;
  double RSSI;
  double LQI;
  }
```

The RSSI value is the value associated with the particular packet passed to different layers when a packet is received and forwarded to the layers above the Physical layer. This value is noted at the end of this packet's reception. Since RSSI is an integration function, i.e. it has memory, then this value represents the average signal strength in the last N symbols of the packet (N is eight by default in the standard radios used in Castalia). The TMAC segregates the several types of received packets, e.g. if the packet-type is "'TMacPacket"' then it uses the values of RSSI and LQI to forward it to the upper layer (Network layer). Otherwise, it will discard the packet.

3.9 Simulation Setup

A dual-channel version (using channels 1 and 2) of the multi-channel AODV routing protocol is implemented in Castalia. Implementing this in Castalia required significant modifications to the existing C++ and network description (.ned) files in the single channel model to add the extra node modules needed (second MAC and second Radio) and insert the extra multi-channel AODV routing protocol functions into the Routing module.

A network of 6 nodes (0-5) is placed at the front of the body as shown in Figure 3.11.

The sink (BNC) is node 0 and nodes 1 to 5 transmit data to that node only. Node 0 does not send any data to the other nodes. The 2.4 GHz IEEE 802.15.4 /Zigbee-ready CC2420 RF transceiver is provided in Castalia. The radio parameters have been derived from the Teleos Mote Data-sheet [138]. The radio is set to IDEAL modulation in Castalia and uses the additive interference collision model, which means a collision is calculated based on SIR (Signal-to-Interference Ratio). The SIR for each of the transmissions is calculated. If any collision, even in a small part of a packet (with model=2 collision means that the SIR is too low to decode the bits at the receiver radio), then the whole packet is assumed to be corrupt and is discarded. The additive interference is used to sum all of the simultaneous interferences, to emulate a more realistic behaviour in dual-channel WBAN [155].

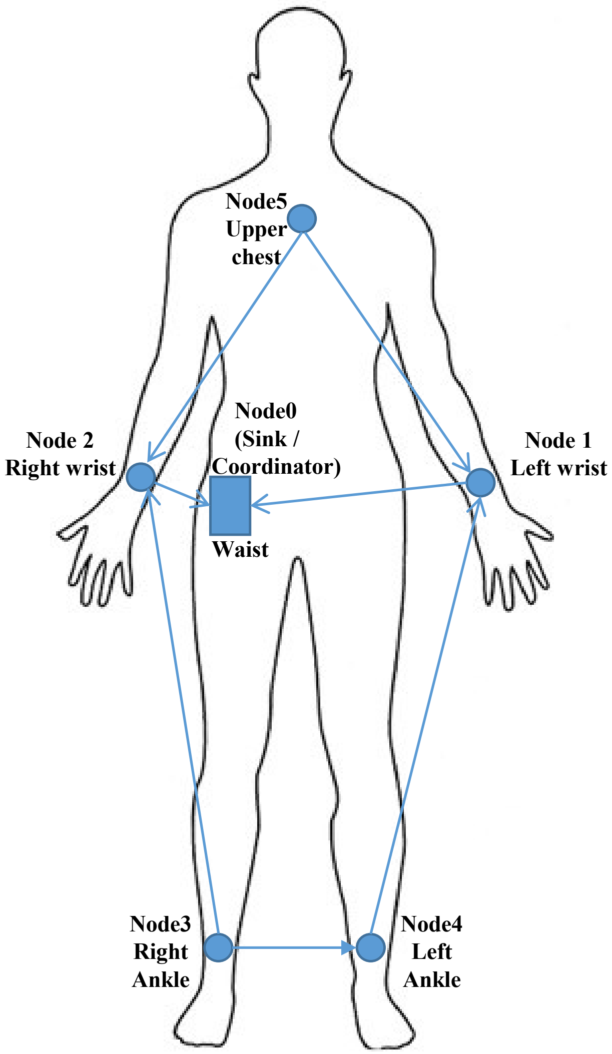


Figure 3.11: Node Setup on a Human Body

The key simulation parameters used are shown in Table 3.2.

Table 3.2: Simulation Parameters

Module	**Parameter and Data Value**
Area Size	2.5 × 2.5 m
Number of nodes	6
Application	50 packets per second, 100 byte payload + 30 byte overhead (application data rate is 20.8 kbps)
Routing	RREQ retries = 2 RREQ rate limit = 10 per sec Active route time-out = 6 sec
Tunable MAC	Default parameters Constant back-off time One transmission attempt
Radio	Sensitivity: −100 dBm Noise floor: −110 dBm Transmit power: 0 dBm
Traffic Type	CBR
Wireless Channel	Bandwidth 20 MHz, Data rate: 250 kbps Modulation type: BPSK Temporal model, static nodes
	Log-normal shadowing, bidirectionalSigma = 0 sigma = 0
Initial energy	18720 J - 2 x AA batteries
Transmission range	CC2420 20 meters

3.10 Results

To determine the operation and effect of the multi-channel routing protocol by itself, the mobility module is disabled in Castalia, and the performance between the SCH (Single-Channel) over channel 1, MC-AoRSS and MC-AoRAND are compared. The simulation duration is set to 1400 seconds. Figure 3.12 shows, for each node, the numbers of packets sent by the application module in a node to the application module in node 0 and the number of packets received by node 0. The labels on the x-axis identify the source node of packets. The top plot in the figure is for SCH, the middle plot is for MC-AoRAND, and the bottom plot is for MC-AoRSS. It is obvious in the MC-AoRAND that node 3 and 4 have picked the wrong channel from the random channels and hence less number of packets will be sent to Node 0. Since the simulation was configured for a constant packet rate in the application layer, all simulations sent around the same number of packets (140,096).

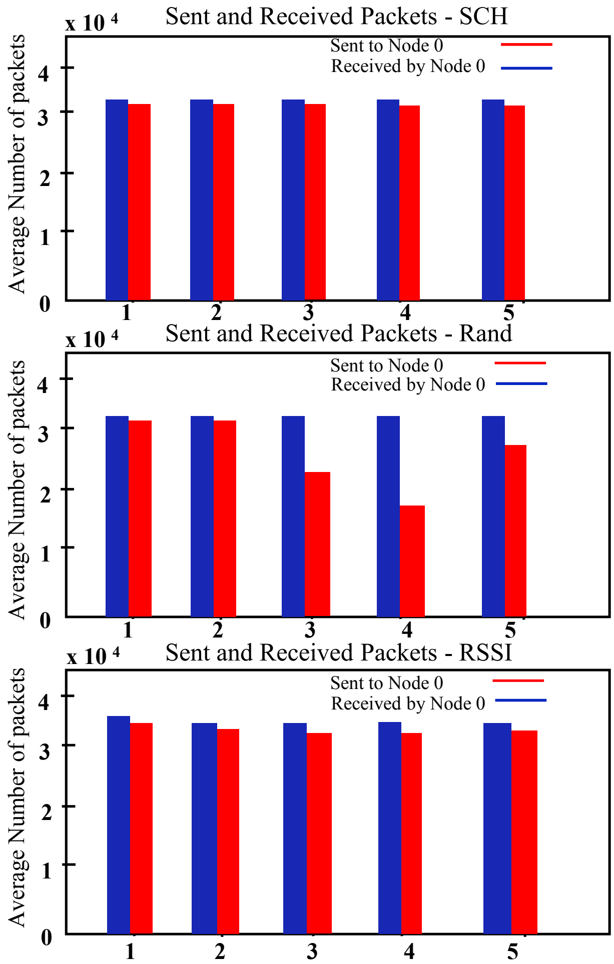


Figure 3.12: Numbers of application packets sent to node 0 (Red Bar) and received by node 0 (Blue bar) for each node for SCH, MC-AoRAND and MC-AoRSS

In the proposed scheme, traffic is distributed among two channels as shown in Figure 3.13 and 3.14 which shows the number of AODV DATA packets sent on channel 1 and channel 2, respectively. In the groups of bars above a source node, each bar is for the different destination nodes (1-5, left-to-right). In the proposed scheme, traffic is distributed among two channels as shown in Figure 3.13 and 3.14 which shows the number of AODV DATA packets sent on channel 1 and channel 2, respectively. In the groups of bars above a source node, each bar is for the different destination nodes (1-5, left-to-right). For SCH all DATA packets were sent on channel 1. Most DATA packets were sent from the source to node 0 in one hop, but there was a small amount of forwarding by other nodes as seen in the received packet counts. For both MC-AoRAND and MC-AoRSS some packets were sent on channel 1 and some on channel 2, depending on which channel was selected (Note that both radios in a node can simultaneously send and receive packets with higher-layer module operation decoupled by buffers.) For MC-AoRAND nearly all packets were sent in one hop to node 0. The same was true for MC-AoRSS except that packets from the node 5 were sent to node 0 via node 3, the first hop using channel 2 and the second hop using channel 1.

Figure 3.14 shows that SCH and MC-AoRSS achieved almost the same packet delivery levels (SCH: total received = 137,687 packets, mean per node=22,948 packets; MC-AoRSS: total received = 138,987 packets, mean per node = 23,165 packets) whereas MC-AoRAND delivered fewer packets (total received = 123,192 packets, mean per node = 20,532 packets). If anything, MC-AoRSS is slightly better than SCH.

Figure 3.15 illustrates the data packets received at the MAC layer. The x-axis shows different scenarios, e.g. 1 - 3 show packets received at MAC1 and 4 - 6 show packets received at MAC2. If we look at 1 and 4, the sent data packets (red bars) are pretty much the same for RSSI channel selection at MAC1 and MAC2, whereas the received data packets (blue bars) at MAC2 are approximately 11000 more than at MAC1. RSSI

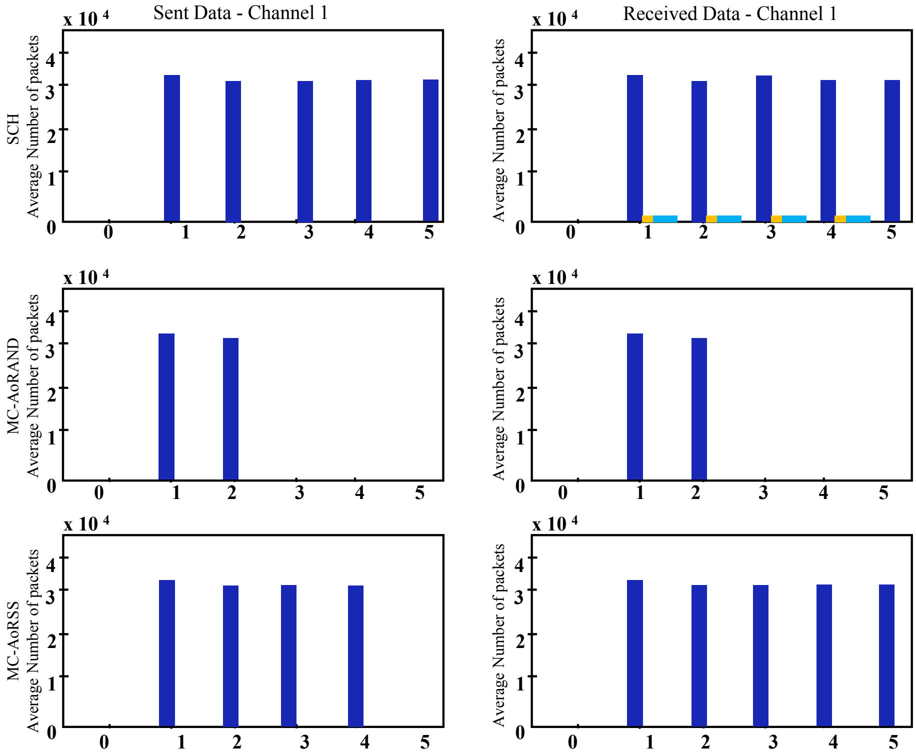


Figure 3.13: Sent and received AODV DATA packets on Channel 1

channel selection gives a better opportunity to receive more data packets at the MAC layer with dual channels.

The graph of the number of MAC DATA packets sent and received per node on each channel is shown in Figure 3.15 and 3.16.

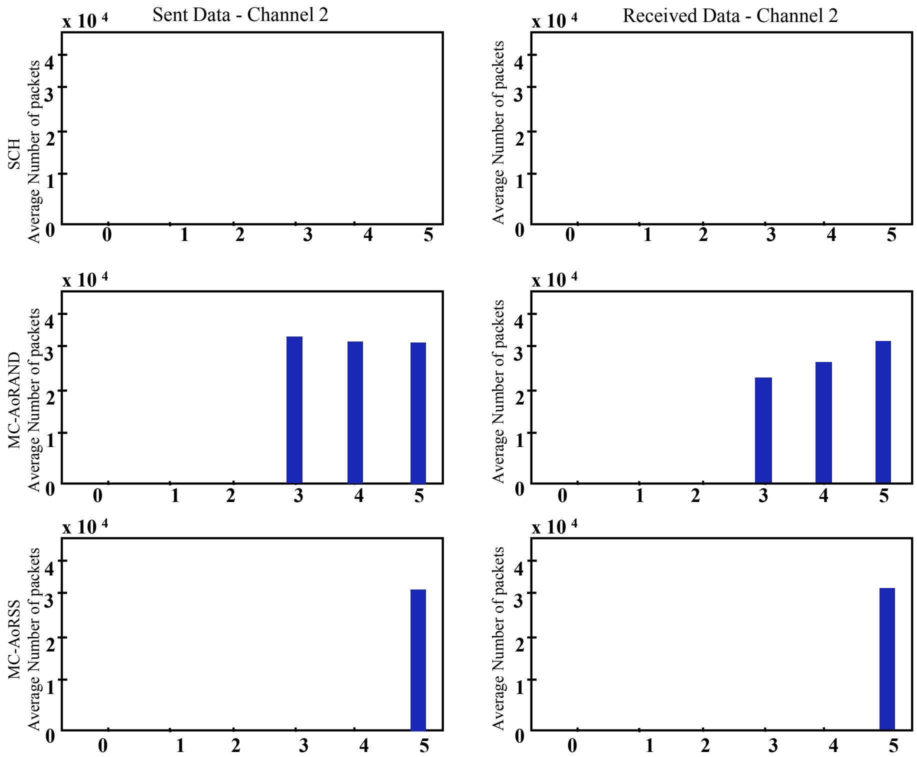
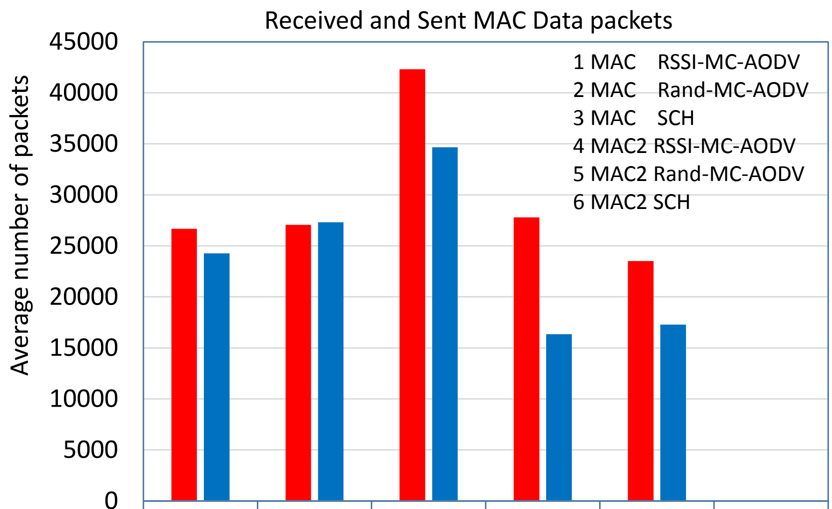


Figure 3.14: Sent and received AODV DATA packets on Channel 2



	1	2	3	4	5	6
sent data pkts	26668	27058	42306	27801	23514	0
recevd data pkts	24263	27310	34668	16352	17288	0

Figure 3.15: Average number of MAC DATA packets sent and received

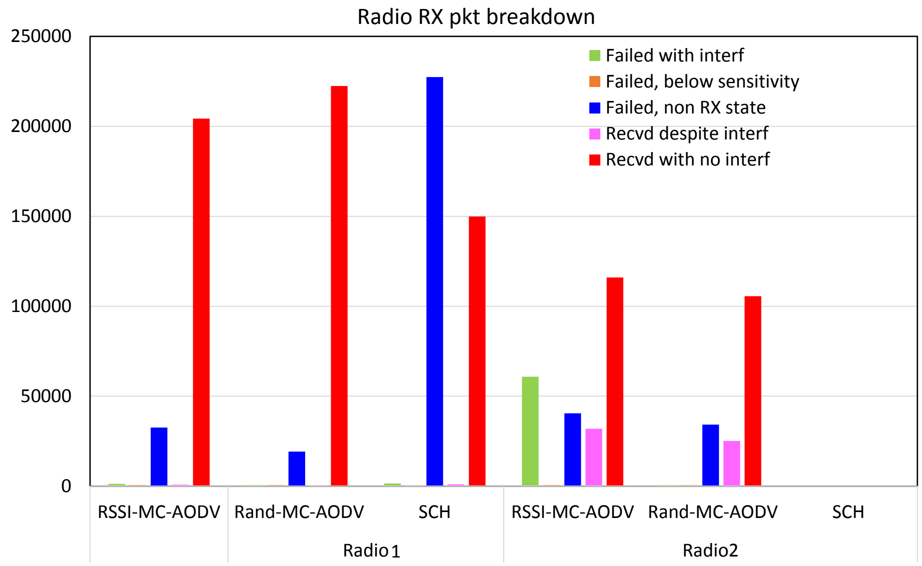


Figure 3.16: RX Packet Breakdown

Figure 3.16 shows the Radio received packet breakdown in terms of 5 different types of packets: failed with interference, failed below sensitivity, failed non-RX state, received despite interference, and received with no interference. The types identify the different conditions in which the packets failed or succeeded. Based on the additive interference model used, the strongest transmission is chosen to receive. "Failed below sensitivity" is quite straightforward because the signal was below the receiver's sensitivity level; that usually happens when the node moves out of the range of a receiver. The received RSSI is smaller than the sensitivity level, which for a CC2420 radio transceiver is -95 dBm. In that case, Received with no interference is much better with random channel selection because there is an equal probability of selecting channels in case of static nodes.

For SCH, a number of control packets were sent from the route establishment to data delivery phase between a destination node and all the other nodes. This overhead creates a taxonomy of AODV control messages being broadcast and then responded to in a path-discovery phase. However, the majority of MAC DATA packets sent from a node were to node 0, carrying AODV DATA packets. The MAC DATA packets sent in MC-AoRAND were nearly all carrying AODV data packets, and the transmission pattern was consistent with the AODV packet-transmission numbers in Figure 3.15. MC-AoRSS was similar, except that the number of MAC DATA packets sent from node 3 to node 0 was about double that of the other nodes, as it was sending its own AODV DATA packets and forwarding the AODV DATA packets of node 5 as well.

The route maintenance and discovery process produce a series of control packets propagating across the network. If these operations need to be frequently repeated, a significant fraction of the available network capacity will be consumed by these control packets, introducing yet more packets into an already-congested environment. The route discovery phase is the critical [156] phase where a number of control messages can be minimised to reduce the network congestion, so in this chapter, the proposed scheme of on-demand routing protocols has better performance with multi-channel AODV.

3.10.1 Average Number of Control Messages

To understand how the dynamics of the different forms of AODV control messages affect the performance of the protocols, a detailed analysis is conducted for each node (the number of AODV messages and packets sent and received). AODV control messages such as RREQ, RREP, RERR, RREP-ACK (denoted by RACK) and HELLO are examined. The sent and received messages by nodes, with message counts, are shown in Tables 3.3 and 3.4, respectively, for the 1400-second simulation. RERR message counts are not shown as none were detected. As a reference point, the total number of application packets sent in each simulation was around 138,987.

The sent message counts are the number of messages sent by a node to all other nodes, and the received message counts are the number of messages received by a node from all other nodes. The SCH data shows that significantly more RREQ, RREP and RREP-ACK messages were sent and received than in MC-AoRAND and MC-AoRSS. Further analysis of the SC-AODV data showed that the network was experiencing routing instability. The maximum RREQ message transmission rate from a node was set to 10 per second (Castalia default). At this rate, not enough RREQ messages could be sent to allow convergence to occur on stable routes. As a consequence RREQ, the retransmission buffers became very full in some nodes that kept on transmitting large numbers of RREQs. Increasing the RREQ message transmission rate from a node to 100 per second removed the instability.

