UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

THE INTERSECTION OF RADAR AND COMMUNICATIONS: A STUDY ON SPECTRUM MANAGEMENT FOR ADDRESSING SIGNAL INTERFERENCE

A THESIS
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE

By

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Norman, Oklahoma
2023

THE INTERSECTION OF RADAR AND COMMUNICATIONS: A STUDY ON SPECTRUM MANAGEMENT FOR ADDRESSING SIGNAL INTERFERENCE

A THESIS APPROVED FOR THE
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

BY THE COMMITTEE CONSISTING OF

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Acknowledgments

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Abstract

The radio frequency (RF) spectrum is a fruitful yet competitive frontier, enabling technologies like 5G, Wi-Fi, Bluetooth, GPS, long-range telescopes, microwave ovens, radar, and more. With finite supply and increasing demand, the RF spectrum is highly sought after for both government and private use. Industry innovators need an increasing stake in the spectrum to keep up with modern data consumption needs, yet the government requires the same spectrum for important issues like national defense. This duality in demand often results in highly congested bands of frequency that host both stakeholders in dense configuration, increasing interference and difficulties in managing the spectrum. Interference of radar signals by communication waveforms, like OFDM, is on the rise and can greatly impact performance. In this paper, we introduce a novel interference mitigation technique that leverages the known structure of OFDM waveforms to estimate and subtract interference from a pulse-doppler radar system. We demonstrate that this proposed technique can significantly improve radar performance in the face of OFDM interference and quantify interference metrics to inform new transmission regulations.

Chapter 1

An Overview of Spectrum Management: Common Practices and Emerging Markets

The radio frequency (RF) spectrum is one of the most sought after, yet scarce, global resources. Many governments, industries, and consumers utilize spectrum for wireless communication, radiolocation, media broadcasting, and even combustion-free cooking. This wide-spread utility, however, elicits more demand than supply. Moreover, demand inherently increases as society advances technologically. Modern society is more digitally linked than ever before and many visions for the future involve even more interconnectedness. The Internet of Things (IoT) is a somewhat prophetic vision of forward societal progression where historically "dumb" devices, such as washing machines and refrigerators, are wirelessly linked to increase the daily efficiency of individuals. For instance, one's alarm clock might signal to their TV to turn on the morning news after their first morning alarm occurs. These wireless connections, though, occupy bands of frequency. A single household could harbor dozens — or possibly hundreds — of these connections, which is not something that current wireless infrastructure could support on a large scale due to spectrum efficiency issues. The current 5th generation mobile broadband network (5G) is working to remedy this problem, but significant improvement must be made on the frontier of spectrum management. Spectrum management is a broad term referring to the regulation of RF transmission to increase spectrum efficiency and eliminate harmful interference. It has been both historically and presently done through the management of transmission space, time, and frequency. More recent methods also employ oversight of things like signal orthogonality and signal polarization. Despite modern-day spectrum management following the same basic outline, it has evolved considerably in the last few decades and will likely continue to evolve in the coming decades. As researchers and engineers work to advance this area of focus, the importance of rigorizing metrics of spectrum efficiency for every niche outlet of signal generation is indeed apparent, but so too is the proportionate workload of accomplishing this.

1.1 Radio Frequency Spectrum

The radio frequency spectrum is defined (loosely) as the electromagnetic field (EMF) propagation ranging from 0 to 300 GHz of frequency. At 300 GHz, EMF propagation starts to become infrared light [1]. Among the RF community, though, frequencies below 6 GHz are considered “beachfront” spectrum, meaning that most entities find that spectrum in this range is most valuable to their operations (due to ideal propagation characteristics). This boundary is certainly subject to the technological capability of present society. Modern innovations are beginning to utilize higher transmission frequencies and are obscuring previous limitations. 5G NR Release 17, for instance, specifies plans for utilizing frequencies as high as 71 GHz, where signal wavelengths are expressed in millimeters (“mmWave”) [2]. By comparison, 4G LTE only occupies frequencies as high as 5.9 GHz (though usually much lower) [3].

The frequency spectrum is divided into allocations, allotments, and assignments. Allocations are granted to specific radio services [4]. These services include things like radionavigation, maritime mobile, radiolocation, and so on. The National Telecommunications and Information Administration (NTIA) periodically releases a chart that positions each U.S. frequency allocation from 0 GHz to 300 GHz on a horizontal scale [5]. It serves as a simple way to determine which services are in which bands, as opposed to sifting through archives of federal regulatory code [6]. Allotments confine certain services to geographical regions or countries [4]. Assignments specify authorizations given by a radio frequency authority to operate at specific discrete frequencies [4, 7].

The RF spectrum is also divided into frequency designations. As specified by the International Telecommunications Union Radiocommunication Sector (ITU-R), the frequency range from 3 to 30 kHz is designated as very low frequency (VLF); 30 to 300 kHz is low frequency (LF); 300 to 3000 kHz is medium frequency (MF); 3 to 30 MHz is high frequency (HF); 30 to 300 MHz is very high frequency (VHF); 300 to 3000 MHz is ultra high frequency (UHF); 3 to 30 GHz is super high frequency (SHF); 30 to 300 GHz is extremely high frequency (EHF) [8]. Notice that each adjacent designation is separated by one numerical decade. It is important to note that perceptible bandwidth occupancy is subject to logarithmic scaling depending on where the frequencies are located on the frequency axis. For instance, AM broadcasting ranges from 540 kHz to 1700 kHz, or about 1.16 MHz of occupied bandwidth. This same bandwidth at, say, 30 GHz, would be insignificant for wide-scale broadcasting. Excluding the discussion of the propagation characteristics of different frequency ranges, this phenomenon is a primary result of the inverse correlation between signal generation and reception sensitivity and frequency of transmission.

In addition to frequency boundaries specified by man, there are also frequency boundaries specified by physics. Frequency ranges can be broken into characteristics based on how signals propagate through various environments. For instance, signals under 2 MHz abide by the principle of ground-wave propagation and can travel along Earth's surface around the horizon. It works most effectively across water, thus ground-wave frequencies are good for maritime communication. Similarly, signals in the HF band can optimally refract off the Earth's ionosphere or troposphere, making this band of frequencies a suitable selection for long-range communication. These properties exist for many variables, such as humidity, temperature, precipitation, foliage, man-made physical structures, like buildings, and so on. Picking the right frequency is important to the function of a system. Unfortunately, however, the complex world of spectrum issuance has established a legacy system of first come, first served assignment, meaning that many systems are utilizing frequencies that are not optimized for their service. Moreover, legacy allocations are often at gridlock for issues concerning human nature, so redistributing spectrum is difficult [1].

