WIRELESS MOORE'S LAW

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STATEMENT OF CANDIDATE

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

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Date: November 13, 2017

ABSTRACT

Wireless data transfer saw development as early as the late 19th century. Since that time it has evolved and become prevalent amongst society. Moore's Law of integrated circuit transistor count is an exponential projection against time, regarding the density increase of transistors on a wafer of semi-conductor material. This paves the way for the research and conclusions proposed in this project: to analyse past and present wireless communication technologies and draw a valid phrase or figure of merit to describe relevant trends in data transfer rate progression in wireless technologies over time. This project will primarily take into account Moore's law, transistor theory and various forms of wireless technology implementations over time and suggest a relevant relationship; Thus providing access to such noticeable trends in data transfer rate progression over time. It will also investigate the development of the transistor and its relation to Monolithic Microwave Integrated Cicruit technology progression in wireless communications.

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Chapter 1

Introduction

1.1 Background

When technology was first emerging with the discovery of the advantages of Silicon in the electronics industry, a Chemist by the name of Gordon E. Moore [72] presented a theory along the lines of ' computing power doubles every 18 months' [75] [42]. This powerful statement was based in regards to the number of components fitted onto a silicon wafer of a given size. At the time, this law's credibility gave us expectations in regard to the future of the semiconductor industry.

In the current era it is closely estimated that 62.9% of the world's population in the year 2016 own a form of wirelessly connectable device with growth expected to reach 67% by 2019 [70]. As the percentage of wireless users increase, there is a natural increase in wireless infrastructure in order to maintain the functional operation of the system. Concurrently data transfer rates have climbed respectively. It is to be noted that the infrastructure alone is not the sole influence in this positive outcome.

This leads us to the subject of this project: can a relationship be drawn between data transfer rates and any other underlying factors, which may be used to present a valid figure of merit to forecast wireless communications. A law that can reliably predict the data transfer rate per unit time would be a useful tool in the ideation of future models which predict the possible outcomes of the future of ' wireless'.

1.2 Aim

The fundamental aim of this project is to undertake an approach similar to that of Gordon Moore's in finding a law or 'figure of merit' aimed at wireless communication data transfer rates. Primarily all relationships between data transfer rates and any other underlying factors will be analysed. Subsequently, such a figure of merit will reliably predict the data transfer rate for wireless communications per unit time.

1.3 Scope

The scope of this project is to:

- Understand the meaning behind Moore's Law and how his derivation came about.
- Analyse and tabulate a broad spectrum of past and present wireless technology data transfer rates with respect to time.
- Detail the opertaion, hisorical development, material composition and relevent mathematical modelling of the Transistor.
- Outline the nature of the Technology Node with respect to wireless technologies and Transistors accordingly.
- Disect current and relevant literature which can aid in the development of a 'wireless figure of merit'
- Collate all background work and related literature to support all extrapolated reasoning and calculated results.
- Analyse all results and compile an appropriate reasoning behind a proposed figure of merit, phrase or law to support any claimed trends, if they exist.

1.4 Report Structure

Chapter 2 of this report will detail historical milestones, evolution and current wireless technologies with close respect and reference to the general underlying meaning of Moores Law. It will delve into the mathematical relationships which characterise transistors. Similarly, it explores the increasing data transfer rates seen in wireless technologies around the world.

Chapter 3 gives an insight into similar work performed in wireless communications and extracts measures of power efficiency and a means of assessing component efficiency in wireless systems design.

Chapter 4 will look at the trends of data transfer rates over time in wireless communications and the relationship between the physical scaling of transistors, transistor count and the respective speeds obtained i.e data transfer rates.

Additionally, Chapter 5 will address any future work or research which could assist in further supporting the long life and validity of the theories drawn in this Report for a Wireless Moores Law and Chapter 6 presents a concise summary of the successes and drawbacks in this project.

Chapter 2

Background and Related Work

2.1 Moore's Law

Gordon Earle Moore was born in California on January 3, 1929 [16] [20]. From a young age, Moore uncovered a strong desire to study Chemistry. By 1954, he was awarded a Ph.D in Chemistry and Physics [16]. Following his interests he examined the 'physical chemistry of solid rocket propellants used by the U.S. Navy in missiles' [16].

The recent invention of the Transistor by Willian Shockley, further eluded Moore into researching manufacturing methods of the transistor. Moore then resigned, alongside seven of his colleagues from Shockley's Semiconductor Laboratory to concurrently co-find the Fairchild Semiconductor Corporation and the Fairchild Camera and Instrumentation Corporation. In 1968, Robert Noyce and Moore left to create the Intel Corporation [16]. From this, Gordon Earle Moore derived his ever so famous law, commonly known today as Moore's Law.

2.1.1 Moore's Original Law

In 1965, Moore was approached to write a small article on his predictions regarding the number of transistors per silicon wafer over the next decade. From this, the infamous Moore's Law was conceived. 'The number of transistors per silicon chip doubles each year' [16] [42]. When this powerful statement went global at the time, very little attention was paid to its life. It did appear to be a long term proposal, however the rate in which technology has advanced amongst the world has occurred at a non-anticipated rate.

2.1.2 Moore's Revised Law

In 1975, Moore revised his initial prediction as he noticed a trend in the timeline since initial production grew. He amended his law to read 'the number of transistors per silicon chip doubles every two years' [16] [42]. However, 40 years on from this revision we can clearly identify a trend that 'the number of transistors per silicon chip doubles every eighteen months' [16]. Figure 2.1 [42] below represents Moore's original plot to derive his theorem over an observed period from 1959 to 1975. Figure 2.2 [48] below represents Moore's Law over the past 46 years from 1970 to 2016. Both Figures summate the data samples of transistor counts on a given silicon wafer size across respective intervals of time.

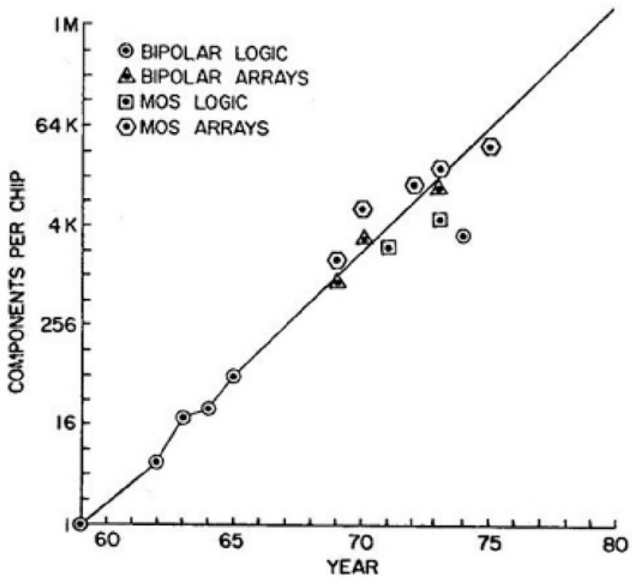

Figure 2.1: Moore's Law Graph: Approximate Component (Transistor) Count for Silicon Chips [42].

Figure 2.1 incorporates data from a period of the early 1960's until 1975 when Moore approximated his law.

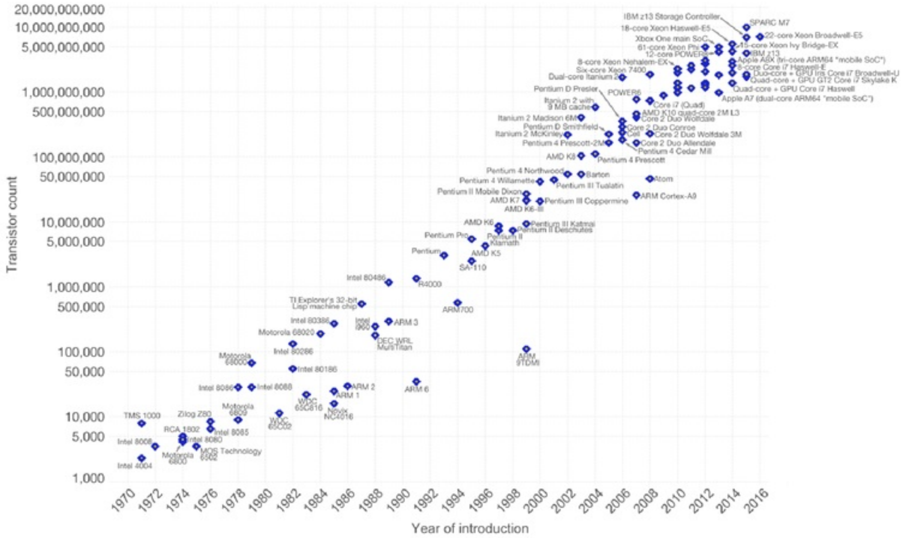

Figure 2.2: Moore's Law Graph: Transistor Count on Integrated Circuits per Year (1971-2016) [48].

Figure 2.2 appends the years from 1971 to the present era so we have a longer spectrum of data to view. From this, Moore's law can be seen to have highly regarded validity with some slight oscillation. The plot straightens up in the later years as we introduce Dennards scaling factor (to be detailed in Section 2.6.1) to transistors, and manufacturers implement Moore's law as a guide for challenges rather than a prediction of future technologies.

2.2 Bandwidth

Bandwidth can be defined as 'the range of frequencies occupied by a modulated radio-frequency signal' [12]. In simpler terms, it can be recognised as a measure of how much data can be transmitted and or received in a fixed time interval, commonly known as Hertz (Hz). Since bandwidth is time difference between upper and lower frequencies of a wave, with advancements in the operational frequency range of RFIC's and primarily MMIC's in wireless technologies, we can sample data at extremely fast rates, hence we can achieve imense data transfer rates in modern times.

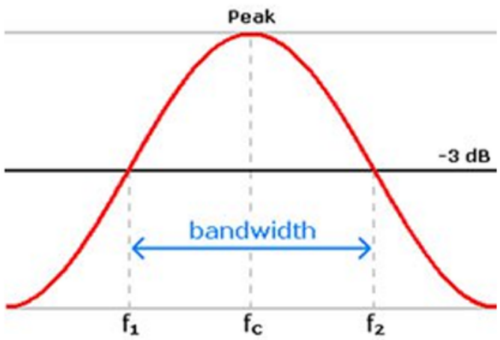

Figure 2.3: Indication of Bandwidth On a Carrier Wave [7] [14].

2.2.1 Bandwidth Vs. Speed

The term speed is widely used when making reference to any form of digital system. It can be used to describe all relevant criterion in regards to moving digital information across a medium; this includes, but is not limited to, theoretical data transfer rates, actual data transfer rates and connection speed. However, misconceptions exist when referring to bandwidth and speed at the same time. They can be seen to complement one another and work hand in hand. Speed can be defined as the physical limitation of a network such as maximum cable data transfer rates and bandwidth can be generalised as 'the amount of speed available for use' [23].

Assessing a simple example allows us to gain more clarity. If we have a service provider supplying a home with a 100 Megabit wireless service and the home uses a 500 Megabit wireless connection, the allocated bandwidth will be 100 Mbps and the speed will be 500 Mbps [23]. With the extremely high frequencies we are capable of operating at in the 21st century, the amount of data sent and received in a given cycle is concurrently increasing Therefore, we can allocate increased amounts of bandwidth without overloading system limits. Thus yielding much faster download and upload speeds across multiple networks worldwide.

2.3 Wireless Technology

With evolution of technology, naturally the diversification into many wireless forms has resulted. This section presents all relevant wireless technologies in order of data transfer rate from lowest to highest. It summarises their release, functionality, iteration (if applicable) and respective data transfer rate to be used for the length of this project.

2.3.1 Global System for Mobile Communication

Global System for Mobile Communication (GSM) is a digitally based mobile phone system widely adopted in most parts of the world, especially Europe. It was originally made public in Finland in 1991 and still serves mobile phone users worldwide, where newer forms of telephony have not yet been implemented. GSM operates with a combination of Time Division Multiple Access (TDMA), GSM itself and Code Division Multiple Access (CDMA). TDMA is a way to allow multiple user access on the same frequency by dividing the channel into a range of time slots. CDMA is a type of multiplexing, thus allowing multiple data signals to travel along the same transmission channel simultaneoulsy. In GSM, data is essentially converted using a Digital to Analogue Convertor (DAC), compressed and sent over two time streams with identifiable time slots [6].

GSM supports data transfer rates of up to 14.4Kbps [73] [44]. For the duration of this project, GSM will have its maximum approximate data transfer rate converted to Bits per Second at 14,400 b/s.

2.3.2 Advanced Mobile Phone System

Advanced Mobile Phone System (AMPS) operates in the 850 MHz cellular band and was widely deployed across the United States of America which later saw adoption into other countries around the world. It is a standard system for analog based signal cell telephones which was developed in 1970, when the Federal Communications Commission (FCC) first allocated parts of the electromagnetic radiation spectrum for communications use [59]. It was later rolled out by American Telephone and Telegraph (AT&T) [5] in 1983 and widely encompassed American citizens in one of the most large scale cellular networks of its time.

