An Universal Communication Device for Improving Interoperability

Final Report

Hen-Geul Yeh
Hsien-Yang Yeh
Charles Van Houten

CSULB

6/30/2007

ACKNOWLEDGEMENT

The authors would like to thank the following agencies for their invaluable support over the past years and contributions to this project: Mr. George Cummings (Director of Homeland Security for the Port of Los Angeles), Mr. Cosmo Perrone (Director of Security for the Port of Long Beach), Mr. Daren Palacios (Chief of Los Angeles Fire Department at the Port of Los Angeles), Mr. John Black (Manager of Wireless Communications Division, City of Long Beach), Mr. Alan Patalano (Operational Chief of Long Beach Fire Department), Mr. Bill Bisson (Assistant Chief for communications, LAFD Operations Control Division), and Mr. Jack Pearson (Chief of Police for CSULB). Specifically, thanks to Mr. Greg Pascal (Communications Supervisor for the CSULB Police Department) for helping the technical survey, and to Dr. Tom O'Brien (Director of Research, Center for International Trade and Transportation) and Ms. Marianne Venieris (Director of CITT) for their encouragement and suggestions.

Table of Contents

1. Introduction

"In January 1982, during a snowstorm, Air Florida flight 90 crashed into the 14th Street bridge in Washington, D.C. Half an hour later a Metrorail accident occurred just a few miles away. Responding rescue personnel from federal, state, and local public safety agencies quickly discovered that coordinating their efforts was extremely difficult because radios from each agency used different frequencies and signaling techniques. On-scene commanders were forced to borrow radios from one another to coordinate their crew activities." [1] This series of events exposed a glaring weakness in the interoperability of communication systems used by the public safety agencies. Although radio interoperability has improved greatly since those events in 1982, interoperability issues still exist.

The purpose of this report is to understand and analyze the current communication systems used by port community agencies and to determine the future communication requirements. In the first section, the current radio systems will be analyzed with the focus of determining the most important problems with the system today. This includes a look into the progress of the interoperability initiative, Project 25 (P25), as well as other proposed changes/improvements to the radio system.

The subsequent sections are a preliminary study on alternatives for a future radio system. This includes a software-defined radio and a fast-growing technology known as orthogonal frequency division multiplexing (OFDM). OFDM has been around for awhile in other applications and is recently being developed as a wireless broadband solution, such as worldwide interoperability for microwave access (WiMAX), also known as IEEE802.16. These sections deal with some of the major challenges of implementing OFDM technology on the mobile radio side. This includes maintaining the BER requirement through adaptive modulation and the reduction of peak-to-average power ratio (PAPR) in OFDM signals.

2. The Current Radio System and Needs

2.1 The Current Radio System

From our surveys conducted in 2006, the radio systems used by agencies date back to the 1980s. The current radio systems used by the public safety agencies have many modes of operations. This includes analog, digital, and trunked modes. There are also many frequency bands used for communication such as UHF, VHF, 800 MHz. An additional issue is vendor incompatibility due to proprietary technology.

Another factor is the assortment of frequency bands allocated for public safety. As of 2003, there were thirteen frequency bands available including VHF-low, VHF-high, UHF((low, T-band), 700 MHz, 800 MHz, and NPSPAC. This introduces issues because the frequencies require hardware tuned for those frequencies, so radios operating on one frequency will not work on another frequency.

Proprietary technology is another hurdle towards interoperability. One of the older problems towards interoperability was the lack of standards, which is an issue due to multiple vendors. An introduction of standards to create a basic foundation on which to design and operate radios helps with proprietary technology. Basically, one creates units of black boxes so that the input and output to that black box are consistent, so it doesn't matter who or how the black boxes are created so as there are the same number of inputs and outputs use the same known input and output type.

Since there are many agencies using radio systems spanning many levels of government including federal, tribal, state, county, and local; there are many systems in use. This makes interoperability a challenge in terms of defining standards, selecting technology and equipment, and non-technological aspects such as planning and implementing changes to the radio systems.

2.2 Project 25 – Standards for Interoperability

Endorsed by public safety agencies, Project 25 provides standards for many radio interfaces such as the inter-RF subsystem, air, console subsystem, and fixed station interfaces. Some of the key problems it tries to solve are equipment interoperability through backward/forward compatibility and digital standards, vendor compatibility, and improved spectrum efficiency. It is also concerned with smooth migration between technologies and it is based on open standards to prevent vendor lock-in and encourage competition for the best products and the lowest prices. P25-compliant technology is being deployed in several phases, based on Telecommunications Industry Association (TIA) engineering committee work and the P25 standards TIA publishes.

Vendors are currently shipping Phase I P25 compliant systems. These systems involve standardized service and facility specifications, ensuring that any manufacturer's compliant subscriber radio has access to the services described in such specifications. Abilities include backward compatibility and interoperability with other systems, across system boundaries, regardless of system infrastructure. In addition, the P25 suite of standards provides an open interface to the radio frequency (RF) subsystem to facilitate interoperability of different vendors' systems.

P25 Phase II implementation involves time and frequency modulation schemes, with the goal of improved spectral efficiency. Significant attention is also paid to interoperability with legacy equipment, interfacing between repeaters and other subsystems, roaming capacity and spectral efficiency/channel reuse. In addition, Phase II work involves console interfacing between repeaters and other subsystems, and man-machine interfaces for console operators that would facilitate centralized training, equipment transitions and personnel movement.

Recognizing the need for high-speed data for public-safety use, as expressed in the Public Safety Wireless Advisory Committee (PSWAC) Final Report, the P25 standard committee established the P25/34 committee to address Phase III implementation. Phase III activities are addressing the operation and functionality of a new aeronautical and terrestrial wireless digital wideband/broadband public safety radio standard that could be used to transmit and receive voice, video and high-speed data in a ubiquitous, wide-area, multiple-agency network. Due to common needs, the European Telecommunications Standards Institute (ETSI) and TIA will work collaboratively for the production of next-generation mobile broadband specifications for public safety users. This international collaboration is known as Project MESA (Mobility for Emergency and Safety Applications). Current P25 systems and future Project MESA technology will share many compatibility requirements and functionalities [2].

2.3 Levels of Interoperability

There is a move to provide interoperable communication defined as the "ability for public safety first responders to communicate with whom they need to, when they need to, when authorized." The ability to provide interoperable communication is not strictly dependent on technological solutions, although it is the most obvious segment to providing interoperability.

According to the DHS, there are six levels of interoperability based on scale and complexity. They are radio swapping, talkaround, mutual aid channels, gateway consoles, system specific roaming, standards based shared systems.

Radio swapping is the physical exchange of radios between the agencies. This is the simplest form of interoperability, but is impractical for large scale events involving many agencies/officials. Talkaround is the direct communication between radios and its successful use is dependent on the air interface used by the radios involved. Both radio swapping and talkaround are simple solutions best suited for small scale events.

Mutual aid channels are designated channels in a frequency band such as VHF, UHF, or 800 MHz. Implementation of mutual aid channels requires dedicated infrastructure and spectrum. This allows first responders to communicate on the designated channel in areas with RF coverage.

Operability between frequency bands is achieved by linking radio systems. There are several methods to link radio systems, including fixed gateways, field deployable gateways, and cross-band repeaters.

The next level of interoperability is system specific roaming. This is analogous to cellular system roaming, allowing radios to operate when outside of the home system/coverage area.

The final level of interoperability is standards based shared systems. This revolves around standardization of equipment so that any system based on the standards can be inserted into the network with functionality with all other radios currently in the network. The purpose of this is large scale, seamless coverage and Project 25 is the set of standards in development for the digital land mobile radio system. Table 1 shows the levels of interoperability defined by the Department of Homeland security and a brief description of their impact. The state of interoperability in California [3] is provided in Appendix.

Table 1 - Department of Homeland Security's levels of interoperability.

DHS levels of Interoperability		
Level	**Method**	**Description**
6	Standards-based shared systems	Most complete long term solution
5	System Specific Roaming	Full featured wide area
4	Gateway Console	Short-term system modification
3	Mutual Aid Channels	Widespread use with public safety agencies
2	Talkaround	Short-term simple solution
1	Radio swap	Short-term simple solution

2.4 Non-technological Aspects of Interoperability

Implementing and advancing the level of radio communication interoperability in a region is a challenging endeavor and requires overcoming non-technical obstacles. Some of the commonly listed requirements for successfully implementing interoperability include planning, leadership, partnership, funding, and practice.

The essential component is comprehensive planning, which is needed to develop the necessary policies, procedures, and to determine best practices. Leadership is stressed through the creation of a governance to guide all agencies involved towards a common goal. Multi-agency partnership is important for successful interoperable implantation, since the goal is to bring the agencies together. This ensures all agencies, regardless of size have input to the process, which includes the need to select technologies. Partnership is important to sharing costs as the radio systems may not be affordable to all agencies. Regular practice of the procedures required for interoperable communication is essential so that they are not forgotten when needed [4].