1.2 Categories of Service

There are many services that occupy bands of the radio frequency spectrum. According to [4], these services fall within three categories: radiodetermination, radiocommunication, and radio astronomy. Radiodetermination is the process of utilizing radio waves to determine aspects of an object pertaining to its position or velocity. Within radiodetermination is radionavigation and radiolocation (radar). Generally, what separates these two technologies is the context of their use, rather than the methods in which they operate. Both work by transmitting a waveform and then interpreting the changes incurred by that waveform upon reception to describe the nearby environment. Radionavigation uses these techniques for the purposes of maneuvering a vehicle or craft from one location to another. There are many types of radionavigation depending on the medium of travel; maritime radionavigation is used by ships; aeronautical radionavigation is used by airplanes; satellites are equipped with radionavigation-satellite service. Radiolocation is defined (rather circularly) by the ITU-R as "radiodetermination used for purposes other than those of radionavigation." These "other purposes" include the missile defense systems created and used by the Department of Defense (DoD), Doppler radar systems used by meteorologists, and much more [9].

Accoding to [4], Radiocommunication is the broadest category of RF service. It includes mobile and fixed communications, broadcasting, telemetry, and amateur (ham) radio. A mobile service, according to the ITU-R, is "a radiocommunication service between mobile and land stations, or between mobile stations." Maritime mobile pertains to mobile communication links between ships or between ships and base stations. Unsurprisingly, aeronautical mobile, mobile-satellite service, and land mobile all abide by similar relationships but with aircraft and aircraft stations, space stations and earth stations, and mobile stations on land and base stations, respectively. A fixed communication service, by contrast, operates between fixed locations. An RF broadcasting service provides direct media to the general public. The form of media is usually either sound (FM and AM radio), or television. Radiotelemetry is a process by which statistical data or measurements are remotely transmitted from the collection site to another location for processing. It is used in a wide variety of applications, from monitoring animal populations to surveilling patient vitals in a medical context [10, 11]. Amateur radio is the final subcategory of radiocommunication. It provides a resource in which individuals can operate radiocommunication systems for nonpecuniary purposes [4].

Radioastronomy is the final category of radio frequency service [4]. According to [12], until the 1930s, astronomy was limited to the visible spectrum. After several discoveries made by radio engineers like Karl Jansky and Grote Rober, it was concluded that, along with the visible spectrum, there was also extraterrestrial radiation in the radio spectrum. In fact, by observing the radio spectrum, astronomers can peer much deeper into the universe than by observing the visible spectrum due to the relatively low propagative attenuation experience by radio waves. Also, since the universe is constantly expanding, most extraterrestrial objects are moving away from the Earth at considerable velocities (up to 90% of the speed of light for distant quasars). The Doppler effect — which describes a shift in the perceived radiated frequency of an object that is moving relative to an observer — can severely shift the visible radiation of objects into the infrared and radio spectrums. Radioastronomy allows astronomers to view these otherwise invisible objects.

1.3 The Evolution of Spectrum Management

In the early 1900s, when wireless communication was in its infancy, the first widely-adopted application of RF technology was maritime communications. Guglielmo Marconi was the first to demonstrate the long-range wireless telegraph. His ingenuity, though, was fueled by shrewd business operation. He started the Marconi Wireless Telegraph Company and quickly established himself as the leading service provider. His company set up an extensive network of shore stations that refused to handle telegraph signals that were emitted with equipment that was manufactured by his competitors. Several nations congregated in protest when Marconi stations refused to handle their messages, despite many of them pertaining to maritime safety. It was quickly ruled among many nations that every station must handle telegraphs from any seafaring vessel. This sequence of affairs kickstarted the desire for widespread coordination and assembly of government to organize and manage issues pertaining to radiocommunications. Today's ITU-R was born from this debacle. [1].

During the rise of wireless communication and broadcasting in the early 20th century, it was quickly realized that signal interference was a big problem [13]. The Radio Act of 1912 bolstered itself as "an act to regulate radio communication," but did not specify any apparatuses or guidelines for spectrum organization, so its efforts were futile [14]. In 1922, however, the Interdepartment Radio Advisory Council (IRAC) was formed from several agencies that utilized RF transmission, marking the first coordinated attempt at assigning and distributing frequency licenses [15]. Though the IRAC only sought to organize government use of spectrum, it still played a pivotal role in establishing modern spectrum management practices [15]. The Federal Communications Commission (FCC) was established through the Communications Act of 1934 [16]. The Communications Act sought to make both wire and radio communications as fair and equitable as possible. It repeatedly cites "the public interest, convenience, and necessity" as motivations for its judgment. The Act did not allocate specific frequency bands through statute, but granted the newly formed FCC to establish non-governmental frequency allocations through its own procedures and discretion.

The NTIA, much like the FCC, was created to oversee radio spectrum usage [17]. It was established in 1978 by Executive Order 12046 [18]. While the FCC serves as a regulatory body for non-governmental radio communications and broadcasting, the NTIA serves to regulate governmental use of spectrum [19, 17]. As such, the NTIA is advised by the IRAC [20]. Together, the FCC and NTIA manage the United States RF spectrum, often collaborating with each other to coordinate frequency allocations and spectrum usage [21].

Beginning in 1933, the Supreme Court of the United States (SCOTUS) adopted a doctrine of spectrum scarcity [22]. The doctrine, later rigorously outlined in 1943 during National Broadcasting Co. v. the United States, recognized the RF spectrum as a limited resource and granted the FCC control over not just the “technical aspects of radio communication“ but also “the public interest” [23, p. 190]. This marked a (temporary) formal recognition by the United States that the public owns the spectrum and not corporate America. This doctrine was later extended in 1969 during Red Lion Broadcasting Co. v. Federal Communications Commission to include FCC oversight of broadcasting content to ensure ample expression of opposing viewpoints [24]. In 2005, the FCC argued that technological advancements had made broadcasting much more accessible and that “The Scarcity Rationale no longer serves as a valid justification for the government’s intrusive regulation of traditional broadcasting” [25, p. 8]. Notably, these three variables — spectrum demand, spectrum regulation based on perceived public interest, and spectrum efficiency technology — seem to be in constant fluctuation with one another. That is, when demand surpasses technology, the community favors tight regulation. However, when technology surpasses demand, the community favors deregulation. In this way, spectrum management is at the mercy of human nature.

