MOBILE WIFI-CALLING FEATURE AND ALGORITHMS

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STATEMENT OF CANDIDATE

I, (Ali Alsaihan), declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Telecommunications Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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Date: November 6, 2017

ABSTRACT

The increasing demand for mobile broadband services urged communication system operators to take advantage of small cells and frequency reuse factor of one in 4G LTE. However, a key problem is the weak coverage of cellular network within indoor places. On the other hand, wireless local area networks (WLAN), which have become increasingly popular over the recent years, cover most of the interior areas in residential and commercial areas as well as shopping malls. However, the problem of performance degradation when transitioning between open areas where cellular networks have coverage and indoor places where WiFi Access Points (AP) provide better connectivity is of paramount importance to be tackled. The technology which allows seamless transition between WLAN and cellular network is referred to as vertical hando. Vertical handover is the automatic fall-over (or switch) between two technologies aiming to maintain communication. However, the hando requires a certain amount of time to be complemented, which might result in temporary disconnection of the communication link, which results in call dropping. One way to alleviate the issue is to add a hand-o trigger node (HTN) which helps the mobile station to initiate the vertical hando prior to reaching the WLAN coverage border. This way, the mobile station will have ample time to accomplish vertical hando before WiFi coverage is lost. This report outlines the background concept of vertical handover and presents the HTN methodology as a practical solution for seamless transition between WLAN and cellular networks. MATLAB simulations are presented to validate the efficacy of the proposed method.

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Chapter 1

Introduction

1.1 Background

Surging demand for newer mobile broadband services everywhere, urged 3GPP to take advantage of small cells and frequency reuse factor of one in 4G LTE. However, the problem of performance degradation when transitioning between open areas where cellular networks have coverage and indoor places where WiFi Access Points (AP) provide better connectivity is of paramount importance to be tackled. While Cellular networks provide wide coverage (km range) for large number of users with low speeds (in Kbps) and high deployment costs; Wireless Lanes are Inexpensive complementary solutions with speeds up to 108 Mbps, low coverage, accommodating Small number of users. In fact, taking advantage of efficient hand over techniques is crucial to maintain seamless connectivity for end users. WiFi to cellular handover enables a truly seamless mobile experience. The major goal is to give mobile users a great calling experience with no interruption, whether on WiFi or cell. Vertical hand off is a technique that allows a mobile user to roam between different networks and access technologies, in a manner that is transparent to the applications and users without disrupted connectivity. It enables users to Simultaneously use different access networks and technologies with Seamless transfer between them. Vertical handover brings higher bandwidth and extended coverage for large number of users. In this context, Fixed Mobile Convergence (FMC) solutions enable seamless hand off of calls and call features across wire line (Wi-Fi or 802.11) and wireless (cellular) networks. Two approaches to Fixed Mobile Convergence are: Hand off Trigger Node(HTN) and Unlicensed Multiple Access(UMA). In this research, we propose and evaluate an HTN handover algorithm to generates link layer triggers which cause the initiation of the vertical hand off process as smooth as end user experiences seamless connectivity.

1.2 Goals of the Project

The aim of this research project is to propose an efficient HTN based wifi-cellular hand over algorithm in LTE-Advanced that provides uninterrupted connectivity with small delay and acceptable throughput for different types of traffic.

1.2.1 Short term goals

The goals to be achieved in short term are as follows:

Project Scope Document Understanding the basics of propagation environment in LTE cellular networks. Doing the literature review on current techniques for hard and soft vertical handover. Proposing an algorithm based on HTN for vertical handover.

1.2.2 Long term goals

The suggested long term goals to be done on this project will be as: Designing a simulation setup to test our proposed algorithm. Simulating the LTE-A using WINNER II channel model. Analyzing the simulation results and discussing the achieved performance improvements based on Hand off Dropping Probability and Call Dropping Probability. Recommendations for future research.

1.3 Methods and Techniques

Scientific Methods to be employed in this research are pinpointing the bottlenecks of current approaches towards handover between WiFi and Cellular networks in an LTE-A environment. We will also come up with a handover algorithm supported by a mathematical model. The simulation setup for LTE-A will be designed using WINNER II channel model and MATLAB will be used to perform the simulation.

1.4 Deliverables

The final dissertation out of this research will be including simulation results for proposed hand off algorithm based on Hand off Dropping Probability and Call Dropping Probability. Moreover, the ability of proposed algorithm for satisfying applications with different types of traffic will be examined.

1.5 Equipment and Facilities

In total, this research project will not be costing anything than time and effort since MATLAB license which will be used for the simulation part is provided by university. Because the simulations are demanding in terms of processing power, I will make use of parallel computing in MATLAB. The simulation results will be stored on my PC, an external hard drive and Dropbox for the purpose of redundancy.

1.6 Risk Assessment

In this section, we will discuss about probable risks and limitations that may hinder the possibility and feasibility of generating authentic scientific results.

1.6.1 Risks and Limitations

The risks and limitations associated with this project are that some research papers for literature review may not be accessible and source codes to redo the simulation for current methods may not be available. Simulations may will take so long using a normal PC I will have access to it.

1.6.2 Available solutions

University portal will be used to access the relevant papers for this research and corresponding authors will be contacted directly to make sure that we will redo their work under the identical setup. The whole simulation process can be broken down into several parts to be performed on different machines.

Chapter 2

Project background

2.1 Introduction

Over the recent years, wireless local area networks (WLAN) have become increasingly popular. Currently, WLAN transceivers cover most of the interior areas in residential and commercial areas as well as shopping malls. However, WLAN networks are characterized by short transmission range, hence their coverage area is commonly limited to the interior of buildings. On the other hand, the cellular network coverage might be weak inside the buildings and houses due to the attenuation of signals when passing through the walls. The low signal strength of cellular network is associated with low quality of voice/speed of data and might eventually lead to call dropping. Therefore, a viable solution is to use a combination of WLAN and cellular network for maximizing the network reliability and performance. Since most of the modern mobile handsets are equipped with WiFi, this scheme can be easily implemented on the current generation cellphones without imposing additional cost [1].

The technology which allows utilization of both WLAN and cellular network for achieving seamless communications both inside and outside of building is referred to as vertical handoff or hand over. Vertical handoff allows the communication devices such as cellphones to switch between the communication channels. The state of the art hand off algorithms provide seamless transition between the WLAN and cellular network. As a consequence, the user can continue using mobile services including data and talk without experiencing an interruption while moving in and out of a building [2].

The concept of vertical handoff and its application in WiFi calling have become a hot research topic in the past few years. This chapter presents a detailed literature review on the topic. The chapter begins with an overview of background concepts including the notion of wireless communication networks and orthogonal frequency division multiplexing. Following, the idea of vertical handover is defined and the methodology utilized for implementation of the technique is described.

2.2 Wireless communication networks

Wireless communication, also shortened as wireless, is a sort of communication of either data or power between two or more points where there is no physical connector like a cable or wire. The most popular technologies tend to employ radio waves. The benefit of radio waves relates to its flexibility in distances over which data can be transferred. This means that they can be used to send data for short-distance devices such as to a television set or to extremely distant devices such as those used for deep-space communications. The range of applications are diverse from fixed to portable or mobile applications; they are seen in two-way radios, the common cellular telephones, and wireless networking. The applications of radio wireless technology have seen a marked growth, finding itself in GPS units, computer accessories such as keyboards and headsets, garage door openers, radio receivers, satellite television, and cordless telephones [3].

The most popular and recent wireless technologies include Bluetooth, LTE, LTE-Advanced, and Wi-Fi. Wi-Fi is a rather new technology for wireless local area networking (LAN) where devices employed operate according to the IEEE 802.11 standards. Various devices can use this technology, among which are PCs, digital cameras, video-game consoles, phones and tablets, smart TVs, as well as some modern printers. Devices which are Wi-Fi compatible can be connected to the Internet through a WLAN in conjunction with a wireless access point. The access point, which is frequently called a hotspot, has quite a limited range (approximately a 20-metre span) indoor and a wider range outdoors. Simple hotspot coverage may be restricted to a room where walls does not allow passage, while by means of multiple overlapping access points, the range can be much further expanded to square kilometers. The common frequency bands used are 2.4 GHz UHF and 5 GHz SHF ISM radio bands. Despite many benefits introduced by eliminating the wire, Wi-Fi is less secure than a wired connection like Ethernet [4].

LTE (Long-Term Evolution) is a wireless standard representing high-speed wireless communication invented to allow for higher speeds, higher bandwidth and better quality for mobile phones and data terminals. Technologies which operate with this standard are mainly GSM and UMTS. Core network improvements in conjunction with a different radio interface were used by the 3GPP (3rd Generation Partnership Project) in developing LTE, enhancing data capacity and speed. Different countries have opted for different LTE bands and frequencies, the result of which is that multi-band phones would be needed to accommodate this diversity in different countries, if the phone is to be functional in all countries.

It is said that the current LTE, marketed as 4G LTE, does not truly meet the requirements set forth by 3GPP Release 8 and 9 document series. This happened as a result of some marketing pressure together with some enhancements made to this technology that ITU decided to call what was in fact a 3G technology a 4G. Also, LTE Advanced standard meets the ITU-R requirements in a way that it can be called an IMT-Advanced. LTE Advanced and WiMAX-Advanced have been decided to be called as True 4G as a way of distinguishing them from the present 4g technology.

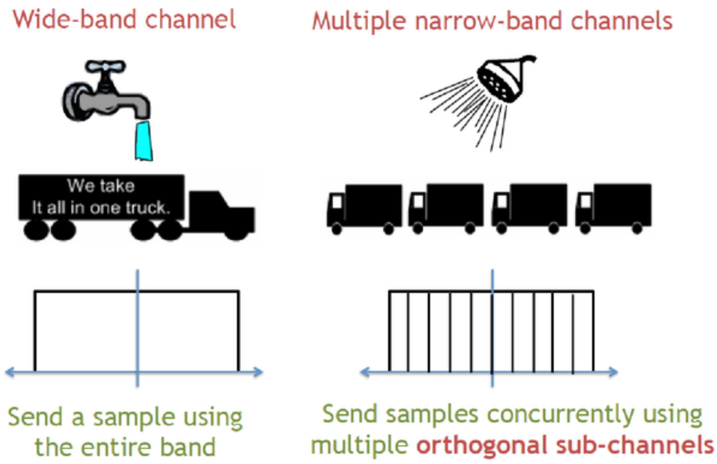


Figure 2.1: Basic concept of OFDM.

2.3 OFDM modulation

2.3.1 Concept of orthogonal frequency-division multiplexing

Orthogonal frequency-division multiplexing (OFDM), which stands for Orthogonal frequency-division multiplexing, is a multiple-carrier frequency method of encoding (or modulation) digital data. It differs from a normal wideband channel in a number of ways. Most importantly there are multiple narrower band channels instead of a single wide one. It is become increasingly popular for wideband digital communication. The applications vary, from digital television and audio broadcasting to power line networks, and 4G mobile communications, to DSL Internet access. The following picture illustrates how the output result of an OFDM is different from a wide-band channel.

There is another variation for OFDM, known as COFDM, which adds a Coded to the beginning of OFDM. This variation has an advantage of better error reduction, which is thanks to performing the error correction prior to signal transmission.

OFDM is in fact a type of FDM (frequency-division multiplexing) scheme, where data in the forms of numerous orthogonal sub-carrier signals is transmitted over a number of parallel data channels. Any single sub-carrier employs the same modulation technique as a customary carrier does, using a conventional scheme such as phase-shift keying. The symbol rate for modulation is kept low, in a way that the total data rate does not differ much from a conventional single-carrier modulation with equal bandwidth.

What distinguishes OFDM from a single-carrier scheme is its unique ability to be resistant against undesirable channel conditions which lead to signal loss or distortion. It is particularly robust against attenuation of high-frequencies in long wires, interferences occurring on a narrowband, and frequency-selective fading. This can eliminate the need

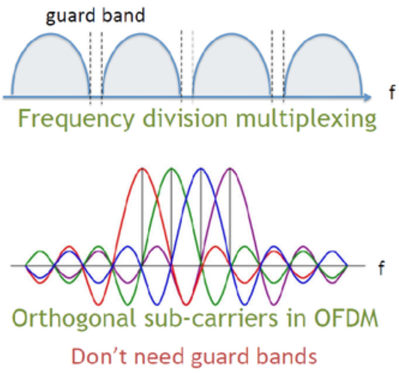


Figure 2.2: Difference between FDM and OFDM.

to employ complex equalization filters. In reality, what OFDM yields is numerous slowly modulated narrowband signals as opposed to a rapidly modulated wideband signal. This helps facilitate Channel equalization.

The symbol rate being low allows a guard interval between symbols to be implemented with more ease. This is advantageous since it helps eliminate inter-symbol interference, thus allowing for a better signal-to-noise ratio. This feature can also come in handy in single frequency network designs. In these systems, there are normally a set of transmitters all sending the same signal at the same time and with equal frequencies. Using OFDM, the signals emitted from distant transmitters can be incorporated into a single transmission with minimal interference, opposed to a traditional single-carrier system, which would involve certain degree of interference [5].

2.3.2 Characteristics and principles of operation

Orthogonality

OFDM is in fact a particular type of FDM where carrier signals are chosen to be orthogonal in respect to each other. In other words, we opt for sub-carrier frequencies which result in orthogonality for the sub-carriers. This is beneficial indeed since both the so-called cross-talk between sub-channels and the need to have inter-carrier guard bands are eliminated [6].

The orthogonality also to a large extent makes the transmitter and receivers design simpler when compared to a conventional OFD. This is because orthogonality eliminates the need for a separate filter for each sub-channel. With a sub-carrier spacing of $\Delta f = k/T_U$ Hertz, and N sub-carriers, the overall bandwidth occupied will be $BN\Delta f(Hz)$, T_U (seconds) representing the symbol duration and k, as a positive integer customarily set to 1.

The frequencies being set orthogonal brings about excellent spectral efficiency, the total symbol rate being close to the Nyquist rate. This means that the entire fluency band can be well used. It is said that OFDM possesses an almost 'white' spectrum, meaning that it is least influenced by electromagnetic interferences. On the other hand, meeting the orthogonality requirement is a very accurate task, the receiver and the transmitter requiring a high degree of accuracy in frequency synchronization. Should there be any deviation in frequency, the orthogonality will be lost. The would cause inter-carrier interference or a cross talk, also known as ICI.

