SPECTRUM SHARING FOR WIRELESS COMMUNICATION SUBJECT TO REGULATORY CONSTRAINTS ON POWER

A Thesis submitted by

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Abstract

Spectrum is or soon will be a scarce asset, and hence methods for efficiently *sharing spectrum* are important. Concern about the possible effects of wireless radiation on health are also growing because of the widespread and growing use of devices that communicate wirelessly. Although some of this concern can be attributed to ill-informed alarm, international agreements and industry standards recognise the need for prudence in managing exposure to electromagnetic fields (EMF). When efficient shared use of spectrum is investigated, it is necessary to consider *why* the power available for wireless transmission is limited, and *how* this limitation on available power is expressed, and therefore the issue of spectrum sharing cannot be addressed without taking into account safety-related constraints on power. EMF levels need to be regulated to levels well below levels where there might be harm and therefore below the internationally agreed EMF exposure limit standards. Hence, we do not expect to see any health effects at these levels.

In Chapter 3 of this dissertation, it is argued that for the safety of human health, we should assume that there must be constraints on the power, or EMF, used at each device participating in the shared communication. These constraints on EMF affect the way we share the spectrum. The way these regulations are expressed needs great care because it will have an effect on the design of the wireless communication systems.

In Chapter 4, a Spread Spectrum-Orthogonal Frequency Division Multiplexing (SS-

OFDM) model is developed for efficient sharing of the spectrum among nearby users. Efficient sharing is shown to be consistent with nearby WiFi domains appearing as noise to each other (which is the characteristic property of spread-spectrum).

In Chapter 5, we assume that there must be constraints on the power, or EMF, used at each device participating in the shared communication. This thesis considers five different forms of power/EMF constraint and compares the sum-throughput achieved by all devices, under these different constraints. Note that the five different approaches to meeting power/EMF constraints that are considered here vary slightly in the way the constraint is expressed, but also, and this is the more significant aspect, in the way in which the constraint is enforced. These five approaches are; Carrier-Sense Multiple Access (CSMA) method, Orthogonal Frequency-Division Multiple Access (OFDMA), EMF limited, SS-OFDM, and mutually interfering.

In Chapter 6, cross-subchannel noise in OFDMA is modelled, which shows that nearby systems interfere with each other to a greater degree than might be expected. Conclusions are presented in Chapter 7.

Certification of Thesis

This Thesis is entirely the work of **Mohammad Kaisb Layous Alhasnawi** except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors signatures of endorsement are held at the University.

Principal Supervisor: **Associate Professor Dr. Ronald G. Addie**

Associate Supervisor: **Dr. Shahab Abdulla**

Associated Publications

Alhasnawi, M. K. L., Abdulla, S., Fatseas, D. and Addie, R. G. (2020), 'Spectral density constraints on wireless communication', Heliyon 6(5), e03979.

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Acronyms & Abbreviations

OFDM	Orthogonal Frequency-Division Multiplexing
CDMA	Code-Division Multiple Access
SS-OFDM	Spread Spectrum- Orthogonal Frequency-Division Multiplexing
ISI	Inter Symbol Interference
ADSL	Asymmetric Digital Subscriber Line
DSSS	Direct Sequence Spread Spectrum
M-QAM	M-ary Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
Netml	Network Modelling Language
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
EMF	Electric and Magnetic Field
WHO	World Health Organization
NIEHS	National Institute for Environmental Health Sciences
RPC	Radiation Protection Committee
NRPB	National Radiological Protection Board
BER	Bit Error Rate
SRSA	Swedish Radiation Safety Authority

SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks
PSD	Power Spectral Density
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineer
FCC	Federal Communications Commission
ACGIH	Association Advancing Occupational and Environmental Health
OFDMA	Orthogonal Frequency-Division Multiple Access
LTE	Long-Term Evolution
WiMAX	Worldwide Interoperability for Microwave Access
3GPP	3rd Generation Partnership Project
PUs	Primary (licensed) Users
SUs	Secondary (unlicensed) Users
CR	Cognitive Radio
IR	Infra-Red radiation
WLAN	Wireless Local Area Network
CSMA	Carrier-Sense Multiple Access
DCF	Distributed Coordination Function
TIM	Traffic Indication Map
RAW	Restricted Access Window

Nomenclature

C	Channel capacity in bits per second
B	Bandwidth in hertz
SNR	Signal-to-noise ratio
S	Average received of signal power at the bandwidth, measured in Watts
N	Average power of the interference and noise at the bandwidth
ρ	A prime number
$GF(\rho)$	Galois field
p	A primitive, which is an element of the field
l	Length of the antenna
μ	Permeability of the medium
ϵ	Permittivity of the medium
θ	Angle between the dipole antenna and the line to the receiver
β	Phase constant
λ	Wavelength of the radiation
r	Distance from the dipole to the receiver
E_θ	Magnitude of the EMF of a WiFi signal transmitted from a Hertzian dipole antenna
P_{rad}	Power radiated by a wireless access point
$E_{2.45,\theta}$	Regulated limit on the magnitude of the EMF in the 2.45 GHz
$E_{5,\theta}$	Regulated limit on the magnitude of the EMF in the 5 GHz

P_n	Power constraints
T_P	Regulate total EMF
g_{jk}	The ratio of the power received at node k
D	Directivity of the aerial at node S_j
r_{jk}	Distance between the source of transmission j and the source of transmission k
u	A vector of $1's$ and $*'s$. If $u_j = *$

Chapter 1

Introduction

Spectrum sharing is a problem of considerable interest and importance at the moment because it is a limited resource, and there is more and more use of it (Martínez-Vargas et al. 2016, Cordeiro et al. 2005). Throughout this research, we seek to maximise total transmission rate, subject to constraints on resources. We can achieve higher transmission rate quite easily by just using more power. However, transmitted power is subject to international and national regulation. So, from the very outset, there is a connection between constraints and regulations on power (or its associated EMF) and high-speed communication. Hence, this research undertakes to investigate optimal use of spectrum subject to constraints on EMF in a series of four steps, which enhance the efficiency of the available spectrum sharing to achieve high- speed communication subject to regulation of levels of generated EMF.

The first step we take in this research, in Chapter 3, is to more closely investigate the manner in which regulations on EMF are, or should be, expressed (Alhasnawi et al. 2020). The level of EMF should be well below levels where there might be harm, hence we do not expect to see any health effects at these levels. Current regulations fail to place a strict limit on EMF in situations where multiple nearby devices transmit simultaneously. Currently, power constraints are expressed as if devices share spectrum by never using the same frequency at the same time as a nearby device. However, efficient use of spectrum over time forces wireless protocols to use the same spectrum at the same time as nearby devices (IEEE Standards Association and others 2012). Under these circumstances, if many users cluster together, the health impact of their wireless communication will be cumulative. Furthermore, if the regulatory constraint continues to be expressed in terms of the transmitted power of each device it becomes possible to subvert the intention of this constraint by using a collection of devices which share the same spectrum, and all transmit at the same time. This goes against the spirit of the regulations on wireless communication, or, looking at the problem a little differently shows that regulations on transmitted power should be expressed differently to avoid this type of abuse.

In order for such regulations to be expressed in a convenient and clear manner, since we cannot anticipate the full range of ways in which spectrum is sub-divided by devices, it is logical that the regulated constraint should be expressed in EMF spectral density $V/m/Hz$, or total transmitted power spectral density W/Hz, or total received power spectral density $W/m^2/Hz$. These three approaches are all possible, and under reasonable assumptions might be regarded as equivalent. However, in order to express the central problem most clearly, and because these measures of intensity of electromagnetic radiation are closely related, it is preferable to focus on one of these quantities. In Chapter 3, consequently, the parameter which is emphasised is total EMF spectral density (for both the device which is regulated and nearby independent devices) for *all* frequencies, expressed in $V/m/Hz$.

In Chapter 4, the second step of the research is undertaken, which is the development of a *spread-spectrum OFDM* system (Alhasnawi. et al. 2018). Spread-spectrum systems which are nearly co-located systems perceive each other as noise, and when doing so do not necessarily (depending on how the system is implemented) suffer any loss in the overall efficiency of spectrum use, so the use of spread-spectrum with OFDM has the potential to enable efficient spectrum sharing. However, the evaluation of SS-OFDM from the point of view of spectrum efficiency has not received close attention in much of its literature up to this point. OFDM is currently used for several of the latest standards for wireless, telecommunications, and digital video broadcasting (Wen et al. 2016, Sung et al. 2010, Armstrong 2009, Coleri et al. 2002). OFDMA appears to provide efficient sharing of the spectrum but has the effect of concentrating power in narrow ranges of frequencies, which is undesirable from the viewpoint of Chapter 3.

The third step of the research compares the throughput of different methods of sharing spectrum subject to a constraint on power, or EMF, used at each device participating in the shared communication (Alhasnawi. & Addie. 2019). If shared use of spectrum is mediated by time-segregated use, which is often the case (e.g. as in CSMA/CA), a limit on the power transmitted by any device imposes a constraint on the total electrical field strength (and magnetic field strength), which can occur. Regulations on transmission power are not necessarily imposed for this purpose, however, as the number of devices sharing the same physical and spectral location increases, it may become appropriate, or necessary to view regulation of power in this light, i.e. as a means to limit total electromagnetic field strength.

In Chapter 5, this study supposes five different approaches to limiting power which vary in the way the aggregate EMF due to all the devices is considered. Note that the five different approaches to meeting power/EMF constraints that are considered here vary slightly in the way the constraint is *expressed*, but also, and this is the more significant aspect, in the *way* in which the constraint is *enforced.*

Finally, in Chapter 6 investigates cross-subchannel noise in OFDMA, between sub-channels which would be orthogonal to each other, if used in a single OFDM system, but are not, when used in different geographically nearby locations.

The four steps of the research combine together to show how we can efficiently share spectrum. First the constraint on power is investigated, then it is shown how the available power, in these terms, can be efficiently used by means of SS-OFDM. Different schemes for spectrum sharing are compared, from which it is seen that SS-OFDM is as efficient as all others and preferable when the need to express the power constaint in terms of spectral density is taken into account. Finally, it is shown that OFDMA has a further weakness due to cross-sub-channel noise.

1.1 Problem statement

According to (Zhang, Chu, Guo & Wang 2015) a big challenge facing researchers in wireless communication is efficient spectrum sharing. There is an imbalance between the rapidly growing demand and the limited resources of wireless spectrum. The authors (Martínez-Vargas et al. 2016, Ji & Liu 2007) show that in order to achieve efficient and full utilisation of valuable common spectrum, the protocols and/or technologies used in wireless communication need to be changed so that efficient spectrum sharing is one of the key design objectives.

Another related problem is the multiplexing and optimal allocation of power to different devices. When these communication devices take place in the same region, they use the shared spectrum.

Environmental exposure to man-made electromagnetic field (EMF) has been rising as modern technologies have grown and changes in social behaviour have generated more synthetic sources. For safety of human health, EMF levels need to be regulated. The level of EMF should be well below levels where there might be harm, hence we do not expect to see any health effects at these levels.

1.2 Research questions

1. How can we achieve better utilisation of spectrum?
2. How can spread spectrum OFDM systems be developed and deployed?
3. In what way should power, or EMF, constraints be expressed?
4. To what extent should possible health effects of EMF on biological forms be taken into account in expressing power/EMF constraints?
5. If possible health effects are taken into account, how should constraints on power/EMF be expressed?

1.3 Philosophy and aims of this thesis

The aim of this project is to investigate several different techniques, which allow efficient sharing of the spectrum for achieving high-speed communication that occurs with moderate additional complexity.

OFDM is considered as a highly effective technique and is being used for several of the latest standards for wireless, telecommunications, and digital video broadcasting (Sung et al. 2010, Armstrong 2009, Coleri et al. 2002). However, it is not obvious *how best* to share available spectrum efficiently while using OFDM and respecting appropriate power/EMF constraints. SS-OFDM is an emerging approach which combines OFDM (Alhasnawi. et al. 2018, Akare et al. 2009, Xia et al. 2003, Jaisal

2011, Meel 1999) with spread-spectrum concepts to allow optimal sharing to occur with very little additional effort.

In this research, a model and algorithm for predicting WiFi throughput of SS-OFDM systems will be developed. Initially, it appears that optimal spectrum sharing can be achieved by OFDMA. However, OFDMA inevitably causes EMF to be concentrated in certain narrow ranges of frequencies. Although the particular range of frequencies where EMF is concentrated is likely to vary, geographically, when OFDMA is used, this may be considered undesirable from the point of view of possible health effects of wireless communication. In particular, if the constraint on power/EMF is expressed as a bound on EMF spectral density, in $V/m/Hz$, then SS-OFDM becomes more efficient in sharing of spectrum than OFDMA.

1.4 Significance of research

This study improves the available spectrum sharing significantly through:

- **Guidance to network managers:** this research provides guidance to network managers how to distribute channels without any waste of available spectrum.
- **Regulation of EMF levels:** this research suggests that a *technical limit* on EMF spectral density, introduced somewhere in the range from 100 to 1000 $V/m/logHz$. All except very low power devices should ensure that the EMF spectral density generated by their own, and other nearby devices is below this level (i.e. some number, yet to be specified, between 100 and 1000 $V/m/logHz$) at all times, in the range of frequencies where they generate EMF. We do not expect to see any health effects at these levels. Nevertheless, the way these regulations are expressed needs great care because the way they are expressed

will have an effect on the design of wireless communication systems.

- **Efficient spectrum sharing:** an essential idea for this research is that the concept of SS-OFDM has the potential to significantly enhance efficient utilisation of shared spectrum.

1.5 Contributions

The essential contributions of this thesis are :

- Using constraints on EMF spectral density, rather than (or as well as) on transmitted power. Such constraints can be used to express limits for health reasons or for technical reasons, or both. For consistency and simplicity, these constraints can be uniform across all frequencies when expressed in $V/m/logHz$.
- An SS-OFDM has been demonstrated that achieves the desired performance.
- The SS-OFDM system that was implemented demonstrated that SS-OFDM is able to achieve nearly optimal spectral efficiency when used as a method for sharing media.
- Experiments showed that OFDMA and the EMF-limited cases provide nearly identical performance. This is because in all the cases considered, the EMF limits on power are not significantly different from simply limiting the transmitted power of each device. If configurations where devices are very close together were considered, this would no longer be the case.
- Another consistent result was that OFDMA consistently out-performed all other sharing mechanisms, except SS-OFDM, when the EMF constraint was expressed in terms of total EMF, rather than EMF spectral density.

- The SS-OFDM case considered assumed non-orthogonal codes, with a correlation between codes at level 0.1. If orthogonal codes are used, the performance of SS-OFDM is identical to OFDMA. Such experiments were conducted, but not shown (since the throughput of SS-OFDM then simply becomes identical to that of OFDMA).

- The spectral distribution of SS-OFDM is essentially flat, unlike that of OFDMA. If this is an important consideration, SS-OFDM is therefore the preferred option.

- This study shows that cross-subchannel noise exists and might significantly compromise the performance of OFDMA. The results showed that nearby systems using the same OFDMA configuration are no longer orthogonal, because of the large differences in latency. OFDMA is an alternative that looks as good as SS-OFDM, but it is not quite as good as it seems because of cross-channel noise, given health constraints, and efficient spectrum sharing, it is important to use SS-OFDM.

- Since SS-OFDM is able to achieve the same throughput as OFDMA with a flat power spectral density, it is actually more efficient in use of spectrum, once the EMF constraint is expressed in terms of its spectral density.

1.6 Organization of the thesis

This dissertation consists of seven chapters, as shown in Figure 1.1, including the current introductory chapter, which presents the problem statement, its significance, and reviews its scope and main contributions. The remaining chapters are as follows:

- Chapter 2 gives a brief overview of the current WiFi standards, which are used

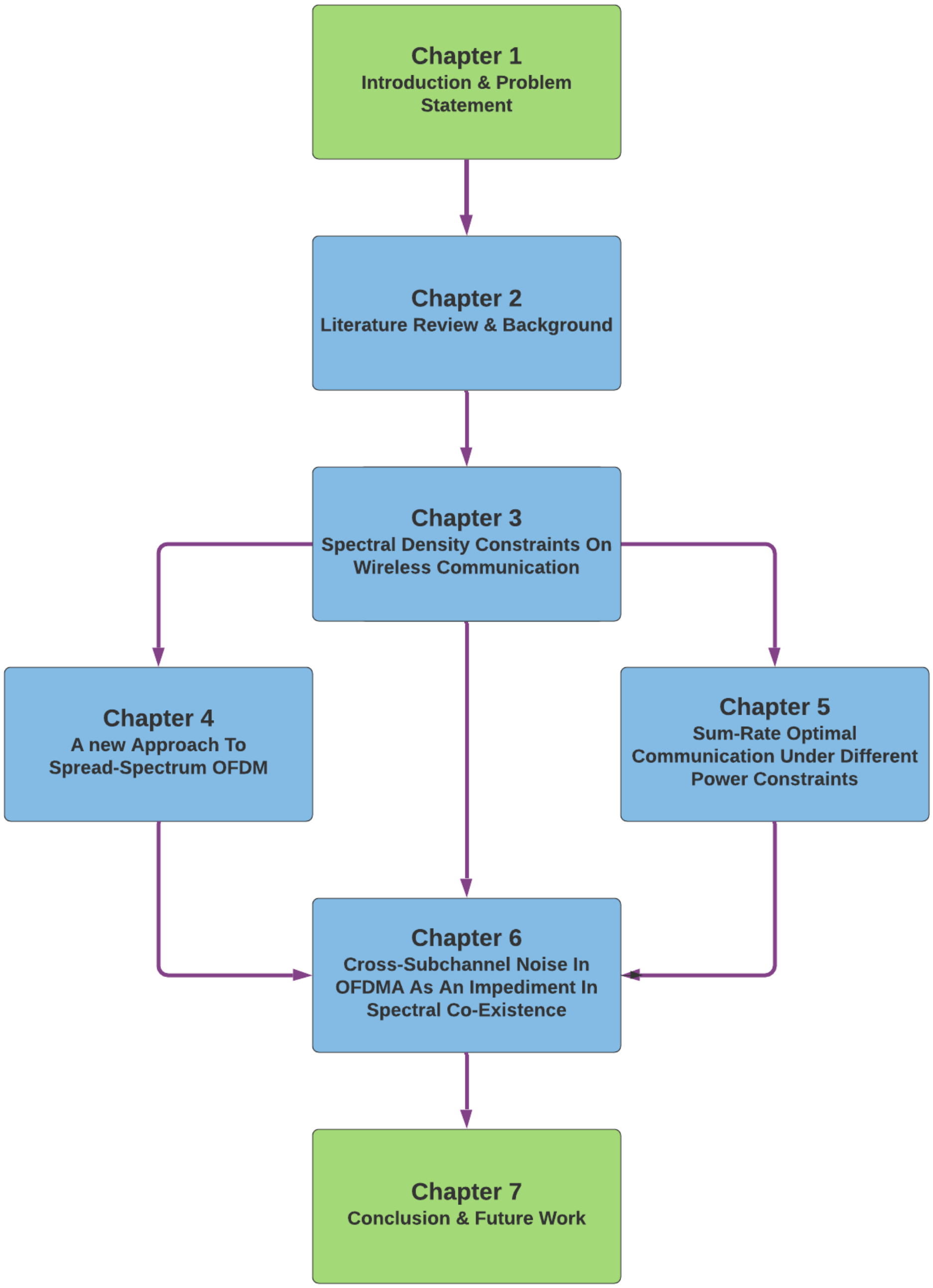

Figure 1.1: Thesis structure

in wireless communication. This chapter reviews the background about the problems, which are facing the researchers and experts for available spectrum sharing. Also, it provides the literature review and background on OFDM and on the concept of spreading spectrum in OFDM. . Then, it explains the communication fundamentals and how we can calculate the transmission capacity between two systems by using the Shannon formula.

- In Chapter 3, it is argued that transmitted power constraints on wireless communication devices should be expressed in a different way, namely that devices should actively seek to limit by their own behaviour, the EMF spectral density (in $V/m/Hz$), due to each device's own transmission and that of other devices operating in close vicinity.

- In Chapter 4, OFDM systems are reviewed and the Shannon bound is discussed as a criterion of efficient spectrum use and a design criterion. The problem of efficient sharing of spectrum by wireless communication systems is discussed and combined use of Direct-Sequence Spread-Spectrum (DSSS) coding and OFDM is proposed as an approach that can achieve efficient spectrum sharing. A system which enables DSSS, with codes from the Galois field of order ρ where ρ is a prime larger than 2, to be used efficiently in conjunction with OFDM is then defined, analysed, and implemented. Experiments with this system are described.

- In Chapter 5, the problem of optimal allocation of power to different devices and spectrum when communication takes place in the same region, using shared spectrum, is investigated. This research assumes that there must be constraints on the power, or EMF, used at each device participating in the shared communication. This study considers different forms of power/EMF constraint and compares the sum-throughput achieved by all devices, under these different constraints.

- Chapter 6 investigates the issue of noise generated by the interference of one sub-channel with another in OFDMA, which is a further limitation on the effectiveness of OFDMA as a spectrum sharing mechanism. In this chapter cross-subchannel noise due to undesirable interference between nearby OFDMA systems is modeled and it is shown that cross-subchannel noise may significantly impact OFDMA systems.

- Finally, conclusions and future research directions of the thesis are presented in Chapter 7.

Chapter 2

Literature Review and Background

2.1 Communication fundamentals

The Shannon-Hartley formula provides the maximum rate of data, which can be transmitted reliably across a noisy channel in a Gaussian noise environment (Rioul & Magossi 2014):

$$C = B \log_2 \left(1 + \frac{S}{N}\right), \tag{2.1}$$

where C is the channel capacity in bits per second, B is the bandwidth in Hertz, S is the average received signal power, and N is the average power of the noise received in the same spectrum (measured in the same units) (Mishra et al. 2006).

2.2 WiFi standards

Wireless networking is a technology nearly as fundamental today as computing itself. WiFi networking has pushed user experience and performance of wireless communication to the point where it is keeping pace with rapidly increasing demand. Meanwhile, these higher speeds must be available to the users without causing a degradation of quality or harm to users (Briso-Rodríguez et al. 2017, Verma et al. 2013). This technology enables devices to easily connect with each other without requiring a cable to be connected to either device. The studies (Miao et al. 2016, Gast 2005) discuss the fact that wireless provides several benefits over fixed or wired networks like mobility, ease and speed of deployment, flexibility, and less cost. There are different types of wireless communication, including, Infra-Red (IR) radiation , Blue-tooth technology, broadcast radio, satellite communication, Microwave radio, cellular mobile systems (3G, 4G, and 5G), and Wireless Local Area Network (WLAN).

The Institute of Electrical and Electronic Engineers (IEEE) has developed a family of specifications under the general code, 802.11. IEEE 802.11 is the original wireless specification. There are many wireless networking standards of the IEEE 802.11 protocol family . The first protocol in this family was an 802.11-base version, which provides up to 2 Mbps maximum data rate in the 2.4 GHz frequency band, followed by 802.11b, which operates up to 11 Mbps data rate in the 2.4 GHz band. The next protocol was 802.11a, which supplies up to 54 Mbps data rate in the 5 GHz band. Other standards in the family included 802.11g, 802.11n, and 802.11ac, more details of which are shown in Table 2.1 (Nurchis & Bellalta 2019, Yao et al. 2019, Ali et al. 2018, Tian et al. 2017, Boucouvalas et al. 2015, Wong et al. 2006, Pefkianakis et al. 2010).

Table 2.1: IEEE 802.11 network standards

802.11 Protocol	Release date	Frequency (GHz)	Bandwidth (MHz)	Stream data rate Min-Max (Mbit/s)	Allowable MIMO streams	Modulation Antenna	Range (m) In	Range (m) Out
802.11-base version	Jun 1997	2.4	22	1 - 2	1	DSSS, FHSS	20	100
a	Sep 1999	5	20	6 - 54	1	OFDM	35	120
		3.7						
b	Sep 1999	2.4	22	1 - 11	1	DSSS	35	140
g	Jun 2003	2.4	20	6 - 54	1	OFDM, DSSS	38	140
n	Oct 2009	2.4 & 5	20	Up to 288.8	4	OFDM	70	250
			40	Up to 600				
ac	Dec 2013	5	20	Up to 346.8	8	OFDM	35	...
			40	Up to 800			35	...
			80	Up to 1733.2			35	...
			160	Up to 3466.8			35	...
ax	Mar 2019	< 6	160	> 10000	8	OFDM, OFDMA	70	240

Note : Range In or Out refers to indoor or outdoor respectively.

2.3 Power and EMF regulation

Electromagnetic Field (EMF) is a combination of an Electric Field (EF) and a Magnetic Fields (MF), which exists everywhere in our environment (Consales et al. 2012). This phenomenon occurs from natural sources and because of human activity. Some of the most common natural sources occurring of EMFs are; the earth, sun, and ionosphere. As for EMF caused by man-made activity, this includes: radio and television waves, electrical appliances, wiring in homes, workplace pieces of equipment, and WiFi, i.e. computers, ipads, and phones using wireless LANs (Exponent 2017).

Constraints on transmitted power and on the electrical and magnetic field strength due to transmission exist currently in documents prepared and published by several international standards organizations (Ahlbom et al. 1998, IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards 1992, Fields 1997, Sliney & Hathaway 2016). Some of these regulations are explicitly formulated for the purpose of avoiding possible harmful effects on health (Qureshi et al. 2018, Vermeeren et al. 2018), and others are formulated as technical restrictions on the use of electromagnetic spectrum, for communication (Rubtsova et al. 2018), without explicitly acknowledging the potential for harm to be caused.

Currently, power constraints are expressed as if devices share spectrum by never using the same frequency at the same time as a nearby device. However, efficient use of spectrum over time forces wireless protocols to use the same spectrum at the same time as nearby devices (Alhasnawi. & Addie. 2019).

The public exposure to EMF is regulated by means of a collection of voluntary and formal standards. The study (World Health Organization and others 2000) reviewed the most significant guidelines and exposure limits on electric and magnetic fields. The guidelines are prepared by international standards bodies which are aiming to avoid risks to health resulting from short or long term exposure, adopting a large margin of safety. The most important of the standards on exposure to EMF is (Ahlbom et al. 1998, International Commission on Non-Ionizing Radiation Protection and others 2010). Table 2.2 summarizes this standard and three others (IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards 1992, Fields 1997, Sliney & Hathaway 2016).

A weakness of these regulations is that multiple compliant devices in close proximity can produce field strengths in excess of the proposed limits. This issue is explored in Chapter 3, where regulation of EMF *spectral density* is proposed as an alternative way to constrain emissions from devices. Table 2.1 will be expanded in Chapter 3 to include the implied spectral density constraints, as shown in Table 3.1 .

The sources of the standards in Table 2.2 are shown in Table 2.3.

2.4 OFDM modulation scheme

In (Jaradat et al. 2019), OFDM is identified as one of the most essential systems used in communication networks. This technique uses multi-carrier modulation of signals over a collection of sub-channels at nearby frequencies. OFDM works by dividing the high rate stream into parallel lesser rate streams and stretching the duration of each symbol, as shown in Figure 2.1. These factors may lead to reduce inter symbol interference (ISI) (Borra & Chaparala 2013, Morelli & Mengali 2001). All major communication systems recently developed are using OFDM as their modulation method, especially on transmission scheme such as WLAN, Asymmetric Digital Subscriber Line (ADSL), broadband indoor wireless systems, Digital Video Broadcasting (DVB), and Digital Audio Broadcasting (DAB) (Rabinowitz & Spilker Jr 2008, Bölcskei et al. 2003). This technique provides quality of data transmission and widely implemented in different systems (Christodoulopoulos et al. 2011). The authors of (Sivanagaraju 2014, Weiss et al. 2004, Mostofi & Cox 2006) claim that OFDM will remain a promising choice for high speed data rate systems in the future. It is an effective method that reduces the ISI and noise, and avoids dispersion impact of multi-path channels, particularly when this method deals with big data rates (Jiang & Wright 2016, Mahmoud et al. 2009). OFDM appears to be an indespensible feature of most communication systems for the forseeable future.

Table 2.2: EMF exposure limit standards

Standard	**Frequency range**	**Electric field strength (V/m)**
ICNIRP	Up to 1 Hz	—
	1-8 Hz	10000
	8-25 Hz	10000
	0.025-0.8 kHz	$250/f$
	0.8-3 kHz	$250/f$
	3-150 kHz	87
	0.15-1 MHz	87
	1-10 MHz	$87/f^{\frac{1}{2}}$
	10-400 MHz	28
	400-2000 MHz	$1.375f^{\frac{1}{2}}$
	2-300 GHz	61
IEEE	0.003-0.1 MHz	614
	0.1-3.0 MHz	614
	3-30 MHz	$1842/f$
	30-100 MHz	61.4
	100-300 MHz	61.4
	300-3000 MHz	—
	3000-15000 MHz	—
	15000-300000 MHz	—
FCC	0.3-3.0 MHz	614
	3.0-30 MHz	$1842/f$
	30-300 MHz	61.4
	300-1500 MHz	—
	1500-100,000 MHz	—
ACGIH	30-100 kHz	1842
	100 kHz-1 MHz	1842
	1-30 MHz	$1842/f$
	30-100 MHz	61.4
	100 MHz-300 MHz	61.4
	300 MHz-3 GHz	—
	3-30 GHz	—
	30-300 GHz	—
Note: f , in column 3, denotes frequency, in Hz.		

Table 2.3: Sources for EMF exposure limit standards

Organization	Source
ICNIRP	(Ahlbom et al. 1998), Table 7
IEEE	(IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards 1992), Table 1, part A
FCC	(Fields 1997), Appendix A
ACGIH	(Sliney & Hathaway 2016), Table 15.1

2.4.1 OFDM system and wireless networking

OFDM is a particularly dominant as the digital modulation system for wireless communication systems. Transmission speeds for wireless communication systems have dramatically increased over recent years (Abdullahi et al. 2020). The researchers (Basar 2016, Nee & Prasad 2000) have shown that OFDM modulation provides flexible bandwidth, improves the protection of multi-path fading, and enhances robustness by insertion of the guard interval, which solves the requirements of bandwidth for data users. In effect, OFDM is one of the key developments, with turbo and related codes, which has enabled modern wireless communication systems to get close to achieving the Shannon bound.