1.4 Spectrum Management Techniques

Spectrum management has been historically (and is presently) done through the regulation of transmission space, time, and frequency. Within each of these domains, though, is significant innovation. What separates modern methods of spectrum management from past methods is the reigning technologies of that period. As technology progresses, researchers have discovered increasingly efficient ways to accomplish the same problems. These innovations are the reason that the global infrastructure can support as many services and allocations as it does.

Isolating a signal in space is most commonly done by controlling both transmission power and spatial positioning. These are particularly important for frequency reuse applications and in cases of shared spectrum allocation between government and non-government users. The 5 GHz band, for instance, features shared frequencies between Unlicensed National Information Infrastructure (U-NII) devices and federal radar systems like the Terminal Doppler Weather Radars (TDWRs) of the Federal Aviation Administration (FAA) [26]. In this case, TDWRs operate with primary status over the shared spectrum and U-NII devices operate with secondary status [26]. Secondary status users must typically accept any unwanted interference, while immediately correcting their own interference inflicted on other devices [26, 1]. U-NII devices are generally short-range consumer devices like garage door openers and wireless car keys [26]. If U-NII devices transmit too much power at a shared frequency, then a TDWR might receive interference, which could corrupt weather forecasting results [26]. Moreover, distance limitations must be implemented as well. Federal radar systems must be segregated from densely-populated U-NII device use. Research has shown that even small amounts of transmission power can interfere with radars “at distances of tens of kilometers” [26]. Result corruption is generally a function of how much interference is received, thus U-NII devices must take careful precautions to limit their transmission power to stay under the TDWR interference threshold [26]. These transmission guidelines are rigidly defined by the FCC and enforced upon device manufacturers [27].

The elements of spatial separation include geographical separation, altitudinal separation, use of directional antennas, such as parabolic dish antennas and phased arrays, and utilizing higher transmission frequencies to lessen signal propagation distance. Geographical and altitudinal separation are separating transmission regions and elevations, respectively. They embody the concept of incorporating distance between competing radio systems to reduce interference. They are considered elementary concepts and were among the first spectrum management practices performed by the radio community. Directional antennas spatially separate signals by only intentionally transmitting in relevant directions, which reduces harmful interference and allows for more devices to operate within the same area and frequency band. Parabolic antennas are concave in shape and rely on the reflection of the passive disk material to focus RF radiation. They are highly directive and used for things like home satellite television, WI-FI, and simple radar systems. They must be mechanically steered, however, making them ill-suited for highly dynamic systems like target tracking radar. Phased array antennas utilize an array of fixed antennas and variations in signal phase between each antenna to create and steer a concentrated beam of transmission in a certain direction [28]. The beam can be directed electronically, making phased array systems highly adaptive [28]. They are commonly used for modern radar systems and communications systems like 5G [28, 29]. Finally, transmission frequency is an important consideration for spatially segregating signals. Frequency of transmission and distance of propagation are inversely correlated. Systems that require frequency reuse between areas of close proximity, for instance, are better suited for higher frequency transmission.

Separating RF transmissions in time is an intuitive concept for humans to understand. Similar to how people take turns talking to each other to prevent speech interference, radio systems separate their transmissions in time to prevent RF interference. A simple example of this is in the previously mentioned U-NII system regulatory guidelines [26]. The FCC requires a listen-before-talk (LBT) protocol in all U-NII devices where the device must monitor the channel for radar waveforms for one minute before transmitting [26]. If a radar signal is detected, the device must not transmit on the channel for 30 minutes [26]. This focus of technological advancement whereby real-time frequency allocation of secondary users is based on the occupied channels of primary users is known as dynamic frequency selection (DFS) [26]. Coordinating transmission timing of multiple radio devices, in general, is an extremely frequent practice in spectrum management. Other aspects of spectrum management in time involve transmitting multiple data streams at the same time using time-division multiplexing (TDM). It works by alternating samples of each signal (at least twice per period per signal as per the Nyquist theorem), lowpass filtering the resultant signal, transmitting, sampling and separating the received signal back into pulse signals, then lowpass filtering each constituent pulse signal to get the original signals back [30]. It can be used to transmit multiple inefficient signals (in terms of bit rate) at the same time and frequency.

Spectrum management in frequency is indeed the embodiment of why RF transmission is so valuable. To isolate a signal, devices are equipped with filtering capacities, either analog or digital, allowing them to segregate desired frequency bands. This allows many services and users to use the radio frequency spectrum without interfering with one another, as with the other variables of spectrum management. As previously discussed, the RF spectrum is organized into allocations, allotments, and assignments. Moreover, individual services can subdivide their issued frequency band to accomplish more granular tasks. In cellular networks, for instance, users operating within the coverage of the same base station (cell) are assigned different adjacent frequencies within that station's band and sent together on a combined transmission. The mobile device can then filter the signal to extract its respective communication. This concept is known as frequency-division multiplexing (FDM). Moreover, each adjacent base station utilizes different frequency bands to prevent interference among neighboring cell areas. Another practice that relates to the concept of spectrum management in frequency is narrowbanding. Narrowbanding is a spectrum refarming method that involves transforming wide bandwidth channels into multiple narrowband channels [1].

Signal polarization is another important dimension of spectrum management. It is generally determined by the orientation and configuration of the transmitting antenna. For example, a vertically oriented dipole antenna will emit a vertically polarized signal [31]. In order to optimally receive the transmitted signal, the receiver antenna should be matched in configuration to the transmitting antenna [31]. If the receiver antenna is polarized orthogonally to the transmit antenna or falls out of orientation, then significant signal loss can occur [31]. This can be a problem in mobile systems that are highly dynamic in signal polarization [31]. Recent research has prioritized designing dynamic polarization control (DPC) systems utilizing phased array technology [31]. Such a system can adaptively optimize signal polarization for the best possible reception. Conversely, system designers can utilize orthogonal signal polarization to distinguishably send and receive two different signals at the same frequency, time, and location [1]. In practice, this is hard to do because of multipath.