2.6 Old Radios and New Equipment

A major concern here is the basic operability of radios. In some agencies, radios date back to the 1980's and some may date back further. Many of these radios have been in operation for much longer than their expected lifespan. Obsolescence is another factor associated with older radios. Older radios may not be supported anymore by the manufacturers and other radios may not adhere to current FCC technical requirements. For this reason, new equipment is needed and primary requirements for public safety communications are voice communication, reliability, coverage, interoperability, cost efficiency, high data rates, spectral efficiency and security.

Coverage issues can occur because of damaged infrastructure due to a natural disaster, lack of infrastructure in remotes regions, high system usage due to a large multi-agency response, or poor reception due to physical location such as tunnels. Equipment needed for this issue revolved around mobile infrastructure. This includes mobile gateways and repeaters, which is needed in urban areas to provide enhanced in-building, tunnel, and subway coverage. Mobile equipment is also useful as repeaters for regions with poor coverage [5].

For procurement of new radios, P25 compliant radios are currently purchased and this should be continued. Project 25 standards ensure compatibility with future systems as standards mature, while working with today's radio systems. P25 standards were developed for a migration to digital transmissions, which improves voice quality, signal reliability, spectral efficiency, and security. The downside to P25 compliant radios is that they are more expensive since they have backward compatibility built-in.

Regarding regions with lack of level-4 interoperability, multi-frequency band radios can be considered. These are radios with the capability of operating on more than one frequency band. This is also beneficial for operation in congested areas. For example, the California Highway Patrol (CHP) has experienced problems with interference on some bands and radios capable of operating in several bands offers alternatives if multiple radios are not already in use.

Considering the public safety communications requirements for high spectral efficiency and high data rates, an alternative system is proposed in the next section, based on orthogonal frequency division multiplexing (OFDM) signaling and adaptive modulation.

High spectral efficiency is desirable because the spectrum is a limited resource and it is congested, even with another band opening up for public safety agencies. A goal for standards development is to make the most efficient use of the spectrum as possible and a technique that is efficient is OFDM. Improved data rates can be achieved through a combination of technology and advanced techniques to improve signal quality such as adaptive modulation and power control as mentioned in IEEE802.16.

The prevalence of many different radio networks and constantly evolving technology raises the question of whether mobile radios can be used that are not limited to a single network or technology. This would allow a radio operator to operate on theoretically any type of network and allows flexibility to upgrade the radio as newer technology comes out. This is where software defined radio (SDR) comes in and this possibility is explored as well.

3. Software-defined Radio for Improving Interoperability

3.1 SDR Transceiver Architecture

The idea behind software radio is to move from hardware to software components to increase the design and operating flexibility of a radio system through programmability. Software defined radio basically refers to a set of techniques that permit the reconfiguration of a communication system without the need to change any hardware system element. The goal of software defined radio is to produce communication devices capable of supporting different services. These terminals must adapt their hardware in function of the wireless networks. One very important point is the fact that this adaptation should be dynamic, more or less in real time [6-10].

The basic functional components of software radio architecture include the power supply, antenna, multiband RF converter, analog-to-digital (ADC) and digital-to-analog converters (DAC), a general processor, and memory. Software radios aim to place the analog-to-digital and digital-to-analog conversion as close to the antenna as possible and perform radio functions in software. Software radio aims to move the dependency of frequency band, channel bandwidth, channel coding, and modulation from hardware to software. The general architecture of the SDR transceiver is shown in Figures 3.1-3.2. Figure 3.1 shows the software reconfigurable transmitter block diagram. Figure 3.2 shows the software reconfigurable receiver block diagram.

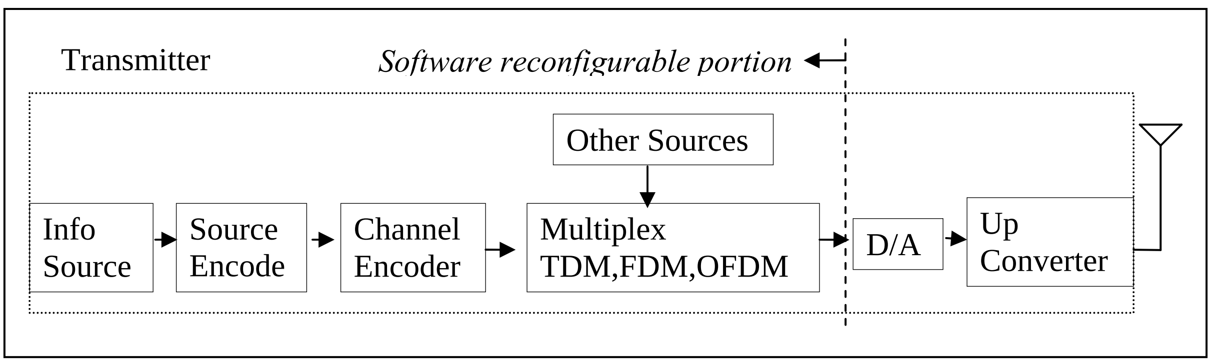

Figure 3.1. Software reconfigurable transmitter block diagram.

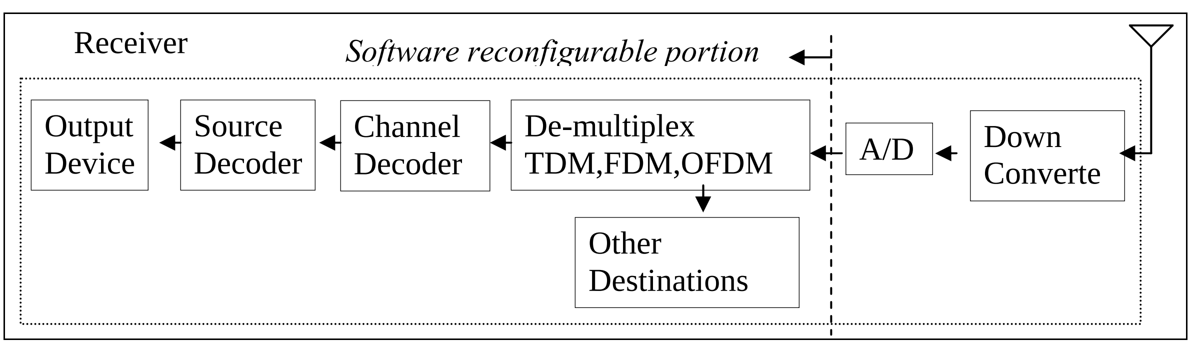

Figure 3.2. Software reconfigurable receiver block diagram.

The benefits of SDR for the radio system end-users are the co-existence, dynamic configurability, and connectivity of the radios. SDR allows equipment to operate in different standards by selecting the appropriate software. It facilitates smooth transition between future technology, multiple vendors, modes, bands, and other infrastructure standards.

SDR does not allow simultaneous use of different standards. It gives flexibility to switch over to a standard being used, which facilitates transitions between radio technologies and standards. For example, base stations implementing SDR technology can be inserted today and programmed to operate on frequencies, bandwidths, and modes currently used. When sufficient progress has been made in upgrading a local/regional network, then they can be easily reprogrammed to operate using different standards or technology.

Multi-mode operation is a desirable trait in mobile systems because it also opens the possibility for global roaming with a change in software which could be downloaded from a library of standards. In order for global roaming to be effective, system standards would have to be accessible so that a library of software downloads could be established for every radio system. Additionally, knowledge of the type of system used in any particular region is needed, so that the correct system software can be installed on the mobile radio. A SDR could then be used, if authorized, to communicate on any standard and on any network which has been fully defined in software.

SDR technology has some drawbacks like higher power consumption, higher processing power**,** such as million instructions per second (MIPS) requirement, and higher initial costs. SDR technology may not be suitable for all types of radio equipment due to these factors. It is much easier to implement SDR in a fixed radio station because it does not have power or size limitations of a portable radio [7]. Design difficulties lead to higher costs for SDRs. "Problems include difficulty in designing wideband, low-loss antennas and radio frequency (RF) converters. It is difficult to accurately estimate the processing demands of applications and processing capacity. Another problem is sustaining consistent data rates across inter-processor interfaces [8]. Additionally, the performance of software defined radios is subpar compared to specialized single system radios built on hardware.

3.2 General SDR chips

Software-defined radios can be implemented on several types of architecture which vary according to processing power and flexibility. This includes digital-signal processors (DSP), field programmable gate arrays (FPGA), and applications-specific integrated circuits (ASIC).

Applications-specific integrated circuits are chips designed for a specific purpose. Digital filters and forward error correction are a few applications where ASIC have efficient performance. ASICs have the best performance, but lack reconfigurability.

Field programmable gate arrays are chips with configurable logic, interconnects, and memory components. These devices are organized into sequential logic that detects the inputs and generates outputs, lookup tables for state memories and transition maps

[9]. The types of devices that effectively use FPGAs are buffer registers, decoders, and multiplexers. FPGAs lie in the middle ground between ASICs and DSPs in terms of performance and flexibility. These chips are faster to market than ASICs, but the other drawbacks for FPGAs are large computational overhead for reconfiguration and lack of high-productivity programming tools.