2.4.2 Optimal spectrum sharing and power allocation for OFDM

The authors (Li et al. 2017, Dong & Shahbazpanahi 2010) consider that the modern techniques in WiFi networks improve the overall performance of radio communication, in the specific context of a simplex relay network. In (Lu et al. 2018, Wu

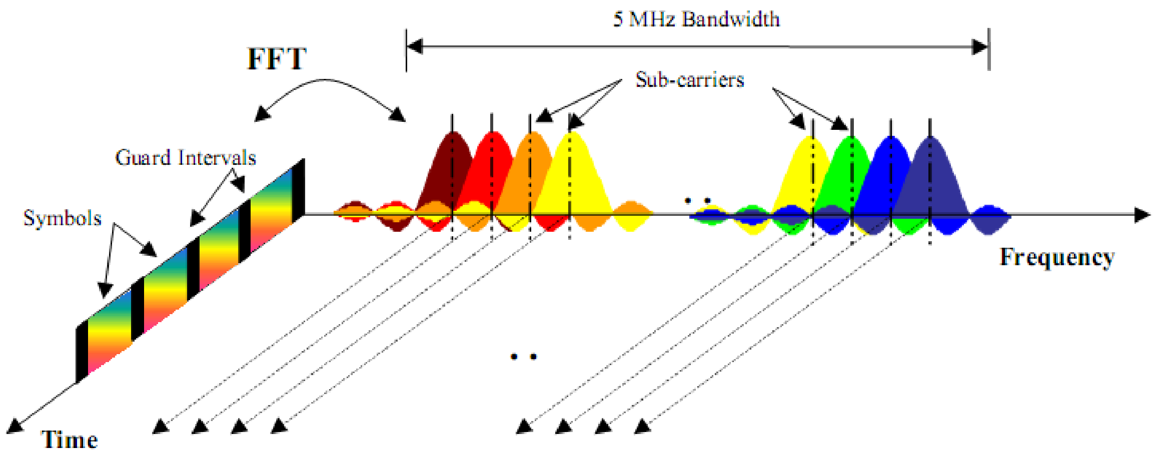

Figure 2.1: OFDM system (Lima et al. 2008)

et al. 2005), the performance of radio communication under consideration includes data transmission range and capacity (Lu et al. 2018, Wu et al. 2005). These studies investigated the a two-way relay scheme, which is receiving and sending the signal between node 1 and node 2, and it assumes the two nodes used the same sub-carriers to data transmission, as shown in Figure 2.2. This figure describes using a single radio channel and operates in a half-duplex mode, which is only one user on the channel can transmit at a time, so users in a user group must take turns transmitting. Another study (Liu et al. 2013) indicated that some essential results for two-way relay communication such as, can be achieved the Signal to Noise Ratio (SNR) balance among the all nodes at a system and two-way relaying technique can improve the efficiency of available spectrum in relay-assisted directional of networks. Moreover, it creates the compatibility of power allocation for relay path sub-carriers on each node. Those results lead to use the spectrum sharing and power allocation effectively.

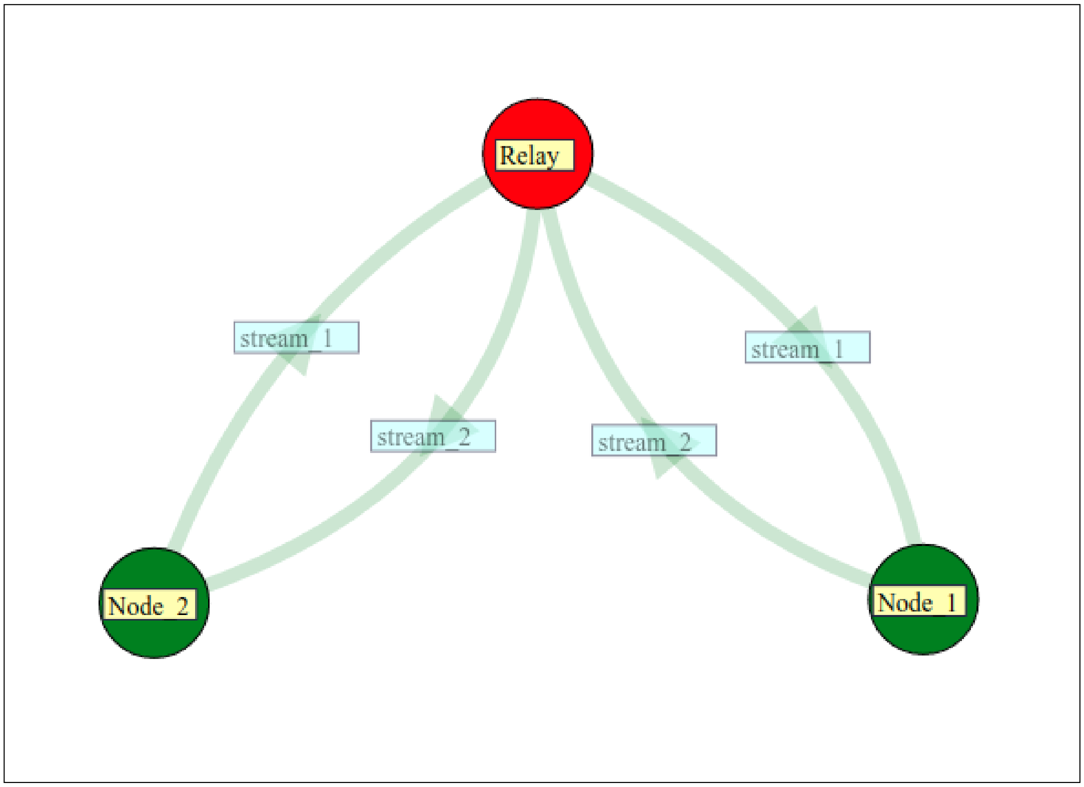

Figure 2.2: Two-way relay method in an OFDM scheme

2.5 Available spectrum sharing

In recent decades, the efficient sharing of electromagnetic spectrum is considered an essential factor in telecommunication systems (Fitzgerald 2018, Matinmikko et al. 2014, Peha 2013). Scarcity of spectrum is an increasingly important issue, with a rapid increase in the number of devices using this spectrum (Cheng et al. 2020, Bhandari et al. 2019, Baek & Lim 2016, Jorswieck et al. 2010), as suggested by Figure 2.3.

Hence the sharing of available spectrum needs development. The authors of (Cheng et al. 2020, Saint & Brown 2019, Cordeiro et al. 2005) are referring to such mecha-

Figure 2.3: Spectrum sharing (Safe Living 2019)

nisms, suggest that they may lead to maximising the benefit from new technologies and use of available spectrum, by preventing inefficient interference.

Radio-communication technology has used steady increase in the capability and speed of microprocessors to provide more advanced and new services. Other studies (Shi et al. 2019, Zhang, Wang, Cai, Zheng, Shen & Xie 2015, Ryan 2004) have pointed to other modern technologies, which have given an opportunity to use the available spectrum more efficiently. This chance has been achieved by increase in aggregate communication efficiency, more precise discrimination of the desired signal from interference, better reduction of noise, and improvement in the directionality of antennas.

One of the major contributors to the improvement in communication system efficiency is the development of mature OFDM systems, which has solved the multi-path problem so efficiently that the capacity of the OFDM system applied in the presence of multi-path fading, is the same as if there was no multi-path problem (Talebi et al. 2014).

2.6 Effective electromagnetic spectrum sharing

Many researchers and experts have suggested approaches and techniques to develop or create new methods to improve the spectrum sharing for effective communication between users using wireless communication (Jamoos et al. 2019, Chowdary & Rao 2019, Garcia-Luna-Aceves 2019, Xu et al. 2019, Wang et al. 2018). These techniques include:

1. Cognitive Radio (CR) networks, which is discussed in detail in Subsection 2.6.1,
2. Carrier-Sense Multiple Access (CSMA) method, the modelling of which is presented in Subsection 2.6.2,
3. Orthogonal Frequency-Division Multiple Access (OFDMA) modulation scheme, which is treated in Subsection 2.6.3, and is explored in more detail in Chapter 6, and,
4. Spread Spectrum-Orthogonal Frequency Division Multiplexing (SS-OFDM) , which is presented in Subsection 2.6.4, and is explored in more detail in Chapter 4.

2.6.1 Cognitive radio networks

In spite of increasing demand for spectrum being used by wireless devices and applications, the researchers (Babu & Amudha 2014) found that the electromagnetic spectrum is not fully exploited due to static distribution of the available spectrum, as evident in Figure 2.4. The study (Pandit & Singh 2017) pointed to the traditional strategies of static spectrum usage in the licensed bands' allocation leading to widespread presence of underutilized spaces. Therefore, the inefficient utilisation of the spectral resource leads to scarcity of spectrum. Hence there is an urgent need to consider a new approach such as a Cognitive Radio (CR) that is capable of managing spectrum more effecticiently.

Cognitive Radion was introduced in 1999 by (Mitola et al. 1999). This technique is an adaptive and intelligent radio, based on knowing of the surrounding environment and automatically handling and adapting the data transmissions that depend on interference, noise, and available channels (Alijani & Osman 2020, Moghaddam 2018). Cognitive radio is highly suited to choice and the use of the best wireless available channels in its region to avoid the transmission interference and congestion for users in wireless spectrum. Also, this technique can change its operational parameters such as operating frequency, modulation scheme, transmission power, and communication technology to improve the performance of users that provides more reliable and effective communication for users and improve operating behaviour of radio networks (Onumanyi et al. 2019, Babu & Amudha 2014).

For example, Figure 2.5 shows that cognitive radio, has the ability to allow using the temporally unused frequency spectrum . When this frequency band is utilised by a Primary User (PU), the unlicensed user moves to a spectrum hole or remains in the same a frequency band, but the cognitive radio changes its level of transmission power or the modulation technique to prevent interference between users of the same system.

Figure 2.6 illustrates the concept of a cognitive cycle, which is used to manage spectrum in Cognitive Radio systems:

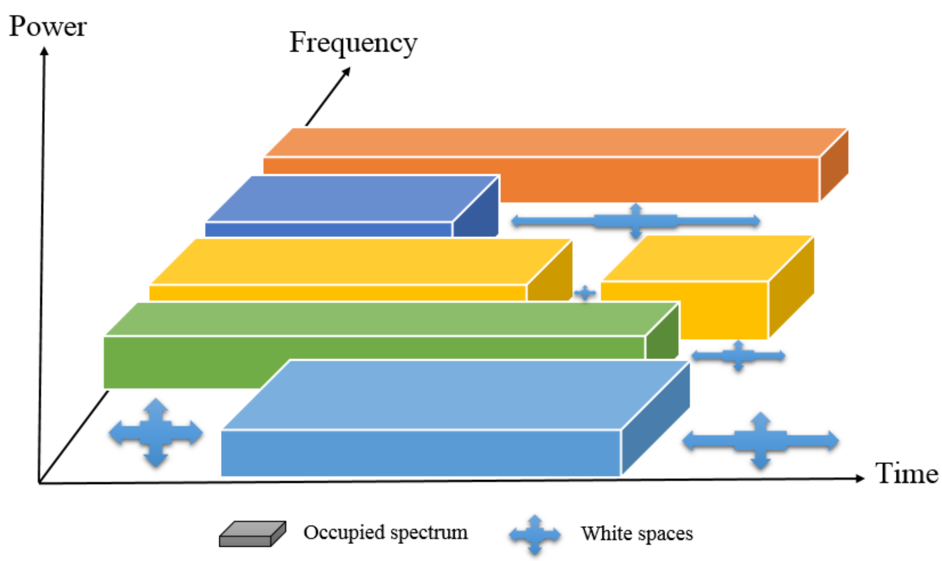

Figure 2.4: White spaces and occupied spectrum

1. **Spectrum sensing:** the principal role of spectrum sensing is to detect the status of the spectrum. This technique determines whether the spectrum is being used by the Primary (licensed) users (PUs), the Secondary (unlicensed) users (SUs), or whether it is idle (not occupied by PUs or SUs) (Liu et al. 2019, Babu & Amudha 2014, Subhedar & Birajdar 2011).

   In (Arjoune & Kaabouch 2019, Pelechrinis et al. 2013), the authors pointed to the significant challenge is calculating interference in the licensed receiver, which is caused by SUs through data transmission. The first problem is the some SUs may not know the exact location of the licensed receiver, which needs interference measurement of transmission. Secondly, the licensed receiver is passive and the transmitters may not realise the essential operations of a receiver. This situation may lead to transmission interference. Therefore, these problems need to be addressed and special attention is needed by experts and researchers to limit interference at the licensed receiver.

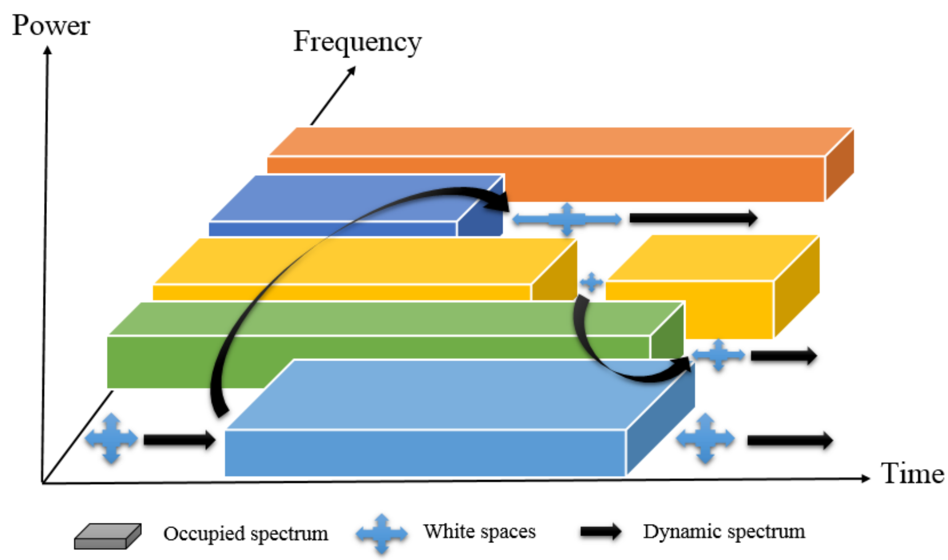

Figure 2.5: White spaces and occupied spectrum with cognitive radio

2. **Spectrum analysis:** the spectral bands were estimated by spectrum sensing. The estimation results of these bands as their capacity and reliability is to be sent to the next step, which is named a spectrum decision (Unissa et al. 2019, Sun 2011).

3. **Spectrum decision:** as a result of the previous spectrum analysis, in this stage, the study (Al Attal et al. 2019, Sun 2011) referred to a convenient frequency band that will be chosen for a cognitive radio node. Then the cognitive radio selects or changes the transmission parameters such as operating frequency, modulation scheme, transmission mode, and transmission power for avoiding harmful interference between the users in the same vicinity, and improving the transmission performance of the system.

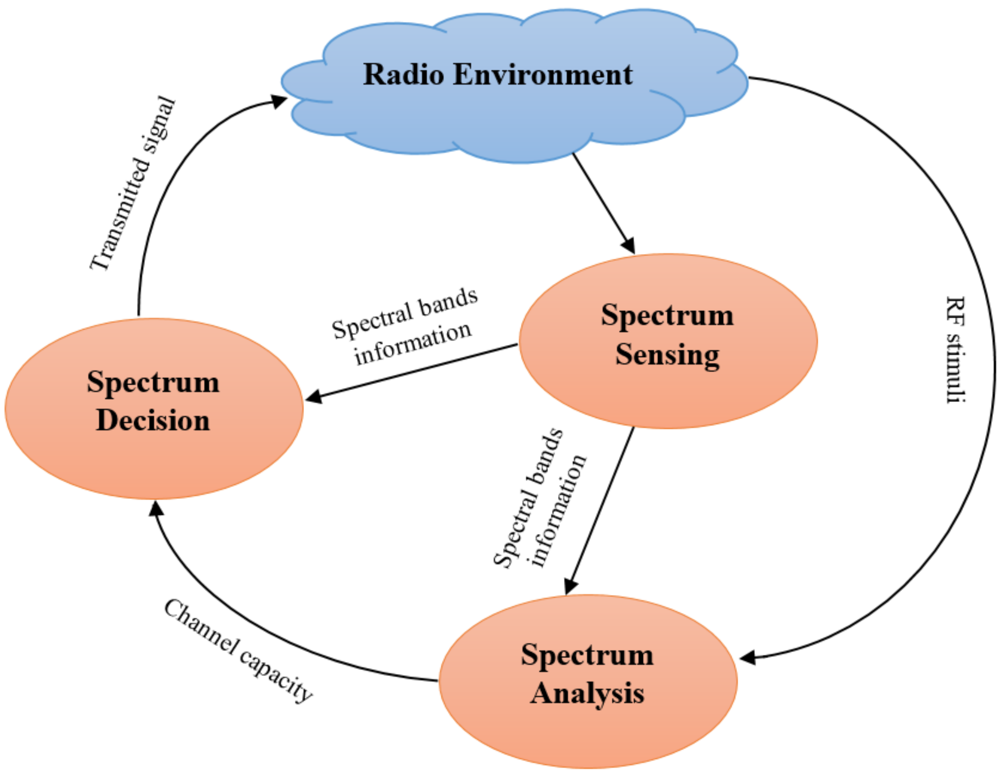

Figure 2.6: Cognitive radio cycle

2.6.2 CSMA network protocol

A Carrier-Sense Multiple Access (CSMA) technique was first introduced in 1975 by Kleinrock and Tobagi (Kleinrock & Tobagi 1975), who were the first to address the issue of the hidden terminal in CSMA. In the IEEE 802.11 Wireless LAN or WiFi, CSMA/CA is used for media access control, with the exception that 802.11 is able to use, also, OFDMA (Garcia-Luna-Aceves & Carvalho 2018).

This technique controls the communication of multiple users on a participated and decentralised radio channels in WLAN or ad-hoc networks (Garcia-Luna-Aceves & Carvalho 2018, Gross et al. 1998). CSMA has the ability to decrease the probability of collision between signals . CSMA remains highly relevant to all wireless communication systems because it is still in wide use, and because there are situations, as explained later, where it might actually be the most efficient form of spectrum sharing.

CSMA protocol uses several algorithms based on to select the suitable time to transmission on the shared medium. The fundamental characteristic of these algorithms is how persistent or aggressive, are in beginning transmission. These different algorithms are :

1. **1-persistent:** the studies (Lu, Ding, Yang, Bao, Wang & Liu 2019, Zhang et al. 2019) refer that the 1-persistent CSMA protocol is an algorithm of an aggressive transmission . When communication channel is ready to transmit a packet on the frame which first, it should sense the transmission medium, is it idle (no data packets on the transmission medium from another station) or busy. If it is idle, then the channel or transmitting node transmits instantly the frame. If the transmission medium is busy, then transmitting node senses the transmission medium constantly up to it becomes free, hence it transmits data packets. In a collision case, the transmitter waits for a random time period and attempts to follow the same steps or procedure again.

2. **Non-persistent:** is an algorithm of a non-aggressive version of CSMA protocol (Saenmuang & Sitjongsataporn 2018). When the channel is ready to transmit a packet on the frame, the transmitting station senses whether the transmission medium that is idle or not. If the transmitting station is free, then it transmits data packets immediately. If the station is busy, the communication channel waits for deferral time intervals through, does not sense whether the station idle or busy. Hence, at the end of waiting time, it again senses the situation of the transmission station and restarts the algorithm. This method reduces a collision and leads to increase the throughput of a transmission medium, but with a delay of transmission compared to 1-persistent version.

3. **P-persistent:** this is an algorithm that combines between the advantages of 1-persistent and non-persistent CSMA access modes (Lu, Ding, Han, Yang, Wang & Bao 2019, Bruno et al. 2003). When a channel is ready to send a packet on the frame, the transmitting station senses whether the transmission medium is free or not. If it is busy, the channel waits and checks at the same time up to the transmission medium becomes idle. When transmission medium is free, the channel transmits data packets with a probability p. But if transmission medium is busy, the channel waits for next time slot, transmits with a probability (1 - p). If the next time slot becomes free, it again sends with a probability p, and waits with a probability (1 - p). The channel repeats this process up to either the frame, has been sent or another channel has started to transmitting. If another channel begins transmitting, the channel waits for a random intervals of time and repeats the algorithm.

4. **O-persistent:** the study (Gross et al. 1998) points out that in an approach of O-persistent CSMA, each data node is assigned a transmission order by a nodes monitor. When the transmission medium becomes idle, the first node in line, which is already assigned as the transmitter sends data packets immediately. Then, the next node waits for its an order time to transmit data packets, when the transmission medium goes idle again. Hence, the nodes monitor has updated the transmission order for each node, detected what nodes have already transmitted, and moving each node in the assigned order through the queue.

2.6.3 OFDMA wireless communications scheme

Orthogonal Frequency Division Multiple Access (OFDMA) technology, is a combination of OFDM system with the Frequency Division Multiple Access (FDMA) protocol. This technique was suggested by Sari and Karam for cable TV (CATV) networks (Sari & Karam 1998). In (AlSabbagh & Ibrahim 2016), OFDMA is considered an essential transmission method in broadband mobile systems. More recently, it has become part of Fourth-Generation (4G) systems employ OFDM and OFDMA, including Long Term Evolution (LTE), LTE-Advanced, and mobile WiMAX. OFDMA may be regarded as an extension and multi-user version of the OFDM architecture (Tsai et al. 2017, Zhang et al. 2016).

The authors of (Abrão et al. 2016) indicated that OFDMA scheme is considered promising candidate for achievement next-generation of wireless communication systems because of its flexibility in allocation of resource and ability to multi-user diversity. OFDMA system transforms a wideband channel into orthogonal narrowband sub-channels and multiplex the data stream of many users on various sub-carriers. In (Khoramnejad et al. 2018), the maximum throughput in OFDMA system can be achieved through choice the user on each sub-channel and distributing the transmit power over all sub-channels by using the water-filling method (Ng et al. 2013, Choi et al. 2006). In OFDMA multi-cell environments, the multiple access is carried out by selecting subsets of sub-channels to various users, allows several users to transmit data packs simultaneously (Alhasnawi. & Addie. 2019, Miao et al. 2008), and OFDMA is explored in more detail in Chapters 5 and 6.

2.6.4 Spread-spectrum OFDM

Spread spectrum OFDM (SS-OFDM) has emerged from the combination of Direct Sequence Spread Spectrum (DSSS) with OFDM (Akare et al. 2009). In (Wang et al. 2018), these techniques are used together to overcome a radio channel weakness, and improve reliable communication with frequency selective channels. The SS-OFDM systems adopted a technique, which repeated transmissions where various copies of each symbol are transmitted on all available N sub-carriers (Wang et al. 2016, Xia et al. 2003). Most spread spectrum systems are of the DSSS type (after all, DSSS stands for Direct Sequence Spread Spectrum) (Jaisal 2011).(Jaisal 2011), However, if OFDM is needed, because of multi-path fading, for example, a DSSS system without OFDM will not be usable.

2.6.4.1 Performance of SS-OFDM

In (Ye et al. 2017), the data rate is regarded as the key criterion for evaluating modern communications systems for wireless communication between mobile users. OFDM technique has been using for many decades. This modulation is widely utilised in modern telecommunications system such as digital radio and TV, wireless networking, transmission of data through the phone line. OFDM is a suitable system especially for communication with high speed cause of its resistance to inter symbol interference (ISI), avoids multi-path in wave transmission (Wang et al. 2018).

On the other hand, the researchers in (Garnaev & Trappe 2016, Farhang-Boroujeny & Moradi 2016, Prasad 2004) indicated that OFDM has been facing many challenges for adoption in extra complex networks. For example, in the uplink of multi-user mobile (cellular) networks, the OFDM employs the OFDMA system.

To overcome these challenges, some studies resort to DSSS, is a spread spectrum technique by which the original data signal, is increased with a pseudo-random noise for spreading code (Tang et al. 2019, Meel 1999). This spreading code has a higher rate of the chip, which leads to a wide band time continuously scrambled signal. DSSS system enhances protection against interfering signals, especially narrowband. It also supplies of transmission security, if the encryption is not known to the public.

The study (Akare et al. 2009) proposes to use the combination of OFDM system with DSSS for the multi-user system, which is named SS-OFDM model. This model is to control the received signal bandwidth through the design of matching filters. The bandwidth of transmission can be selected flexibly to suit different modern telecommunication systems under various circumstances.

2.7 The language of Netml

Network Modelling Language (Netml) was developed at department of mathematics and computing in University of Southern Queensland (USQ) (Addie et al. 2011). This study has referred to the purpose of this language that is teaching and researching to design and analyse the network protocol easily (Addie & Natarajan 2015). Moreover, it is important to help students for describing the networks. The authors (Addie et al. 2006) declare that Netml language provides the describing to networks and an efficient working environment as an interface of website, which helps the students, researchers, and lecturers at networks field for using and development of software design and files of network data for a telecommunications network, as depicted in Figure 2.7. The Netml system is freely available in the cloud at https://netml.org.

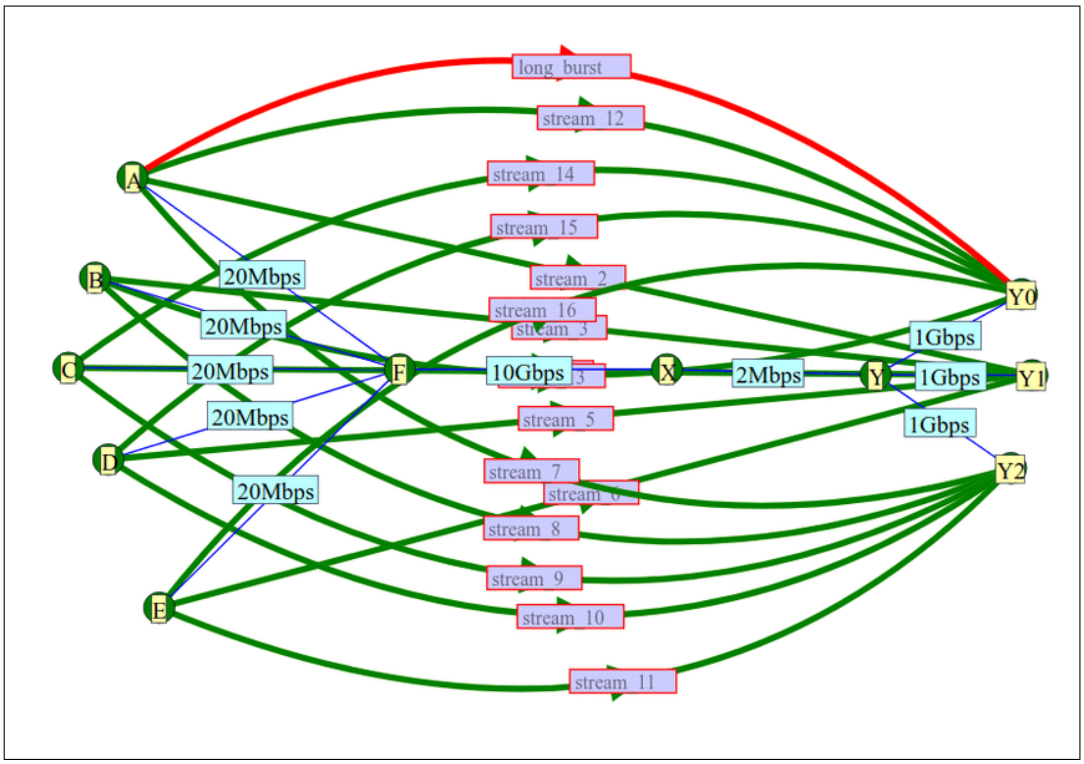

Figure 2.7: Describing, analysing and simulating communication networks by Netml

Chapter 3

Spectral Density Constraints on Wireless Communication

Environmental exposure to man-made Electromagnetic Field (EMF) has been rising as modern technologies have grown and changed in social behaviour have generated more synthetic sources. For safety of human health, EMF levels need to be regulated. The level of EMF should be well below levels where there might be harm, hence we do not expect to see any health effects at these levels. Current regulations fail to place a strict limit on EMF in situations where multiple nearby devices transmit simultaneously. The way these regulations are expressed needs great care because it will have an effect on the design of wireless communication systems. In this chapter, it is argued that transmitted power constraints on wireless communication devices should be expressed in a different way, namely that devices should limit the EMF spectral density that they generate to the difference between the maximum allowed, by the standard, and the amount currently present, as measured by the device, in the spectral region where it is active. Note that the limit on EMF should be expressed in terms of its *EMF spectral density* rather than as a total EMF over each of a series of separate bands. If all devices limit their own EMF spectral density, in the spectral region where they are active, in such a way that total EMF spectral density is below the regulated limit in that region, then it is certain that the aggregate EMF spectral density will be below the regulated limit at all frequencies.

3.1 Introduction

Constraints on transmitted power and on the electrical and magnetic field strength due to transmission exist currently in documents prepared and published by several international standards organizations (Ahlbom et al. 1998, IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards 1992, Fields 1997, Sliney & Hathaway 2016). Some of these regulations are explicitly formulated for the purpose of avoiding possible harmful effects on health (Qureshi et al. 2018, Vermeeren et al. 2018), and others are formulated as technical restrictions on the use of electromagnetic spectrum, for communication (Rubtsova et al. 2018), without explicitly acknowledging the potential for harm to be caused.

Currently, power constraints are expressed as if devices share spectrum by never using the same frequency at the same time as a nearby device. However, efficient use of spectrum over time forces wireless protocols to use the same spectrum at the same time as nearby devices (IEEE Standards Association and others 2012). Under these circumstances, if many users cluster together, the health impact of their wireless communication will be cumulative. The total EMF spectral density (Electromagnetic field spectral density, in $V/m/Hz$), of all nearby devices, is what needs to be regulated, for the health of those in the vicinity of these devices.

Furthermore, if the regulatory constraint continues to be expressed in terms of the transmitted power of each device it becomes possible to subvert the intention of this constraint by using a collection of devices which share the same spectrum, and all transmit at the same time. This goes against the spirit of the regulations on wireless communication, or, looking at the problem a little differently, shows that regulations on transmitted power should be expressed differently to avoid this type of abuse.

Consider, for example, a bus with 20 passengers with their mobile phones and other devices. All of the devices in the bus are permitted to transmit, or receive, signals simultaneously. If they are all using the same protocol, for example 802.11n, it is possible that simultaneous transmission will be inhibited but there is no reason to presume that all MAC protocols inhibit simultaneous transmission. In fact, in future (Alhasnawi. & Addie. 2019), simultaneous transmission could be the best way for these devices to share spectrum. Each person in the bus could be exposed to 20 devices' signals at the same time. If there are 200 devices, each person may be exposed to 200 simultaneous signals. In effect, the aggregate signal is unregulated. We need a way to express the regulation on EMF to be enforced, even when there are many devices simultaneously active in the same location.

In order for such regulations to be expressed in a convenient and clear manner, since we cannot anticipate the full range of ways in which spectrum is sub-divided by devices, it is logical that the regulated constraint should be expressed in EMF spectral density $V/m/Hz$, or total transmitted power spectral density W/Hz, or total received power spectral density $W/m^2/Hz$. These three approaches are all possible, and under reasonable assumptions might be regarded as equivalent. However, in order to express the central problem most clearly, the quantity which should be regulated should be total EMF spectral density (for both the device which is regulated and nearby independent devices) for *all* frequencies, expressed in $V/m/Hz$.

The fact that *total* EMF (or received power), due to all nearby transmitting devices, is what needs to be regulated is acknowledged, implicitly, in (Lin et al. 2010).

However, it seems unrealistic to impose this constraint on the entire range of electromagnetic spectrum, from 1 Hz to 300 GHz. When electromagnetic spectrum is used for communication, efficient use requires that power is distributed across frequencies as a density, rather than at discrete frequencies. Therefore, if a regulation is imposed on the spectral density of transmitted power, or EMF, it does not limit the efficiency of communication. Research into techniques for efficient use of spectrum without focused use of specific frequency ranges is a topic in its own right which has been studied in (Alhasnawi. et al. 2018). By expressing regulations in terms of a spectral density, we can avoid the need for communicating devices to make use of narrowly selective spectra when limiting transmitted power. It is necessary, and appropriate, for all devices to be aware of other devices transmitting in the same range of frequencies, but it is not necessary to be aware of devices transmitting in disjoint ranges of frequencies. This observations enables a practical, and realisable, but fundamentally more rigorous approach to regulating spectrum use to be expressed.

The chapter is organised as follows: Section 3.2 provides the literature review and the background about current regulations on EMF exposure. Subsection 3.2.1 clarifies the potential effects of EMF on health. Subsection 3.2.2 explains and defines the concept of EMF spectral density, which is then used in Subsection 3.2.3 to express a limit on EMF spectral density. Subsection 3.2.4 explicates the regulated limit on the magnitude of the EMF of a WiFi signal transmitted from 2.45 GHz, and the 5 GHz band. The health safety implications of a constraint on EMF spectral density are discussed in Section 3.2.5. The conclusion is presented in Section 3.3.