Orthogonality is an important concept in the world of spectrum. In fact, the Fourier transform — the operation that converts a signal from the time domain to the frequency domain — is predicated on the orthogonality of sine waves at different frequencies. Two signals are said to be orthogonal if their inner product evaluates to zero. RF engineers often use orthogonality to multiplex signals and make better use of the available spectrum. Code-division multiple access (CDMA) was one of the first widespread uses of orthogonality in a modulation scheme and enabled technologies like 3G. It works by XORing many users' signals by fast-changing, orthogonal pseudo-noise (PN) sequences and combining them on a single carrier [1]. Because each PN coding sequence is orthogonal, a user can simply perform the same XOR operation with their unique PN code on the received signal to extract their data [1]. Also, the act of incorporating fast-changing PN sequences spreads the frequency band occupied by the signal, thus CDMA is a spread spectrum technology [1]. Orthogonal frequency division multiplexing (OFDM) is another technology that relies on orthogonality. It works by spacing subcarriers in frequency such that the nulls of each subcarrier align with the peaks of the other subcarriers. This compact way of arranging subcarriers allows for much greater spectrum efficiency. In fact, one can save nearly half the bandwidth by using OFDM over traditional FDM [32]. Modern OFDM implementations rely on an IFFT and an FFT operation, which are very computationally efficient [32]. OFDM is also inherently resilient to phenomena such as multipath fading and narrowband interference which plague other multiplexing schemes [32]. OFDM has thus been instrumental in enabling technologies like 4G LTE and 5G New Radio (NR).

Out-of-band (OOB) transmission of radar systems can have a significant impact on other radio systems. To combat this, regulatory entities set restrictions on transmission frequency, transmission power, and the shape of transmitted waveform in the frequency domain. One tool to help regulate these variables is the NTIA's Radio Spectrum Engineering Criteria (RSEC) emission mask. An emission mask defines the outline (in frequency) that a radar waveform should start stay within to prevent undue interference of neighboring services. Some of the parameters controlled within this "mask" are -40 dB "chimney" bandwidth, OOB roll-off, and suppression levels of -X dB. The exact specifications of these parameters are given by a set of equations provided by the NTIA [33].

Another important aspect of spectrum management is determining the efficiency of a particular service in terms of occupied spectrum [34]. This allows radio engineers to decide which technologies are worth occupying parts of the spectrum. It is often difficult to do this, though, for two reasons. First, different types of radio systems, even similar ones, can often differ enough that their spectrum efficiency calculations are incompatible [35]. It is only appropriate to compare calculations of identical services, otherwise the varying nuances of each service can obscure the result [35]. It follows that no objective measure of spectrum efficiency currently exists that encompasses all services, accoding to [34]. Second, some services, like radar and unlicensed systems, can be difficult to gauge due to the inconsistent and varying operation. "Spectral efficiency" is a type of spectrum efficiency metric that refers specifically to communication systems. It is expressed in terms of bits per second per Hertz (b/s/Hz). Depending on the purpose, though, this metric may not relay enough information. Analogues of this calculation factor in things like coverage area, users supported, and financial burden.

Software-defined radio (SDR) has been instrumental in the progression of modern radio systems. Until SDR, radio systems were generally single purpose. A traditional radar, for example, could not easily become an FM receiver without extensive modification, even if most of its components can support this shift in functionality. If the same radar were implemented in software, however, a dramatic shift in functionality could be as simple as running a different file on one's computer. As such, SDRs open the door to promising new technologies, such as cognitive radio and radar [36, 37]. They also bridge the gap between conception and implementation, which significantly reduces production time. In some ways, SDR in the field of radio systems is analogous to 3D printing in the field of prototyping and manufacturing. Cheap SDRs, like the RTL-SDR, can be purchased for around $30 and grant the user basic control over frequencies ranging from 24 MHZ to 1.766 GHz (RTL-SDR). More expensive systems, like the Ettus X series, offer more control, but can cost the operator upwards of $24k [38]. The GNU Radio project, though, attracts many SDR enthusiasts and practitioners regardless of their hardware. It is an open-source, easy-to-use assembly of advanced digital signal processing (DSP) tools that have become a staple in the RF community [39].

1.5 Current and Emerging Spectrum Sharing Characteristics in Radiocommunications

The Internet of Things is widely accepted as the future of radiocommunications among industry leaders in wireless technology. Manufacturers like Samsung, Intel, and Qualcomm are devoting significant resources to making faster, cheaper, more efficient, and lower latency devices to support this progression [40]. These innovations, however, come at the price of bandwidth [40]. Moreover, failure to allocate the required bandwidth could have significant implications on a nation's economy [41]. 5G NR is the most promising technology to support these advancements but existing spectrum allocations are insufficient [40]. Utilizing DFS techniques in pre-existing industrial, scientific, and medical (ISM) bands, Citizens Broadband Radio Service (CBRS) bands, 4G LTE bands, U-NII bands, and other spectrally inefficient bands can remedy spectrum scarcity issues surrounding 5G. Furthermore, working closely with the DoD can help prevent instances of 5G interference with radio operations pertaining to national security and military dominance [42].

The Department of Defense is currently the largest holder of Federal spectrum, making them a persistent target of opportunity by the spectrum-hungry telecommunications industry [42]. While expanding 5G allocations threatens the reliability of existing DoD services, the DoD understands the economic benefits of a strong 5G network. In fact, the DoD stands to benefit themselves from 5G deployment. Having a faster, more reliable, and more dynamic radio access network (RAN) can drive further innovation in previously unfeasible domains. The Army, for instance, is experimenting with using 5G to enable enhanced augmented/virtual reality tactical training [42]). The Navy and the Air Force are working on using 5G to remotely access airplane diagnosticsD [42]. The DoD also stands to benefit from the development of highly agile radio capabilities that are robust in complex, "near-peer" environments — an interest that aligns with the development of 5G [43]. These mutual interests promote greater cooperation between both entities.