Table 3.3: Count of AODV control messages sent from a node to all other nodes for SCH, MC-AoRAND and MC-AoRSS AODV

SCH (sent messages)							
Ch	**Pkttype**	**Node:0**	**1**	**2**	**3**	**4**	**5**
1	RREQ	0	1	1	110	1	109
1	RREP	6327	33938	32058	40911	29920	40749
1	RACK	0	21802	19912	27213	17700	27056
1	HELLO	0	57	57	57	57	57
DCH Rand (sent messages)							
Ch	**Pkttype**	**Node:0**	**1**	**2**	**3**	**4**	**5**
1	RREQ	0	2	1	3	2	2
1	RREP	3	2	2	0	1	0
1	RACK	0	1	1	0	0	0
1	HELLO	0	56	57	0	0	0
2	RREQ	0	1	3	1	2	3
2	RREP	3	2	1	2	2	0
2	RACK	0	0	0	1	1	1
2	HELLO	0	0	0	57	56	56
DCH RSSI (sent messages)							
Ch	**Pkttype**	**Node:0**	**1**	**2**	**3**	**4**	**5**
1	RREQ	0	2	1	2	3	2
1	RREP	2	2	2	4	1	1
1	RACK	0	1	1	2	1	0
1	HELLO	0	56	57	56	56	0
2	RREQ	0	2	4	2	2	3
2	RREP	5	1	0	2	1	0
2	RACK	0	0	0	0	0	1
2	HELLO	0	0	0	0	0	56

Table 3.4: Count of AODV control-messages received by a node from all other nodes for SC-AODV, MC-AoRAND and MC-AoRSS

SCH (Received messages)							
Ch	**Pkttype**	**Node:0**	**1**	**2**	**3**	**4**	**5**
1	RREQ	68983	55078	55068	55296	55051	55198
1	RREP	0	21802	19912	27213	17700	27056
1	RACK	6230	19680	17775	26879	15711	26558
1	HELLO	282	224	227	225	224	222
DCH Rand (Received messages)							
Ch	**Pkttype**	**Node:0**	**1**	**2**	**3**	**4**	**5**
1	RREQ	10	7	7	8	8	7
1	RREP	0		1	0	0	0
1	RACK	2	0	0	0	0	0
1	HELLO	113	57	56	113	113	113
2	RREQ	8	7	6	6	6	3
2	RREP	0	0	0	1	1	1
2	RACK	3	0	0	0	0	0
2	HELLO	150	152	146	98	105	91
DCH RSSI (Received messages)							
Ch	**Pkttype**	**Node:0**	**1**	**2**	**3**	**4**	**5**
1	RREQ	13	7	10	8	10	8
1	RREP	0	1	1	2	1	0
1	RACK	5	0	0	0	0	0
1	HELLO	224	168	167	168	168	223
2	RREQ	11	9	7	10	9	8
2	RREP	0	0	0	0	0	1
2	RACK	0	0	0	1	0	0
2	HELLO	56	55	56	56	56	0

Both dual-channel AODVs, i.e. MC-AoRAND and MC-AoRSS, have much better routing convergence and stability than SC-AODV. In summary, MC-AoRSS delivered similar numbers of application packets to what SC-AODV could deliver but needed fewer control messages to be sent and received (control message overhead). Although MC-AoRand has a similar control message overhead to MC-AoRSS, the number of application packets delivered was more with MC-AoRSS.

3.10.2 Energy usage in Multi-channel Context

In terms of energy usage, only small differences between actual energy usages are noted in the different simulations; see Table 3.5. However, MC-AoRSS gave the best energy efficiency (nJoules per bit) of the three cases.

Table 3.5: Comparison of total consumed energy (Joules)

	Node=0	**1**	**2**	**3**	**4**	**5**
SC-AODV	52.2543	52.0576	52.0548	52.0503	52.0584	52.0559
MC-AoRand	52.2583	52.1071	52.1022	52.1035	52.1075	52.1086
MC-AoRSS	52.2581	52.107	52.102	51.9579	52.1073	52.1108

Table 3.6: Comparison of energy efficiency (nJoules/bit)

	Node=1	**2**	**3**	**4**	**5**
SC-AODV	8109.57	7988.91	7943.16	7914.98	8028.41
MC-AoRand	7858.16	7737.82	14145.5	10932.8	8075.25
MC-AoRSS	7873.09	7736.83	7855.56	7878.14	8040

Several parameters need to be configured in TMAC, and additional studies and analyses showed that the interaction between the TMAC and AODV parameters and the time-out values could be quite complex. For example, increasing the number of allowed RREQ retries also increases the RREQ expiry time-out value. Increasing the number of RREQ retries also leads to more contention in the MAC layer. On the other hand, more contention in the MAC layer leads to more failures to deliver RREQ packets and consequent time-outs. The optimum configuration of parameters in dual-channel operation is an open issue.

3.11 Conclusions

In this chapter, a multi-channel AODV routing protocol was proposed that was developed and implemented in OMNeT++ based Castalia. The results show that MC-AoRSS gave equal performance to SC-AODV in terms of packet delivery, but with less AODV control overhead, better routing stability and slightly better energy efficiency. The route discovery overhead of Dual-CHannel (DCH) appears to be large, the overhead per channel is the same as that of a single-channel protocol. Following chapters will examine how node mobility will affect the operation, and the use of remaining energy and other metrics such as ETX (Expected Number of Transmissions) and WCETT (Weighted Cumulative Expected Transmission Time) that require additional changes to the Castalia Radio module.

Chapter 4

A Multi-channel Routing Protocol based on LQI Channel Selection for Wireless Body-Area Networks with Mobile Nodes

Contents

4.1 Introduction

Wireless Body-Area Networks (WBANs) are dynamic, and hence mobility becomes a critical factor in WBAN design and performance. The network topology and the quality of wireless links vary over time (due to posture changes and body movement) [157] - [158]. Mobility has been chosen for this chapter because it is one of the most critical issues in next-generation networks such as WBANs, mobility-based communication prolongs the lifetime of devices and increases the connectivity between nodes and sink.

Routing is a challenging problem in the presence of mobility. As in mobile WSN applications, the Ad-hoc On-Demand Distance Vector (AODV) has several advantages which make it the most suitable routing protocol, for example, it quickly adapts to: frequent link changes (dynamic link conditions due to mobility), low memory and processing overhead requirements, different mobility rates (low-to-high), and variety of data traffic levels [159].

When the topology changes, it causes the formation of the new links and the disconnection of the existing ones. It also affects the reliability of the data delivery. When links get disconnected, they require extra effort from a routing protocol, and in the meantime existing link connections must be repaired. More accurately, when a link to an active connection breaks, the routing protocol re-initiates the route discovery process, which results in more control-packet overhead due to the multiple copies of packets needing to be sent. These packets consist of Route REQuest (RREQ), Route (RREP), and Route ERRor (RERR) packets, and sending these packets repeatedly is considered to be an expensive operation. Sudden changes can create a high volume of route-update messages which may cause the protocol overhead to become excessively high, leading to possible disruption of normal network operations. The reason for the routing instability lies in some unstable links existing and being chosen for the construction of the route to the destination [160]. This control message overhead leads to unbalanced and rapid energy depletion. It has been shown [161] that distributing the traffic generated by each sensor node through multiple channels and multiple paths instead of using a single channel and a single path allows energy saving.

To alleviate such problems, in this chapter a multi-channel routing protocol is proposed that periodically notifies wireless channels about nodes' mobility based on the node position knowledge and exploits the calculated mobility value to determine the best reliable route between the source and destination during the route-discovery process. The benefits of dual-channel operation appear to come from the capacity to reduce the number of nodes trying to communicate with each other, leading to fewer control messages being sent and better convergence.

Unlike prior work, in this chapter, a Multi-Channel AODV routing protocol using Link-Quality Indicator (LQI) channel selection with Mobile nodes (MC-AoLQM) is developed. It is implemented by modifying the single-channel AODV Castalia model with mobility support built on the OMNeT++ network simulator [162]. MC-AoLQM is compared against an MC-AoRSS and MC-AoRand (Random channel selection) for mobile and static nodes. With one mobile node and the rest static, this multi-channel protocol reduces the number of unwanted data packets received by the mobile nodes. Through a change in time, if the percentage of nodes moving is low in comparison to the static nodes, it is more likely to have more stable links [163]. The proposed MC-AoLQM routing protocol with mobile nodes achieves fewer AODV control messages needing to be sent and better routing stability.

4.2 Motivation and Related Work

Mobility support in WBANs and Wireless Sensor Networks (WSNs) is a major challenge and increases the applicability of these technologies. Most applications of these networks only assume static nodes and the protocols in those networks are based on this assumption. To achieve a continuous connectivity with mobile body nodes, it is essential to develop an uninterrupted link-assessment mechanism that can handle the fluctuations on a link quality between the different on-body nodes.

4.2.1 Motivation: Taking LQI into consideration for Mobility Support

The LQI values and Received Signal Strength Indication (RSSI) values are utilised to maintain the link connectivity and the best channel to transmit on when the link-breakages occur due to node movement. When a node observes that its link quality has degraded beyond a certain threshold (either LQI or RSSI), it assumes that the node is moving [164]. The RSSI does not distinguish between different link categories because it does not depend on the Packet Reception Rate (PRR) [165]. It is also observed that LQI has a better correlation with a PRR than RSSI. However, it needs to be averaged over many packets. The PRR across multiple channels on the intermediate links are not correlated, and it is common on such links for the nodes to find channels that change the link quality over time. In real networks such as WBANs where they experience contention between nodes and simultaneous transmissions, an RSSI sometimes may produce errors in the evaluation of PRR. Concurrent transmissions increase the RSSI and decrease the probability of correct decoding leading to a lower PRR. In this case, the estimation based on RSSI would result in misleading values of PRR. The reason for including LQI in the proposed routing protocol in this chapter is that LQI has been found to have better correlation with Packet Delivery Ratios (PDRs) than RSSI, as multipath fading and interference may result in smaller LQI even though RSSI has increased.

4.2.2 Related Work

Unlike sensor nodes in conventional wireless networks such as WSNs, nodes in multi-channel sensor networks additionally have to deal with potentially more channels for the data routing [166] and need to select a channel to use for transmission (the better the channel selection, the better the overall system performance). Therefore, appropriate channel-quality measurement methods are needed. Since the behaviour of wireless channels is probabilistic (which makes channel-quality assessment a repetitive task), any instantaneous channel-quality assessment such as Mean LQI, Average LQI cannot by its nature provide an adequate measure of the channels' health.

A change in wireless link quality can affect network connectivity; thus, link quality may be taken into account as a link-quality assessment metric. The LQI metric is used over the RSSI metric because as explained above the aggregate LQI is a more accurate estimate of the link quality than RSSI. The LQI metric is used as an indicator of how satisfactory the local network conditions are. It is assumed that the quality of all links is the same on a particular frequency channel in a neighbourhood, and may reflect the channel quality in the corresponding locality. Otherwise, each sensor node may have to record the quality of all available channels for each link in a neighbourhood separately, which may increase the system complexity accordingly.

An LQI, a transmission success ratio and data-dropped (buffer overflow) are used for the reliability of the data being sent over the multiple channels. Different link and mobility aware routing protocols have been proposed to forward data efficiently and effectively between the on-body sensors to on-body sensors [163], [167] - [168].

Overall, since good-quality links with high LQIs will lead to less first-hop retransmissions, thus reducing the first-hop latency. The Collection Tree Protocol (CTP) [152] by TinyOS [169] forwards vital signs to the gateway. Patients are limited to stay within the area covered by the Relay Points (RPs). Therefore, limited mobility is supported. CTP uses only the one-frequency channel, and route selection is based only on the LQI. Performance highlights of CTP are that it uses the frequency channel with least interference and provides high values of LQI, and hence higher LQI provides better performance than using a frequency channel with high interference. This demonstrates that a solution that can select a frequency channel with higher LQI is preferable.

[163] discusses the impact of mobility on route discovery, route maintenance, and node degree stability. This protocol is developed for Mobile Ad-hoc Networks (MANETs), where the degree of mobility is relatively high as compared to WBANs.

In [170] a modification of AODV called AD-AODV is proposed for MANETs in which nodes used HELLO messages to help determine mobility. They define nodes relative mobility as the ratio Q = (J+L)/N where J is the number of nodes that join a node's coverage area during a hello interval, L is the number of nodes that leave a node's coverage area during a hello interval and N is the number of neighbour nodes calculated from its neighbour list. Using this an average node mobility value is calculated, and a routing metric is proposed that combines a number of hops with average node mobility.

[171] also proposes a single-channel opportunistic scheme to exploit the body move-

ments during walking to increase the lifetime of the network. In this opportunistic protocol, a relay node is introduced to the moving part of the body. However, the relay node is the major overhead energy consumer in the network. Moreover, this protocol does not provide any link characterisation scheme when link breakage occurs due to body movement.

In [172], the Stable Increased-throughput Multi-hop Protocol for Link Efficiency (SIMPLE) for WBAN is proposed. It is an energy-efficient protocol, but no attention is paid to the channel quality measurements and the path loss taking place in the links connecting the sensors among themselves as well as the sink. It is a single-channel, single-path routing protocol.

[173] proposes a new protocol Enhanced-AODV (E-AODV) which is a modified version of AODV with an enhanced Packet Delivery Ratio (PDR) and a minimised end-to-end (E2E) delay when frequent link failures occur in the network due to the mobility of the nodes. However, this protocol emphasises similar data rates and does not consider the link-quality estimation.

[174] develops a new routing protocol called a Reverse AODV (RAODV). The RAODV tries multiple RREPs which reduces the number of path-fail-correction packets and obtains better performance than other protocols. However, RAODV has the most control packet overhead. Therefore, in their study, they propose an Enhanced- RAODV (EN-RAODV) that improves the RAODV. Simulation results show that the proposed EN-RAODV increases the performance of the network compared with RAODV and AODV in most nominated performance metrics such as PDR, an E2E delay, throughput, routing packets sent and routing overhead.

[168] proposes an AODV algorithm for MANETs taking into account various node mobility environments. However, this protocol does not consider the link qualities when the nodes are mobile. The LEEP protocol [175] measures the link quality based on the

packet reception ratio (PRR), but not considering the packet acknowledgements such as RREP-ACK, resulting in increased retransmissions. It is based on a static network.

In multi-channel scenarios, various routing protocols are presented [32] - [124] - [167], but mostly routing protocols are valid for Wireless Mesh Networks (WMNs) that have many channels available.

[32] is a simulation-based analysis of the energy efficiency of WSNs with static and mobile sinks. It is shown that, for small values of the duty cycle (sleep and active-time period), a static sink is best in terms of both maximum and average energy consumption; for more significant values of the duty cycle, a mobile sink has benefits over a static sink, especially regarding maximum energy consumption. This is one reason that the proposed protocols in this thesis use a WBAN multi-path routing topology with a static or mobile sink.

In [124] a multi-channel version of AODV called Congestion Adaptive-AODV (CA-AODV) is proposed. In this protocol, if the source does not yet have a channel to transmit on it randomly picks a channel from the set of all available channels. Any node that receives an RREQ packet selects a channel that none of its former k-hop neighbours has selected. The RREQ message conveys the node-ids and channel numbers that its k preceding nodes are using. This method of channel selection may be practical in WMNs, that have more channels available, but in WBANS there is usually a small number of channels available, so the approach is less practical there.

Section 4.2 describes the motivation behind this chapter and related work on multi-channel routing. Section 4.3 describes our proposed multi-channel AODV protocol. Section 4.4 describes the dual-channel WBAN system with mobility management. Section 4.5 explains how the mobility manager works with multiple channels. Section 4.6 explains the metrics used in the simulation to evaluate the proposed protocol. Section 4.7 presents the simulation parameters used and Section 4.8 presents the results of our simulation experiments along with a discussion. Section 4.9 presents conclusions.

4.3 Multi-Channel AODV Routing Protocol based on LQI Channel Selection with Mobile Nodes (MC-AoLQM)

To enhance the features of such an environment, a multi-channel version of the AODV routing protocol for WBANs with mobile nodes is developed and tested using the Castalia WBAN simulation model, which not only selects the best channel available using higher values of LQIs and then RSSIs but also chooses the best route based on a next-hop routing metric. This contributes to fewer unwanted messages, minimum energy consumption whether the sink node is mobile or static. It also contributes to the routing stability.

In this chapter, AODV is extended to the multi-channel case with mobile nodes. The sequence of procedures carried out for a multi-channel AODV is as done in the multi-channel routing protocol explained in Chapter 3 and is not reproduced here. The single-channel AODV operation is already presented in the previous Chapter 3. This protocol is based on a sink-node mobility and uses the same criteria dependent on the node mobility, such as node coordinates, node direction of movement or node speed, in the calculation of the routing stability.

AODV is an on-demand (reactive) routing protocol that determines the routes for transmission only if a node needs to deliver packets to target nodes, thus reducing excessive consumption of network bandwidth and energy [129]. The proposed methodology integrates channel assignment with the AODV routing algorithm. It supports both unicast and multicast packet transmissions even for nodes in constant movement [176]. Typically, the movement parameters comprise the node position, velocity, and movement direction.

However, in this protocol, route discovery messages and hello messages are exploited for collecting coordinate information of neighbour nodes, to avoid the overhead of sending specific messages to collect these node coordinates. The MAC layer collects information for each channel and passes it to the routing layer in a cross-layer manner. Based on it, the routing layer will choose an appropriate channel to forward data packets or control packets to the next hop.

4.3.1 Channel Selection

AODV is extended to multi-channel AODV by adding channel selection, $3D$ coordinates of the node, and next-hop-channel information into the routing table and adding separate RREQ timers for each channel. This protocol is implemented using two different methods of channel selection. One is using RSSI, and the other uses LQI.

As incoming messages to the node are received both RSSI and LQI are determined in the Radio module, and this information is passed up through the MAC module to the Routing module which records the current value of each, and the time the latest value is received. When a channel is to be selected using the RSSI method a test is first done to determine that each channel has received an RSSI value that is no older than a maximum allowed time called `max_time`. This is done to ensure that stale values of RSSI are not used. If all RSSI values are not stale, then the channel with the largest RSSI is selected. If any single channel has a stale value, then a channel is selected at random. LQI operates along similar lines.

4.3.2 Mobility of Nodes

The mobility of nodes in WBANs is a function of both speed and movement patterns. Due to the frequent body movements, the topology of the WBAN frequently changes because of the high degree of node mobility [177]. The current research is being carried out in optimising the basic AODV protocol in MANET applications aimed at reducing the control-packet overhead, reducing the periodic HELLO messages during route maintenance and reducing active-link failures due to node mobility [159].

Some studies have been conducted to model node mobility and develop methods of managing mobility. A broad review of mobility models [24] is carried out by including single-node random-walk models and group models, where a group vector models the motion of a group of devices. The authors use a Markov chain to model posture change. In [51], they consider different types of movement including standing still, slow walking and fast jogging in taking measures for their channel models. In developing a model for the wireless link that includes antenna position and line-of-sight, partial line-of-sight and non-line-of sight cases, [178] develops a time-cyclic model for activities such as walking.

When a static sink is placed, the sensor nodes that are the neighbours of the sink tend to deplete their energy faster than other nodes. They consume energy to communicate their data, and also they relay the data of other nodes, and the sink gets isolated from the rest of the network due to the early death of its neighbours even though most of the sensor nodes are still fully operational. This problem is termed the "Sink Neighbourhood Problem" [179] that leads to premature disconnection of the network.

Sink Mobility

The nodes that are deployed near to the sink exhaust very quickly in the reactive routing protocols, where the base station is static or fixed. As a result, networks get disconnected very quickly. To overcome this problem and prolong the lifetime of the network, a mobile sink is used to collect the data. The sink node changes its position randomly according to the requirement of mobility. There are many ways in which the sink can move in a network: it can move to the top of the network, the bottom of the network, diagonally in the network and in many other directions. When a node sends data, the sink broadcasts another beacon frame to stop transmission, which reduces the packet drop. The network lifetime can be extended if a mobile sink balances the traffic load of nodes.

4.3.3 Data Delivery

When an RREQ message is received by the preceding node, its location coordinates and the incoming channel on which it is received are stored as the next-hop node and the next-hop channel leading back to the source in the routing table. Later, when the matching RREP packet is received, the next hop and next-hop channel are used to forward RREP back to the source. Also when the matching RREP message is received the following node and incoming channel are stored as the next hop and next-hop channel to forward packets and messages to the destination. When a route has been established all DATA packets are unicast using the next-hop and next-hop-channel information stored in the routing table.

4.3.4 Route Maintenance

When a node detects a link breakdown, it may initiate a local repair (using the route discovery mechanism in AODV) by broadcasting RREQ. The bi-directional route is re-installed with the reception of the unicast RREP. However, any packet reception for a destination for which the link is down will be buffered for a further forward to the destination. The buffer counts a number of the higher-layer packets that are dropped because the MAC could not receive any acknowledgement for the retransmission of those packets or their fragments. A routing buffer at the network layer could store up to 64 data packets. This buffer keeps in waiting the data packets for which the route discovery had started, but no reply had yet arrived. The buffering uses the "First-In, First-Out" (FIFO) method. If a route discovery has been attempted $RREQ\_TRIES$ times at the maximum TTL without receiving any RREP packet, all data packets destined for that destination will be dropped from the buffer.

AODV features a rate limitation for control messages and makes it configurable. However, given the dual-channel AODV, the RREQ rate limit is set to 10 per second (no more than ten control messages can be sent per second), and under these conditions SCH displays instability. This value is deliberately set to highlight the differences between single and multi-channel operation. With the relatively low RREQ rate limit, many of these RREQs are buffered and later transmitted when the rate limit timer allows. When the constant flow of these control messages reaches the rate limit, then any further control message will be dropped including RREQs which could succeed. If more routes are available, then the routing overhead decreases. A node generates a RERR if it does not have a route to the destination in the routing table. If a bidirectional link goes unidirectional (one of the links breaks), then a previous hop can send a lot of data packets (DATA PACKETS) and never receives the RERR. The previous hop (k-1, where k is a number of connecting nodes) assumes that the route will remain active and continue transmitting data packets at possibly high rates, to be forwarded by the RERR sender.

AODV retransmits RREQ messages if an RREP message has not been received in a given time. The RREQ retransmission queue is modified in such a way that the selected channel on which an RREQ is transmitted is stored with a message so that the RREQ message could be retransmitted on the same channel as previously. For the HELLO message, each channel has to be managed separately, and each channel has its own HELLO expiry and refreshes timers.

4.4 Dual-channel WBAN System Model with Mobility

This chapter also focuses on the on-body to the on-body scenario. It is assumed that the WBAN consists of K dual channels for mobile or static nodes. Each node has two transceivers with each transceiver supporting broadcast communication over a separate frequency channel to other nodes. This dual-channel WBAN model also incorporates a mobility module.

4.4.1 Mobility Model

The structure of a dual-channel node with the mobility module included is shown in Figure 4.1. It consists of an Application module (APP), a Communication module (COMM), a Resource Manager (ResM) as described in the previous chapter and a Mobility Manager (MM). As described in the previous chapter, the Application module is the source and sink of all application data transmitted. The COMM module supports the transmission of data between nodes and consists of one Routing module (RouteM), two MAC modules (MAC1 and MAC2), and two Radio modules (Radio1 and Radio2). RouteM implements the dual-channel AODV protocol.

