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OFDM in Digital Communication

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Abstract- Channel estimation and prediction algorithms are developed and evaluated for use in broadband adaptive OFDM downlinks over fading channels for vehicular users. Accurate channel estimation may be obtained by using a combined pilot aided and decision-directed approach based on Kalman filtering and prediction. The correlation properties of the channel in both time and space are taken into account. Kalman performance at much lower computational complexity is attained with recently developed constant gain adaptation laws. We present and evaluate a state-space realization of such an adaptation law, with computational complexity of the order of the square of the number of parallel tracked pilot subcarriers. In an adaptive OFDM system, prediction of the channel power a few milliseconds ahead will also be required. Frequency-domain channel estimates can be transformed to the time domain, and used as regressors in channel predictors based on linear regression. We also make a preliminary evaluation of the direct use of complex channel prediction in the frequency domain for channel power prediction.

Index Terms-OFDM System, Kalman Filter, Regression, FDM, CDMA, GSM

I. INTRODUCTION

Initial proposals for OFDM were made in the 60s and the 70s. It has taken more than a quarter of a century for this technology to move from the research domain to the industry. The concept of OFDM is quite simple but the practicality of implementing it has many complexities. So, it is a fully software project. OFDM depends on Orthogonality principle. Orthogonality means, it allows the sub carriers, which are orthogonal to each other, meaning that cross talk between co-channels is eliminated and inter-carrier guard bands are not required. This greatly simplifies the design of both the transmitter and receiver, unlike conventional FDM; a separate filter for each sub channel is not required. Orthogonal Frequency Division Multiplexing (OFDM) is a digital multi carrier modulation scheme, which uses a large number of closely spaced orthogonal sub-carriers. A single stream of data is split into parallel streams each of which is coded and modulated on to a subcarrier, a term commonly used in OFDM systems. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation) at a low symbol rate, maintaining data rates similar to conventional single carrier modulation schemes in the same bandwidth. Thus the high bit rates seen before on a single carrier is reduced to lower bit rates on the subcarrier. In practice, OFDM signals are generated and detected using the Fast Fourier Transform algorithm. OFDM has developed into a popular scheme for wideband digital communication, wireless as well as copper wires. Actually, FDM systems have been common for many decades. However, in FDM, the carriers are all independent of each other. There is a guard period in between them and no overlap whatsoever. This works well because in FDM system each carrier carries data meant for a different user or application. FM radio is an FDM system. FDM systems are not ideal for what we want for wideband systems. Using FDM would waste too much bandwidth. This is where OFDM makes sense. In OFDM, subcarriers overlap. They are orthogonal because the peak of one subcarrier occurs when other subcarriers are at zero. This is achieved by realizing all the subcarriers together using Inverse Fast Fourier Transform (IFFT). The demodulator at the receiver parallel channels from an FFT block. Note that each subcarrier can still be modulated independently. Since orthogonality is important for OFDM systems, synchronization in frequency and time must be extremely good. Once orthogonality is lost we experience inter-carrier interference (ICI). This is the interference from one subcarrier to another. There is another reason for ICI. Adding the guard time with no transmission causes problems for IFFT and FFT, which results in ICI. A delayed version of one subcarrier can interfere with another subcarrier in the next symbol period. This is avoided by extending the symbol into the guard period that precedes it. This is known as a cyclic prefix. It ensures that delayed symbols will have integer number of cycles within the FFT integration interval. This removes ICI so long as the delay spread is less than the guard period. The aim of this project is to investigate the OFDM scheme, and realize a fully functional system in software and analyzing how it is reducing the inter-symbol interference caused by the multipath fading channels and different effects and estimating, evaluating the performance of it.