3.2 Current EMF exposure limits

EMF exposure is not a new phenomenon. EMF exists everywhere in our surroundings quite naturally, and in particular both natural and artificial light are forms of

EMF (Frankel et al. 2019). In (Mazloum et al. 2019), EMF is generated by mobile-phones and their base stations, 802.11 devices, microwave ovens, computer screens, telecommunications devices, broadcast facilities and any similar transmitters. This radiation reaches the body of any human in its path, so that part of its power is reflected away from the body, and another part is absorbed, and a third part passes through (Lin et al. 2010, International Commission on Non-Ionizing Radiation Protection and others 2010).

In wireless communication, the number of mobile phones used has overtaken the population in advanced countries since 2007, with the percentage of devices very close to 90% in those countries. Many new applications have lead to smart phones and tablet devices needing to receive and/or transmit data frequently and at a high rate (Tesanović et al. 2014).

The public exposure to EMF is regulated by means of a collection of voluntary and formal standards. The study (World Health Organization and others 2000) reviewed guidelines and exposure limits on electric and magnetic fields. The guidelines are prepared by international standards bodies which are aiming to avoid risks to health resulting from short or long term exposure, adopting a large margin of safety. The most important of the standards on exposure to EMF is (Ahlbom et al. 1998, International Commission on Non-Ionizing Radiation Protection and others 2010). Table 3.1 summarizes this standard and three others (IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards 1992, Fields 1997, Sliney & Hathaway 2016). Columns 4 and 5 of this table are explained in Subsection 3.2.2, below.

All of these standards are expressed as limits on total EMF, or on total magnetic field, in each of a series of spectral bands. In the most complete standard ((Ahlbom et al. 1998, International Commission on Non-Ionizing Radiation Protection and others 2010)), there are 7 such separate bands, and the limit on EMF in each band is separately specified. Since, under most circumstances, EMF is proportional to magnetic field, and conversely, this study confines its attention to the expression of standards in terms of EMF.

The sources of the standards in Table 3.1 are shown in Table 3.2.

3.2.1 Electromagnetic radiation effects on health

The study (Jiali & Yanan 2016) has reported that health effects of exposure to Radio-Frequency Electromagnetic Fields (RF EMF) are a serious concern not only from the users of smart-devices or people who live next to the base stations, but also from government and non-government organisations which are responsible for public health. Other studies (Touitou et al. 2020, Cansiz et al. 2018, Arendash et al. 2010) also have indicated that RF EMF affects not just human health but also animal and plant health.

Numerous epidemiological and clinical studies underline that the review and evaluation of potential health risks of exposure to EMF includes several uncertainties (Russell 2018, Pall 2018, World Health Organization and others 2000, Exponent 2017). They found a weak relationship between exposure to radiation and harmful human health effects.

The following organisations: the World Health Organisation (WHO) agency of the United Nations, the National Institute for Environmental Health Sciences (NIEHS) of the United States, the Radiation Protection Committee (RPC) of Canada, the National Radiological Protection Board (NRPB) of the United Kingdom, the Swedish Radiation Safety Authority (SRSA) and the European Union's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) have undertaken assessments of epidemiological and laboratory research (World Health Organization

Table 3.1: EMF exposure limit standards with spectral density constraints

Standard	**Frequency range**	**Electric field strength** (V/m)	**EMF spectral density** ($V/m/Hz$)	**EMF spectral density** ($V/m/logHz$)
ICNIRP	Up to 1 Hz	–	–	–
	1-8 Hz	10000	1428.57	11074
	8-25 Hz	10000	588.23	20202
	0.025-0.8 kHz	$250/f$	$0.32/f$	0.139
	0.8-3 kHz	$250/f$	$0.11/f$	0.0478
	3-150 kHz	87	0.00059	51.21
	0.15-1 MHz	87	0.0001	105.58
	1-10 MHz	$87/f^{\frac{1}{2}}$	$0.00001/f^{\frac{1}{2}}$	$0.00000435f^{\frac{1}{2}}$
	10-400 MHz	28	0.00000007	17.48
	400-2000 MHz	$1.375f^{\frac{1}{2}}$	$0.000000000086f^{\frac{1}{2}}$	$0.000000000037f^{\frac{3}{2}}$
	2-300 GHz	61	0.00000000002	28.03
IEEE	0.003-0.1 MHz	614	0.00633	403.15
	0.1-3.0 MHz	614	0.00021	415.71
	3-30 MHz	$1842/f$	$0.00007/f$	0.00003
	30-100 MHz	61.4	0.0000009	117.40
	100-300 MHz	61.4	0.0000003	128.72
	300-3000 MHz	–	–	–
	3000-15000 MHz	–	–	–
	15000-300000 MHz	–	–	–
FCC	0.3-3.0 MHz	614	0.00023	614
	3.0-30 MHz	$1842/f$	$0.00007/f$	0.00003
	30-300 MHz	61.4	0.000000023	61.40
	300-1500 MHz	–	–	–
	1500-100,000 MHz	–	–	–
ACGIH	30-100 kHz	1842	0.0263	3522
	100 kHz-1 MHz	1842	0.002	1842
	1-30 MHz	$1842/f$	$0.000063/f$	0.000027
	30-100 MHz	61.4	0.0000009	117.40
	100 MHz-300 MHz	61.4	0.0000003	128.72
	300 MHz-3 GHz	–	–	–
	3-30 GHz	–	–	–
	30-300 GHz	–	–	–

Note: f, in columns 3, 4 and 5, denotes frequency, in Hz.

Table 3.2: Sources for EMF exposure limit standards

Organization	Source
ICNIRP	(Ahlbom et al. 1998), Table 7
IEEE	(IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards 1992), Table 1, part A
FCC	(Fields 1997), Appendix A
ACGIH	(Sliney & Hathaway 2016), Table 15.1

and others 2000, Exponent 2017). None of them reported that long-term exposure to low-levels of EMF has caused any adverse human health effects.

The study of human health effects due to exposure to EMF (Muharemovic et al. 2012) concluded that short and long-term exposure levels to electrical and magnetic field are generally less than the safety limit values specified by international standards. On the other hand, the meta-study (Scientific Committee on Emerging and Newly Identified Health Risks 2007) of the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) referred to some studies which presented evidence that biological systems are affected by exposure to EMF, at intensity levels which occur in practice, associated with frequencies in the range from 100 kHz to 300 GHz, which are within the scope of international standards.

3.2.2 EMF spectral density

The Power Spectral Density (PSD) is a measure of signal power density as a function of frequency (Barbour & Parker 2015). The concept of spectral density is often used in communication systems analysis and design. The power spectral density shows how the power of a time series or signal is distributed over a range of frequencies.

The PSD can be calculated from the Fourier transform of the signal. If the original signal is measured in Watts, the PSD will be expressed $Watts/Hz$.

The concept of spectral density is not limited to power. Any quantity which varies with time also has a Fourier transform which expresses how this quantity varies with frequency, and if this Fourier transform has a density, it will be expressed in terms of the original quantity per Hz. Since EMF is a function of time, this research can apply the Fourier transform to it, and thereby obtain an *EMF spectral density*, which identifies the EMF per Hz, in $V/m/Hz$. Columns 4 and 5 of Table 3.1 , titled *EMF spectral density ($V/m/Hz$)* and *EMF spectral density ($V/m/logHz$)* have been *inferred* from the standards by assuming that instead of the EMF existing as a small number of discrete components, it is spread continuously in the range of frequencies which is relevant, in each row. In the cases where the original standard does not vary with frequency, within a row, in Column 4 the power spectral density is assumed to be uniform in $V/m/Hz$, and in Column 5, it is assumed to be uniform in V /m/logHz. For consistency and simplicity, the constraints have been assumed to be uniform across all frequencies when expressed in two different ways, either when epxressed in V/m/Hz, or when expressed in V/m/log Hz.The existing ICNIRP standard exhibits alignment to V/m/logHz; also, the proposal merely presents the V/m/logHz as an option. Throughout this chapter "log" denotes logarithm to the base 10.

In the cases where the original standard is a constraint which varies with f, the standard for EMF spectral density in Column 4 is chosen so that the functional form is the same as in the original standard and imposing the same total limit on power, assuming that the EMF is spread over frequencies separated by 1 Hz. In these cases, where the constraint depends on f, the formula in Column 5 is obtained by converting the spectral density constraint in Column 4 to a constraint expressed in $V/m/logHz$ (by multiplying by $f/\ln 10$). Column 4 of Table 3.1 is plotted in Figure 3.1 and Column 5 is plotted in Figure 3.2. These figures also include plots the EMF spectral density due to WiFi, and 5G, which will be generated when WiFi, or 5G devices are transmitting at the full power allowed under national regulations, as guided by the WiFi standard. This is explained in more detail in Subsection 3.2.4. A closeup view, focusing on the frequency range 10^9 to 10^{10} is shown in Figure 3.3. In addition, Figures 3.1, 3.2 and 3.3 include *proposed* limits on spectral density, which are further discussed in the next subsection.

3.2.3 Spectral density constraints

Figures 3.1 and 3.2 suggest that instead, or as well, as existing EMF standards, limits on EMF spectral density could be introduced. To be more specific, it is suggested that a *technical limit* on EMF spectral density is introduced somewhere in the range from 100 to 1000 $V/m/logHz$. All except very low power devices should ensure that the EMF spectral density generated by their own, and other nearby devices is below this level (i.e. some number, yet to be specified, between 100 and 1000 $V/m/logHz$) at all times, in the range of frequencies where they generate EMF. We do not expect to see any health effects at these levels. Nevertheless, the way these regulations are expressed needs great care because the way they are expressed will have an effect on the design of wireless communication systems.

Allocation of spectrum to technologies is currently evolving and changing quite rapidly and is likely to continue to change for the foreseeable future as new uses of spectrum are proposed and old ones cease to have a valid claim. However, regulations on exposure to radiation are formulated in order to protect those exposed to potentially dangerous radiation. Our understanding of the effects of radiation will also evolve and improve over time, which may lead to changes in regulated limits, also. However, the proposed limits should be based on possible risks to health rather than on current usage of spectrum.

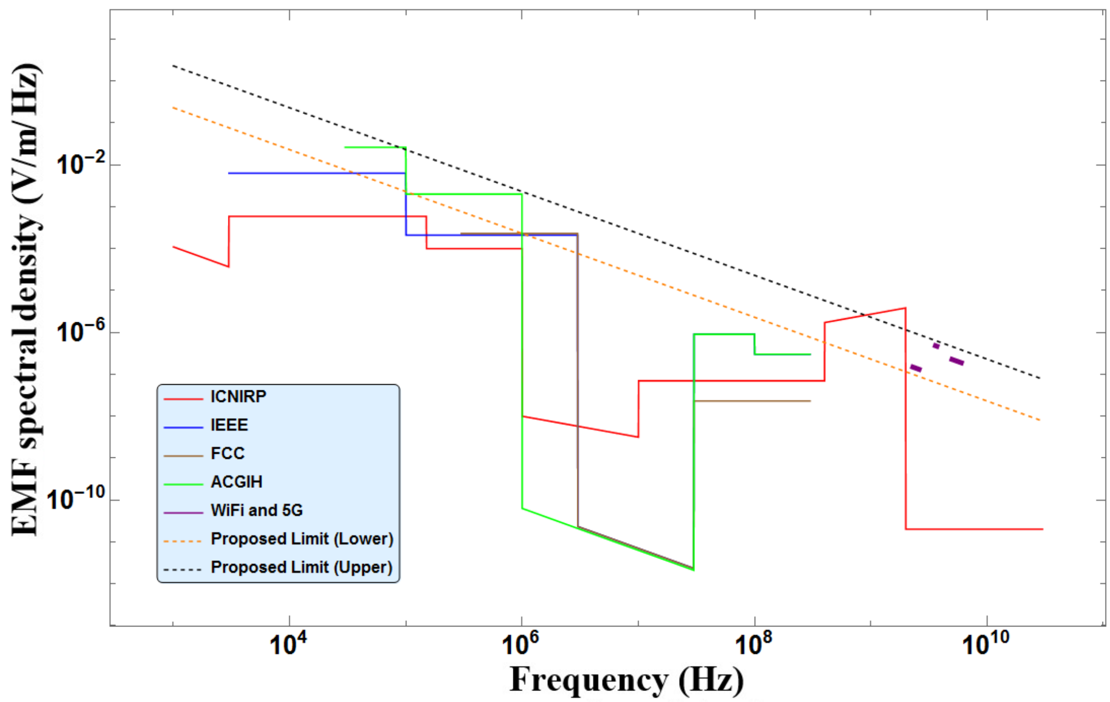

Figure 3.1: EMF exposure limit for human body in ($V/m/logHz$)

3.2.4 EMF due to WiFi and mobile transmission

In this subsection, we present an example in which the regulated limit on the magnitude of the EMF of a wireless signal transmitted in the 2.45 GHz, or the 5 GHz band, or by a fifth generation mobile communication (5G) device, is estimated.

The magnitude of the far-field EMF of a wireless signal transmitted from a Hertzian dipole antenna is (Popovic & Popovic 2000):

$$E_\theta = \frac{\beta I l sin\theta}{4\pi r}\sqrt{\frac{\mu}{\epsilon}}. \tag{3.1}$$

The parameter l is the length of the antenna; μ is the permeability of the medium, which for a vacuum is $4\pi \times 10^{-7}/m$ (and also approximately for the earth's atmo-

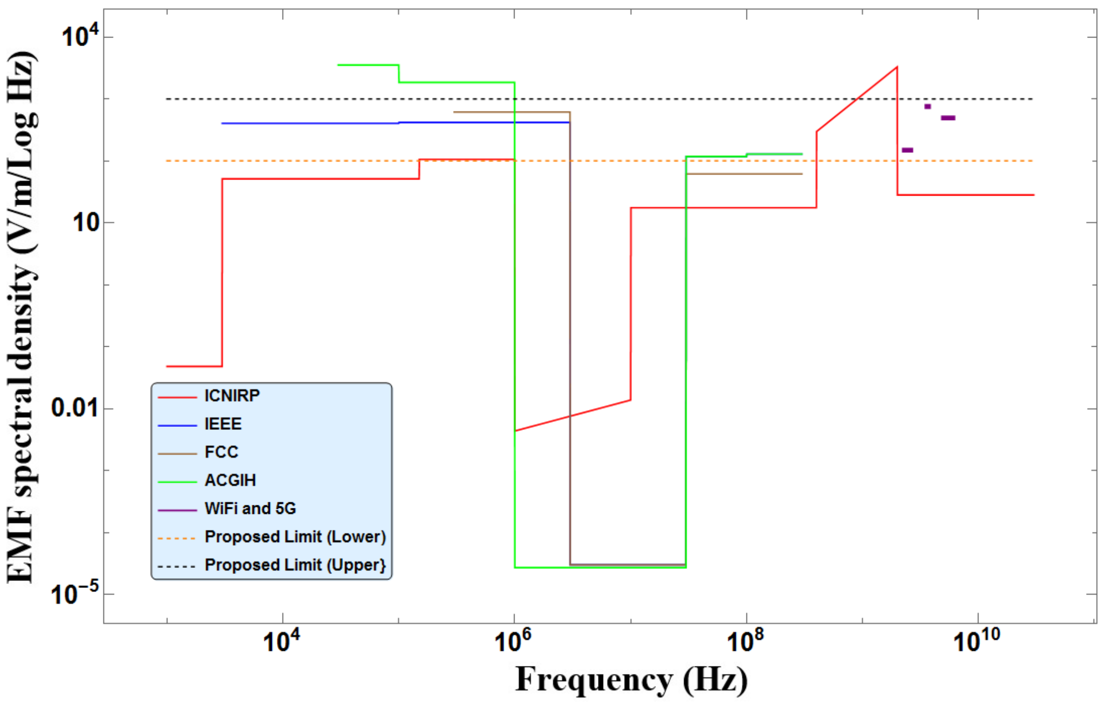

Figure 3.2: EMF exposure limit for human body in $(V/m/logHz)$

sphere); ϵ is the permittivity of the medium, which for a vacuum (and approximately also for air) is $8.85419 \times 10^{-12} F/m$; I is the current through the antenna; θ is the angle between the dipole antenna and the line to the receiver, which is assumed to be $\frac{\pi}{2}$ because this produces the strongest field; β is the phase constant which is $\frac{2\pi}{\lambda}$, where λ is the wavelength of the radiation; and, finally, r is the distance from the dipole to the receiver.

Power radiated (P_{rad}) by a wireless access point is not explicitly limited by the WiFi standard (IEEE Standards Association and others 2012) however a power limitation of either 10 mW, or 100 mW is implied. National regulation bodies have often adopted the lower of these two standards (Fields 1997), i.e. $P_{\text{rad}} = 10^{-2}$ W. Since $P_{\text{rad}} = R_{\text{rad}} * I^2$, where $R_{\text{rad}} = 50\,\Omega$ (Popovic & Popovic 2000), $I = \sqrt{P_{\text{rad}}/R_{\text{rad}}}$. All of the calculations for the field strength and field strength spectral density in any particular range of frequencies, and for any power, are carried out by the script

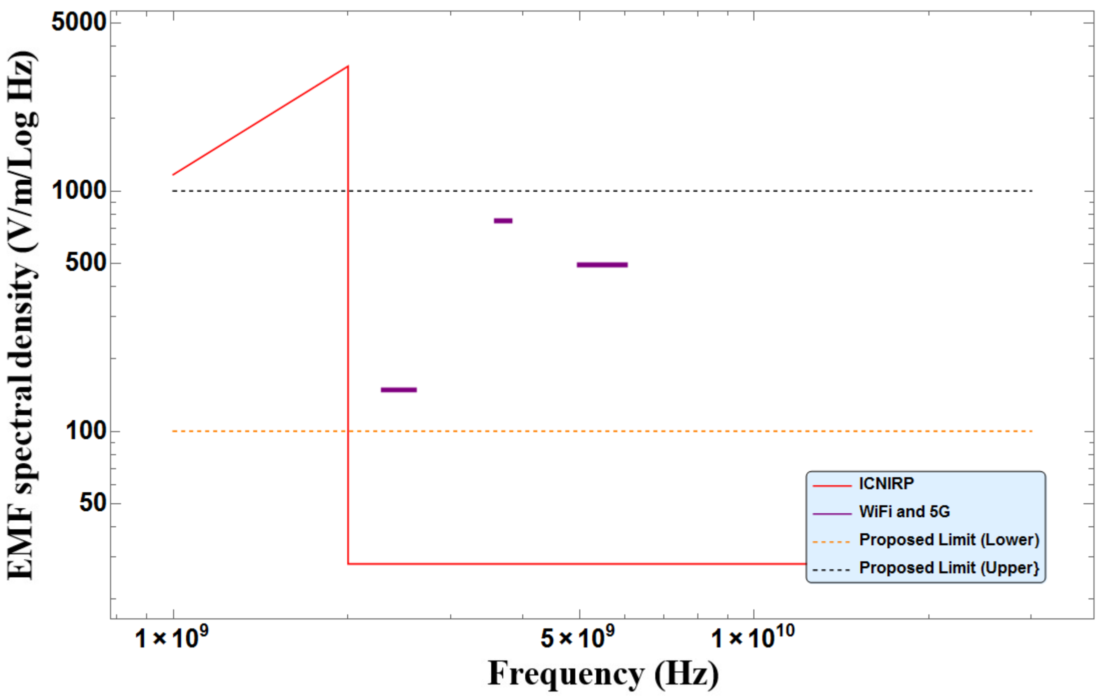

Figure 3.3: EMF spectral density of WiFi and 5G in the range 10^9 to 10^{10} in $(V/m/logHz)$

shown in Figure A.4. This script has been used to complete the calculations for three important cases, WiFi 2.4 GHz, WiFi 5 GHz, and 5G 3.6 GHz, and the results are shown in Figure A.5.

In the case of 5G (Fifth Generation mobile communication), operating at 3.6 GHz, the script shown in Listing A.4 is still applicable, with power level 23 dBm (200 mW) (Australian Communications and Media Authority 2019, The European Telecommunications Standards Institute 2017) and the results for EMF and EMF spectral density are also shown in ListingA.5 and Table 3.3.

It should be kept in mind that mobile phones do not operate at full power unless conditions require it, and also they are used less frequently than WiFi devices. Measurements of the EMF generated by a wireless access point situated in a typical work environment have found that it has a magnitude in the range 0.5 to 5 V/m

Table 3.3: Parameters of the far-field EMF, at distance twice the wavelength, of a wireless signal transmitted from a Hertzian dipole antenna

Parameters	**WiFi 2.45 GHz**	**WiFi 5 GHz**	**5G**
l	0.031 m	0.015 m	0.021 m
I	0.014 A	0.014 A	0.063 A
β	50.27	104.72	75.40
λ	0.125 m	0.060 m	0.083 m
r	0.25 m	0.12 m	0.17 m
EMF	2.664 V/m	5.550 V/m	17.870 V/m
EMF/m/Hz	2.664×10^{-8}	3.700×10^{-8}	3.574×10^{-8}
EMF/m/logHz	150.258	432.318	316.386

(Powerwatch 2020), which is consistent with the preceding estimates.

The aggregate EMF due to several nearby transmitters, assuming each transmitter limits its own power independently, without concern for ambient EMF, is plotted in Figure 3.4. This figure shows a typical situation of several devices inside the same building or vehicle which are using the same spectrum. Each device transmits at the same time. The EMF intensity is higher than that of a single transmitter because it is the aggregate effect of all the transmitting devices.

Now suppose that all devices sense and measure the EMF in the region where they are active. The resulting aggregate EMF, with the same configuration of devices as previously, is shown in Figure 3.5. In this case, the regulated limit on aggregate EMF is respected. This approach is therefore safer. Mathematica code which calculates the aggregate EMF as shown in Figures 3.4 and 3.5, is provided in (Alhasnawi & Addie 2020).

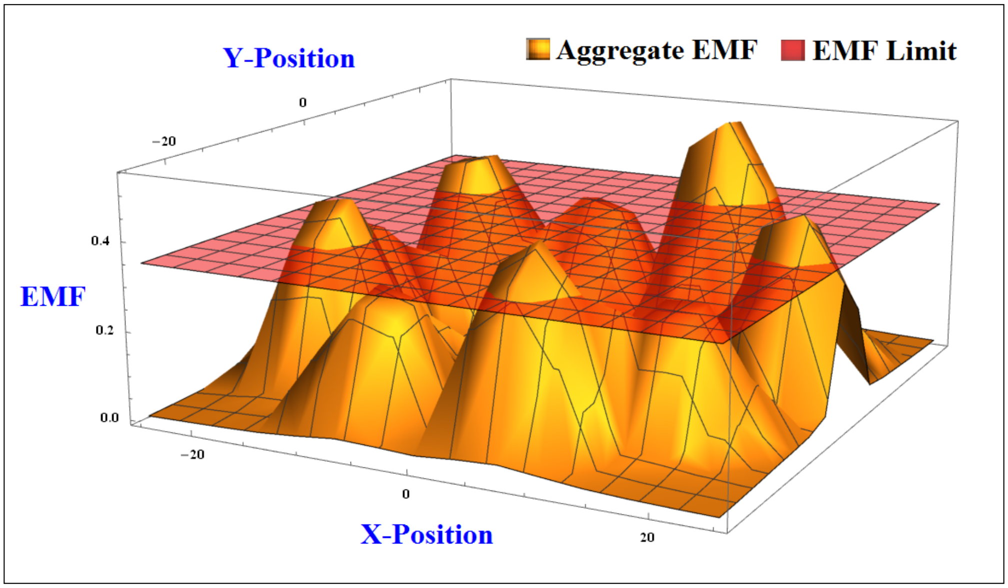

Figure 3.4: The aggregate EMF due to several nearby transmitters

3.2.5 Safety interpretation

A spectral density constraint is significantly different from a total power limit constraint, or a power limit on each of a sequence of bands. Spectral density can only be fully accurately measured by an infinite-duration sample, which cannot ever be completed. However, a spectral density measured over a finite time interval (eg a few seconds in duration) is also a logical interpretation of the concept of spectral density. Although this is not strictly the spectral density, a constraint based on this concept of spectral density is still significantly different from a constraint based on total EMF or total power overall, or total EMF or total power in a sequence of bands.

If biological response to EMF varies significantly with frequency, and if this variation cannot, or has not yet, been measured, it is safer to limit EMF spectral density uniformly than to limit total power in a band, because no individual frequency will be used with a significant amount of power, and hence the “dangerous” frequencies

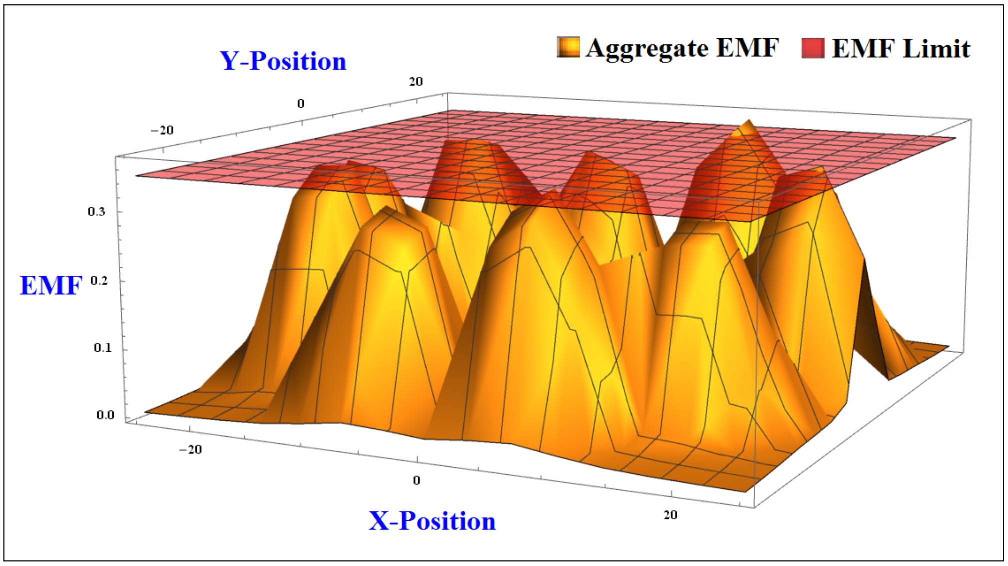

Figure 3.5: The aggregate EMF when devices measure ambient EMF and limit the total

will not then be used at levels where harm might occur. There are some frequencies which have traditionally been used widely and consistently, and for which, therefore, strong evidence exists concerning the unlikeness that harmful effects due to these frequencies needs to be avoided. If a spectral density constraint is imposed, as suggested in Section 3.2.3, an exception for a small number of such frequencies may be required.

Many devices already sense and measure the EMF in the region of spectrum where they are active. Therefore there is no additional cost for them to be required to make such measurements. On the other hand, expecting devices to measure EMF in other regions of spectrum would be costly and unnecessary so long as the regulated limits are expressed as suggested in this chapter, ie as limits on spectral density.

There may be some devices which generate sufficiently low EMF that regulations on their operation could omit the need for measurement of ambient EMF, although in such cases it should be a requirement that their deployment should never be in such large numbers that the regulation on ambient EMF might be breached by their aggregate contribution.

Suppose the threshold of harm caused by EMF, as a function of frequency, is not uniform, but is instead highly variable across frequencies (Ahlbom et al. 1998), as shown in red in Figure 3.6. Suppose, in addition, that the exposure to EMF, as a function of frequency, also varies randomly, as shown in blue in this figure. Under these circumstances there is a significant probability that there are some frequencies where the exposure to EMF exceeds the harm threshold. It will therefore be safer to limit EMF intensity as uniformly as possible, as depicted by the dashed line in this figure.

The simplest model of harm caused by EMF is to assume that it is proportional to the total absorbed energy, irrespective of frequency, or the intensity with which it is delivered. However, existing standards are not so irresponsible to accept this simple concept. Limits are placed on *power*, not total absorbed energy. Harm can be caused by quite small amounts of energy if delivered in a very short space of time.

By placing a limit on power, rather than total absorbed energy, the *intensity over time* with which energy is delivered is restricted. Likewise, we should aim to restrict *intensity over space* and *intensity over frequencies*. Just as it can be dangerous to deliver a moderate amount of energy over a very short time, it may also be dangerous to deliver a moderate amount of energy over a very small range of frequencies, or a small region in space.

It therefore seems unwise, until we have more experimental data concerning the human response to EMF over different frequencies, to *assume a uniform additive model of harm due to EMF over different frequencies is correct.*

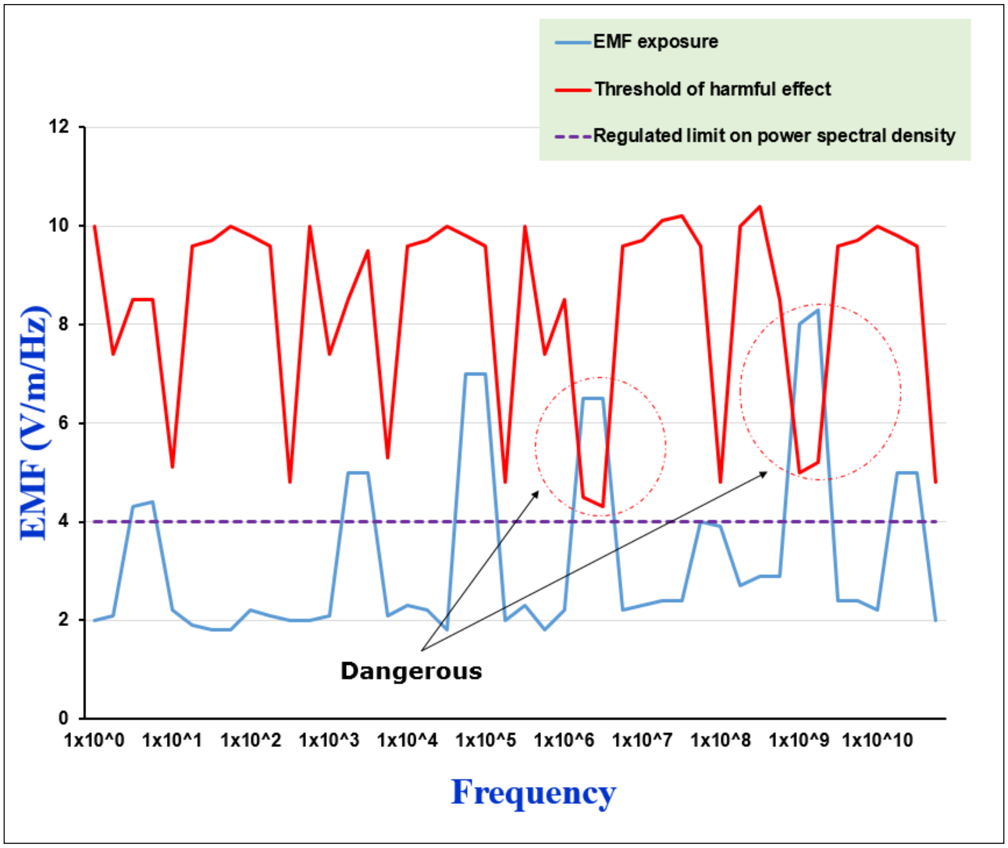

Figure 3.6: Threshold of harm, EMF exposure, and propose uniform limit on power spectral density

3.3 Summary

Power constraints on wireless devices should be expressed in a different way: devices should actively seek to limit total EMF spectral density, in $V/m/Hz$, due to their own transmission and the existing activity of other devices. Our recommendation is to use constraints on EMF spectral density, rather than (or as well as) on aggregate EMF over several large spectral ranges. EMF spectral density constraints can be used to express limits for health reasons or for technical reasons, or both. For consistency and simplicity, these constraints can be uniform across all frequencies when expressed in $V/m/\log Hz$. By the Shannon-Hartley theorem, for any maximum total power constraint, a uniform distribution of power over spectrum achieves optimal throughput, for the given power, so imposing a regulated limit on EMF spectral density does not inhibit efficient use of spectrum.