Digital signal processors are designed to efficiently execute functions that have heavy computations such as filtering and fast Fourier Transforms (FFT). These chips tend to emphasize multiply-add computations. DSP chips can have high instantaneous processing power, but the overall throughput depends on the amount of on-chip and off-chip accesses. DSPs are the least computationally efficient, but are the most flexible of the chips.

4. ODFM with Adaptive Modulation

4.1 OFDM

OFDM is a technique [12-15] implemented in wireless devices beginning with wireless local area networks (WLAN). The incorporation of OFDM techniques in wireless technology continues with the development of standards for wireless metropolitan networks (WMAN) and IEEE 802.20 for mobile wireless connectivity. Hence it is employed in this study as the universal communication technology for interoperability among different data rate.

OFDM is a multi-carrier modulation scheme, which uses a large number of closely spaced (in the frequency domain) orthogonal sub-carriers. The technique splits a serial block of data into parallel blocks in order to transmit the parallel blocks on individual, orthogonal sub-carrier frequencies. Each sub-carrier is modulated at a lower symbol rate, but the overall data rate of an OFDM channel maintains the data rate of a single carrier channel with the same bandwidth. Figure 4.1 shows a simple OFDM transmitter block diagram. Figure 4.2 shows a simple OFDM receiver block diagram. Note that the baseband operation of the transmitter and receiver is done by using reconfigurable software. Figure 4.3 shows the spectra of a single subchannel, and Figure 4.4 shows the spectra of an OFDM signal waveform with a total of six subchannels. Note that the OFDM is a spectrally efficient waveform since the spectra of each subchannel overlap as depicted in Figure 4.4.

.

The current radio systems use frequency division multiple access (FDMA). “FDM is implemented over a relatively wide bandwidth channel using a separate carrier frequency for each signal. To facilitate separation of the signals at the receiver, the carrier frequencies were spaced sufficiently far apart so that the signal spectra did not overlap. Empty spectral regions between the signals assured that they could be separated with readily realizable filters. The resulting spectral efficiency was therefore quite low.“

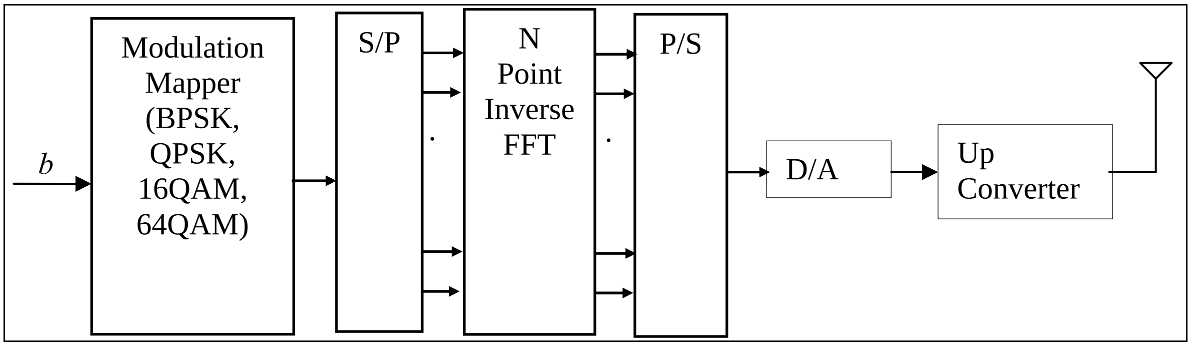

Figure 4.1. Simple OFDM transmitter block diagram.

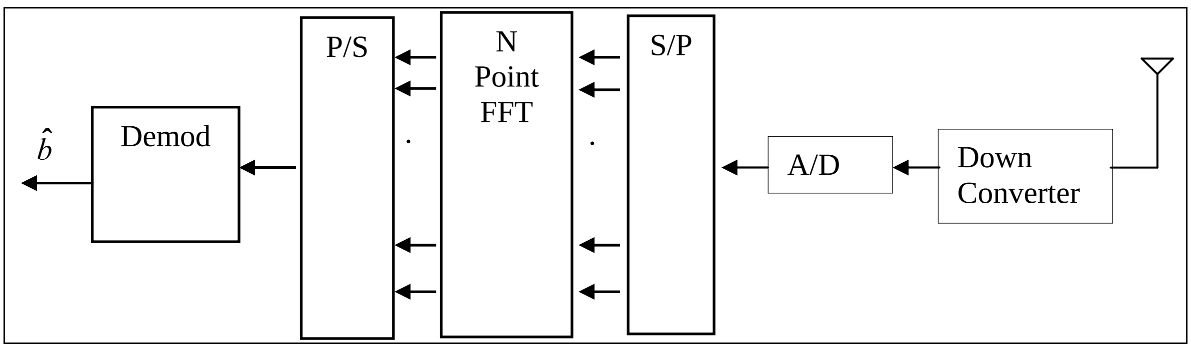

Figure 4.2. Simple OFDM receiver block diagram.

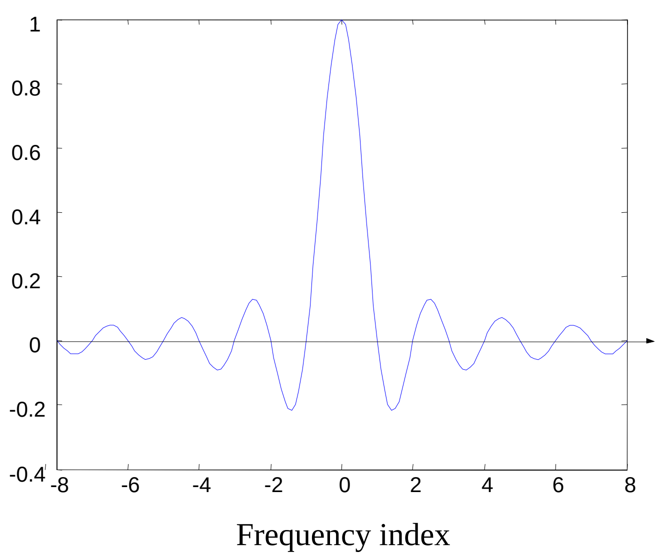

Figure 4.3. Spectra of a subchannel.

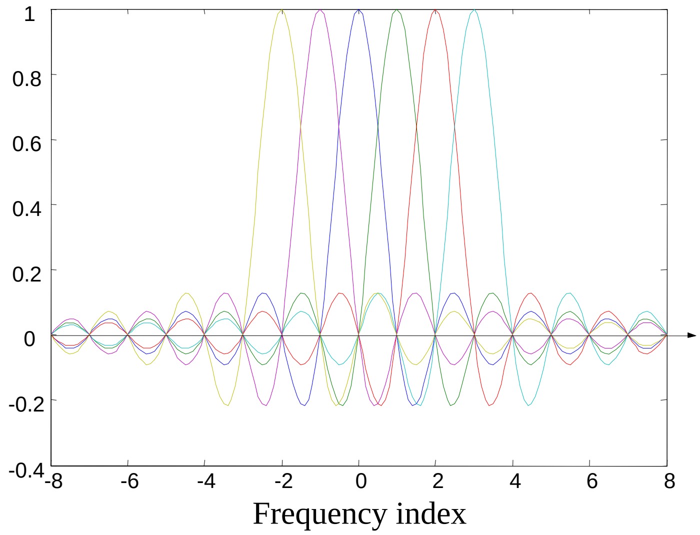

Figure 4.4. Spectra of an OFDM signal.

There are many advantages to implementing an OFDM system, which are relevant to the future needs of the radio systems. OFDM has high spectral efficiency since the spectra of each sub-carrier within an OFDM spectra are designed to overlap, while maintaining orthogonality as depicted in Figure 4.4. Another benefit of OFDM is that it is easily and efficiently implemented in software with the fast Fourier Transform (FFT) algorithm. Additionally, OFDM signals perform better in multi-path fading environments without complex equalizers compared to narrowband signals. These benefits lead us to research OFDM systems as a candidate for future radio systems. The research focuses on preliminary studies of base-band signaling methods and architectures. In the next two sections, we demonstrate the interoperability among different data rate by using the link adaptive for different modulation schemes.

4.2 Link Adaptation

A tool for increasing the spectral efficiency and date rates for wireless networks is link adaptation. This involves changing the modulation, coding rate, and other transmission parameters according to channel conditions. The basic idea of link adaptation defines a set of variable parameters as a selectable mode for a measured signal quality. There are three basic steps to link adaptation which are channel quality estimation, adaption selection, and adaptation. Adaptive modulation and coding techniques is a currently implemented link adaptation scheme in the cellular standard Enhanced Data GSM Evolution (EDGE).