One of the main systems that is vulnerable to 5G interference is high-powered radar. According to several wireless communications researchers, "the standard evolution from GSM to the fifth generation (5G) has produced a progressive invasion of frequency bands traditionally used by radar systems" [44, p. 19]. The S and C bands (2-8 GHz) are heavily occupied by federal radar but are also vital for ubiquitous operability of 5G networks [42]. 3GPP Release 17 (March 2022) cites plans to extend 5G coverage up to 71 GHz, which is likely targeting the 60 GHz ISM band [2]. The ISM bands are allocated for use of devices that perform work, like microwave ovens and industrial welding equipment [45]. These applications of RF usage are not generally affected by interference, so operating radiocommunication devices within these bands does not harm legacy allocations [45]. Thus, in 1985, the FCC began allowing for spread-spectrum transmitters to operate without license in certain ISM bands [45]. ISM bands are also wide in bandwidth. The 2.4 GHz ISM band is 83.5 MHz wide and supports many technologies, like Wi-Fi, Bluetooth, and Home RF, as well as traditional ISM devices, like home microwaves [45]). The 60

GHz ISM band is no exception to these conditions. While suffering from severe atmospheric attenuation (21.6 dB of loss for the same transmission distance compared to 5 GHz), this band can still be useful for in-room communications [46]. Moreover, the bandwidth available at this frequency (500 MHz) can support data rates comparable to present wired communications standards [46]. Unfortunately, federal airborne radar systems also occupy this prospective band, so interference is likely unless collaborative measures are taken to avoid it [33]. Power allocation algorithms and joint co-design of systems have been shown to alleviate interference in this band, but more research is required in this area [44]. Similar circumstances are echoed in the K band (20-36 GHz), specifically in the 24 GHz range [44]. This is not just a problem in the United States, either. In China, studies have shown that 5G allocation in the n285 band (24.25-27.5 GHz) has caused interference with narrowband millimeter-wave radar at 24-24.25 GHz [47].

In October 2010, the NTIA began looking at certain bands of frequency in the UHF and SHF bands to allocate toward wireless broadband in hopes that it would spur "innovative new businesses" and a more efficient economy [48, p. iv]. One of the considered bands is the 3550-3700 MHz band, later called the "Citizens Broadband Radio Service" by the FCC in 2012 [49]. This band was primarily used for DoD radar systems, but the NTIA determined that it was also capable of supporting modern wireless broadband schemes without affecting legacy systems to a significant degree [48]. In 2015, the FCC established a three-tier system: (1) Incumbent Access; (2) Priority Access; and (3) General Authorized Access [50]. Each tier communicates with a cloud-based Spectrum Access System (SAS) that coordinates which users may transmit at certain frequencies in certain geographical regions [50]. Incumbent users have the highest preference and represent legacy federal users, Fixed Satellite Service (FSS), and, temporarily, (grandfathered) terrestrial wireless service [50]. Priority Access are “users with critical quality-of-service needs,” like “hospitals” and “public safety entities” [50, p. 9]. They operate on a secondary basis to the incumbent users. Finally, General Authorized Access represents the “widest possible group of potential users,” according to the FCC [51]. They must yield completely to the previous tiers [50]. In 2020, the FCC authorized “full commercial deployment” of this band, paving the way for 5G deployment in CBRS [52]. The use of this band will allow carriers to deploy small cells where additional coverage is necessary, making 5G faster and more robust [50].

Wi-Fi 6 (802.11ax) is the next continuation of the IEEE 802.11 standard of WLAN. Deployed in 2020, it provides data rates that are over 2.5 times faster than previous generations [53]. In April 2020, the FCC announced that unlicensed operations would be expanded into 1200 MHz of spectrum (5.925-7.125 GHz), “ushering in Wi-Fi 6 ... and boosting the growth of the Internet of Things” [53]. This allocation is a monumental step forward for Wi-Fi because it more than quadruples the previous bandwidth allocated to it [54]. The incumbent services of this band include mobile, fixed, fixed satellite, and radioastronomy services that must remain in operation [55]. Like the other previously discussed bands, a series of rules must be made to prevent interference with these services [55]. The commission determined that an Automatic Frequency Control (AFC) system utilizing a centralized database of frequency ranges and maximum permissible powers for a location would best prevent interference [55]. This model of spectrum management has already been proven effective due to its similarities with the successful CBRS spectrum access system [55].

1.6 Fundamental Challenges with Spectrum Management

Spectrum allocation has been historically done by stacking new frequency allocations above existing ones on a chronological basis [1]. This is because time allows for technologies that utilize higher frequencies to become more established [1]. Unsurprisingly, though, this rather instinctive system for organizing spectrum acts as a metaphorical sedimentary rock, permanently casting obsolete technologies in the layers of spectrum allocation. Spectrum refarming delineates a process of reorganizing these legacy allocations to make room for services deemed more spectrally efficient [1]. MmWave 5G NR, for instance, does not have enough propagative penetration to reasonably provide consistent service to all users [56]. It is therefore imperative that low-band and mid-band frequencies be used in combination with mmWave [56, 57]. Existing allocations, though, completely occupy desired bands, so refarming preexisting 4G LTE bands for 5G NR is a likely step in modernizing wireless communication infrastructure [56]. This same process is an inevitable progression for every generation of broadband cellular network technology. On October 28, 2021, the FCC issued a PSA alerting consumers to the planned retirement of most 3G networks in the U.S. by the end of 2022 “to make room for more advanced network services” [58]. Older devices that do not support 4G LTE or 5G NR will lose connectivity, including the ability to contact emergency services, warns the FCC [58]. In fact, fixed hardware is a probable culprit for why 3G — an obsolete technology — is only recently being phased out.

Legacy equipment is a central reason for the slow adaptation of spectrally efficient technology. The economic loss suffered during the shifting of technology can sometimes haze the perceived benefits of greater spectral efficiency. For this reason, reallocation of presently inefficient bands can be a lengthy, bureaucratic process that almost always results in the monetary loss of at least one party [1]. To make the 3G retirement plan more palatable, many network carriers are offering free device upgrades to their affected users [58]. In other instances, though, legacy equipment operators are not as fortunate. Upgrading or replacing legacy equipment can impose significant financial burden on industries, so proactive change can take years depending on how many users are negatively affected [1]. It is important for policymakers to consider the motivation for the proposed reallocation. Parties that emphasize the inefficiency of legacy users, rather than improved efficiency of their own proposed technology, are likely operating with selfish intent and will only worsen the related spectrum scarcity issue [1].

1.7 Conclusion

In conclusion, radio frequency use is an ever-expanding frontier, on one hand, and a finite, competitive resource, on the other. It is highly valuable to both government use and private industry, creating a fertile area for government regulation of private use. The major industrial benefit of RF use is that it allows systems to share data wirelessly. The related lure of vast financial reward brings industry innovators to the arena. Meanwhile, governmental use of RF drives use of weather, national defense, aviation, and maritime services that are essential and therefore in the public good. Interference of those essential government operations must be prevented, but in a manner that allows private industry to also make productive use of spectrum. Spectrum management is the recognized key to multi-use of radio frequency bands.