A mismatched transmitter and receiver oscillator can also lead to frequency offsets; alternatively, frequency offsets can be caused by Doppler shift arisen as a result of some movement. It is true that Doppler shift can be offset by the receiver; however, multipath involvement can aggravate the situation, the reflections appearing at various frequency offsets, which obviously will be far harder to rectify. This undesirable effect tends to get worse with the speed of the receiver increasing; it is this stumbling block which limits applications of OFDM in vehicles with high speed.

There are ways to alleviate the inter-carrier interference, some of which involve pulse shaping and using filters at the transmitter in conjunction with a sub-carrier equalization which yields excellent reconstruction; WCP-OFDM is such a technique which is considered a relatively low complexity scheme. There are other schemes which are considered generally highly complex [7].

Implementation using the FFT algorithm

The FFT algorithm can be efficiently used to implement modulation at the receiver side and the inverse FFT or IFFT can be applied to do demodulation at the sender side.

Guard interval

It is generally known that low symbol rate modulation schemes are less affected by intersymbol interference, which is usually caused by multipath propagation. This is the basic idea used in OFDM, using several low-rate streams in parallel rather than a single high-rate stream. Each symbol has a relatively long duration, making it possible to put in a guard interval between the OFDM symbols. The result of this would be elimination of the inter-symbol interference. In addition to the advantage related to inter-symbol interference elimination, the guard interval introduction also obviates the need for a pulse-shaping filter as well as decreasing the system sensitivity to problems caused by time synchronization.

An illustrating example is presented here. Employing conventional single-carrier modulation to send a million symbols per second would yield a microsecond duration for each symbol. Synchronization will hence see severe constraints and this would require the elimination of multipath interference. Imagine the same million symbols per second were to be transmitted through one thousand sub-channels. Each symbol could assume a much longer duration, by a factor of a thousand in fact, maintaining the same bandwidth.

If we consider to put in a guard interval equal to one-eighth of the symbol length, we can avoid Intersymbol interference providing that the multipath time-spreading has a

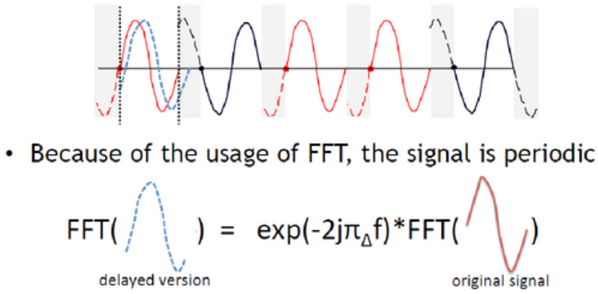


Figure 2.3: Principle of operation of cyclic prefix

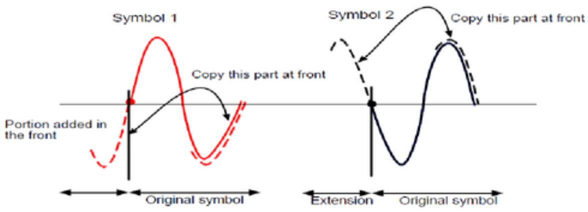


Figure 2.4: Modeling of cyclic prefix at the receiver end

shorter duration than the guard interval (i.e., 125 microseconds). The would be equivalent to a gap of 37.5 kilometers between the lengths of the paths.

The end part of the OFDM symbol is copied and attached onto the guard interval. This is called the cyclic prefix, which is transmitted as being followed by the OFDM symbol. The cyclic prefix, which includes the end part of the OFDM symbol, comprises a part of the guard interval as the symbols are streamed and transmitted. This allows for the receiver being able to integrate over an integer number of sinusoid cycles once the OFDM demodulation is performed using FFT. The following picture shows how the cyclic prefix is formed and transmitted [8].

There are some standards where the transmitted power is of higher priority and hence cyclic prefix will not be considered, leaving the guard interval containing zero data. This task, however, falls on the receiver which has to model the cyclic prefix function by having the end part of the OFDM copied and added to the starting part.

Simpler Equalization

Provided that the sub-channel is narrow-banded enough, we can assume that the effects made by the frequency-selective channel conditions are almost constant over an OFDM sub-channel . In other words, the higher the number of sub-channels, the more narrow-banded the channels will be, and the closer to flat the effects of frequency-selective channel conditions. One of these effects is fading, which is the result of multipath propagation.

The constant effect allows for the process of frequency domain equalization at the receiver. The equalization like this in the frequency domain is by comparison much simpler than the one used in conventional single-carrier modulation where a time-domain equalization has to be performed. This facility comes from the fact that in OFDM, each identified sub-carrier corresponding to each OFDM symbol (which is in fact a Fourier coefficient) is only to be multiplied by a nearly fixed complex number.

There would essentially be no need of equalization if a differential modulation is used for each sub-carrier. The examples of these modulation schemes are DPSK or DQPSK which the phase distortion and slowly changing amplitude has no bearing on.

In some cases, a number of sub-carriers may contain pilot signals to provide measurement of the channel conditions. For example, information such as phase shift or the equalizer gain corresponding to each sub-carrier may be carried on the sub-carriers. The pilot signals and training symbols are in some cases applied to achieve time synchronization as well as frequency synchronization. The former is to be achieved to prevent inter-symbol interference and the latter helps prevent inter-carrier interference induced by Doppler shift.

Originally OFDM had been designed to operate under stationary conditions, either to be utilized for wired or some non-mobile wireless communication. The increasing popularity of mobile devices, nevertheless, has extended the application of OFDM to be increasingly used for mobile devices. This has highlighted the impact of dispersive fading which is primarily the result of multi-path propagation and Doppler shift. Research is being done to discover ways of equalizing OFDM transmission through doubly selective channels [9].

Channel coding and interleaving

Chanel coding is a function used whenever OFDM is chosen as a communication scheme and interleaving either time or frequency is also used in majority of cases. The frequency interleaving is undoubtedly advantageous since it creates higher resistance to frequency-selective channel conditions, one of which is fading. It works in this way: once a portion of the channel bandwidth undergoes fading, frequency interleaving makes sure that the received bits which have gone wrong (the error bits), yielded as a result of some subcarriers being in the faded section of the bandwidth, are not concentrated (positioned adjacent or in near proximity) and that are instead spread out separately over the bit-stream. In a similar way, what time interleaving does is to observe that bits originally adjacent in the bit-stream are transmitted with appreciable gap in time. This helps a great deal in reducing severe fading.

Nevertheless, time interleaving does little to help cases where slowly fading channels are involved, cases similar to a stationary reception. Also, frequency interleaving can hardly do anything of significance to resolve the distortion caused in narrow-banded channels suffering from flat-fading, in which the entire bandwidth fades simultaneously.

In fact, interleaving, in its either form, has a unique function of distributing the errors throughout the bit-stream and not allowing them to be closely positioned in the bit-stream. This function assumes its significance from the fact that the error correction decoder can only function effectively if the errors are sufficiently widely spaced since a highly concentrated error stream disrupt the decoder and prevents it from correcting all the errors. This is the primary reason interleaving is employed.

Adaptive transmission

In order to make the system more robust and lessen the undesirable effects of severe channel conditions, information related to the channel can be sent over a return channel. Based on the information attained from the feedback loop, channel coding, adaptive modulation, and power allocation can be applied either to each sub-carrier or across all sub-carriers. In the former case, knowing that a range of frequencies are undergoing interference or experiencing attenuation enables us to choose to either disable the subcarriers in that range or make them run more slowly using a more robust modulation. Even error coding can be applied to the sub-carriers positioned in that frequency range [7].

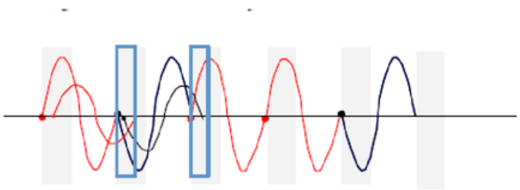
2.3.3 WINNER-II Path Loss Model

A path loss is essentially the power lost before a signal is received when going through a communication channel. In other words, it is the subtraction of the received power from the transmitted one. The path loss may vary a lot between depending on the path, ranging from some dB to over a 100 dB. As an example, imagine the transmitted power of a wireless system is 20 dBm, while the received power stands at -70 dBm, the path loss can be determined as 20-(-70)= 90 dB. IN general, path loss is considered as a large scale effect, as opposed to fading, which is considered a small scale effect. WINNER-II model provides the following formula to calculate the path loss:

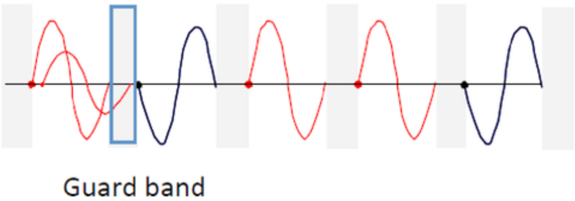
$$PL = Alog_{10}(d[m]) + B + Clog_{10}((f_c[GHz])/5.0) + X$$

$$PL_{free} = log_{10}(d) + 46.4 + 20log_{10}(f_c/5.0)$$

The parameters involved are: d denotes the distance between the transmitter and receiver [meters]. Fc is the signal frequency in GHz. A and B are the path loss exponent and the intercept, respectively. C represents the frequency dependent parameter. X stands for the environment parameter which reflects the effect of the signal barrier/blocker on the pass loss. PL free is the path loss corresponding to a free space environment where there is no barrier such a wall, and the path loss of the line of sight transmission, attained by substituting A=20, B=46.4 and C=20 in the first formula. There is a table indicating various environments as defined and categorized in the WINNER-II model. The first step to calculate the path loss is to determine the environment type, then the A,B and C parameters can be extracted from the table.



(a) Delayed version of symbol overlaps with the adjacent symbol



(b) The overlap is avoided by introducing guard bands

Figure 2.5: Illustration of inter symbol interference

2.4 Vertical handover

2.4.1 Definition

Vertical handover also called vertical handoff refers to the action of a certain node opting for a different type of connectivity it employs to access a supporting infrastructure. This function has been made to meet the demands of mobile devices, and to optimize coverage and access. A common example can be about a laptop which can use both a high speed wireless LAN and a cellular technology such as 4G to access the internet. It is generally assumed that the wireless LAN technology provides a higher speed, whereas a cellular technology gives a more widespread coverage. Naturally, the user will prefer to use a wireless LAN connection as long as it is available and to switch to a cellular connection in places where wireless LAN is not supported or has no coverage. Vertical handover is the automatic fall-over (or switch) between two technologies aiming to maintain communication. This is contrasted with a 'horizontal handover' which refers to an automatic switch between wireless access points using the same technology since a vertical handover is all about switching between the data link layer technology that is employed in order to access the network [10].

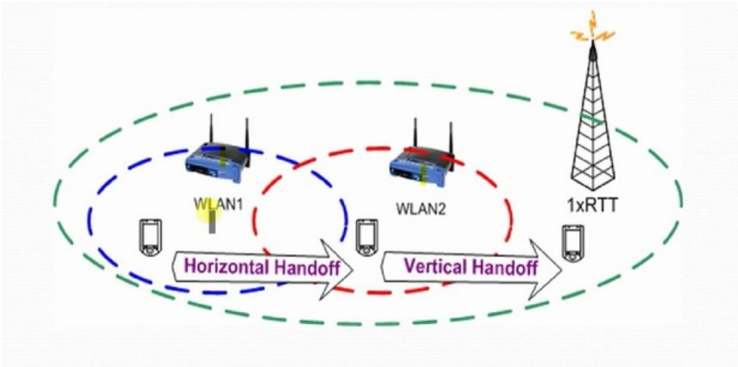


Figure 2.6: Horizontal handout between two WLAN networks and a vertical handoff between a WLAN and an RTT

Factors	Wi-Fi	Wi-Max	UMTS
Data Rate	54Mbps	DL=70 Mbps UL=70 Mbps	DL=2Mbps UL=2Mbps
Bandwidth	20MHz	5-6GHz	5MHz
Multiple Access	CSMA/ CA	OFDM/ OFDMA	CDMA
Coverage	300 m	16Km	Wider
Mobility	Low	Medium	High

Table 2.1: 3G-4G ACCESS TECHNOLOGIES

2.4.2 Types of handoff

There are mainly two types of handoffs: horizontal or symmetric handoff and vertical or asymmetric hand off. The former means the handoff or switch is taking place within the same wireless network technology, while the latter relates to handoffs occurring between different wireless access network technology. Fig. 2.6 illustrates this distinction [11]. Horizontal and Vertical Handovers take on varying parameters, as can be seen in the table 2.1. Being an asymmetric process, vertical handoff involves moving between two different networks having dissimilar characteristics. Hence, it is crucial to identify and select the network yielding the highest performance. This operationthe handoffshould ideally take place with minimum overhead. It is also of great significance to maintain the connection and authentication in a way which results in a minimum packet loss and transfer delay [12].

2.4.3 Handoffs in 4G Networks

A handoff schemes main aim is to sustain connectivity as mobile devices move from place to place, while keeping disturbances to ongoing transfers to a minimum. It is expected of handoffs to maintain a minimum amount of data loss, and to show low latency. There has been extensive research and deployment on handoffs made in cellular systems (wireless wide area networks), and these schemes are becoming increasingly popular in other networks such a wireless LANs as well [13].

2.4.4 Handover Process

There are generally three phases considered for a handover process. Fig. 2.7 summarizes the phases and what they involve. First, a handover initiation; this is followed by a handover preparation, and finally there will be a handover execution. The handover initiation involves a mobile terminal seeking new links. Having identified neighboring networks, the mobile terminal will choose among a number of options what is sees as the most appropriate network. This comparison process is based on some certain handover criteria. The criteria are made based on some information gathered related to the network from different layers such as Link Layer, Transport Layer and Application Layer. Information such as RSS, bandwidth, jitter, cost, power, link speed, throughput, etc. will be supplied by these layers. After the selection is done, handover negotiation will be forthcoming [14].