OFDM creates a need for integrating temporal, spatial, and spectral components together. Frequency adaptation over individual OFDM subcarriers offers high theoretical gains, but is not practical due to the high computational overhead and requirement for significant channel condition information. Spatial adaptation involves the angle of transmission and reception and is significant to multiple input and multiple output

(MIMO), multiple input and single output (MISO), single input and multiple output (SIMO) transmissions and beamforming. Temporal adaptation refers to tracking fast fading with times between update rates being less than the coherence time. It is also important for exploiting multipath delays in signal reception when the channel is frequency selective.

Challenges associated with the implementation of link adaptation include determination of adaptation thresholds, adaptation rate, and feedback. Adaptation thresholds are determined through simulations or measurements and accurate calculation is difficult, so there is a trade-off between calculating the least amount of statistical channel information and adequately representing the channel characteristics [16].

Tradeoffs for channel estimation methods are open-loop and closed-loop adaptation. Closed-loop estimation measures the channel quality at the receiver and relays the information back to the transmitter for subsequent transmissions. Open-loop estimation relies on estimating the channel quality on the opposite transmission, which means the outgoing signal's adaptive parameters are based upon the channel conditions for an incoming signal [17].

Degrees of freedom in adaptive modulation refer to the number of parameters that are available for adaptation. As mentioned earlier, adaptive modulation involves varying parameters such as modulation scheme, transmission power, or coding rate. Chung and Goldsmith [18] demonstrate that by restricting power or rate of adaptive modulation, near optimal performance can be achieved. This indicates that only a few parameters need adaptive feedback in order to maximize the spectral efficiency [18]. Therefore, spectral efficiency is relatively insensitive to the degrees of freedom adapted.

Another important facet to determine the adaptive parameters and threshold levels for adaptive changes is the type of transmission data. Voice transmissions have different requirements than data transmissions. Voice requires a reliable transmission, real-time delays, and does not require high data rates. These requirements contrast with the needs for data transmissions, which demand high data rates for certain applications and delays are less important [19].

Adaptation rate is based on tracking of the channel conditions and there is a trade-off in tracking fast and slow changes. This trade-off occurs between performance gain in tracking channel conditions and the amount of resources needed to transmit control messages [16].

Another tradeoff associated with the adaptation segment involves the method used to detect the desired changes. The first method is to transmit the desired changes on a side channel. The problem with this is that if errors in the signaling channel data propagate to the transmitted data. However, errors in detection can be reduced using multiple signaling symbols. The other method is blind detection and the performance of this depends on the number of sub-channels used and the number of modulation schemes.

Greater number of either of these variables leads to decreased performance of the blind detector [17].

The feedback issue relates to the amount of information to send back and where the mode calculation takes place. Calculation at the receiver allows minimal use of channel resources, since only mode and not channel conditions are transmitted [16].

4.3 BER requirement and Adaptive Modulation

Adaptive modulation is the on-the-fly changes to modulation scheme and transmit-power to satisfy instantaneous propagation conditions, interference scenarios, or traffic and data rate requirements. Adaptive modulation effectively improves BER, so we look into various modulation techniques with OFDM including *M*-ary PSK, differential *M*-ary PSK, and QAM for waveforms ranging from M=2 to 64 and perform OFDM simulations for these modulation techniques in AWGN and Rayleigh fading channels to gather performance data. Data from these simulations can be used to define criteria modulation types for specific channel conditions. Figure 4.5 shows BER for *M*-ary PSK modulation schemes in AWGN channel. Figure 4.6 shows BER for *M*-ary PSK modulation schemes in flat Rayleigh fading channels. Clearly, the higher data rate (i.e. M is larger) requires higher transmission power in order to achieve the same BER.

To simply the receiver circuit, differential modulation techniques may be applied to avoid the channel estimation. Furthermore, both 16 and 64 differential amplitude and phase shift keying (16DAPSK and 64DAPSK) are studied. The constellation diagram of 16DAPSK is shown in Figure 4.7. In this case, the data sequence is divided into 4 bits per symbol. The first bit b_0 is for differential amplitude modulation and the rest three bits $b_1b_2b_3$ are for differential phase modulation. Therefore, differential 16DAPSK is a combination of D-8PSK and 2DASK. In simulation, the ring ratio is chosen as 2.0. Similarly, for 64DAPSK, the data sequence is divided into 6 bits per symbol. The first two bit b_0b_1 is for differential amplitude modulation and the rest four bits $b_2b_3b_4b_5$ are for differential phase modulation. Therefore, 64-DAPSK is a combination of D-16PSK and 4DASK. In simulation, the ring ratio is chosen as 1.4 for 64DAPSK.

Figure 4.8 shows BER for differential *M*-ary PSK modulation schemes in AWGN channel. Note that both 16DAPSK and 64DAPSK are compared to D-16PSK and D-64PSK in Figure 4.8. It shows that the BER performance of 16DAPSK and 64DAPSK is better than that of D-16PSK and D-64PSK by 1.7 dB and 6.3 dB, respectively, at BER = 10^{-5}. Figure 4.9 shows BER for *M*-ary PSK modulation schemes in flat Rayleigh fading channels. Similarly, it shows that the BER performance of 16DAPSK and 64DAPSK is better than that of D-16PSK and D-64PSK by 1.7 dB and 6.3 dB, respectively, at BER = 10^{-2}.

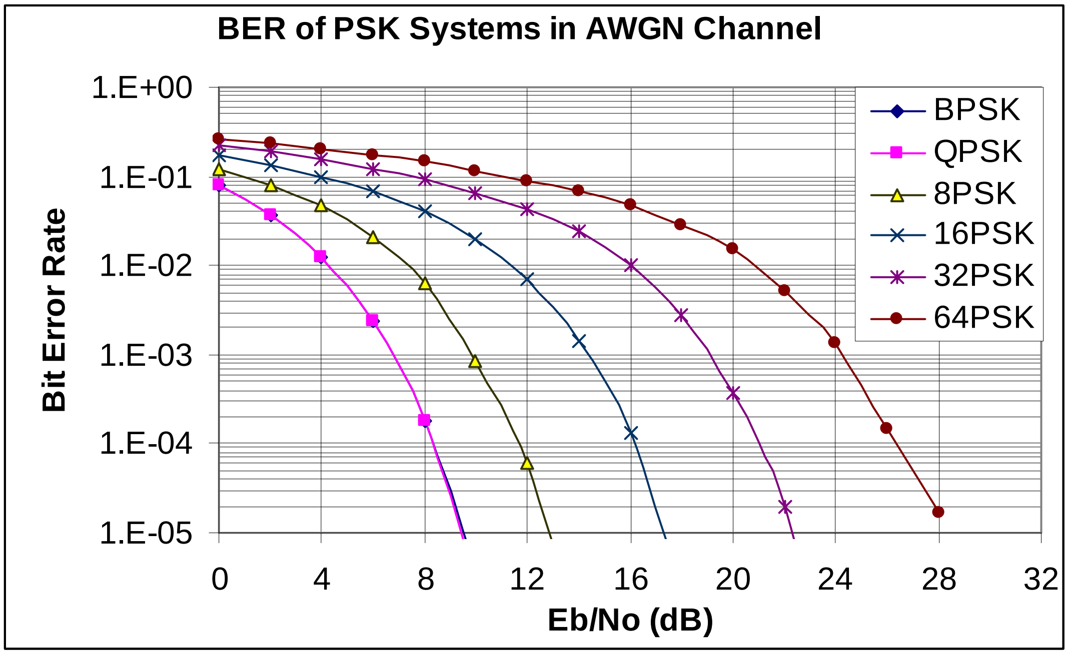

Figure 4.5. BER for *M*-ary PSK modulation schemes in AWGN.

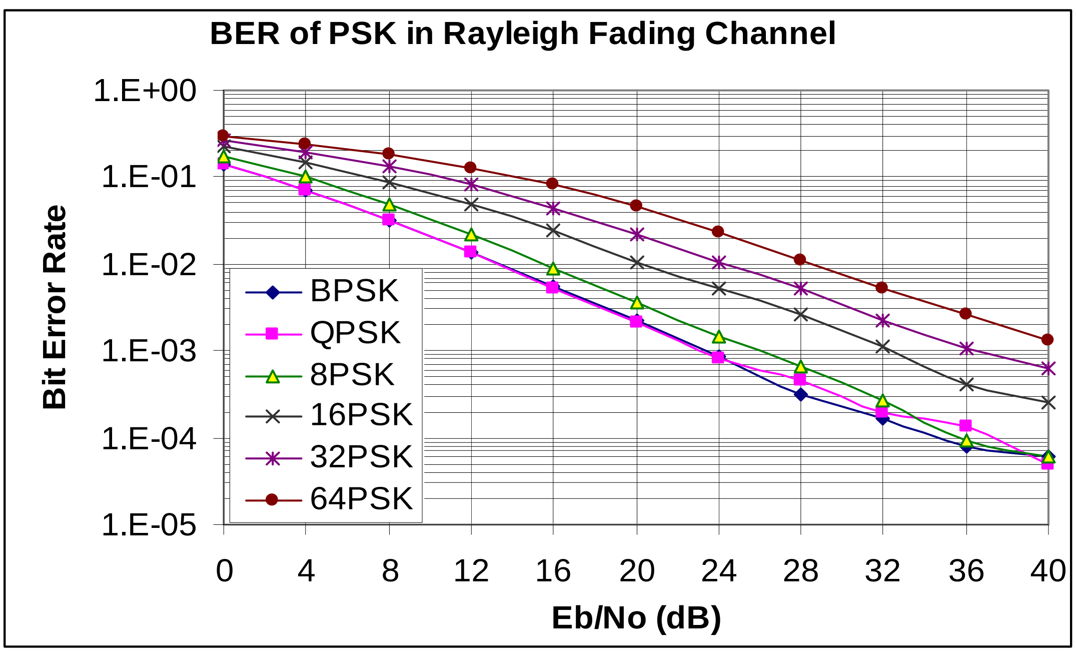

Figure 4.6. BER for *M*-ary PSK modulation schemes in a fading channel.