AMPS works based on a cell system, where a user of a mobile telecommunications device, (cell phone) places a call thus, transmitting and receiving signals through the coverage area commonly referred to as a cell. As the cell user progresses through various cell boundaries, the signals are transferred across differing channels so interference does not result. Towards the end of AMPS' life, there were enhancements including the addition of TDMA which converted the once was analog system to a digital cellular service known as D-AMPS [59].

AMPS supports data transfer rates of up to 19.2Kbps [44]. For the duration of this project, AMPS will have its maximum approximate data transfer rate converted to Bits per Second at 19,200 b/s.

2.3.3 General Packet Radio Service

General Packet Radio Service (GPRS) is a packet type data delivery service and is used within the GSM communication network [62]. GPRS is fundamentally the transmission and reception of data packets by occupying a number of channels concurrently for data transfer whenever it is needed. When a user is not sending data, these channels are vacant and can be used by others with capable devices [33].

GPRS supports data transfer rates of up to 53.6Kbps [61]. For the duration of this project, GPRS will have its maximum approximate data transfer rate converted to Bits per Second at 53,600 b/s.

2.3.4 Code Division Multiple Access

Code Division Multiple Access (CDMA) is a combination of protocols used in 2nd and 3rd Generation wireless communication topographies [67]. It was unveiled at a commercial level in 1995 and progressed towards being the worlds fastest growing wireless technology of its time [13]. CDMA is a form of multiplexing used to allow numerous amounts of signals to inhabit a single channel of transmission, hence resulting in optimised use of bandwidth. It is used in Ultra High Frequency (UHF) mobile or cellular telephone systems in the 0.8 to 1.9 GHz spectral band [67].

CDMA uses Analogue to Digital Conversion (ADC) to digitize audible data in binary form. This data is then transmitted at a specific varied frequency so that it can only be received by the intended receiver. The receiver is programmed with the defined frequency or code of the transmission which acts as a data specific encoder/decoder style system to increase privacy and inhibit interception, since the volume of possible frequency sequences that are possible is quite large. Unlike AMPS discussed earlier, CDMA employs a pass over called soft handoff to pass a signal from one cell to another during an active data transfer such as a phone call. This minimizes the chance of signal breakup [67].

CDMA supports data transfer rates of up to 115 Kbps [67]. For the duration of this project, CDMA will have its maximum approximate data transfer rate converted to Bits per Second at 115,000 b/s.

2.3.5 Wide Area Paging

Wide Area Paging (WAP) is a network of radio frequency based base stations. Motorola first introduced the first consumer purchasable pager called the 'Pageboy' in 1974 [6]. It consisted of basic functionality with no screen, unlike newer pager developments, and was capable of 'paging' the user that a message had been sent. By the 1994, pager usage surged into sub 60 million users on a global scale and has steadily declined with mobile telephone technology rapidly evolving on a yearly basis [6].

WAP works in a sense that a series of messages are spread across the entire base station network until the pager user is found and the message can be delivered. These radio signals operate in the Very High Frequency (VHF) range, which in turn, renders them a more reliable source of message delivery as they can be used in concrete dense areas such as hospital environments for doctors [77].

WAP supports data transfer rates of up to 115Kbps [44]. For the duration of this project, WAP will have its maximum approximate data transfer rate converted to Bits per Second at 115,000 b/s.

2.3.6 ZigBee

ZigBee is a form of wireless networking technology standards which were developed for implementation in remote locations and intended for 'harsh radio environments' [68]. It was first released in 2005 and labeled ZigBee 1.0 (2004). Following this release, there were multiple revisions up until 2009 that refined previous versions respectively. These being: ZigBee 2006, 2007, PRO and RF4CE [54]. ZigBee is built upon the Institute of Electrical and Electronics Engineers (IEEE) 802.15 standard and aimed at use in remote sensing and data acquisition fields. It is primarily a low expense and low power consumption Machine to Machine (M2M) and Internet of Things (IOT) type of network [68].

In contrast to standard WiFi networks, ZigBee supports far less data transfer rates and prides its existence on low data requirement control systems. There are a profound number of industry partners who host ZigBee in many of their services such as the growing phase of the Smart Home era [68].

ZigBee supports data transfer rates of up to 250Kbps [56]. For the duration of this project, ZigBee will have its maximum approximate data transfer rate converted to Bits per Second at 250,000 b/s.

2.3.7 Enhanced Data Rate for GSM Evolution

Enhanced Data Rate for GSM Evolution (EDGE) is an enhancement to data delivery in the GSM service, and was adopted in the year 2000. The EDGE implementation was also commonly referred to as EGPRS as it was essentially very similar to its predecessor GPRS but offered speeds up to 384 Kbps, twice the theoretical maximum of GPRS [53]. The eye opening speed of EDGE compared with GPRS is with regard to a modulation change from Gaussian Minimum Shift Keying (GMSK) in GPRS to 8 Phase Shift Keying

(8PSK) Modulation [78].

EDGE supports data transfer rates of up to 384Kbps [53]. For the duration of this project, EDGE will have its maximum approximate data transfer rate converted to Bits per Second at 384,000 b/s.

2.3.8 Bluetooth

Bluetooth is a low power short range wireless communication type. Bluetooth Version 1.0 was released in 2003, Bluetooth Version 2.0 in 2007 and Bluetooth Version 3.0 in 2009. It operates on the 2.4 GHz frequency band and is capable of only short range communication. All versions of Bluetooth are backward compatible with their predecessor and each has unique refinements to their data transfer rates. Bluetooth operates using GFSK as a modulation means and is used for streaming audio, broadcasting information between devices and transferring various data forms across many platforms [79].

Bluetooth Low Energy (BLE) works in a similar nature to that of Bluetooth Versions 1.0, 2.0 and 3.0 previously outlined and was introduced in 2010. Bluetooth by definition is a short range low energy communication form. However, the main difference between BLE and the previous versions is the way in which the connections are established. Ordinary bluetooth maintains a continuous connection using point to point topology types for one to one device communications [9].

BLE however, uses short burst technology to establish connections for small periods of time and not continuously, hence if it were connected for half the time, power consumption would decrease by a factor of half. Bluetooth Versions 1.0, 2.0 and 3.0 are ideal for applications such as wireless audio, headsets and hands free close personal communication systems. BLE is ideal for devices such as health monitoring bands and fitness trackers which require long term data transmission at reduced power consumption rates [9].

BT1 supports data transfer rates of up to 720 Kbps [79]. For the duration of this project, BT1 will have its maximum approximate data transfer rate converted to Bits per Second at 720,000 b/s.

BT2 supports data transfer rates of up to 2.1 Mbps [79]. For the duration of this project, BT2 will have its maximum approximate data transfer rate converted to Bits per Second at 2,100,000 b/s.

BT3 supports data transfer rates of up to 24 Mbps [79]. For the duration of this project, BT3 will have its maximum approximate data transfer rate converted to Bits per Second at 24,000,000 b/s.

BLE supports data transfer rates of up to 2.16 Mbps [79]. For the duration of this project, BLE will have its maximum approximate data transfer rate converted to Bits per Second at 2,160,000 b/s.

2.3.9 Wi-Fi

Wi-Fi is a wireless networking protocol which allows device to device communication. Essentially it is a radio wave based variant of the Local Area Network (LAN) protocol and is based on the 802.11 networking standard, to later be defined as the IEEE 802.11 base standard [49]. It was released in 1997 and supported up to 2 Mbps [49] [30]. Wi-Fi for household applications surfaced in 1999 and sky rocketed up until present time where adoption is still current on a global scale. Wi-Fi operates on two main frequency bands, 2.4 GHz and 5 GHz [76].

As the years progressed, new variants of Wi-Fi were released such as IEEE 802.11 a, b, g, n or ac with the common trends of improved data transfer rates each time. The release of IEEE 802.11n in 2009 introduced the fastest Wi-Fi speeds yet. This great improvement in speed was attributed to by the implementation of Multiple Input Multiple Output (MIMO) antenna technology which was being commonly implanted over various wireless system technologies for their ability to maximize transmission and reception power without sacrificing bandwidth [76].

Currently, the 2.4 GHz stream is the preferred option of connectivity due to its appealing range benefits; naturally as Wi-Fi becomes more prevalent, this increases the local area density of Wi-Fi radio waves. As the density of Wi-Fi increases, the resulting overcrowding becomes a significant problem. In recent times, 5 GHz streams have been slowly transitioning into regions as the more ideal means of connection. However, the use of the 5 GHz stream has a smaller range of coverage as compared to 2.4 GHz [76].

In 2012 IEEE 802.11ac was introduced with four times the capable data transfer rates as its predecessor IEEE 802.11n and was directed at enhancing the experience of the 5 GHz channel. It consisted of an increased number of antennas for the MIMO systems which meant the transmission frequency of data as well as the reception frequency of data transfer could increase greatly hence improving the data transfer rate [76].

IEEE 802.11 supports data transfer rates of up to 2 Mbps [30]. For the duration of this project, IEEE 802.11 will have its maximum approximate data transfer rate converted to Bits per Second at 2,000,000 b/s.

IEEE 802.11a supports data transfer rates of up to 54Mbps [30]. For the duration of this project, IEEE 802.11a will have its maximum approximate data transfer rate converted to Bits per Second at 54,000,000 b/s.

IEEE 802.11b supports data transfer rates of up to 11Mbps [30]. For the duration of this project, IEEE 802.11b will have its maximum approximate data transfer rate converted to Bits per Second at 11,000,000 b/s.

IEEE 802.11g supports data transfer rates of up to 54Mbps [30]. For the duration of this project, IEEE 802.11g will have its maximum approximate data transfer rate converted to Bits per Second at 54,000,000 b/s.

IEEE 802.11n supports data transfer rates of up to 600Mbps [30]. For the duration of this project, IEEE 802.11n will have its maximum approximate data transfer rate converted to Bits per Second at 600,000,000 b/s.

IEEE 802.11ac supports data transfer rates of up to 1.3Gbps [57]. For the duration of this project, IEEE 802.11ac will have its maximum approximate data transfer rate converted to Bits per Second at 1,300,000,000 b/s.

2.3.10 Universal Mobile Telecommunication Service

Universal Mobile Telecommunications Service (UMTS) is a 3rd generation broadband based data packet delivery service [60]. UMTS is a service based on the widespread GSM standards and was introduced in 1998 with the first release in 1999 [80]. With the increased bandwidth and data rate handling, additional functionality was implemented to the network such as video conferencing and multimedia messaging [60].

UMTS supports data transfer rates of up to 2Mbps [60]. For the duration of this project, UMTS will have its maximum approximate data transfer rate converted to Bits per Second at 2,000,000 b/s.

2.3.11 Infrared Data

Infrared Data (IrDa) was first introduced in 1993 and was an industry sponsored communication type. IrDa is fundamentally a radio transmission in which a focused ray of light is modulated with data and sent from a transmitter directly to a receiving destination across a relatively small distance. The ray of light in question is in the infrared frequency range of the invisible light spectrum [63].

Still to this day, in almost every household around the world, there is some device which employs a means of communication via infrared, such as a television remote control. IrDa is extremely convenient for sending small forms of information quickly just by holding two devices together or keeping them in a short range of one another with an unimpeded line of sight between them. It eliminates the need to pair devices, such as in bluetooth applications, and offers relatively competitive transfer speeds [63].

According to the IrDA-1.1 standard the maximum data size that may be sent is 2048 bytes and the maximum transmission rate is 4 Mbps [63]. For the duration of this project, IrDa will have its maximum approximate data transfer rate converted to Bits per Second at 4,000,000 b/s.

2.3.12 High Speed Packet Access

High Speed Packet Access (HSPA) is a type of broadband mobile communication technology released in 2007 and is of the 3rd generation nature. HSPA references two fast acting and highly specific protocols used back to back. These are High Speed Uplink Packet Access (HSUPA) and High Speed Downlink Packet Access (HSDPA) [65].

HSPA supports data transfer rates of up to 7.2 Mbps [52]. For the duration of this project, HSPA will have its maximum approximate data transfer rate converted to Bits per Second at 7,200,000 b/s.

2.3.13 High Speed Packet Access Evolved

High Speed Packet Access Evolved (HSPA+) is a 'new and improved' version of the previously discussed HSPA technology. The newly evolved decendant of HSPA was released in 2008 and utilizes dual cell deployment and MIMO structures to achieve greater data transfer rates of up to 42 Megabytes per cell. Each release of HSPA+ aimed to improve the existing release of HSPA by adding greater functionality or improving a current feature or parameter [65].