Chapter 2

The Fundamentals of OFDM in Communication Systems

OFDM, as previously described, is a modulation technique that utilizes multiple narrowband subcarriers to transmit data. It has very efficient bandwidth utilization and is robust against narrowband interference and multipath fading. Each subcarrier is spaced orthogonally in frequency, meaning the peak of one subcarrier aligns with the zero crossings of the others. This allows for OFDM to be almost twice as spectrally efficient compared to traditional frequency division multiplexing techniques. Also, since it modulates data on many different subcarriers, the loss of a few subcarriers due to narrowband interference is easily corrected for by using error correction techniques. Things like encoding, interleaving, and puncturing can be used to minimize errors and maximize throughput. Moreover, equalization is greatly simplified with OFDM. OFDM, however, is sensitive to frequency offset, has a high peak-to-average power ratio (PAPR), and requires precise timing and frequency synchronization [32].

2.1 Background

OFDM was introduced in 1966 by Robert W. Chang at Bell Labs. Chang's groundbreaking paper, titled, "Synthesis of band-limited orthogonal signals for multichannel data transmission," proposed to transmit data on multiple parallel narrowband orthogonal sub-channels. The proposed technique was one that utilized analog modulation using the Fourier Transform and a bank of oscillators at the subcarrier frequencies. In 1971, Weinstein and Ebert eliminated the need for many oscillators by digitally implementing OFDM with the discrete Fourier Transform (DFT) and greatly reducing implementation complexity. This is made OFDM feasible for widespread implementation. Modern advances in digital FFT (the DFT but computationally efficient) chips further improve the implementation complexity of OFDM and allow for things like Orthogonal Frequency Division Multiple Access (OFDMA) [59].

2.2 Transmitter and Receiver Design Structure

The basic OFDM transmitter design structure leverages an N-length inverse discrete Fourier Transform (IDFT) where N is the number of subcarriers, to produce in-phase and quadrature (IQ) data from constellation mapping of bits to discrete time domain data. The real components of the TD data are passed through an digital-to-analog converter (DAC) and mixed with a carrier frequency generated by a local oscillator (LO). The imaginary components of the TD data are passed through an ADC and mixed with the same local oscillator, but phase shifted by 90 degrees to produce orthogonal basis functions sine and cosine. Both resultant waveforms are added together then transmitted as a single waveform.

The OFDM receiver design structure is tasked with undoing the various steps the transmitter took in order to effectively transmit the data. This involves quadrature mixing the received signal with the same carrier frequency and low-pass filtering off reflected higher frequency components of each signal at 2*fc. Both resultant

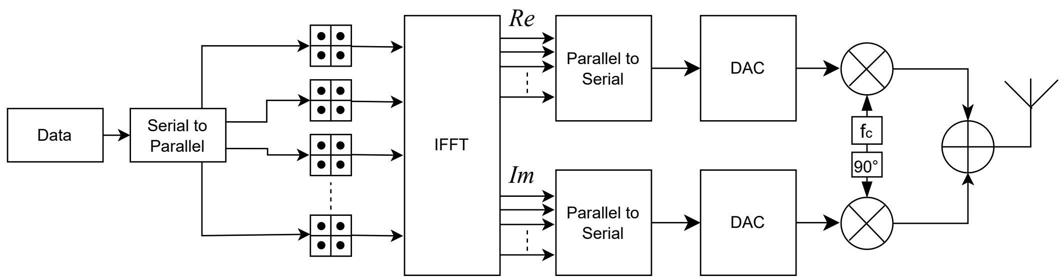


Figure 2.1: Simplified OFDM Transmitter Block Diagram

continuous time (CT) signals are then passed through an analog-to-digital converter (ADC) and taken as the real and imaginary values of an N-length DFT. This yields a parallel array of complex values that corresponds to the same constellation points that were mapped at the transmitter. Due to the noise and channel effects that are found in a real-world system, the received constellation points will be different than the original ones. If all constellation points are equiprobable as is often assumed, the receiver will map each received constellation point to the closest point on the expected constellation. If there is not significant interference and distortion, then these values will match the ones mapped at the transmitter and the data will be recovered. It is important to note these diagrams are simplified arrangements and real-world systems have many additional components, like equalizers, cyclic prefix insertion, and encoders/decoders to account for things like multipath delay spread and noise.

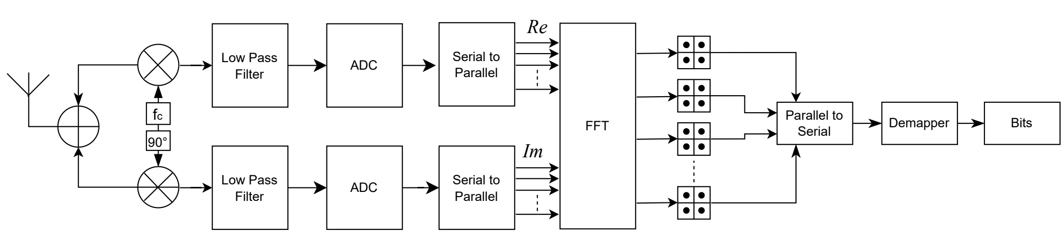


Figure 2.2: Simplified OFDM Receiver Block Diagram

2.3 The Cyclic Prefix

A cyclic prefix (CP) is used in OFDM to combat inter-symbol interference (ISI) caused by multipath fading. The cyclic prefix is a copy of the last N samples of a symbol appended to the front of the symbol in the guard interval. This preserves the orthogonality of subcarriers by including a full symbol of the delayed multipath reflection in the sampling interval. Increasing the cyclic prefix duration helps mitigate ISI caused by longer delay spreads, but it also increases the length of the OFDM symbol, which reduces throughput. This creates a tradeoff [32].

The cyclic prefix can also be used for timing and frequency synchronization by mixing the OFDM symbol with a time-delayed and conjugated version of itself then integrating across the guard time, TG. This process, known as autocorrelation, allows timing estimation by observing the peak correlation value and frequency offset estimation by determining the phase of the maximum correlation [32].

Systems with large relative multipath delay spread use longer cyclic prefixes than systems with shorter delay spread; for example, LTE uses an extended CP duration of 16.7 µs [60], while Wi-Fi 6's longest configurable CP is 3.2 µs. This is because LTE signals have to propagate long distances in outdoor environments, which leads to longer delay spreads than indoor Wi-Fi applications. Delay spread is generally controlled by several system factors, like the carrier frequency, transmit power, and implementation of technologies like multi-user MIMO (MU-MIMO) which service more users by using multiple antenna elements to direct radiation in the direction of specific users. Different configurations of these variables factor into the required delay spread tolerance of a system.