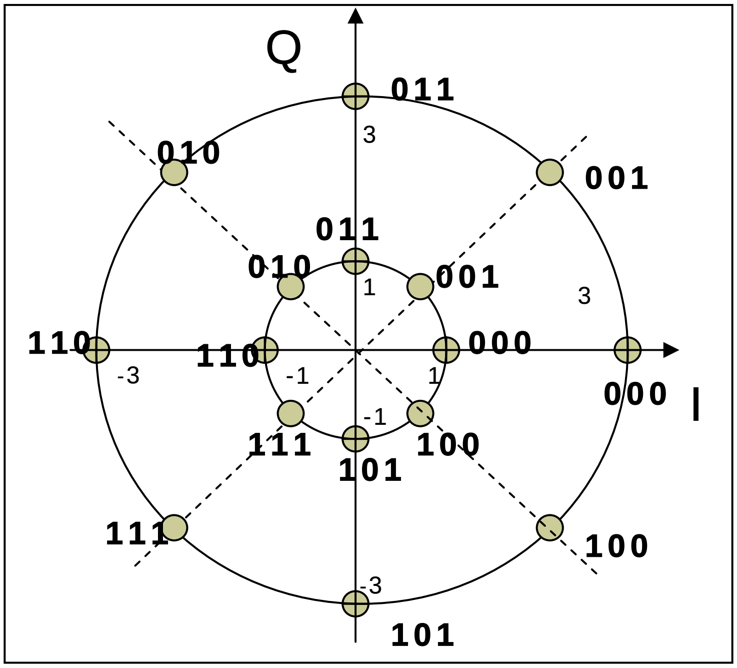

Figure 4.7. Constellation diagram for 16DAPSK.

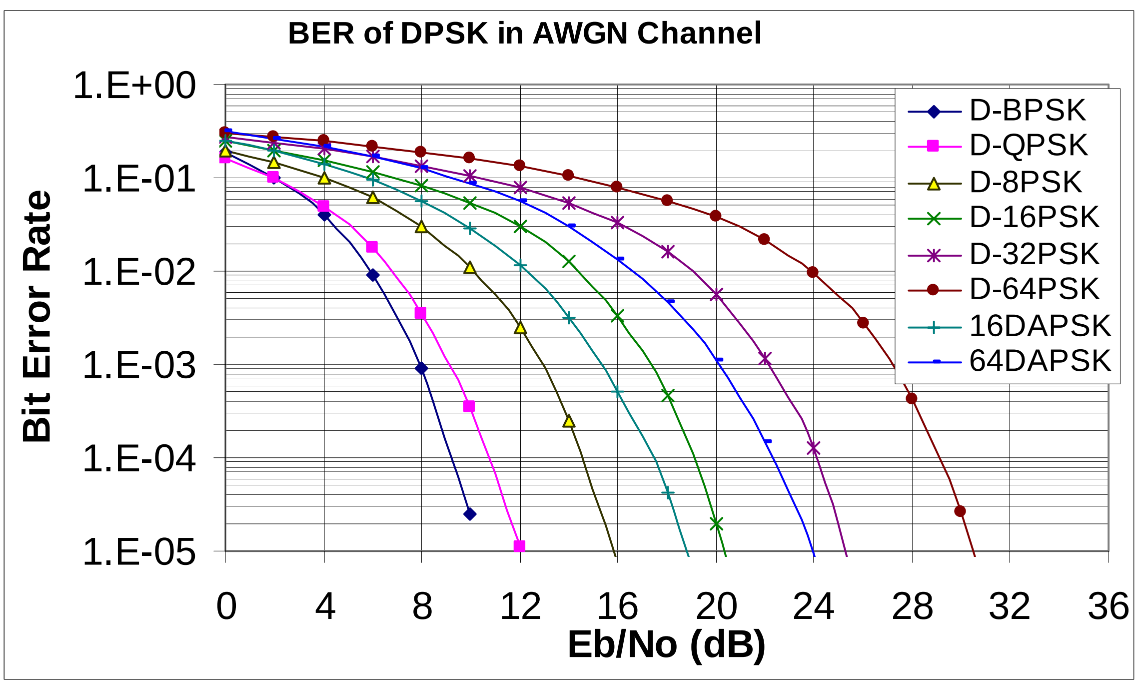

Figure 4.8. BER for DPSK and DAPSK modulation schemes in AWGN.

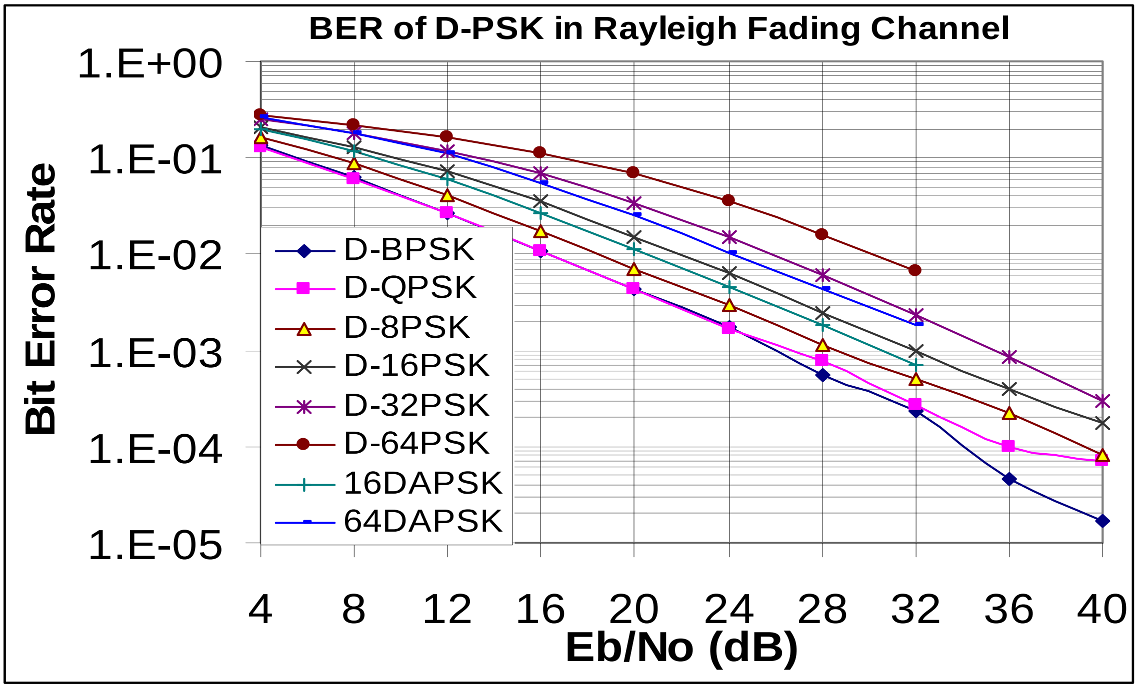

Figure 4.9. BER for DPSK and DAPSK modulation schemes in a fading channel.

Both 16 and 64 -QAM are studied. Furthermore, differential 16 and 64 -QAM (D-16QAM and D-64QAM) are also studied for comparison. Figure 4.10 shows BER performance of 16-QAM, 64-QAM, D-16QAM, and D-64QAM in AWGN channel. Note that the BER performance of 16 and 64 -QAM is better than that of D-16QAM and D64-QAM by about 0.3 dB at BER = 10^{-5}. Figure 4.11 shows BER performance of 16-QAM, 64-QAM, D-16QAM, and D-64QAM in flat Rayleigh fading channel. Note that the BER performance of 16 and 64-QAM is better than that of D-16QAM and D-64QAM by about 4 dB at BER = 10^{-3}.

The performance for each channel degrades as the number of waveforms per modulation type increases. This is indicated by the higher E_b/N_0 required in maintaining the same BER as the waveforms increase. In comparing the modulation types PSK, DPSK, and QAM, the graphs demonstrate the performance of PSK is better than DPSK. The graphs also show that QAM performance is better than PSK performance for the same number of waveforms. Additionally, the performance relationship between the modulation types hold for both AWGN and Rayleigh fading channels.