The points below list data transfer rates and year of release for each HSPA+ revision:

HSPA+ Release 6

- Released in 2008 [73]
- 14,400,000 Bits per Second [73]

HSPA+ Release 7

- Released in 2009 [73]
- 28,000,000 Bits per Second [73]

HSPA+ Release 8

- Released in 2010 [73]
- 42,200,000 Bits per Second [73]

HSPA+ Release 9

- Released in 2012 [73]
- 84,400,000 Bits per Second [73]

HSPA+ Release 10

- Released in 2013 [4] [73]
- 168,800,000 Bits per Second [4] [73]

HSPA+ Release 11

- Released in 2014 [4]
- 336,000,000 Bits per Second [4]

2.3.14 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) was formed in April of 2001 by multiple organizations of the industry [50]. The primary aim being to promote and certify interoperability of most broadband capable access equipment that complies with both (IEEE) 802.16 and European Telecommunications Standards Institute (ETSI) HIPERMAN standards [2] [50].

Operation of WiMAX is similar to that of WiFi. However, WiMAX speed capabilities extend far over that of WiFi with the added advantage of much greater distance coverage for a broad range of users. WiMAX offers theoretical maximum data transfer rates nearing 70Mbps [51].

WiMAX supports data transfer rates of up to 70Mbps [51]. For the duration of this project, WiMAX will have its maximum approximate data transfer rate converted to Bits per Second at 70,000,000 b/s.

2.3.15 Long Term Evolution

Long Term Evolution (LTE) is a technology of the 4th generation broadband architecture and was launched on a commercial level by AT&T in 2010. It was given the name LTE by the Third Generation Partnership Project (3GPP) as it closely represented the leap forward from GSM and UMTS. LTE adopts a modulation technique referred to as Orthogonal Frequency Division Multiplexing (OFDM). As LTE was further improved it integrated MIMO antenna technologies similar to the ones used in IEEE 802.11 WLAN applications. Through using MIMO antennas combined with OFDM modulation, much higher Signal to Noise Ratios (SNR) were attainable at the receiving end resulting in greater scope of reception. The intention of LTE was to bring wireless connectivity to mobile users such that is emulates that of a wired system. [64].

LTE supports data transfer rates of up to 100 Mbps [64]. For the duration of this project, LTE will have its maximum approximate data transfer rate converted to Bits per Second at 100,000,000 b/s.

2.3.16 Long Term Evolution Advanced

Long Term Evolution Advanced (LTE-A) is an improvement to the prior LTE release in 2010 with the added advantage of highly increased data transfer capability. LTE-A employs similar MIMO technologies as its predecessor to deliver outstanding data transfer rates. MIMO technology requires a matrix of antenna systems receiving groups of signals in unison, thus use in smart phones and compact form devices at the time of its release limited its adaptability until later years. The main purpose of LTE-A was to refine LTE and obtain the approval of the International Telecommunications Union (ITU) to meet the established requirements of the Fourth Generation (4G) standards [66].

LTE-A supports data transfer rates of up to 1 Gbps [52]. For the duration of this project, LTE-A will have its maximum approximate data transfer rate converted to Bits per Second at 1,000,000,000 b/s.

2.3.17 Ngara by CSIRO

Ngara is a point to multipoint wireless communications technology aimed at maximising spectral efficiency [34]. It has been designed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) [15]. Ngara has been in development since 2009 and presents three associated technologies. These are point to multipoint, point to microwave and point to point E-band. Lab testing has proven effective and real world implementation is in practice today. The Ngara network in trial uses a point to multipoint backbone to deliver wireless performance higher than existing wireless infrastructure by a factor of 10. It is considered to be the most spectrally efficient wireless technology of the modern era and lies in the 3.4 GHz frequency. It is currently hosted by Optus for the duration of the trial [34].

The Ngara system works by delivering simultaneous standalone connections at a minimum of 35 Mbps per direction to six select locations around the trial area. Each direction only requires 14 MHz of total spectral consumption and this is a result of CSIRO's patented Ngara spatial multiplexing technology. The aim of the Ngara trial is to successfully test new wireless technologies that will replace existing systems and form the future base infrastructure for mobile communications [34].

Ngara supports data transfer rates of up to 5 Gbps [32]. For the duration of this project, Ngara will have its maximum approximate data transfer rate converted to Bits per Second at 5,000,000,000 b/s.

2.3.18 Fifth Generation (5G)

5th Generation (5G) is another of the many forms of wireless mobile technologies in development and set to enhance cell phone use with the aid of increased bandwidth and data transfer capabilities. Today, mobile broadband is shaping the way we use our mobile devices with media streaming of all forms a prerequisite wherever we may be [55]. 5G has profound theoretical data rates of up to 10 Gigabits per second. This speed is achievable with 5G's plans to employ Millimeter Wave (MW) or Extremely High Frequency (EHF) technology between the 30 - 300 GHz frequency band. As we progress higher into the frequency band of the invisible spectrum, data sampling rates increase per cycle. With this beneficial increase comes the dilemma of transmission distance and shorter wavelength interferences from buildings, internal structures or even weather events [27].

5G technology as of 2017 has has not yet been released. A successful implementation of 5G technology would require a number of factors heavily considered. An increase in antenna density is essential to cater for the now reduced transmission range, since operational frequency has dramatically increased. Mobile device efficiency must increase to handle to power requirements of dealing with higher frequencies of operation, and existing LTE-A foundations must be free of dysfunction as a base for 5G [27].

5G supports data transfer rates of up to 10 Gbps [71] [36]. For the duration of this project, 5G will have its maximum approximate data transfer rate converted to Bits per Second at 5,000,000,000 b/s.

2.4 Wireless Communications and Antennas

In all wireless technologies there must be both transmitters to send radio waves and receivers which detect these radio waves. Both of these systems employ antennas as a medium to make their transmission/reception characteristics possible. Communications systems in wireless forms would be rendered useless without extensive forethought in the area of how to transmit and recieve data without a physical medium, hence an 'Antenna'. An antenna as defined by the National Aeronautics and Space Administration (NASA) [18] to generally be a large and relatiely tall structure of metallic make designed to emit and/or receive electromagnetic radio waves [40].

Apart from the system as a whole, antennas should be considered the most important component of any wireless topography, as without their full functional presence no data can be sent or received. Antennas are not always of large stature and are designed for the type of wireless system environment they are to be implemented with. Across the many micro to global scale wireless systems, a number of varying antenna technologies are used. Such technologies include wideband and multiband antennas [37].

2.4.1 Transmitters

Transmitters bridge the gap between a signal in a circuit telemetry and a radio wave to be sent through the atmoshpere. Without them, there would be no way of producing a type of data in a form simple enough to send to its intended destination. They can work in multitudes of variations, but they do not solely send the radio waves by themselves. Transmitters require the aid of antennas to focus the radio waves they produce into a receivable form [28].

A basic transmitter works by performing a modulation technique, depeding on the relevant wireless technology, to a generated base VHF oscillating carrier wave with a digital form of data from an encoder further up in the circuit. The oscillating carrier wave frequency is what is changing over time, inherently resulting in faster data transfer speeds with the ability to transmit information at greater rates per cycle. This modulated radio frequency data carrying wave is then amplified, so it can progress through the circuit to the inline antenna for sending across the atmosphere to a select destination or broad group [28]. Figure 2.4 is an overview of how the transmitter produces the digital signal to an antenna for sending into the atmosphere for reception by the recepticle style circuit.

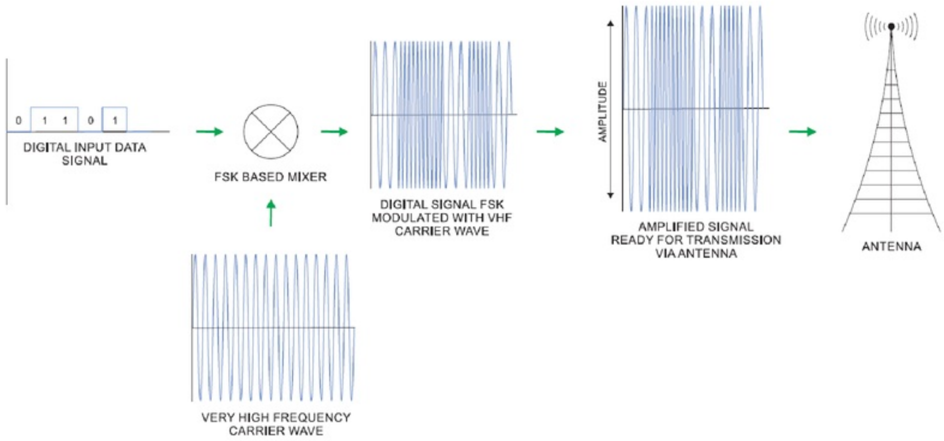

Figure 2.4: A Digital Input Signal in a Transmitter Circuit Telemetry and Application to an Antenna as a Radio Frequency

2.4.2 Receivers

Like the necessity for a transmitter in a wireless communications system, a receiver must also be present, or there will be no way to intercept incoming radio waves and process them into a useable data form. A receiver, as its name describes, has an intended purpose to only detect radio frequencies of a given range in which they are tuned for.

Ultimately, a receiver is just a transmitter operating in reverse with an additional amplifier inline in some instances. From sensing the correct radio frequency on the given spectrum range through the antenna, the signal is then amplifed and passed through a demodulator to seperate the data signal from the carrier wave. The data signal is then processed further up the circuit chain wherever it is needed to be used such as an output to a transducer, audio or video circuitry [28].

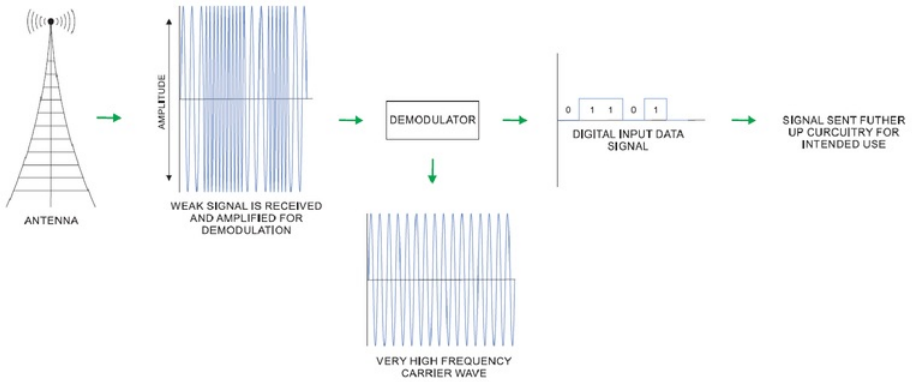

Figure 2.5: A Radio Frequency Detected by an Antenna and the Processing through a Receiver

2.4.3 Codependency of Transmitters and Receivers

Transmitters and Receivers can be seen to have a co-depenedent like nature. In wireless systems transmitters and receivers do not necessarilly need the presence of each other to perform their intended function, however wireless systems are dependent on both in order to send and receive data in radio frequency form. They are solely responsible for eliminating wired topographies and birthing the foundations of 'wireless' in communications. As we progress through the invisible spectrum and increase the radio frequency at which wireless technologies operate, both transmitters and receivers must be concurrently redesigned and improved so they can work in unison to continue seamless wireless performance into the future.

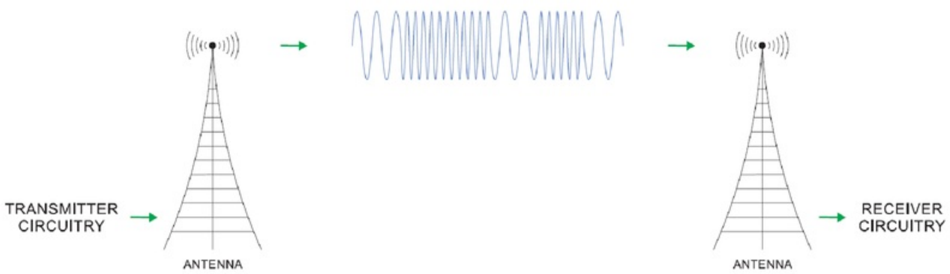

Figure 2.6: Antenna to Antenna Signal Transmission and Reception

2.4.3.1 Monolithic Microwave Integrated Circuits in Wireless Communications

Monolithic Microwave Integrated Circuits (MMICs) are also referred to as Integrated Circuits (ICs) [8]. Their range of operation can vary from 1 GHz to in excess of 100 GHz in the microwave frequency range [69]. Essentially a MMIC is a circuit operating at microwave frequencies in which both the active and passive componentry are 'fabricated on the same semiconductor substrate' [58].

Silicon is a widely desired doping agent in the semiconducter industry, however for high frequency microwave applications such as MMIC's, Gallium Arsenide (GaAs) is often the preferable material [69]. This is due to silicons undesirable resistive properties being too high [69]. The first GaAs based MMICs were not heavily complex circuits and consisted of an array of diodes and microstrip lines. Microstrip lines in MMIC fabrications are the micro level planar type electrical transmission lines for which microwave frequency signals travel along. Their makeup consists of a conducting strip, isolated from a ground plane by a substrate or dielectric layer [58] [35].