The Mobility Manager module determines the coordinates of the current location of a mobile node and periodically notifies the wireless channel about the node's location. A detailed explanation of the Mobility Manager is available in the next section. In this chapter, TunableMAC is used for the MAC, as provided by Castalia [143]. Further details can be found in [180]. In this implementation, two radios where each Radio module not only transmits and receives signals, accepting signals whose signal strength is above the radio receiver sensitivity but also provides RSSI and LQI information about channels to

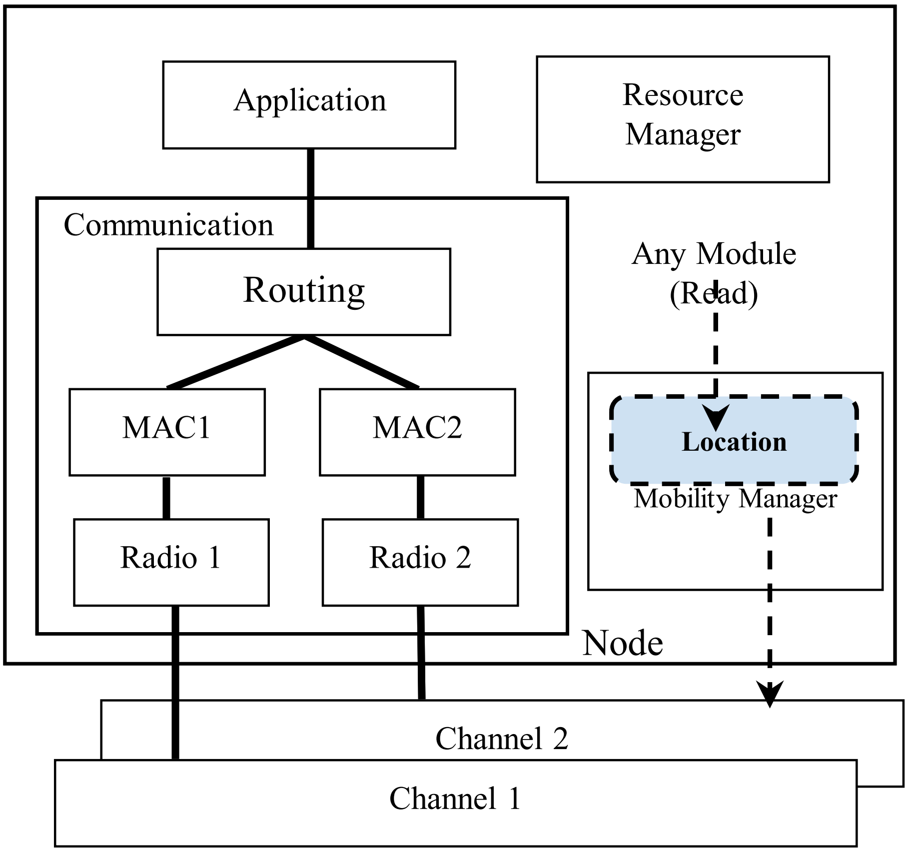


Figure 4.1: Mobility Model in Dual-channel Castalia Structure

higher layer modules. Each Wireless module operates on a different frequency channel and is responsible for broadcasting wireless signals to other nodes. As discussed earlier, the Resource Manager module's main function is to keep track of energy usage in a node and control node start-up and shut-down.

4.5 The Mobility Manager

The Mobility Manager is responsible for handling the node movement. The location of the nodes can be provided to other modules. This location information is relevant for the wireless channel module since it has to communicate with the locations very often to enable computation of the signal propagation from one point to another. The location of the node is periodically updated (the interval of the updates may be adjusted). Thus, it would be inefficient to retrieve location information on their position from all the nodes all the time before computing the wireless channel behaviour.

4.5.1 Allowing for Node Mobility

The channel model for the WBAN is available in Castalia, and it is based on [52] which shows that posture changes of human bodies can cause temporal correlations and that many of the WBAN probability models are inaccurate. The authors developed a more empirically based model in which the body is divided into regions called cells using similar concepts to the virtual coordinate system developed by [49]. There may be more than one node in a cell. Each source-destination cell pair has a given path loss. The problem of node mobility is dealt with by segmentation of the $2D$ environment (possibly a third dimension can be added at the cost of high computation requirements and memory usage) into the cells with adjustable cell size. This implies that the space in discrete cells is needed to break and calculate the path losses from each cell to each other cell as shown in Figure 4.2. This is valid only for a single transmitter cell.

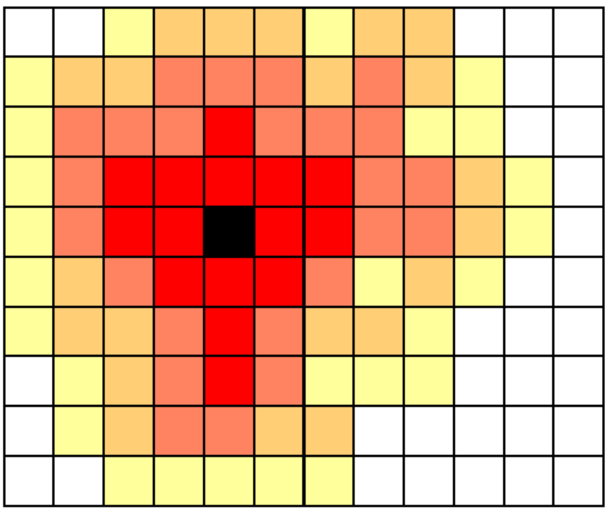


Figure 4.2: Path-loss Map in 2D Space Segmented in Cells

Two parameters should be defined: the size of the field where the nodes are located and the cell size. Cells have a pre-computed path-loss map. There is a trade-off between a more accurate path-loss map and the memory needed for such segmentation. The cell locations and their IDs are taken according to node positions. A more detailed description of the node mobility modelling can be found in [143]. There is currently only one simple mobility behaviour implemented in Castalia. It is called LineMobilityManager, and the nodes can only move from the starting point to the pre-defined destination point along the line back and forth. The speed of the movement can be specified. Chapter 4 will discuss the implementation in detail.

Table 4.1: Parameters of Castalia Line-Mobility Manager

Parameter	**Description**
updateInterval	When to inform the simulation about the new position of the node (time)
xCoordinates	x coordinate of the targeted position
yCoordinates	y coordinate of the targeted position
Speed	The speed of the node when moving from the start position to the target position

When a transmission instance from one cell to another occurs, the actual signal loss is the sum of the cell-to-cell path loss plus a fading loss whose value is determined by a random look-up from a look-up table whose values have been determined from measurement studies.

4.5.2 Mobility Implementation

For mobile nodes, the Castalia-provided "LineMobility" module is used to determine the position (xCoordinate and yCoordinate) of the mobile node. The parameters of the LineMobility are defined in Table 4.1. Many research proposals assume general mobility patterns rather than specific mobility since the latter demands high complexity for modelling. In this module, the node was made to move linearly along a straight line segment with given endpoints at a given speed between the endpoints. Static nodes used Castalia "NoMobility" module. We use the 2.4 GHz IEEE 802.15.4/Zigbee-ready RF transceiver provided in Castalia. When *MOBILITY_PERIODIC* is set to 1, then "LineMobility" Manager will be selected. The algorithm for node movement and wireless channel notification is as follows:

```
For ChannA
setX
setY
setZ
setPhi
setTheta
setNodeID
sendDirect(positionUpdateMsg, channA)
positionUpdateMsg -> ChannelNodeMoveMsg
                        ("location update message")
For ChannB
set X
set Y
set Z
setPhi
setTheta
setNodeID
sendDirect(positionUpdateMsg, channB)
positionUpdateMsg -> ChannelNodeMoveMsg
```

```
                        ("location update message")
```

So the pointers for both channels will be updated along with the node location according to the channel selection procedure. The virtualMobility module collects the node location (xCoordinate, yCoordinate) along with the node ID of the next-hop channel, and then notifies the wireless channel about the node movement as shown in Section 4.3. The starting locations of these nodes are pre-defined according to a virtual coordinate system [49] as shown in Table 4.2. The Virtual Mobility Manager notifies the Wireless Channels when there is a movement detected. Moreover, all other mobility modules should be derived from this Virtual Mobility Manager. In the configuration file (.ini), there is a need to define the speed and the destination point of a line-segment (starting point is referred to as the starting location/point of the node) and thus defines a trajectory for the node to move in the defined direction (back and forth). The Mobility Manager has these parameters in the .ned file:

- SN.node[*].MobilityManager.xCoorDestOftheNode
- SN.node[*].MobilityManager.yCoorDestOftheNode
- SN.node[*].MobilityManager.zCoorDestOftheNode (3D is considered)
- SN.node[*].MobilityManager.speedOftheNode

With a multi-channel implementation, a sensor network gets pointers to all the available wireless channels that need to be created.

```
if wchannel1{
positionUpdateMsg = new WirelessChannelNodeMoveMessage
                           ("Location Update Message");
update xCoor;
```

```
update yCoor;
update zCoor;
sendDirect(positionUpdateMessage, wchannel1,
                                  fromMobilityModule);
} else
{
  sendDirect(positionUpdateMessage, wchannel2,
                                  fromMobilityModule);
}
```

4.6 Metrics

To analyse the performance of the dual-channel approach with mobile nodes in-comparison with static nodes, several experiments have been performed with the following metrics.

1. Number of Control Packets – This parameter presents the average number of control messages, i.e. RREQs, RREPs, DATA, Acknowledgment (ACKs) that are required for the protocol operation. As transmitting and receiving packets consume a considerable amount of energy, this has a high impact on the network lifetime.

2. Remaining Energy – It is the average percentage of energy available at the battery of the nodes once the simulation finishes in static and mobile scenarios.

3. Buffer Overflow – Congestion is generated by buffer overflow. Congestion is also known as a load of a route, as the number of packets buffered in the queue of the node is known.

4. Convergence – As neighbour discovery keeps propagating through routing-table information exchange between nodes, the nodes gain knowledge about the entire network topology and are said to converge.

4.7 Simulation Setup

The dual-channel routing protocol with mobile nodes is developed on Castalia (a dual-channel version (using channels denoted 1 and 2) of the multi-channel AODV routing protocol). Implementing this in Castalia requires significant modifications to the existing C++ and OMNeT++ network description (.ned) files in the single-channel model to add the extra node modules needed (as described in the previous chapter) and the Mobility module. A network of 6 nodes (0-5) is considered which is deployed on a lying patient and he can only move his hand within short range i.e. diagonally. It is done for simplicity. The nodes are placed on the body front in a field of size 2.5 m $\times$ 2.5 m as shown in Figure 4.3 using a virtual coordinate system [49].

Table 4.2: Nodes Deployment

Node No.	**x-coordinate (m)**	**y-coordinate (m)**
node-0	0.4	1.25
node-1	2.1	1.25
node-2	0.3	1.25
node-3	2.1	0
node-4	0.4	0
node-5	1.25	1.8

The sink (BNC) is node 0, and nodes 1 to 5 transmit data to that node only. Node 0 does not send any data to the other nodes. The default configuration of the simulation sets node 1 to be mobile while sending nodes 2, 3, 4 and 5 are static. Node 1 is mobile,

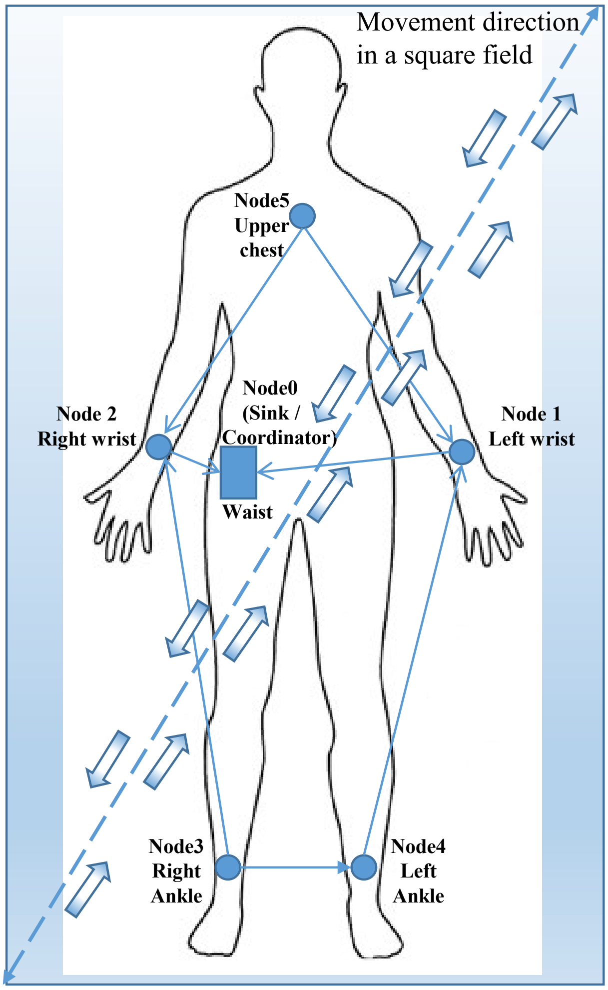


Figure 4.3: LineMobility Model in a Square Field

whereas receiving node node0 or BNC will move in a diagonal pattern, allowing it to receive packets from nodes 1, 2, 3, 4 and sometime later from node 5. This can be seen in the trace files produced by Castalia. In the initial simulation, node 1 is set to be a mobile node, and all the other nodes are set to be static. This way the impact of mobility can be isolated for the mobility assessment. The key simulation parameters used are shown in Table 4.3. The simulation duration is set to 202 sec (200 + 2 sec for dual MAC start-up).

Table 4.3: Simulation Parameters

Module	Parameter and Data Value
Area Size	2.5 x 2.5 m
Application	20 packets per second, 100 byte payload + 30 byte overhead (Application data rate is 20.8 kbps)
Routing	RREQ retries = 2 RREQ rate limit = 10 per sec Active route time-out = 6 sec
Tunable MAC	Default parameters, Constant back-off time, one transmission attempt
Radio	Sensitivity: -100 dBm, Noise floor: -110 dBm Transmit power: 0 dBm
Traffic Type	CBR
Buffer Size	32 Packets
Radio mode	PSK
Data rate	50 packets per second
Mobility Model	Line (Back and Forth) Mobility Update Interval = 10 ms xCoorDestination = 2.5 yCoorDestination = 2.5 Speed = 2 m/sec
Wireless Channel	Bandwidth 20 MHz, Data rate: 250 kbps Modulation type: BPSK, Temporal model, mobile nodes
Initial energy	18720 J (2 $\times AAbatteries$)
Transmission range	CC2420 20 m
Number of Static and mobile nodes	5 and 1

4.8 Results

Four different simulation studies are considered for five static node positions and one mobile node respectively:

1. Single-CHannel (SCH)

2. Multi-Channel with Random Channel Selection (Rand-MC-AODV)

3. Multi-Channel with RSSI channel Selection (RSSI-MC-AODV)

4. Multi-Channel with LQI channel Selection (LQI-MC-AODV)

In Castalia, LQI is based on the Signal-to-Interference-plus-Noise Ratio (SINR). The mobile node in the second case is node 1 (left wrist), which moves diagonally along a predefined path as shown in Figure 4.3.

Figures 4.4 and 4.5 show, for each node, the numbers of AODV DATA packets received by a node on channel 1 and channel 2 for all static nodes and one mobile node, respectively. The labels on the x-axis identify the node receiving the packets and the bars the packet counts from different source nodes. The plots in the figure are for SCH, Rand-MC-AODV (DCH Rand), RSSI-MC-AODV (DCH RSSI), and LQI-MC-AODV (DCH LQI).

All simulations are configured for a constant packet rate in the application module. In the case of static nodes, for SCH all DATA packets are sent on channel 1. Most DATA packets are sent from the source to node 0 in one hop, but there is a small amount of forwarding by other nodes. For both Rand-MC-AODV, RSSI-MC-AODV and LQI-MC-AODV some packets are sent on channel 1 and some on channel 2, depending on which channel is selected (Note that both radios in a node can simultaneously send and receive packets with higher-layer module operation decoupled by buffers.). For Rand-MC-AODV nearly all packets are sent in one hop to node 0. For RSSI-MC-AODV and LQI-MC-AODV some packets are forwarded by another node (nodes 3 and 4 respectively). In the case of one mobile node, there is much more forwarding by other nodes in SCH compared to dual-channel.

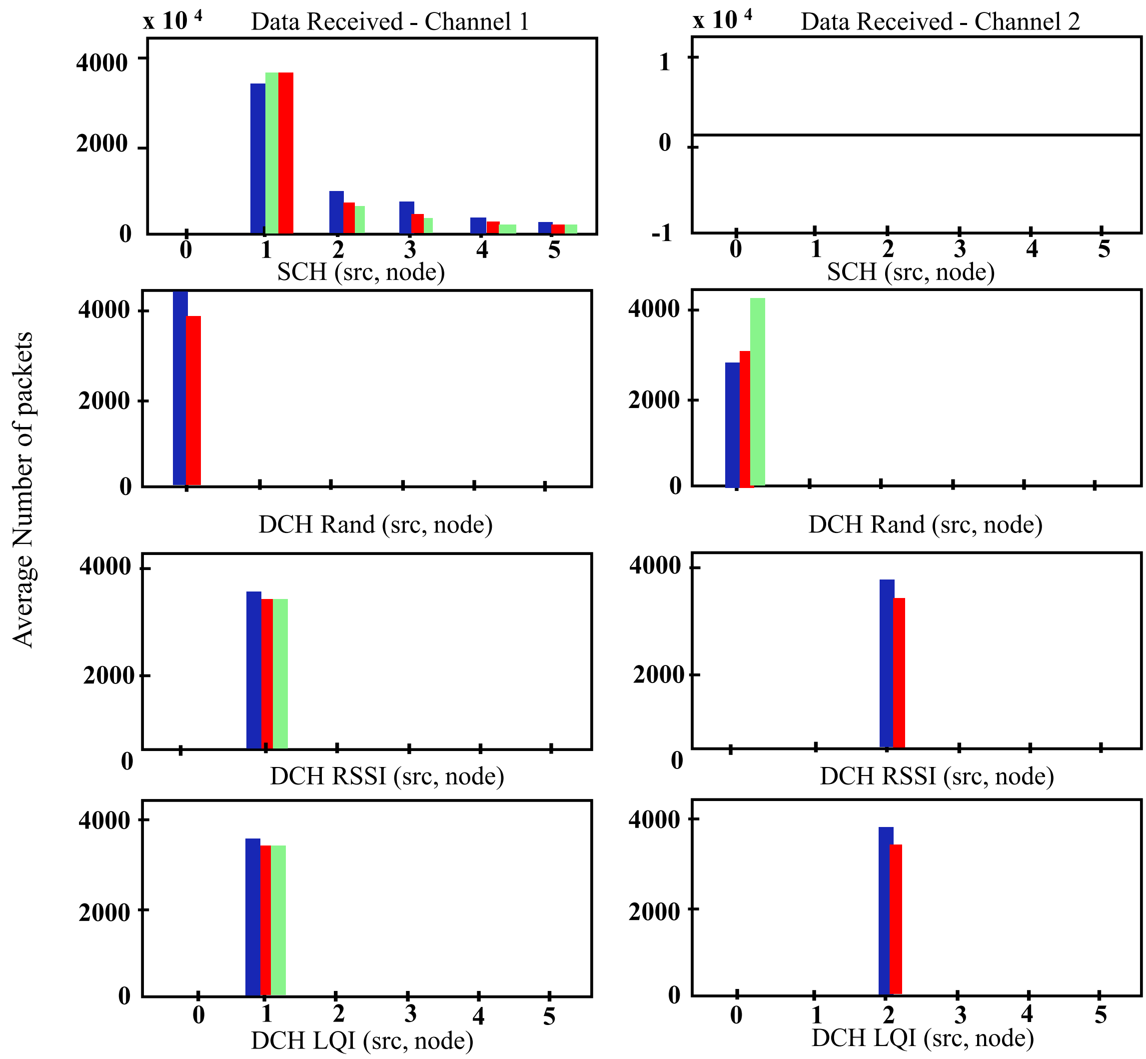


Figure 4.4: Counts of AODV DATA packets received on Channel 1 and Channel 2 in the case of static nodes

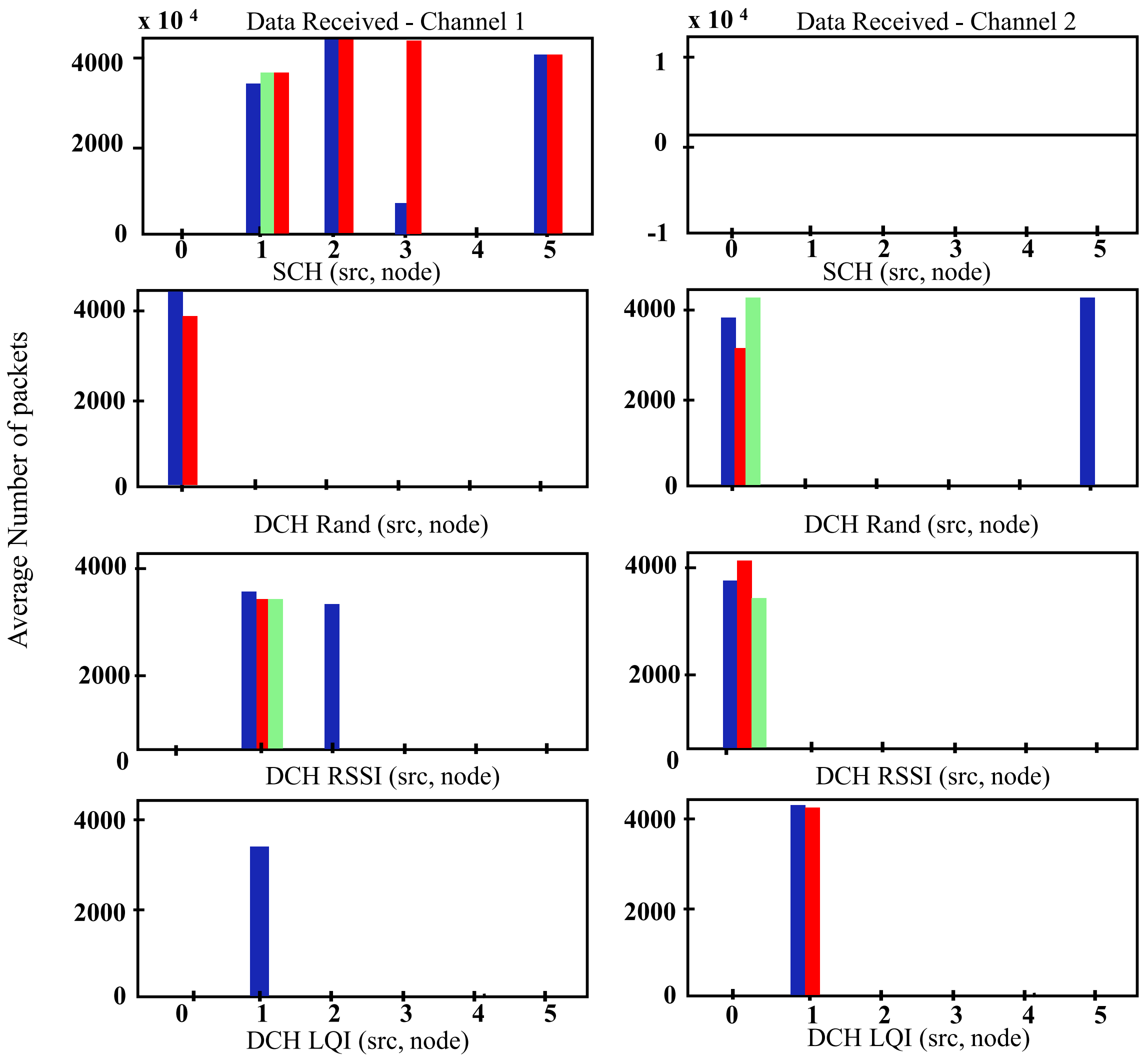


Figure 4.5: Counts of AODV DATA packets received on Channel 1 and Channel 2 in the case of one mobile node

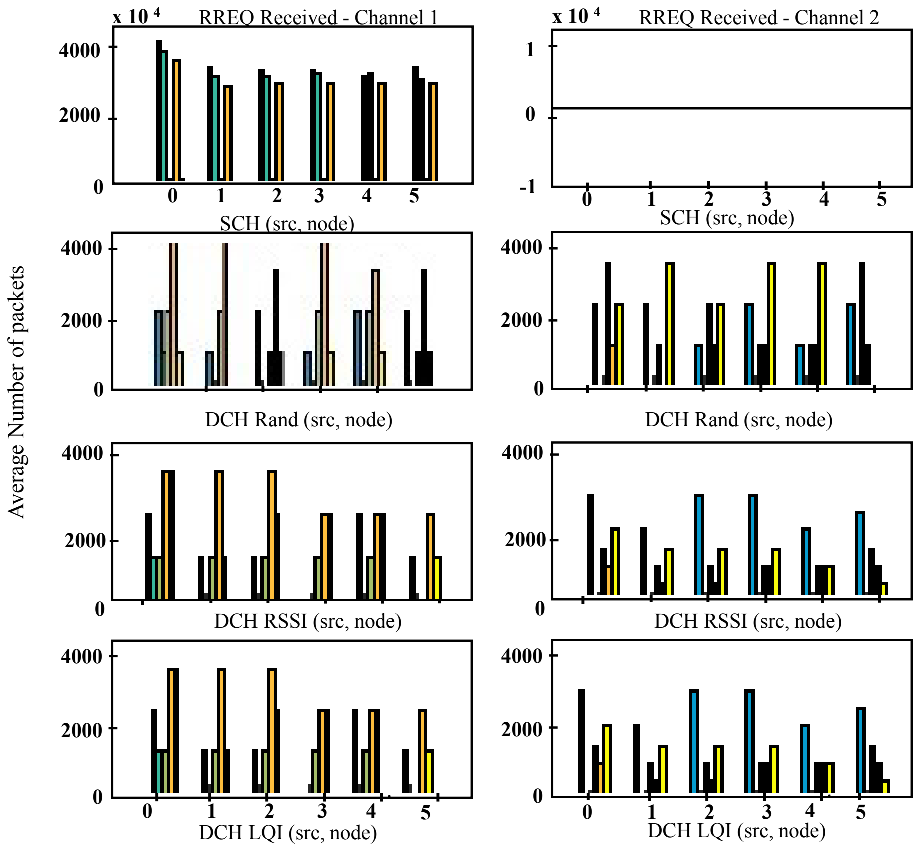


Figure 4.6: Counts of AODV RREQ messages received on Channel 1 and Channel 2 in the case of static nodes.