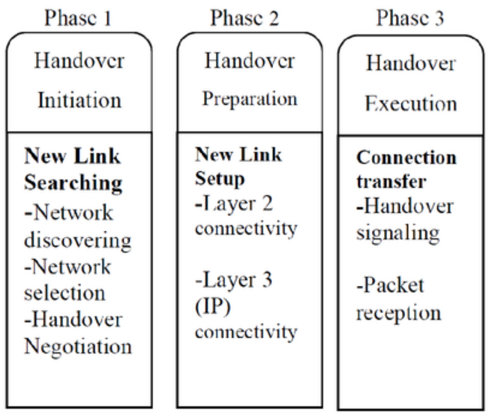


Figure 2.7: Three phases of handover process.

The second phase- hand over preparation: once the new network is chosen, a connection is set up between the mobile terminal and an access point which is located in the new network. Layer 2 of the network, medium access as well as layer 3, the IP, will have their connectivity and protocols established.

The third phase- handover execution: subsequent to the setup of a new link, the entire communications belonging to the old link are to be transferred to the new one.

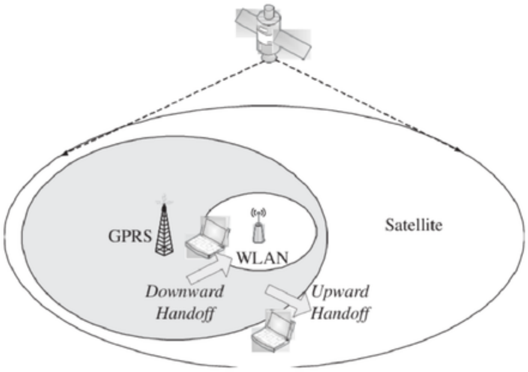


Figure 2.8: Downward and upward handover.

More specifically, all the control signals as well as data packets have to be allocated to the connection corresponding to the new access point. The handover execution also involves the authentication and authorization processes.

2.4.5 Classification of vertical handover

In general, four types or classifications of vertical handover are considered, basing upon four parameters, namely direction, process, control and decision.

Upward and downward handoffs

An upward handoff is referred to a switch or handoff from a small coverage network to a larger one. The reversed is called a downward handoff, indicating a network handoff from a large coverage to a smaller one. Fig. 2.8 illustrates a handoff from a GPRS coverage (relatively small coverage) to a WLAN network (small coverage) as a downward handoff and a handoff from a GPRS coverage (relatively large) to a satellite coverage (larger coverage) as an upward handoff.

Hard and Soft handoffs

Fig. 2.9 demonstrates two different handoff schemes, namely hard and soft hadnoff. A hard handoff is referred to a scheme where the mobile node would not establish a connection to the target network until it has first disconnected from the current network. The hard hand off is also known as break before make. By contrast, in a soft handoff, a mobile node would not cut off its connection with the current base station until its entire associations with the new base is completed. As the concept suggests, this hand off is known as make before break.

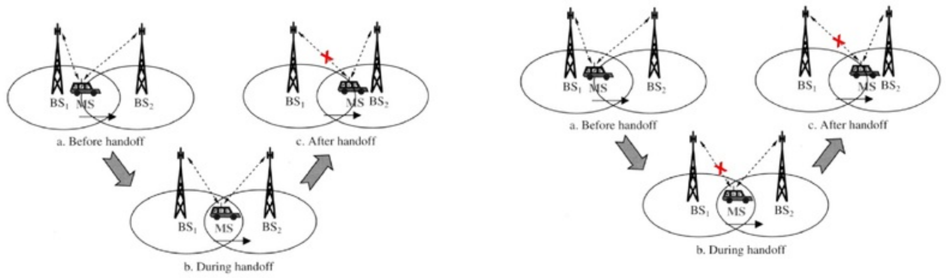


Figure 2.9: Comparison of hard and soft handoff process. a)soft handoff and b) hard hand off.

Chapter 3

handoff between WLAN and cellular networks

3.1 Reference Signal Received Power and Quality

3.1.1 Basic concept

It is a requirement for a mobile to measure the signal strength/quality of the neighboring cells when it moves across the cells performing cell selection. Two parameters are measured by a UE in LTE networks: RSRP, which represents the Signal Received Power and RSRQ, standing for Reference Signal Received Quality.

Generally, in an LTE network, the following are measured by a UE.

1-RSSI, which stands for the Received Signal Strength Indicator. The carrier RSSI does the act of measuring the average aggregate received power corresponding exclusively to OFDM symbols which contain reference symbols for the antenna port, which are traditionally OFDM symbols 0 and 4 in a slot.

2-RSRP, representing Reference Signal Received Power, is some type of RSSI measurement.

3-RSRQ, short for Reference Signal Received Quality: It is the quality taking into account RSSI and the number of used Resource Blocks, which is measured over the same bandwidth. RSRQ is a C/I measurement type which provides an indication of the quality of the received reference signal. The measurement RSRQ provides is another useful alternative index which plays a deciding role in cases when RSRP is hardly adequate to make a reliable decision about a handover or a cell re-selection. (N) RSRQ = (N * RSRP) / RSSI

RSRP Definition

RSRP, short for Reference Signal Received Power, is the linear average taken over all the power contributions (in LWJ) corresponding to the resource elements carrying cell-specific reference signals within the frequency bandwidth where measurement is considered. In order to determine RSRP, the cell-specific reference signals RO are to be used. It is only when UE can detect R1 in a reliable manner that it may combine R1 and R0

Reported value	Measured quantity value	Unit
RSRP_00	RSRP < -140	dBm
RSRP_01	-140 ≤ RSRP < -139	dBm
RSRP_02	-139 ≤ RSRP < -138	dBm
...	...	...
RSRP_95	-46 ≤ RSRP < -45	dBm
RSRP_96	-45 ≤ RSRP < -44	dBm
RSRP_97	-44 ≤ RSRP	dBm

Table 3.1: Categorization of RSRP

in order to determine RSRP.

The reference point designated for the RSRP must be the antenna connector of the UE.

If UE is having the receiver diversity in use, there must be an assurance that the reported value Is not lower than the calculated RSRP corresponding to any of the individual diversity branches.

The principal aim of RSRP measurement is to provide a sort of ranking between the candidate cells which is based on how strong their signal is. In general, the first antenna port is chosen to base the RSRP measurement on, but the reference signals which are sent on the second port are able to be used besides the RSS on the first port providing that UE detect that they are too being transmitted.

In can be said that RSRP measurement represents the average power of Resource Elements (known as RE) carrying cell specific Reference Signals (RS) across the whole bandwidth. In other words, RSRP is exclusively measured in the symbols that carry RS.

RSRP is the average received power corresponding to a single RS resource element, and to determine the RSRP, the power of multiple resource elements which are used to transfer the reference signal is measured by UE, and subsequently an average of them is taken.

The RSRP reported values are obtained from categorization based on ranges of value from -140 dBm to - 44 dBm, on 1dB increment. The way the values are mapped to reported values can be seen in the following table.

RSRP provides a sound measurement for a signal power from a specific sector as well as proving to be less susceptible to either noise or potential interference from other sectors.

RSRQ, short for Reference Signal Received Quality, is defined as per the following formula:

$$RSRQ = N_{PRB} * \frac{RSRP}{E - UTRAcarrierRSSI}$$

It is important to note that the same set of resource blocks shall be used to calculate the numerator and denominator of this ratio.

N denotes the number of Physical Resource Blocks used in measuring the RSSI, which tends to be the same as system bandwidth.

Reported value	Measured quantity value	Unit
RSRQ_00	RSRQ < -19.5	dB
RSRQ_01	-19.5 ≤ RSRQ < -19	dB
RSRQ_02	-19 ≤ RSRQ < -18.5	dB
…	…	…
RSRQ_32	-4 ≤ RSRQ < -3.5	dB
RSRQ_33	-3.5 ≤ RSRQ < -3	dB
RSRQ_34	-3 ≤ RSRQ	dB

Table 3.2: Categorization of RSRQ

RSSI represents pure wide band power measurement. This measurement encompasses intracell power, interference as well as noise power.

RSRQ reporting range is categorized from values ranging -3...-19.5dB, as illustrated in the following table.

3.1.2 Practical test results

To demonstrate the significance of vertical handover in practice, a simple test is carried out using an Apple cellphone. The test involves measurement of RSRP for two different locations, namely inside and outside of a building. The measurements are acquired using an application called "RF Monitor", which calculates the RSRSP level and displays the values in dBm. The test results are depicted in Fig.5.7. As shown in Fig.5.7(a), when the user is inside the building, the cellular power is as low as -91dbm which is much weaker compared to -50dbm of the WiFi power. Comparing the measurements with the RSRP catogorization shown in table 3.1, it is revealed that the WiFi power is in category RSSP-91 whereas cellular power is RSSP-43. As shown in Fig. Fig.5.7(b), the situation changed when the mobile station is moved out of the building. In this case, the signal received from cellular antenna becomes stronger than the WiFi signal. Specifically, cellular power is -81dbm whereas WiFi power is -85dbm. If the mobile station moves further away from the building, the WiFi power will gradually decline, hence making cellular a more viable wireless communication hub.

3.2 Concept of handoff trigger nodes

To clarify the concept of vertical handoff, consider the example communication system shown in figure 1. In this figure, the internal area is equipped with three WLAN access points (APs) marked as AP1, AP2 and AP3. The outdoor area is covered by a cellular base station (BS). The user is initially located inside the building and moves towards the outside while on a call. The objective is to provide seamless communication for the user by minimizing the probability of call dropping.

In general, two internetworking solutions might be deployed in this case. In the first approach, the two networks are tightly coupled, i.e., the WLAN hotspot is integrated

(a) (b)

Figure 3.1: Reference Signal Received Power for a)indoor area, b)outdoor area

into the cellular network. This can be achieved by operating the WLAN APs as slave hotspots while BS serves as the master. Alternatively, in a loosely coupled solution, the WiFi hotspots are independent from the cellular network. The later solution is simple and provides more flexibility. Specifically, it allows different service providers to operate the WLAN and cellular network without requirement of data exchange among the two networks. However, seamless performance is more difficult in loosely coupled networks. To explain the transition process, consider the time that a mobile user reaches the border of the building and outdoor area while moving out. At this time, APs are not reachable hence the mobile station initiates the transition to the cellular network. However, the handoff requires a certain amount of time to be complemented. Specifically, a significant latency occurs due to the power up of cellular network circuit, searching for the nearest BS and signal processing. Such time delay might result in temporary disconnection of the communication link, which results in call dropping. One way to alleviate the issue

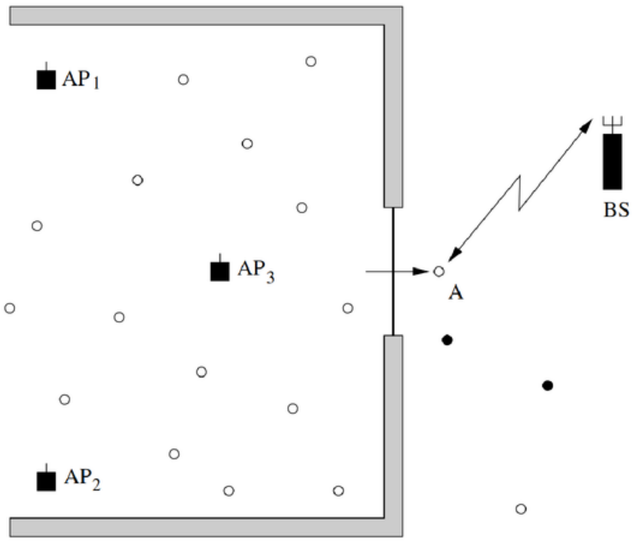


Figure 3.2: Implementation of WLAN/cellular handoff in a transition area.

of call dropping is to design the WLAN such that the WiFi coverage drops gradually, hence allowing the handoff to be completed while WiFi is still available. This might require relocating APs within the building and adding new APs but also cause WiFi overcrowding. An alternative solution is to add a hand-off trigger node (HTN) to the system. The HTN is a simple data station which helps the mobile station to initiate the vertical handoff prior to reaching the WLAN coverage border. This way, the mobile station will have ample time to accomplish vertical handoff before WiFi coverage is lost. Therefore, a seamless operation is achieved.

3.3 Implementation of handoff trigger nodes

The integration of HTN in a hybrid WLAN/cellular network is shown in Fig. 3.3. The HTN serves as a data station which informs the mobile station it is getting close to the border of WiFi coverage. Without HTN, when the mobile station reaches the boundary, the cellular base station might not recognize the handoff request from a new request for call. As a consequence, the probability of rejecting the handoff request will be the same as the probability of call blocking, which is too high. To resolve this issue, the HTN initiates handoff request early enough to allow sending two or more handoff requests to the base station. This way, the probability of call dropping can be significantly reduced [15].

The HTN utilizes link layer to initiate handoff in the mobile station which are approaching the border of WLAN network. For simplicity, consider the case of single channel communication network. The HTN is linked with the closest WiFi AP (AP3 in Fig.

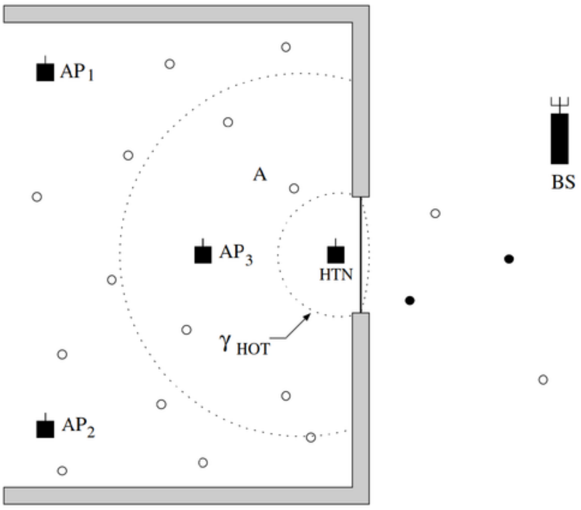


Figure 3.3: Incorporation of handoff trigger nodes in the hybrid WLAN/cellular network

3.2). The HTN scans the AP data in promiscuous mode. In this mode, all messages transmitted by AP are received at the HTN by disabling the HTN MAC. The received data is then processed to distinguish voice connections from other types of connection. If the data are encrypted, the voice and data connections might not be possible. In this case, handoff request will be transmitted to both voice and data connections. Obviously, data connections will ignore handoff requests [16].