MMIC circuits can input a baseband low frequency signal, upscale its frequency and process it through multiples of subcircuits in their construction at microwave frequencies. This allows processing time to dramatically reduce as the dependency of external circuitry is lessened. Through low noise amplifiers, resulting from technological advancements in transistor technologies and shrinking minimum feature size, MMICs are becoming more and more capable of efficiently handling long term operation at even higher microwave freqeuncies.

As the technology node (to be detailed in Section 2.6) changes hence shrinking the minimum feature size, designers and manufactures can rework MMICs. This will reduce overall package dimensions, increase performance, increase operating frequency and improve efficiency in their intended applications whilst reducing the number of components on the device itself.

2.4.3.2 Radio Frequency Integrated Circuits in Wireless Communications

Radio Frequency Integrated Circuits (RFICs) are generally operational in the 900 MHz to 2.4 GHz frequency range [69]. RFICs are of similar nature to MMICs, but due to their lower end frequency of operation they are composed in more of an analogous fashion. Complementary Metal Oxide Semiconductor (CMOS) fabrication are viable processes and are very high yielding cheap solutions to the fabrication of RFICs [11].

2.5 The Transistor

Ideally a transistor can be seen as a semiconductor device that can act like a switch or amplify a signal of electronic nature. Their sole development was influenced by the desire to replace vacuum tubes due to their large nature, inefficiency and unreliability. Transistors today come in many different forms and can be a range of sizes [26]. The very first transistor was quite large and hand-built, to say the least, but with driving technological advances there has been successful construction and operation of transistors as small as 1 nanometer long in recent times [26] [81].

2.5.1 Discovery

The very first transistor (Figure 2.7) was developed by William Shockley and his associates John Bardeen and Walter Brattain, while working under the roof of Bell Labs in 1947. The grand design of the point contact transistor consisted of two gold contacts gently resting on a germaium crystal that was on a metal plate and connected to a voltage power source. This was to be the worlds first ever solid state style amplifier [25].

In 1948 the transistors design was reworked into what is known today as the Bipolar Junction Transistor (BJT) which superceeded the initial point contact type in 1947. Bell Labs progressed the transisitor into public release in 1948 which revolutionised the electronics sector at the time, by the replacement of vacuum tubes and large unnecessary mechanical relays. Shockley then left Bell Labs to start the Shockley Semiconductor Company in California, to be later known as Silicon Valley [25].

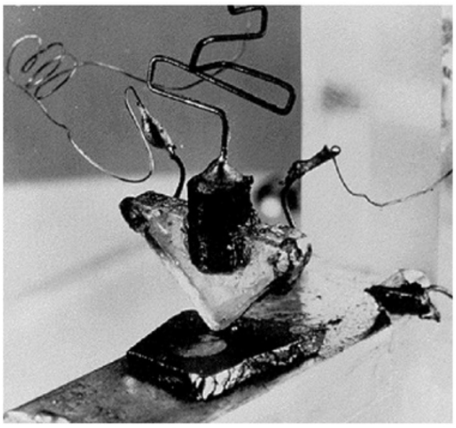

Figure 2.7: The First Transistor in 1947 [17].

Today, Transistors are readily available at local electronics retailers in many packages. They are constructed of varying material types and range from tangible size to microscopic. They can range from, but are not limited, to Bipolar, Darlington, Insulated Gate Bipolar Transistor (IGBT) and Metal Oxide Semiconductor Field Effect Transistors (MOSFET) [24]. Figure 2.5 shows just a small segment of the range available today in through-hole applications.

For the length of this project, most transistor references will solely relate to those fabricated using lithographic technology on silicon wafers and the changing nature of their minimum feature size.

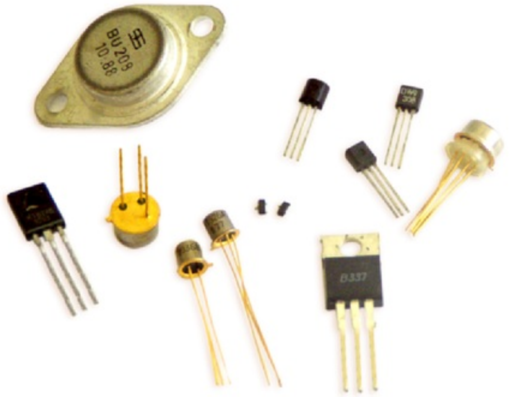

Figure 2.8: Various Through-Hole Transistor Types [19].

2.5.2 Operation

Conceptially, a transistor is basically a three legged assembly composed of an Emitter, Base and Collector see (Figure 2.9). As an example, for an N-P-N type device both the emitter and collector are connected to the n-type substrates. The base is positive charge deficient and so the flow of current across the emitter and collector is stationary. When a small current is applied at the base with a positive charge, electrons are pulled from the emitter into the base and then into the collector and a flow of large current is then initiated and the transistor is effectively in its 'ON' switched like state. When the current to the base is reduced and stopped, little or no current flows from emitter to collector and the transistor effectively switches 'OFF'. The base can be seen as the input trigger for the switching of the solid state device [31].

For a P-N-P type transistor the emitter and collector would be connected to a positive substrate and the base will be electron deficient, hence applying a 'ground' or 0 input will enable the transistor 'ON' and inputting a positive voltage greater than 0 will switch it 'OFF' [31].

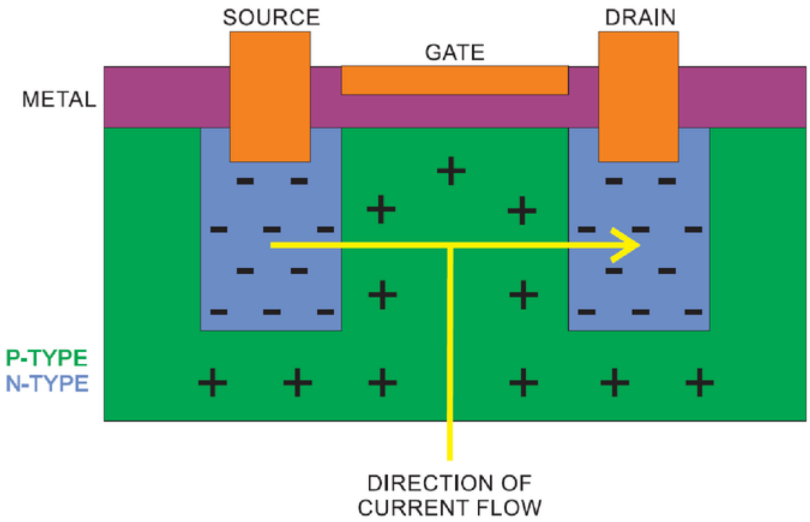

Figure 2.9: Flow of Electrons in a N-P-N Type MOSFET Transistor

2.5.3 Material Composition

The material elements which compose a transistor are not only key to its operation, but also its efficiency. These elements are of semiconductor nature and are commonly identifiable as group III - V elements in the periodic table of elements. Germanium was the first of elements bearing appropriate properties for use in transistor applications. Its discovery came about with identification of its ability to allow or inhibit the flow of current [82].

Silicon also has the ability to block or allow the flow of current but it has the added properties of its heavy abundance and wider bandgap to that of Germanium. A bandgap in semiconductors is the 'energy like barrier' which must be overcome to start the flow of current in a given direction. This is an ideal characteristic in transistor design, as it reduces the likelihood of current leak whilst it is not in a state of operation. Finally, Silicon possesses greater thermal conductivity properties, making heat draw a much easier process so circuitry can be kept cooler, more easily [82].

In current fabrication methods, especially semiconductor technologies where componentry counts are in excess of tens of billions, GaAs is the preferable material. It has a greater bandgap to Germanium and Silicon and an electron mobility approximately twice that of Germanium and six times that of Silicon. Indium Arsenide (InAs) has the lowest bandgap of all the semiconductors but an electron mobility of approximately four times GaAs [82]. There are multiple specialty semiconductor element combinations feasible for transistor design in many applications. However, GaAs is the preferable material in the current period of fabrication due to previously outlined factors.

2.5.4 Cut-off Frequency f_T

In all transistor fabrications, a desired property in the progession of technology to be considered is the increase in cut-off frequency (f_T). The cut-off frequency can be defined as the frequency at which the current gain for the transistor is unity and also describes the volume of electrons which can move from source to drain per unit time. If we pass the cut-off frequency and the unity gain surpasses 0 Decibels (dB), the transistor will begin operating inefficiently and introducing unwanted levels of distortion dependent on how far past the cut-off point we are. In a long-channel MOSFET the unity gain frequency can be expressed as shown in Equation 2.1 [39].

$$f_T = \frac{g_M}{2\pi C_G} = \frac{3\mu(V_{GS} - V_T)}{4\pi L^2} \tag{2.1}$$

In a short-channel MOSFET the unity gain can be expressed as shown in Figure 2.2 [39].

$$f_T \approx \frac{3v_{SAT}}{4\pi L} \tag{2.2}$$

Equations 2.1 and 2.2 will be used in Chapter 4 to show the relationship between transistor gate length and the cut-off frequency of a transistor, hence affecting its operational speed.

2.6 The Technology Node

The Technology Node, also referred to as the minimum feature size of any given semiconductor, is effectively the the minimal length of the Metal Oxide Semiconductor (MOS) between the source and drain. This term is also often referred to as the current technology node and is scaled every 18 to 24 months as per Moore's Law, as a benchmark or target so to speak. From the design and implementation of the very first transistor, to the current MFS, there has been a constant design goal to effectively double the number of transistors fit onto semiconductor technologies. Moore's Law in modern times is being used a challenge with our technological ability to conform to such elaborate design conditions [38].

As we improve the MFS through the years, we not only relieve space constraints, but improve the operational characteristics resulting in an onflow of benefits. Thus, reducing the overall transistor length will decrease the required current to place the transistor in a state of operation and also reduce heat generation. Inherently lowering the transient response time of gate switching hence achieving faster overall performance in system designs, reducing costs of fabricating existing devices and improving the technology as a whole. [29].

2.6.1 Dennards Law of Scaling κ

In 1974, Robert H. Dennard and associated members of the IEEE proposed a 'scaling factor' for decreasing MOSFET device size whilst improving performance characteristics. This factor was labelled as $\kappa = \sqrt{2}$ and was based on the main scaling parameter of transistor gate length. Each semiconductor manufacturer primarily aimed at developing technology with regard to the next challenge set on the International Technology Roadmap for Semiconductors (ITRS) and effectively used Dennard's scaling factor to multiply the current transistor gate length by $1/\kappa = \frac{1}{\sqrt{2}}$ [10].

By scaling the length of the gate by $\frac{1}{\sqrt{2}}$, we can see that the transistor as a whole would effectivley scale down by half its current size and hence provide space for twice the number of transistors. For example, if the current technology node is at 180 Nanometers (nm) then 18-24 months along the ITRS we could estimate to aim for an approximate transistor gate length of $180 \times \frac{1}{\sqrt{2}} \approx 130nm$. Concurrently scaling the total current transistor area is a bi-product of transistor gate length reduction, and is scaled by

$$(\frac{1}{\sqrt{2}})^2 \approx 0.5 = 50\%$$

Chapter 3

Literature Review

3.1 A Consumption Factor for Wireless Communication System Design

In wireless communictions, especially mobile applications, energy efficiency is highly prioritised. What good would a high powered device be with five minutes battery life, or a device that has an extensive battery life that cannot deliver to the approximate standards it should be capable of in its current time. For mobile devices, estimated power consumption plays a key role in the development and hence in the article 'Consumption Factor: A Figure of Merit for Power Consumption and Energy Efficiency in Broadband Wireless Communications', James Murdock and Theodore Rappaport propose a means of estimating 'the power efficiency of wireless communications devices or links'. This universal figure of merit identified in their research has been deemed the 'Consumption Factor' (CF) [43].

The CF, (Equation 3.1 [43]) essentially measures the 'maximum ratio of data rate versus consumed power as a function of transceiver subsystem and channel parameters' [43]. It provides a good metric for an individual component analysis for improving systems efficiency in wireless architectures. Stepping through the components of the CF we can set the desired properties of the system we intend to design such as data rate and SNR. The remaining subcomponents that comprise the system such as gain, efficiency, power consumption etc can be reworked in many configurations to alter the CF and obtain the most desirable outcomes [43].

$$CF = \frac{Blog_2(1+SNR) \times c^2 \times G_{RX}}{(SNR/M_{SNR})KTBF_{RX}(4\pi f_{OSC}D)^2(1+(\frac{1}{\eta_{ANT}}-1)+\frac{1}{G^{ANT}}(\frac{1}{\eta_{PA}}-1)+\frac{1}{G^{ANT}G^{PA}}(\frac{1}{\eta_{MIX}}-1))+(P^{BB}+P^{OSC}\times c^2 X G_{RX})} \tag{3.1}$$

If we apply the CF, Equation 3.1 with repsect to 'high powered' radio applications in terms of SNR we can see this also gives us viable data. Just from looking at the equation we can extrapolate that the SNR is a variable of great importance in the formula. Thus, higher SNRs will yield a greater ratio of data rate versus consumed power. This is highly regarded in modern system designs and is easily achievable and as technology develops. We are continually targetting not only efficient system designs but aiming for increased SNRs to acquire the supreme level of data transfer rates we are capable of, given the correct design measures.