The best way to adjust transmission power from devices using wireless transmission will probably be different for 802.11 devices than for mobile cellular devices. In the former case the shared protocol for device access will have an additional constraint to take into account, while in the cellular mobile case the spectrum management undertaken by the base-station, in coordination with all the devices in its cell, will need to be adjusted. We have suggested above, already, that such changes do not need to reduce spectral efficiency, however this is a topic which needs to be investigated in its own right, is therefore a subject for future research.

Chapter 4

A New Approach to Spread-Spectrum OFDM

OFDM is an essential factor of modern wireless communication. Effective use of available spectrum by multiple uses appears to dictate that they transmit simultaneously. One way to do that is combine spread spectrum with OFDM. This chapter investigates how to do this and demonstrates how it has been done.

4.1 Introduction

Spectrum sharing is a problem of considerable interest and importance (Pandit & Singh 2017). The number of wireless devices has been growing significantly in the last decade, including IPTV receivers, tablets, smart-phones, remote controls, GPS devices, wireless sensors (Xin & Song 2015). This growth of wireless devices leads to increased demand on the available and more need for efficient spectrum sharing. This study investigates improvement in the efficiency of spectrum use by using

Spread Spectrum Orthogonal Frequency Division Multiplexing (SS-OFDM) (Akare et al. 2009, Xia et al. 2003, Jaisal 2011, Meel 1999, Tu et al. 2006).

Spread-spectrum systems which are nearly co-located systems perceive each other as noise, and when doing so will not suffer any loss in overall efficiency of spectrum use, therefore the use of spread-spectrum *with* OFDM has the potential to enable efficient spectrum sharing. However, evaluation of SS-OFDM from the point of view of spectrum efficiency has not received close attention in much of its literature up to this point.

In this chapter, the Direct-Sequence Spread-Spectrum (DSSS) system uses symbols from the Galois field $GF(\rho)$, where $\rho > 2$ is a prime number. For efficiency it is likely that ρ will usually be larger than 10. Most DSSS systems use symbols from $GF(2^m)$ for some $m > 0$. This choice is more straightforward to implement and seems more natural, given that most digital hardware uses binary arithmetic and binary representation for numbers, but the nearly-orthogonality property of codes based on this field does not directly lead to the necessary orthogonality conditions when used with OFDM, as shown in Subsection 4.6.8. Use of a field $GF(\rho^m)$ with $m > 1$ is also possible, but has not been investigated in this study.

According to (Zhang, Chu, Guo & Wang 2015) the significant challenge facing researchers in wireless communication is efficient spectrum sharing. There is an imbalance between the rapidly growing demand and the limited resources of wireless spectrum. The authors (Ji & Liu 2007) show that in order to achieve efficient and full utilisation of available common spectrum, the protocols and/or technologies used in wireless communication require to be changed so that efficient spectrum sharing is one of the key design objectives. The aim of this chapter is to investigate a strategy for using OFDM which allows efficient sharing of spectrum to occur without excessive additional effort.

OFDM systems are considered to be effective techniques and are used for several of the latest standards for wireless, telecommunications standards and digital video broadcasting (Sung et al. 2010, Armstrong 2009, Coleri et al. 2002). However, it can be difficult to share available spectrum efficiently while using OFDM.

In this chapter, a new method for combining DSSS with OFDM has been defined and implemented in Matlab and an algorithm for predicting WiFi throughput of a full implementation of such an SS-OFDM system has been developed. The optimal sharing can be consistent with nearby WiFi domains appearing as noise to each other (which is the characteristic property of spread-spectrum).

The SS-OFDM system has been implemented in Matlab and used to demonstrate simultaneous communication of a large number of co-located users (for example, 1000), using spread-spectrum to share access to the medium, with minimal impact on spectral efficiency. It has also been estimated that when users are not co-located, total system throughput achievable is significantly greater than systems in which the available spectrum is used exclusively by each pair of communicating devices one at a time.

This chapter is organized as follows with the arrangement; Section 4.3 explains the mathematical model by using Shannon Bound theory to model a wireless system. Section 4.4 provides the literature review and background on SS-OFDM. The design of an idealised SS-OFDM is clarified at Section 4.5. In Section 4.6 displays the execution the SS-OFDM system. Section 4.7 demonstrates the proof of the proposed system. The conclusion is set out in Section 4.8.

4.2 OFDM modulation schemes

In (Basar 2016), OFDM is an essential system used in modern communication systems. This technique uses multi carrier modulation of transmission of signals over wireless channels. The OFDM scheme works to divide the high rate stream into parallel lesser rate data with longer duration symbols. This reduces inter symbol interference and overcomes the challenge of multiple-path channels (ISI) (Borra & Chaparala 2013, Morelli & Mengali 2001).

All major communication systems recently developed use OFDM as their modulation method, especially on transmission scheme such as Wireless Local Area Network (WLAN), Asymmetric Digital Subscriber Line (ADSL), broadband indoor wireless systems, Digital Video Broadcasting (DVB), and Digital Audio Broadcasting (DAB) (Farhang-Boroujeny & Moradi 2016, Rabinowitz & Spilker Jr 2008, Bölcskei et al. 2003). This technique provides quality of data transmission and is widely implemented in different systems (Christodoulopoulos et al. 2011). The papers (Sivanagaraju 2014, Weiss et al. 2004, Mostofi & Cox 2006) claim that communication systems in the future are likely to continue to choose to use OFDM.. OFDM is an effective new method to reduce the ISI and noise, and avoid dispersion impact of multi-path channels, particularly when this method deals with big data rates (Jiang & Wright 2016, Mahmoud et al. 2009).

4.2.1 OFDM system and wireless networking

OFDM is a widely used digital modulation system. Development of wireless communication technologies is expected to enhance the reliability and speed of data transmission (Li et al. 2017, Yao 2009). At the same time, the increase in the number of mobile devices will increase demand for these services. The researchers (Lu et al. 2018, Nee & Prasad 2000) have shown that OFDM modulation provides flexible bandwidth, improves the protection of multi-path fading and enhances robustness by insertion of the guard interval. It solves the requirements of bandwidth for data users. In effect, OFDM is the key technology which has enabled modern wireless communication systems to get close to achieving the Shannon bound, which is the theoretical upper-limit to data communication efficiency.

4.3 Shannon Bound theory

When OFDM is used, with highly efficient error-correcting codes, system capacity can be relatively close to the Shannon-Hartley bound. As a consequence, it can be used as a design principle. Any innovation or method (coding, modulation, filtering, ...), can be evaluated according to the degree to which it brings us closer, or further, from the Shannon-Hartley bound.

From the fact that OFDM gets close to the Shannon bound, it follows that we can use it to estimate system capacity. This is useful in itself, as a simple and effective way to model wireless systems. For example, this study uses this principle to model the bandwidth which can be achieved in a configuration of access points and users of the sort depicted in Figure 4.1.

Consider a situation where several WiFi networks operate in the same geographical region, and share the same spectrum, as shown in Figure 4.1.

Currently, the conventional way to model such a system would be to simulate it, for example, using Ns3 (Henderson et al. 2008), Omnet (Varga & Hornig 2008), or Opnet (Guo et al. 2007). However, setting up such a simulation would be very time consuming and will not necessarily and can be achieved using a relatively simple

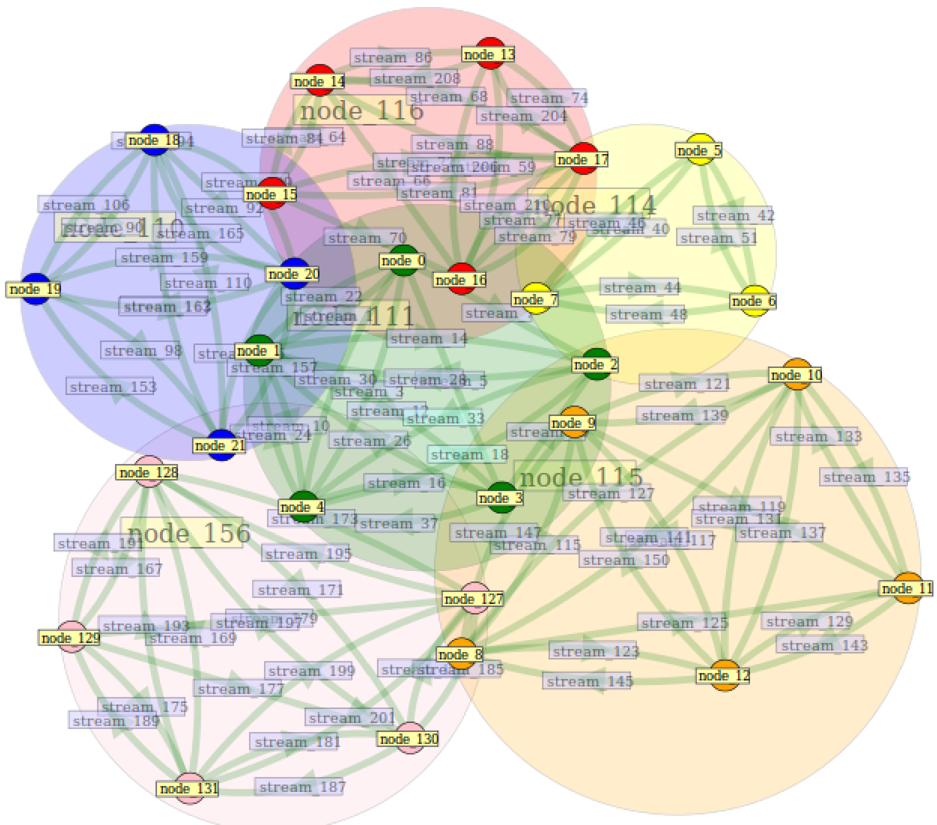

Figure 4.1: Six wireless networks sharing spectrum

mathematical formula.

Using the Shannon bound to model the capacity of such a system does not require simulation over time, and can be achieved using relatively simple mathematical formula. For example, if two adjacent communication WiFi systems are modelled in this way, and they are placed sufficiently apart so that each appears to the other with an additional loss of 20 dB, due to geographical separation, this study assumes each system makes use of half the available bandwidth from the same spectrum. The Shannon formula tells us that the total throughput of the system about 30%

more than a single system operating in isolation. This research easily works out the change in the SNR experienced by each system, due to the presence of other wireless systems, and develops a formula for the bandwidth available in each system, and in total.

On the other hand, if nearby wireless communication systems *do not* share spectrum by treating each other as noise, for example if they use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to share bandwidth, it is also easy to model the throughput achieved by each system and by the system as a whole. In the example where two systems are operating in the same region, total throughput of the two systems will be approximately 100% of the throughput achievable by one system, and assuming fair sharing, each has half the bandwidth that it would have in isolation.

If the number of co-located systems is larger than two, the benefits of each system treating the other as noise will be greater (Gupta & Kumar 2000).

In this chapter, the mathematical model of multiple nearby communication systems, as in Figure 4.1, has been developed, and implemented in the Netml system (Addie et al. 2011, Addie & Natarajan 2015), so that users who wish to model wireless systems can easily estimate their capacity, under various assumptions regarding the type of sharing. This include details concerning the choice of wireless spectrum by each wireless domain, which have not been discussed here.

4.3.1 Using the Shannon Bound as a design principle

The concept of *nearly orthogonal* codes was introduced as part of the CDMA mobile communication system, is sometimes referred to as 2.5 G mobile communication.

The concept of *nearly orthogonal* systems can be applied not just to codes. It shows that the other wireless communication appears as noise, of the same power as its actual power, is not correct. It is essential for the two wireless systems to use coordinated codes, so that they can achieve sharing which is consistent with the Shannon bound, as displayed in Figure 4.2, but also to, for example, OFDM systems as depicted in Figure 4.3.

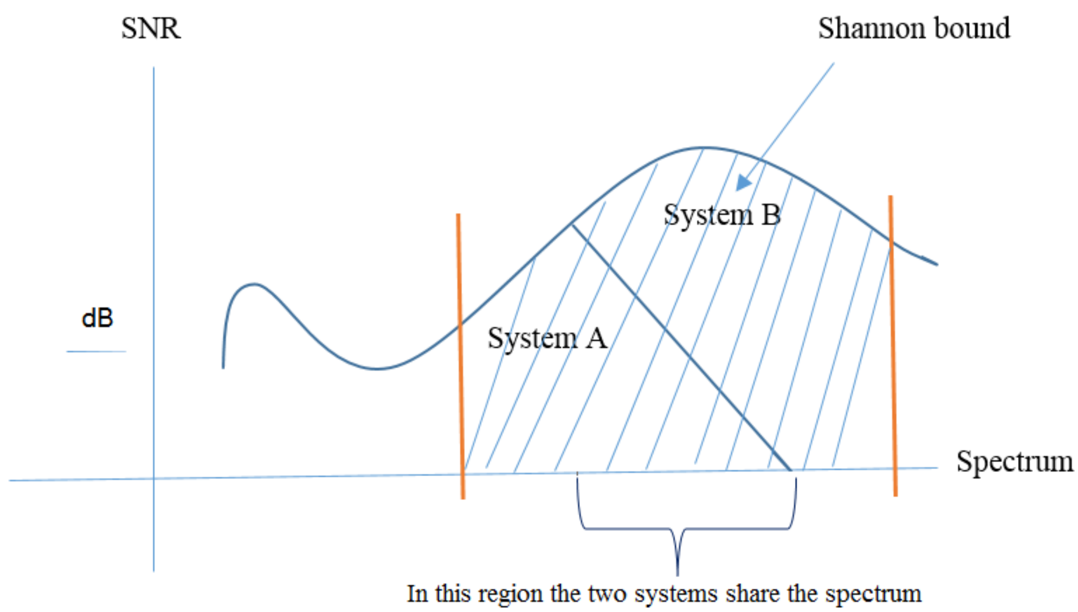

Figure 4.2: Overlapping spectrum

Currently, WiFi tends to be managed so that those concurrently operating WiFi domains use either the same channel, or channels which do not overlap. A typical example (from the USQ campus) is shown in Figure 4.4.

This approach to designing WiFi networks reduces capacity for two different reasons. Firstly, part of the spectrum is not used at all. Secondly, the type of sharing used between WiFi systems using *the same* WiFi channel, will be of the inefficient type.

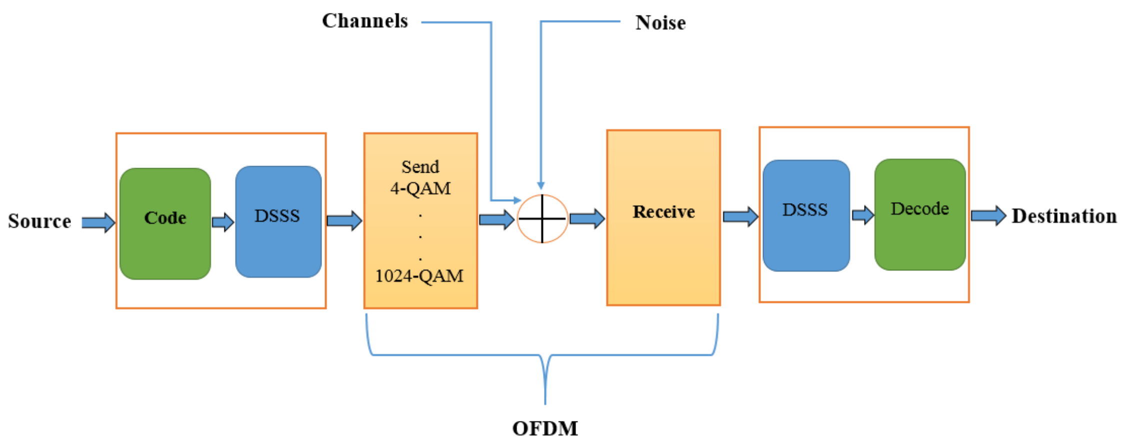

Figure 4.3: Spread spectrum of OFDM systems

Each system shares with the others by CSMA/CA, therefore the total throughput will be the same as one system operating in isolation.

However, it is not clear how to enable nearby OFDM systems to share spectrum while treating each other as noise. This has been done by each system using codes. How effectively these nearby systems are able to communicate, at the same time, may depend on the choice of OFDM parameters made in each system. In this chapter, the concept of *nearly* orthogonal systems for OFDM is introduced. This means that each sub-channel in one system experiences the signals of the other OFDM systems as white noise at *lower* power than the actual OFDM signal power. The power of the signals from other users is further reduced by propagation loss. The reduced power of neighbouring systems in this situation leads to the complete system achieving greater spectral efficiency than time-division or frequency-division multiplexing.

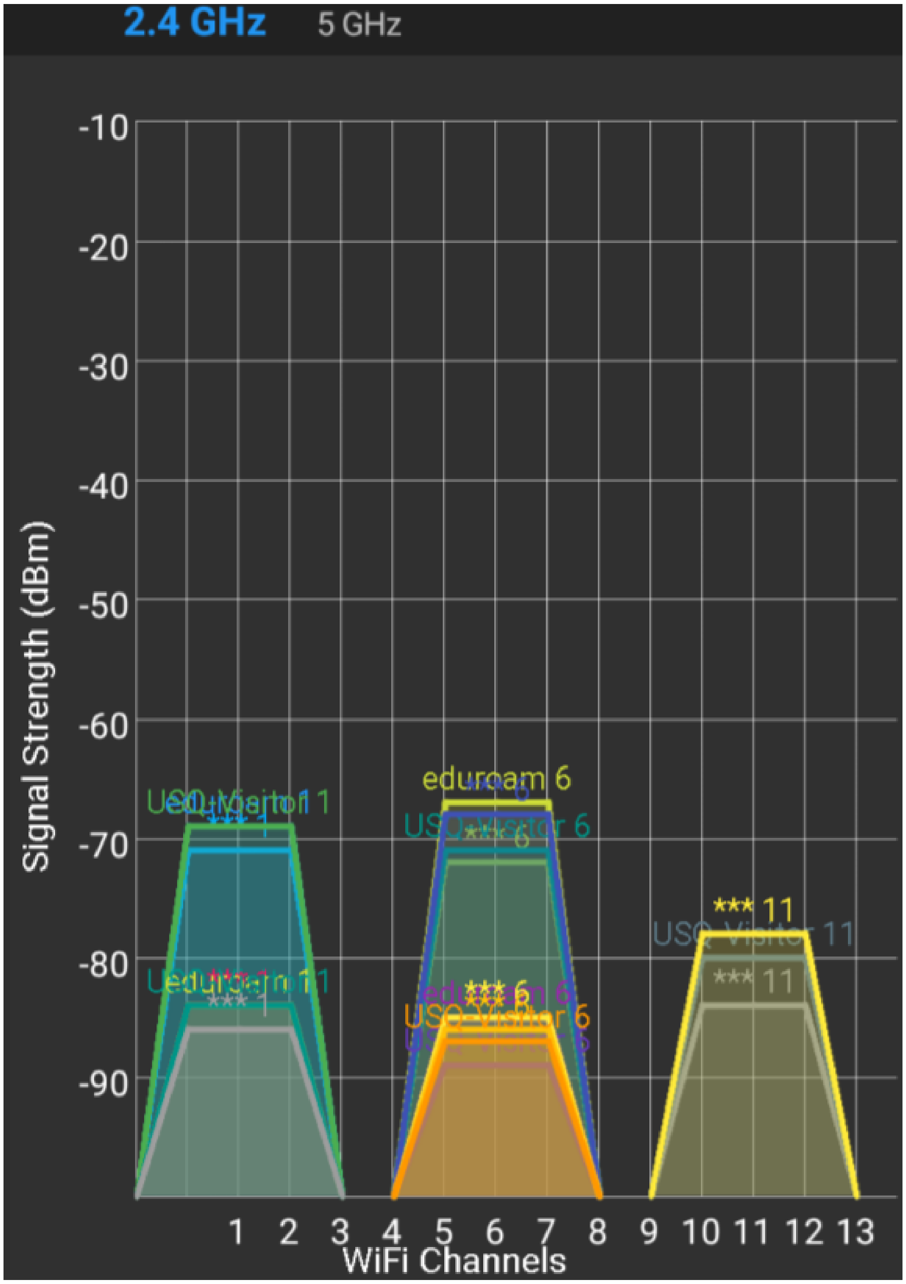

Figure 4.4: Sample of WiFi sharing on a campus

4.4 Existing Models of SS-OFDM

The approach using SS-OFDM systems has emerged from the assembly of DSSS with OFDM (Akare et al. 2009). Using these techniques together overcomes radio channel weakness, and improves reliable communication with frequency selective channels. The SS-OFDM systems adopt a technique whereby various copies of each symbol, are transmitted on all avai N sub-carriers (Wang et al. 2016, Xia et al. 2003). On this study (Jaisal 2011) referred to spread spectrum OFDM systems having many features such as DSSS technique. The main difference between the two models is that the SS-OFDM model utilises a spreading waveform consisting of samples with non-discrete values of amplitude. On the other hand, the DSSS model utilises a binary spreading code which consisting of a sequence 1's and -1's.

Previous papers on SS-OFDM (Tu et al. 2006, Akare et al. 2009, Xia et al. 2003, Jaisal 2011, Meel 1999) all use, primarily, DSSS in combination with OFDM in the form set out in Figure 4.5. The best choice for the OFDM system when a DSSS module is used with it, is a key topic explored in these papers. In this study, by contrast, the OFDM module *assumed* to be *ideal* (in a sense explained below), and the focus will be instead on the best choice of DSSS module.

In DSSS, a stream of data at the transmission point is combined with a pseudo-random bit sequence to become a higher data-rate signal. This technique of spreading the data helps the signal resist interference and also enables the original data to be recovered if data bits are destroyed during transmission from the origin point to the destination. In addition, when this technique is used by two or more communicating systems at once, they are able to perceive each other as noise, and therefore share the same spectrum without destructive interference. This last feature of spread-spectrum is often more important than the spreading idea itself.

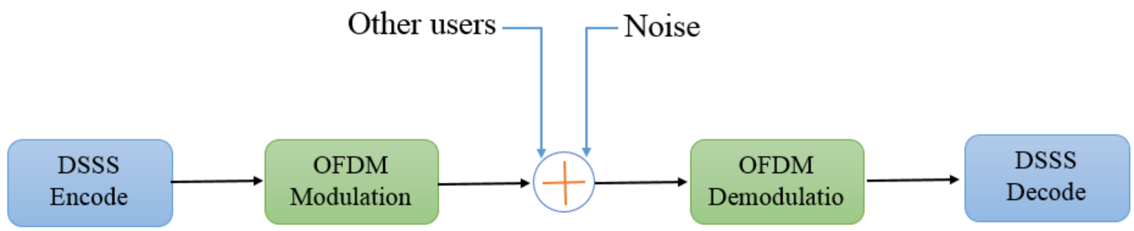

Figure 4.5: SS-OFDM systems

4.4.1 Performance of SS-OFDM

The high rate of data is a key component of modern communications systems for wireless access networks of mobile users. OFDM techniques have been used for many decades. This modulation is widely utilised in modern telecommunications systems such as digital radio and TV, wireless networking, and transmission of data through the phone line. OFDM is a suitable system, especially for high speed communication because of its resistance to Inter Symbol Interference (ISI), avoiding multi-paths in wave transmission. Also, DSSS is a spread spectrum technique by which the original data signal is increased with a pseudo-random noise for spreading code (Wang et al. 2018, Meel 1999). This spreading code uses a higher rate of the chip which leads to a wide-band time continuously scrambled signal. A DSSS system enhances protection against interfering signals, especially narrow-band. It also supplies transmission security, if the code is not known to the public.

The study (Akare et al. 2009) proposes to use the combination of OFDM system with DSSS for the multi-user system. The combination is named the SS-OFDM model. This model can be used to control the received signal bandwidth through the design of matching filters. The bandwidth of transmission can be selected flexibly to suit different modern telecommunication systems under various circumstances. SS-OFDM techniques supply reliable communications with a frequency-selective channel. The fading of multi-path impacts on the performance of wireless broadband link (Jaisal 2011).

The essential results of this study mean that the SS-OFDM model used for wireless broadband. Also, it has been established that this model can efficiently deliver communication over short or long distances by using M-ary Quadrature Amplitude Modulation (M-QAM) with effectively reduced interference and improved Bit Error Rate (BER). In addition, the authors (Tu et al. 2006) referred to the results of simulation showing that the theoretical curves and the simulation curves matched well. This indicates that SS-OFDM can achieve the desired level of performance.

4.5 Design of an idealised SS-OFDM system

A study undertaken by (Tu et al. 2006) used the Shannon-Hartley formula to justify a theory of the aggregate capacity achievable by spread-spectrum communication systems. When spread-spectrum systems interact, one system perceives the other as noise with power reduced in accordance with the mechanism of interaction of the two systems.

In this chapter, rather than exploring the changes which are needed in the OFDM module, a specific hypothesis for the form this module should take is posited. The hypothesis is that the OFDM module transforms the original channel into an ideal (i.e. flat frequency-response) channel with additive Gaussian white noise. This OFDM module will exhibit a fixed non-zero *latency*. Minimising overall system latency may be a concern, and it is well-known that any system which achieves an ideal (or close to ideal) transfer function must introduce a large delay; however this issue will be put to one side initially.

This hypothesis needs to be tested first. Then be used as a starting point for the *other* question which needs to be investigated in SS-OFDM, namely what form of DSSS should be used in a system of the form shown in Figure 4.5? The hypothesis enables us to investigate this question in a much simpler form, as shown in Figure 4.6.

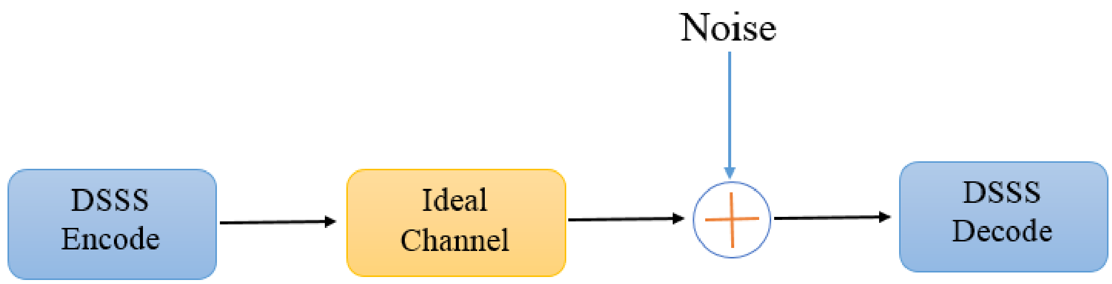

Figure 4.6: Ideal channel

4.6 An implementation of DSSS-OFDM

Assuming an ideal OFDM system, a design which exhibits effective working with a DSSS module to provide a combined DSSS-OFDM system is described in this section. The details of how the DSSS module and the OFDM module work together must be clearly specified and need to be checked that the desirable properties of both DSSS and OFDM are achieved in the combined system. A key requirement for this to be achieved is that the DSSS system uses higher-order symbols (not binary digits), so that when these symbols *interfere* with other users of similar DSSS-OFDM systems, the nearly orthogonal property of the DSSS sequences is preserved algebraically even when the different signals are combined together as electromagnetic radiation before being decoded, as depicted in Figure 4.7.

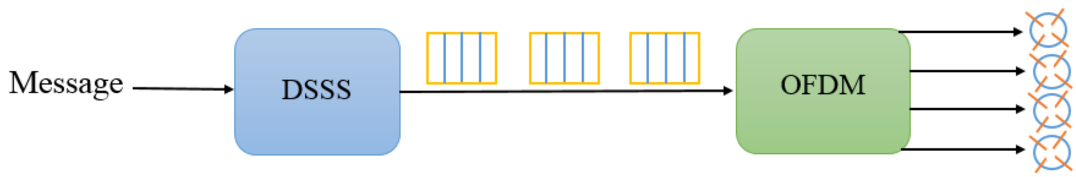

Figure 4.7: SS-OFDM with DSSS uses higher order symbols

4.6.1 An example system

There are many parameters of the system which affect the design as with all DSSS systems. This subsection arbitrarily chooses these parameters, and adopts choices with a view to simplicity rather than capacity or performance. However, it should be clear how the parameters can be changed to suit other objectives.

The system we consider is based on the Galois field with prime $p = 5$, and power $m = 1$.

4.6.2 Orthogonality property

The SS-OFDM system must have an orthogonality or *nearly orthogonal* property for any DSSS system to work efficiently which is, firstly, a mathematical property of the codes and, secondly, is preserved by the way signals are modulated, aggregated, and demodulated by the system. If the DSSS system has a (nearly) orthogonality property, but the implementation does not actually operate in the way required by this principle, it will not serve our purposes.

4.6.3 The Galois field theory of DSSS codes in the complex domain

The theory of DSSS codes formed from binary sequences is well understood and widely used. However, in the present context, where the DSSS codes must be transmitted through an OFDM system, the DSSS codes needed must be represented as sequences of complex numbers. Let us therefore review the theory of Galois fields and apply it to identify the necessary codes.

Suppose ρ is a prime number. Then, $GF(\rho)$ denotes the Galois field of numbers $\{0, 1, \ldots, \rho - 1\}$, with addition operation defined as addition modulo ρ and multiplication operation defined as multiplication modulo ρ. This field is known to possess a *primitive*, p, which is an element of the field, with the property that 1, p, p^2, $\ldots$, $p^{\rho-1}$ is an enumeration of all the non-zero elements.

Let $z_k = e^{2\pi ki/\rho}$, $k = 0, \ldots, \rho - 1$. When symbols in this field are used for transmission, these complex numbers are a better representation of the physical form taken by the signal. The magnitude of the complex number represents the power, and the complex argument represents the phase, of the transmitted signal.

4.6.4 Near-orthogonality

Suppose $x = (x_1, \ldots, x_4)'$ and $w = (w_1, \ldots, w_4)'$ are complex vectors. The appropriate inner-product between these vectors is $(x, w) = \sum_{k=1}^{4} x_k \overline{w_k}$.

Observe that $z_k = \overline{z_{-k}}$ and $z_k \times z_j = z_{k+j}$. Define $\chi_j = (z_{p^{j-1}}, z_{p^j}, \ldots, z_{p^{(j-2) \bmod \rho}})$, $j = 1, \ldots, \rho - 1$. These will form the codes of our DSSS-OFDM system.

Proposition 1

$$(\chi_k, \chi_j) = \begin{cases} \rho & k = j, \\ -1 & k \neq j. \end{cases} \tag{4.1}$$

Proof

Observe that in all cases the components of χ_j form an enumeration of all the complex numbers corresponding to elements of the field except 1 (which corresponds to the field element 0). The complex numbers of this form are the ρ-th roots of unity, i.e. they form a list of all the solutions of the equation:

$$z^\rho = 1.$$

Hence (Tirkel & Hall 2004) their sum (including 1) is zero. The sum of the components of χ_k is therefore equal to -1, for any $j \in \{1, \ldots, \rho - 1\}$. Let us now show that $(\chi_k, \chi_j) = -1$, also, j, $k = 1$, $\ldots$, $\rho - 1$, , so long as $k \neq j$.