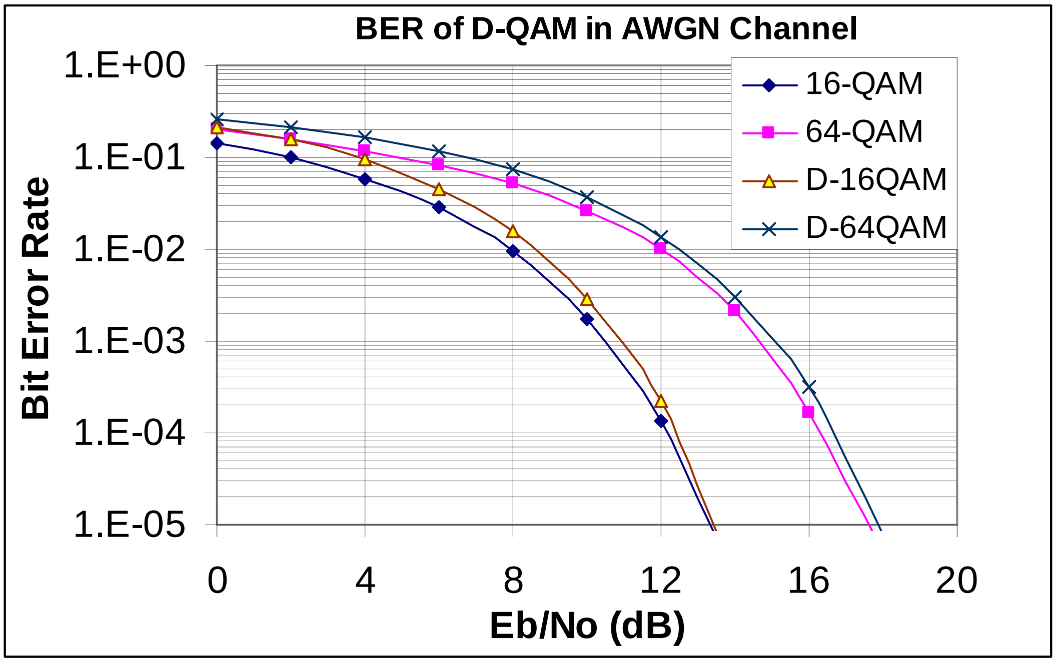

Figure 4.10. BER for QAM and DQAM modulation schemes in AWGN channel.

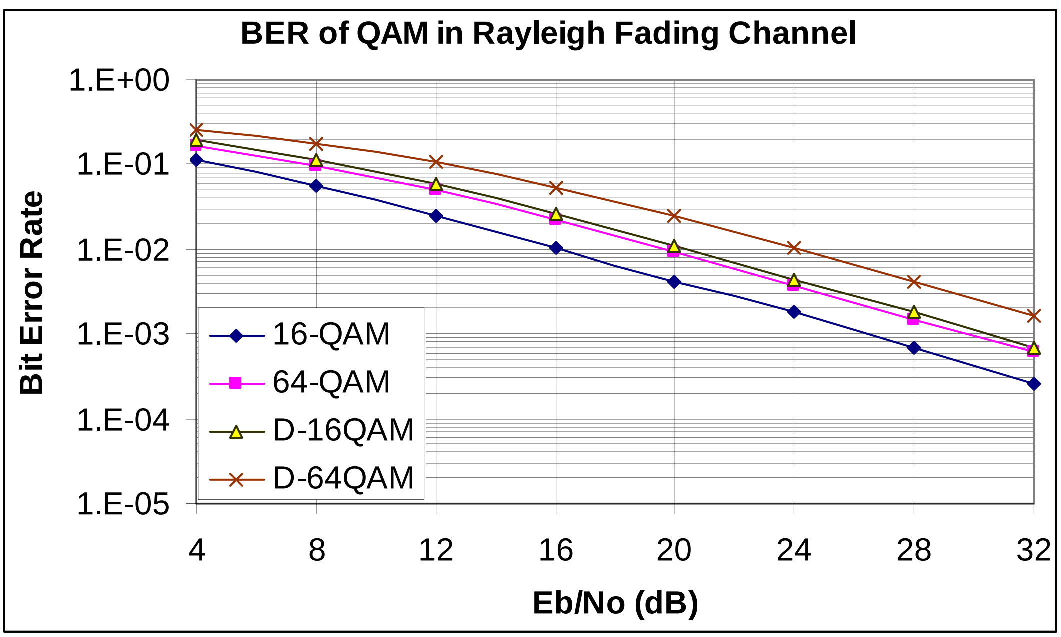

Figure 4.11. BER for QAM and DQAM modulation schemes in a fading channel

This BER data is used to determine the modulation type and number of waveforms to use for any particular channel condition. As mentioned earlier, desired threshold BER is chosen for a transmission type and as measured channel conditions change, the modulation type changes to maximize the data rates while maintaining the similar BER performance. For example, as a mobile station moves further from a base station, the E_b/N_0 will decrease and consequently, the BER will increase. Therefore, two options are available to increase the E_b/N_0. The first is to increase transmit power, and the other is to change the modulation type from a high throughput modulation scheme such as 64-QAM to a lower rate scheme such as BPSK.

Although there are many advantages to implementing OFDM systems, there are a few obstacles to overcome. Two primary issues with OFDM are its frequency offset sensitivity and its high peak-to-average power ratio (PAPR). The frequency offset estimation and related topics are given in [12, 25]. Here we focus the discussion on the PARP reduction and related solution.

5. PAPR Reduction

OFDM signals are a parallel transmission of signals over several frequencies and as a result, the signals can coherently add up resulting in large peak-to-average power ratios. This is undesirable because it decreases the power efficiency of transmission. In order to compensate for the high peak to average power, either a highly linear amplifier is needed or clipping of the high peaks occurs reducing the system performance.

There have been several methods suggested to remove peaks including amplitude clipping, tone reservation, tone injection, partial transmit sequences (PTS) [20], selective mapping (SLM), and active constellation extension. The common element to all these techniques is the change in phase of individual subcarrier transmissions to reduce any large peaks. The techniques studied are the PTS and sign flipping method proposed by Sharif.

The commonly used measure of performance for PAPR is the CCDF which is the measure of the probability the PAPR of an OFDM symbol exceeds a given threshold. We have the performance for an unmodified OFDM symbol, a PTS technique, and Sharif's sign flipping technique. Figure 4.12 shows the PAPR reduction with the PTS technique.

Partial Transmit Sequences technique divides the input data of size Y into X blocks. Complex phase factors $b_m = e^{j\varphi m}$ ($m = 0, 1, \ldots W$-1 where W is the number of allowed phase factor) are introduced to rotate the phase of an entire block of data to reduce the PAPR. The number of blocks and the number of allowed phase factors increases the complexity and PAPR reduction ability. In order to get the optimal PAPR per OFDM symbol, all possible subcarriers and phase rotations must be tested. Currently there is no way to do this faster than testing each scenario. Blocking the data reduces the complexity by lumping subcarriers into groups and testing phase rotations on those groups. One method used to reduce the search complexity is to limit the phase rotations to two possibilities. This is used in the tested PTS method. For a given OFDM symbol, the PAPR is tested and if it exceeds the given threshold, then PTS is implemented. Starting with the second block, the phase of all data subcarriers within that block is rotated and the PAPR is tested to see if it falls below the threshold. If it doesn't then each successive block is phase rotated, PAPR tested, and the rotation with the lowest PAPR is kept. This is done until the PAPR falls below the threshold or all blocks of data have been tested [20].

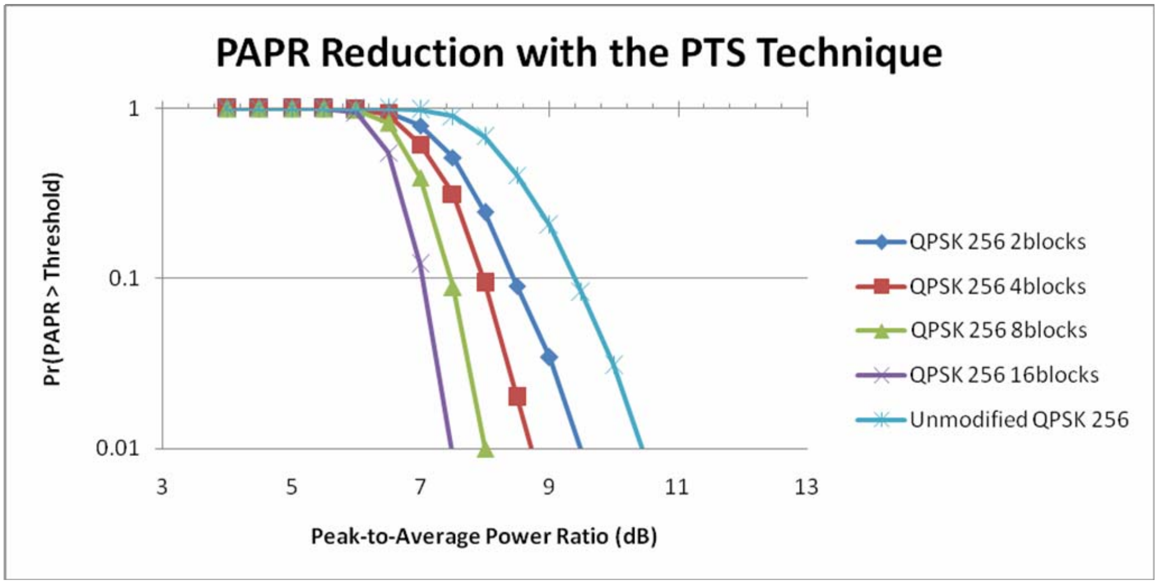

Figure 4.12. PAPR Reduction with the PTS Technique.