2.4 Wireless Standards

In an OFDM communication system, there are a variety of design specifications that an engineer can tailor to the physical limitations of the channel and the desired application. These design specifications include things like subcarrier spacing, FFT size, cyclic prefix length, and constellation type/modulation order. Different standards pave different formal descriptions for these parameters. For example, 802.11.ax, or Wi-Fi 6, uses a variety of FFT sizes depending on the available bandwidth of the channel, SNR, and desired data rate. A 20 MHz Wi-Fi 6 channel, for instance, contains 256 subcarriers and uses Quadrature Amplitude Modulation (QAM) with a modulation order of up to 1024. Wi-Fi 6 also specifies frameworks for 40 MHz, 80 MHz, and even 160 MHz channels [61].

2.5 Error Correction Techniques

Encoding and interleaving are error correction techniques that are often used in OFDM systems to maximize throughput and minimize errors. Encoding is the process of introducing redundancy into the data so that if an error occurs we can retrieve the original bitstream. Since groupings of bit errors from subcarriers lost to deep fades reduces the performance of error correction capabilities of the encoding/decoding process, an interleaver is used to “blend” the bits up and evenly distribute the errors. Puncturing can be used to achieve higher data rates when the coding rate is too conservative for the current SNR. It works by removing certain bits of data from the input bitstream, transmitting, then inserting dummy bits in place of the removed bits before decoding the data.

2.6 Carrier Frequency Offset

OFDM systems are especially susceptible to carrier frequency offset (CFO) caused by mismatched transmitter and receiver oscillators and Doppler shift. Small errors in frequency can result in significant inter-carrier interference (ICI) because any deviation from the subcarrier peaks causes neighboring subcarriers to not be completely nulled out, which damages orthogonality. It can also result in a loss in received power from the target subcarrier in frequency. An illustration of these factors can be observed in Figure 2.3. A system's oscillator tolerance before experiencing significant distortion is usually given in parts per million (ppm). For instance, if an OFDM system at a carrier frequency of 5 GHz has a subcarrier spacing of 300 kHz, then its oscillator accuracy might need to be within a range of 3 kHz, or have an accuracy better than 0.6 ppm. Generally, a carrier frequency offset of less than 1% is required to limit degradation to 0.1 dB. CFO correction, however, can greatly improve the tolerance for frequency errors. Moreover, pulse-shaping filters can be used to shape the subcarriers in such a way that when frequency offset does occur, there is not as much ICI. [32]

In Paul Moose's 1994 paper, "A Technique for Orthogonal Frequency Division Multiplexing Frequency Offset Correction," he outlines a method for CFO correction using duplicate data symbols. Since the phase of the modulated subcarriers does not change between symbols, any observed change is due to CFO. The frequency offset is then estimated using a derived Maximum Likelihood Estimate (MLE) algorithm. A receiver can then shift the incoming signal in time by $e^{-2\pi \cdot \Delta f_{\text{est}} \cdot n/fs}$ to correct for the distortion. The performance of the algorithm is a function of the SNR of each subcarrier and the frequency offset. The estimated

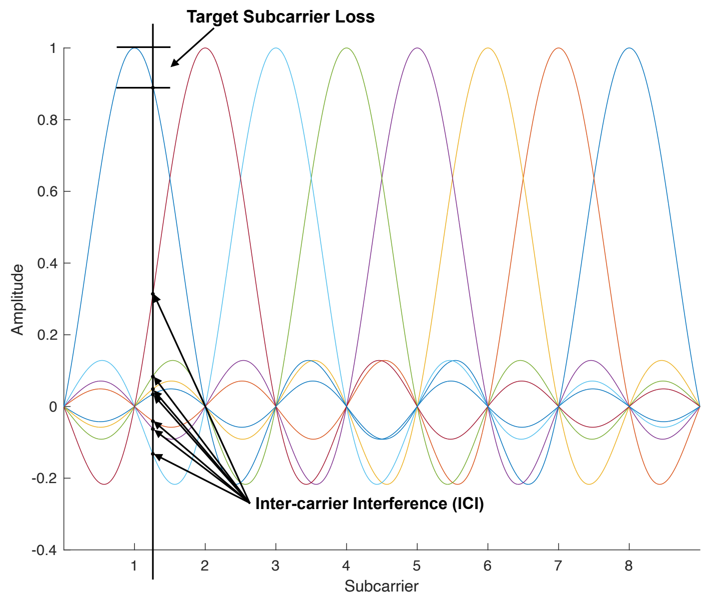


Figure 2.3: ICI and target subcarrier loss as a result of carrier frequency offset (CFO)

CFO, $\hat{\epsilon}$, is shown in equation 2.1 [62].

$$\hat{\epsilon} = \frac{1}{2\pi} \tan^{-1} \left\{ \frac{\sum_{k=-K}^{K} (\mathrm{Im}[Y_{2k} Y_{1k}^{*}])}{\sum_{k=-K}^{K} (\mathrm{Re}[Y_{2k} Y_{1k}^{*}])} \right\} \tag{2.1}$$