Suppose $j \neq k$. Then

$$\begin{aligned} (\chi_j, \chi_k) &= z_{p^j}\overline{z_{p^k}} + z_{p^{j+1}}\overline{z_{p^{k+1}}} + \cdots + z_{p^{j-1}}\overline{z_{p^{k-1}}} \\ (\chi_j, \chi_k) &= z_{p^j} z_{-p^k} + z_{p^{j+1}} z_{-p^{k+1}} + \cdots + z_{p^{j-1}} z_{-p^{k-1}} \end{aligned}$$

which, using the property $z_s \times z_t = z_{s+t}$,

$$= z_{p^j - p^k} + z_{p^{j+1} - p^{k+1}} + \cdots + z_{p^{j-1} - p^{k-1}}.$$

Now $p \times (p^j - p^k) = p^{j+1} - p^{k+1}$ so the sequence $z_{p^j - p^k}$, $\ldots$, $z_{p^{j-1} - p^{k-1}}$ is one of the codes χ_k and hence has sum -1. □

Example: $\rho = 5$

The field GF(5) has primitive element 2. This means that all non-zero elements are enumerated by 2^k, $k = 1, \ldots, 4$. The codes corresponding to this primitive element are:

$$\chi_1 = (1, 2, 4, 3),\ \chi_2 = (2, 4, 3, 1),$$
$$\chi_3 = (3, 1, 2, 4),\ \chi_4 = (4, 3, 1, 2).$$

4.6.5 Encoding

The DSSS-OFDM system replaces each symbol of the user's message by a sequence of κ complex numbers to encode the message before transmitting it over the network. The number κ is termed the *chip length*. This scheme is directly analogous to the traditional way that pseudo-random noise is traditionally used in DSSS, with the generalisation that now each symbol comes from a finite field, or the corresponding complex number, rather than from $\{0, 1\}$. Suppose the messages to be transmitted are stored in an array:

$$m = \begin{pmatrix} m_{11} & \ldots & m_{1,n} \\ \vdots & \ddots & \vdots \\ m_{L,1} & \ldots & m_{L,n} \end{pmatrix} \tag{4.2}$$

and the code used for user u is $\chi_u = (\chi_{1,u}, \ldots, \chi_{\kappa,u})$, with the defining property $\chi_{k+1,u} = \chi_{k,u} \times p \bmod \rho$, in conjunction with the obvious necessity that each user has a distinct value for $\chi_{1,u}$, in which κ denotes the chip-length. Thus, each code *rotates* (by multiplication of each element by the primitive of the field) during use and the different users are distinguished by their different *starting codes*.

For notational convenience we define $\chi_{k,u} = \chi_{(k-1) \bmod \kappa+1,u}$ for all k. E.g. $\chi_{0,u} \doteq \chi_{\kappa,u}$.

The array of messages expressed as *symbols* (complex numbers with magnitude less than 1)

$$S = \begin{pmatrix} s_{11} & \cdots & s_{1,n} \\ \vdots & \ddots & \vdots \\ s_{M,1} & \cdots & s_{M,n} \end{pmatrix} \tag{4.3}$$

in the usual way, based on an arbitrary constellation (e.g. as in Figure 4.8). The value of M depends on L and also on the constellation.

The codes also have a complex representation:

$$X = \begin{pmatrix} \xi_{11} & \cdots & \xi_{1,\kappa} \\ \vdots & \ddots & \vdots \\ \xi_{\kappa,1} & \cdots & \xi_{\kappa,\kappa}, \end{pmatrix} \tag{4.4}$$

where

$$\xi_{kj} = e^{2\pi i \xi_{kj}/\rho}, \tag{4.5}$$

$k = 1, \ldots, \kappa$, $j = 1, \ldots, \kappa$. The symbols of the message are *encoded* into an array

$$C = \begin{pmatrix} C_{11} & \ldots & C_{1,n} \\ \vdots & \ddots & \vdots \\ C_{\kappa M,1} & \ldots & C_{\kappa M,n}, \end{pmatrix} \tag{4.6}$$

by the formula:

$$C_{kj} \quad = \quad S_{k \mathsf{div} \kappa, j} \xi_{k \mathsf{mod} \kappa, j}, \tag{4.7}$$

$k = 1, \ldots M\kappa$, $j = 1, \ldots, n$. The values of $\chi_{1,j}$ may be arbitrarily chosen, so long as they are different for each j. An obvious choice, which has been used in the implementation, is $\chi_{1,j} = j$, $j = 1, \ldots, \rho - 1$.

The signals of all users are transmitted simultaneously into the medium which we model as numerical addition:

$$Z_j = \sum_{k=1}^{n} Z_{kj}, \tag{4.8}$$

$j = 1, \ldots, L$.

4.6.6 Decoding

Consider the user with index j and let us ignore the signal due to the other users. For simplicity, assume $M = 1$, or putting it another way, we show the decoding for the first symbol only.

The chip $(Z_{1j}, \ldots, Z_{\kappa j})'$ is converted to a symbol by first using the formula:

$$
\begin{aligned}
W_j &= \sum_{k=1}^{\kappa} Z_{kj}\overline{\xi}_{kj} \\
&= \sum_{k=1}^{\kappa} S_{1j}\xi_{kj}\overline{\xi}_{kj} \\
&= \kappa S_{1j}
\end{aligned}
\tag{4.9}
$$

$j = 1, \ldots, L$. The signal is therefore recovered with a gain in amplitude of the factor κ.

Next, these estimates of the signal are translated to symbols by finding the closest element of the constellation, and then to bits by using the inverse of the algorithm originally used to create the symbols from the message.

4.6.7 User noise

The desired outcome is that when the message of User 1 is demodulated, the messages of all other users appear as noise of low power. The demodulation algorithm, when applied to a message using a nearly orthogonal code, should produce a result with power much lower than white noise of the actual power of the interfering signal.

Consider now how the decoding algorithm applies to a signal from a user with a different code. An appropriate way to quantify their impact is to determine the power of the signal appearing in the form W_j, at (4.9), which is caused by the targeted user, and compare this to the power of the signal appearing in W_j caused by the other users.

We assume, without loss of generality, that the radius of the constellation is 1 (a signal constellation is the physical diagram, which used to describe all the possible symbols employed by a signalling system to transmit data. The constellation helps to design best communications systems, and aids to design a transmission system that is less prone to errors and can possibly recover from transmission problems without relying on higher level protocols. It also helps to understand how a particular modulation mechanism works). Without loss of generality, let us assume the targeted user is using code 1 (i.e. the code which starts with symbol 1), and the interfering user uses code $j \neq 1$. In this case, (4.9) becomes

$$W_j = \sum_{k=1}^{\kappa} Z_{kj}\overline{\xi}_{kj},$$

which, assuming worst case zero loss for the interfering signal

$$\begin{aligned} &= \sum_{k=1}^{\kappa} S_{1j}\overline{\xi}_{kj}\xi_{k1} \\ &= S_{1j}\sum_{k=1}^{\kappa}\overline{\xi}_{kj}\xi_{k1} \\ &= S_{1j} \times (-1) \end{aligned}$$

by the near orthogonality property. Thus, the noise power due to one other user is 1. If there are n users, the power of their combined signal will therefore be n. As for the *signal*, each symbol of the chip independently communicates the original message symbol, so the strength of the signal, when this study calculates the effective signal to noise ratio in this system, should be the square of $\kappa\times$ half the distance between different symbols in the constellation.

The spreading gain due to use of chips of length κ is κ, i.e. the power of the received signal is increased by the factor κ^2. On the other hand, because n users are sharing the same medium, each of the n users must use less than the full power available, by the factor $\sqrt{\kappa}$ (making the conservative assumption that there are $n = \kappa$ users which are all are co-located). Due to the arrangement of symbols in the constellation, assuming the *size* (number of symbols) of the constellation is ϕ, signal strength is not 1, but instead, $\approx \frac{1}{2}\sqrt{\pi/\phi}$. Thus, the signal power due to the whole chip is $\approx \kappa\pi/(4\phi)$. For example, if 32 symbols are used, as in the constellation shown in Figure 4.8, the distance to half-way between two symbols is approximately 0.16. Background noise at the detector is $\kappa\eta^2$ (increased from η^2 because there is a contribution from each symbol in the chip). It follows that the SNR of a system with background noise power η and n users will be $\approx \kappa\pi/(4\phi(\kappa\eta^2 + n/\kappa))$.

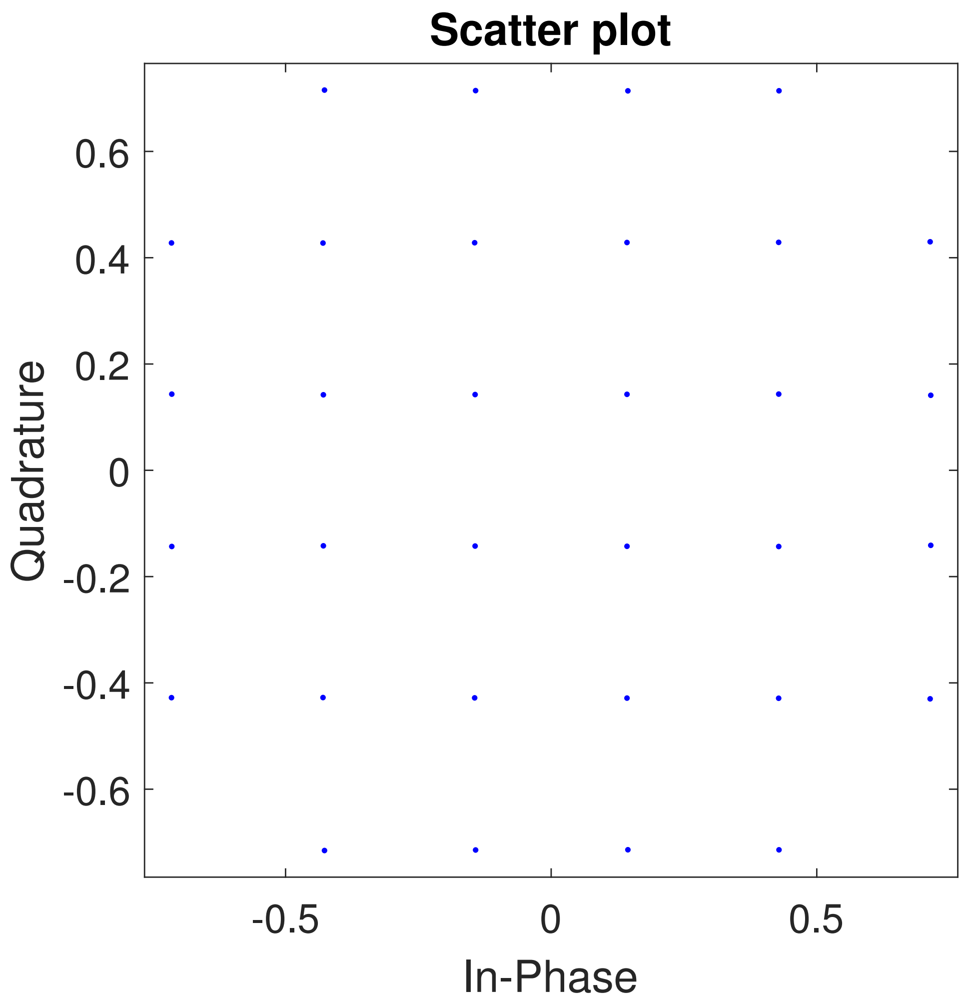

Figure 4.8: A QAM constellation for

Hence the system capacity according to the Shannon-Hartley formula is

$$C \approx \frac{Bn\log_2(\phi)\log_2\left(1+\kappa\pi/(4\phi(\kappa\eta^2+n/\kappa))\right)}{\kappa}.$$

The total throughput achievable in this system is shown as the curve labelled `Sharing by DSSS-OFDM` in Figure 4.9 as a function of the number of users.

In Figure 4.10, physical separation of domains is modelled. The measured power due to other nearby WiFi domains, is reduced by propagation loss. Hence, the power transmitted by each user can be increased, while still respecting the regulated power constraint. The ratio between the maximum power which be transmitted when all κ users are present at the same location, and when they are so distant from each other that their power is insignificant is κ, so a "typical" situation can be modelled, simplistically, by assuming that a user can transmit at κ^α times the allowed power, for $0 \leqslant \alpha \leqslant 1$. With this assumption, system capacity is

$$\frac{Bn\log_2(\phi)\log_2\left(1+\kappa^{1+\alpha}\pi/(4\phi(\kappa\eta^2+n\kappa^{\alpha-1}))\right)}{\kappa}.$$

The choice $\alpha = 0.5$ is plotted in Figure 4.10, again assuming $n = \kappa$.

4.6.8 Why $\rho > 2$

Let us now return to the issue of how to choose ρ. Traditionally, DSSS systems use code from $\mathrm{GF}(2^m)$. If we use a DSSS system with codes from $\mathrm{GF}(2^m)$ in conjunction with OFDM, the nearly orthogonal property, Proposition 1, fails, because the proof of this proposition relies on the mapping $k \mapsto z_k$, from $\mathrm{GF}(2^m)$ to the unit circle ($\{z :\mid z \mid= 1\}$), being a morphism, i.e. $z_k \times z_j = z_{k+j}$.

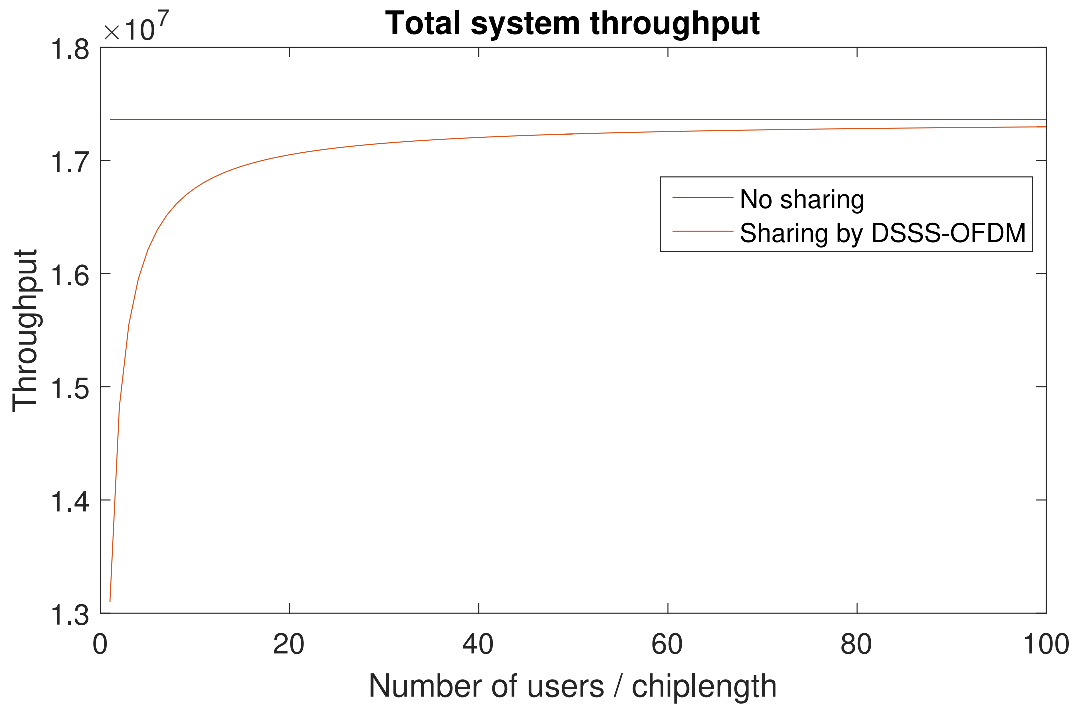

Figure 4.9: Throughput when users are co-located

The choice $\rho = 2$ is only consistent with this requirement when the constellation is limited to the choices ± 1, which might not be efficient for operation with OFDM.

4.7 An experiment with DSSS-OFDM

The DSSS-OFDM wireless communication system has been implemented in Matlab (Alhasnawi & Addie 2018) and a number of experiments have been carried out, for different choices of ρ, η and the constellation. In this subsection we explore an experiment in which $\rho = 1023$. This experiment is sufficient to convey the key features of the system.

In this system it was found that if the number of users is less than or equal to 1000,

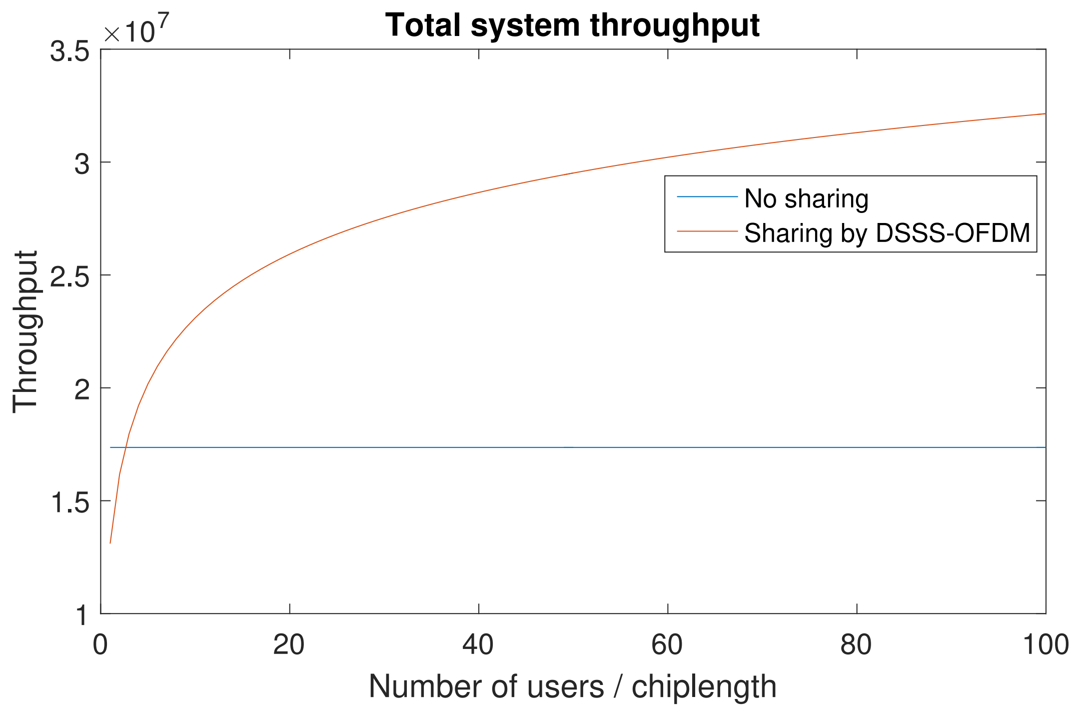

Figure 4.10: Throughput when users are separated ($\alpha = 0.5$)

and the constellation size was 60, all users were able to communicate simultaneously with a low error rate (usually without error). The system implemented did not include error-correction.

The background noise of this system has a standard deviation of 0.05, so the Shannon capacity is approximately 8.65 bits/s/Hz. The implemented system was transmitting at ≈ 5 bps/Hz. The details of this experiment are provided in the report (Alhasnawi and Addie 2018). This report has Table B.1 provides a list of all the matlab files in the system, together with a description of the purpose of that particular script or function, as shown in B.1, B.2, B.3, B.4, B.5, B.6, and B.7.

A complete run of the system is demonstrated in the script wholesystem.m (see Figure 4.11). In this version of the script, the number of users is set to 1000, $\rho = 1023$, and each user transmits a different random message of length 200 bits. All of these

```
wholesystem
============


phi = 343.6667

constlength = 60

bkgndnoise_actual_stdev = 0.0500

errorcount = 1

meanusernoise = 1.3762e-04 - 4.8027e-04i

variancetotalnoise = 8.4687e-07

stdevtotalnoise = 9.2025e-04

throughput = 5.9069e+03

symbolstdeviation = 0.6873

rmsnoise = 0.0017
```

Figure 4.11: Implementation results of the SS-OFDM system

parameters can be changed, arbitrarily. The constellation can also be changed easily.

Each message is coded using the DSSS system of Section 4.6, then all messages are combined together (by numerical addition, simulating the aggregation of their electromagnetic signals), then each receiver decodes their own message from the aggregate signal.

The output of a run of the script wholesystem.m, which conducts an experiment in which 1000 user's simultaneously transmit messages of length 200 bits, is shown in Figure 4.11. Additional output from the script can easily be generated by modifying the script wholesystem.m.

4.7.1 Measured user noise

A key design objective of any spread-spectrum system is to achieve low interference between users. We can quantify this interference by the power (or standard-deviation) of the interfering signal due to the presence of other users. Confirming that user noise is at the level predicted by theory is the most critical validation to apply to an experiment of this type. Once this is confirmed, we can be confident that the theory *and* its implementation are sound.

In the experiment, the constellation size was $\phi = 60$, so signal strength is $\approx \frac{1}{2}\sqrt{\pi/(\phi\kappa)} = 0.003578853$. Note: the reduction in signal strength by $1/\sqrt{\kappa}$ is to ensure that total signal power is within the original regulated limit, as discussed in Section 4.6.

Given that the estimates from each symbol in the chip are *averaged*, at the detector, signal strength is still 0.003578853. The standard deviation (σ_t) of total noise in the experiment, where the chip length is 1022 and the number of users is 1000, was measured at the detector and found to be 0.0017. Background noise standard deviation was 0.05, at the point where it enters the system, so after averaging over chip symbols, this becomes $0.05/\sqrt{1022} = 0.00156$ at the detector. Taking account that the standard deviation of the symbols, in the constellation used in this system is 0.6873, the standard deviation of user noise, at the detector, predicted by theory, in this system, is $0.6873\sqrt{1000/1022}/\kappa = 0.000665$. Thus, standard deviation of total noise is expected to be $\sqrt{(}0.00156^2 + 0.000665^2) = 0.001695$ which is almost exactly the same as measured in the experiment.

These experiments confirmed that the system described in theory, in Section 4.6, can be readily implemented, and performs as predicted by the theory.

4.8 Summary

A communication system which combines spread-spectrum codes and OFDM with the potential to operate at optimal efficiency has been defined, implemented and tested. The predicted performance of the system is reproduced in the implementation to a good approximation, confirming that the theoretical characteristics of the system are achievable, and that the implementation is correct. The system demonstrates that DSSS-OFDM systems are able to achieve nearly optimal spectral efficiency when used as a method for sharing media.

Chapter 5

Sum-Rate Optimal Communication Under Different Power Constraints

In this chapter the problem of optimal allocation of power to different devices and spectrum when communication takes place in the same region, using shared spectrum, is investigated. This study assumes that there must be constraints on the power, or EMF, used at each device participating in the shared communication. This research considers different forms of power/EMF constraint and compares the sum-throughput achieved by all devices, under these different constraints.

5.1 Introduction

Since the introduction of CDMA more than twenty years ago, it has been understood that efficient use of spectrum resources is to a high degree connected with power management, i.e. the choice of how much power is used by each device, in each part of the available spectrum. In the commercial deployment of CDMA, nearly orthogonal codes were used, which gives the impression that efficient power management relies on the shared use, i.e. overlapping use, of spectral resources. However, this chapter argues that efficient power management is actually better explained by the concept that meeting the power constraint is inherently a shared responsibility. Even when different devices use orthogonal resources, such as transmission at different times, or in different frequencies, the collection of devices communicating in the same geographical region at approximately the same time share responsibility for keeping the total field strength of transmitted signals below a regulated level.

The OFDMA technique has strong support as the radio transmission technology for the next generation of cellular mobile wireless systems (Yang 2010, Yadav et al. 2017). This technique is a variant of OFDM which also implements frequency division multiple access, using the orthogonal sub-frequencies. This scheme is used in several generations mobile systems such as 3GPP Long Term Evolution (LTE), IEEE 802.16m advanced WiMAX, and also 802.11ac. A weakness of OFDMA that appears to have been overlooked is investigated in the next chapter.

The chapter is organised as follows. Section 5.2 provides the background about OFDMA system and explains the mathematical model by using Shannon Bound theory to a model wireless system. Section 5.3 compares throughput under the five different configurations; time-segregated transmission, OFDMA, EMF constrained, SS-OFDM, and mutually interfering. The maximum sum-rate throughput for each of the power allocation and sharing those five configurations is determined at Section 5.4. Section 5.5 displays the throughput model implemented in Netml. The conclusion is set out in Section 5.6.

5.2 Background

5.2.1 Relationship between OFDMA and sum-rate optimality

OFDMA is an important multiple access scheme for wireless networks (Yang 2010, AlSabbagh & Ibrahim 2016). It is reputed to have all the communication advantages of OFDM together with efficient sharing of spectral resources (AlSabbagh & Ibrahim 2016, Castro e Souza et al. 2016).

In broadband multiple access, a significant performance measure is a sum-rate capacity. (Li & Liu 2007) investigated the sum-rate optimality of an OFDMA system in an up-link. They found conditions under which OFDMA is sum-rate optimal. They found that the gap between OFDMA and the optimal solution is very small when the number of sub-channels is large. Also, they investigated maximising the sum rate of an OFDMA system in the up-link multi-carrier situations with a limited number of sub-channels.

An important question which is investigated in this chapter is whether, and in what sense, is OFDMA sum-rate optimal, i.e. does it achieve, under the appropriate constraints, the optimal total throughput achievable by a given collection of communicating devices?

5.2.2 System model

The model used here is similar to that of (Chen & Oien 2008) except that as well as n separate power constraints, this model also considers a uniform constraint on total EMF spectral density. The reasons for doing so were discussed in Chapter 3.

This constraint also applies at all of the nodes (both origins and destinations) of the network, but it is reasonable to suppose that the constraint is now *the same* at all nodes. This does not imply that all nodes are transmitting with the same power because if there are nodes close to each other, they may be forced to limit their individual power to keep total power below a regulated level.

5.2.3 Overlapping wireless domains

From the fact that this study gets close to the Shannon-Hartley bound, it follows that we can use it to estimate system capacity. This is useful in itself, as a simple and effective way to model wireless systems. For example, this research uses this principle to model the bandwidth which is achieved in a configuration of access points and users of the sort depicted in Figure 4.1.

Currently, the conventional way to model such a system would be to simulate it, for example, using Ns3 (Henderson et al. 2008), Omnet (Varga & Hornig 2008), or Opnet (Guo et al. 2007). However, setting up such a simulation would be very time consuming and would not necessarily provide useful insight into spectrum sharing.

The study (Alhasnawi. et al. 2018) also used the Shannon Hartley bound to model the capacity of wireless communication systems.

5.3 Power/EMF constraints

To meet regulations and standards governing wireless communication, all wireless devices must limit the power of their transmissions. This effectively also limits the total EMF generated by these transmissions. In addition, it has been explained in

Chapter 3 that it can be argued that regulatory constraints should be expressed in terms of total EMF spectral density, rather than power generated by each individual device. This chapter seeks to compare and contrast different approaches to regulating or limiting EMF and/or power.

If shared use of spectrum is mediated by time-segregated use, which is often the case (e.g. as in CSMA/CA), a limit on the power transmitted by any device imposes a constraint on the total electrical field strength (and magnetic field strength), which can occur. Regulations on transmission power are not necessarily imposed for this purpose, however, as the number of devices sharing the same physical and spectral location increases, it may become appropriate, or necessary to view regulation of power in this light, i.e. as a means to limit total electromagnetic field strength. This point of view was investigated in Chapter 3.

Suppose there are n transmissions required to take place, as shown in Figure 5.9, let the transmission power at source k be denoted by P_k, and suppose the maximum power allowed to be transmitted, in order to regulate total EMF, is T_P. More precisely, if there was only one transmitter, in order to achieve the desired limit on EMF, it could not transmit with more power than T_P. We now consider five different approaches to limiting power which vary in the way the aggregate EMF due to all the devices are considered.

Note that the five different approaches to meeting power/EMF constraints that are considered here vary slightly in the way the constraint is *expressed*, but also, and this is the more significant aspect, in the *way* in which the constraint is *enforced*.

These five approaches are:

1. Carrier-Sense Multiple Access (CSMA) method, the modeling of which is presented in Subsection 5.3.1,

2. Orthogonal Frequency-Division Multiple Access (OFDMA), treated in Subsection 5.3.2,
3. Electromagnetic Fields (EMF) limited, in Subsection 5.3.3,
4. Spread Spectrum-Orthogonal Frequency Division Multiplexing (SS-OFDM), in Subsection 5.3.4, and,
5. Mutually interfering (i.e. all transmitters use the entire bandwidth, simultaneously, treating each other as noise), treated in Subsection 5.3.5.

The purpose of this comparison is not simply to show that one approach has more throughput than another. For example, throughput is always lower when total EMF is adopted as the appropriate constraint, rather than transmitted power at each device. The reason for comparing these constraints is that an EMF constraint is more rigorous, and therefore safer as discussed in Chapter 3. The experiments show that adopting this constraint does not dramatically reduce throughput relative to a constraint on power, and that is the conclusion of interest from these particular experiments.

Likewise, the transmission model adopted is very simple and cannot be used as the basis for designing a communication system. This study assumes that all communication systems use OFDM with careful channel estimates made dynamically during actual operation. The simple transmission model is being used to compare throughput under the five different configurations which are compared, and is sufficient for that purpose.

5.3.1 Time-segregated transmission

If all devices communicate only when others are idle, and when this is the case they use all the available spectrum, the power constraints can be expressed thus:

$$P_k \leq T_p, \quad k = 1, ..., N \tag{5.1}$$

These constraints also ensure that at every location, the EMF never exceeds the EMF which would be generated by one device transmitting continuously at the limit power.

5.3.2 OFDMA

In this case, the power constraints are still expressed by (5.1). However, because the devices are able to transmit simultaneously, total throughput can be quite different, as shown in the Section 5.5.

5.3.3 EMF constrained

Let

$$G = \begin{pmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{n1} & \cdots & g_{nn} \end{pmatrix}$$

where g_{jk} is the ratio of the power received at node k to the power transmitted at node j, if $j \neq k$, or 1 otherwise. These values can be estimated from a Friis transmission formula (Popovic & Popovic 2000):

$$g_{jk} = \frac{DA}{4\pi r_{jk}^2} \tag{5.2}$$

in which D is the directivity of the aerial at node S_j, the source of transmission j, A denotes the relative effective area of the receiving aerial (i.e. the human body) at node S_k, the source of transmission k, and r_{jk} is the distance between the source of transmission j and the source of transmission k. By *relative effective area* of the aerial at node S_k we mean how much less effective a human present at node S_k is, at receiving power from a distant aerial, than they are at receiving power from the source of transmission k. Hence, a simple choice for A is 1.

A constraint on total EMF due to all transmissions, at all the sources, can therefore be expressed in the form:

$$\sum_{j=1}^{n} g_{k,j} P_j \leq T_p, \quad k = 1, ..., n. \tag{5.3}$$

5.3.4 SS-OFDM

Now suppose we use codes, either orthogonal codes or nearly orthogonal ones, in conjunction with OFDM. Thus, codes are used to mediate access rather than frequencies, as in OFDMA. The case where the codes are orthogonal is, in many respects, no different from OFDMA.

Two approaches to limiting power can be distinguished in this case: (a) a simple limit on total power, as in OFDMA, and (b) a limit on total EMF, as in the EMF-limited case. Since the two cases are very similar, we shall confine our investigation in this case to the second of these alternatives.

In this case, the constraints on power are also expressed by (5.3). If the codes are orthogonal, the throughput was also the same as in the previous case. A formula for the throughput when the codes are not orthogonal is given in Section 5.4.5. The only difference is that in this case the power spectral density of the transmitted signal will be different. By judicious use of codes it should be feasible to achieve a virtually flat power spectral density.

However, if the codes are *nearly orthogonal*, as in (Alhasnawi. et al. 2018), the throughput of this system will be quite different, and provides an approach intermediate between that of Subsection 5.3.3 and 5.3.5.

5.3.5 Mutually interfering

In this case, also, the constraints on power are also expressed by (5.3). Instead of seeking complete independence of different transmissions, by using of time, frequency, or code segregation, in this case we make no attempt to prevent interference between different transmissions, and simply allow them to proceed simultaneously, with each transmitter treating the others as white noise. We may suppose, for example, that each uses a unique coding which ensures that its signal appears, statistically, as white noise for the others. In a situation where transmitters are far from each other, or where background noise is already of relatively high power, this approach will be nearly optimal.