The HTN detects an approaching mobile station through receive signal strength indication (RSSI). The system administrator sets a threshold for the RSSI. The HTN continuously scans for the signals of the base stations in its vicinity. When the base station is close enough to HTN, the RSSI of the base station signal received by HTN exceeds the RSSI threshold (HTN), a handoff trigger command is transmitted to the mobile station. Following, the mobile station commences the handoff procedure. In the first step, the mobile station turns the cellular radio on and sends call transfer requests to the base station. If the base station rejects the mobile station, the requests will be repeated every tw seconds until the handoff is successful or the WLAN coverage is lost [17].

Chapter 4

Simulation Setup

4.1 Introduction

Vertical handoff is an efficient way for achieving reliable wireless communications both inside and outside of the buildings. In this chapter, a simulation setup is implemented in MATLAB to assess the effectiveness of the method and present the reliability in terms of statistical measures. The simulation setup considers physical aspects of the wireless communication systems including path loss, noise and movement of mobile stations. Additionally, it accurately models the communication systems taking into account modulation and demodulation algorithms, carrier frequency, antenna gains and amplifier gains.

The simulation setup implements two handoff algorithms. In the first algorithm, the mobile station compares the reference signal strength index of WiFi and cellular networks to find out which network provides a better signal to noise ratio. In case that the signal strength of one of the networks goes above the other, the algorithm performs a handoff to switch to the stronger channel. In the second algorithm, a handoff trigger node is utilized as a beacon to inform the mobile station about requirement of a handoff to the other network. In this scheme, the handoff trigger node is usually placed at the entrance of the buildings to initiate handoff to WiFi network when the mobile station is entering the building and vice versa when the mobile station is exiting.

The proposed communication system model and handoff algorithms are explained in detail in the following subsections. Specifically, the overall communication layout is described in Section 4-2. In this section, the structure of the transmitter and receiver modules embedded in mobile station, WiFi and cellular network are described Furthermore, the model of wireless communication channel and the physical structure of the system model are detailed. Following, the handoff algorithms are presented in Section 4-3 and the implementation of those algorithms in MATLAB coding is addressed.

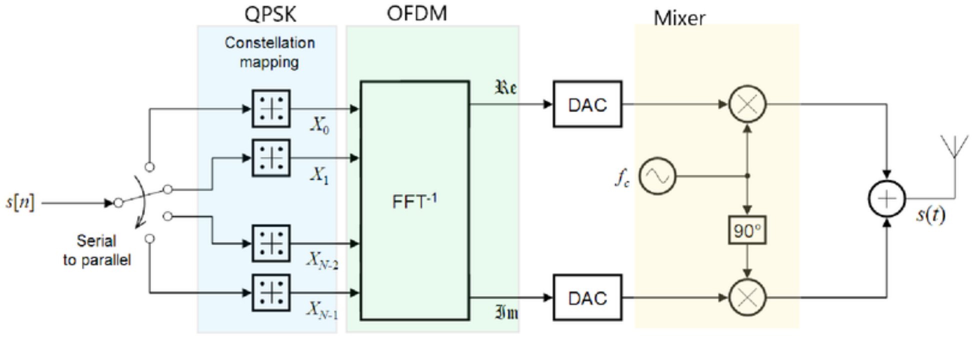


Figure 4.1: Block diagram of the transmitter

4.2 Fundamentals of Communication system model

The communication system model is the backbone of the simulation setup. The main parts of every communication system are transmitter, receiver and channel. In this section, each of these parts are explained and the MATLAB commands for implementation of these components is presented.

4.2.1 Transmitter

Communication starts with transmission of data towards a channel, which links the transmitter to the receiver. Here, three transmitters are considered, namely, cellular transmitter, WiFi transmitter and handoff trigger node transmitter. These transmitters have some common features. Specifically, all of them use modulation techniques to mix the data with a carrier signal and use an antenna to change the signal from an electrical voltage to electromagnetic waves. The most common modulation algorithms which are utilized in Cellular and WiFi wireless communications are quadratic phase shift keying (QPSK) and orthogonal frequency division multiplexing.

The block diagram of the transmitter is shown in figure 4.1. In the first stage, the digital data, which is expressed as a stream of bits, is converted from serial to parallel form by using a de-multiplexer. Then, the parallel data is passed through QPSK and OFDM modulators. The OFDM modulated signal is then mixed with sin and cosine carrier waveforms and added together. The resulting signal is sent to the transmitter antenna.

In the following subsections, each of the fundamentals of the aforementioned blocks and the MATLAB implementation of the receiver is addressed.

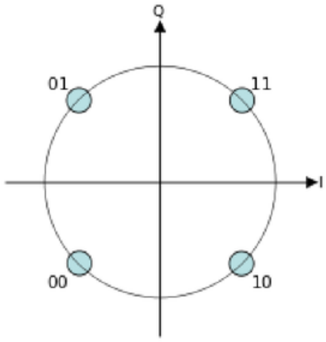


Figure 4.2: Constellation map for QPSK modulation with phase offset of $\pi/4$ radians

QPSK modulator

QPSK is a modulation method which mixes binary data with sinusoidal carrier signals through changing the phase of the carrier. In this method, the binary data is divided into binary digit pairs, each of which is equivalent to numbers 0-3 in decimal format. The input data to the communication system is commonly expressed as a series of binary digits. In QPSK modulation, each pair of digits is assigned as a symbol. Therefore, the possible symbols are 00,01,10 and 11. Furthermore, each symbol is associated with a phase angle.

The one-to-one relationship between the symbols and phase angles is commonly shown on complex plane as a so-called constellation map. The constellation map for QPSK modulation with phase angle offset of 45 is shown in figure 4.2. It can be seen that the points corresponding with the QPSK symbols lie on the unity circle. The distance between each of the points and the origin explains the amplitude of the carrier signal and the phase angle corresponding with each of the points shows the phase angle of the carrier signal.

In order to clarify the mechanism of operation of QPSK, an example is addressed in figure 4.3. Here, the data stream is 11,00,01,10. The I and Q components associated with each bit pair are shown in the figure. For the I component, the first bit determines the polarity, and for the Q component the polarity is determined by the second bit. Here, the I component has a phase shift of 0 degree and the Q component has a phase shift of 90 degrees. Consequently, the output signal will have different phase shifts depending on the polarity of I and Q components. It is seen that for the bit pair of 11, the signal angle is 45 degrees and for the bit pair of 00 the signal angle is 225 degrees. For inputs of 01 and 10, the signal angle is 135 and 335 degrees, respectively.

The diagram of QPSK modulator is shown in figure 4.4. As seen, the input is a series of zeros and ones, which is regarded as a binary stream. A multiplexer is used here to separate the even bits from the odd ones. Therefore, the output of multiplexer will be two bit streams, each of which has half the length of the input bitstream. Next, the bit streams are encoded to positive and negative signals, the sign of which is dependent on

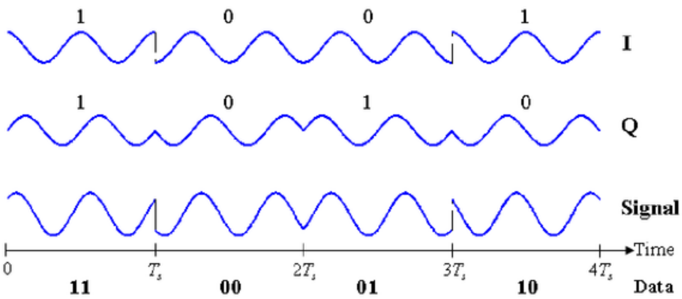


Figure 4.3: Example of QPSK modulation

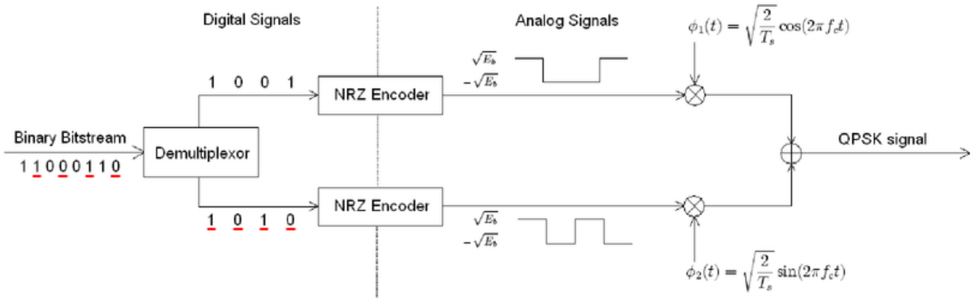


Figure 4.4: Block diagram of the QPSK modulator

the input bit. The encoded signals are then mixed with cosine and sine carriers to obtain the I and Q components. Then, these components are added together and sent to the output.

The OFDM modulator is implemented in MATLAB by calling the function QPSKModulator from the MATLAB communication toolbox as shown in the following code. Here, comm. refers to communication toolbox and BitInput, true means that the input of the modulator is a binary stream, as shown in figure 4.4. An alternative option is using BitInput, where the input is a series of symbols ranging from 0-3. The modulator is saved as a MATLAB object named hpsk_m. This object will be used later on to modulate binary data using QPSK method.

```
hpsk\_m=comm.QPSKModulator('BitInput',true);
```

OFDM modulator

The fundamentals of OFDM modulation has been addressed in detail in Section 2.3. Here, the implementation of OFDM modulation in MATLAB is addressed. The communication toolbox facilitates the implementation of OFDM modulation. The command for defining OFDM modulator is shown below. Similar with the QPSK modulator, the

OFDMModulator routine from communication toolbox is called to define a MATLAB object named hofdm_m. The modulator is characterized by a number of parameters, including FFTLength, CyclicPrefixLength and NumGuardBandCarriers. Each parameter is assigned to a corresponding variable. Specifically, the length of FFT is equal to NFFT. Typical values of FFT length for OFDM in wireless communication applications are 64, 128 and 256. In this project, the FFT length is selected as 128. The cyclic prefix length is set to Ncp, which has a value of 0 and the number of guard carriers is also set to the default value of zero. Therefore, the OFDM modulator does not uses cyclic prefix or guard carriers. It is important to use the same settings for the OFDM demodulator.

```
hofdm\_m = comm.OFDMModulator('FFTLength',NFFT,'CyclicPrefixLength',Ncp,'
   NumGuardBandCarriers',[0;0]);
```

MATLAB implementation of transmitter

The transmitter module is implemented in MATLAB by cascading QPSK and OFDM modulators. The MATLAB code for implementation of the transmitter module is shown below. The input data stream is passed through QPSK and OFDM modulators by using the step command from communication toolbox. The first argument of step function is the modulator object and the second argument is the input of the modulator. For the QPSK modulator, the input is the binary stream. The output of the QPSK modulator (Data_psk) is used as the input of the OFDM modulator. The OFDM modulator output signal is then mixed with a carrier sinusoidal signal and sent to the transmitter antenna.

It is worth mentioning that the QPSK and OFDM modulation are implemented in communication toolbox of MATLAB as base frequency modulators. In other words, the output of each modulator is indicated as a time series of complex numbers. The amplitude and angle of each complex number determines the amplitude and phase of the carrier signal at the associated instant of time. This way, the computation complexity is reduced and the simulations can be executed much faster.

```
Data_psk = step(hpsk_m,Inputdata);          %Apply PSK modulation
Data_ofdm= step(hofdm_m,Data_psk);          %Apply OFDM modulation
```

4.2.2 Receiver

The transmitter antenna converts the modulated signal into electromagnetic waves. These waves pass through the channel and hit the receiver antenna. The received data is then demodulated and converted back to a digital bit stream. In the proposed model, OFDM and QPSK demodulators are connected in series.

The schematic diagram of the receiver is shown in in figure 4.5. It is comprised of mixer/low pass filters, OFDM demodulator, QPSK demodulator and multiplexer. The received signal is first passed through a mixer which multiplies the received signal with the carrier, removes the high frequency components by using a low pass filter and computes the FFT. The output of the FFT block is then evaluated by the QPSK demodulator (symbol detection). In this part of the receiver, each sample is reflected to the constellation

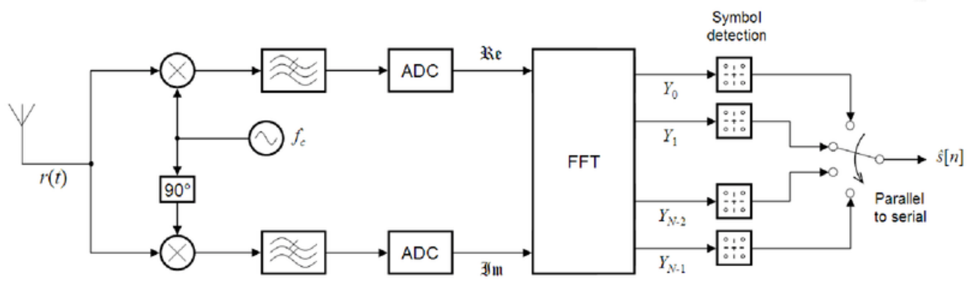


Figure 4.5: Schematic diagram of the receiver

diagram of QPSK (see figure 4.2). The location of the sample is then compared with the location of symbols and the symbol which has the least phase difference with the sample is selected as the received symbol. For instance, if the sample is situated in the first quarter of the complex plane (I¿0 and Q¿0), then the corresponding symbol will be 11. The symbols are then sent to a multiplexer, which converts the parallel data to a serial bit stream.

4.2.3 Channel model

The electromagnetic waves produced by the transmitter are propagated through the environment around the transmitter . Only a small part of the transmitted signals is captured by the receiver antenna. In addition to the signal from the transmitter, the received signal includes noise and interference caused by various different sources including other transmitters, nearby electrical equipment, power lines, etc. Therefore, between the received signal is an attenuated version of the transmitted signal which is contaminated with noise.

In communication terminology, the medium between the transmitter and receiver is called channel. The input to the channel is the transmitted signal and its output is the received signal. Knowing the transmitter power, the channel model should estimate the strength of the received signal. Also, noise should be modelled as a random process and added to the received signal.