Rand-MC-AODV, RSSI-MC-AODV, and RCH LQI exhibit similar behaviour to the all-static-nodes case, but channel selection is slightly different. The random channel selection is not feasible in the case of mobility because of unpredictable changes in the wireless channel environment. The noticeable difference can be seen in RSSI and LQI channel selection. In the case of a moving node, channel selection based on LQI gives us better link-quality measurements and thus fewer control messages as compared to RSSI-MC-AODV.

Figures 4.6 and 4.7 show the number of RREQ messages received by each node on channels 1 and 2 for four static and one mobile node respectively. RREQ messages are received under four circumstances: (1) when a node has new application data to send

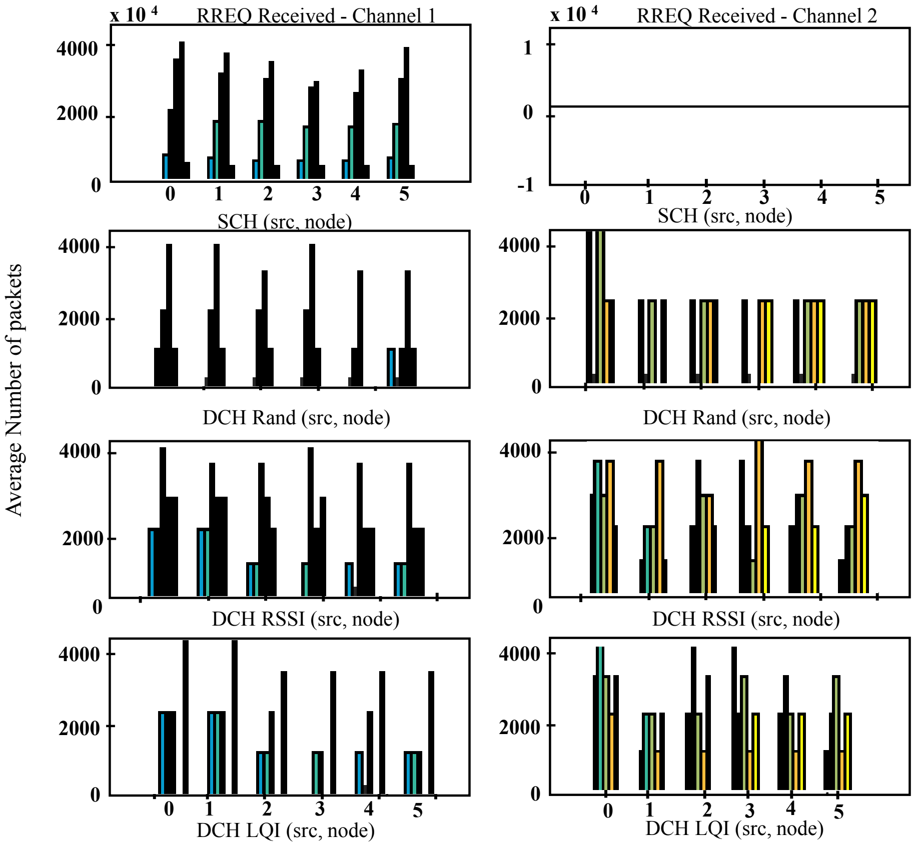


Figure 4.7: Counts of AODV RREQ messages received on Channel 1 and Channel 2 in the case of one mobile node

and no route exists, (2) when a node rebroadcasts a received RREQ, (3) when an RREQ is transmitted from the RREQ buffer because it is put there because of the RREQ rate limit and (4) when an expiry time goes off, and a retry attempt is made. SCH has many more RREQ messages, indicating a little instability in the network with RREQs received by some nodes being forwarded copies sent by several other nodes.

In the case of one mobile node, for SCH fewer RREQs are received than in the static case, indicating less connectivity between nodes, although it still has many more RREQs being sent than in the dual-channel simulations. Overall, RSSI-MC-AODV and LQI-MC-AODV deliver similar numbers of packets to what SCH can deliver but need fewer control messages to be sent and received (control message overhead).

Figure 4.7 shows that our proposed work is able to reduce the routing overhead of packets when compared with SCH and RSSI-MC-AODV. Since routing overhead is in direct relationship with the number of nodes, this also shows that LQI-MC-AODV sends fewer control messages in the case of link disruption and helps in achieving better convergence. Such a collision causes a link break, and subsequently, error packets and route request packets will increase the number of these links broken due to the mobility.

Although Rand-MC-AODV has a similar control-message overhead to RSSI-MC-AODV, the numbers of packets delivered are greater with RSSI-MC-AODV and LQI-MC-AODV.

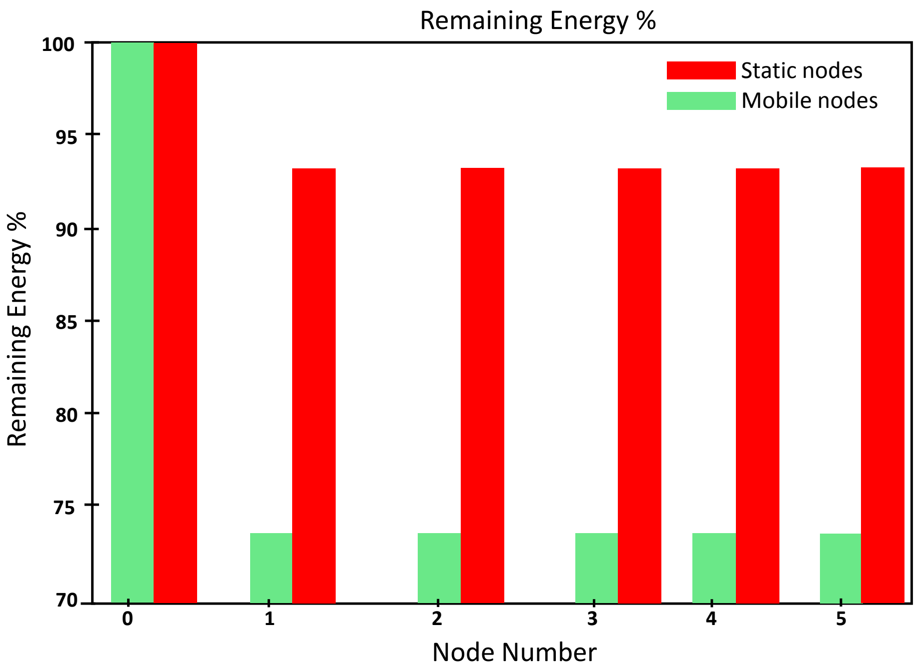


Figure 4.8: Remaining Energy

Regarding energy usage, only small differences were found between the energy usages in the different simulations as shown in Figure 4.8. The simulation shows that there is much forwarding at the intermediate nodes, which consumes more energy in mobile nodes. However, despite the high energy consumption in a mobile scenario, it still complies with balanced energy consumption leading to a better network lifetime.

In this chapter, the buffer flow is computed for all three cases: LQI-MC-AODV, RSSI-MC-AODV and Rand-MC-AODV, as shown in Figure 4.9. It is evident that, by using LQI channel selection, more reliable links can deliver packets to the destination without buffering them in the intermediate nodes. This results in fewer packets dropped at intermediate buffers.

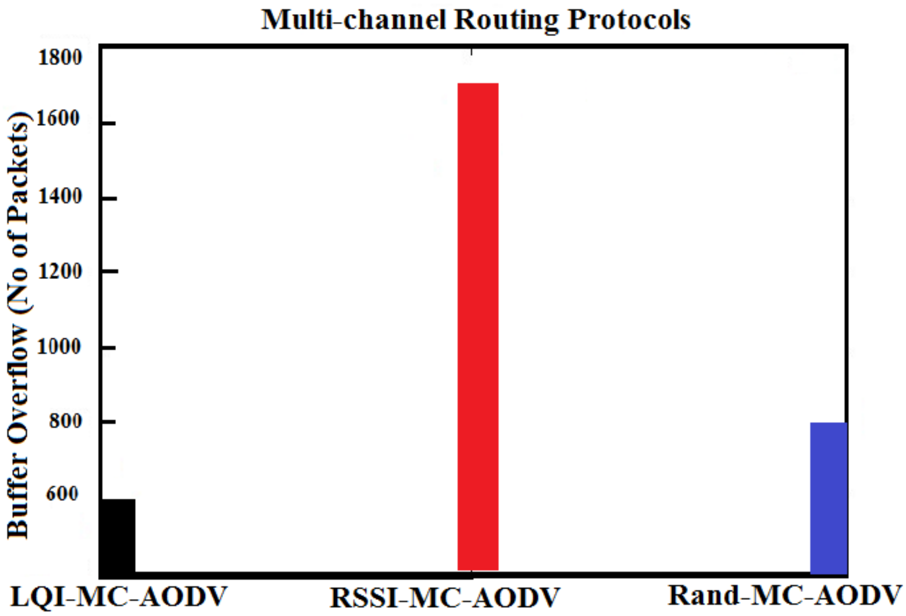


Figure 4.9: Buffer Overflow

Adding just one mobile node results in DATA packets being more widely dispersed in the SCH case, but not so much in the dual-channel cases. The primary objective of congestion control is to minimise the delay and buffer overflow caused by network congestion and hence enable the network to perform better. This means that if a number of packets are sent through a network, network congestion should result in a high packet loss rate, re-routing instability, higher consumption of energy, higher bandwidth, and retransmission of lost packets. LQI-MC-AODV has lower buffer overflow than RSSI-MC-AODV and Rand-MC-AODV, because, with LQI-MC-AODV, more connectivity is observed by the links.

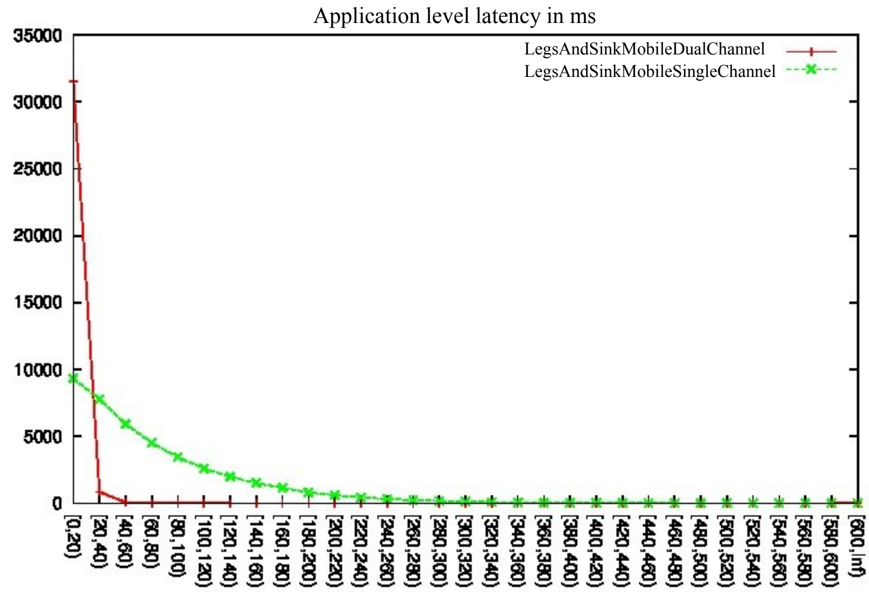


Figure 4.10: Latency when more nodes are mobile

If the legs and sink are made mobile, in case of dual channel routing protocol it gives negligible latency as compared to a single channel routing protocol as shown in Figure 4.10. It is because more channels are available for the data delivery. If we made all nodes mobile, It could improve the network throughput and energy. However, it also increases the number of RREQs being sent and more link dynamics will affect the transmission.

4.9 Conclusions

In this chapter, considering node mobility, a multi-channel routing protocol MC-AoLQM for WBANs is proposed. The operation of the proposed protocol is compared with one mobile node and the rest static nodes against all-static nodes using dual channels and a single channel. Sink mobility changes the link dynamics and leads the network to partition many times till it gets into the stability period. Link dynamics are best compensated by either (i) adaptive routing, or (ii) multi-channel communication. Adaptive routing is out of the scope of this thesis whereas multichannel routing protocol can be best perceived in the presence of mobile nodes (mobile patient). Lossy and bursty links can cause severe degradation in the performance of a network, since it causes many nodes to retransmit packets, increasing interference and energy consumption. So the dual channel will provide the node with the best channel to communicate meanwhile when another channel is busy in transmitting which reduces delay and increases the throughput. The protocol selects a channel based on the LQI, and compares it with an RSSI and a random channel selection and chooses the best route. Compared to a routing protocol without mobility estimation such as static single-channel AODV, the proposed algorithm significantly reduces the number of overhead messages for the route discovery and data delivery. For example, the proposed algorithm reduces the number of overhead messages by about one-third compared to the original single-channel AODV. Such a reduction of overhead messages results in performance improvements such as routing stability, lower energy consumption, and lower congestion. For simulation purposes two channels were used. If more channels were available it is expected that control message overhead will increase, there will be less interference and throughput will increase as well. In the next chapter, the use of energy and other metrics such as the Expected Number of Transmissions (ETX) and Weighted Cumulative Expected Transmission Time (WCETT) would be investigated.

Chapter 5

A Multi-channel Routing Protocol based on a Diversity Path metric for Wireless Body-Area Networks

Contents

5.1 Introduction

In a traditional multi-channel network, the intra-flow interference of a path is relevant to channel diversity. But if a single channel is assigned to all nodes along the path, the channel diversity does not exist [181]. In this chapter, a multi-channel routing metric called Weighted Multi-channel Hop Count (WMHC) is proposed to provide better multi-channel diversity and reduced intra-flow interference for inclusion in a multi-channel extension to the Ad-hoc on Demand Distance Vector (AODV) routing protocol for Wireless Body-Area Networks (WBANs). This metric essentially captures intra-flow interference by reducing the number of nodes on a path of flow on the same channel; it gives low weight to paths that have more-diversified channel assignments. It is shown that the proposed metric WMHC chooses a route with more diversified channels that have less intra-flow interference and hence higher throughput in a multi-channel WBAN.

In earlier Chapters 3 and 4 the development of a multi-channel routing protocol for WBANs is presented. This was based on extending the single-channel AODV routing protocol to operate in a dual-channel model that includes channel selection. This protocol is able to increase throughput over the single-channel AODV protocol. The HOP metric is used. However, if the same channel is used over many hops there can be increased interference between links. This chapter presents a metric WMHC included in the multi-channel AODV protocol that can be used to reduce interference between links by increasing the diversity of the channels used.

In the remainder of the chapter, Section 5.2 describes existing routing protocols and their metrics. Section 5.3 discusses the proposed multi-channel routing metric WMHC. Section 5.4 describes the working of the WMHC metric in a multi-channel AODV. Section 5.5 presents and analyses the results of our simulation experiments along with a discussion, and finally Section 5.6 presents the conclusion.

5.2 Routing Protocols and Metrics - Related Work

In this section is presented a brief overview of routing metrics that appeared previously in the literature review, identifying where they differ from the (Weighted-Metric-Hop-Count) WMHC metric proposed in this chapter.

5.2.1 Hop Count

The HOP metric has been used to decide the shortest path and has been widely used in existing protocols such as AODV [3], DSR [118], and DSDV [119]. An advantage of HOP is that it generates minimal overhead in routing packets and that it does not require learning processes to acquire link quality information. However, factors such as interference, transmission rate, link quality and packet loss ratio on different links (channel diversity) are not considered [30]. As a result, HOP may result in reduced performance in multi-channel network environments. [182] shows that using a radio-aware routing metric that incorporates the link condition can result in better performance than the minimum HOP approach.

5.2.2 Expected number of Transmissions (ETX)

[115] defines the ETX metric for a link as the expected number of transmission attempts required to deliver a packet successfully over the link. ETX assumes that packets are retransmitted if packet errors occur. ETX is designed for a single radio, single-channel environment. For a given link (ab) ETX can be obtained by estimating the probabilities of successful transmission in each direction $\overrightarrow{ab}$ and $\overleftarrow{ba}$. To find the ETX of a link $\overrightarrow{ab}$

$$ETX\overleftrightarrow{ab} = \frac{1}{P\overleftrightarrow{ab}} = \frac{1}{P\overrightarrow{ab} * P\overleftarrow{ba}} \tag{5.1}$$

$P\overrightarrow{ab}$ is the probability that a packet sent by node a will be correctly received by node b, and $P\overleftarrow{ba}$ is the probability that a packet will be both correctly received and acknowledged in a single try. It captures the different packet-loss ratios at wireless links by measuring the expected number of MAC-layer transmissions (ETX) needed to send a unicast packet on a link. The weight of a path is defined as the summation of the ETX's of all links along the path. However, ETX does not consider that different links may have different transmission rates. ETX does improve the throughput of a wireless network (with less mobility) when compared to HOP, but it does not track the variations on the channel (link conditions) at short time scales due to potential route instability.