5.4 Sum-rate optimal throughput

The transmitters sharing the available spectrum are always assumed, when time, frequency, or code resources are shared, to be allocated equal shares. It is therefore possible that higher throughputs than those we obtain below could be attained by unequal allocation of resources. The purpose of this chapter is primarily to compare the different sharing strategies rather than to optimise throughput as such. In any case, since focussing on total throughput would often result in some users being allowed no resources at all, it is unlikely that total throughput in this sense is an appropriate objective.

This section determines the maximum sum-rate throughput, per Hz, for each of the power allocation and sharing schemes considered in Section 5.3. This research assumes that each transmitter has identical access to communication resources. Allocation of these resources is not optimised. Rather, it is allocation of power to the resources which is under consideration. This part seeks to compare the throughput achieved by the alternative schemes, under different network conditions.

In the first two cases (time segregated, and individual power constraints), the optimal power allocation to devices is obvious. In both these cases, devices simply transmit at their maximum power, while they are active.

In the EMF-constrained case, set out in Subsection 5.3.3, the vector of power levels is $P = (P_1, \ldots, P_N)'$ where

$$P = T_P G^{-1} u \tag{5.4}$$

Where u is a vector of $1's$ and $*'s$. If $u_j = *$ we require $P_j = 0$. In other words, we select a subset of sources to transmit at full power and another set of sources that will be idle. One such selection will be optimal.

To work out which ones should be transmitting and which should not, consider a small change to the power of a transmitter, along with the consequential changes to all other transmitters which keep them within their constraint. If this change leads to more throughput, with more power, then this should be one of the transmitters.

The special case where all sources are transmitters will occur frequently because the matrix G will frequently have rather small off-diagonal terms. In this case the vector u, at (5.4), consists of all 1's.

The total throughput of the system is the same as the *sum rate*, which is the objective of the multiplexing and channel allocation problem considered in this chapter. This objective is expressed mathematically in Equation (4) in (Chen & Oien 2008). In their formulation, the signal from each communication interferes with all others, and appears as white noise of the same power.

5.4.1 Time-segregated transmission

In this case each transmitter operates at power $P_n = T_P$ while it is transmitting. The total rate of transmission, in bits/s/Hz, in this case is

$$\sum_{n=1}^{N} \frac{1}{N} \log_2 \left(1 + \frac{P_n G_{n,n}}{\sigma_n^2} \right) . \tag{5.5}$$

5.4.2 OFDMA

Because the power allocated to the bandwidth assigned to each transmitter is the whole of the allocated power, for this transmitter, i.e. $P_n = T_P$, while the noise is just a $\frac{1}{N}$-th share, and the bandwidth for each transmitter is $\frac{1}{N}$-th of the whole, the total rate of transmission, in bits/s/Hz, in this case is

$$\sum_{n=1}^{N} \frac{1}{N} \log_2 \left(1 + N \frac{P_n G_{n,n}}{\sigma_n^2} \right). \tag{5.6}$$

5.4.3 EMF constrained

The throughput in the EMF-limited case is also given by (5.6), except that in this case the P_n are given by (5.4).

5.4.4 SS-OFDM

In this case, as well as background noise, receiver n experiences user noise, u_n^2, which is given by the formula

$$u_n^2 = \sum_{k \neq n} c P_k G_{k,n} \tag{5.7}$$

in which c is the correlation between codes (given by their inner product), which we assume is the same for all pairs of codes. Naturally $0 \leqslant c \leqslant 1$; in the case $c = 0$, we say the codes are orthogonal. Throughput is therefore,

$$\sum_{n=1}^{N} \frac{1}{N} \log_2 \left(1 + \frac{P_n G_{n,n}}{\sigma_n^2/N + u_n^2} \right). \tag{5.8}$$

5.4.5 Mutually interfering

In this case, as in the previous case, as well as background noise, receiver n experiences user noise, u_n^2, which is now given by the formula

$$u_n^2 = \sum_{k \neq n} P_k G_{k,n} \tag{5.9}$$

Each transmitter is active all the time, and receivers experience the full background noise, so throughput is

$$\sum_{n=1}^{N} \log_2 \left(1 + \frac{P_n G_{n,n}}{\sigma_n^2 + u_n^2} \right). \tag{5.10}$$

5.5 Experiments

The throughput model from the previous section has been implemented in Netml (Addie et al. 2011, Addie & Natarajan 2015) allowing for five different sharing strategies, namely CSMA/CA, OFDMA, EMF-constrained OFDMA, mutually-interfering (i.e. all transmitters use the entire bandwidth, simultaneously, treating each other as noise), and SS-OFDM. This model of sharing which has been implemented in the Netml system is not the same as simulation, and is therefore not available in alternative systems like Opnet, Omnet, or ns-3. Equations (5.2), (5.5)–(5.10) have been used to estimate throughput, instead of simulation. This is much faster and, since it focuses on principles underlying shared use of spectrum, more appropriate in the present context.

The precise values of received power and SNR at each receiver, in (5.9), depend on the power levels at the transmitters and gain across each pair ($G_{n,n}$), and hence on the geographical layout of the pairs. All these parameters are relatively easy to calculate once the layout has been determined. Using the Netml system, different configurations of communicating pairs can easily be created, the distances between all nodes calculated, the power levels allowed by the constraints for the particular case determined, the gain matrix G calculated by means of (5.2), and the total throughput calculated.

This research has undertaken three experiments, in each of which the geographical configuration of the pairs of communicating devices is arranged somewhat differently. The three cases considered are as follows:

(i) the nodes of each pair are relatively close to each other and the pairs are widely separated. There are 8 pairs of nodes. This case is referred to as *widely separated pairs*, as shown in Figure 5.1.

(ii) The pairs are closer together than in the previous case, and there is only three pairs, as in Figure 5.4. This case is referred to as *three close pairs*.

(iii) In this case eight pairs overlap. We refer to this case as *overlapping pairs*, as in Figure 5.7.

5.5.1 Widely separated pairs

The results, plotted in Figure 5.2, show that the sum-throughput rate of OFDMA and EMF-constrained OFDMA was equal for all levels of background noise. Total throughput in the CSMA/CA case was always worse than OFDMA and quite significantly so for high levels of noise.

The mutually interfering and SS-OFDM total throughputs were very similar and both were also similar to OFDMA for high noise levels, but a little worse than OFDMA for low noise.

The power of the signal in each frequency range, when OFDMA is used, has been calculated as well as throughput, and is shown in Figure 5.3. The power vs frequency distribution will be the same in the EMF-limited case. In the time-segregated case, the SS-OFDM case, or the mutually interfering case, the power vs frequency distribution will be essentially flat.

5.5.2 Three close pairs

The results in this case, plotted in Figure 5.5 exhibit the same key features: OFDMA and EMF-limited cases are almost identical and deliver better throughput than all other cases. CSMA/CA is worse, and more significantly so under high noise. The SS-OFDM case is closer to OFDMA but a little worse under low noise. One difference from the previous experiment is that now the mutually interfering case exhibits worse performance than SS-OFDM.

The power of the signal in each frequency range, when OFDMA or the EMF-limited case applies, has been calculated and is shown in Figure 5.6. In the time-segregated case, the SS-OFDM case, or the mutually interfering case, the power vs frequency

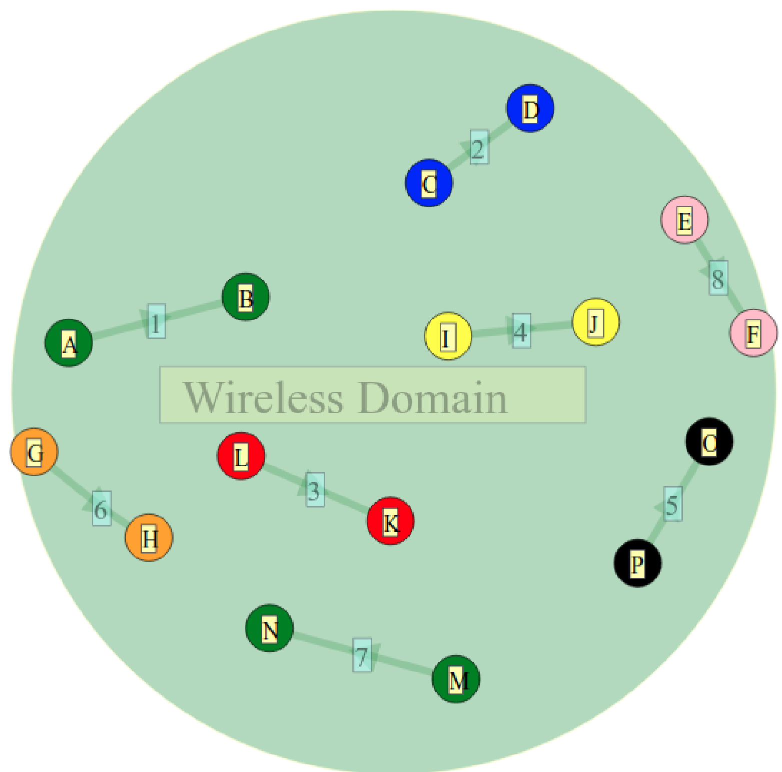

Figure 5.1: Eight widely separated pairs of nodes

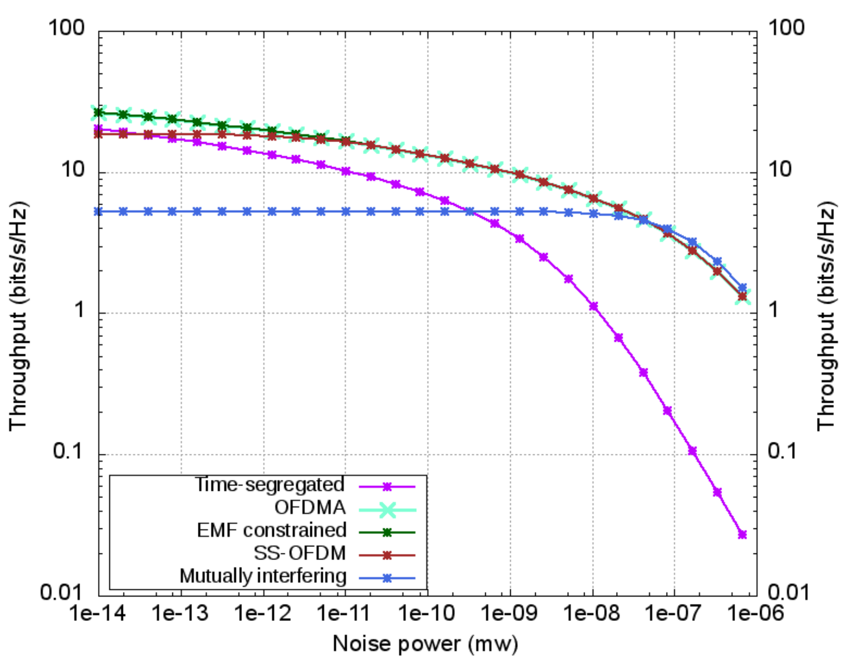

Figure 5.2: Wireless throughput for widely separated pairs

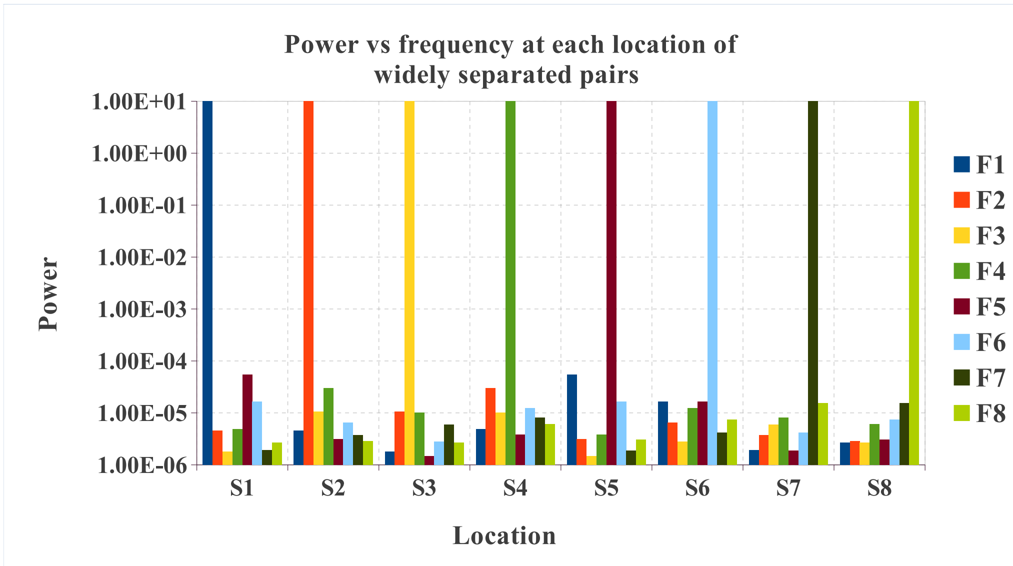

Figure 5.3: Power vs frequency for widely separated pairs

distribution will be, as in the first experiment, essentially flat.

5.5.3 Overlapping pairs

The results, plotted in Figure 5.8, again show that the OFDMA and EMF-limited cases have higher total throughput than all others. CSMA/CA is again significantly worse for high noise, and SS-OFDM is close to OFDMA, but a little worse for low noise. Also, the mutually interfering case is worse again than SS-OFDM.

The power of the signal in each frequency range, in the OFDMA or EMF-limited cases, has been calculated and is shown in Figure 5.9. In the time-segregated case, the SS-OFDM case, or the mutually interfering case, the power vs frequency distribution will be, as in the previous experiments, essentially flat.

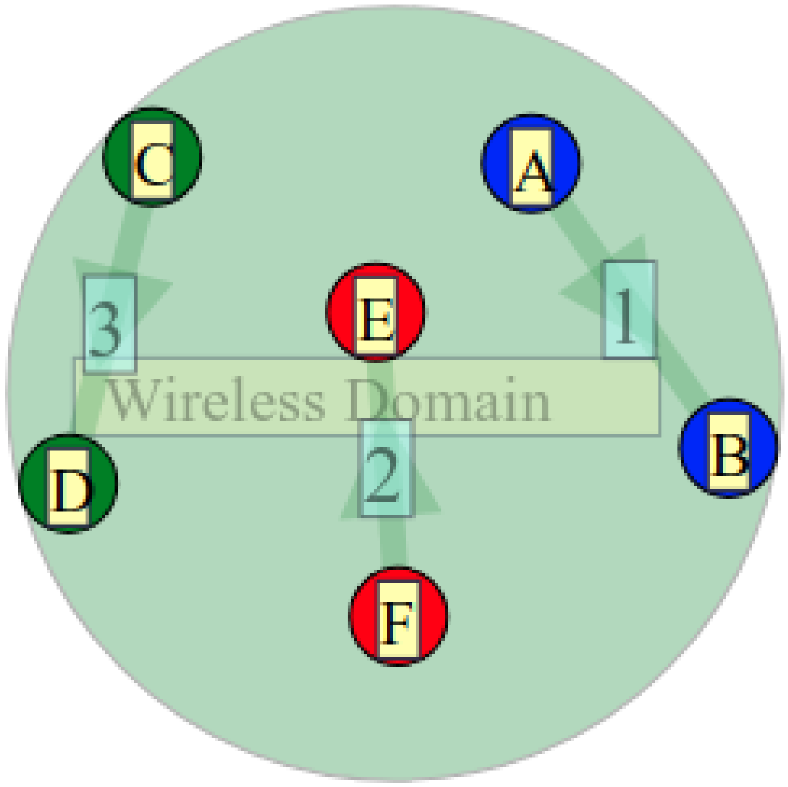

Figure 5.4: Three pairs of close nodes

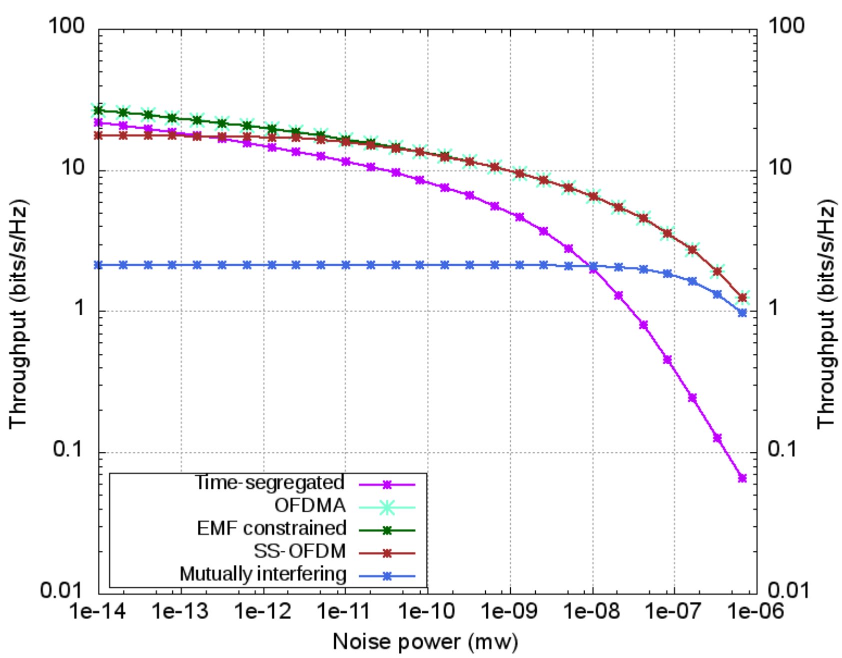

Figure 5.5: Wireless throughput for three close pairs of nodes

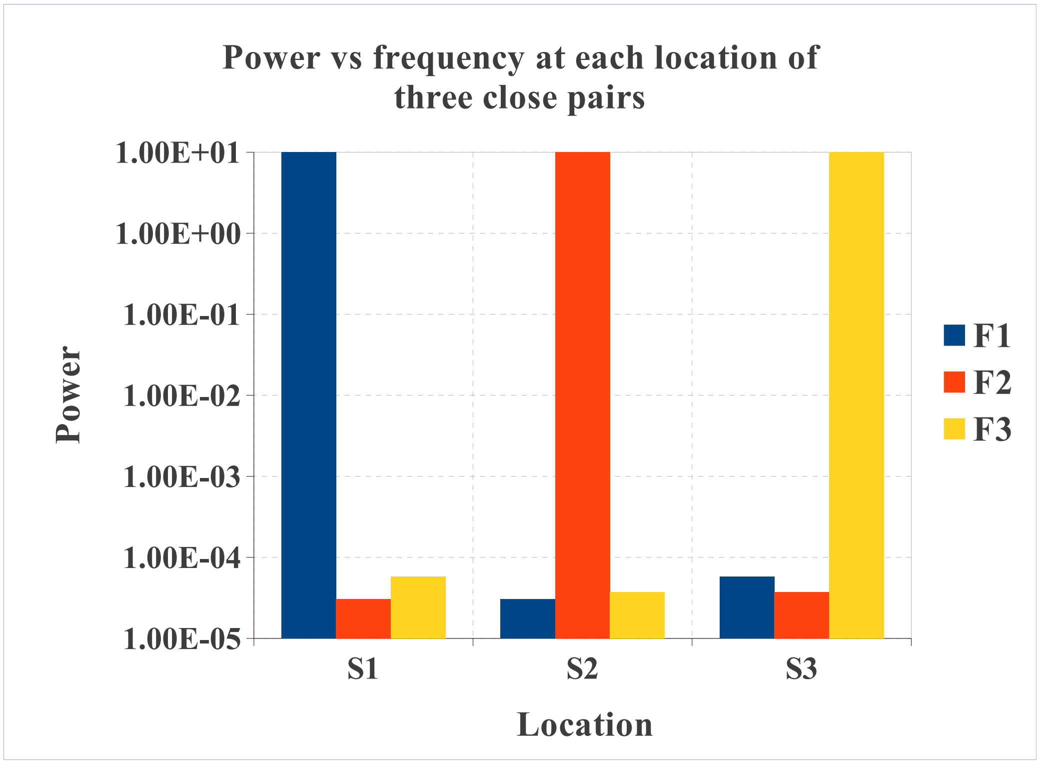

Figure 5.6: Power vs frequency at each source location of three close pairs

5.6 Summary

The experiments all show that OFDMA and the EMF-limited cases are nearly identical. This is because in all the cases considered, the EMF limits on power are not significantly different from simply limiting the transmitted power of each device. If configurations where devices are very close together were considered, this would no longer be the case. Consideration of such cases remains for future work.

Another consistent result was that OFDMA consistently out-performed all other sharing mechanisms. The SS-OFDM case assumed non-orthogonal codes, with correlation at the level 0.1. If orthogonal codes were used, the performance of SS-OFDM would be identical to OFDMA. Such experiments were conducted, but not shown,

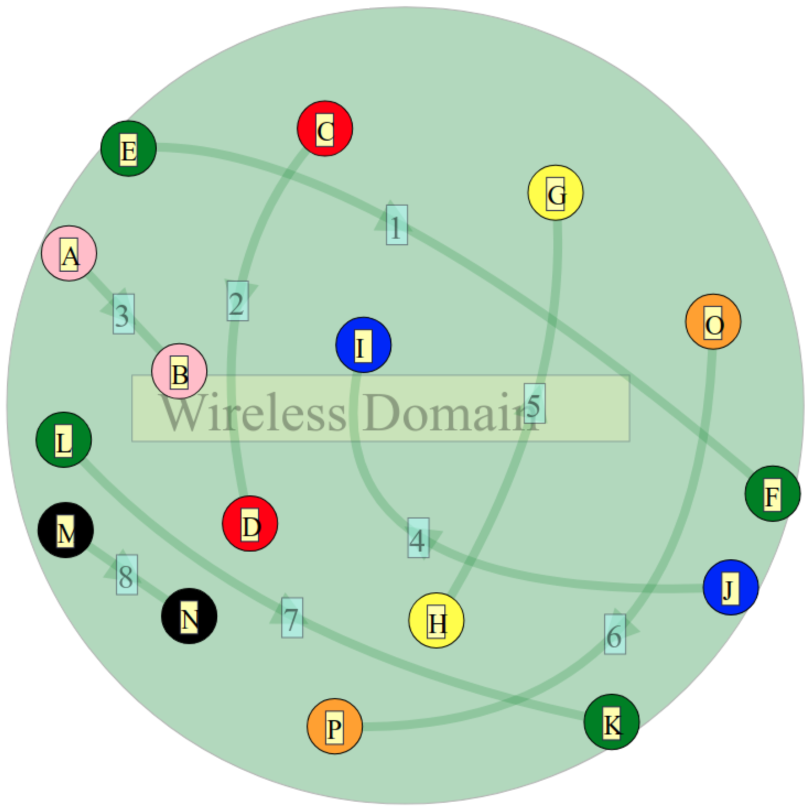

Figure 5.7: Overlapping communicating pairs

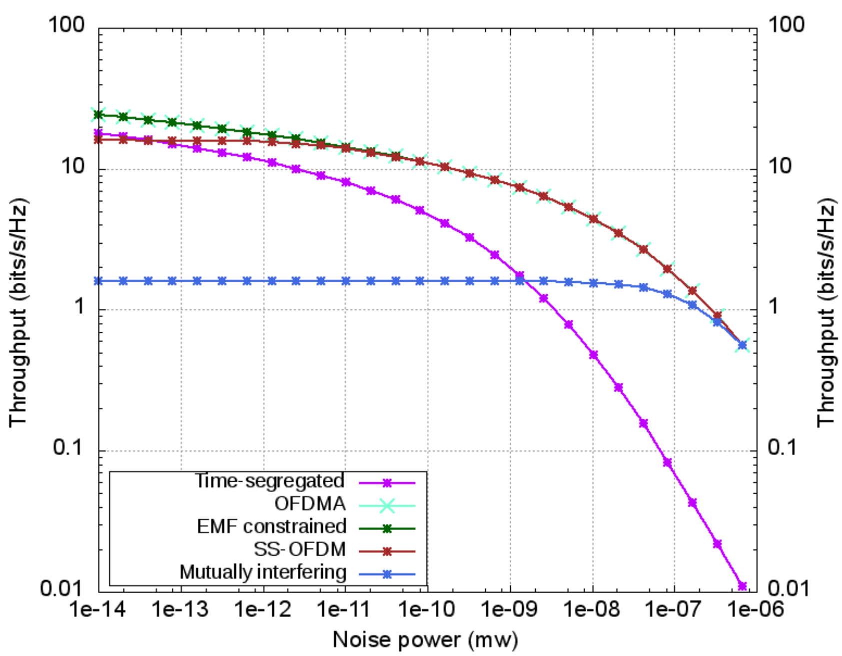

Figure 5.8: Wireless throughput of overlapping communicating pairs

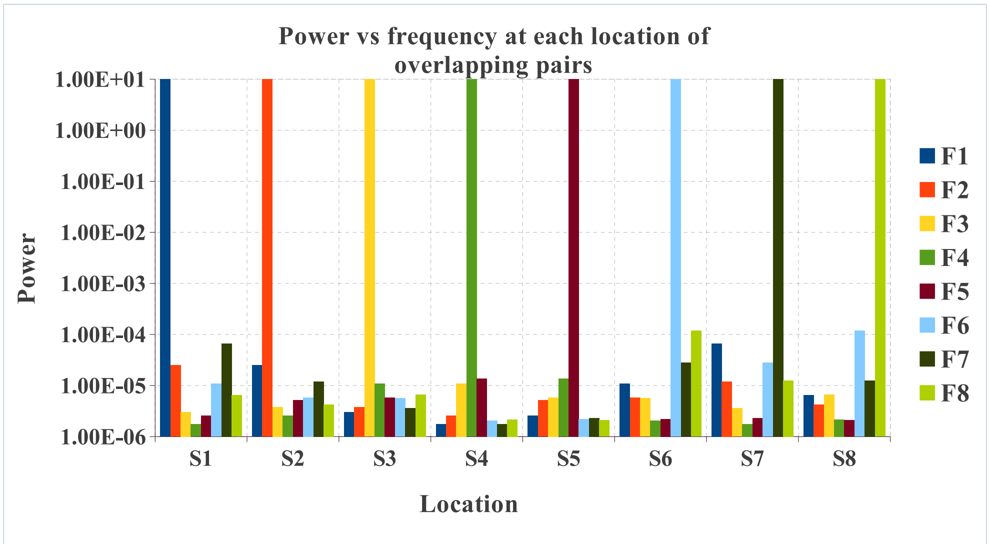

Figure 5.9: Power vs frequency at each source location of overlapping pairs

because the two performance curves would simply be superimposed.

However, the spectral distribution of SS-OFDM is essentially flat, unlike that of OFDMA. If this is an important consideration, SS-OFDM is therefore the preferred option. It achieves the same throughput as OFDMA, but within a much tighter constraint on the power spectral density. Since SS-OFDM is able to achieve the same throughput as OFDMA with a flat power spectral density, it is actually more efficient in the use of spectrum, once the EMF constraint is expressed in terms of its spectral density.

Chapter 6

Cross-Subchannel Noise in OFDMA As An Impediment in Spectral Co-Existence

In this chapter an overview is presented of the existing status of OFDMA system, which is a strong candidate for managing sharing of spectrum resources in all nearby wireless communication to share the available spectrum. Also, it investigations of cross-subchannel noise. We model cross-channel noise that depends on selected frequencies of all nearby wireless communication systems which use the same OFDMA wireless systems.

6.1 Introduction

Spectrum sharing is a problem of considerable interest and importance (Pandit & Singh 2017). Spectral sharing by time segregation, for example by using CSMA/CA, is inefficient by comparison with either OFDMA or SS-OFDM (Alhasnawi. & Addie. 2019). However, it is not correct to assume that signals from nearby OFDMA systems are nearly orthogonal to each other, even if they are using the same system of frequencies and the same frame length. This chapter investigates that OFDMA has some significant weaknesses that might make it unsuitable as a method for spectral sharing. Also, it shows that sub-channels that would be orthogonal to each other, if used in a single OFDM system, will generate significant noise, when used in geographically nearby locations.

This chapter is organized as follows with the arrangement; Section 6.2 explains the an experiment demonstrating cross-channel noise in OFDMA. Section 6.3 estimates the power of the cross-channel noise from *one other* system, and then estimates the noise due to several such systems by simply adding their power. The conclusion is set out in Section 6.4.

6.2 An experiment demonstrating cross-channel noise

A situation in which cross-subchannel noise arises is depicted in Figure 6.1. This figure assumes three nearby OFDM systems named A, B, and C that are used in geographically nearby locations, domains A, B, and C, respectively. Those systems are using the same system of frequencies and frame length. The signals in each OFDM system are orthogonal to each other, because the sub-channel frequencies are orthogonal over the interval T, i.e. the frame-length, and the frame boundaries of each reflection of the signal always occur in the cyclic extension of all the other reflections of the signal.

However, let us now consider the situation where system A is sending a signal to another location named domain B and system B is sending a signal also to another location called domain C. Then, we have three pairs of frames which are labelled 1, 2, and 3 in Figure 6.1.

Each of these pairs of frames represents two reflections arriving at the destination aerial of an individual OFDM system. The cyclic extensions ensure that the combined signals in each sub-frequency, are mutually orthogonal, within one system.

However, the frame boundary of the pair of frames from system A does not occur within the cyclic extensions of system B or C; and the boundary of the frames from system B does not occur within the cyclic extensions of systems A or C. And so on.

As a result, the signals from nearby OFDMA systems are not orthogonal to each other. Consequently, the signals from nominally orthogonal frequencies from other OFDM systems will contribute *cross-subchannel noise*.

6.3 Cross-subchannel noise power

When a signal is being received which has been encoded using phase modulation, or quadrature amplitude modulation, the optimal receiver multiplies the signal by any of the "expected signals" and integrates. The size of this integral indicates the presence or absence, and whether it is positive or negative, of that particular expected signal and can therefore be used to determine what symbol was being sent.

When quadrature amplitude modulation is used, this is the logical, and probably optimal, method for estimating the symbol which was sent. Establishing that this method of estimation method is optimal would take a considerable time and space, which would not sit well in this dissertation. Since it is well-established that optimal

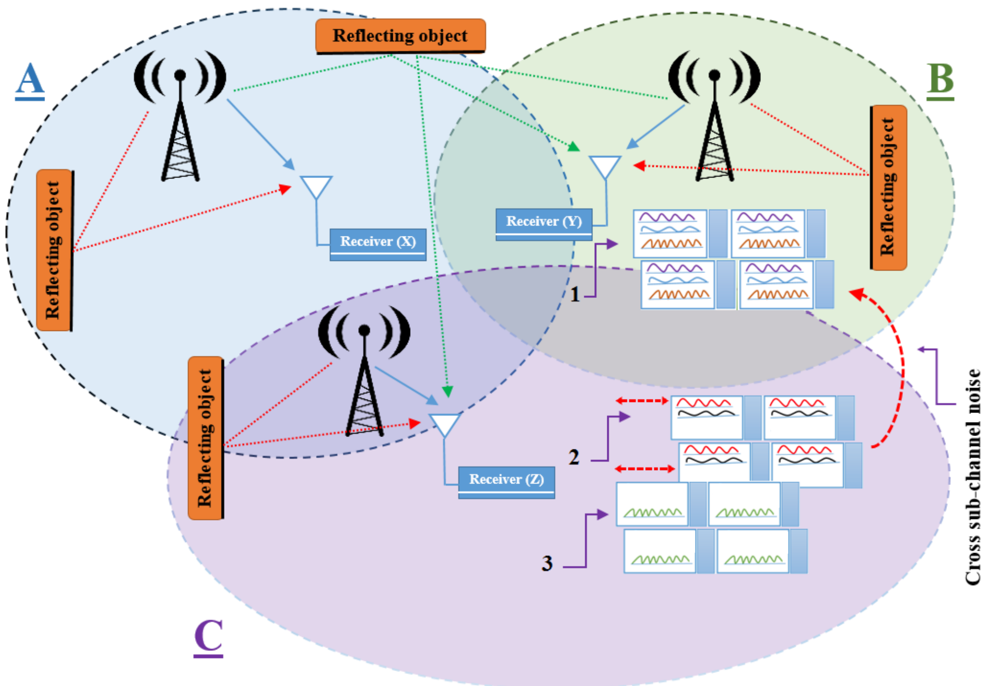

Figure 6.1: OFDMA cross-subchannel noise

estimators usually take this form, it is reasonable to proceed on that assumption here. Therefore this study assumes that this technique used to determine the received message.