Link budget

The expression relating the power of received signal (PRX) to the power of transmitted signal is:

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - PL + G_{RX} - L_{RX} \tag{4.1}$$

in which P_{TX} is the transmitter output power, G_{TX}/G_{RX} are the transmitter/receiver antenna gains in dB, $L_{TX}/\ L_{RX}$ are the losses associated with connectors and coaxial cables inserted between the transmitter/receiver circuit and the antenna, and PL is the path loss.

The above equation is commonly referred to as link budget. This terminology refers to the fact that a portion of transmitted signal power is consumed by the communication link (channel). So, the output power is equal to the input power minus the link budget. It should be pointed out that in the link budget equation, powers are expressed in dBm scale and the gains and losses are expressed in dB. Therefore, summation/subtraction is similar to multiplication/division of actual values.

Path loss

The gains and losses in the link budget equation are fixed parameters of transmitter and receiver modules except the path loss. The path loss expresses the difference between the power of electromagnetic waves emitted from the transmitter antenna and the power of the electromagnetic wave captured by the receiver antenna. The transmitted waves travel through air, hit several objects and might even pass through walls before reaching the receiver antenna. Consequently, the effect of path loss on the received signal is significant. So, accurate modeling of the path loss is of paramount importance.

In addition to the effect of the distance between the transmitter and receiver antennas, the path loss model must consider the physical characteristics of the channel. For instance, in case of the cellular communication network, the following factors should be considered: Does the mobile phone have a line of sight with the cellular base station? Is the mobile phone inside a building or outdoors? How many walls are there between the mobile phone and the base station?

A widely accepted path loss model for wireless communication networks is Winner II. In this model, the path loss is calculated as a logarithmic function of distance between the transmitter and receiver antennas and the carrier frequency. In addition, the type of channel (e.g., indoor to outdoor, office, urban environment, large indoor had), line of sight, existence of walls between the transmitter and receiver and the height of transmitter antenna are considered in the model. Winner II method presents several mathematical models for different situations. The equation describing the path loss is:

$$PL = Alog(d[m]) + B + Clog(f_c/5.0) \tag{4.2}$$

The factor A determines the sensitivity of the path loss to the distance between the transmitter and receiver. Since path loss is expressed in dB, the logarithm of distance is used in path loss equation. B is a constant which is dependent on the type of channel. C determines the sensitivity of the path loss to the carrier frequency. The parameter fc is the carrier frequency which is around 2.4GHz for WiFi and 1.9GHz for LTE cellular.

In this project, five types of channel are considered as shown in Table 4-1. The first channel type is indoor office-line of sight, where the factors A, B and C are equal to 18.7, 46.8 and 20, respectively. In this case, both transmitter and receiver antennas are located inside the same office room and the receiver antenna sees the transmitter (line of sight). Therefore, the path loss is relatively low.

The second channel type is large indoor hall with line of sight. This type is similar to type 1 except that because the size of the indoor area is large, the waves can hit the

Type	Description	Model
1	Indoor office (LOS)	$A = 18.7, B = 46.8, C = 20$
2	Large indoor hall- line of sight	$A = 13.9, B = 64.4$, C =20
3	Large indoor hall- non line of sight	$A = 37.8, B = 36.5$, C =23
4	Urban micro-cell- non line of sight	$PL = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + 34.46 + 5.83\log_{10}(h_{BS}) + 23\log_{10}(f_c/5.0)$
5	Urban macro outdoor-to-indoor	$PL = 40\log d + 35.87 + 6\log f_c/5 - 14\log h_{BS} - 14\log h_{MS} - 0.8h_{MS} + 0.5d_{in}$

Table 4.1: Details of path loss models utilized in this project

walls and be reflected towards the reciever more frequently compared with a small office. Consequently, the sensitivity of the path loss to the distance (A) is lower compared with the first type. However, the constant parameter B is larger due to the channel fading effects caused by signal multipath.

The third model describes the case that the transmitter and receiver are located inside a large indoor hall, but there is no line of sight between them. In this case, the sensitivity of the path loss to the distance (A) is much larger compared to type 1 and type 2. The reason is that as the distance is increased, the transmitted wave will hit more objects and lose more energy before reaching the receiver.

The models 4 and 5 are focused on cellular communication networks. In case of type 4, the cellular base station and the receiver are located in an urban area. However, the receiver cannot directly see the cellular base station because of the existence of buildings between the transmitter and receiver. In this case, the factor A ($A = 44.9 - 6.55 logh_{BS}$) is a function of base station height (hBS). As the base station height is increased, A is reduced. The reason is that when the base station is moved higher, the transmitted waves are less likely to hit the ground and hence the path loss in case of long distances is reduced. On the other hand, a new term is added to the pathloss($5.83logh_{BS}$) to model the effect of base station height on the special distance between the transmitter and receiver.

Model 5 described the situation which the mobile station is inside a building. In this case, the waves transmitted from the cellular base station must travel through building walls and windows to reach the mobile station. Therefore, this type of channel is expected to have a larger path loss compared with type 4. Here, the factors A, B and C are equal to 40,13.47 and 6, respectively. However, additional terms are added to the model. Specifically, the terms $-14log(h_{BS}$ and $-14log(h_{MS} - 0.8h_{MS}$ take into account the effect of base station height and mobile station height (h_{MS}). Furthermore, $0.5d_{in}$ models the increased losses when the wave is traveling through the building.

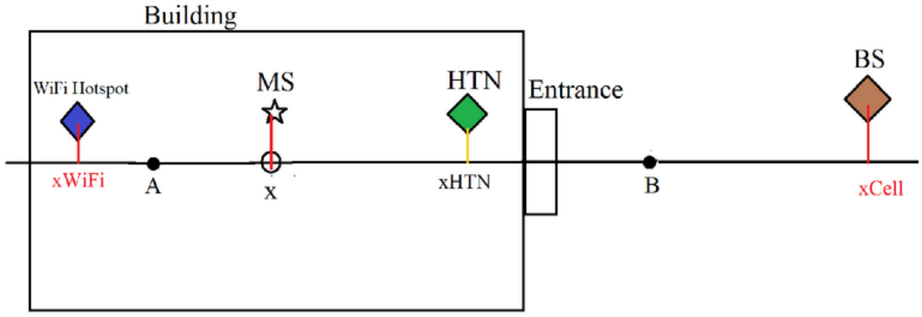


Figure 4.6: Placement of the cellular base station, WiFi hotpost, HTN and mobile station along x axis

4.3 MATLAB Implementation of the model

To study the performance of the proposed handover technique, a communication system model comprising of a WiFi hotspot, a cellular base station (BS), a mobile station (MS) and a handoff trigger node (HTN) is presented in this section. The physical arrangement of the model is shown in figure 4.6. In this model, the location of WiFi hotspot, MS, HTN and BS is specified as $xWiFi$, x, $xHTN$ and $xcell$. It is observed that the WiFi hotspot is located inside a building. The MS can move between point A, which is situated inside the building and point B, which is outside of the building. The HTN is placed close to the building entrance to facilitate the process of handover despite the limited response time of BS in establishment of the connection.

When the MS is inside the building, the signal strength of WiFi is higher than the Cellular network. So, the MS is connected to the WiFi network. However, if the MS is moved towards the point B, the WiFi signal strength drops and the Cellular network signal becomes stronger. When the MS reaches the entrance, the handover process is initiated and the MS switches to cellular network. In the case that the MS moves from point B towards point A,the reverse of the aforementioned process is conducted.

In this section, the MATLAB functions for implementation of WiFi, HTN, BS and MS modules are presented. Furthermore, a MATLAB function is dedicated to calculation of path loss according to Winner II model. The path loss function will be used by the WiFi, HTN and BS functions to calculate link budget associated with each of these modules.

4.3.1 Path loss function

Winner II path loss model is implemented as a MATLAB function named PathL. The inputs of the function are the type of the model, the distance and the carrier frequency and the output is the path loss in dB. A switch-case structure is used to select the proper path loss equation from table 1 based on the specified type. For each model type, the parameters A,B and C are copied from table 4.1 and the path loss is calculated according to the Winner II equation.

```
function PL=PathL(Type,d,fc)
global xHTN
switch Type
    case 'IndoorOffice'
        A=18.7;B=46.8;C=20;X=0;
        PL=A*log10(d)+B+C*log10(fc/5)+X;
    case 'IndoorLOS'
        A=13.9;B=64.4;C=20;X=0;
        PL=A*log10(d)+B+C*log10(fc/5)+X;
    case 'IndoorNLOS'
        A=37.8;B=36.5;C=23;X=0;
        PL=A*log10(d)+B+C*log10(fc/5)+X;
    case 'CellNLOS'
        hbs=25;
        PL=(44.9-6.55*log10(hbs))*log10(d)+34.46+5.83*log10(hbs)+23*log10(
           fc/5);
    case 'CellOutIn'
        hbs=25;hms=1.5;
        PL=(40)*log10(d)+35.87-14*log10(hbs)-14*log10(hms)+6*log10(fc/5)
           -0.8*hms+0.5*abs(d-xHTN);
end
end
```

4.3.2 WiFi hotspot and HTN modules

The WiFi module is implemented as a MATLAB function called WiFihot, as shown below. This function integrates the WiFi transmitter and the channel into a single module. The input parameters of the function are binary bit stream (Inputdata) and the location of the receiver. The output of the function is the WiFi signal at the receiver. A number of global parameters are also indicated for the function. These parameters are shared between the function and the main code. Specifically, knoise indicates the power of noise within the frequency band of the WiFi signal, hpsk_m and hofdm_m, are the QPSK and OFDM modulator objects, Gnat_WiFi represents the total gain of WiFi hotspot and receiver antennas and the transmitter amplifier, XWiFi represents the location of WiFi hotspot and xHTN is the location of HTN.

```
function Data_ch=WiFihot(Inputdata,x)
global knoise hpsk_m  hofdm_m Gant_WiFi xWiFi xHTN
```

After defining the parameters, the transmitted signal (Data_ofdm) is computed as the output of QPSK and OFDM modulators. The transmitted signal is then fed to the channel model to obtain the received signal.

```
Data_psk = step(hpsk_m,Inputdata);      %Apply PSK modulation
Data_ofdm= step(hofdm_m,Data_psk);      %Apply OFDM modulation
```

As detailed in Section 4.2.3, the recieved signal is an attenuated and noise contaminated version of the transmitted signal. In order to obtain the amount of signal attenuation, the distance between the transmitter (WiFi hot spot) and receiver (MS) is calculated according to the following equation:

$$d = \sqrt{(x - x_{WiFi})^2 + h_{WiFi}^2} \tag{4.3}$$

The calculated distance is then used to obtain the path loss by calling the function PathL. Here, two different path loss models are utilized. If the location of MS is within 5 meters of point A (see figure 4.6), it is assumed that the MS is located within the same area as the WiFi transmitter and hence the in door office model is selected. Otherwise, the MS loses the line of sight of the WiFi hot spot and hence the indoor non line of sight model is chosen. Another input of the pathloss model is the WiFi carrier frequency, which is set to standard value of 2.4GHz. Then, the path loss is used to obtain the link budget according to equation 4.1. A complex white Gaussian noise is generated using MATLAB command randn. The amplitude of noise is specified by parameter knoise. Next, the received signal is computed as

$$x_R = x_T * 10^{Linkbudget/20} + noise \tag{4.4}$$

```
d=sqrt((x-xWiFi)^2+3^2);
if x<5
    Pathloss=PathL('IndoorOffice',d,2.4);
else
Pathloss=PathL('IndoorNLOS',d,2.4);
end
LinkbudgetWiFi=Gant_WiFi-Pathloss;
%Define noise as a random complex variable
noise=(randn(128,1)+randn(128,1)*1i)*knoise;
% Pass the signal through the channel: Add noise, Weaken the signal by PL
Data_ch =Data_ofdm*(10^(LinkbudgetWiFi/20))+noise ;
end
```

The HTN module is defined as the MATLAB function "HTN" with input binary stream and location of MS as input parameters, respectively. It should be emphasized that HTN is esentially another WiFi hotspot but it is not necessarily connected to the internet. Therefore, the code for HTN modules is similar with the WiFi hotspot (see the Appendix), expect that some of the parameters are changed accordingly.

4.3.3 Cellular base station module

The cellular base station module is defined as the MATLAB function "CellBS". The main difference between the BS and WiFi/HTN modules is the path loss model. Here, two path loss models are utilized, namely urban macrocell non line of sight and urban macrocell outdoor to indoor models. When the MS is located inside the building ($x < x_{HTN}$), the outdoor to indoor model is chosen. Otherwise, the urban non line of sight model best describes the path loss.

```
if x<xHTN
    Pathloss=PathL('CellOutIn',d,1.9);
else
    Pathloss=PathL('CellNLOS',d,1.9);
end
```

4.3.4 Receiver module

The MATLAB implementation of receiver is shown in the code below. The OFDM demodulator object (hofdm_dem) is defined using OFDMDemodulator command from the communication toolbox. The parameters of the OFDM demodulators are selected the same as the OFDM modulator to ensure compatibility. Similarly, the QPSK demodulator is defined and named as hqpsk_dem. The receiver is then implemented, by calling the step function from the communication toolbox. Here, the input to the OFDM demodulator is the received signal (Data_ch). The output of the demodulator is then passed through QPSK demodulator to obtain the output data stream.

```
hofdm_dem = comm.OFDMDemodulator('FFTLength',NFFT,'CyclicPrefixLength',Ncp,
   'NumGuardBandCarriers',[0;0]);
hpsk_dem=comm.QPSKDemodulator('BitOutput',true);
function Outputdata=recv(Data_ch)
global hofdm_dem hpsk_dem
Data_dem = step(hofdm_dem,Data_ch);        % Apply OFDM demodulation
Outputdata = step(hpsk_dem,Data_dem);     % Apply PSK/QAM demodulation
end
```

4.4 Proposed handover algorithm

The handover algorithm automatically switches between the WiFi and cellular networks to maximize the reliability of connection despite weak cellular signals within indoor areas. The flowchart of the proposed handover algorithm is shown in figures 4.7 and 4.8. Depending on the direction of movement of the MS, in-out and out-in scenarios can be simulated. The algorithm checks whether the MS is moving from outdoors environment towards the building (out-in), or starts moving from inside of the building towards outside (in-out). In the case of in-out scenario, the location of MS starts from point A and increases with time (see figure 4.6). So, x is calculated as:

$$x = x_A + Velocity * Time \tag{4.5}$$

Since point A is regarded as reference point, the above equation is simplified to:

$$x = Velocity * Time \tag{4.6}$$

In case of the second scenario, however, the MS is moving from point B towards point A. Hence,

$$x = x_B - Velocity * Time \tag{4.7}$$

Next, the input data is calculated as a random binary stream by calling the function randi:

```
Inputdata = randi([0,1],[framesize,1]);
```

The WiFi, HTN and cellular simulation modules, which were defined in section 4.3 are then called to calculated the signals from WiFi, HTN and cellular network received by the MS antenna. Following, the energy and RSSI of these signals is calculated. Based on the computed RSSI values, the proposed algorithm can decide whether a handover is required or not.

```
DataChan(:,1)=WiFihot(Inputdata,x);
DataChan(:,2)=HTN(Inputdata,x);
DataChan(:,3)=CellBS(Inputdata,x);
for k=1:3
        Eframe=sum(abs(DataChan(:,k)).^2);
        RSSI(k)=10*log10(Eframe/1e-3/framesize);
end
```

Here, two different vertical handover methods are realized. In the first method, the RSSI of the current network is compared with RSSI of the alternative network. If the alternative network has a higher signal strength, then the handover is initiated. This method is independent from HTN and hence is easier to implement. However, it suffers from high probability of error caused by the handover delay time.