If we apply the CF with lower SNR equipped radio systems we can see that the CF estimation begins to decrease, and our system approaches the inefficient side of the spectrum. Hence when using the proposed CF as an esitmation tool in wireless systems design, aiming for higher component sensitivity with increased SNRs will effectively result in higher achievable data transfer rates. As we progress through the previously mentioned technology nodes in (Chapter 2.6), integrated circuit technology simultaneously evolves, previous technologies can be reworked, thus rendering them more efficient.

Chapter 4

A Wireless Law

This Chapter consolidates all research, tables, figures produced and details the decision making process behind a Wireless Moore's Law. Section 4.1 gives a brief overview of the trends in data transfer rates in terms of bits per second per year. Section 4.2 summates modern transistor counts to produce a current Moore's Law based trend. Section 4.3 applies Moore's Law to select results for verification of extrapolated trend in Section 4.1. Section 4.4 presents the transistor and its properties as an underlying factor to be scientifically explained, thus increasing data transfer rates in wireless technologies.

4.1 A Trend Over Time

In Chapter 2, a range of wireless communications technologies are detailed and their respective data transfer rates highlighted. These data samples were processed and tabulated as seen in Table A.1: Wireless Technologies and their Data Transfer Rates. From driectly reviewing the collection of data over the past 4 decades, we begin to see that as we would expect, there is an increase in data transfer rates over time. Furthermore, these data points can be plotted on a logarithmic scale versus time as shown below in Figure 4.1.

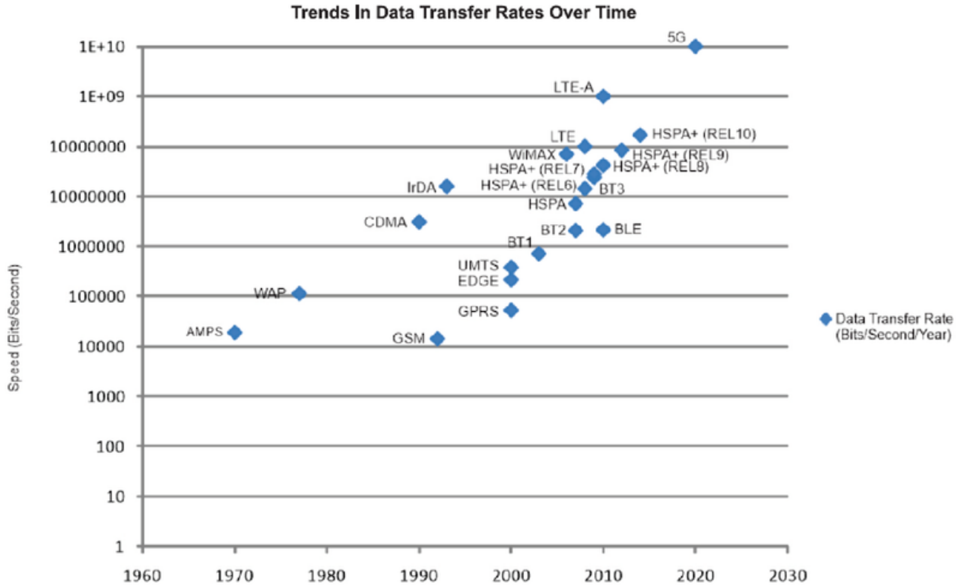

Figure 4.1: Trend in Data Transfer Rates Over Time (1970-2020)

The collection of bit rates obtained from Table A.1 have been plotted in units of bits per second on the vertical axis against time in years on the horizontal axis. From viewing the data in its graphical form, we can see that from 1970 when AMPS was introduced through to modern wireless technologies such as LTE-A and 5G, the data follows a visually linear path. Furthermore, we can clearly see two distinct trend lines which are parallel. Both identified trend lines follow an exponential relationship over time. The reason for the existance of two seperate trendlines rather than a singular linear path, is due to a later release along the technology timeline, either a major wireless technology release or development, or a refinement of an existing base wireless technology. All of these factors are represented by the line shifted approximately 20 years forward as shown in Figure 4.1.

Since the appropriate lines of best fit of this graph are visually linear whilst the vertical axis increases by a factor of 10 over its duration, we can deduce that wireless data transfer rates have increased exponentially in relation to time. The previously identified exponential trend gives some insight into the beginning of an explanation of how to relate data transfer rates with semicondutcor technologies over time. It is to be noted that there may be a simultaneous trend similar to that of Moore's. Therefore, it is appropriate to examine respective transistor counts over the same period of time to produce a modern Moore's Law graph for formulation and verification purposes (see section 4.3).

4.2 A Continuation of Moore's Transistor Count Law

In Section 4.1 the data transfer rates in wireless communications revealed their exponential nature. Following this, a range of modern Integrated Circuits were tabulated in terms of their Transistor Counts. These Integrated Circuits were selected due to them sharing the same release year as their relevant wireless technology data transfer rate. Please refer to Appendix B for tabulated data. The purpose of continuing Moore's trendline was to superimpose the data collated for each wireless technology and relate their progression to that of Moore's, noting if there was anything similar or substantially different.

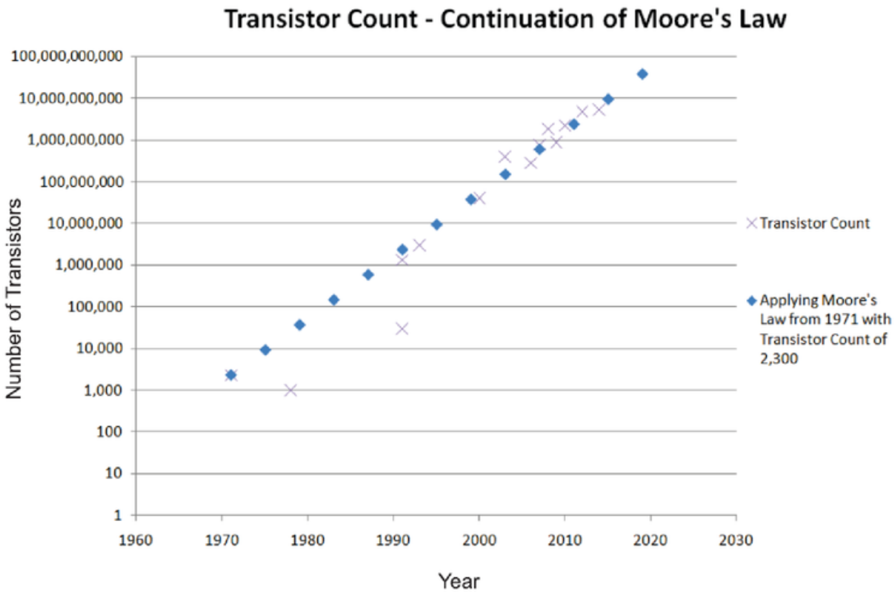

Figure 4.2: Data Transfer Rate Versus Transistor Count Trends

Figure 4.2 displays a continuation of transistor count based on modern technologies. We can extract that Moore's law still applies in the modern era since its development in the late 1970's. The trendline still follows the aforementioned exponential progression, thus it can be used as an analysis tool to review the visible trend in the initial plot.

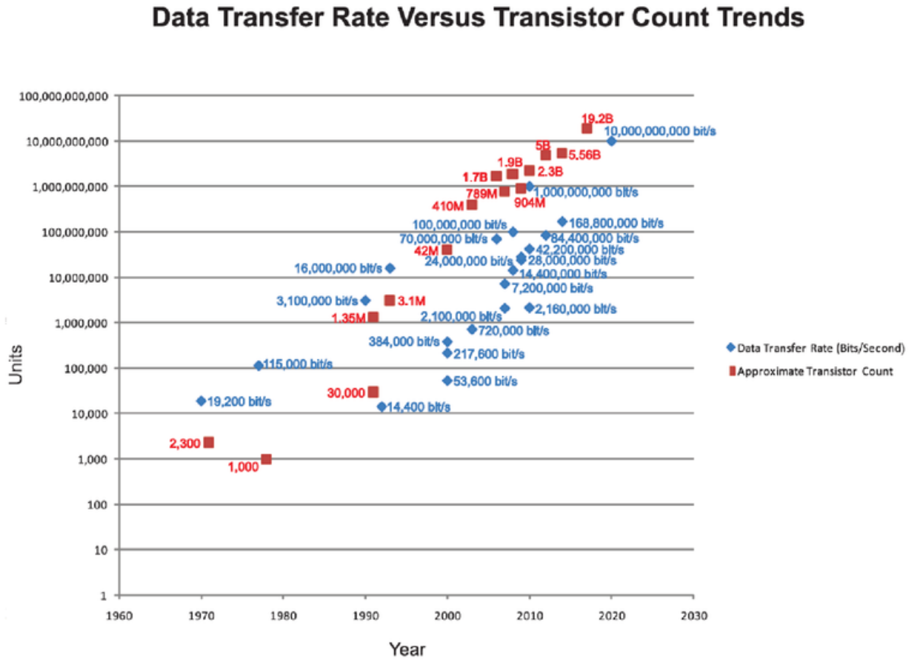

Figure 4.3: Continued Transistor Count Vs. Data Transfer Rate

Figure 4.3 displays a superimposition of modern fabricated ICs categorised by transistor count per year along with the data transfer rate of wireless techologies per year. Firstly we can notice that both plots are progressing exponentially throughout the same period of time, and the data transfer rates per year are almost parallel to the previouclsy documented transistor count progressions. This leaves us with the notion that data transfer rates of wireless technology are following the same trend to that of Moore proposed law for integrated circuit transistor counts in 1975. Now lets take Moore's law and apply it to specific data points to map the progression over time in Section 4.3.

4.3 Using Moore's Law for Validity of Trends

In Figure 4.4 below we can see two additional sets of data plots overlayed on Figure 4.1. The series indicated in red can be identified as the data transfer rate of 19,200 bits per second in the year 1970 progressed throughout the duration of the graph as per Moore's Law. We can then compare the trend seen in Figure 4.1 or with the data transfer rate (blue series), to deduce that they do follow a similar parallel trajectory of exponential progression. Further the series indicated in green can be described as the data transfer rate of 14,400 bits per second, similar to the speed defined in 1970 but with a starting year of 1992. Incrementing this with respect paid to Moore's Law also yields, as proposed, an exponential trend parallel to the initial trendline plotted in Figure 4.1.

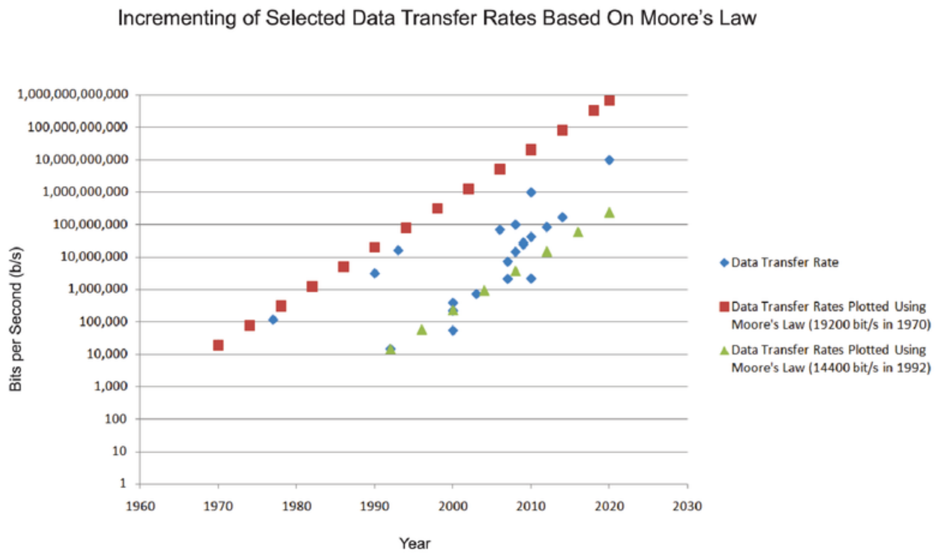

Figure 4.4: Using Selected Data Transfer Rates as a Base Value for Moore's Law Projections

Simply by plotting multitudes of data and noticing a trend we can deduce that there is more than likely a trend of very similar nature that relates Moore's Law to wireless technologies in terms of data transfer rates. Additionally, there must a greater underlying factor responsible for driving data transfer rates of wireless communications over the last 4 decades, at almost identical rates to transistor counts. If we delve deeper into the plotted results and recall Dennards Law of scaling and how the transistor gate length scales by an approximate factor of $1/\kappa$ (which is equal to $\frac{1}{\sqrt{2}}$) every 18 to 24 months, there may be a clearer explanation at a mathematical level.