In general cross-subchannel noise will arise from all nearby wireless communication systems which use the same OFDMA system, and the same spectrum. However, we can confine ourselves to estimating the power of this noise from *one other* system, and then estimate the noise due to several such systems by simply adding their power.

Initially, let us consider just three cases of cross-subchannel noise that comes from all nearby wireless communication systems which use the same OFDMA wireless systems.

The three cases are:

Assume f_0 is the frequency the receiver is trying to use, f_1 is the frequency being used by the interfering signal, ϕ represents the phase displacement of the interfering signal, relative to the one the receiver is listening to, and T represents length of a frame.

1. The first case is ordinary OFDM, where the other received signal is orthogonal, because the message being transmitted is 00 or 11, and hence, their are no phase transitions. The integral, for receiving the signal in this case, is

$$\begin{aligned}
&\int_0^{T-\phi} \frac{1}{T}\cos\left(2\pi f_1(t+\phi)+\pi\right)\cos\left(2\pi f_0 t\right)\,dt + \\
&\int_{T-\phi}^{T} \frac{1}{T}\cos\left(2\pi f_1(t+\phi)+\pi\right)\cos\left(2\pi f_0 t\right)\,dt \\
&= \int_0^{T} \frac{1}{T}\cos\left(2\pi f_1(t+\phi)+\pi\right)\cos\left(2\pi f_0 t\right)\,dt = 0,
\end{aligned} \tag{6.1}$$

   because frequencies f_0 and f_1 are orthogonal when received over a frame of length T.

2. The second case is OFDMA with good time synchronisation, where the received signal is used the same frequency; the integral, for detecting the symbol sent, is

$$\begin{aligned}
&\int_0^{T-\phi} \frac{1}{T}\cos\left(2\pi f_0(t+\phi)\right)\cos\left(2\pi f_0 t\right)\,dt + \\
&\int_{T-\phi}^{T} \frac{1}{T}\cos\left(2\pi f_0(t+\phi)\right)\cos\left(2\pi f_0 t\right)\,dt
\end{aligned}$$

which, assuming $\phi = 0$ because the receiver is synchronized,

$$= \int_0^{T} \frac{1}{T}\cos\left(2\pi f_0 t\right)^2\,dt = \frac{1}{2}. \tag{6.2}$$

3. In the last case, we assume that the base frequency, f_0 is equal $2.4 * 10^9$, and a frame has length, T, equal to 4 periods, hence $T = 4/f_0 = 1.67 * 10^{-9}$. Hence, T is the equal base of the frame in cycles divided base of frequency that is approximately 0.0017. The interfering signal is using a different frequency,f_1, and is transmitting 01, so that the frequency f_1 exhibits a phase shift during the time when it is interfering with the main signal being received. The level of this interference to the main signal is given by the integral:

$$
\begin{aligned}
&\int_0^{T-\phi} \frac{1}{T} \cos\left(2\pi f_1(t+\phi)\right) \cos\left(2\pi f_0 t\right) dt + \\
&\int_{T-\phi}^{T} \frac{1}{T} \cos\left(2\pi f_1(t+\phi)+\pi\right) \cos\left(2\pi f_0 t\right) dt \\
&= 2\int_0^{T-\phi} \frac{1}{T} \cos\left(2\pi f_1(t+\phi)\right) \cos\left(2\pi f_0 t\right) dt \\
&= \frac{1}{T}\int_0^{T-\phi} \cos\left(2\pi f_1(t+\phi)+2\pi f_0 t\right) + \cos\left(2\pi f_1(t+\phi)-2\pi f_0 t\right) dt \\
&= \frac{1}{T}\left(\frac{1}{2\pi(f_1+f_0)}(\sin\left(2\pi f_1 T+2\pi f_0(T-\phi)\right) - \sin(2\pi f_1\phi)) + \frac{1}{2\pi(f_1-f_0)}\right. \\
&\left.\left(\sin\Big(2\pi f_1 T - 2\pi f_0(T-\phi)\Big) - \sin(2\pi f_0\phi)\right)\right)
\end{aligned}
\tag{6.3}
$$

$$
\begin{aligned}
&= \frac{1}{T}\left(\frac{1}{2\pi(f_1+f_0)}\left(\sin\left(2\pi f_1 T\right)\cos\left(2\pi f_0(T-\phi)\right)+\cos\left(2\pi f_1 T\right)\right.\right. \\
&\left.\sin\left(2\pi f_0(T-\phi)\right)\right) - \sin\left(2\pi f_1\phi\right) + \frac{1}{2\pi(f_1-f_0)}\left(\sin\Big(2\pi f_1 T\Big)\right. \\
&\left.\left.\cos\left(2\pi f_0(T-\phi)\right) - \cos\left(2\pi f_1 T\right)\sin(2\pi f_0(T-\phi))\right) - \sin(2\pi f_0\phi)\right) \\
&= \frac{1}{T}\left(\frac{1}{2\pi(f_1+f_0)}\left(\sin\left(2\pi f_0(T-\phi)\right)\right)\right. \\
&\left.-\sin\left(2\pi f_1\phi\right) - \frac{1}{2\pi(f_1-f_0)}\left(\sin(2\pi f_0(T-\phi))\right) - \sin\left(2\pi f_0\phi\right)\right)
\end{aligned}
\tag{6.4}
$$

Equation (6.4) has been plotted, and the result is shown in Figure 6.2. The noise due to cross-subchannel interference is significant for some displacements, and therefore the supposition that sub-channels of nearby OFDM systems are orthogonal, or even nearly orthogonal, is not supported.

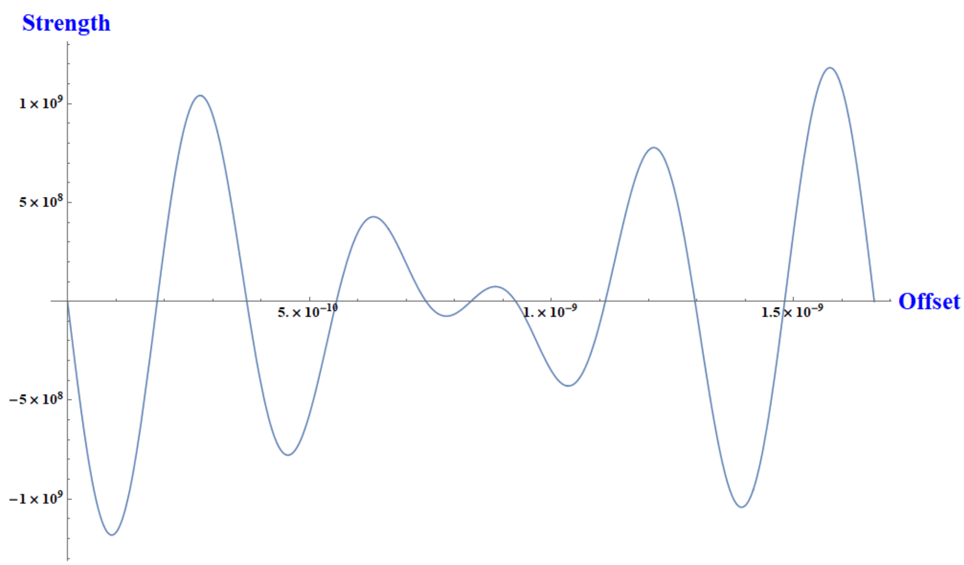

Figure 6.2: Estimating of OFDMA cross-subchannel noise

6.4 Summary

Cross-channel noise of all nearby wireless communication systems, which use the same OFDMA configuration of frame and sub-frequencies are modelled in the three different cases which reveal the phenomenon of cross-channel noise. We considered three cases, which are: the first case is ordinary OFDM, the second case is OFDMA with good time synchronisation, and the last case assumed that two nearby systems are not sufficiently well synchronised for the cyclic extensions of the two systems to overlap. These showed that even when nearby systems are using the same OFDM configuration, because of the large differences in latency, sub-channels of nearby systems are no longer orthogonal. Therefore OFDMA is not necessarily as effective as a method for sharing wireless spectrum as it might appear.

Chapter 7

Conclusion and future work

Spectrum is a crucial resource for wireless communications systems. Health safety imposes an essential constraint closely aligned with transmission power, which is also a key parameter determining transmission capacity and therefore the issue of spectrum sharing cannot be addressed without taking into account safety-related constraints on power. EMF needs to be regulated to levels well below where there might be harm and therefore below the internationally agreed EMF exposure limit standards, which are presented in Table 2.2. Hence, we do not expect to see any health effects at these levels.

This study, therefore, assumed that there must be constraints on the power or EMF, used at each device participating in the shared communication, which is due to health considerations. These constraints on EMF affect the way we share the spectrum. The way these regulations are expressed needs great care because it will have an effect on the design of the wireless communication systems. The limit on EMF should be expressed in terms of its EMF spectral density rather than as a total EMF over each of a series of separate bands. In each spectral region, if all devices limit their own EMF spectral density where they are active, in such a way that total EMF spectral density is below the regulated limit in that region, then it is certain that the aggregate EMF spectral density will be below the regulated limit at all frequencies, as investigated in Chapter 3.

In chapter 4, a SS-OFDM system was developed for the optimal sharing of the spectrum among the nearby users. The SS-OFDM system has been implemented in Matlab and used to demonstrate simultaneous communication of a large number of co-located users (up to 1000), using spread-spectrum to share access to the medium, with high spectral efficiency. It has also been estimated that when users, are not co-located, total system throughput achievable is significantly greater than systems in which the available spectrum is used exclusively by each pair of communicating devices one at a time. The Shannon bound has been used to model the capacity of this system, which does not require simulation, and can be achieved using a relatively simple mathematical formula, as shown in (2.1).

In Chapter 5, power constraints on wireless devices have been expressed in a different way, namely that devices should actively seek to limit, by their own behaviour, the total EMF, in $V/m/Hz$, due to their own transmission and the existing activity of other devices. This study considered using constraints on EMF spectral density, rather than (or as well as) on EMF discrete spectrum. Such constraints are used to express limits for health reasons or for technical reasons, or both. For consistency and simplicity, these constraints are uniform across all frequencies when expressed in $V/m/logHz$. Hence, all wireless devices must limit the power of their transmissions to meet regulations and standards governing wireless communication. This effectively also limits the total EMF generated by these transmissions. This study considered and compared five different approaches to limiting power which vary in the way the aggregate EMF due to all the devices are considered, but also, and this is the more significant aspect, in the way in which the constraint is enforced. These five approaches are; CSMA, OFDMA, EMF-limited, SS-OFDM, and mutually interfering. The experiments all showed that OFDMA and the EMF-limited cases are nearly identical. This is because in all the cases considered, the EMF limits on power are not significantly different from simply limiting the transmitted power of each device. If configurations, where devices are very close together, were considered, this would no longer be the case.

Another consistent result was that OFDMA consistently out-performed all other sharing mechanisms. The SS-OFDM case assumed non-orthogonal codes, with correlation at the level 0.1. If orthogonal codes were used, the performance of SS-OFDM would be identical to OFDMA. Such experiments were conducted, but not shown, because the two performance curves would simply be superimposed. However, the spectral distribution of SS-OFDM is essentially flat, unlike that of OFDMA. If this is an important consideration, SS-OFDM is therefore the preferred option. It achieved the same throughput as OFDMA, but within a much tighter constraint on the power spectral density. Since SS-OFDM is able to achieve the same throughput as OFDMA with a flat power spectral density, it is actually more efficient in use of spectrum, once the EMF constraint is expressed in terms of its spectral density.

Finally, this thesis investigated the existing status of the OFDMA system through modelled cross-channel noise of all nearby wireless communication systems, which used the same OFDMA configuration of frame and sub-frequencies. The results showed that nearby systems using the same OFDMA configuration are no longer orthogonal, because of the large differences in latency. Therefore OFDMA is an alternative that looks as good as SS-OFDM, but it is not quite as good as it seems because of cross-channel noise, given health constraints, and efficient spectrum sharing, it is important to use SS-OFDM. The SS-OFDM system was implemented and this implementation confirmed that the theoretical characteristics of the system are achievable and that the proposed system is readily implementable. The system demonstrates that SS-OFDM systems are able to achieve nearly optimal spectral efficiency when used as a method for sharing media, as shown in Chapters 4 and 6.

Future work should compare the finite-field SS-OFDM implemented and investigated in this dissertation to binary SS-OFDM systems, and in particular, to investigate the efficiency of binary systems. The issue of how EMF regulations are expressed has not been adequately exposed in the research community at this stage, and additional publications and discussion are warranted. Also, the problem of cross-subchannel noise, in nearby OFDMA systems, has not been discussed in the research literature at all, as far as we are aware, and publications which expose this problem should be prepared and submitted.

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Appendix A

Mathematica Code for Implementing The Aggregate EMF

This appendix has three Mathematica files and two R scripts; firstly, the Mathematica file Listing A.1 in the system descriptions the main program of aggregate EMF spectral density. Secondly file, Listing A.2 shows the aggregate EMF due to several nearby transmitters, assuming each transmitter limits its own power, without concern for ambient EMF, is plotted in Figure 3.4. This figure shows a typical situation of several devices inside the same building or vehicle which are using the same spectrum. Each device transmits at the same time. The EMF intensity is higher than that of a single transmitter because it is the aggregate effect of all the transmitting devices. Thirdly, the Mathematica file Listing A.3 displays the resulting aggregate EMF, with the same configuration of devices as previously, all these devices sense and measure the EMF in the region where they are active is shown in Figure 3.5. In this case, the regulated limit on aggregate EMF is respected. This approach is therefore safer.

Fourthly, the R script Listing A.4 presents the calculation of the EMF and EMF density for WiFi and 5G. Finally, the script Listing A.5 shows calculations of the EMF and EMF density for WiFi 2.45 GHz, WiFi 5 GHz, and 5G.

```
Aggregate Field Strength
************************

Parameters
~~~~~~~~~~

The parameters of the location of transmitters, and their
transmission characteristics are defined here. We can use
systematic, random, or arbitrary locations (specify each
one explicitly). The first choice we have here is
systematica -- a grid.


Location Parameters
*******************

Grid
~~~~

hseparation = 5; vseparation = 5; hnum = 5; vnum = 5;
locations = Flatten[Table[
   Table[{j hseparation, k vseparation},
    {j, 0, hnum - 1}], {k, 0, vnum - 1}], 1]

{{0, 0}, {5, 0}, {10, 0}, {15, 0}, {20, 0}, {0, 5},
 {5, 5}, {10, 5},{15, 5}, {20, 5}, {0, 10}, {5, 10},
 {10, 10}, {15, 10}, {20, 10},{0, 15}, {5, 15},
 {10, 15}, {15, 15}, {20, 15}, {0, 20}, {5, 20},
 {10, 20}, {15, 20}, {20, 20}}
```

```
{{0, 0}, {5, 0}, {10, 0}, {15, 0}, {20, 0}, {0, 5},
 {5, 5}, {10, 5}, {15, 5}, {20, 5}, {0, 10}, {5, 10},
 {10, 10}, {15, 10}, {20, 10}, {0, 15}, {5, 15},
 {10, 15}, {15, 15}, {20, 15}, {0, 20}, {5, 20},
 {10, 20}, {15, 20}, {20, 20}}
```

```
locations[[1]]
```

```
{0, 0}
```

```
Circle
~~~~~~
```

```
nloc = 10; radius = 20; locations1 :=
 Table[{radius Cos[k 2 Pi /nloc],
   radius Sin[k 2 Pi /nloc]},
  {k, 0, nloc - 1}];
N[locations1]
```

```
{{20., 0.}, {16.1803, 11.7557}, {6.18034, 19.0211},
 {-6.18034, 19.0211}, {-16.1803, 11.7557}, {-20.,
  0.}, {-16.1803, -11.7557}, {-6.18034, -19.0211},
 {6.18034, -19.0211}, {16.1803, -11.7557}}
```

```
xoffset = 1; yoffset = 1.5; nloc2 = 5; radius = 20;
locations2 := Table[{radius Cos[k 2 Pi /nloc2] + xoffset,
    radius Sin[k 2 Pi /nloc2] + yoffset},
   {k, 0, nloc2 - 1}];
N[locations2]
```

```
{{21., 1.5}, {7.18034, 20.5211}, {-15.1803,
  13.2557}, {-15.1803, -10.2557}, {7.18034, -17.5211}}
```

```
locations := Union[locations1, locations2,
   {{6.22, 18.75}}];
N[locations]

{{-20., 0.}, {6.22, 18.75}, {20., 0.},
{21., 1.5}, {-16.1803, -11.7557},
{-16.1803, 11.7557}, {-6.18034, -19.0211},
{-6.18034, 19.0211}, {6.18034, -19.0211},
{6.18034, 19.0211}, {16.1803, -11.7557},
{16.1803, 11.7557}, {-15.1803, -10.2557},
{-15.1803, 13.2557}, {7.18034, -17.5211},
{7.18034, 20.5211}}


ourorder = {1, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14,
            15, 16, 2, 10};
locationswithextra := Table[locations[[ourorder[[k]]]],
                            {k, 1, 16}];

N[locationswithextra]


{{-20., 0.}, {20., 0.}, {21., 1.5}, {-16.1803, -11.7557},
 {-16.1803, 11.7557}, {-6.18034, -19.0211},
 {-6.18034, 19.0211}, {6.18034, -19.0211},
 {16.1803, -11.7557}, {16.1803, 11.7557},
 {-15.1803, -10.2557}, {-15.1803, 13.2557},
 {7.18034, -17.5211}, {7.18034, 20.5211},
 {6.22, 18.75}, {6.18034, 19.0211}}

Length[locationswithextra]

16
```

```
Random

Transmission Parameters
~~~~~~~~~~~~~~~~~~~~~~~

gamma = 2 (* Distance decay exponent *);

nearfieldthresh = 6;
```

Listing A.1: The main program of aggregate EMF spectral density

```
Aggregate EMF
*************:

1) Aggregate EMF with no Measurement of Ambient EMF
***************************************************

Length[locations];
margin = 5

emf[r_] :=
  Which[r > nearfieldthresh, r^- gamma,
   r <= nearfieldthresh,
   nearfieldthresh^-gamma +
    0.05 Sqrt[nearfieldthresh^2 - r^2]];
SourceEMF[x_, y_] := Module[{r = (Sqrt[(x[[1]]
         - y[[1]])^2 + (x[[2]] - y[[2]])^2])},
  emf[r]]

Plot3D[SourceEMF[{u, v}, {5, 5}],
 {u, - margin hseparation,
```

```
  (1 + margin) hseparation},
 {v, - margin vseparation,
  (1 + margin) vseparation},
 PlotRange -> Full]


EMFLimit[x_] := 0.35;
AggEMF[x_] :=
 Sqrt[Sum[SourceEMF[x, locationswithextra[[k]]]^2, {k ,
    Length[locationswithextra]}]];
    hleft = -radius - margin;
    hright = radius + margin;
    vleft = -radius - margin;
    vright = radius + margin;


Plot3D[{AggEMF[{u, v}], EMFLimit[{u, v}]},
 {u, hleft, hright}, {v, vleft, vright},
 PlotStyle -> {, {Opacity[0.5], Red}},
 PlotLegends -> Placed[
   {"Aggregate EMF", "EMF Limit"},
   {Right, Above}], AxesLabel -> {Style
     ["X-Position", 25, Bold, Blue],
   Style["Y-Position", 25, Bold, Blue],
   Style["EMF", 25, Bold, Blue]},
 LabelStyle -> Directive[15, Black, Bold,
   FontFamily -> "Times New Roman"],
 MaxRecursion -> 15]
```

Listing A.2: Aggregate EMF with no measurement of ambient EMF

```
2) Aggregate EMF with Measurement of Ambient EMF
************************************************

AggEMFFromOthers[x_, self_] :=
  Sqrt[Sum[SourceEMF[x, locationswithextra[[k]]]^2,
    {k , Table[kk, {kk, 1, self - 1}]}]];
AggEMFWithAmbientMsmnt[x_] :=
  Sqrt[Sum[(((SourceEMF[locationswithextra[[k]],
          locationswithextra[[k]]])/
        (AggEMFFromOthers[locationswithextra[[k]], k] +
          SourceEMF[locationswithextra[[k]],
           locationswithextra[[k]]]))
      SourceEMF[x, locationswithextra[[k]]])^2,
    {k , Length[locationswithextra]}]];

Plot3D[{AggEMFWithAmbientMsmnt[{u, v}],
  EMFLimit[{u, v}]}, {u, hleft, hright},
 {v, vleft, vright}, PlotStyle ->
  {, {Opacity[0.5], Red}}, PlotLegends ->
  Placed[{"Aggregate EMF", "EMF Limit"},
   {Right, Above}], AxesLabel ->
  {Style["X-Position", 25, Bold, Blue],
   Style["Y-Position", 25, Bold, Blue],
   Style["EMF", 25, Bold, Blue]},
 LabelStyle -> Directive[15, Black,
   Bold, FontFamily -> "Times New Roman"],
 MaxRecursion -> 15]
```

Listing A.3: Aggregate EMF with measurement of ambient EMF

```
fieldstrength = function(freq,R,P,frange) {
  C = 3 * 10^8
  lambda = C / freq
  beta  = 2 * pi /lambda
  I = sqrt (P /R)
  ell = lambda/4
  theta = pi /2 # [so sin theta = 1]
  r  =  2 * lambda
  mu     = 4 *pi* 10^(-7)
  eps = 8.85419* 10^(-12)

  fstrength =(beta * I * ell * sin(theta)) * sqrt(mu/eps)/(4 * pi * r)
  fsperHz = fstrength/frange
  fsperlogHz = fstrength/(log10((freq+frange)/freq))
  c(fstrength,beta,fsperHz,fsperlogHz)

  cat ("lambda = ",lambda,"beta =", beta, "I =",I ,"ell =",ell
      ,"r =",r,"fstrength =",fstrength,"fsperHz =",
      fsperHz,"fsperlogHz =",fsperlogHz, "\n")
}
```

Listing A.4: Script for calculation of the EMF and EMF density for WiFi and 5G

```
          # EMF of 2.45 GHz frequency band

> R_2.45GHz=fieldstrength(2.4*10^9,50,0.01,1*10^8)

lambda =  0.125 beta = 50.26548 I = 0.01414214
ell = 0.03125 r = 0.25 fstrength = 2.663885
fsperHz = 2.663885e-08 fsperlogHz = 150.2578

            # EMF of 5 GHz frequency band

> R_5GHz=fieldstrength(5*10^9,50,0.01,15*10^7)

lambda =  0.06 beta = 104.7198 I = 0.01414214
ell = 0.015 r = 0.12 fstrength = 5.549761
fsperHz = 3.699841e-08 fsperlogHz = 432.3178

              #  EMF of 5G

R_5G=fieldstrength(3.6*10^9,50,0.2,5*10^8)

lambda =  0.08333333 beta = 75.39822 I = 0.06324555
ell = 0.02083333 r = 0.1666667 fstrength = 17.86989
fsperHz = 3.573977e-08 fsperlogHz = 316.3856
```

Listing A.5: Calculations of the EMF and EMF density for WiFi 2.45 GHz, WiFi 5 *GHz*, and 5G

Appendix B

Description of SS-OFDM System Code

Table B.1 provides a list of all the matlab files in the system, together with a description of the purpose of that particular script or function. All but two of the files define matlab functions. The script `wholesystem.m` performs an experiment in which `NU` users send and receive messages of length `ML` simultaneously. The script `TotalBR.m` creates graphs showing the total capacity of a collection of SS-OFDM systems operating simultaneously, either in the same location, or at locations separated in space geographically sufficiently to have a certain signal power loss relative to each other.

For an explanation of how the system works, and how to interpret the experiments conducted by means of `wholesystem.m`, and how to interpret the graphs produced by `TotalBR.m`, please see (Alhasnawi. et al. 2018).

Table B.1: Codes clarification

Name of function /file	**Description**
Generate_codes	Generate codes for each user.
findConst	Find a constellation with `f` as the prime, `n` the number of different circles, and `phi` is the number of symbols in the outer circle.
constSep	Find the minimum separation of constellation symbols
Primitive	Find a primitive element of the group.
decodeFromConst	Decode a message using a certain constellation of symbols.
encodeToConst	Encode a message using a certain constellation of symbols.
findLattice	construct a constellation as a lattice, with a specific number of symbols per row.
TotalBR	Calculate the total bandwidth per user of the whole system.
Matlab main program	The whole system, with `NU` users sending different messages and each message is coded using DSSS, then all messages are combined together, then each receiver decodes their own message from the aggregate signal.

```
function codes = generate_codes(f, p)
    gs = f-1;
    codes = zeros(gs,gs);
    ppowerforkloop = 1;
    for k = 1:gs
        ppowerforjloop = ppowerforkloop;
        for j = 1:gs
            codes(j,k) = ppowerforjloop;
            % mod(p^(mod(j+k-2,gs)),f);    this method leads to overflow
            ppowerforjloop = mod(ppowerforjloop*p,f);
        end
        ppowerforkloop = mod(ppowerforkloop*p,f);
    end
end
```

Listing B.1: Generate_codes

```
function [const,totalcount] = findConst(f, n, phi, full)
  % find a constellation with f as the prime, n the number
  % of different circles, and phi is the number of symbols
  % in the outer circle

skip = ceil(f/phi);
totalcount = 0;
for circle = n:-1:1
    step = ceil(n/circle)*skip;
    count = floor(f/step);
    totalcount = totalcount + count;
end

const = zeros(totalcount,1);
thisindex = 1;
j = 0;
alternatingfraction = 0;
```

```
step = 1;
for circle = n:-1:1
    if (~full)
        step = ceil(n/circle)*skip;
    end
    count = floor(f/step);
    for k = 1:count
        const(thisindex) = (circle/n) * exp(2 * pi * i *
         (((ceil((k-1+alternatingfraction)*step))/ f))) ;

        thisindex = thisindex + 1;
    end
    j = 1;
    if (~full)
        alternatingfraction = 0.5-alternatingfraction;
    end
end
end
```

Listing B.2: findConst

```
function minsep = constSep(const, len)
     minsep = 10;
     for k = 1:len
         for j = 1:(k-1)
             if (abs(const(k)-const(j))) < minsep
                 minsep = abs(const(k)-const(j));
             end
         end
     end
end
```

Listing B.3: constSep

```
function p = primitive(f)
    for k=2:(f-1)
        success = true;
        test = k;
        for j=1:(f-3)
            test = mod (test*k,f);
            if test==1
                success = false;
                break;
            end
        end
        if success
            p = k;
            return;
        end
    end
end
```

Listing B.4: Primitive

```
function [msg,unoise] = decodeFromConst(const, fullconst, code,
                        signal, f, h, sentMsg, beta)
%   decode a message using a certain const of symbols
    unoise = zeros(size(sentMsg));
    totalcount = length(const);
    % this only works in the initial case, where the
    % const is on the outer circle

    chiplen = length(code);
    symbol = zeros(1,length(signal));  % for some reason
                                       % we are using rows
    West = zeros(size(const));
    for k=1:(length(signal)/chiplen)
        W = 0;
```

```
        for j=1:chiplen
            if (code(j)==0)
                thisest = signal(chiplen*(k-1)+j);
            else
                thisest = signal(chiplen*(k-1)+j)*
                            conj(fullconst(code(j)+1));
            end
            % signalmag = abs(signal(chiplen*(k-1)+j));
            % signalarg = myangle(signal(chiplen*(k-1)+j));
            % signalsymbol = mod(round(f*signalarg/(2*pi)),f);
            % signalsymbol = mod(signalsymbol * code(j),f);
            % thisest = signalmag * exp(2*pi*i*signalsymbol/f);
            W = W + thisest;
            % chipcode = mod((primitive*chipcode), fs);
            % rotation (not used)
        end

        W = W / (chiplen*beta);  % scale it up so it fits the
                                 % original symbols
        West(k) = W;
        absw = abs(W);
        symbolk = findSymbol(const, W)-1;
        if (k<length(sentMsg))
             unoise(k) = beta*(W - sentMsg(k)); % measure noise
                                                % before rescaling
        end
        symbol(k) = symbolk;
    end
    msg = bitcodemsg(symbol,totalcount);
    % hold on;
    % scatterplot(West,1,0,'.r',h);
end
```

Listing B.5: decodeFromConst

```
function [signal,lengthinsymbols,complexmessage] = encodeToConst
                     (const, outerconst, code, msg, NoOfBits, f)
    % encode a message using a certain constellation of symbols

    % initially se assume the constellation is equispaced complex
    % numbers around the unit circle

    constlength = length(const);
    % this only works in the initial case, where the constellation
    % is on the outer circle

    chiplen = length(code);
    siglen = ceil(2*chiplen*length(msg)/NoOfBits);
    symsignal = zeros(siglen,1);
    signal = zeros(siglen,1);
    msgInSymbols = symbolcodemsg(msg,constlength);
    complexmessage = msgInSymbols;
    lengthinsymbols = length(complexmessage);
    for k=1:lengthinsymbols
        complexmessage(k) = const(msgInSymbols(k)+1);
    end
    lengthmsginsymbols = length(msgInSymbols);
    lengthsignal = length(signal);
    NoOfBits;
    for k=1:(length(msgInSymbols));
        for j=1:chiplen
            % signal(chiplen*(k-1)+j,1) =
            % gfdiv(msgInSymbols(k),code(j),f);
            if (code(j)==0)
                signal(chiplen*(k-1)+j,1) = complexmessage(k);
            else
                j;
                indexforouterconst = mod(code(j),f)+1;
                signal(chiplen*(k-1)+j,1) =
```

```
                outerconst(indexforouterconst)*complexmessage(k);
            end
        end
    end
end
```

Listing B.6: encodeToConst

```
function [ const, const_count ] = findLattice(rowcount)
   % UNTITLED Summary of this function goes here
   % Detailed explanation goes here

const_count = 0;
for rowk=1:rowcount
    for colk=1:rowcount
        x=-1+2*(colk-1)/(rowcount-1);
        y=-1+2*(rowk-1)/(rowcount-1);
        % check if this candidate is inside unit circle
        if (x*x+y*y<1)
            const_count = const_count +1 ;  % if so add 1 to
                                            % the constellation
                                            % count
        end
    end
end

const = zeros(const_count,1);
k=1;
for rowk=1:rowcount
    for colk=1:rowcount
        x=-1+2*(colk-1)/(rowcount-1);
        y=-1+2*(rowk-1)/(rowcount-1);
        % check if this candidate is inside unit circle
        if (x*x+y*y<1)
```

```
            const(k) = x + i*y;
            k = k+1;
        end
    end
end

end
```