5.2.3 Expected Transmission Time (ETT)

To solve the problem of keeping track of link variations due to route instability, Expected Transmission Time (ETT) [11] was proposed and improves ETX by considering the differences in link rates. The Expected Transmission Time (ETT) [54] is essentially an ETX adjusted value to give the expected time to transmit a data packet. If S is the packet size in bits and B is the link bandwidth-link transmission rate in bits/s, then ETT is given by

Equation:

$$ETT\overleftrightarrow{ab} = ETX * \frac{S}{B} \tag{5.2}$$

ETT improves ETX by considering the differences in link transmission rates. Similarly to ETX, the drawback of ETT is that it still does not fully capture the intra-flow and inter-flow interference in the network. For example, ETT may choose a path that only uses one channel, even though a path with more diversified channels has less intra-flow interference where higher throughput is available [183].

The sum of the ETT metrics for all links belonging to a path considers the rate diversity of different links but does not capture the intra-flow interference or channel diversity [184]. ETT was not designed for multi-Radio networks and therefore does not attempt to minimise intra-flow interference by choosing channel-diverse paths.

5.3 Multi-Channel Metrics

5.3.1 Weighted Cumulative ETT (WCETT)

To reduce intra-flow interference, WCETT [130] was proposed and this assumes that communications on the same channel always interfere. The WCETT is based on the ETT and is aware of the loss rate (due to ETX) and the bandwidth of the link. WCETT explicitly considers interference among links that use the same channel, minimum hop count and link quality. [127] suggests computing the path metric as not just the sum of the metric values of the links that form this path. When simply summing the link metrics, it neglects the fact that concatenated links may interfere with each other, if they use the same channel [130]. This forces the links to split up the bandwidth. For this reason, WCETT also incorporates the number of channels, as shown in Equation (5.3). Over a path, the contribution to the link delays from the individual link ETT's delays is given by the Equation:

$$WCETT = (1 - \beta)\, D_0 + \beta * \max_{1 \le j \le k} X_j \tag{5.3}$$

WCETT is the sum of the ETTs of all the links in path p operating on X_j channel j, in a system with a total of k orthogonal channels. β is a tunable parameter subject to $\beta\,(0 \le \beta \le 1)$. The term X_j is defined as:

$$X_j = (1 - \beta)\, D_0 + \beta * \max_{1 \le j \le k} X_j \tag{5.4}$$

The latter term is essentially dependent on which channel is the bottleneck link. WCETT is a weighted combination of this term and D_0 by means of the parameters $\beta\,(0 \le \beta \le 1)$ that can be used to adjust the balance between the two components. $\max_{1 \le j \le k} X_j$. This term reflects the diversity of the channels used and as such can be used to control the interference between links.

An enhancement to ETX was proposed which is called WCETT. It uses only the loss rate but not the link bandwidth. It is designed for multi-radio, multi-channel, large, and low-traffic networks. Although WCETT performs well for shorter paths, its performance decreases when the path length increases. WCETT does avoid intra-flow interference, but it does not guarantee the shortest paths now avoid inter-flow interference; which may lead WCETT to select congested routes. Unfortunately, such a metric may not be adequate to reflect the actual channel-diversity level of a route. Due to the drawbacks of WCETT, e.g. risking of loop routing, and overlooking inter-interference [185], WCETT sometimes selects a path with low throughput.

5.3.2 Exclusive Expected Transmission Time (EETT)

When channels are distributed on a long path, EETT selects multi-channel routes with the least interference to maximise the end-to-end throughput. The EETT is used to give a better evaluation of a multi-channel path. For a n-hop path with K channels, on a link l, its Interference Set (IS) is the set of links that interfere with it (a link IS also includes the link itself). Then this link l's EETT is defined as:

$$EETT_l = \sum_{l}^{N} ETT_l \tag{5.5}$$

But EETT would perform well in Large-Scale Multi-Radio Mesh Networks (LSM-RMNs), like multi WBANs where most of the traffic has much longer paths than in small-scale Wireless Mesh Networks (WMNs), the same as single WBAN. EETT reflects the optimality of the channel distribution on a path, as this results in less intra-flow interference. The high density WBANs gives more interference and more re-transmissions will be experienced by the nodes and hence more energy will be consumed. To remove the complexity of larger WBANS, in this proposed protocol only one small-scale WBAN is considered.

5.3.3 Interference Aware (iAWARE)

Besides considering the multi-channel routing metrics mentioned in the literature review, iAWARE [186] also incorporates the Interference Ratio (IR). The IR depicts the interference based on the ratio between SNR and SINR. iAWARE considers the variation of the link quality. It uses the Signal-to-Noise Ratio (SNR) and the Signal-to-Interference-and-Noise Ratio (SINR), continuously updating the routing metrics according to the variations of the adjacent interference. In order to exploit the channel diversity and to find optimal paths with less intra-flow interference, X_j is defined as:

$$X_\mathrm{j} = \sum_{\texttt{conflicting link i on Channel j}} iAware_i \tag{5.6}$$

Similarly with the equation of WCETT, iAWARE for a path can be measured by Equation:

$$iAWARE_p = (1-\alpha) * \sum_{linkl \in pathP} iAWARE_l + \alpha . \max_{1 \le j \le k} X_j \tag{5.7}$$

where α is a tunable parameter bounded in $[0, 1]$.

In order to choose the optimal routing paths, iAWARE considers the intra-flow interference and the external interference. However, iAWARE is sensitive to link traffic and to interfere traffic among neighbouring nodes. Thus, iAWARE can affect route stability, i.e., it may cause frequent changes of established paths and disrupt normal network operation. It may choose a path with lower ETT but higher interference. All of these metrics ETX, ETT, WCETT, MIC (Metric of Interference and Channel switching) [132] may not follow the link-quality variations and/or may produce prohibitive control-message overhead.

5.3.4 Weighted Cumulative Channel Cost Metric based on Link-level (WCCCM-L)

[91] proposed a multi-channel path metric named WCCCM-L, which selects interference aware paths to send packets, mainly based on channel utilisation. WCCCM-L aims at reflecting the channel utilisation and being aware of interference. Besides considering the parameters in ETT, WCCCM-L also uses the Channel Cost Metric (CCM) to reflect channel utilisation that incorporates the equivalent fraction of airtime, which can be evaluated by:

$$CMM - L_l = ETT^l \star F^{l,l_\star} \tag{5.8}$$

where $F^{l,l_\star}$ represents the equivalent fraction of air time of different channels based on one common reference channel, the one with the largest capacity. Similarly to the equation for WCETT, the WCCCM-L of a path can be calculated as:

$$WCCCM - L = (1 - \beta) * \sum_{l=1}^{N} CMM - L_l + \beta . \min_{1 \le l \le k} X_j \left(\sum_{ionl} CMM - L_i \right) \tag{5.9}$$

where link i is conflicting on channel l.

Application of all the above-mentioned metrics requires knowledge of PDR estimates of link quality that are usually obtained by means of probe packets. This is an additional overhead that is not considered in this chapter. Further, these metrics are designed for protocols employing retransmissions.

5.3.5 Weighted multi-channel Hop Count (WMHC)- The proposed Routing Metric

Based on the above observations, in this chapter, a new routing metric, called WMHC for multi-channel WBANs, is proposed. The work is inspired by the following observation. By selecting a route on which hops are selected based on the channel diversity, the interference and channel contention may be minimised, hence improving the routing stability.

The proposed protocol is implemented in a Castalia simulator using the Tunable MAC protocol which does not use retransmissions. Thus, the proposed multi-channel metric seeks a simpler metric but wishes to retain the channel diversity aspects of WCETT. A metric WMHC is to increase the channel diversity of hops defined as: If N_0 is the number of hops over a path and N_j is the number of hops in the path using channel j, then WMHC is given by

$$WMHC = (1 - \beta)\, N_0 + \beta * \max_{1 \le j \le k} N_j \tag{5.10}$$

For $\beta = 0$ the normal HOP metric is considered. For $\beta = 1$ equalising the number of links using the different channels is considered.

An Example to illustrate the metric in the following:

Figure 5.1 depicts a simple topology that shows that how WCETT and WMHC select a route. In this figure, two numbers are associated with each link, the ETT and the channel number (CH), respectively. To show the effectiveness of the WMHC metric with multi-channel, we use 3 channels (Ch1, Ch2 and Ch3) in this example only. Otherwise, for the simulation purpose, we have used the dual-channel approach.

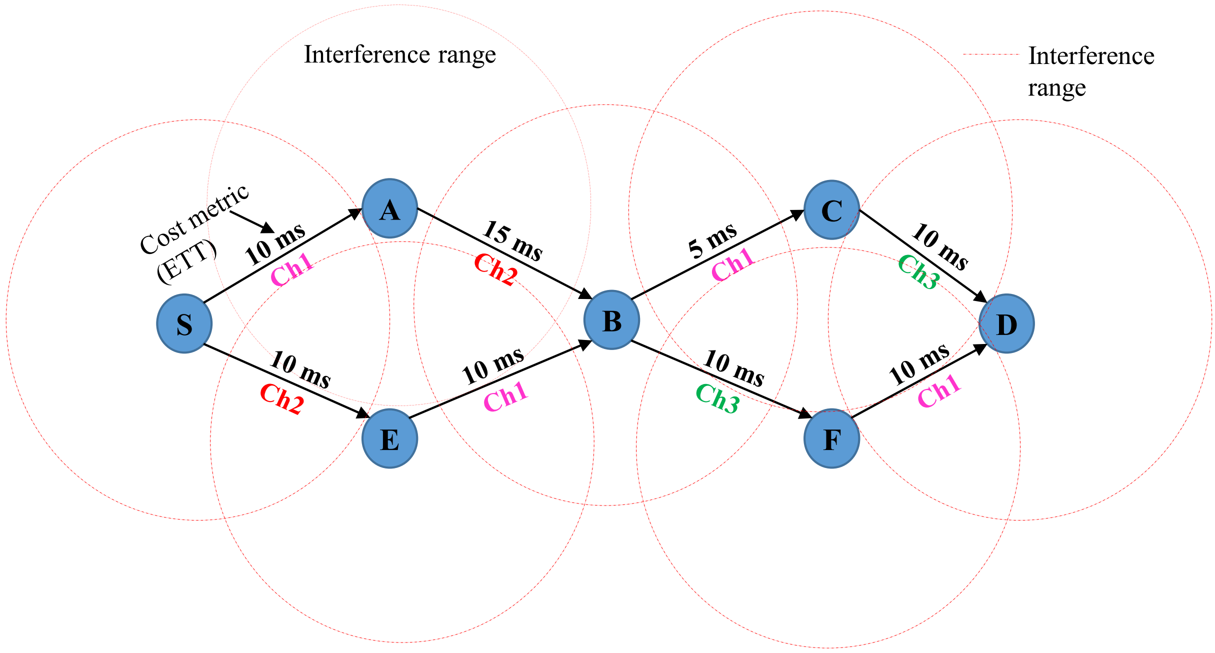


Figure 5.1: An Example Network Topology

Table 5.1: WMHC and WCETT

$\mathbf{N}_j$	$\mathbf{X}_j$	β	WMHC	WCETT
2	**15**	0	6	65
3	**45**	0.5	4.5	55
1	**5**	1	3	45

When selecting a path from source node S to destination node D, there is parallel flows S → A → B → C → D and S → E → B → F → D, which are within the interference range of each other. The number on each link denotes the corresponding channel (at the bottom of the arrow) assigned to the link and the cost metric – ETT (at the top of the arrow).

Considering the definition of WMHC (see Equation (5.10)) when β is set to 0.5, the minimum weight path from Node S to D is 4.5. However, due to the non-isotonic property of WCETT, when node S uses Dijkstra's algorithm to calculate its path to node D, the minimum weight path from node S to D will be 55. N_j and X_j are the channel diversity terms. The higher value of β gives more preference to channel diversity whereas, lower value gives more preference to shorter paths.

We assume node S (Source) wants to send a data packet to node D (Destination), but node S does not have a valid routing table entry for node D (Send src No-Active). Node S activates a route-discovery mechanism by broadcasting a Route RREQuest (RREQ) message, which is received by S's immediate neighbours A and E. Before broadcasting the RREQ, the originating node buffers the RREQ ID and the source address (its own address) of the RREQ (Buff push src no-active) for $PATH\_DISCOVERY\_TIME$. Thus, when the node receives the packet again from its neighbours, it will not reprocess and forward the packet again. Here it is assumed that neither node A nor node E, knows a route to D. Therefore, they simply rebroadcast the message, as shown in Figure 5.1. Each RREQ message has a unique identifier (ID) which allows nodes to ignore duplicate RREQ (having same IDs) messages that they have sent before. When forwarding the RREQ message, each intermediate node updates its routing table and adds a Reverse Route (RevRoute) entry to node S, indicating via which next-hop the node S can be reached, and the distance in a number of hops. Once the first RREQ message is received by the destination node D (we assume via A), node D also adds a RevRoute entry in its routing table, indicating that node S can be reached via node C or F, at a distance of n number hops.

5.4 Multi-Channel AODV Routing Protocol

AODV is an on-demand (reactive) routing protocol that determined routes for transmission only if a node needs to deliver packets to target nodes, thus reducing excessive consumption of network bandwidth and energy. A multi-channel version of AODV has used a WBAN routing protocol in this chapter. AODV uses because it responds quickly to topological changes that may affect active routes.

5.4.1 Neighbour table

In the proposed protocol, nodes maintain a neighbourhood table containing routes to every node on the network, whereas single channel AODV nodes only log the ID of the next-hop node needed to forward the packet to the intended destination. The WMHC metric is implemented by adding three fields to the RREQ and RREP message headers: HOPCOUNT (HC), HOPCOUNT1 (HC1), HOPCOUNT2 (HC2). HC is the number of hops in total that the RREQ/RREP has traversed from the source/destination. HC1 is the number of hops traversed over channel 1 and HC2 is the number of hops traversed over channel 2. If an RREQ/RREP is received on channel 1, then HC and HC1 are incremented by one, and if an RREQ/RREP is received on channel 2, then HC and HC2 are incremented by one. When the RREQ/RREP is received the WMHC metric is computed using Equation (5.10) where $maxN_j$ is equal to max(HC1, HC2). The routing table, next-hop node, and next-hop-channel are updated to the source/destination if the metric is smaller than the current metric.

In emerging WBAN applications, memory could be a problem but in networks like WBANs, it won't be a problem where limited number of nodes are available per WBAN.

5.4.2 AODV Procedure

A route-discovery process is initiated at a source node when it wants to send DATA packets to a given destination. It begins by broadcasting an RREQ packet on a given channel. The modified RREQ format is shown in Table 5.2. A unique sequence number is included in all RREQ packets to avoid packet looping. The RREQ packet also includes path metric information to enable a route to be found back to the source. On receiving an RREQ, a node computes new path metric information using the path metric information (HC, HC1 and HC2) in the RREQ and the metric link information for the link (LQIs - Link Quality Indicator) on which the RREQ was received. The node updates the Routing Table (RT) metric to the source node if the new path metric is smaller than the previous value, updating the next-hop node and next-hop channel back to the source.

Table 5.2: RREQ Packet

RREQ ID	**Seq Num**	**Seq Num**	**HopCount**	**HopCount1**	**HopCount2**

If the receiving node is the destination or if it already has an active route to the destination, it generates a Route Reply (RREP) message that is uni-cast hop-by-hop back to the source using the previously stored next-hop information in the node routing table. The RREP contains path metric information (HopCount1, HopCount2) for establishing a route to the destination. As the RREP propagates back towards the source, each intermediate node updates path metric information and updates RT entries for the path to the destination in much the same way as the RREQ did for the source node. When the initial source receives the RREP message, it records the next hop to the destination in its routing table, records that there is an active route to the destination, responds to the RREP message with an RREP Acknowledgement (RREP-ACK) message that is sent to the destination, and begins sending data to the destination using DATA packets.

If a route has not been used for some period of time route-expiry-timer time out and the node has removed the route from a node's routing table. If a link break is detected, a Route Error (RERR) message is sent to the source and the source re-initiates the route discovery if necessary. When RREP messages are received HELLO messages are broadcast to neighbour nodes on a regular basis.

5.5 Performance Evaluation and Results

The structure of the dual-channel node is already discussed in earlier chapters and the modified version is presented in 5.2. The Radio module transmits and receives signals, accepting signals whose signal strength is above the radio-receiver sensitivity, but also provides RSSI (Receive Signal Strength Indication) and LQI information about channels to higher-layer modules. The quality of multiple channels is considered in the routing module, which leads to the link-quality-aware design of our dual-channel routing protocol. Each Wireless module operates in a different frequency channel and is responsible for broadcasting wireless signals to other nodes. In the Castalia simulator, the wireless channel module implements a channel model to determine the received signal levels. The Resource Manager module's primary function is to keep track of energy usage in a node and control node start-up and shut-down.

The two MAC modules (MAC1 and MAC2) each contain an instance of a single-band MAC protocol module. In this chapter, the MAC protocol used is the Tunable MAC implemented in Castalia. Each of the two radios is a single-band radio with a separate wireless connection to separate Wireless channel modules.

The dual-channel AODV routing protocol and the WMHC metric described in Section 5.3 and Section 5.4 are proposed. This metric is developed on dual-channel routing protocol in Castalia simulator [143] based on the OMNeT++ platform [162]. Implementing

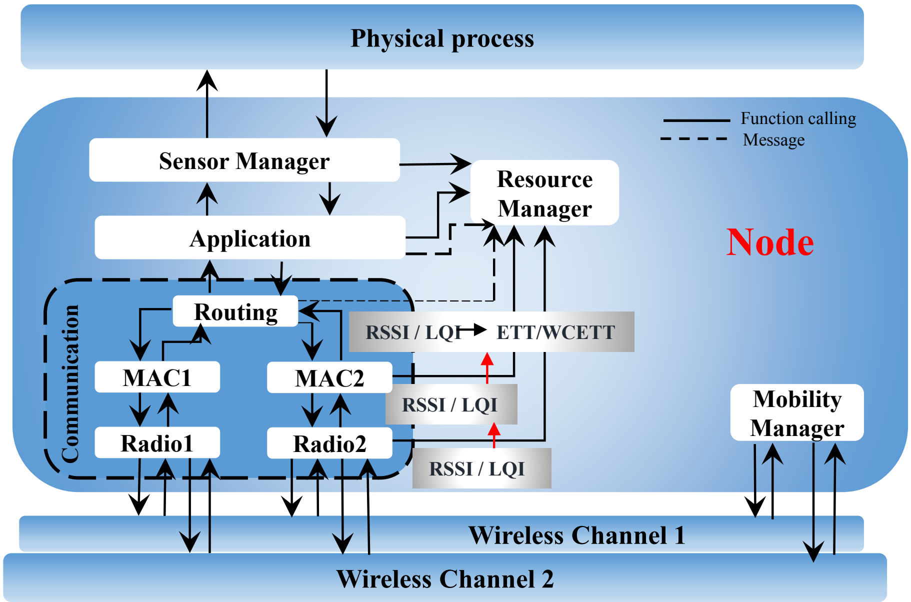


Figure 5.2: Multi-Channel Node Structure

this requires significant modifications to the existing C++ and network description (.ned) files in the single-channel model to add the extra node modules needed (second MAC and second Radio) and add the extra multi-channel AODV routing protocol functions into the Routing module.

A network of 6 nodes $(0-5)$ placed on the body front is considered as shown in Figure 5.3, according to the Castalia-supplied placements. The sink (BNC) is node 0 and nodes 1 to 5 transmit data to that node only. Node 0 does send any data to the other nodes. The 2.4 GHz IEEE 802.15.4/Zigbee-ready CC2420 RF transceiver provided in Castalia is used. The key simulation parameters used are shown in Table 5.3.

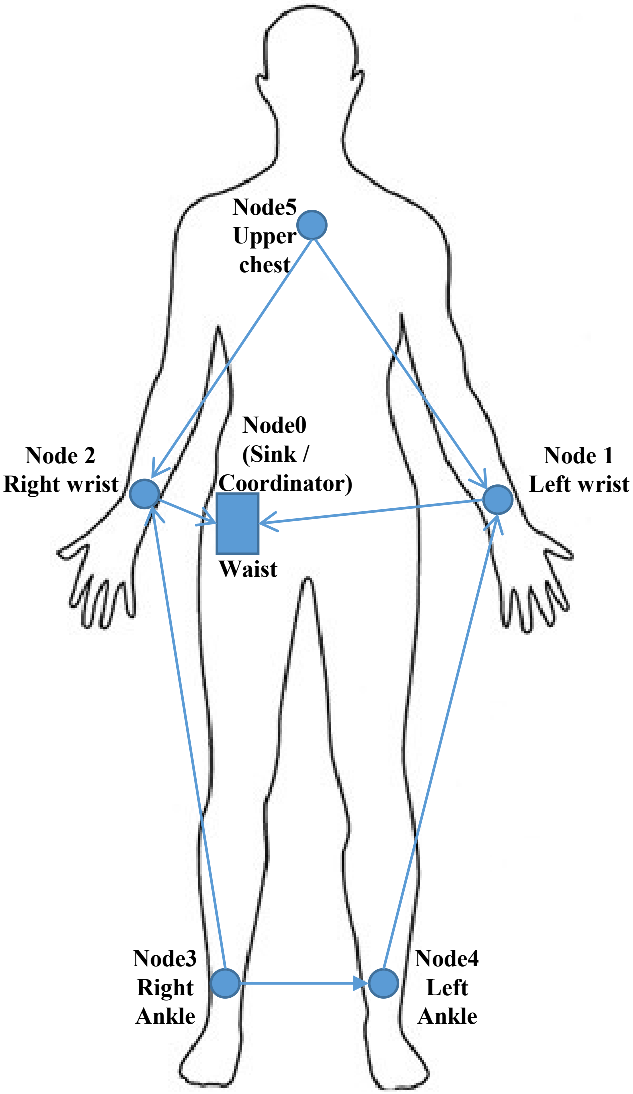


Figure 5.3: WBAN Nodes

Table 5.3: Simulation Parameters

Name	Parameter and Data Value
Area Size	2.5 x 2.5 m
Number of nodes	6
Application	50 packets per second, 100 byte payload + 30 byte overhead (application data rate is 20.8 kbps)
Routing	RREQ retries = 2 RREQ rate limit = 10 per sec Active route timeout = 6 sec
Tunable MAC	Default parameters, Constant back-off time, one transmission attempt
Radio	Sensitivity: −100 dBm, Noise floor: −110 dBm Transmit power: 0 dBm
Traffic Type	CBR
Buffer Size	32 Packets
Radio mode	PSK
Data rate	50 packets per second
Beta	$\beta = 0$, $\beta = 0.5$, $\beta = 1$
Wireless Channel	Bandwidth 20 MHz, Data rate: 250 kbps Modulation type: BPSK, Temporal model, static nodes
Initial energy	18720 J (2 × AA batteries)
Transmission range	CC2420 20 meters

The radio parameters have been derived from the Teleos Mote Data-sheet [89]. The radio is set to PSK (Phase Shift Keying) modulation in Castalia and uses the additive-interference collision model. The radio-propagation model adopts the default model of Castalia. Each node is equipped with two NICs. The off-the-shelf CC2420 adapters or access points allow different transmit-power settings one of 1, 5, 20, 30, 50, and 100mW. We adopt $30mW$and $100mW$in our simulation. The SINR threshold is set at 6.02 , and the noise floor at each node is $120dBm$. The traffic flow type is CBR (Constant Bit Rate), and the packet sizes are 1000. These six nodes transmit data to the sink node through the CSMA/CA mechanism.