4.4 The Transistor, Driving Data Transfer Rates

The graphs in the previous sections sum visual interpretations of the data transfer rate trends of a broad range of wireless technology forms. The plot ranges from the early 1970's until present and future times and relates them to Moore's Law. As they can be seen to have similar growth, they cannot simply just progress at exponential rates similar to that of Moore's prediction for semiconductor transistor density counts. There are a number of factors influencing the ability to achieve faster data transfer rates in wireless applications and it is apparent that they have a direct relationship to the efficiency, material composition and size scaling over time for transistors. This will be detailed in subsections below.

4.4.1 Transistor Size

The size of a transistor has been a long time associated influence to its operational speed. Effectively, the larger the transistor, the larger the input current required to switch it to a state of operation. As we apply Robert Dennard's law of scaling from Section 2.6.1, we begin to see the impact it has on not only the single transistor but the entirety of the IC. As we scale the trasistor gate by a factor of $\frac{1}{\sqrt{2}}$ we not only reduce the gate length by that factor but scale the entire area of each transistor by effectively 50%. If we take an MMIC with a total density of 500,000 transistors within an area of 10 mm^2, and scale it we effectively halve the chip size to 5 mm^2 and increase the transistor density to 1,000,000. Aside from the increased computational benefits of added transistor counts, scaling the transistor has also reduced the capacitance of the IC as a whole which reduces the switching delay time and heat dissipation thus keeping out unwanted noise. Eliminating this unwanted noise allows use to obtain the higher more desired SNRs resulting in greater data rates per consumed unit of power if we were to use the previously mentioned CF put forward by Murdock and Rappaport [43].

4.4.2 Properties of Gallium Arsenide Vs. Silicon

Through the decades, transistors have seen many sizes, and applications but lastly they have been constructed with various materials all possessing beneficial traits. The most common semicondictor in the Group III - V element categorisation of the periodic table of elements used widely around the wide in transistor fabrication is Gallium Arsenide (GaAs) as outlined in Chapter 2, Section 2.5.3.

In wireless communication systems of the modern era we commonly see freqeuncies of operation well into the tens and hundreds of Gigahertz regions. For appications under the average 2.4 GHz network seen in most households such as in WiFi operation we would employ Silicon as a semiconductor as it is cheaper and more abundant than GaAs, and the shear volume of WiFi equipped households worldwide would not utilise all of GaAs' advantageous characteristic properties. In MMIC and transistor fabrication for wireless communciation systems in excess of 2.4 GHz, GaAs is the preferable material of choice due to its lower gate drive voltages and current requirements, thus increasing its ability to reach logic voltages in digital circuitry much faster, therefore reducing noise levels compared to Silicon. Similarly it also imposes much greater electron mobility.

Electron mobility in GaAs is greater than that of Silicon by a factor of 6×, making GaAs a more applicable material in VHF applications such as in MMIC tehcnologies. This is one of the fundamental characteristics of GaAs that has carried it as far as it has come with semiconductor design and manufacturing in modern times.

4.4.3 Cut-Off Frequency f_T Increases as Transistor Gate Length L Decreases

As outlined in Chapter 2, cut-off freqeuncy refers to the maximum operable frequency of the transistor for which the unity gain is 1. It can also be charaterised as the quantity of electrons able to be moved from source to drain of the transistor per cycle. Equations 2.1 and 2.2 provide a base for analysis of how transistor gate length impacts the cut-off frequency over time. Note that many of the parameters used in calculating actual cut-off frequency have been either omitted or set as a constant value for evaluation purposes only. These are documented at length when relevant.

If we take Equation 2.1 in Chapter 2 for the unity gain of long-channel MOSFETs, and examine the parameters we can see that there are a number of factors which can be kept constant for evaluation purposes. Starting with Equation 2.1 we can isolate (μ) and (π) as their values are independent of time. ($V_{GS} - V_T$) may also be omitted from the equation due to the fact that as transistor technology improves, and they become more efficient, the voltage thresholds and current requirements to create the conductive path decreases and this number is a negligible value in regards to this verification. This delivers Equation 4.1 below.

$$f_T = \frac{1}{L^2} \tag{4.1}$$

If we evaluate Equation 4.1 we can see that if we input values of transistor gate length (L) over time as gate length decreases, we will not obtain an actual value for the cut-off frequency but we can observe the nature of how transistor gate length impacts the cut-off frequency result, if were to use Equation 2.1 in its full form.

In short-channel MOSFETs the unity gain can be expressed as shown in Figure 2.2 in Chapter 2. For review purposes we can take the same approach as performed in Equation 2.1, and omit all components deemed as constants. This would mean that (π) and the saturation voltage (V_{SAT}) would be omitted for the purpose of this review. (V_{SAT}) can be removed because the saturation voltage of a very small lithographically fabricated transistor would be close to negligible and we are not calculating (f_T), but rather reviewing the impact of (L) on it over time. This forms Equation 4.2 below.

$$f_T \approx \frac{1}{L} \tag{4.2}$$

If we evaluate Equation 4.2 we can see a similar trend to Equation 4.1. If we input values of transistor gate length (L) over time, as gate length decreases, we will not obtain an actual value for the cut-off frequency. Instead, we can observe the nature of how transistor gate length impacts the cut-off frequency result if we were to implement Equation 2.1 in its full form with all original parameters in effect.

As the inputted value of (L) decreases over time, the values for (f_T) can be seen to increase and so we can begin to speculate that transistor gate length is inversely proportional to cut-off frequency and has a direct impact on the the amount of data we can process through a transistor per second as we progress through the various technological nodes. All constants were ommitted purely to observe the effects of transsitor gate length reduction over time on the outcome of the formed Equations 4.1 and 4.2. When calculating the actual value of (f_T), Equations 2.1 and 2.2 would need to be used in original formation.

Semiconductor elements are another factor which greatly influences the cut-off frequency obtainable as (L) decreases. This is with strong regard to their (μ) values. If we take either Equation 4.1 or 4.2 and do not omit (μ) in relevant calculations we can see the additional impact that mobility has on the cut-off frequency alongside transistor gate length. As an example, lets take the mobilities of Silicon and Gallium Arsenide and review what is yielded from each. Silicon has an electron mobility $\mu = 1400cm^2/V.s$ and Gallium Arsenide has an electron mobility $\mu = 8500cm^2/V.s$.

If we do not omit (μ) from Equation 4.1 we obtain Equation 4.3 below:

$$f_T \approx \frac{\mu}{L^2} \tag{4.3}$$

For a given technology node with $L = 130nm$ and mobility for Silicon $\mu = 1400cm^2/V.s$, substituting the noted values for Silicon into Equation 4.3 yields

$$f_T = \frac{1400}{130^2}$$

$$f_T \approx 0.083$$

For a given technology node with $L = 130nm$ and mobility for Gallium Arsenide $\mu = 8500cm^2/V.s$, substituting the noted values for Silicon into Equation 4.3 yields

$$f_T = \frac{8500}{130^2}$$
$$f_T \approx 0.503$$

The obtained values above are not equal to the cut-off frequencies with respect to changing semiconductor elements, but are rather useable in the sense that we can see how the mobility of varying Group III - V semiconductor elements would impact cut-off freuency when calculated in full form (Equation 2.1) in addition to the reduction in transistor gate length. Simply from changing semiconductor elements from Silicon to Gallium Arsenide we are able to increase the cut-off freuency on a major scale, hence moving larger amounts of data on the same technology node. From this we can also deduce that the introduction of Gallium Arsenide into the fabrication of MMICs, and transistor technology in general, has also been a significant factor working alongside gate length reduction. This inherently drives the large scale increases in data transfer rates of wireless technology implementations over time.

4.5 A Wireless Increase Factor

From the data samples shown in sections 4.1, 4.2 and 4.3, we can see that the data transfer rates over time prove exponential in nature. From multiple interpolations we can associate Moore's law as a 'figure of merit' to describe this trend reliably. However, the underlying cause for this trend is more complex. This behaviour is contributed to by the scaling of transistors, and more noteably, the transistor gate length. The onflow effect will naturally decrease conputational time required to maintain the identical system function.

From this we can deduce that the reason for data transfer rates progressing at a rate identical to the transistor count of integrated circuits, is accounted for when examining transistor efficiencies. As we decrease transistor size, we decrease the drive current and gate voltage required to initiate the conductive path from source to drain. As we decrease the voltage, logic levels in a circuit are reached quicker each time, hence reducing delay further. As each scaling fator is applied, these attributes improve, further improving the cut-off frequecy and transistor as a whole.

If we take the cut-off freqeuncy by definition to be the number of electrons able to move from source to drain in one cycle per unit time, and we assume data is represented by a number of electron groups for this case, we can see another trend. As we decrease the transistor gate length, the number of electrons we can move through the transistor per unit time increases each iteration of the scaling factor. It is then safe to say that the data transfer rate is influenced by the efficiency of transistors in a circuit, as data reaches its intended destination quicker, the more they scale from year to year. Additionally, as we scale we free up approximately 50% more space each iteration of the technology node, and so the computational power to perform the same function increases yet again. Therefore, providing us with greater accessible wireless data transfer rates per cycle.

Chapter 5

Conclusions and Future Work

The following chapter is constructed as follows. Section 5.1 provides a critical analysis of the future work possible as we approach the physical space constraint limits associated with transistor scaling and Moore's Law respectively. It will subsequently prove or disprove the initial phrase put forward in this project. Section 5.2 gives a breif summary of the project and a conclusion for the document in its entirety.

5.1 Future Work

This document acts as a consolidation of all collated real time data, which logically and sequentially presents a phrase to descirbe the trend in wireless communication data transfer rates over a given period of time. Use of this document in wireless communcations would prove beneficial for any party. Since time is used as a consistent point of reference for all calculations and assumptions throughout all research and development of this document, it maintains the proposed phrase's validity and relevance where applicable. Use of the data in this report would essentially assist in: a) keeping the proposed law valid, or b) retiring the proposed law to propose a new law based on recent technologies non-existant at the time of the original laws conception.

Future work of this project, ideally, would sample the current data transfer rates available and future expectations, to find a point at which the proposed phrase in this project may become irrelevant. As Moore's Law proves a high level of validity over a lengthy time interval, especially for the time periods investigated throughout this project, space is not infinite. Furthermore, possible future work may be relevant to such questions as: since data transfer rates mimic the exponential progression of transistor density on wafer technologies, once Moore's Law reaches end of life, will data transfer rates continue to climb? Is there another factor which could be driving data transfer rate increases over time unrelated to transistor technology developments?

5.2 Conclusions

Throughout the duration of this project we have drawn upon the visual data trends obtained from plotting the various technology transfer rates over a broad spectrum of time in units of bits per second. We noticed a trend which reliably fits that of Moore's Law for transistor density on semiconductor chipsets, and used the law to increment a given point of data to simultaneously graph and review the results. This result gave us an exponential progression as expected which eluded the discussions regarding transistor theory.

In Chapter 3 the authors of [43] proposed a consumption factor for wireless transmitters and we saw that the higher the signal to noise ratio, the greater the data transfer rate per unit of consumed power. From this we can relate to one of the material properties of gallium arsenide, its low noise characteristics, and thus why it is highly regarded in MMIC fabrication. Not only does gallium arsenide possess lower noise propertires over silicon, but its profound mobility, μ, at $\approx 6\times$ that of silicon means we can move $\approx 6\times$ more electrons from the source to the drain of a transistor per cycle. Therefore increasing data transfer mediums whilst reducing propagation delays within circuitry.

Transistors have scaled over time in accordance to Dennards law of scaling κ. It was noted in Section 2.6.1, that as we scale the transistor gate length, the respective area halves, hence effectively allowing twice the number of transistors to be fabricated within newer technologies. Reviewing this using the afformentioned formulas for short and long channel MOSFETs, Equations 4.1 and 4.2 showed us that as transistor gate decreases in length, cut-off frequency increases, thus transistors are inherently becoming more effieicent in operation whilst concurrently becoming smaller in size. Furthermore, this provides us with the ability of moving more and more data across the source and drain per cycle 'On' and 'Off' period.

Additionally, although transistors were noted to have the greatest overall impact, they are not an independant driving force behind increasing data transfer rates in wireless communications. Antenna technology is predominantly becoming more advanced and efficient, especially with inbuilt antennas in MMIC fabrications. With all the data presented and underlying factors thoroughly analysed, a valid phrase of merit describing wireless technology data transfer rates can be specified as, 'Wireless data transfer rates approximately double every two years'.