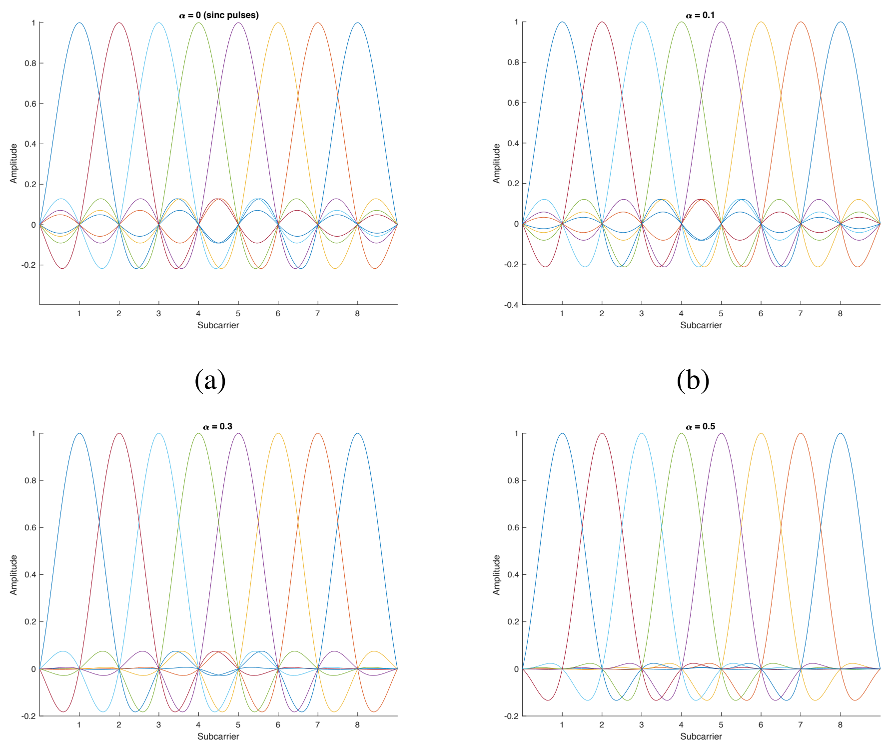
2.7 Pulse Shaping

Pulse-shaping can be applied to the individual subcarriers in the frequency domain so that their spectrum rolls off more rapidly. This reduces ICI by lowing the amplitude of the neighboring subcarriers when the OFDM system has uncorrected frequency offset, as shown in Figure 2.4. Pulse shaping can also be used to limit out-of-band radiation. OOB radiation can decrease slowly when subcarriers are sinc pulses, as seen with the standard rectangular pulse-shaping window. A raised cosine window with a rolloff factor of just 0.05 can reduce OOB radiation significantly, as shown in 2.5. The roll-off factor, α, controls how fast the amplitude drops off in the frequency domain and how much the symbol duration increases in the time domain. The extensions between adjacent symbols in the time domain can be overlapped, though, so the symbol duration is only increased by a factor of 1/2 of α. Tradeoffs exist between limiting the reduction in throughput, decreasing ICI, and increasing out-of-band radiation. Other pulse-shaping windows, like the better than raised cosine pulse (BTRC) and the improved sinc power pulse (ISP), have been used to achieve desired performance of the system. It is important for an engineer to consider the uses of the system, the desired spectral mask, and desired throughput to determine the correct pulse-shaping window [63].

* Piecewise function goes here * Change Beta to Alpha

2.8 The Peak-to-Average Power Ratio Problem

OFDM systems also suffer from a high peak-to-average power ratio because each subcarrier is independently modulated, so when they add up it can result in a large-peaked time domain signal. This is a problem because analog-to-digital converters want to contain the full amplitude range of the received signal through the use of automatic gain control (AGC). When quantization occurs with a signal with high PAPR, then the fidelity of the lower amplitude variations of the signal is limited to fewer quantization steps. The simplest solution to this problem is to clip the high-amplitude portions of an OFDM symbol, but this destroys the orthogonality of the subcarriers and causes in-band and out-of-band interference. The OOB interference can be filtered off, though, which allows this method to be implemented in the real world [64] * Figure here



(a) (b)

(c) (d)

Figure 2.4: Orthogonally spaced raised cosine-shaped subcarriers with various rolloff factors: (a) $\alpha = 0$, which is a sinc pulse, (b) $\alpha = 0.1$, (c) $\alpha = 0.3$, (d) $\alpha = 0.5$

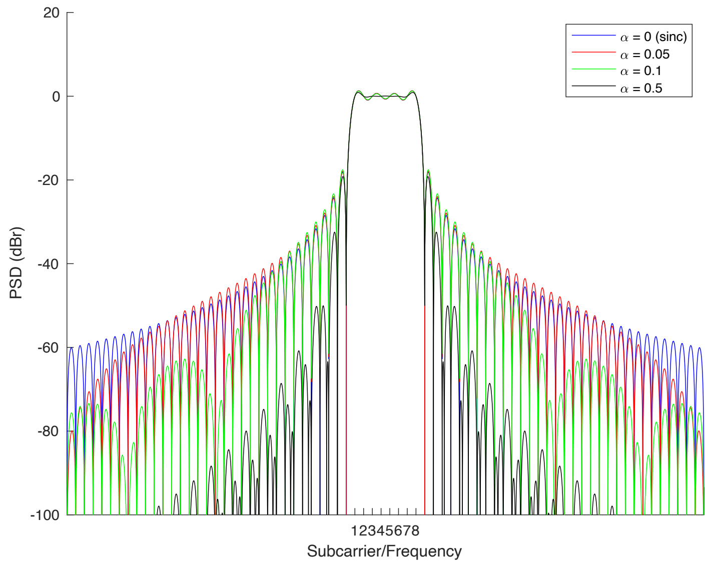


Figure 2.5: Depiction of OOB radiation of OFDM systems with 8 subcarriers orthogonally spaced in frequency with various rolloff factors: $\alpha = 0$, which is a sinc pulse, $\alpha = 0.05$, $\alpha = 0.1$, $\alpha = 0.5$

There are many other techniques that can be used to reduce the average PAPR in an OFDM symbol. One other technique, called the SeLected Mapping (SLM) technique, is to generate a large number of OFDM sequences representing the same data and choose the one with the lowest PAPR. This is accomplished by multiplying the input data symbol by U phase sequences, each of length N. This chosen phase sequence is traditionally transmitted on a side of the OFDM transmission and the receiver uses this information to deconstruct the original data. Another approach is to intentionally transmit data symbols off from their constellation points in such a way that the subcarriers do not add up to tall peaks in the time domain [65].

2.9 Equalization

Equalization reduces the effect that multipath delay spread has on the frequency response on the channel. In OFDM, equalization is much easier than in traditional single-carrier systems due to the narrowband subcarriers having a smaller bandwidth than the coherence bandwidth of the channel. This is because the frequency response of the channel affects each subcarrier as if it were flat fading, so the equalization of each subcarrier is represented as a single complex multiply operation at the receiver. This greatly simplifies the equalization process and improves robustness against fading and other channel effects.

Chapter 3

Introduction

Here is where you will put your introduction. Notice the label right after the chapter command. This allows the writer to reference a chapter like so. See Chapter 3.

3.1 Thesis Outline

Your thesis will usually also have a thesis outline. Here notice the use of the section command and the par command. This section really puts the ref command to work pulling form the labels on the subsequent chapter files.

Chapter **??** describes the second chapter.

In Chapter **??** describes the third chapter.

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