Based on these arrangements, the performance of dual-channel AODV using the WMHC metric for $\beta = 0$, 0.5, 1 was compared with that of a single-channel model using the hop metric (SCH). The simulation sets two different sending rates: one is 100 kbps, and the other is 250 kbps. Recall that the communication channels between neighbouring nodes are randomly assigned in this simulation. Therefore, with more channels assigned randomly in the network, the route selected by WMHC may have better channel diversity. In the dual-channel case, if an RREQ message needs to be transmitted the outgoing channel (1 or 2) is selected at random with equal probability. The simulation time for a run was set to 200 seconds with 30 runs for each setting, and the results averaged.

Fig 5.4 shows the results for the number of DATA packets received at the sink node (0). The results show that WMHC with β equal to 0 and 0.5 achieves slightly better delivery than SCH. β equal to 1 is slightly worse. More detail of packet forwarding is shown in Figure 5.5, which shows the results for the number of DATA packets received by the routing module from the application, the number sent over an already available route (cumulative over both channels for WMHC) at the source, the number buffered at the source, the number received and sent by intermediate nodes and the number received at the destination. These results show that SCH uses very little forwarding by intermediate nodes whereas WMHC for all values of β uses significant forwarding by intermediate nodes. This can be explained by the disposition of WMHC to increase the diversity of channels.

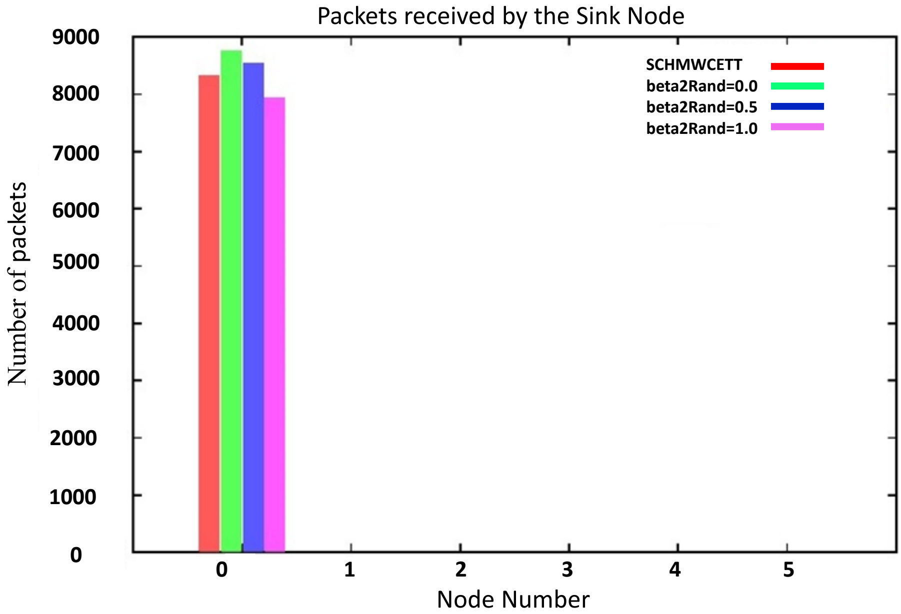


Figure 5.4: DATA Packets Received by Sink Node (0)

The control message overhead was assessed by examining RREQ message flows. Figure 5.6 shows for RREQ messages the number of messages sent by a source node when no active route is available, the number buffered at the source because of the rate limit timer, the number received at an intermediate node when an active route exists to the destination (and an RREP is sent), the number received at an intermediate node when no active route exists, the number forwarded, the number buffered at an intermediate node and the number of requests received at the destination. The maximum RREQ message transmission rate from a node was set to 10 per second (Castalia default). Although numbers are comparable SCH has slightly less forwarding of RREQs at intermediate nodes while WMHC β equal to 0 has the most. The high numbers of RREQ received at an intermediate node when an active route to the destination exists reflects the increased

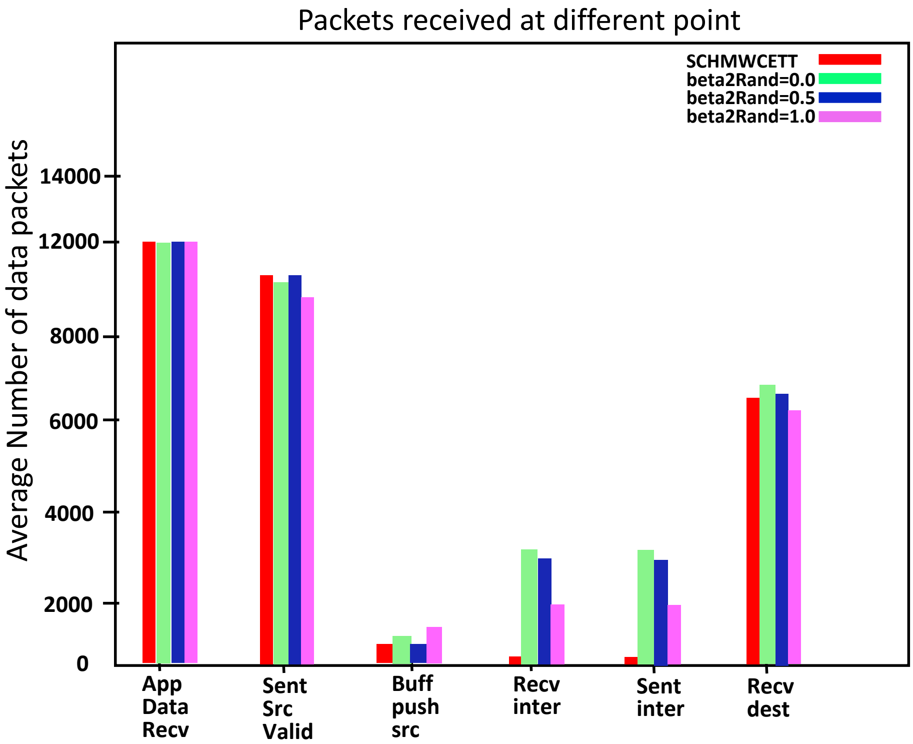


Figure 5.5: DATA Packets at Different Points in the Network

amount of forwarding by intermediate nodes.

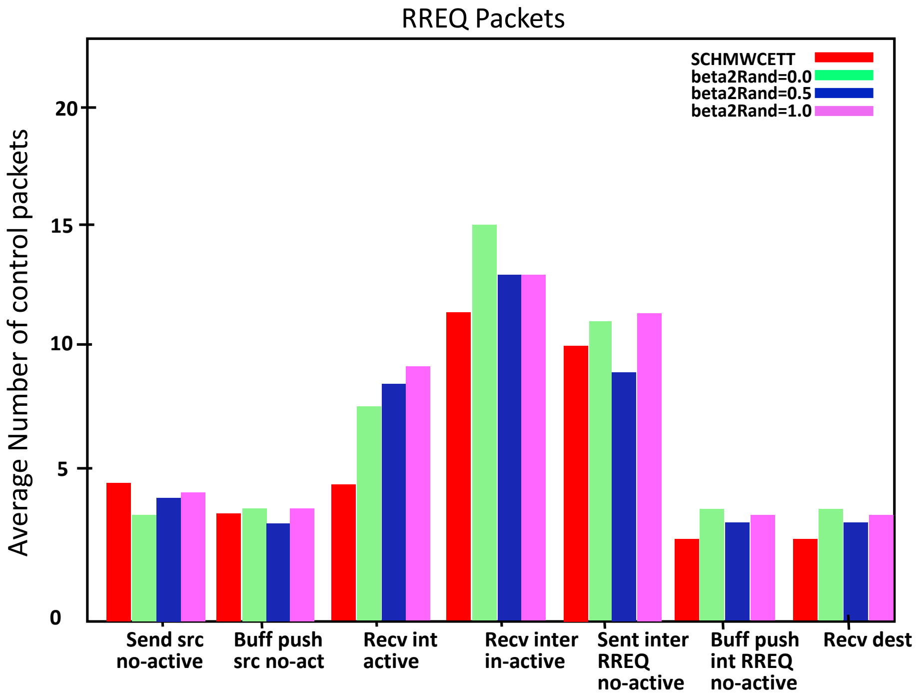


Figure 5.6: RREQs Received

Table 5.4: Interference statistics

	Failed with Interference	**Failed below sensitivity**	**Failed non Rx**	**Failed despite interference**	**Recv with no interference**
$\beta = 0.0$	743	49.5	44327.1	316.5	15536.6
$\beta = 0.5$	289.4	93.8	9676.2	124.6	33824.3
$\beta = 1.0$	391.9	75.3	14545.5	171.3	27856.7
SCH	162.8	88.9	6795.1	78.8	26195.7

The parameters that are considered by the sink node are enumerated as follows [143]:

1. *Received with no Interference*: indicates the average number of packets received successfully without any interference.

2. *Failed despite Interference*: represents the average number of packets failed with possible interference from the neighbour nodes.

3. *Failed with Interference*: are the average number of packets wholly failed because of interference.

4. *Failed below Sensitivity*: indicates the average number of packets reception failure because it is below the receiver sensitivity.

5. *Failed Non-Rx*: refers to the average number of packets failed due to the non-reception state of the transceiver.

Table 5.4 shows the impact of interference. SCH has much higher packet-delivery failures and fewer successful deliveries than WMHC which is to be expected given that WMHC uses two channels. For instance, the normal average number of packets received without interference is equal to 33824.3 when $\beta = 0.5$ in the multi-channel case, compared with 26195.7 for SCH using HC. For WMHC β=0.5 gives the best performance since it tries to obtain a compromise between hops and diversity. The number of nodes used in the network was relatively small, and in larger networks, more interlink interference will occur and as expected WMHC will perform even better. One of the aims of using WMHC is to reduce this interference, and these results show that the WMHC metric is a simple way of achieving this.

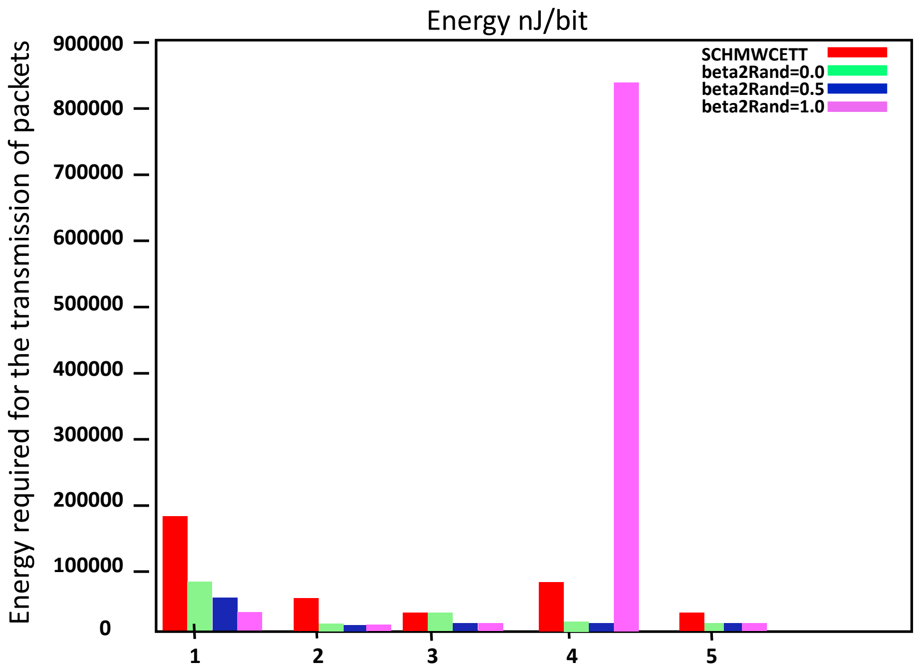


Figure 5.7: Energy Usage per Node

The energy usage per node is shown in Figure 5.7. Although WMHC, on the whole, requires less energy than SCH there is an outlier for WMHC=1 for node 4, meaning that the results on energy usage are inconclusive. There are several parameters that need to be configured in TMAC. Additional studies show that the interaction between TMAC parameters and AODV parameters and timer time-outs could be quite complex. For example, increasing the number of allowed RREQ retries also increases the RREQ expiry time-out value. Increasing the number of RREQ retries also leads to more contention in the MAC layer. On the other hand, more contention in the MAC layer leads to more failures to deliver RREQ packets and consequent time-outs. The optimum configuration of parameters in dual-channel operation is an open issue.

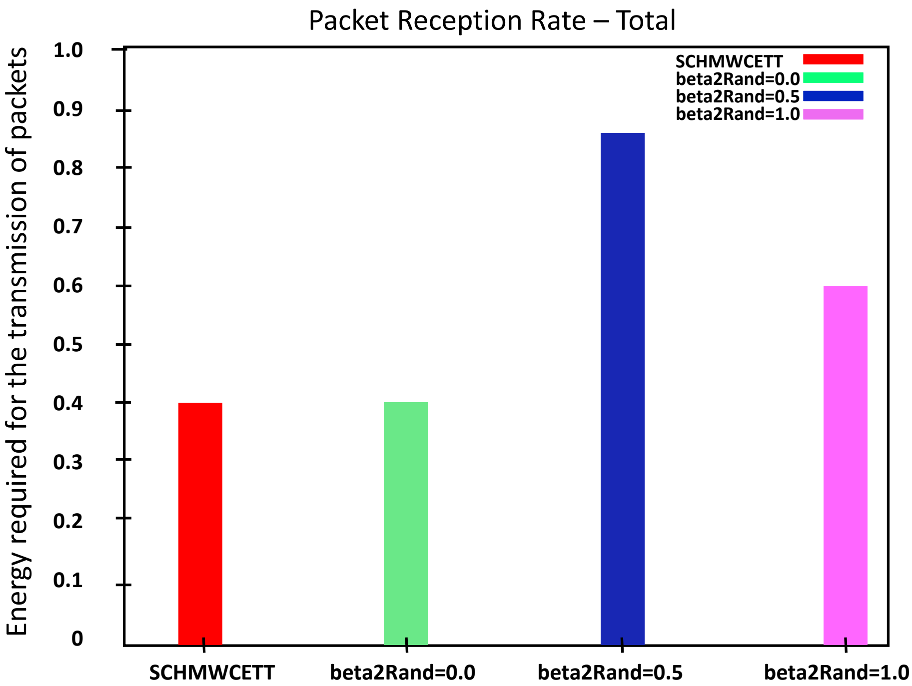


Figure 5.8: Packets Reception Rate

In Figure 5.8 it shows that when the probability of selecting a good channel is equal then β=0.5 gives double PRR as compared to SCHMWCETT and when the next hop is selected in case of β=0.

5.6 Conclusions

A channel-diverse routing metric called WMHC was proposed and implemented in a dual-channel AODV for achieving high-throughput paths with fair and minimal energy consumption as compared to the single-channel routing protocol and the original multi-channel AODV. WMHC uses a random channel selection as it does not rely on additional probe-packet overhead to obtain link-quality information. It has been shown that WMHC is a simple method of reducing interference and improving throughput in a multi-channel environment. WMHC improves the connectivity between the nodes, reduces the inter-channel interference and helps in improving network throughput. Better packet delivery is achieved but with less AODV control overhead (Reduced number of control messages, i.e. AODV RREQ, RREP etc.). Better routing stability and better energy efficiency are achieved as compared to using the single-channel metrics and protocols.

Chapter 6

A Multi-Channel Routing Protocol based on Remaining Energy and Link Quality for Wireless Body-Area Networks

Contents

6.1 Introduction

There is a strong correlation between LQEs (Link Quality Estimators) such as LQI and the Hop Count (HC). LQE decreases sharply if the moving node moves away from the sink node (SINK) beyond a certain number of hops called the Hop Count Threshold (HCT), e.g. node reaches more than 3 hops away from the SINK, and maintains that HC for more than 2 s, [37]. When the LQE significantly decreases, the connection latency increases as a result and leads to sensor-node link disconnection [187]. In that case, more retransmissions would be required to get the connection back on. This traffic overhead decreases the network efficiency and increases the energy consumption drastically. A non-uniform energy consumption causes network performance degradation and network lifetime shortening [188].

To increase the energy efficiency and reliability of a Wireless Body Area Network (WBAN), this chapter presents a multi-channel routing protocol that uses a lexical routing technique to select routes on the basis of a composite metric (combination of one or more primary metrics). The uniqueness of the proposed scheme is that it uses only local information for the Link Quality Indicator (LQI values) and requires no additional communication or cooperation between nodes. It incorporates a bad-link avoidance technique (number of low-quality links in the path called the Bad Link Quality Indicator (BLQI) metric) and is compatible with the primary AODV (Ad-Hoc on Demand Distance Vector) data formats and operation [3], making it easy to adopt.

The proposed Multi-Channel Routing Protocol is based on the Remaining Energy and Link Quality (MC-REL) using the composite metric (number of hops, BLQI and the Path remaining energy (PRE)) for the next-hop selection. It is a multi-hop, multi-path routing protocol. MC-REL is implemented in the Castalia simulator [143] and is compared with single-path Routing based on the Remaining Energy and Link quality indicator (REL) [151] and the single-path, single-channel routing protocol based on the Remaining Energy and Link quality (S-REL) proposed in Chapter 3. It uses the channel-selection features developed for the multi-channel AODV protocol in previous chapters.

The simulation results show that MC-REL not only reduces the energy consumption but also achieves a more uniform energy usage between the nodes, reduces the control-packet overhead resulting in a longer network lifetime. The results also show that energy utilisation is uniform among the nodes of the network, enabling nodes to stay alive for a more extended period to deliver data. It assures the stability of the route while data is transferred, and avoids high-rate dissemination of control packets (giving low control-traffic overhead) in the multi-channel routing outcome as compared to the single-channel one.

In the remainder of this chapter, Section 6.2 describes related work, Section 6.3 presents the system model, Section 6.4 describes the routing protocol operation and the proposed metric, Section 6.5 presents the Castalia energy model used in this protocol. Section 6.6 presents results of the simulation experiments along with discussion, and then Section 6.7 presents the conclusions.

6.2 Related Work

The HC metric has been used to decide the shortest path and has been widely used in existing protocols such as AODV [170]. A routing metric is monotonic if the weight of a path can be only increased, never decreased. If a metric includes this feature, it can be considered loop-free and creates an optimal path. On the other hand, a routing metric is isotonic if the order of two path weights is preserved whether or not they are linked to a common third path. Hop Count is one of the most common isotonic metrics, and it is used in several protocols such as AODV and REL that can find loop-free paths with minimum HC. However, HC does not consider the differences in the transmission rates and packet-loss ratios between different wireless links, or the interference in the network. The disadvantage of HC in AODV is that this metric favours long, low-bandwidth links over short, high-bandwidth links. To take account of using a less congested and optimal path while considering low HC, it is sometimes necessary to include the remaining energy of that path (remaining energy of all the nodes) to balance the overall energy consumption along that path for the routing decision.

The Remaining Energy (RE) is a metric used by energy-aware routing protocols with the objective to increase the network lifetime. The RE value determines the lowest energy level between the nodes that compose a path. But as the RE is not strictly monotonic, and it can generate loops in the forwarding packet process. Paths with loops increase the network energy consumption and the probability of packet loss, besides reducing the network lifetime.

The Link Quality Indicator (LQI) is a parameter offered by the standard IEEE 802.15.4 physical layer which aims to represent the quality of a link at the moment of a frame reception [128]. LQI values change between 0 and 255 where the higher value represents, the better link quality between two nodes. Thus, LQI is a dynamic metric that defines the quality of a link locally. To allow the use of LQI to quantify the quality of a path from the beginning to the end, some authors propose various techniques. In REL [151] and [189], a threshold based on the LQI value (BLQI) is used to avoid path with weak links in a lexical routing metric.