The PAPR reduction performance of the PTS technique is dependent on the number of sub-blocks used. For each doubling of the number of sub-blocks, the PAPR reduction is approximately 0.75 dB. However, sub-block addition increases the maximal number of iterations possible per OFDM symbol resulting in more computations per symbol.

Sharif's method flips the sign of sub-carriers to reduce the PAPR. The deterministic algorithm proposed by Sharif is based on a de-randomization of the search for the sign vectors. This is based on de-randomization of random algorithms and it basically optimizes the search for optimal signs of each subcarrier, instead of testing each possible vector of signs for the best PAPR [21]. Figure 4.13 shows the plot of PAPR reduction with the de-randomization method. The downside of this method is the inability to send information in the signs for BPSK and requires the implementation of another method for BPSK using dummy subcarriers to reduce the PAPR. Another drawback for this method is its computational complexity, which increases as the number of sub-carriers increase. The reason for this is that it does not exploit the efficient calculations of IFFT to create the OFDM signals. However, it reduces PAPR by about 4dB to slightly over 6dB for Pr(PAPR>threshold) of 0.01. This method works effectively on QPSK and 16QAM modulation schemes.

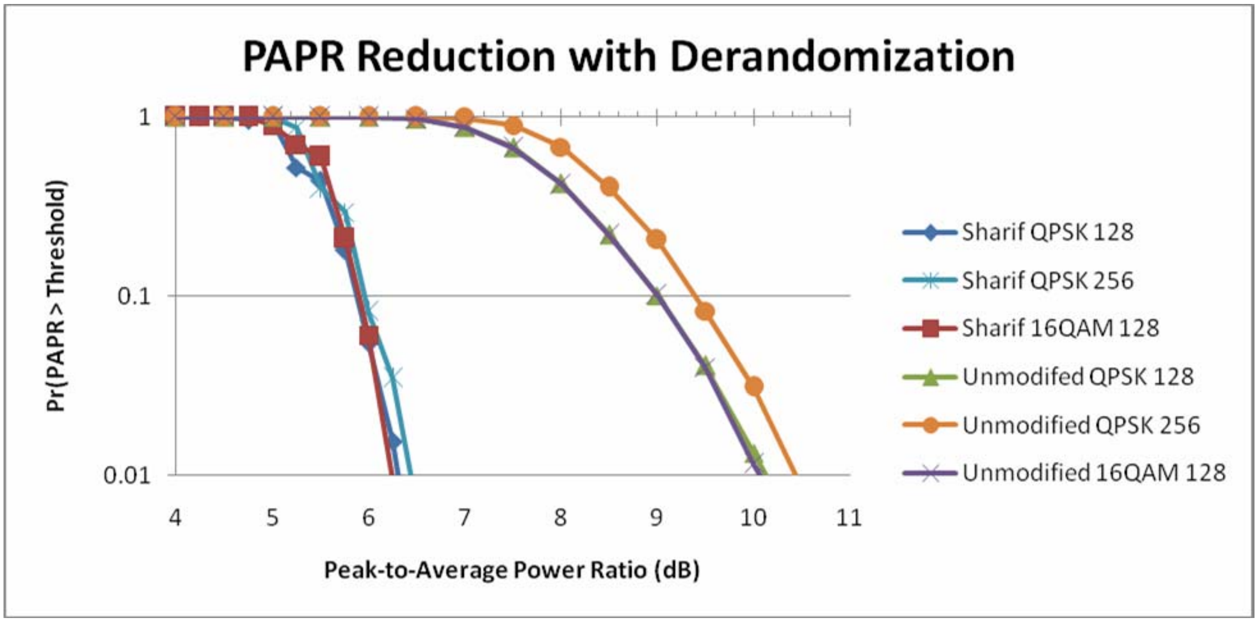

Figure 4.13. PAPR Reduction with the De-randomization Method.

6. Conclusion

From a technological standpoint, P25 compliant radios are based on standards to ensure backward compatibility, vendor compatibility, future interoperability, to reduce equipment costs, and increase spectral efficiency. These radios are the choice for public safety agencies in the region and it is recommended that they continue with that policy. Other equipment that is important to expand coverage is the use of mobile gateways/transceivers to bring radio coverage outside of the home region or to increase building/tunnel penetration.

Alternative solutions for interoperable radios presented are based on software-defined radios, orthogonal frequency division multiplexing, and adaptive modulation. As processing power increases, software-defined radios become more realizable than ever. A reconfigurable architecture opens the door for interoperable communications on multiple standards and networks, presenting the opportunity for wide-scale roaming. For OFDM adaptive modulation, bit error rates were simulated for varying modulation types including M-ary PSK, DPSK, QAM, and DQAM. As M increases from 2 to 64, the performance degrades in both AWGN and Rayleigh fading channels, but this data provides the framework for setting parameters of adaptive modulation. One of the downsides to OFDM is high peak-to-average power ratio, and two methods are simulated here. The partial transmit sequences method with iterative sign flipping demonstrates good PAPR reduction as the number of blocks increases, approaching the reduction provided by the de-randomization method proposed by Sharif [21]. While, the PTS method does not have the best PAPR reduction, it is significantly faster to compute since it takes advantage of the efficient IFFT algorithm.

7. Recommended Research

Further research would expand on the BER rates given here for the various modulation types to test throughput increases of adaptive modulation. To further the PAPR reduction, algorithms that enhance the search for optimal signs while implementing the IFFT algorithm are ideal for study to both reduce the PAPR and preserve low computational complexity.

Additional topics related to OFDM signaling include multiple-input multiple-output (MIMO) communication and related issues such as sensitive frequency synchronization [22-26]. More study is needed, specially, for the interoperability for the high performance MIMO OFDM areas.

Appendix

A.1 State of Interoperability in California

A DHS scorecard rates some of the major urban locations in California on governance, standard operating procedures (SOP), and usage. The ratings are based on Safecom's continuum of interoperability. Governance is defined as the plans for implementing shared systems and solutions to facilitate regional communications. This includes identifying long-term goals, a leadership that prioritizes interoperability, and access to various forms of funding. Standard operating procedures refer to the policies and procedures set in place to support interoperable communication during crises. This also covers the effective use of command and control to coordinate communications between agencies. Usage is a measure of the proficiency an agency has in operating interoperable equipment in a multi-agency event as well as how often the equipment is used. Table A.1 shows the ratings given to select urban areas in California and Table A.2 describes the ratings.

Table A.1 – Interoperability Maturation Ratings for California's urban areas.

City	***Governance***	***SOP***	***Usage***
Anaheim	4	3	3
Long Beach	3	4	4
Los Angeles	3	4	4
Oakland	2	4	4
Sacramento	3	3	3
San Diego	4	4	4
San Francisco	2	2	3
San Jose	4	4	3
Santa Ana	4	3	3

1 = early implementation
2 = intermediate implementation
3 = established implementation
4 = advanced implementation

Table A.2 - Communications Interoperability Maturation Ratings defined.

Elements	1 *Early Implementation*	2 *Intermediate Implementation*	3 *Established Implementation*	4 *Advanced Implementation*
Standard Operating Procedures (SOP)	Region-wide SOPs were developed and formalized for the first time through the TICP, but have not been disseminated to all included agencies. Some elements of NIMS/ICS procedures for command and control are in place, but understanding varies among agencies and was an area of difficulty during exercise(s).	Some existing SOPs were incorporated in the TICP and steps have been taken to institute these interoperability procedures among included agencies. Formal NIMS/ICS procedures are in place, but understanding varies among agencies leading to some issues during the exercise(s).	Existing regional SOPs were reviewed and included in the TICP, and are in use by included agencies. NIMS-compliant command and control has been instituted by all agencies and disciplines in the region. Despite minor issues, all SOPs were successfully demonstrated during exercise(s).	Regional SOPs, reviewed through the TICP process, are in place and regularly used by included agencies. NIMS procedures are well established among all agencies and disciplines. All procedures were effectively utilized during exercise(s).
Usage	Interoperable communications solutions are rarely used for multi-agency communication and difficulties were encountered in achieving interoperability during exercise(s).	First responders use interoperability solutions regularly and demonstrated the ability to achieve multi-agency communications despite some challenges during exercise(s).	First responders use interoperability solutions regularly and easily. The region demonstrated successful multi-agency (which may have included state, federal, and support organizations) communications during exercise(s).	First responders regularly and seamlessly utilize interoperability solutions. The region demonstrated successful multi-agency communications during exercise(s), including state, federal and support organizations.
Governance	Decision making groups are informal, and do not yet have a strategic plan in place to guide collective communications interoperability goals and funding.	Some *formal* agreements exist and *informal* agreements are in practice among members of a decision making group; regional strategic and budget planning processes are beginning to be put in place.	Formal agreements outline the roles and responsibilities of a decision making group, which has an agreed upon strategic plan that addresses sustainable funding for collective, regional interoperable communications needs.	Decision making bodies proactively look to expand membership to ensure representation from broader public support disciplines and other levels of government, while updating their agreements and strategic plan on a regular basis.