Listing B.7: findLattice

```
% Calculate the total bandwidth per user of the whole system

NU = 100;
Z= 1: NU;
chiplen = Z;
f = chiplen+1;
B= 1000000;
kappa = 1022;   % an alternative notation for chip length
phi = 28;       % constellation size
eta2 = 0.0025;
alpha = 0.5;
logbit = log2 (1 +  (sin(pi*ones(1,NU)./f)).^2 .* chiplen.^2
         ./ ((alpha*(Z-1)+eta2)));

logbit(1) = log2(1+1/eta2);  % correction for the case n=1
totalBRcircperim = B * Z.* logbit ./ chiplen;
totalBRcircarea = B * Z.* logbit /pi^2;
singleuserBR = B * log2 (1 + 1/eta2) * ones(1,NU);  % Shannon formula
newsingleuserB = B * (log2(phi)) * log2(1 + pi/(4*phi*eta2)) * ones(1,NU);
totalBRnew = B * (log2(phi) / kappa) * Z .* log2(ones(1,NU) + kappa * pi *
             ones(1,NU) ./ (4*phi*(kappa*eta2*ones(1,NU) + (alpha/kappa)*
             (Z - ones(1,NU)))));

totalBRnew2 = B * log2(phi) * log2(ones(1,NU) + pi * Z.^(1+alpha)
```

```
            ./ (4*phi*eta2*(Z + Z.^alpha));

figure();
subplot(2,1,1);
plot(Z,newsingleuserB, Z, totalBRnew2);
title('Total system throughput')
ylabel('Throughput')
xlabel('Number of users / chiplength')
legend({'No sharing', 'Sharing by DSSS-OFDM'},'Location','east')
return;

% plot a diagram with different alphas

figure();
subplot(2,1,1)
alpha = 0.1;
logbit = log2 (1 +  pi^2 * chiplen.^2 ./ (f.^2 .*(alpha*(Z-1)+eta2)));
logbit(1) = log2(1+1/eta2);  % correction for the case n=1
totalBRcircarea0_1 = B * Z.* logbit /(2*pi);

alpha = 0.2;
logbit = log2 (1 +  pi^2 * chiplen.^2 ./ (f.^2 .*(alpha*(Z-1)+eta2)));
logbit(1) = log2(1+1/eta2);  % correction for the case n=1
totalBRcircarea0_2 = B * Z.* logbit /(2*pi);

alpha = 0.4;
logbit = log2 (1 +  pi^2 * chiplen.^2 ./ (f.^2 .*(alpha*(Z-1)+eta2)));
logbit(1) = log2(1+1/eta2);  % correction for the case n=1
totalBRcircarea0_4 = B * Z.* logbit /(2*pi);

alpha = 1;
logbit = log2 (1 +  pi^2 * chiplen.^2 ./ (f.^2 .*(alpha*(Z-1)+eta2)));
logbit(1) = log2(1+1/eta2);  % correction for the case n=1
totalBRcircarea1 = B * Z.* logbit /(2*pi);
```

```
plot(Z, totalBRcircarea0_1, Z, totalBRcircarea0_2, Z, totalBRcircarea0_4,
     Z, totalBRcircarea1);
title('Total system bandwidth')
ylabel('BR')
xlabel('Number of users')
legend({'alpha=0.1', 'alpha=0.2', 'alpha=0.4', 'alpha=1'},'Location',
       'east')

% Plot the Correlation between  variance of user noise vs number of users

Z = 1:NU
% figure();
% subplot(2,1,1)
%correlation = plot(Z,varianceusernoise);
% title('Correlation between  variance of user noise vs number of users')
% ylabel('variance of user noise')
% xlabel('Number of users')
```

Listing B.8: TotalBR

```
% The whole system, with N users sending different messages and each
% message is coded using DSSS, then all messages are combined together,
% then each receiver decodes their own message from the aggregate signal
% parameters: NU: number of users
global usess;
NU = 1000 ;
ML = 200; % ML: message lengths
bkgndnoisestdev = 0.05;
usess = true;
if (usess)
    f = 1031;      % prime number, which is the size of Galois Field
    chiplen = f-1;% : length of chips
    p = primitive(f); % the primitive element of the group
    code = generate_codes(f, p);% codes for each user
```

```
    phi = f/3
else
    f = 1031;
    ML = ML*NU;
    NU = 1;
    n = 3
    phi = 16;
    code = ones(1,1);
end
beta = 1/sqrt(chiplen);    % we reduce signal power to keep
                           % within regulations
rowcount = 10;
[const,constlength] = findLattice(rowcount);
[outerconst,fullcount] = findConst(f, 1, f, true);
constlength
bps = floor(log2(constlength)+0.001);

 % bits per symbol (only approximate -- actually its bps
 % sometimes and bps-1

if (usess)
    siglen = chiplen*ceil(ML/bps);
else
    siglen = ceil(ML/bps);
end
minsep = constSep(const,constlength);
h = 0;  % h = scatterplot(const,1,0,'.b');
        % scatterplot(outerconst,1,0,'.b');

messages =  round(rand(ML,NU)); % Generate messages

signals = zeros(siglen,NU); % Modulate message to create N signals
for k=1:NU
    [x,lengthinsymbols,msgInSymbols] =
```

```
    encodeToConst(const, outerconst, code(k,:), messages(:,k), bps, f);
    signals(1:length(x),k) = beta * x;
end

% signals(1,1), Add signals together
aggregatesignal = zeros(length(signals(:,1)),1);
aggregatesignal(1:length(signals(:,k))) = signals(:,1);
for k=2:NU
   vec = aggregatesignal(1:length(signals(:,k))) + signals(:,k);
   aggregatesignal(1:length(signals(:,k))) = vec;
end

bkgndnoise = random('norm',0,bkgndnoisestdev,[length(signals(:,1)),1]);
phase = random('uniform',0,2*pi,[length(signals(:,1)),1]);
bkgndnoise = bkgndnoise .* exp(i*phase);
bkgndnoise_actual_stdev = rms(bkgndnoise)
aggregatesignal = aggregatesignal + bkgndnoise;
% Demodulate and decode N messages from the combined signal
decodedmessages = messages;
for k=1:NU
    [dm,tnoise] = decodeFromConst(const, outerconst, code(k,:),
                  aggregatesignal, f, h, msgInSymbols, beta);

    decodedmessages(:,k) =  dm(1:ML);

end

totalnoise = tnoise(1:lengthinsymbols);
% Check error rate
errorcount = sum(xor(messages(1:(ML-1)),decodedmessages(1:(ML-1))))
% Estimate the standard deviation of user-noise and mean of signals
meanusernoise = mean(totalnoise)
variancetotalnoise = var(abs(totalnoise))
stdevtotalnoise = sqrt(variancetotalnoise)
```

```
throughput = NU * log2(constlength)
symbolstdeviation = rms(const)
rmsnoise = rms(totalnoise)
```

Listing B.9: Matlab main program

Appendix C

The Throughput Model for Five Different Sharing Strategies

Table C.1 provides a list of all the java files in the system, the throughput model from the previous section has been implemented in Netml (Addie et al. 2011, Addie & Natarajan 2015) allowing for five different sharing strategies, namely CSMA/CA, OFDMA, EMF-constrained OFDMA, mutually-interfering (i.e. all transmitters use the entire bandwidth, simultaneously, treating each other as noise), and SS-OFDM. This model of sharing which has been implemented in the Netml system is not the same as simulation, and is therefore not available in alternative systems like Opnet, Omnet, or ns-3. Equations (5.2), (5.5)–(5.10) have been used to estimate throughput, instead of simulation. This is much faster and, since it focusses on principles underlying shared use of spectrum, more appropriate in the present context.

Table C.1: Codes clarification

Name of function /file	**Description**
Time segregated throughput	Estimate the wireless throughput of CSMA/CA sharing strategie.
Device constrained throughput	Estimate the wireless throughput of OFDMA system.
EMF constrained throughput	Estimate the wireless throughput of EMF-constrained.
Interfering throughput	Estimate the wireless throughput of all transmitters use the entire bandwidth, simultaneously, and treating each other as noise.
SSOFDM throughput	Estimate the wireless throughput of SS-OFDM system.
Calculate wireless throughputs	Calculate the total wireless throughput for five different sharing strategies (time segregated (CSMA), OFDMA, EMF constrained, mutually-interfering, and SS-OFDM.

```java
public double tsegthrough(double[][] rcvdpwr, double noisepwr
     , double maxtransmitpwr, int n) {

        // Now calculate total throughput in each model
        // time-segregated
        double timesegregatedthroughput = 0;
        for (int k=0; k<n; k++) {
            double snr = maxtransmitpwr * rcvdpwr[k][k]/noisepwr;
            timesegregatedthroughput = timesegregatedthroughput
            + (Math.log(1+snr)/Math.log(2))/n;
            // divide by n because each transmission is active
            // for only 1/n of the time
        }
        return timesegregatedthroughput;
    }
```

Listing C.1: Time segregated throughput

```java
 public double devicethrough(double[][] rcvdpwr, double noisepwr
                            , double maxtransmitpwr, int n) {

        // Now calculate total throughput in each model
        // device-power-constrained, using separate frequencies

        double deviceconstrainedthroughput = 0;
        for (int k=0; k<n; k++) {
            double snr = n*(maxtransmitpwr * rcvdpwr[k][k]/noisepwr);

            // noise is from 1/n of the spectrum, so snr is n* better
            deviceconstrainedthroughput = deviceconstrainedthroughput
                                        + (Math.log(1+snr)/Math.log(2))/n;

            // Each transmitter is using only 1/n of the bandwidth,
```

```
            // hence throughput divided by n
        }
       return deviceconstrainedthroughput;
    }
```

Listing C.2: Device constrained throughput

```
public double emfconstrainedthrough(double[][] rcvdpwr,
                                    double[][] rcvdpwratsrc,
                                    double noisepwr,
                                    double maxtransmitpwr,
                                    int n) {

        // total-emf-constrained

        double emfconstrainedthroughput = 0;
        Matrix G = new Matrix(rcvdpwratsrc);
        Matrix Tpvec = new  Matrix(n,1,maxtransmitpwr);
        Matrix transmitpwr = G.solve(Tpvec);
        double[][] tpwr = transmitpwr.getArrayCopy();
        double[] reducedrcvdpwr = new double[n];
        for (int k=0; k<n; k++) {

            // logf.println("Transmitpwr["+k+"] = " + tpwr[k][0]);
            // logf.flush();
            double a = tpwr[k][0];
            double b = rcvdpwr[k][k];
            reducedrcvdpwr[k] = a*b;
            double snr = n * (reducedrcvdpwr[k]/noisepwr);

            // noise from only 1/n of the spectrum
            emfconstrainedthroughput = emfconstrainedthroughput
                                     + (Math.log(1+snr)/Math.log(2))/n;
```

```
            // 1/n of the bandwidth per transmission
        }
        return emfconstrainedthroughput;
    }
```

Listing C.3: EMF constrained throughput

```
public double interferingthrough(double[][] rcvdpwr,
                                 double[][] rcvdpwratsrc,
                                 double noisepwr,
                                 double maxtransmitpwr,
                                 int n) {

        // total-emf-constrained
        double interferingthroughput = 0;
        Matrix G = new Matrix(rcvdpwratsrc);
        Matrix Tpvec = new  Matrix(n,1,maxtransmitpwr);
        Matrix transmitpwr = G.solve(Tpvec);
        double[][] tpwr = transmitpwr.getArrayCopy();
        double[] reducedrcvdpwr = new double[n];
        for (int k=0; k<n; k++) {

            // logf.println("Transmitpwr["+k+"] = " + tpwr[k][0]);
            // logf.flush();
            double a = tpwr[k][0];
            double b = rcvdpwr[k][k];
            reducedrcvdpwr[k] = a*b;
            double interferingpwr = 0;
            for (int j=0; j<n; j++) {
                if (j!=k) {
                    interferingpwr = interferingpwr + tpwr[j][0]
                                     *rcvdpwr[j][k];
                }
            }
```

```
            double snr = (reducedrcvdpwr[k]/(noisepwr+interferingpwr));
            interferingthroughput = interferingthroughput
                                    + (Math.log(1+snr)/Math.log(2));

            // using the full amount of time and bandwidth,
            // but noise is higher
        }
        return interferingthroughput;
    }
```

Listing C.4: Interfering throughput

```
public double ssofdmthrough(double[][] rcvdpwr,
                            double[][] rcvdpwratsrc,
                            double noisepwr,
                            double maxtransmitpwr,
                            int n,
                            double codecorrelation) {

        // total-emf-constrained
        double ssofdmthroughput = 0;
        Matrix G = new Matrix(rcvdpwratsrc);
        Matrix Tpvec = new  Matrix(n,1,maxtransmitpwr);
        Matrix transmitpwr = G.solve(Tpvec);
        double[][] tpwr = transmitpwr.getArrayCopy();
        double[] reducedrcvdpwr = new double[n];
        for (int k=0; k<n; k++) {
            logf.println("Transmitpwr["+k+"] = " + tpwr[k][0]);
            logf.flush();
            double a = tpwr[k][0];
            double b = rcvdpwr[k][k];
            reducedrcvdpwr[k] = a*b;
            double interferingpwr = 0;
            for (int j=0; j<n; j++) {
```

```
                if (j!=k) {
                    interferingpwr = interferingpwr +
                                     tpwr[j][0]*rcvdpwr[j][k]*
                                     codecorrelation;
                }
            }
            double snr = (n*reducedrcvdpwr[k]/
                         (noisepwr + interferingpwr));


            // because the decoding averages over noise,
            // it increases its pwr by n, but
            // the signal is increased in pwr by n^2;
            // since the interference is also statistically
            // independent, it is also increased in pwr by n,
            // by decoding hence, the net effect is to
            // increase snr by n

            ssofdmthroughput = ssofdmthroughput +
                               (Math.log(1+snr)/Math.log(2))/n;

            // rate reduced by n due to chip length
        }
        return ssofdmthroughput;
    }
```

Listing C.5: SSOFDM throughput

```
public void calcWirelessThroughputs(String username, PrintWriter logf) {
        int n = getNumStreams();
        NetTrafficstream streama, streamb;
        NetNode origin, destn;
        if (logf!=null) logf.println("This network has " + n
```

```
        + " traffic streams. Calculating the matrix of distances"
        + " from origins, of traffic streams, to destinations
        ,  of the streams");

double noisepwr, maxtransmitpwr, directivity, rcvrarea
        , codecorrelation;String noisepwrstring, transmitpwrstring
        , directivitystring, rcvrareastring, ccstring String model;

noisepwrstring = getParameterValue("noisepwr");
transmitpwrstring = getParameterValue("transmitpwr");
directivitystring = getParameterValue("directivity");
rcvrareastring = getParameterValue("rcvrarea");
ccstring = getParameterValue("codecorrelation");
noisepwr = Double.parseDouble(noisepwrstring);
maxtransmitpwr = Double.parseDouble(transmitpwrstring);
directivity = Double.parseDouble(directivitystring);
rcvrarea = Double.parseDouble(rcvrareastring);
codecorrelation = Double.parseDouble(ccstring);
model = getParameterValue("sharingmodel");
if (logf!=null) {
    logf.println("Parameters\nnoisepwr: " + noisepwr
        +", transmitpwr: " + maxtransmitpwr + ", directivity: "
        + directivity + ", rcvrarea: " + rcvrarea
        + ", sharingmodel: " + model + "\n");
    logf.println("Received power at destination matrix");
}

double[][] rcvdpwr = new double[n][n];
double[][] rcvdpwratsrc = new double[n][n];

for (int k=0; k<n; k++) {
    streama = getStream(k);
    for (int j=0; j<n; j++) {
        streamb = getStream(j);
```

```
            origin = streama.getOrigin();
            destn = streamb.getDestination();
            double r = (origin.getPosition().
                        minus(destn.getPosition())).
                        length();
            rcvdpwr[k][j] = maxtransmitpwr * directivity *
                           (rcvrarea/10000) /
                            (4*Math.PI*r*r);
            if (k==j) {
                double selfr = 1;
                rcvdpwratsrc[k][j] = 1;

                // rcvdpwratsrc[k][j] = maxtransmitpwr *
                                    // directivity *
                                    // (rcvrarea/10000) /
                                    // (4*Math.PI*selfr*selfr);

            } else {
                double srctosrcr = (origin.getPosition().
                                    minus(streamb.getOrigin().
                                    getPosition())).length();

                rcvdpwratsrc[k][j] = directivity /
                                    (4*Math.PI*srctosrcr*srctosrcr);
            }
            if (logf!=null) {
                logf.print(rcvdpwr[k][j]);
                logf.print("\t");
            }
        }
        if (logf!=null) {
            logf.println();
        }
    }
```

```
if (logf!=null) {
    logf.println("Received power at source matrix");
    for (int k=0; k<n; k++) {
        for (int j=0; j<n; j++) {
            logf.print(rcvdpwratsrc[k][j]);
            logf.print("\t");
        }
        logf.println();
    }
    logf.println();
}

double timeSegregatedThroughput = tsegthrough(rcvdpwr,
                                    noisepwr,
                                    maxtransmitpwr, n);

double deviceconstrainedthroughput = devicethrough(rcvdpwr,
                                        noisepwr,
                                        maxtransmitpwr, n);

double emfconstrainedthroughput = emfconstrainedthrough(rcvdpwr,
                                    rcvdpwratsrc, noisepwr,
                                    maxtransmitpwr, n);

double interferingthroughput = interferingthrough(rcvdpwr,
                                rcvdpwratsrc, noisepwr,
                                maxtransmitpwr, n);

double ssofdmthroughput = ssofdmthrough(rcvdpwr,
                            rcvdpwratsrc, noisepwr, maxtransmitpwr,
                            n, codecorrelation);

if (logf!=null) {
    logf.println("Time-segregated total throughput (bits/s/Hz) = "
```

```
                    + timeSegregatedThroughput
          + ",\nDevice constrained throughput = "
          + deviceconstrainedthroughput
          + ",\nEMF constrained throughput = "
          +  emfconstrainedthroughput
          + ",\nmutually interfering throughput = "
          +  interferingthroughput
          + ",\nSS-OFDM throughput = " +  ssofdmthroughput);
}

// Now look for traces built into the network

Node nd, ndd;
NodeIterator tl=null, pvl = null, tnode = null;

try {
    pvl = XPathAPI.selectNodeIterator(getDom(),
          "//nodes/node/parametervariation");
} catch (Exception ex) {
    getLogFile().println("Exception in RealNetwork.
                          calcWirelessThroughputs, when
                          calling XPathAPI.selectNodeIterator:
                          " + ex);
}

while (pvl!=null && (ndd = pvl.nextNode()) !=null) {

    String nselementtype = ((Element)ndd).
                       getElementsByTagName("nselementtype").
                       item(0).getTextContent();
    String itertype = ((Element)ndd).
                       getElementsByTagName("itertype").
                       item(0).getTextContent();
    String startstring = ((Element)ndd).
```

```
                   getElementsByTagName("start").
                   item(0).getTextContent();
String finishstring = ((Element)ndd).
                   getElementsByTagName("finish").
                        item(0).getTextContent();
double start = Double.parseDouble(startstring);
double finish = Double.parseDouble(finishstring);
logf.println ("Parameter variation parameters: itertype = "
              + itertype
              + ", start = "
              + start + ", finish = "
              + finish + ", itertype = "
              + itertype);

String ratiostring = null, incrementstring = null;
if (itertype.equals("geometric")) {
    ratiostring = ((Element)ndd).
                    getElementsByTagName("ratio").
                    item(0).getTextContent();

} else {
    incrementstring = ((Element)ndd).
                        getElementsByTagName("increment").
                        item(0).getTextContent();

}
double ratio = Double.parseDouble(ratiostring);

try {

    tnode = XPathAPI.selectNodeIterator(getDom(),
            "//nodes/node[nstrace]");
} catch (Exception ex) {
    getLogFile().println("Exception in RealNetwork.
```

```
        calcWirelessThroughputs, when
        calling XPathAPI.selectNodeIterator:
        " + ex);
    }
    Element nodeel = (Element)(tnode.nextNode());
    String nodeid = nodeel.getAttribute("id");
    logf.println("In RealNetwork.calcWirelessThroughputs,
                  the node with the nstraces is " + nodeid);

    try {
        tl = XPathAPI.selectNodeIterator(getDom(),
            "//nodes/node/nstrace");

    } catch (Exception ex) {
        getLogFile().println("Exception in
        RealNetwork.calcWirelessThroughputs,
        when calling XPathAPI.selectNodeIterator:
        " + ex);
    }

    logf.println();
    while (tl!=null && (nd = tl.nextNode())!= null)

    {
        String tracename = ((Element)nd).
                           getElementsByTagName("tracename").
                           item(0).getTextContent();
        Element nsattribute = (Element)(((Element)nd).
                            getElementsByTagName("nsattribute").
                            item(0));
        String attributename = nsattribute.
                            getElementsByTagName("attributename").
                            item(0).getTextContent();
        String evaluationconcode= nsattribute.
```

```
                    etElementsByTagName("code").item(0).
                    getTextContent();
String tracefilename = RealNetwork.getNetmlPath()
                     + "/Results/" + username
                     + "/T" + getName()
                     + "_" + nodeid + "_"
                     + replaceEach(tracename,"-,
                     ;/$:@&*^%#!.",
                       "______________")
                     + "_trace.txt";

logf.println("In RealNetwork.CalcWirelessThroughput,
              processing a trace: tracename = "
              + tracename
              + ", attributename = " + attributename + ",
              evaluationcode = " + evaluationcode
              + " and the file name will be "
              + tracefilename + ".");



FileWriter tfile = null;
PrintWriter tpfile = null;
try {
    tfile = new FileWriter(tracefilename);
    tpfile = new PrintWriter(tfile);
} catch (Exception ex) {
    logf.println("In RealNetwork.CalcWirelessThroughput,
                  not able to write to file "
                  + tracefilename);
}

double x = start;
while (x<finish) {
    tpfile.print(x);
```

```
        tpfile.print(":");

        if (evaluationcode.
            equals("CSMA/CA sum-throughput"))
           {
            tpfile.println(tsegthrough(rcvdpwr, x,
            maxtransmitpwr, n));
        } else if (evaluationcode.
                  equals("OFDMA sum-throughput"))
                  {
                   tpfile.println(devicethrough(rcvdpwr, x,
                   maxtransmitpwr, n));
        } else if (evaluationcode.equals("EMF-constrained
                   OFDMA throughput")) {
                   tpfile.println(emfconstrainedthrough
                   (rcvdpwr, rcvdpwratsrc, x,
                    maxtransmitpwr, n));

        } else if (evaluationcode.equals("Mutually
                   interfering throughput")) {

                 // Mutually interfering throughput

            tpfile.println(interferingthrough(rcvdpwr,
                           rcvdpwratsrc, x,
                           maxtransmitpwr, n));

        } else {    // SS-OFDM throughput
            tpfile.println(ssofdmthrough(rcvdpwr,
            rcvdpwratsrc, x,
            maxtransmitpwr, n, codecorrelation));
        }
        x = x*ratio;
    }
```

```
            tpfile.close();

            logf.flush();
        }
    }
}
```

Listing C.6: Calculate wireless throughputs

Appendix D

Mathematica Code for Implementing Cross-Subchannel Noise in OFDMA

This appendix has five Mathematica files; firstly, Listing D.1 in the system descriptions the main program, which has the parameters of OFDM system. Secondly, Listing D.2 shows signal of system B. Initially, we assumed system B transmits the signal 11 on frequency 1. Next, system B transmits the signal 01 on frequency 1. Then, System B transmits the signal 00 on frequency 0. Thirdly, Listing D.3 describes the system A matched signal, has three cases of cross-channel noise that comes from all nearby wireless communication systems which use the same OFDMA wireless systems. The first case is ordinary OFDM, the second case is OFDMA with good time synchronisation, and the last case assumed that two nearby systems are not sufficiently well synchronised for the cyclic extensions of the two systems to overlap. The forth code, which Listing D.4 is plotted cross - channel noise analytic formula. Finally, experiments cross - channel noise with orthogonal in Listing D.5.

Table D.1: Codes clarification

Name of function /file	**Description**
Parameters of OFDM system	Generate the parameters of OFDM system.
System B signal	Transmit the signal with three cases, the signal 11 on frequency 1, the signal 01 on frequency 1, and the signal 00 on frequency 0.
System A matched signal	Calculate the cross-channel noise in different three cases.
Plot of cross-channel noise	Plot cross - channel noise analytic formula.
Experiments with orthogonality	Experiments cross - channel noise with orthogonal.

```
Parameters of OFDM system
*************************

basefrequency = 2.4*10^9;
baseframeincycles = 4;
T = baseframeincycles/basefrequency;
numberofsubchannels = 4;
highestfrequency = ((baseframeincycles
                     + numberofsubchannels - 1)/
                       baseframeincycles);

freq[chan_] := ((baseframeincycles + chan)/
                 baseframeincycles)
                 basefrequency;

offset = T/2



8.33333*10^-10

T

1.66667*10^-9

freq[1]

3.*10^9
```

Listing D.1: Parameters of OFDM system

```
System B Signal
***************

Case 1
~~~~~~


Initially, let us assume System B
transmits the signal 11 on frequency 1.

bsignal[t_, ph_] := Switch[(t + ph) < T,
                    True, Cos[2 Pi freq[1]
                    (t + ph) + Pi], False,
                    Cos[2 Pi freq[1]
                    (t + ph) + Pi]];

Plot[bsignal[t, 0], {t, 0, 2 T}]




Case 2
~~~~~~


Now, let us assume System B transmits
the signal 01 on frequency 1.

bsignal2[t_, ph_] := Switch[(t + ph) < T,
                     True, Cos[2 Pi freq[1]
                     (t + ph)], False,
                     Cos[2 Pi freq[1]
                     (t + ph) + Pi]];

Plot[bsignal2[t, 0], {t, 0, 2 T}]
```

```
Case 3
~~~~~~

Now, let us assume System B transmits
the signal 00 on frequency 0.

bsignal3[t_, ph_] := Switch[(t + ph) < T,
                     True, Cos[2 Pi freq[0]
                     (t + ph)], False,
                     Cos[2 Pi freq[0]
                     (t + ph)]];

Plot[bsignal3[t, 0], {t, 0, 2 T}]



Clear[T];
Integrate[(1/T) Cos[2 Pi f0 t]^2, {t, 0, T}]

1/8 (4 + Sin[4 f0 \[Pi] T]/(f0 \[Pi] T))
```

Listing D.2: System B signal

```
System A Matched Signal
***********************

AMatchedSignal[t_, phase_] := Cos[2 Pi freq[0]
                              (t + phase)];

Plot[AMatchedSignal[t, 0], {t, 0, 2 T}]
```

```
Cross-channel Noise, Case 1
~~~~~~~~~~~~~~~~~~~~~~~~~~

This is the case where the other signal is
orthogoncal, because the message being
transmitted is 00 or 11, and hence their
are no phase transitions.

rsignal[phase_] := (1/T) NIntegrate[
                   bsignal[s, phase]
                   AMatchedSignal[s, 0],
                   {s, 0, T*1.01/4, T}];

Plot[rsignal[ph], {ph, 0, T},
    AxesLabel -> {"offset", "strength"}]



T

1.66667*10^-9


Cross-channel Noise, Case 2
~~~~~~~~~~~~~~~~~~~~~~~~~~

This is the case where the other signal is
interfering, using a different frequency.

rsignal2[phase_] := (1/T) NIntegrate
                    [bsignal2[s, phase]
                    AMatchedSignal[s, 0],
                    {s, 0, T*1.01/4, T}];
```

```
Plot[rsignal2[ph], {ph, 0, T}, AxesLabel ->
    {Style["Offset", 25, Bold, Blue],
     Style["Strength", 25, Bold, Blue]},
     LabelStyle -> Directive[15, Black, Bold,
     FontFamily -> "Times New Roman"],
     MaxRecursion -> 15]

Clear[T];

xn[ph_] := (1/T) Integrate
                      [Cos[2 Pi freq[1] (s + ph)]
                  AMatchedSignal[s, 0],
                   {s, 0, T - ph}] + (1/T)
                      Integrate[Cos[2 Pi freq[1]
            (s + ph) + Pi] AMatchedSignal[s, 0],
                  {s, T - ph, T}];

Plot[xn[ph], {ph, 0, T},
     AxesLabel -> {"offset", "strength"}]




xch[ph_] := (1/T) (1/(2 Pi (freq[1]
            + freq[0])) (Sin[2 Pi freq[0]
            (T - ph)]
            -Sin[2 Pi freq[1] ph])
            + (1/(2 Pi (freq[1]
            - freq[0]))) (Sin[2 Pi freq[0]
            (T - ph)] - Sin[2 Pi freq[1] ph]));

Plot[xch[u], {u, -T/2, T/2},
    AxesLabel -> {"offset", "strength"}]
```

The noise variance
~~~~~~~~~~~~~~~~~~

We then use that as an estimate of
the strength (z say) of x - channel noise,
ie the numerical value of the interfering
signal.To convert this into "power" we
must observe that the actual values,
in the worst case of synchronization,
will be this value, or zero, or minus
this value, with probabities 0.25, 0.5,
and 0.25.From this, we can deduce the noise
variance, as :

```
nv[z_] := 0.25*z^2 + 0.5*0 + 0.25*z^2;
Plot[nv[z], {z, -T, T},
          AxesLabel -> {"offset", "strength"}]
```

The maximum lies, over all possible values for ph
~~~~~~

We need to find the maximum, over all possible
values for ph.We do that by taking a derivative
wrt ph, and equating to zero, then solve for
ph.This finds the stationary points, and
the maximum must be a stationary \
point.

```
der[ph_] = D[xch[ph], ph];

General::ivar: 0 is not a valid variable. >>



der2[ph_] := (-2 freq[1]/T (freq[1]^2
              - freq[0]^2)) (freq[0]
                Cos[2 Pi freq[0] ph]
              + freq[1]
                Cos[2 Pi freq[1] ph]);

Plot[der2[ph], {ph, -T, T},
     AxesLabel -> {"offset", "strength"}]




Cross-channel Noise, Case 3
~~~~~~~~~~~~~~~~~~~~~~~~~~

This is the case where the other signal
is actually a valid signal, using the same
frequency.

rsignal3[phase_] := (1/T) NIntegrate
                    [bsignal3[s, phase]
                    AMatchedSignal[s, 0],
                    {s, 0, T*1.01/4, T}];

Plot[rsignal3[ph], {ph, 0, T},
     AxesLabel -> {"offset", "strength"}]
```

```
Plot[{bsignal[s, 0.0003],
     AMatchedSignal[s, 0.0]}, {s, 0, T}]
```

```
T
```

```
1.66667*10^-9
```

```
Plot[bsignal[s, 0.002]
        AMatchedSignal[s, 0.0], {s, 0, T}]
```

Listing D.3: System A matched signal

```
Plot of Cross - channel noise analytic formula
*********************************************

freq[0] = 2.4 10^9; freq[1] = 5 freq[0]/4;
T = 4/freq[0]

1.66667*10^-9

xchnoise[ph_] := (1/T) (1/(2 Pi (freq[1]
                  + freq[0])) (Sin[2 Pi freq[0]
                    (T - ph)])
                  - Sin[2 Pi freq[1] ph]
                  - (1/(2 Pi (freq[1]
                  - freq[0])))
                    (Sin[2 Pi freq[0] (T - ph)])
                  - Sin[2 Pi freq[0] ph]);

Plot[xchnoise[ph], {ph, 0, T}, AxesLabel ->
      {Style["Offset", 25, Bold, Blue],
      Style["Strength", 25, Bold, Blue]},
```

```
    LabelStyle -> Directive[15, Black, Bold,
  FontFamily -> "Times New Roman"],
     MaxRecursion -> 15]
```

Listing D.4: Plot of cross-channel noise

```
Experiments with Orthogonality
******************************

signal[t_, ph_, f_] := Cos[Pi f (t + ph)];
 f = 3; ph = 0;
Plot[{signal[t, ph, f], signal[t, 0, 5],
      signal[t, ph, f] signal[t, 0, 5],
      signal[1 - t, ph, f]
      signal[1 - t, 0, 5]}, {t, 0, 1}]
```

Listing D.5: Experiments with orthogonality