Among the protocols for WSNs [189], [151] that evaluate other metrics in addition to the number of hops as discussed in Chapter 2 Link quAlity-Based LExical (LABILE) [189] is based on the physical layer (LQI) of the IEEE 802.15.4 standard. Using an LQI metric, LABILE can evaluate the link quality. The LABILE protocol evaluates end-to-end link quality, by classifying the possible values of LQI into good or bad. LABILE selects routes having good links (link-quality). Thus LABILE is built on the single-path, single-channel AODV routing protocol that includes a lexical metric built from the path-link quality and the number of hops where the path-wise link quality has the higher priority. LABILE uses short hop paths, which makes it suitable for WBANs. However, it does not consider energy efficiency, and this behaviour implies that routes have exhaustive use and lead to the premature death of these nodes so reducing its applicability in WBANs.

Routing by Remaining Energy and Link quality (REL) [151] is an extension of LABILE whose metric combines energy, link quality and HC. It is a reactive cross-layer routing protocol designed for flat networks, i.e., large-scale applications, single-path, and multi-hop WSNs. REL selects routes based on an end-to-end link quality, RE, and HC. The end-to-end link quality is a metric provided by the physical layer. Additionally, HC and the energy of each node along the same path are part of the evaluation to define the route. In WBANs, where link quality and interference can compromise the communication between nodes, the proposed protocol in this chapter with these characteristics will be a good choice. However, in WBANs it is often desirable to use multi-channel, multi-path routing protocols because they can provide a number of parallel paths on different channels to deliver data, and offer network load balancing, minimise energy and increase throughput.

In previous Chapters, 3 and 4, multi-channel routing protocols were proposed based on extending the single-channel AODV routing protocol with joint-channel selection based on LQEs to operate on multiple channels. These protocols were able to increase the throughput over the single-channel AODV protocol. However, the metrics used were the HC so that, if the same channel is used over many hops, there can be increased interference between links which reduces capacity. A cross-layered approach incorporating the link-quality information into routing decisions is used to offset this.

6.3 System Model

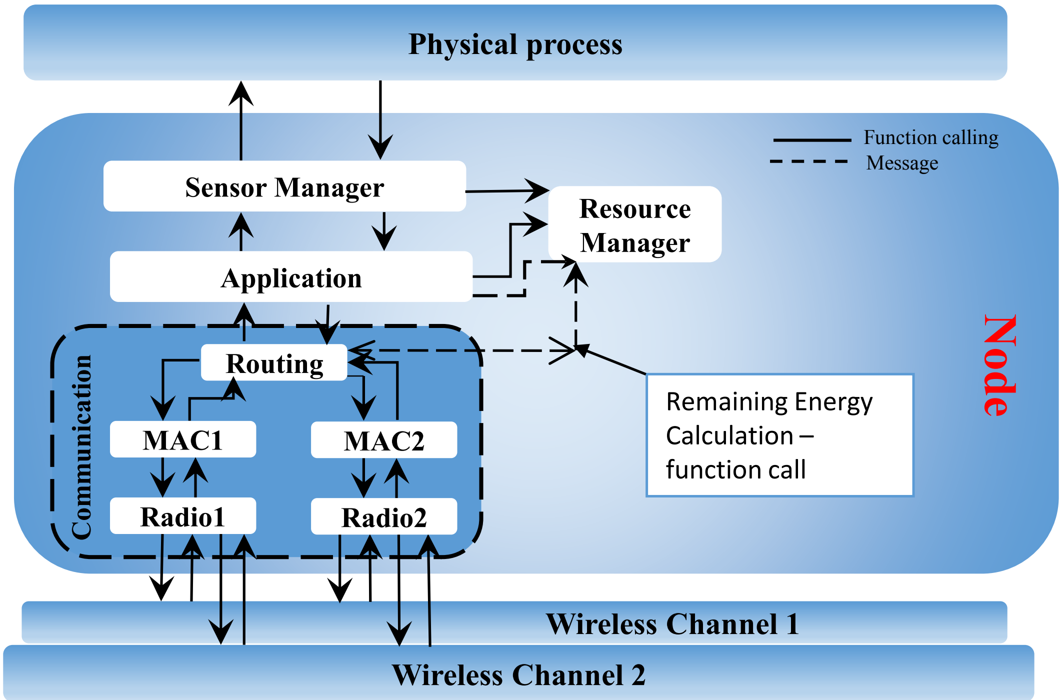


Figure 6.1: Dual-Channel Castalia Node Structure

6.3.1 Multi-Channel WBAN Nodes

The multi-channel WBAN system model comprises a number of nodes connected to two wireless channels as mentioned in previous chapters. Each node is equipped with two radios, and the node can potentially transmit and receive at the same time on separate channels. The structure of a node is shown in Figure 6.1. It consists of an Application module, a composite Communication module and a Resource Manager. The Resource Manager module provides the battery status (energy spent by the node) of each node to all of the modules. To do that, modules that implement hardware devices (i.e., the Radio and the Sensor Manager module) notify how much power they have drawn to the Resource Manager. Then, the consumed energy is calculated, both periodically and each time a variation of power occurs. Castalia supports a linear energy consumption model (see Section 6.5). The computation of energy consumption is the primary task for the Resource Manager and is discussed in Section 6.5. Every single module's setting specifies the amount of energy used by the sensor node.

In this chapter, Tunable MAC is implemented in Castalia. Each of the two radios is a single-band radio with a separate wireless connection to separate Wireless Channel modules. The Radio module transmits and receives signals and accepting signals whose signal strength is above the radio-receiver sensitivity, but it also provides RSSI (Receive Signal Strength Indicator) and LQI (Link Quality Indicator) information to higher layers.

The higher-layer modules perform dynamic channel selection in response to channel impairment. Mechanisms for this are available in IEEE 802.15.4 ZigBee, such as LQI which assesses the current channel status on a packet-by-packet basis. Each Wireless module operates in a different frequency channel and is responsible for broadcasting wireless signals to other nodes.

6.4 MC-REL Routing Protocol Operation

The extension proposed of the single-channel, single-path Routing Protocol to the multi-path case for a multi-channel and dual-radio WBAN is based on REL [151]. The proposed protocol uses a lexical composite routing metric that uses information from a combination of metrics to make routing decisions. In a composite metric, different primary metrics are arranged as a vector where ordering is established on lexical ordering. That is, when comparing two vectors, the order depends on the first component, if those components are equal, then the second component is considered and so on.

The objectives of our MC-REL protocol are:

1. Select the optimal channel in terms of link quality;
2. Apply the lexical routing procedure for the next-hop selection;
3. Allow simultaneous transmissions on different channels in the neighbourhood based on the lexical metric.

The proposed routing metric arranges three primary metrics: HC, BLQI and PRE in a vector. The precedence for lexical ordering in case of multi-channel routing protocol is HC, BLQI and then PRE. When HC has precedence, MC-REL will at the highest level work as a standard AODV routing protocol without any extra overhead. BLQI then provides additional adjustment using the associated threshold factor to prefer good links over bad ones. After that, PRE provides further refinement by selecting a path with most energy resources available to transmit packets. An LQI is typically associated with a threshold to separate good links and weak links, such as is presented in [151]. The PRE field sums the total remaining energy of all nodes in a path. This metric is used to consider the energy information of a path and to avoid the use of routes with a low energy level to combat creation of hot-spots leading to early network failure. Thus, with the composition of these primary metrics, it is expected to reduce the impact of sensor network limitations on multi-channel WBAN applications, i.e. achieve minimum energy consumption.

In MC-REL, the structure of Route Request (RREQ) and Route Reply (RREP) messages is modified to support lexical routing as shown below in Table 6.1. The RREQ/RREP messages include fields for packet type identifier, destination address (Dest), a sequence number (SeqNum), HC, BLQI and PRE.

Table 6.1: Structure of RREQ and RREP messages

RREQ ID	Dest	SeqNum	Hop Count	BLQI	Path Remaining Energy
RREP ID	Dest	SeqNum	Hop Count	BLQI	Path Remaining Energy

6.4.1 Neighbour Table

MC-REL nodes maintain a neighbourhood table containing routes to every node on the network whereas AODV nodes only log the ID of the next hop node needed to forward the packet to the intended destination.

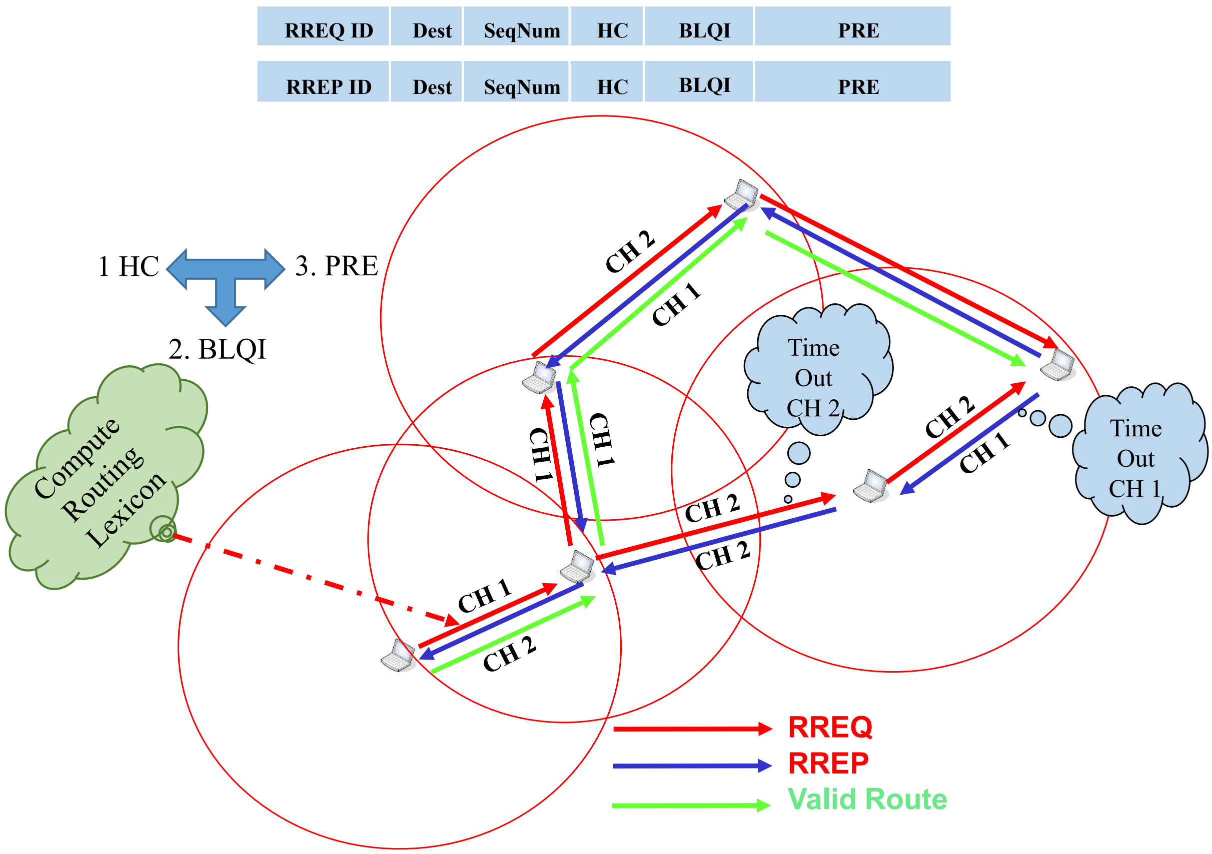


Figure 6.2: AODV Route Discovery and Lexical Routing Procedure

The proposed routing protocol MC-REL is composed of different phases, as shown in Fig: 6.2, such as route discovery, and data-delivery phases. In this section, the proposed multi-channel routing procedure will be discussed. Firstly, a brief overview of the solution will be presented, and then the details of each component will be discussed.

6.4.2 Route Discovery

In the initialisation phase, all nodes broadcast a "HELLO" message on each channel and record the HC by using the distance information of the sink node and the adjacent node attached to the message. Meanwhile, each node forms the required path information for the sink node.

Table 6.2: Hello Message structure

LQI	RSSI	Energy	PathIdx	PktSize

When a node has some packets to send, it initiates a route discovery (RouteDiscovery) by broadcasting a RREQ packet on all channels as opposed to one channel in a single-channel protocol [25]. In a multi-channel network, nodes may tune in different channels as opposed to the single-channel network where the route discovery process is initiated at a source node when it wants to send DATA packets to a given destination. As an RREQ message are forwarded the RE of the node and added to PRE.

Suppose that node S wants to find node D in a network with 2 channels as shown in Figure 6.2. Also, assume that node S was initially tuned on channel 1. Then, S broadcasts RREQ in both channels, one by one. More precisely, S broadcasts RREQ on the first channel (chann 1), switches to another channel (chann 2), broadcasts RREQ on chann 2, and so on. After going through all the channels, the node returns to its original channel where it was initially staying. So when an in-between node receives RREQ, it forwards the packet also on all channels. The intermediate nodes also return to their original channel after forwarding the packet. Since RREQ packets are forwarded to all channels, e.g. chann 1 and chann 2, node D can receive the packet irrespective of which channel it is on. Also, as the RREQ is forwarded, the nodes set up a reverse path to node S, as in AODV.

In the routing phase, each node determines the path to the sink node by using information such as HC, location, and PRE. When there is a need to discover the route, the source node broadcasts a RREQ on a given channel. If the recipient node is the destination or it already has an active route to the destination, it generates a RREP that is uni-cast hop-by-hop back to the source using the previously stored next-hop information in the node's routing table. As the RREP propagates back towards the source, each intermediate node updates the path metric information in the message and updates the routing table entries for the path to the destination in much the same as RREQ did for the source node. When the initial source receives the RREP message, it records the next hop to the destination in its routing table and records that there is an active route to the destination. After that, it will respond to the RREP message with an RREP Acknowledgement (RREP-ACK) message that is sent to the destination and begins sending data to the destination using DATA packets.

In the route entry as shown in Table 6.3, all fields except the channel, link-cost and path energy are also in AODV. The channel field indicates the channel that the next hop node is on. The link-cost field records the link quality of a node. So the node has to transmit a packet (link quality is given) on the channel indicated in the channel field (channel in the RT table) to reach the next hop. When a node sets up a Reverse Path (RevPath) to the source node , it needs to know which channel the next-hop node is listening on. In order to provide these statistics, a node sends an RREQ packet containing the channel which the node was on before broadcast RREQ packet). This channel information is used by the nodes that received the RREQ packet to establish a reverse path to the source node.

Finally, RREQ reaches the destination node D. Then; node D selects the channel which is to be used for the flow. After the channel selection , node D sends a RREP message to node S using the reverse path from the RT. When the RREP reaches node S, the route is established, and the data packets are transmitted on the selected channel.

Table 6.3: Routing table entry

Dest ID	NextHopAddress	Dest Seq Num	Link cost	Path Remaining Energy	Channel	Link Cost

In a single-path single-channel AODV, the RREP that arrives at the source node first will be via the path that was selected as a communication path, while the rest will be discarded. Paths were selected without considering the remaining energy, possibly resulting in path breakage because the node runs out of energy [190]. On the other hand, in this proposed routing protocol PRE is considered as a part of the composite metric to avoid the path breakage.

If a link break is detected, a Route Error (RERR) message is sent to the source and the source re-initiates the route discovery if necessary. When RREP messages are received, the modified HELLO messages are broadcast to the neighbour node on a regular basis. The structure of the modified HELLO message is shown above in Table 6.2.

On receiving an RREQ on a particular channel, two significant actions are performed. First the RREQ or RREP is forwarded with updated metric information fields in the message header, and second, the message is examined to determine whether it indicates a better route to the source or destination. If it does, then the routing table to the source/destination is updated with the new next-hop node and the new next channel, and metric information in the table is updated accordingly.

To describe these processes in detail denote the relevant fields of the incoming and outgoing RREQ/RREP as:

```
SEQNUM1: Incoming sequence number;
```

```
SEQNUM2: Outgoing sequence number;
HC1:     Incoming HC;
HC2:     Outgoing HC;
BLQI1:   Incoming BLQI;
BLQI2:   Outgoing BLQI;
PRE1:    Incoming path remaining energy;
PRE2:    Outgoing path remaining energy;
```

The fields in the Outgoing RREQ/RREP message are computed as follows

```
SEQNUM2 = SEQNUM1
HC2 = HC1 + 1
BLQI2 = BLQI1 + 1(LQI > LQIth)
PRE2 = PRE1 + RENode
```

where LQI is the link, LQI and RENode is the remaining energy of the node. Each new RREQ issued by a source node is given the next sequence number in the sequence, and the sequence number (SeqNum)of an RREP is that of the corresponding RREQ. At the start of the path the Hop Count2 (HC2), BLQI (BLQI2) and Path Remaining Energy (PRE2) fields are set to 0. To determine the next hop and next channel for the best route to a destination/source the lexical routing procedure is used. Define the following variables stored in the routing table to a given destination:

- HCT = Number of hops to destination/source
- BLQIT = BLQI of path to destination/source

When an RREQ or RREP is received the update operation is described by the following pseudo-code (RT = Routing Table):

Compute HC2, BLQI2, PRE2 from information in message and node information. By combining routing and MAC layer information, we obtain a cross-layer protocol, MC-REL, which selects the next hop based on both the BLQI1 estimated at the transmitter and the BLQI2 measured at the receiver. When a node needs to route traffic to the sink, it selects the best next hop using the BLQI indicator in the RT as shown in Table 6.3 and then data is forwarded to the neighbour that has a lower value of BLQI.

This procedure ensures that the precedence of metric information for lexical ordering is HC, then BLQI and then Path Remaining Energy as shown in Figure 6.2. The routing table update operations are:

```
Update RT:
  SeqnumT  <->  Seqnum1
  HCT  <-  HC2
  BLQIT  <-  BLQI2
  PRET  <-  PRET
  Next-hop-node  <-  RREQ/RREP immediate Source
  Next-hop-channel  <-  Receiving channel
```

6.5 Castalia's Energy Model

In this section, the energy consumption for Narrow-Band (NB) communication at 2.4 GHz based on a commercially available radio CC2420 is evaluated. First, a propagation model and an appropriate energy model are selected. Then, this energy model is subsequently used for analysing the energy consumption of each node. The energy parameters of the CC2420 transceiver are defined below [89].

In this thesis, the Castalia built-in energy model was used. The majority of wireless sensor network simulators nowadays use only the linear battery model. The current energy level of the node is computed with the help of Equation (6.4) which is how the energy consumption of a node is determined by Castalia. The average energy consumed is denoted by E_{TX} and is calculated with the help of Equation (6.1). The average energy consumed during successful transmission of a packet E_S is defined in Equation (6.3). The remaining energy of a node is computed using Equation (6.4).

The nodes involved in the delivery process of packets lose energy after each transmit and receive [191]. Let T_{TX} be the average Transmit Time of one packet, P_{TX} be the Transmit Power for one packet, so the amount of energy E_{TX} consumed during transmission of one packet will be:

$$E_{TX} = T_{TX} * P_{TX} \tag{6.1}$$

$$E_{RX} = E_{RX-elec} = lE_{elec} \tag{6.2}$$

$$E_S = E_{SB} + E_{SC} + E_{TX} \tag{6.3}$$

$$RemainingEnergy = (R+1) * [P_{RX-TX} * t_{RX-TX} + T_c * P_{TX} + P_{TX-RX} * t_{TX-RX}] \tag{6.4}$$

E_{SB} is the average energy consumed during back-off for a successful transmission, E_{SC} is average energy consumed during a collision for a successful transmission. R is the maximum number of retransmissions of a packet, T_c is the average collision time, E_0 is the initial energy of the battery in Joules. To deliver an l-bit message the electronics energy, $E_{RX-elec}$, depends on factors such as the digital coding, modulation, and spreading of the signal.

6.6 Simulation Results And Analysis

Multi-channel operation using the composite metric consisting of the Remaining energy metric and the BLQI metric was compared with that of a single-channel model using the HC metric (SCH). Also, the multi-channel AODV in previous Chapters 3 and 4 is compared with REL and S-REL. In the dual-channel case, if an RREQ message was needed to be transmitted the outgoing channel (1 or 2) is selected at random with equal probability.

To evaluate the proposed protocol, extensive simulation using the Castalia simulator is performed. Castalia is built on the OMNeT++ platform [162]. The main modifications to implement MC-REL were in the Routing module. We studied the performance of the MC-REL routing protocol by comparisons with the S-REL using the HC metric. Further details on dual-channel modifications are described in [180]. Various experiments in three aspects were considered — network lifetime, network traffic, latency and remaining energy, the most important elements of WBAN performance.

6.6.1 Deployment of Nodes

In the simulation studies carried out, ten heterogeneous sensor nodes (0-9) are deployed on the front of the human body as shown in Figure 6.3. The sink (BNC) is node 0 and nodes 1 to 9 transmit data to that node only. The sink node must be at the centre of the body to receive maximum data efficiently from the other sensor nodes. Node 0 does not send any data to the other nodes. The Castalia radio can dynamically change the modulation type. Phase Shift Keying (PSK) modulation with a noise floor equal to -110 dBm is used, and the additive collision model in Castalia is used to model the co-channel interference. The buffer size for the packets is 32.