Becasue HTN is located next to the building entrance, as the MS moves towards the entrance, the HTN signal becomes stronger. When the MS reaches to the vicinity of the entrance, the HTN signal goes above a predefined threshold. This feature is used in the second method to initiate the handover process by comparison of HTN signal strength with the threshold. This way, the MS will have enough time to complete the handover before reaching the building exit. As a consequence, the probability of error will be small even in case of large handover delays.

Next, the algorithm checks the handover conditions. If either of the conditions is satisfied, the handover will be initiated. At this stage, the future network will be selected as Cellular or WiFi depending of the simulation scenario. The handover process needs some time to be completed. The handover completion time is

$$T_{complete} = T_{initiate} + T_{delay} \tag{4.8}$$

The algorithm continuously checks the time to find out if the handover completion time has been reached. If so, the handover process is finalized by changing the current network. Next, the MS receiver selects the signal from the current network using a conditional statement. The selected signal is then demodulated to obtain the output data.

The communication error is computed by comparison of input and output binary streams. The number of bit mismatches is calculated by using the error rate function from the communication toolbox, as shown in the code below. This number is divided by the total number of bits to compute the probability of error.

```
herr = comm.ErrorRate('ResetInputPort',true);
```

```
  errcount = step(herr,Inputdata,Outputdata,1);
Perr=errcount(2)/framesize;
```

In the last part of the algorithm, the time is incremented according to:

$$Time = Time + T_{step} \tag{4.9}$$

in which T_{step} is the step time of simulation. If the simulation is greater than the end time, the simulation will stop. Otherwise, the simulation will be repeated until simulation end time is reached.

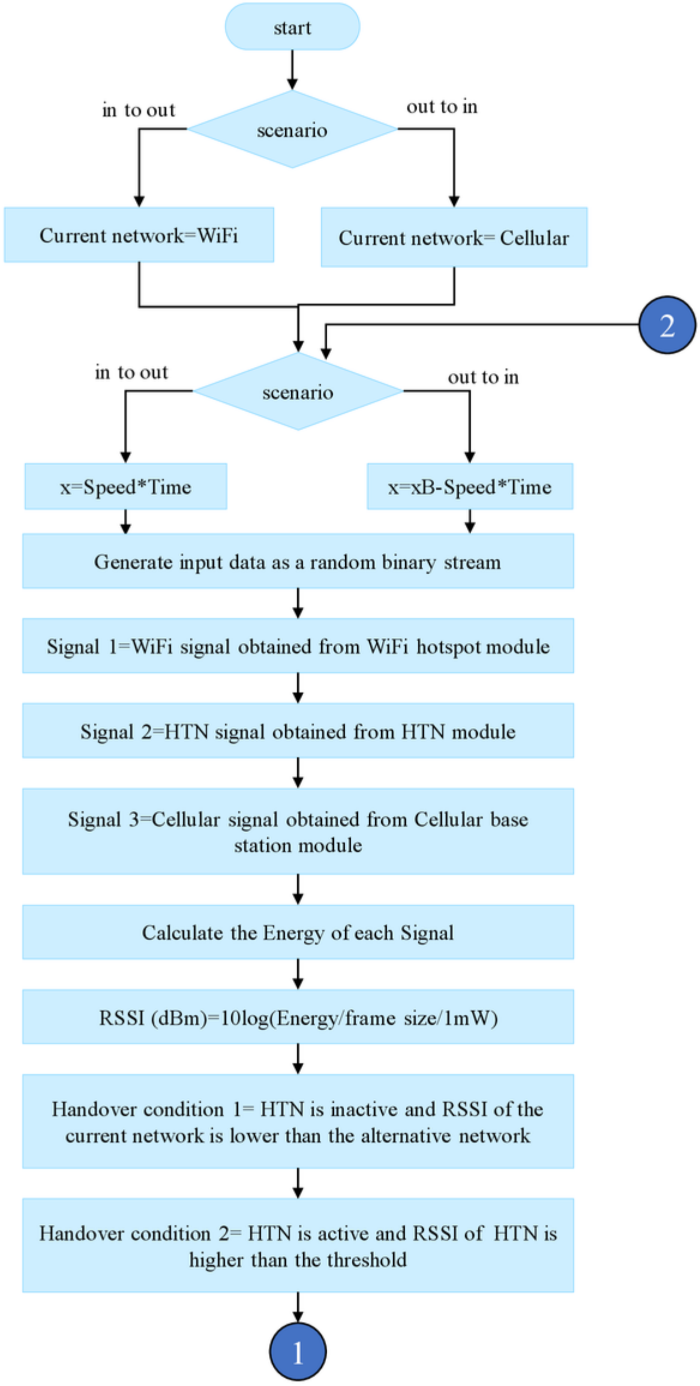


Figure 4.7: Flowchart of the handover algorithm: part 1

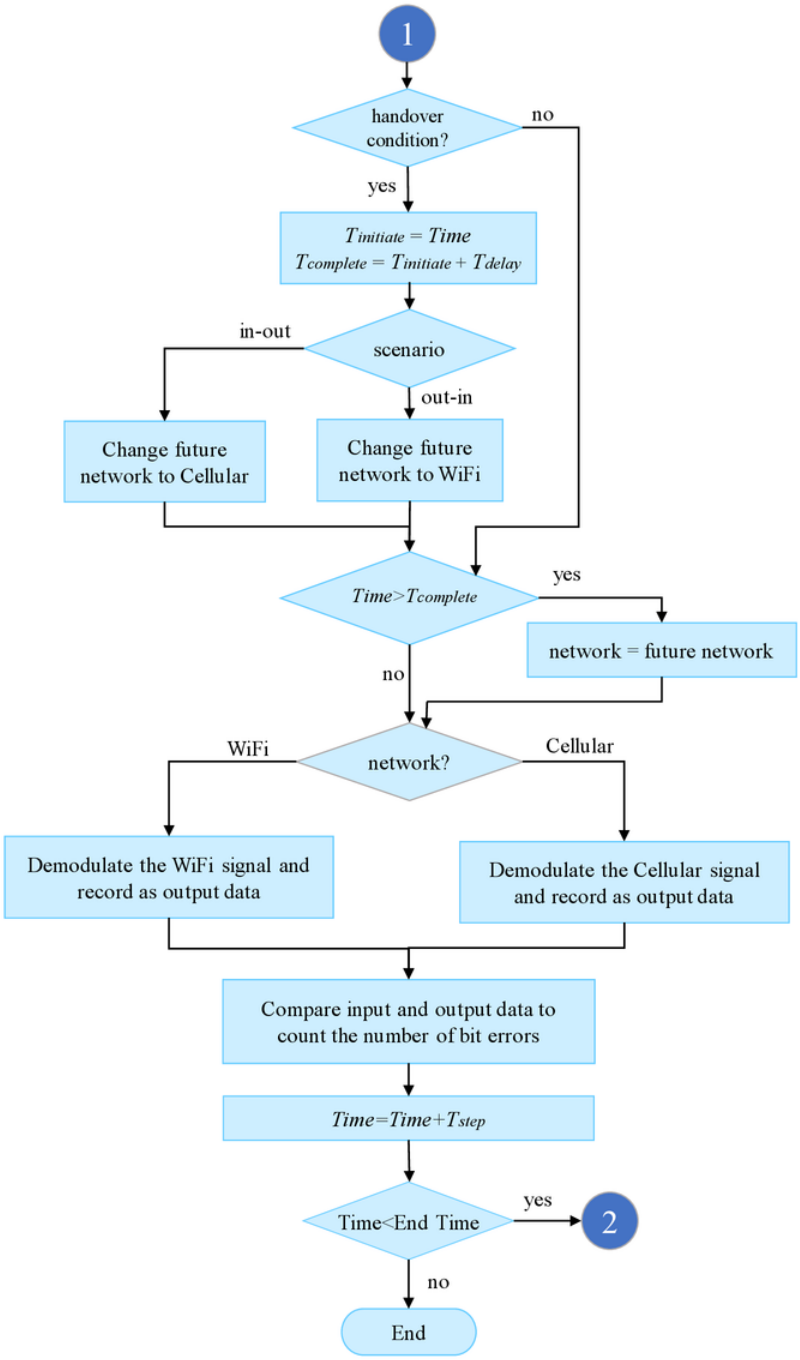


Figure 4.8: Flowchart of the handover algorithm: part 2

Chapter 5

Simulation Results

In this chapter, the simulation results of the proposed vertical handover method are presented and discussed. With the intention of demonstration of the advantages of HTN in enhancement of the communication reliability, the simulation results are presented with and without HTN. The simulations are conducted using two different channel models. In the first case, the channel is modeled as free space. In the second model, realistic channel models are utilized to consider the effect of environment on the path loss and evaluate the performance of the proposed method in practice.

5.1 Simplified path loss model

In the first stage, the simulations are conduceted using a simplified channel model, where path loss is calculated using the basic Winner II model for free space. The generic path loss model is independent from the geometry of the building and the thickness and number of walls. Additionally, this simplification helps us produce test results which are intuitive and easy to understand. Here, two scenarios are studied. In the first scenario, the mobile station is moving from point $x = 0$ within the building to point $x = 20$ outside of the building. In the second scenario, the direction of movement is reversed.

5.1.1 scenario 1-single test

The test results for the first scenario is shown in figures 5.1 and 5.2. Figure 5.1 depicts the variations of signal strength received by MS as a function of location. It is worth mentioning that in the whole simulations, the WiFi access point is located at $x_{WiFi} = -2m$, the HTN transmitter is at $x_{HTN} = 15m$ and the cellular BS is at $x_{BS} = 70m$. It is seen that as x is changed from 0 to 20, the WiFi signal strength drops but the cellular signal strength increases. This result is justified by the fact that for smaller values of x (where WiFi signal is strong), the MS is close to the WiFi access point, which is located on the left side of the origin. On the other hand, as x is increased, the MS gets closer to cellular BS and hence the BS signal strength rises. As for the HTN, the signal strength peaks are $x = 15$, where HTN is located.

The probability of error of the received signal is depicted in figure 5.2. It is observed that for both HTN and RSSI handover algorithms, as MS is moved from x=0 to x=15, the error rate increases due to the decrease in WiFi signal strength and signal to noise ratio. However, after the handover is conducted at around $x = 15$, the probability of error decreases thanks to the higher strength of cellular signal.

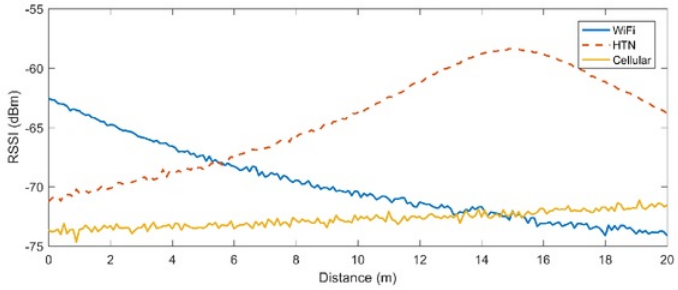
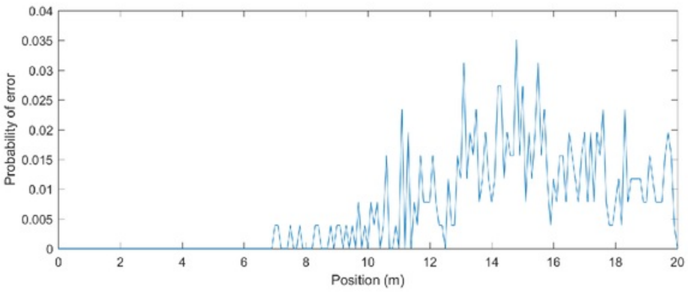
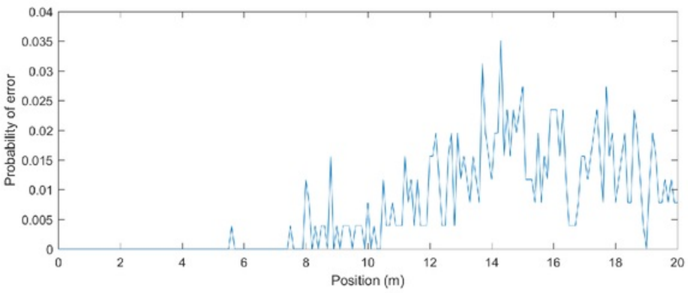


Figure 5.1: Variations of signals strengths for simple path loss model- single test



(a)



(b)

Figure 5.2: Probability of error for simplified path loss model-single test: a) without HTN, b) with HTN

5.1.2 scenario 1-Monte Carlo test

The simulation results of Section 5.1.1 present the performance of the algorithm evaluated in a single test. Since the input data and noise are random processes, a single test does not provide an accurate estimate of the system behavior. Statistically, the accuracy of analysis can be increased by repeating the test over and over and conducting averaging. This method is known as Monte Carlo simulation.