Chapter 6

Abbreviations

2G	2nd Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
8PSK	8 Phase Shift Keying
AMPS	Advanced Mobile Phone System
ADC	Analogue to Digital Convertor
AT&T	American Telephone & Telegraph
BJT	Bipolar Junction Transistor
BLE	Bluetooth Low Energy
BT1	Bluetooth Version 1
BT2	Bluetooth Version 2
BT3	Bluetooth Version 3
CDMA	Code Division Multiple Access
CMOS	Complementary Metal Oxide Semiconductor
CSIRO	Commonwealth Scientific and Industrial Research Organization
CW	Constant Wave
DAC	Digital to Analogue Convertor
DB	Decibels
EDGE	Enhanced Data Rate for GSM Evolution
EHF	Extremely High Frequency
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
GHz	Gigahertz
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HSPA	High Speed Packet Access
HSPA+ (REL6)	High Speed Packet Access Evolved - Release 6

HSPA+ (REL7)	High Speed Packet Access Evolved - Release 7
HSPA+ (REL8)	High Speed Packet Access Evolved - Release 8
HSPA+ (REL9)	High Speed Packet Access Evolved - Release 9
HSPA+ (REL10)	High Speed Packet Access Evolved - Release 10
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Access
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IrDa	Infrared Data
IOT	Internet Of Things
ITRS	International Technology Roadmap for Semiconductors
ITU	International Telecommunications Union
LAN	Local Area Network
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
M2M	Machine To Machine
MIMO	Multiple Input Multiple Output
MMIC	Monolithic Microwave Integrated Circuit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MW	Millimeter Wave
NASA	National Aeronautics and Space Administration
OFDM	Orthogonal Frequency Division Multiplexing
RFIC	Radio Frequency Integrated Circuit
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications Service
UHF	Ultra High Frequency
VHF	Very High Frequency
WAP	Wide Area Paging
WiMAX	WorldWide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

Appendix A

Collated Wireless Communication Speed Trends

A.1 Overview

A summation of the progression of speed across wireless network technologies is shown below in Table A.1.

A.2 Table of Wireless Technology Data Transfer Rates

Table A.1: Wireless Technologies and their Data Transfer Rates

Year	Technology	Speed (Bits/Second)	Citation
1991	Global System for Mobile Communication (GSM)	14,400	[44] [73]
1970	Advanced Mobile Phone System (AMPS)	19,200	[47]
1993	General Packet Radio Service (GPRS)	53,600	[73]
1995	Code Division Multiple Access (CDMA)	115,000	[21] [22] [74]
1974	Wide Area Paging (WAP)	115,000	[44]
2005	ZigBee	250,000	[54] [68] [56]
2000	Enhanced Data Rate for GSM Evolution (EDGE)	384,000	[73]
2003	Bluetooth V1.0 (BT1)	720,000	[79]
1997	WiFi - IEEE 802.11	2,000,000	[49] [76] [30] [57]
1998	Universal Mobile Telecommunication Service (UMTS)	2,000,000	[73]
2007	Bluetooth V2.0 (BT2)	2,100,000	[41]
2010	Bluetooth Low Energy (BLE)	2,160,000	[41] [45]
1993	Infrared Data (IrDa)	4,000,000	[74]
2007	High Speed Packet Access (HSPA)	7,200,000	[73]
1999	WiFi - IEEE 802.11 (b)	11,000,000	[54] [68] [56] [57]
2008	High Speed Packet Access Evolved - Release 6 (HSPA+)	14,400,000	[73]
2009	Bluetooth V3.0 (BT3)	24,000,000	[41]
2009	High Speed Packet Access Evolved - Release 7 (HSPA+)	28,000,000	[73]
2010	High Speed Packet Access Evolved - Release 8 (HSPA+)	42,200,000	[73]
1999	WiFi - IEEE 802.11 (a)	54,000,000	[54] [68] [56] [57]
2003	WiFi - IEEE 802.11 (g)	54,000,000	[54] [68] [56] [57]
2001	Worldwide Interoperability for Microwave Access (WiMAX)	70,000,000	[51]
2012	High Speed Packet Access Evolved - Release 9 (HSPA+)	84,400,000	[73]
2010	Long Term Evolution (LTE)	100,000,000	[73]
2014	High Speed Packet Access Evolved - Release 10 (HSPA+)	168,800,000	[73]
2009	WiFi - IEEE 802.11 (n)	600,000,000	[54] [68] [56] [57]
2010	Long Term Evolution Advanced (LTE-A)	1,000,000,000	[73]
2012	WiFi - IEEE 802.11 (ac)	1,300,000,000	[54] [68] [56] [57]
2009	Ngara by CSIRO	5,000,000,000	[34] [15] [32]
2020	5th Generation (5G)	10,000,000,000	[46] [27]

Appendix B

Collated Transistor Counts of Integrated Circuits Over Time

B.1 Overview

This table presents a concise summary of transistor counts on specified Silicon chip technologies at a given year. The data has been cross correlated and used in Chapter 4, Sections 4.3 and 4.4 to further show Moore's Laws validity and reveal trends that are believed to exist between transistor count and data transfer rates in mobile communications.

B.2 Table of Transistor Counts

Table B.1: Transistor Counts of Integrated Circuits Over the Past 4 Decades

Year	Technology	Transistor Count	Citation
1971	Intel 4004	2,300	[1]
1978	Motorola 6809	1,000	[1]
1991	ARM 6	30,000	[1]
2000	Intel Pentium 4	42,000,000	[1]
2003	Intel Itanium 2 Madison 6M	410,000,000	[1]
2007	IBM Power 6	789,000,000	[1]
2009	AMD Six-Core Opteron	904,000,000	[1]
2010	Intel 8-Core Xeon Nehalem	2,300,000,000	[1]
1991	MIPS R4000	1,350,000	[1]
2008	Intel Six-Core Xeon 7400	1,900,000,000	[1]
2012	Intel 62-Core Xeon Phi	5,000,000,000	[1]
2014	Intel Xeon Haswell-E5	5,560,000,000	[1] [3]
1993	Intel Pentium	3,100,000	[1]
2006	Intel Dual Core Itanium 2	1,700,000,000	[1]
2017	AMD 32-Core Epyc	19,200,000,000	[1] [3]

Appendix C

Consultation Meetings Attendance Form

C.1 Overview

Appendix C shows the meeting schedule between the supervising professor and student throughout the entirety of the project.

C.2 Meeting Attendance Form

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
2	7/8/17	Initial Project discussion	[signature]	[signature]
3	14/8/17	email correspondance, reschedule week 4	[signature]	[signature]
4	22/8/17	Project discussion background research	[signature]	[signature]
5	28/8/17	project correspondance via email	[signature]	[signature]
6	4/9/17	project correspondance via email	[signature]	[signature]
7	11/9/17	Project meeting phone meeting	[signature]	[signature]
8	2/10/17	project correspondance via email	[signature]	[signature]
9	9/10/17	reschedule project meeting — product release at work	[signature]	[signature]
10	16/10/17	reschedule project meeting - Professor overseas.	[signature]	[signature]
11	23/10/17	email correspondence project discussion	[signature]	[signature]
12	30/10/17	Project Finalisation discussion	[signature]	[signature]
13	6/11/17	email correspondance project tidy ups.	[signature]	[signature]
—	13/11/17	project submission	[signature]	[signature]

[signature] Digitally signed by Michael Heimlich
Date: 2017.11.13 09:30:09 +11'00'

Appendix D

ENGG460 Thesis Preparation Document

D.1 Overview

Appendix D shows the original project proposal for this project completed within the ENGG460 unit.

D.2 Thesis Preparation Assignment

Thesis Preparation Assignment: Wireless Moore's Law

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***Abstract*— This document is designed to provide the reader with an overview of the expectations of the given Thesis Project for ENGG411. The Research Project allocated is Wireless Moore's Law. The report will aim to give a concise breakdown of early planning and organization to obtain the most accurate information in the most efficient way for the duration of the Research Project. It provides specifications relevant to the topic and literature reviews of an extended number of sources, all of which will be used to break the project down into relevant subsections. A Gantt chart is included to breakdown all vital components over the period of the research and organize all areas into a stringent time frame to ensure success and efficiency. The report will be written in the IEEE-style format, commonly used in research papers.**

I. Introduction

This specific document incorporates preparation work for the proposed Wireless Moore's Law Research Thesis.

Wireless technology is an ever rapidly expanding area in communications around the world. Bandwidths are getting larger, with greater efficiency and much higher data transfer rates. Moore's Law can be deduced in a nutshell to simply mean 'Computing power doubles every 18 months' [1]. This strong statement was derived based on the rapid increase in transistor speed and the ability to fit twice as many transistors per square inch on a silicon wafer. This statement leaves room for the development of a fundamental theorem to express the rate of change in wireless communication networks around the world. Power consumption, alongside efficiency in wireless communications, is an ongoing area for development in the world as there is no foreseeable limit in technological advances in transmission of data. Although Moore's Law is an accurate representation of the progress of computing power in the world, a finite life-cycle can be seen as there is no infinite amount of space on a silicon wafer.

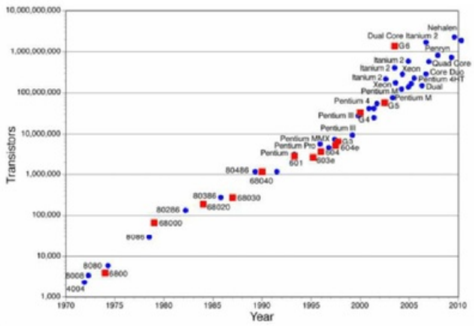
For the length of this report the following terms will appear frequently. Consumption Factor (CF) is simply defined as a measure of the power efficiency of any communications device or link and compares the maximum ratio of data rate to consumed power [2]. (MMIC) refers to Microwave Monolithic Integrated Circuit and is also referred to as just an Integrated Circuit [3]. MMIC's operate at microwave frequencies from a range of 300MHz – 300GHz. (RFIC) refers to a Radio Frequency Integrated Circuit and have a most common application in wireless communications [4]. The Breakdown Voltage (BV) is 'the minimum applied voltage necessary to cause a given insulator to breakdown and start conducting' [5], [6].

II. Project Specifications

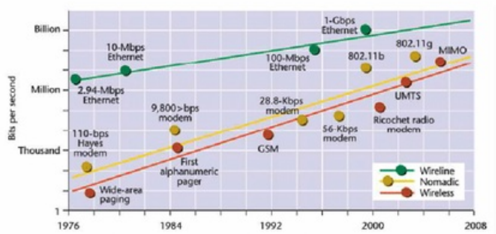
- Wireless Moore's Law will attempt to become a theorem derived by research and suggesting improvements on the relation of Moore's Law to the technological advances in RFICs and MMICs.

Traditionally Moore's Law, when first proposed would have appeared to be a very long term valid proposal, however the rate of technological advances amongst the world has occurred at a rate faster than proposed. Transistors have become much more efficient in their performance at much smaller sizes. This shrinkage of size and increased processing power allowed for whole processing units to double their capabilities every 18 months. This can be seen to be inaccurate over the very long term due to space constraints. At a micro level with such accurate speeds, space will eventually pose a threat to Moore's law. In terms of a Silicon wafer, this may be the case, however if Moore's Law is applied to Wireless Technologies it has a chance of being a long term valid proposal.

MMIC's and RFIC's are readily available devices from a global company called Macom Industries. They have been existent for 60 years and specialize in custom fabrications from 'RF to Light' [7]. They are responsible for some of the founding of Microwave associates from as far back as 1950 and will be a very valuable resource to derive this theorem of Wireless Moore's Law. Below in Fig 1, there is a clear display of Moore's Law in a linear graph. In Fig 2, a linear growth can also be seen in wireless bandwidth rates.



[8] Fig 1 – Moore's Law Graph on Transistor Count per year.



[9] Fig 2 – Wireless Bandwidth Trends from WAP to MIMO from 1976 – 2008.

From relevant sources of data, taking in past wireless bandwidths the chart in Table 1 represents past, current and predicted data transfer rates in wireless communication systems via the IEEE 802.11 framework.

Wireless Type	Year	Bandwidth (MHz)	Data Rate Mbps
802.11-1997	1997	22	2
802.11a	1999	20	54
802.11b	1999	22	11
802.11g	2003	20	54
802.11n	2009	40	150
802.11ad	2012	2160	6912
802.11ac	2013	160	866.7
802.11ay	Pred. 2017	8000	100000

Table 1 – past, present and future bandwidth

When examining Fig 2 and Table 1, a relation can be made between Moore's Law and Wireless Bandwidth increases each year. They both seem to increase on a linear time scale and this poses a strong argument into detailed research to prove the existence of such a theorem of 'Wireless Moore's Law'.