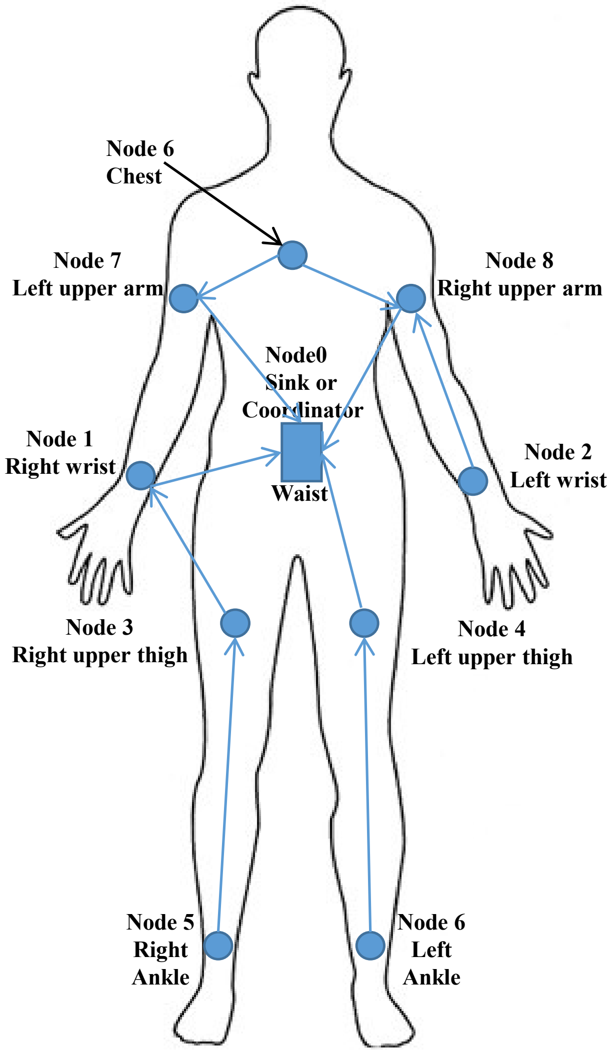


Figure 6.3: Node Positions

6.6.2 Simulation Parameters

Simulation parameters chosen for the study are as shown in Table 6.4. As only static nodes were considered, each one of them is treated as a special cell. In this implementation, LQI is the worst-case SNR in Castalia. The simulation time for a run is set to 72 seconds with 30 runs for each setting, and the results averaged. We consider Chipcon CC2420 , which is frequently used in WBAN technology. The energy parameters for this transceiver are shown in Table 6.5.

Table 6.4: Simulation Parameters

Module	**Parameter and Data Value**
Area Size	$2.5 \times 2.5m$
Number of Nodes	10
Application	50 packets per second, 100 byte payload + 30 byte overhead (application data rate is 20.8 kbps)
Routing	RREQ retries = 2 RREQ rate limit = 10 per sec Active route time-out = 6 sec
Tunable MAC	Default parameters Constant back-off time, transmission attempt
Radio	Sensitivity: -100 dBm Noise floor: -110 dBm Transmit power: 0 dBm
Traffic Type	CBR
Buffer Size	32 Packets
Radio Mode	PSK
Data Rate	50 packets per second
Wireless Channel	Bandwidth 20 MHz, Data rate: 250 kbps Modulation type: BPSK Temporal model, static nodes
Initial Energy	18720 J ($2 \times AAbatteries$)
Transmission Range	CC2420 20 m

Table 6.5: Energy Parameters of the Transceiver

Parameter	**CC2420**	**units**
DC current (TX)	17.4	mA
DC current (RX)	19.7	mA
Min Supply voltage	2.1	V
$E_TXelect$	96.9	nJ/bit
$E_RXelect$	172.8	nJ/bit
ϵ_amp	271	nJ/bit/m^n

6.6.3 Performance Metrics

The following metrics play an important role in order to satisfy the requirements of any WBAN system as discussed in the literature review:

1. *Remaining Energy* is the difference between the initial and consumed energy of a node.

2. *Network lifetime* is the total time till the last node depletes its energy completely. It represents the time for which the network operates. In WBANs, a protocol is required to offer maximum network lifetime.

3. *Control Message Overhead* Control packets are referred as HELLO packets or RREQ and RREP packets, used for connecting nodes and computing paths. Hence control overhead is required for a network to establish effective connectivity, but it should not exceed its limit, which leads to enormous energy wastage [83]. Control-packet overhead is the primary factor that increases the energy consumption in the network.

4. *Application latency*

   The WBAN for medical monitoring requires that various types of data can be transmitted with acceptable latency in a most energy-efficient and straightforward manner. There is a trade-off between battery life and latency in a WSN [192]. The average end-to-end delay of data packets received at the application layer varies considerably, as the number of packets transmitted increases with increasing number of channels. Table 6.6 shows the application latency requirements for physiologic and patient-state measurement according to IEEE 11073 applications, with both having to be less than 3 ms.

Table 6.6: Latencies for some IEEE 11073 applications

Type of application	**latency (ms)**
Physiologic parameters (real-time)	≤ 3
Patient state	≤ 3

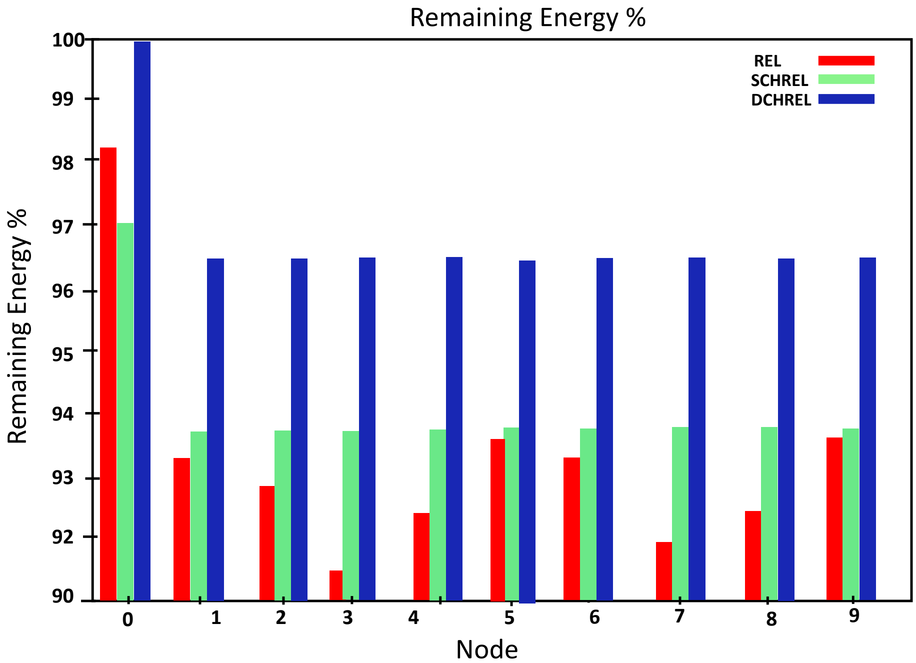


Figure 6.4: Remaining Energy

Figure 6.4 shows the percentage of remaining energy of all the nodes using REL, S-REL and MC-REL. The proposed model uses a multi-hop topology, in which each farthest nodes transmit data to the sink through a forwarder node. As MC-REL elects the next-hop node or forwarder node on the basis of a composite metric (HC, BLQI and PRE of nodes) so energy is consumed in a balanced way. If we combine the characteristics of all these primary metrics, i.e., HC gives the shortest hop path, whereas BLQI prevents choosing paths having higher BLQI values, and PRE already selects the path with nodes having more remaining energy, so energy is consumed in a balanced way by using a lexical procedure. In S-REL, the nodes closer to the sink node have more chances to become a forwarder node using only the channel available, which increases contention between the nodes. So energy consumption increases as compared to MC-REL.

The optimal route is selected using the aforementioned composite metric function. On average REL uses more energy than S-REL and MC-REL. S-REL uses more energy than MC-REL, whereas it can be seen that using S-REL 93 J of energy remains per node, whereas using MC-REL there is a further saving of 2 J/s at each node. Also, the energy consumption in source nodes in REL is variable, whereas the energy consumption of source nodes in both S-REL and MC-REL is uniform. The variable energy shows that the sensor nodes could die earlier rather than later. Uniform energy consumption of nodes is vital for long-term health monitoring applications in WBANs [193]. This helps to increase the network lifetime, and fair usage of energy resources improves the stability period and throughput. Observe that in AODV, LABILE, REL and MC-REL the energy efficiency can also be improved by controlling the broadcasting mechanism of the Hello packets. Further, being on-demand (reactive) routing protocols, routes are determined only if a node needs to deliver packets to target nodes through the best available channel. This reduces the excessive consumption of network bandwidth and energy and responds to topological changes that may affect existing active routes.

Considering that the composite metric selects routes lexicographically in this chapter, the channel-selection methods in multi-channel WBANs impact network performance in a better way. Using the appropriate channel-selection method in each simulation contributes to saving energy. A node might spend a lot of energy retransmitting if the quality of the

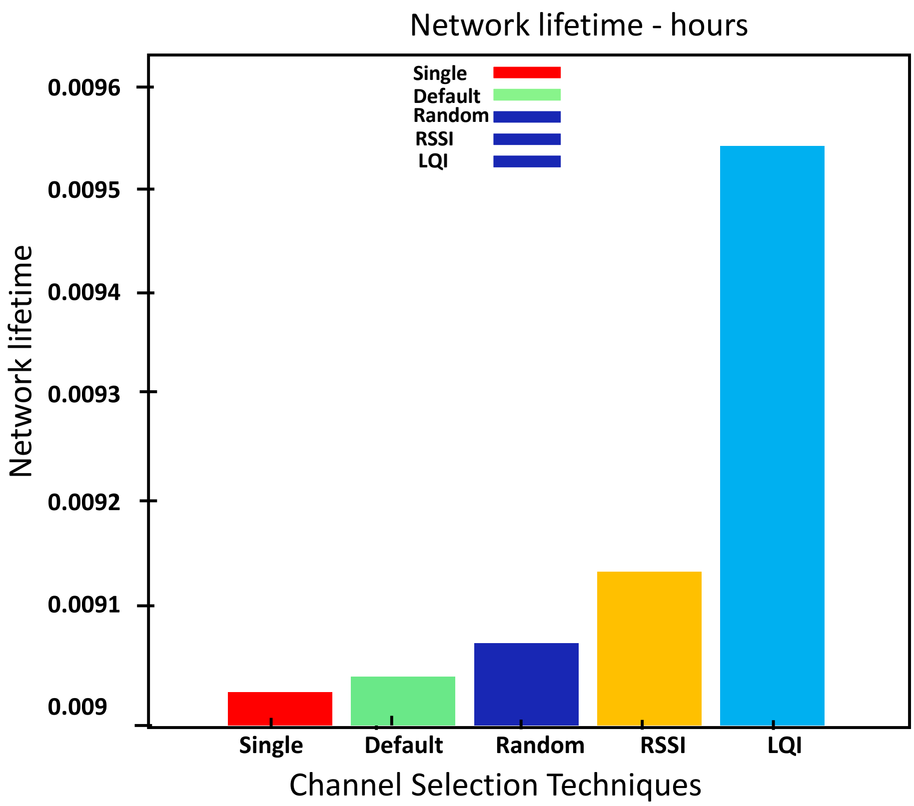


Figure 6.5: Network Lifetime

link is bad, which overall does not increase the network lifetime. As we can see in Figure 6.5, the LQI channel-selection method increases the network performance marginally as compared to RSSI, Random, Default and single channel. But we can further increase the network lifetime by increasing the BLQI threshold, which can be configured to obtain the best value for optimisation.

The control message overhead is assessed by examining RREQ message flows as defined in the literature review. The results (Figure 6.6) show that MC-REL requires more RREQ control messages than S-REL. The higher numbers of RREQ messages received at an intermediate node when an active route to the destination exists reflects the increased amount of forwarding by intermediate nodes using MC-REL.

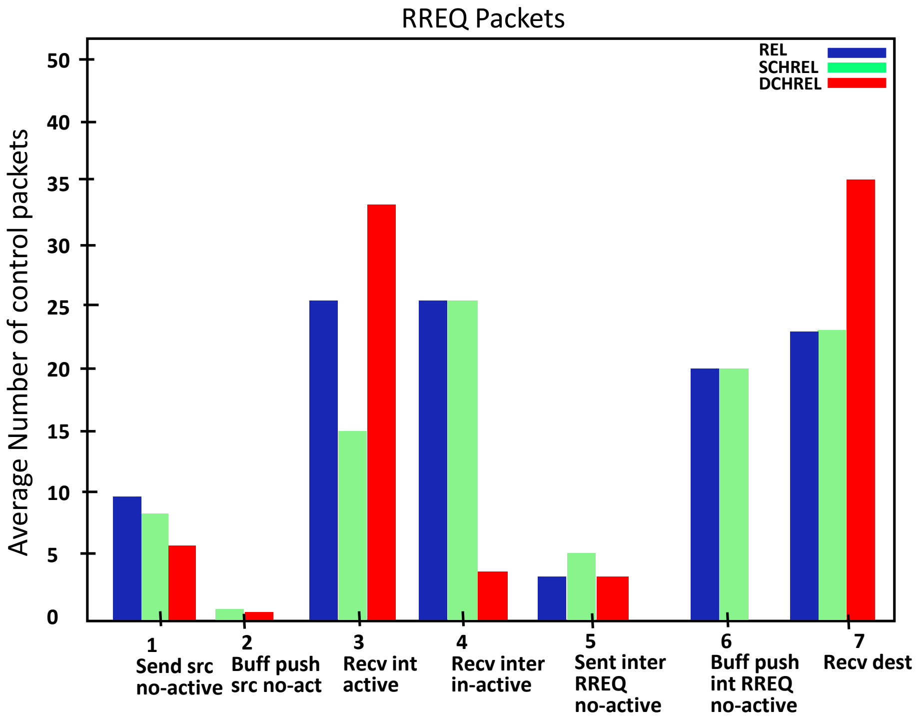


Figure 6.6: Control Traffic RREQ Generated (REL, SCHREL and MCREL)

Table 6.7: Transceiver characteristics

Tx-Rx, Rx-Tx (transition time)	0.01 ms
Rx-Sleep, Tx-Sleep (transition time)	0.05 ms
Sleep-Rx, Sleep-Tx (transition time)	0.05 ms
Tx (power consumed)	62 mW
Rx (power consumed)	62 mW
Tx-Rx, Rx-Tx (power consumed)	62 mW
Sleep-Rx, Sleep-Tx (power consumed)	1.4 mW
Rx-Sleep, TX-Sleep (power consumed)	1.4 mW

The parameters assumed for the transceiver are listed in Table 6.7, which shows the variation of the latency intervals of received packets according to the simulation time. Figure 6.7 depicts that by increasing the simulation time DCHREL and SCHREL sent 90% of the data in the range of (0-50 ms), with a decreasing trend between 50 and 500 ms. DCHREL sends its packets with larger latency because the packets are moving from node to node until they reach the sink, whereas SCHREL is a single-path single-channel protocol and doesn't affect latency. Although the latencies under MC-REL are slightly higher than under S-REL, the MC-REL latency is still 3 ms. The buffer capacity is fixed in the case of multi-channel AODV routing protocol, so packets may be stored for an additional amount of time until regaining access to that channel.

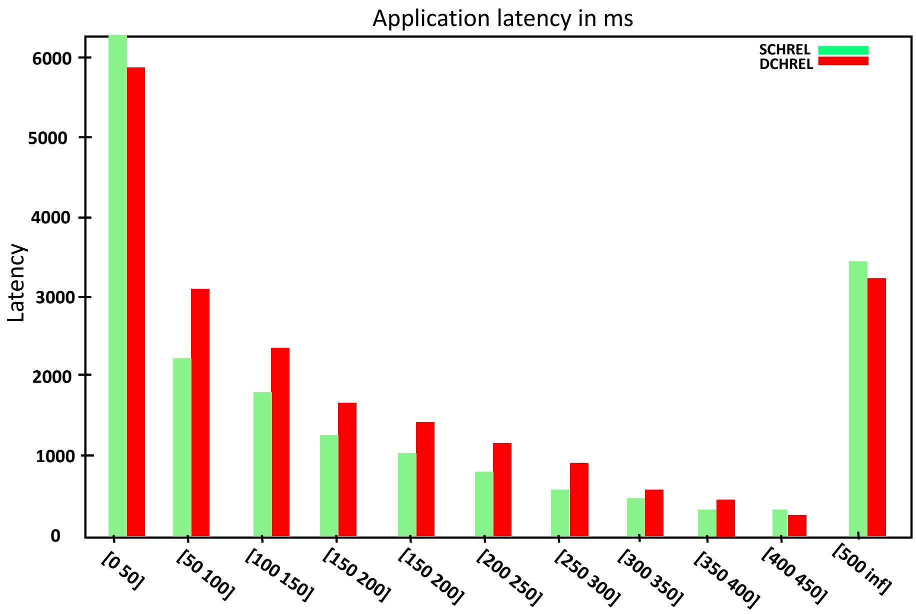


Figure 6.7: Application Latency

One of the main reason for long latency in the range of 500 ms and above is the length of travel route. To minimize the latency, travel route should be shorter.

One of the aims of using a combination of LQI and HC with the HCT constraint is to maximise the energy efficiency in the network, and these results show that the HC and LQI metrics work well together.

6.7 Conclusions

In this chapter, a multi-channel routing protocol is developed using the lexical routing concept based on the next-hop, link-quality indicator values of the physical link and the path's remaining energy. To verify the significance of the proposed multi-channel routing protocol, various experiments are carried out to compare it with two existing routing protocols, REL and S-REL. The MC-REL routing protocol is implemented in the OMNeT++ based Castalia WBAN simulation model. The simulation results show that MC-REL is an energy-efficient dual-channel routing protocol for achieving high-throughput paths with fair and minimal energy consumption, as compared to the single-channel routing protocol and the modified multi-channel AODV. Indeed the proposed scheme can be integrated with any on-demand protocol to improve the protocol's performance. Simulation results highlight the superiority of the proposed protocol with respect to uniform energy consumption and more traffic forwarding between the nodes to improve application latency.

Chapter 7

Thesis Conclusion and Future Work

Contents

In this thesis, multi-channel routing protocols were developed for Wireless Body Area Networks (WBANs) that are implemented in the OMNeT++ based Castalia WBAN simulation model. Multi-channel based routing utilises more than one channel for communication and has the ability to provide high performance by more rigorously countering interference, collisions and re-transmissions than the single-channel routing methodology. This research work aims to establish guidelines for future research and development in the area of WBANs based on critical analysis of the prevalent multi-channel based routing protocols for WBANs. In this thesis, we have developed several multi-channel routing protocols for WBANs ; MC-AoRSS, MC-AoLQM for mobile nodes, a channel-diversity metric (WMHC), MC-REL. It has been shown that the RSSI based channel selection (MC-AoRSS) gave equal performance to single channel SCH in terms of packet delivery but with less AODV control overhead, better routing stability, and better energy efficiency. RSSI is not a good link discriminator if the nodes are mobile. A more sophisticated metric is required to reduce the channel access with more good quality links , which MC-AoLQM has provided. The changeable topology of WBANs provokes overhead messages in order to search available routes and maintain found routes. The overhead messages impede data delivery from sources to the destination and deteriorate network performance. This work also presents how node mobility affects the operation and the use of energy and other metrics such as ETX (Expected Number of Transmissions) and WCETT (Weighted Cumulative Expected Transmission Time), that required additional changes to the Castalia Radio module. A dual-channel routing protocol was developed using the lexical routing concept based on next-hop, link quality indicator values of the physical link and path remaining energy. The Multi-Channel routing protocol was based on Remaining Energy and Link quality indicator (MC-REL). It was shown that MC-REL is an energy efficient dual-channel routing protocol for achieving high throughput paths with fair and minimal energy consumption as compared to the single-channel routing protocol and the original multi-channel AODV. This also shows that energy utilisation is uniform among the nodes of the network, enabling nodes to stay alive for a more extended period to deliver data. It assures the stability of the route while data is transferred, and avoid high rate dissemination of control packets (low control-traffic overhead) in the dual-channel routing outcome as compared to the single-channel. In future work, we will examine how mobility can affect the energy efficiency and throughput of the network with more number of nodes.

7.1 Future Work

In future work, we also plan to investigate the use of dual-channel Radio and/or dual-channel MAC modules. we will also examine how larger networks can impact channel diversity in a multi-hop path selection. WMHC used random channel selection as it did not rely on additional probe packet overhead to obtain the link quality information. Future work will explore methods of obtaining such information that does not require too much overhead, and in networks with a higher number of nodes. It will also be examine how larger networks can impact with channel diversity in multi-hop path selection.

Furthermore, a dual-band sensor node helps in achieving low energy consumption when a sensor node can switch between the two available channels. That was the case of only one WBAN involved. But even in cases where co-located WBANs use the same channel (similar frequencies), transmissions can conflict; as the active periods can overlap. Moreover, with the increase in the number of WBANs that can coexist in short proximity of each other, the communication link can suffer performance degradation. Even in cases where a small number of WBANs are deployed in each other's vicinity, the received signal strength of the interfering signal can be quite high, which affects the performance of a particular WBAN. The performance of multi-WBANs can be achieved by exploiting multiple channels in the communication protocol. We would like to analyse the performance of dual-channel routing protocol in multi-WBANs. In our future work, we would also like to increase the number of nodes in our simulation and implement more realistic mobile scenarios. Synchronisation between biomedical sensor nodes at MAC level has a tremendous impact on the accuracy of the communication protocols. Synchronization enables nodes to transit quickly from transmit mode to receive mode and to wake-up quickly from the sleep mode, which contributes to saving power.

Appendix A

List of Acronyms

A to G	
AODV	Ad hoc On Demand Vector
CM	Channel Models
CBR	Constant Bit Rate
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DSDV	Destination Sequenced Distance Vector
ECG	Electrocardiography
EEG	Electroencephalogram
H to P	
HBC	Human Body Communications
IEEE	Institute of Electrical and Electronic Engineers
ISM	Industrial Scientific and Medical
LOS	Line of Sight
MAC	Medium Access Control
MANETs	Mobile Ad-Hoc Networks
MICS	Medical Implant Communications system
NB	Narrow Band
NLOS	Non-Line-of-Sight
PHY	Physical Layer
Q to Z	
QoS	Quality of Service
RREP	Route Reply
RREQ	Route Request
RRER	Route Error

SINR	Signal to interference plus noise ratio
SpO2	Oxygen Saturation of Peripheral
WBAN	Wireless Body Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

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