In this project, the test is repeated for 50 times, to achieve sufficient accuracy. The Monte Carlo simulation results are shown in figure 5.3. Comparison of figure 5.3 with 5.1/5.2 reveals that Monte Carlo simulation results are smoother compared to the results of a single test. The reason is that the averaging of results eliminates the effect of the randomness of noise on the simulation outcome. From figure 5.3, it is observed that in case of HTN algorithm (figure 5.3(c)), the handover is completed at around $x = 14.5m$ whereas in case of RSSI algorithm the handover is completed at around $x = 15.5m$ (see figure 5.3(b)). The HTN algorithm acts faster thanks to the detection of HTN signal prior to reaching the building entrance. Consequently, the probability of error of HTN algorithm is slightly less than the RSSI algorithm.

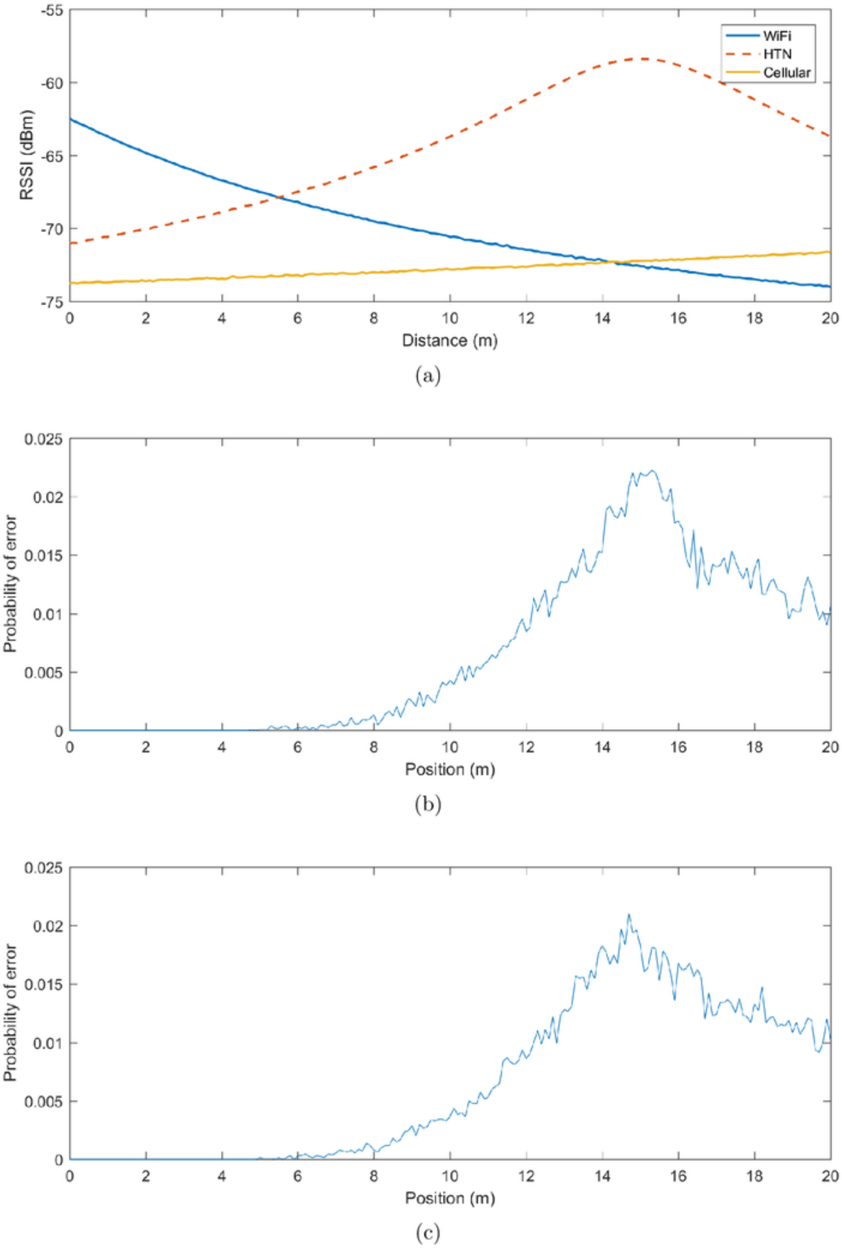


Figure 5.3: Monte Carlo simulation results for scenario in-out using simplified path loss model: a) RSSI, b) probability of error without HTN, b) probability of error with HTN

5.1.3 scenario 2-Monte Carlo test

The Monte Carlo simulation results for scenario 2 are shown in figure 5.4. In this scenario, the MS is moved from point $x = 20$ (outside of the building) to point $x = 0$ (inside of the building). AS shown in figure 5.4 (a), in case of RSSI method the handover is completed at around $x = 13$, whereas the HTN method completes the handover at around $x = 14$ (see figure 5.4(b)). Mote that the MS is moving backwards so the HTN method acts first. As a consequence, the error is slightly lower in case of HTN method.

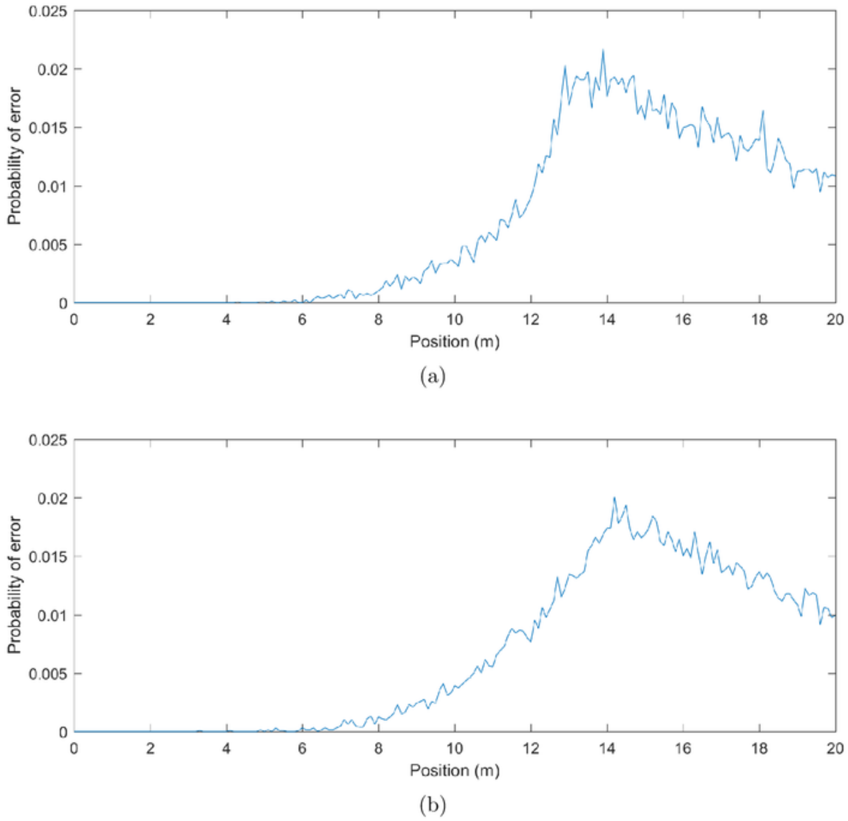


Figure 5.4: Monte Carlo simulation results for scenario out-in using simplified path loss model: a) probability of error without HTN, b) probability of error with HTN

5.2 Detailed path loss model

The simplified path loss model uses a generic free space model to calculate the path loss of each network according to the distance between the transmitter and receiver. In this section, the detailed path loss models described in section 4.2.3 are implemented to obtain realistic simulation results.

Figure 5.5 shows the variations of signal strength for different networks obtained using detailed path loss model and Monte Carlo simulations. Here, it is assumed that while the MS is located in the range $0 < x < 6$, it has a line of sight with the WiFi access point. For higher values of x, the MS loses line of sight with WiFi antenna, which results in a quick drop in the RSSI of WiFi signal. In case of HTN, the MS can see the HTN antenna within the range $13 < x < 17$, where RSSI of HTN is stronger compared to other locations. As for cellular station, when x goes above 15m, the RSSI exhibits a step rise because the MS is moved out of the building.

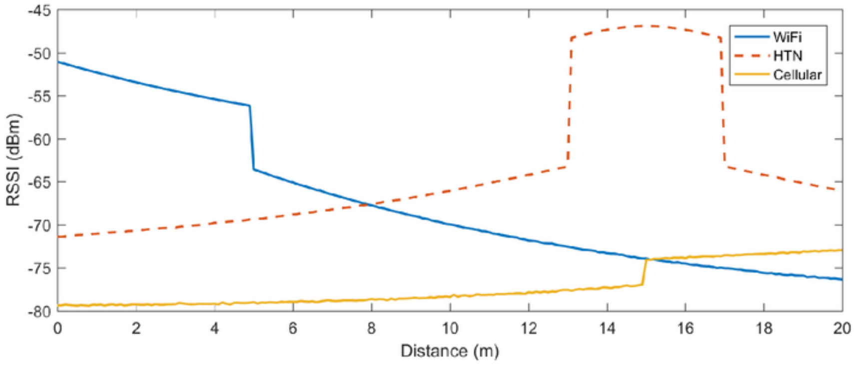
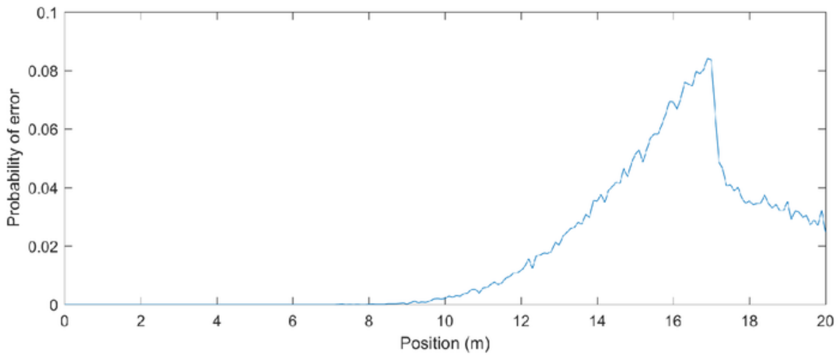


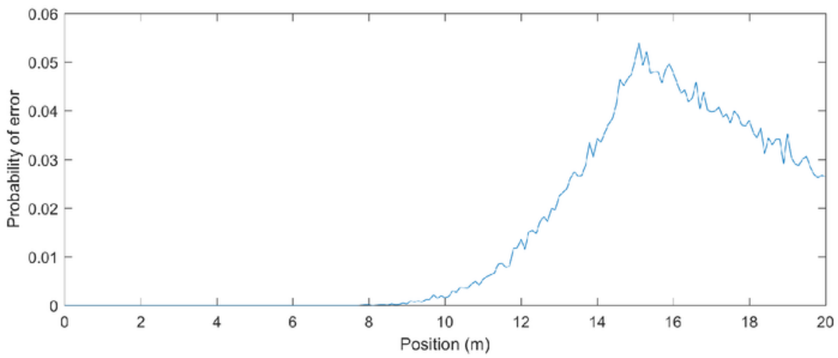
Figure 5.5: Variations of signal strengths of each networks for detailed path loss model

5.2.1 scenario 1

Simulation results of scenario 1 (MS moving from inside to outside of the building) considering the detailed path loss model is shown in figure 5.6. In case of RSSI algorithm, the handover is initiated at $x = 15m$ and completed at $x = 17$. It is worth mentioning that this handover delay is 2s, which corresponds with 2 meters movement of MS. The handover delay causes the probability of error to rise to 0.085 just before handover is completed. The HTN algorithm enhances the performance by initiating the handover at an earlier time. Specifically, the HTN initiates handover at $x = 13m$ hence the handover is completed at $x = 15m$. As a consequence, the maximum error rate is limited to 0.055. So, the HTN algorithm reduces the error rate by around 35% compared with the RSSI scheme.



(a)

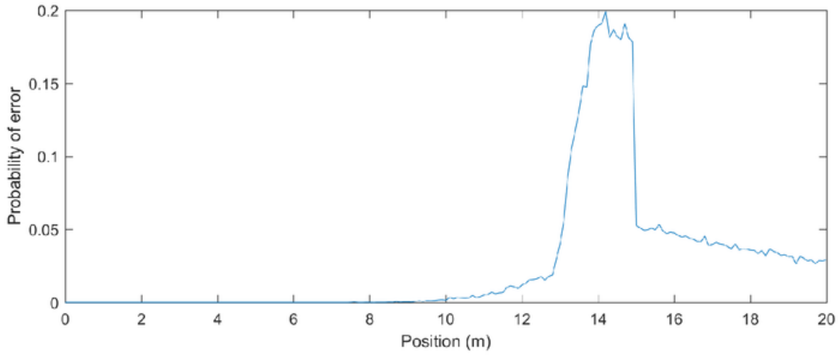


(b)

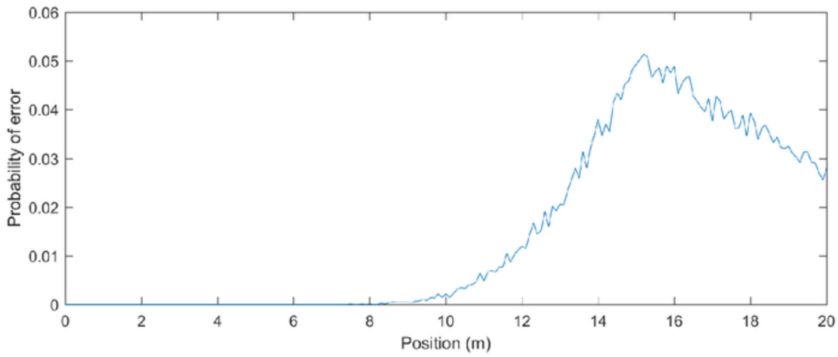
Figure 5.6: Probability of error for scenario 1: a) without HTN, b) with HTN

5.2.2 scenario 2

Simulation results for scenario 2 (MS moving from outside to inside of the building) are shown in figure 5.7. AS illustrated in figure 5.7 (a), the RSSI method exhibits a large error right after the MS enters the building ($13 < x < 15$). The reason is that due the handover delay time, when the MS enters the building, it continues using the cellular network for around 2 seconds. Since the SNR of cellular signal is low inside the building, the probability of error rises to around 20%. This problem is circumvented by HTN through triggering the handover prior to entering the building. Consequently, the MS switches to WiFi as soon as the MS enters the building, hence the error rate remains below 0.05 (see figure 5.7 (b)).