The following are general conclusions on each of the topics as described in the DHS report [4]:

Governance

1. Informal cooperation between agencies precede formal, regional governance
2. Areas with pre-existing DHS urban area working groups are more likely to have regional communications committees
3. Governance indicates a higher likelihood of advanced technology, mature SOPs and proficient usage
4. Few urban areas have a finished plan for regional interoperable communication

SOP

1. Tactical Interoperable Communication Plan provided first regionwide equipment SOP for many areas
2. Most areas have disseminated their equipment SOPs throughout the region
3. Most areas implemented National Incident Management System (NIMS)/Incident Command System (ICS) command and control procedures
4. NIMS certification procedure is needed

Usage

1. Most regions established regional interoperability
2. Many regions use shared systems/channels daily
3. Most common equipment problems involved mobile gateways

4. Aggressive deadlines limited scope of communication exercises

The non-technological issues affecting interoperability are handled very well in California according to the Homeland Security scores. Some of the common recommendations for urban locations in California stressed the need to cooperate with agencies at the state and federal levels. This cooperation is needed to solidify standard operating procedures among the different levels and to expand training exercises to include the various levels of government agencies. Additionally, most problems in operating equipment were found in operating mobile gateways, so SOP and exercises in operating gateways are a priority.

A.2 Plans for Level 4 Interoperability

The current level of interoperability in the state of California is level-3, which are the six established regions with mutual aid channels. Currently, seventeen counties in California have fixed or mobile gateways and there is a plan to deploy mobile gateways to each of the six mutual aid regions by the end of year 2007 [27]. Level-4 interoperability across the state is the next interoperability goal for California, which can be accomplished in several ways. Both Georgia and Texas have chosen methods for linking radios operating in different frequencies, and Georgia has gone a step further with plans to network their radio systems with a private IP network.

Texas has achieved level-4 interoperability throughout the state [28]. The general solutions to achieve level-4 interoperability were P25 radio acquisition for all agencies, dissemination of extra radios to first responders, and linking of existing radio systems.

The first solution to acquire P25 radios for all agencies was not considered due to several concerns. The primary concerns with this solution were the cost and time to migrate each agency, the P25 standards were still in developmental stages, and the impact on the number of frequencies available to each agency. The second solution to provide extra radios was deemed cumbersome, since there are too many agencies to provide additional radios such as police, EMS fire, and highway patrol [27].

Texas chose to link their existing radio systems together as the most practical solution. There are several methods of implementing this solution and the different regions of Texas followed different methods. The methods of linking include fixed or mobile gateways, cross-band repeaters, and network linking. Gateways in the form of console patches are used when available, and mutual aid coverage is expanded for the regions through the use of repeaters, and mobile command and communications interoperability vehicles are available for deployment to any agency [29].

Georgia decided to use its existing radio infrastructure as well, linking the different radio systems with a private network. The state uses multiple protocol label switching (MPLS) internet protocol network, VoIP software, IP network components, and strategic positioning of mobile communications units (MCUs). This system allows transfer of voice, data, and video information. This is an alternative to the gateway implementation in Texas and paves the way for level-5 interoperability [30-31].

References

[1] "The Case for Project 25," *Monitoring Times,* June 2000.

[2] P25 Radio Systems. Daniels Electronics Training Guide. 2004.

[3] Department of Homeland Security, *Tactical Interoperable Communications Scorecards Summary Report and Findings*, January 2007.

[4] Motorola, *Interoperability*, <http://www.motorola.com/governmentandenterprise/northamerica/en-us/public/functions/browsesolution/browsesolution.aspx?navigationpath=id_801i/id_394i/ssone2>

[5] T. Klein, "911-NOW: Network on Wheels for Emergency Response, Tactical Operation and Hotspot Coverage." 2006.

[6] J.P. Delahaye et al. "Software Radio and Dynamic Reconfiguration on a DSP/FPGA Platform," pp. 1-9.

[7] Deshpande, Suyog. "Software Implementation of IEEE 802.11B Wireless LAN Standard."

[8] J. Mitola, "The Software Radio Architecture," *IEEE Communications Magazine*, pp. 26-38, May 1995.

[9] Mitola III, Joseph. *Software Radio Architecture*. New York: John Wiley & Sons, Inc., 2000.

[10] A Rhiemeier, "Modular Software-Defined Radio," *EURASIP Journal on Wireless Communications and Networking*, 2005:3, 333-342.

[11] Y. Lin et al, "SODA: A Low-power Architecture for Software Radio," *Proceedings of the 33rd International Symposium on Computer Architecture*. 2006.

[12] P. H. Moose, "A Technique for Orthogonal Frequency Division Multiplexing Frequency Offset Correction," *IEEE Transactions on Communications*, Vol. 42, No.10, 2908-2913, October, 1994.

[13] Y. Zhao and S-G. Haggman, "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems," *IEEE Trans. Commun.,* vol. 49, no. 7, pp. 1185-1191, July 2001.

[14] H. G. Yeh and C. C. Wang, "New parallel algorithm for mitigating the frequency offset of OFDM systems," *Proc. IEEE 60th Vehicular Technology Fall Conf.*, L.A., CA, Sept. 2004, pp. 2087-2091.

[15] H. G. Yeh, Y. K. Chang, and B. Hassibi, "A scheme for canceling intercarrier interference through conjugate transmission for multicarrier communication systems," IEEE Trans. on Wireless Commun, vol. 6, no. 1, Jan. 2007, pp. 3- 7

[16] S Catreux et al. "Adaptive Modulation and MIMO Coding for Broadband Wireless Data Networks," *IEEE communications Magazine,* pp. 108-115, June 2002.

[17] T. Keller and L. Hanzo, "Adaptive Modulation Techniques for Duplex OFDM Transmission," *IEEE Transactions on Vehicular Technology*, vol 49, no. 5, pp. 1893-1906, Sept. 2000.

[18] T.S. Chung and A.J. Goldsmith, “Degrees of Freedon in Adaptive Modulation: A Unified View,” *IEEE Transactions on Communications*, vol. 49, no. 9, pp. 1561-1571, Sept. 2001.
[19] M.S. Alouini et al. “An Adaptive Modulation Scheme for Simultaneous Voice and Data Transmissions over Fading Channels,” *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 5, pp. 837-850, May 1999.
[20] L. J. Cimini and N. Sollenberger, “Peak-to-Average Power Ratio Reduction of an OFDM Signal Using Partial Transmit Sequences,” *IEEE Communications Letters*, Vol. 4, No. 3, pp. 86-88. March 2000.

[21] M. Sharif et al. “Amplitude and Sign Adjustment for Peak to Average Power Reduction,” *IEEE Trans. on Commun.*, vol. 53, no. 8, pp. 1243-1248, Aug. 2005.
[22] D. Gesbert et al. From Theory to Practice: An Overview of MIMO space-time coded wireless systems.
[23] A.J. Paulraj et al, “An Overview of MIMO Communications – A Key to Gigabit Wireless.” *Proceedings of the IEEE*. 2004.
[24] Nortel, *MIMO Technology*, <http://www2.nortel.com/go/solution_content.jsp?segId=0&catId=0&parId=0&prod_id=61701>
[25] H. G. Yeh and E. Chan, “An Efficient Frequency Synchronization Method for MIMO-OFDM Systems.” Submitted to *IEEE Trans Communications*, June 2007.
[26] A. Bahai et al. *Multi-Carrier Digital Communications Theory and Applications of OFDM*. New York: Springer, 2004.
[27] Public Safety Radio Strategic Planning Committee January 2007
[28] K. Reeves, “Officials praise Texas’ Progress on Emergency System,” *National Journal’s Technology Daily*. April 2007.
[29] Texas Radio Communications Interoperability Plan
[30] Crisis Talk: GTRI helps implement statewide interoperable communications system. Research Horizons. Winter 2006.
[31] F. K. Jondral. “Software-Defined Radio – Basics and Evolution to Cognitive Radio.” *EURASIP Journal on Wireless Communications and Networking* 2005:3, 275-283.