The Research for this project is to be based on MMIC's and RFIC's, taking advantage of Macom Industries past 20+ years of Integrated Circuit libraries and their relevant data specification sheets. The data sheets for past and present IC's is ideal in providing elements of information on certain Bandwidths, sizing and power consumption rates of each of the developments over a significant time frame. A substantial quantity of data will be collaborated and organized into forms of charts for clear indications of possible trends and relations to the linear scale of Moore's Law.

Ideally, the form of theorem to be derived would be placed along the lines of, 'Wireless Bandwidths in communication systems increase at a rate of 1.5 times per year'. A concise and most verbally accurate statement will be generated after clear interpretation of data and comparisons with technology advances, computing power and efficiency in modern Integrated Circuits. The Consumption Factor (CF) will be one of the main measures for this theorem and will have detailed attention paid to it. This is due to the CF providing a means for the efficiency of very high data rate transfers versus very low power consumption.

The stability of the theorem is another area which needs careful and precise addressing. Like Moore's Law, minimal attention was paid to the life of his theorem and most emphasis was placed on its currently validity and accuracy. The expected life of the theorem of Wireless Moore's Law will be evaluated and a relevant theorem life will be detailed if research deems it necessary.

III. BACKGROUND LITERATURE REVIEW

This section of the report will outline some of the various main areas where research will be conducted for the major Research Thesis. These sections will aid the derivation of a relevant theorem to prove the existence of a 'Wireless Moore's Law'. All research presented is thorough and provides more than enough detail as basis for some of the major research to be performed at a later stage in the Research Project. It will detail key areas necessary to develop such a theorem and critically analyze all relevant areas of MMIC's and RFIC's in terms of power consumption, processing speeds and bandwidth allowances.

A. Moore's Law

Gordon E. Moore in 1965 wrote a paper labeled 'Cramming more components onto integrated circuits'. Moore made statements such as 'Integrated Circuits will lead to such wonders as home computers' and 'personal portable communication systems' [1]. Silicon was deemed to be the basic material to be used in most Integrated Circuit fabrications and such materials as Gallium Arsenide to be used in Microwave Functions. There was much emphasis placed on minimized costs due to lower component counts in specific applications, since a single Integrated Circuit could replace the functions of such a large array of individual components. Moore believed that circuits as large as 65,000 components could be built into a circuit on a single wafer.

There was the issue of possible heat generation, having so many operational components on one chip but shrinking the whole dimensions of an integrated structure was found to make it possible to operate the structure at a higher speed with the same power per unit area.

Gordon E. Moore's Law became an accurate representation of what was happening with Integrated Circuitry after 9 of the 10 predictions over a 10 year period were deemed to be true. The original Moore's Law states that 'the number of transistors that can be installed on an Integrated Circuit doubles every two years'. Moore revisited his theorem in later years to make it more accurate by simply deeming the correct law to be 'computing power double every 18 months'. This statement was released after Gordon E. Moore cofounded Intel.

B. Wireless Communication Systems

Since the very first telegraph in the pre-1600 era to Wide Area Paging (WAP) to current 802.11 networks, there has been a profound increase in wireless bandwidth capabilities [10]. This is not only due to globalization and society becoming more competent with modern technologies but as a result of what Gordon E. Moore predicted. Integrated circuits, especially RFIC's and MMIC's are being designed at such small dimensions with such low power and low temperature operating characteristics. This is a major factor in new milestones for wireless communications and bandwidths.

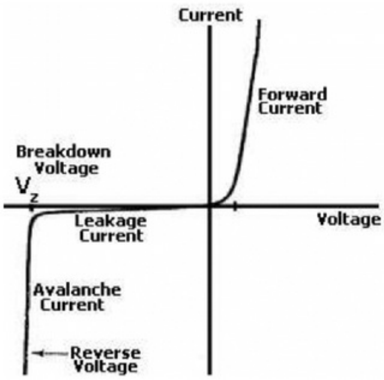
Wireless communication networks all operate at specific frequencies. These frequencies allow a means of data transfer at varying rates. In terms of point to point connections, the frequency used determined how often the cycle of the signal occurs. In a low frequency signal, it would generally take much longer for the cycle of the signal to complete; hence data carried can be decoded at a slower rate. As frequency increases, there is the same amount of data transferred but at a faster rate since the cycles can complete much faster. This is one of the main principles in faster data transfer rates [19].

In terms of RFICs and MMICs, they operate as such a high frequency to obtain greatest data transfer rates. Moore's law shows valuable support in determining the existence of such a theorem as 'Wireless Moore's Law'. As computing power doubles every 18 months, RFICs and MMICs are produced at a much more complex level and so higher frequencies of operation can be achieved. This, in turn allows for the higher data transfer rates (bandwidths) in wireless communications around the world today. It shows a strong link between bandwidth history from the very first of wireless communication systems until current times [19].

C. Breakdown Voltage

The breakdown voltage in any semiconductor application plays a vital role in the efficiency of the device. It is defined as 'the minimum applied voltage to a given insulator or electrode to commence conduction' [12]. Bipolar and Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs) [13] are widely used around the world since their invention and improvements until now. The breakdown voltage as defined above plays a crucial role in determining what application any transistor is applicable for.

In a low voltage, current and high bandwidth application like a home router, MMICs and RFICs would be required to have a very small breakdown voltage. With a small Breakdown Voltage, the semiconductor can operate efficiently and at lower temperatures compared to a component with a higher threshold. Figure 3 below shows a typical graph of how breakdown voltage looks for a component. It can be seen that as a gradual increase in voltage is applied over a small scale, there is a point at which the electrode will allow current to pass freely, hence Forward Current. This is a simple explanation of the phenomena behind the operation of transistors.



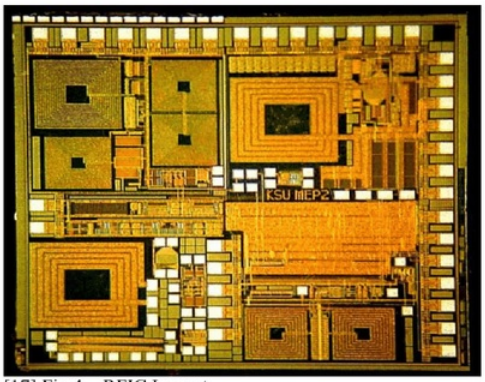
[14] Fig 3 – Breakdown Voltage Chart

Phenomena such as gate recession in whole MMICs and RFICs have been extensively researched and proven inefficient [15]. Research and Development for areas of lowest possible and effective breakdown voltage is an area still considered and highly regarded today in super fast Integrated Circuitry and processor applications.

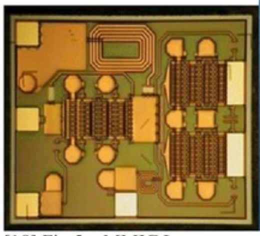
For the length of the Research thesis, Breakdown voltage will be studied in depth and be one of the major factors in deriving the suitable formula for a Wireless Moore's Law.

D. Radio Frequency & Microwave Monolithic Integrated Circuits (RFIC's, MMICs)

RFICs and MMICs as defined above are still widely employed in most high frequency, high speed electronic products such as amplifiers, mixers, oscillators, synthesizers and almost most other electronic devices around the globe. Figures 4, 5 and 6 show the key differences between RFICs and MMICs. Use of an MMIC or and RFIC is determined mainly based on their operating characteristics. This includes frequency of operation, gain, noise figures, power supply voltages and the consumption factor (CF) [16].



[17] Fig 4 – RFIC Layout


[18] Fig 5 – MMIC Layout

[18] Fig 6 – MMIC enclosed

Original first generation GaAs technologies are still commonly used but limited to applications such as switches and classical Radio Frequency circuits at microwave frequencies. They are very reliable and perform at low noise levels but are often overlooked for newer technologies in power amplification systems. Most common MMICs still using GaAs technologies have a slight number of advantages over other technologies. These include higher frequency operation, ease of integrating passive components and either a higher power or lower noise [16].

Silicon Germanium (SiGe) is another replacement for RFIC manufacturing and has widely replaced almost all GaAs around the world. RFICs manufactured with SiGe allowed developments and mass sales of Bluetooth, GPS, and Wireless Local Area Network (WLAN) for household applications. This led to the boom in wireless communications and the increase in bandwidths each year since Wide Area Paging (WAP) was first introduced [16].

As technology continues to rapidly evolve and Integrated circuits such as MMICs and RFICs are readily produced, SiGe equipped devices will allow manufacturing of devices that can operate in the millimeter wave range. This range is considered to be up to 100 GHz and has allowed developers to pursue research and development into areas such as fiber optic communications and automotive sensory [16].

Considering Moore's Law and relating it to the size and processing ability of Integrated Circuits, it can be seen that as computing power doubles, the ability to make more accurate, faster, efficient and more compact RFICs and MMICs is a result. This can be considered as a driving force into the increase in available wireless communication bandwidths achieved each year. Like Moore's law, there may be discrepancies in future growth rates but this can only be determined through extensive research when the Thesis Project is carried out.

E. M/A-COM Industries

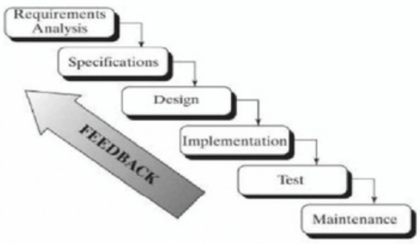
M/A-COM Industries was first established as a company in the name of Microwave Associates in August 1950. They initially began with $10,000 in capital. The Magnetron was the first product ever developed by the company and contributed to the evolution of the Microwave industry in the U.S.A. In the 1960's the company assisted in the development of microwave components to be commonly used as building blocks for radar, missile and communication equipment. 1957 marked a milestone for the company when they first went public on the stock exchange. Following such a successful development run since the company first started there were acquisitions into the naming of the reputable brand. 1978 marked another milestone as the company renamed to M/A-COM, Inc. This name better represented the growing RF and Microwave communications developments that would further refine M/A-COM in the future [11].

In 1979 M/A-COM Industries mass produced Gallium Arsenide semiconductors and became first domestic supplier. As production rates and advances in semiconductor technologies increased dramatically, M/A-COM Industries outsourced manufacturing processes to China [11]. The start of the 1990's spread M/A-COM Industries name across the globe when they developed the first Gallium Arsenide (GaAs) Radio Frequency Integrated Circuit for use in handset applications. Following this release there was much success and future direction for the company and it was taken over by AMP Incorporated and later on AMP was taken over by Tyco Electronics Inc [11].

With technology advancing at such a large rate, RFIC's and MMIC's were becoming ever so powerful with larger component counts on silicon wafers. This started another ever so successful decade for M/A-COM in the 2000's. From uses such as radars, jammers, radio responders, CATV systems, a GPS module was finally patented and mass produced in 2008. In 2010, GaAs semiconductors have achieved operating ranges up to 50 GHz. In 2011 M/A-COM acquired a company by the name of Optomai Inc which developed integrated circuits and modules for next generation 40 and 100 Gbps fiber optic networks [11]. In current times, M/A-COM Industries continues to develop more complex RFIC's and MMIC's with greater processing speeds and much higher bandwidths for some of the most powerful wireless communication systems on the planet.

IV. Project Plan

Planning of any project is the key to organization and success. The style of planning for the successful development of the Thesis document relates to a Waterfall [20] systems engineering approach. Figure 7 below illustrates the Waterfall Process in order from initial planning to full complete professional documentation.



[20] Figure 7 – Royce's Waterfall Process Model

The Waterfall Process Model is almost the perfect description for the type of flow to achieve for the Research Thesis. It follows a 'waterfall' like top-down approach in a steady form. Each of the segments is clear and concise and all relevant documentation is to be performed consistently throughout the duration of the entire project to ensure the most effective management of the project is in place. The Waterfall process is a type that requires each segment to be completed prior to commencing the next. This is the case because every piece of information and observations made previously is used to determine the next phase of the process.

This current document can be used as a prime example in the conceptual design and planning phase of the Waterfall Process. It identifies a problem and suggests possible approaches to achieve the desired result. It also presents a variety of research topics most relevant to the issue outlines and an insight into how those ideas will be further researched to assist in the final results of the Project. If the Waterfall Process is successfully followed through the whole duration of the project, the chance of deriving such a theorem as a Wireless Moore's Law has a much greater chance.

The Thesis Project will run for approximately six months, of which there will be open lines of communication with Prof. Michael Heimlich who will be the academic responsible for the supervision of this research task. At the end of this document, attached in Appendix I, there is a Gantt chart. This Chart illustrates the approximate time allocated to complete each segment of the Research project.

V. Conclusions

This document has been compiled to represent the early planning and research into the Major Research Project, 'Wireless Moore's Law'. It includes Project Specifications, Background Research and a stringent time management plan to ensure the successful completion of the given Thesis.

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APPENDIX I – Thesis Gantt Chart

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