(a)



(b)

Figure 5.7: Probability of error for scenario 2: a) without HTN, b) with HTN

Chapter 6

Conclusions and future work

6.1 Conclusions

Vertical handover has gained attention of both research and industry sectors as a practical way of enhancing the reliability of wireless communication networks in spite of dependency of signal strength and SNR on the location of mobile stations. The basic concept of vertical handover is to make use of both cellular and WiFi technology to provide reliable communications both inside and outside of the buildings. When the mobile station is located inside a building and has access to the WiFi network of the building, WiFi is used to ensure low error rate and high quality calling. If the mobile station moves out of the building, a vertical handover algorithm automatically sends a conecetion requenst to the neasrest cellular base station and changes the source signal from WiFi to cellular upon acknowledgment of the cellular base station.

In this project, two different algorithms are utilized to perform vertical handover. In the fist method, the strength of WiFi and cellular signals are compared to detect which network is stronger. If the RSSI of the current network (e.g., WiFi) falls below the alternative network (e.g., cellular), the algorithm initiate a vertical handover to switch to the alternative network.

The main limitation of RSSI-based handover algorithm is being prone to handover delay time, i.e., the time required to complete handover after its initiation. Due to the handover delay, the mobile station continues using the old network with lower SNR for a period of time before switching to the new network. This can cause call dropping during the transition time. To alleviate this issue, a handover trigger node can be installed at the entrance of the building. The mobile station can then use the handover trigger node signal as a beacon to determine the location at which handover should be conducted.

The RSSI and handover trigger node algorithms have been tested using MATLAB simulations to verify the efficacy of the algorithms and compare their performance. The simulations setup has been implemented considering practical details, including dependency of path loss on the environment, transmission power of WiFi access points and cellular base stations and the time delay of handover process. Simulation results show that:

1-The path loss model has a significant effect on the simulation results. Specifically, while in a simplified path loss model (based on free space model), the WiFi and cellular signal strengths are only dependent on the distance of the mobile station from the WiFi access point and cellular base station, the response of a detailed path loss model is also dependent on the environmental features such as availability of a line of sight between the transmitter and receiver, the type of the environment, thickness of walls, etc.

2- Simulation results demonstrate that the vertical handover provides a practical solution for realization of a reliable wireless communication system. With error rates lower than 5%, this technology can ensure quality audio signals and prevent call dropping during transition between WiFi and cellular networks.

3-The significance of handover trigger node in reduction of call dropping rate and enhancement of quality of call is less obvious in case of simplified path loss model but becomes apparent in the analysis results of the detailed model. Specifically, simulation results show that the error rate can be reduced from 20% to around 5% by deploying a handover trigger node in the proximity of handover location.

6.2 Future work

This project was focused on review, simulating and analysis of vertical handover algorithms in wireless communication networks. In this context, two decision making algorithms based on RSSI comparison and handover trigger node were presented, analyzed and discussed. A future step is to look into alternative handover schemes and compare their performance with the presented methods. Besides from performance comparison, one might examine the economical and technical issues concerning practical implementation of different handover algorithms.

Another suggestion for future work is to evaluate the of handover between different generations of cellular communication technology (2G/3G/LTE) as well as different frequency band of WiFi (2.4GHz, 5GHz) to optimize reliability and minimize the error rate. This strategy is especially useful in case that the received signal has a low SNR and hence reliable connection is hard to achieve.

Appendix A

A.1 MATLAB Code: Initialization subroutine

```
Nmonte=50;                  %Number of Monte Carlo Simulations
%% QPSK
Nqpsk = 4;
QPSKbits = 2;
hpsk_m=comm.QPSKModulator('BitInput',true);
hpsk_dem=comm.QPSKDemodulator('BitOutput',true);

%% OFDM
NFFT = 128;
Ncp = 0;  %Cyclic prefix
Ngaurd=0; % number of gaurd subcarriers
% The number of data subcarriers is the total number of subcarries minus
% the gaurd subcarriers
Ndatacar=NFFT-Ngaurd;
% Define FFT Length and Cyclic prefix length for OFDM
hofdm_m = comm.OFDMModulator('FFTLength',NFFT,'CyclicPrefixLength',Ncp,'
   NumGuardBandCarriers',[0;0]);
hofdm_dem = comm.OFDMDemodulator('FFTLength',NFFT,'CyclicPrefixLength',Ncp,
   'NumGuardBandCarriers',[0;0]);
%define error
herr = comm.ErrorRate('ResetInputPort',true);
% OFDM frame size is equal to the number of data subcarriers *number of PSK
    bits
framesize = QPSKbits*Ndatacar;

%% Channel parameters
%Winner 2 channel: Indoor, non line of sight (Zigzag)
A1 = 18.7; B1 = 46.8; C1= 20;X1=0;
%HTN , non line of sight
A2= 18.7; B2 = 46.8; C2 = 20;X2=0;
%Winner 2 channel: Cellular , non line of sight (outdoor to indoor)
A3= 18.7; B3 = 46.8; C3 = 20;X3=0;

knoise=3.3e-6;          %Narrow band noise power at the receiver
%Antenna and transmitter gains
Gant_WiFi=1.5-5;
```

```
Gant_HTN=1.5-5;
Gant_Cell=2+12;
DataChan=zeros(NFFT,3);
%% Physical Parameters
Speed=1;
StepTime=0.1;
Length=20;
Nsteps=Length/Speed/StepTime;
HandoverTime=0;
HandoverDelay=2;
%Position of each antenna:
xWiFi=-4;
xHTN=Length-5;
xCell=Length+50;
%Vector of movement
 DataRecSingle=zeros(Nsteps+1,4);
DataRecTotal=zeros(Nsteps+1,4);
```

A.2 MATLAB Code: main routine

```
clear;clc; close all;
HTNACTIVE=0;
global knoise hpsk_m  hofdm_m hofdm_dem hpsk_dem
global xCell xHTN xWiFi
global Gant_WiFi Gant_Cell Gant_HTN
%Initialize the parameters
initParam();
scenario=1;

for j=1:Nmonte
    HandoverTime=1e12;    %Just give a large number so it means handover is
        not initiated yet
    switch scenario                  %Scenario selection
        case 1
            direction='InOut';
            CurrentSource='WiFi';
            NewSource='WiFi';
            HandoverFrom=1;
            HandoverTo=3;
            Threshold=-50; %Thresholds for HTN
        case 2
            direction='OutIn';
            CurrentSource='Cell';
            NewSource='Cell';
            HandoverFrom=3;
            HandoverTo=1;
            Threshold=-50; %Thresholds for HTN
    end

    for i=0:Nsteps                    %Repeat the simulation at 100
       different locations
```

```
Time=StepTime*i;
if min(direction=='InOut')
    x=Speed*Time;
else
    x=Length-Speed*Time;
end
if j==1
    xvec(i+1)=x;
end
Inputdata = randi([0,1],[framesize,1]);              %Generate
   random input data
% We have three transmitters here:
DataChan(:,1)=WiFihot(Inputdata,x);
DataChan(:,2)=HTN(Inputdata,x);
DataChan(:,3)=CellBS(Inputdata,x);
%Measure the RSSI for each transmitter
for k=1:3
    Eframe=sum(abs(DataChan(:,k)).^2);
    RSSI(k)=10*log10(Eframe/1e-3/framesize); %RSSI is calculated as
        the power in dbm scale. So the power is energy/framesize.
       dBm power is =10*log10(power/1mW).
end
%Check the handover criteria to initiate the handover porcess
Handover1=(HTNACTIVE==0)&&((RSSI(HandoverTo)>RSSI(HandoverFrom)));
   %We don't have HTN. Compare the RSSI of the future source with
   the current source
Handover2=(HTNACTIVE==1)&&((RSSI(2)>Threshold)); %We have HTN. As
   soon as RSSI of HTN is higher than a threshold do the handover
if (Handover1)||(Handover2)
    if (min(NewSource=='WiFi'))&&(min(direction=='InOut'))
        NewSource='Cell';
        HandoverTime=Time;
    elseif (min(NewSource=='Cell'))&&(min(direction=='OutIn'))
        NewSource='WiFi';
        HandoverTime=Time;
    end
end
%After the handover delay is passed, Finalize the handover
if Time>HandoverTime+HandoverDelay
    CurrentSource=NewSource;
end
%Choose the signal source
switch (CurrentSource)
    case 'WiFi'
        Outputdata=recv(DataChan(:,1));

    case 'Cell'
        Outputdata=recv(DataChan(:,3));

end

errcount = step(herr,Inputdata,Outputdata,1);% Count the bit errors
```

```
            and reset the counter
        Perr=errcount(2)/framesize;
                                                        %Extarct the
           second element of vector errcount. This element shows the actual
            number of errors
        DataRecSingle(i+1,:)=[RSSI,Perr];
    end
    DataRecTotal(:,1:4)=DataRecTotal(:,1:4)+DataRecSingle;
    DataHandover(j)=HandoverTime;
end
DataRecTotal(:,1:4)=DataRecTotal(:,1:4)/Nmonte;
plt();



function Data_ch=WiFihot(Inputdata,x)
global knoise hpsk_m  hofdm_m Gant_WiFi xWiFi xHTN
d=sqrt((x-xWiFi)^2+3^2);
if x<5
    Pathloss=PathL('IndoorOffice',d,2.4);
else
    Pathloss=PathL('IndoorNLOS',d,2.4);
end
LinkbudgetWiFi=Gant_WiFi-Pathloss;
noise=(randn(128,1)+randn(128,1)*1i)*knoise;  %Define noise as a random
   complex variable
Data_psk = step(hpsk_m,Inputdata);              %Apply PSK modulation
Data_ofdm= step(hofdm_m,Data_psk);         %Apply OFDM modulation
Data_ch =Data_ofdm*(10^(LinkbudgetWiFi/20))+noise ;                    %
   Pass the signal through the channel: Add noise, Weaken the signal by PL
end



function Data_ch=HTN(Inputdata,x)
global knoise hpsk_m  hofdm_m Gant_HTN xHTN
d=sqrt((x-xHTN)^2+3^2);
if abs(x-xHTN)<2
    Pathloss=PathL('IndoorOffice',d,2.4);
else
    Pathloss=PathL('IndoorLOS',d,2.4);
end
LinkbudgetHTN=Gant_HTN-Pathloss;
noise=(randn(128,1)+randn(128,1)*1i)*knoise;  %Define noise as a random
   complex variable
Data_psk = step(hpsk_m,Inputdata);              %Apply PSK modulation
Data_ofdm= step(hofdm_m,Data_psk);         %Apply OFDM modulation
Data_ch =Data_ofdm*(10^(LinkbudgetHTN/20))+noise ;                    %
   Pass the signal through the channel: Add noise, Weaken the signal by PL
end

function Data_ch=CellBS(Inputdata,x)
```

```
global knoise hpsk_m  hofdm_m Gant_Cell xCell xHTN
d=sqrt((x-xCell)^2+8^2);
if x<xHTN
    Pathloss=PathL('CellOutIn',d,1.9);
else
    Pathloss=PathL('CellNLOS',d,1.9);
end
LinkbudgetBS=Gant_Cell-Pathloss;
noise=(randn(128,1)+randn(128,1)*1i)*knoise;  %Define noise as a random
   complex variable
Data_psk = step(hpsk_m,Inputdata);              %Apply PSK modulation
Data_ofdm= step(hofdm_m,Data_psk);          %Apply OFDM modulation
Data_ch =Data_ofdm*(10^(LinkbudgetBS/20))+noise ;                    %
   Pass the signal through the channel: Add noise, Weaken the signal by PL
end

function Outputdata=recv(Data_ch)
global hofdm_dem hpsk_dem
Data_dem = step(hofdm_dem,Data_ch);        % Apply OFDM demodulation
Outputdata = step(hpsk_dem,Data_dem);     % Apply PSK/QAM demodulation
end

function PL=PathL(Type,d,fc)
global xHTN
switch Type
    case 'IndoorOffice'
        A=18.7;B=46.8;C=20;X=0;
        PL=A*log10(d)+B+C*log10(fc/5)+X;
    case 'IndoorLOS'
        A=13.9;B=64.4;C=20;X=0;
        PL=A*log10(d)+B+C*log10(fc/5)+X;
    case 'IndoorNLOS'
        A=37.8;B=36.5;C=23;X=0;
        PL=A*log10(d)+B+C*log10(fc/5)+X;
    case 'CellNLOS'
        hbs=25;
        PL=(44.9-6.55*log10(hbs))*log10(d)+34.46+5.83*log10(hbs)+23*log10(
           fc/5);
    case 'CellOutIn'
        hbs=25;hms=1.5;
        PL=(40)*log10(d)+35.87-14*log10(hbs)-14*log10(hms)+6*log10(fc/5)
           -0.8*hms+0.5*abs(d-xHTN);
end
end
```

A.3 MATLAB Code: plot subroutine

```
%Plot the result
close all; lw=1.5;
fig= get(0,'ScreenSize');
set(0,'defaultFigurePosition',[100 100 fig(3)/2 fig(4)/3])
```

```
figure

plot(xvec,DataRecTotal(:,1),'','linewidth',lw); hold on
plot(xvec,DataRecTotal(:,2),'--','linewidth',lw); hold on

plot(xvec,DataRecTotal(:,3),'linewidth',lw); hold on



legend('WiFi','HTN','Cellular');
xlabel('Distance (m)');ylabel('RSSI (dBm)');
figure;
ErrProb=DataRecTotal(:,4);
plot(xvec,ErrProb);
xlabel('Position (m)');
ylabel('Probability of error');

figure;
if direction=='InOut'
    xHandover=Speed*DataHandover;
else
    xHandover=Length-Speed*DataHandover;
end
xHandoverAverage=mean( xHandover)*ones(Nmonte,1);
plot(xHandover); hold on;
plot(xHandoverAverage);
xlabel('Test Number');
ylabel('Handover Location');

set(0,'defaultFigurePosition','remove')
```

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Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
2	9/8/2017			
3	15/8/2017			
5	31/8/2017			
8	12/10/2017			
12	2/11/2017			