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II. Literature Review

The OFDM technology was first conceived in the 1960s and 1970s during research into minimizing ISI, due to multipath. The expression digital communications in its basic form is the mapping of digital information into a waveform called a carrier signal, which is a transmitted electromagnetic pulse or wave at a steady base frequency of alternation on which information can be imposed by increasing signal strength, varying the base frequency, varying the wave phase, or other means. In this instance, orthogonality is an implication of a definite and fixed relationship between all carriers in the collection. Multiplexing is the process of sending multiple signals or streams of information on a carrier at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end. Modulation is the addition of information to an electronic or optical signal carrier. Modulation can be applied to direct current (mainly by turning it on and off), to alternating current, and to optical signals. One can think of blanket waving as a form of modulation used in smoke signal transmission (the carrier being a steady stream of smoke). In telecommunications in general, a channel is a separate path through which signals can flow. In optical fiber transmission using dense wavelength-division multiplexing, a channel is a separate wavelength of light within a combined, multiplexed light stream. This project focuses on the telecommunications definition of a channel. OFDM is a special form of M*ulti* C*arrier* M*odulation* (MCM) with densely spaced sub carriers with overlapping spectra, thus allowing for multiple-access. MCM) is the principle of transmitting data by dividing the stream into several bit streams, each of which has a much lower bit rate, and by using these sub-streams to modulate several carriers. This technique is being investigated as the next generation transmission scheme for mobile wireless communications networks. Back in the 1960s, the application of OFDM was not very practical. This was because at that point, several banks of oscillators were needed to generate the carrier frequencies necessary for sub-channel transmission. Since this proved to be difficult to accomplish during that time period, the scheme was deemed as not feasible. However, the advent of the Fourier Transform eliminated the initial complexity of the OFDM scheme where the harmonically related frequencies generated by Fourier and Inverse Fourier transforms are used to implement OFDM systems. The Fourier transform is used in linear systems analysis, antenna studies, etc., The *Fourier transform*, in essence, decomposes or separates a waveform or function into sinusoids of different frequencies which sum to the original waveform. It identifies or distinguishes the different frequency sinusoids and their respective amplitudes.

The Fourier transform of *f(x)* is defined as:

$$F(\omega) = \int_{-\infty}^{\infty} f(x)\, e^{-j\omega x} dx$$

and its inverse is denoted by:

$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \cdot e^{j\omega x} d\omega$$

However, the digital age forced a change upon the traditional form of the Fourier transform to encompass the discrete values that exist is all digital systems. The modified series was called the Discrete Fourier Transform (DFT). The DFT of a discrete-time system, *x(n)* is defined as:

$$\mathrm{X}(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j\frac{2\pi}{N}kn} \quad 1 \le k \le N$$

and its associated inverse is denoted by:

$$x(n) = \frac{1}{N} \sum_{n=0}^{N-1} \mathrm{X}(k) \cdot e^{j\frac{2\pi}{N}kn} \qquad 1 \le n \le N$$

However, in OFDM, another form of the DFT is used, called the Fast Fourier Transform (FFT), which is a DFT algorithm developed in 1965. This “new” transform reduced the number of computations from something on the order of

$$N^2 \text{ to } \frac{N}{2} \cdot \log_2 N.$$

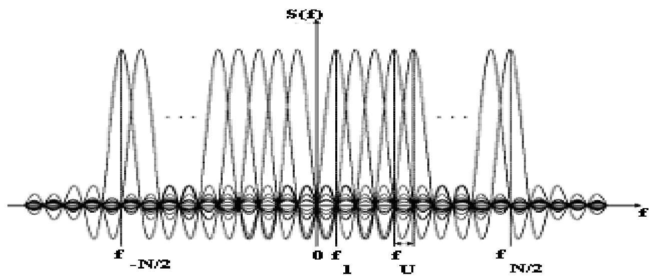
Orthogonality:

In geometry, orthogonal means, "involving right angles" (from Greek *ortho*, meaning *right*, and *gon* meaning *angled*). The term has been extended to general use, meaning the characteristic of being independent (relative to something else). It also can mean: non-redundant, non-overlapping, or irrelevant. Orthogonality is defined for both real and complex valued functions. The functions $\varphi_m(t)$ and $\varphi_n(t)$ are said to be orthogonal with respect to each other over the interval $a < t < b$ if they satisfy the condition:

$$\int_a^b \varphi_m(t)\, \varphi_m^*(t) dt = 0, \qquad \text{Where } n \neq m$$

OFDM Carriers:

As fore mentioned, OFDM is a special form of MCM and the OFDM time domain waveforms are chosen such that mutual orthogonality is ensured even though sub-carrier spectra may over-lap. With respect to OFDM, it can be stated that orthogonality is an implication of a definite and fixed relationship between all carriers in the collection. It means that each carrier is positioned such that it occurs at the zero energy frequency point of all other carriers. The sinc function, illustrated in Fig.1 exhibits this property and it is used as a carrier in an OFDM system.



f_u is the sub-carrier spacing

Fig .1. OFDM sub carriers in the frequency domain

Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. OFDM is similar to FDMA in that the multiple user access is achieved by subdividing the available bandwidth into multiple channels that are then allocated to users. However, OFDM uses the spectrum much more efficiently by spacing the channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers. Coded Orthogonal Frequency Division Multiplexing (COFDM) is the same as OFDM except that forward error correction is applied to the signal before transmission. This is to overcome errors in the transmission due to lost carriers from frequency selective fading, channel noise and other propagation effects. For this discussion the terms OFDM and COFDM are used interchangeably, as the main focus of this thesis is on OFDM, but it is assumed that any practical system will use forward error correction, thus would be COFDM. OFDM overcomes most of the problems with both FDMA and TDMA. OFDM splits the available bandwidth into many narrow band channels (typically 100-8000). The carriers for each channel are made orthogonal to one another, allowing them to be spaced very close together, with no overhead as in the FDMA example. Because of this there is no great need for users to be time multiplex as in TDMA, thus there is no overhead associated with switching between users.

III. Proposed Work

To generate OFDM successfully the relationship between all the carriers must be carefully controlled to maintain the orthogonality of the carriers. For this reason, OFDM is generated by firstly choosing the spectrum required, based on the input data, and modulation scheme used. Each carrier to be produced is assigned some data to transmit. The required amplitude and phase of the carrier is then calculated based on the modulation scheme (typically differential BPSK, QPSK, or QAM).

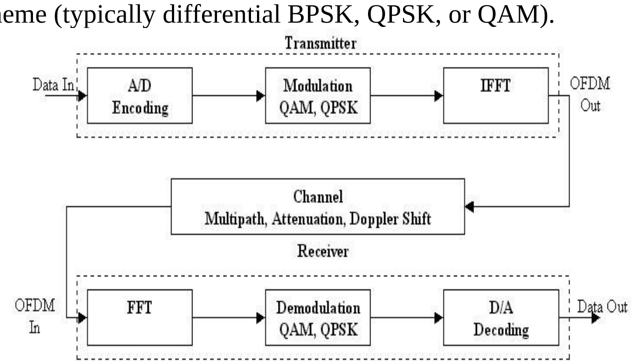


Fig. 2. OFDM Block Diagram

Fig. 2.2 shows the setup for a basic OFDM transmitter and receiver. The signal generated is a base band, thus the signal is filtered, then stepped up in frequency before transmitting the signal. OFDM time domain waveforms are chosen such that mutual orthogonality is ensured even though sub-carrier spectra may overlap. Typically QAM or Differential Quadrature Phase Shift Keying (DQPSK) modulation schemes are applied to the individual sub carriers. To prevent ISI, the individual blocks are separated by guard intervals wherein the blocks are periodically extended. In practice, OFDM systems are implemented using a combination of FFT and IFFT blocks that are mathematically equivalent versions of the DFT and IDFT, respectively, but more efficient to implement. An OFDM system treats the source symbols (e.g., the QPSK or QAM symbols that would be present in a single carrier system) at the Tx as though they are in the freq-domain. These sym's are used as the i/p's to an IFFT block that brings the sig into the time domain. The IFFT takes in N sym's at a time where N is the num of sub carriers in the system. Each of these N i/p sym's has a symbol period of T secs. Recall that the basis functions for an IFFT are N orthogonal sinusoids. These sinusoids each have a different freq and the lowest freq is DC. Each i/p symbol acts like a complex weight for the corresponding sinusoidal basis fun. Since the i/p sym's are complex, the value of the sym determines both the amplitude and phase of the sinusoid for that sub carrier. The IFFT o/p is the summation of all N sinusoids. Thus, the IFFT block provides a simple way to modulate data onto N orthogonal sub carriers. The block of N o/p samples from the IFFT make up a single OFDM sym. The length of the OFDM symbol is NT where T is the IFFT i/p symbol period mentioned above.

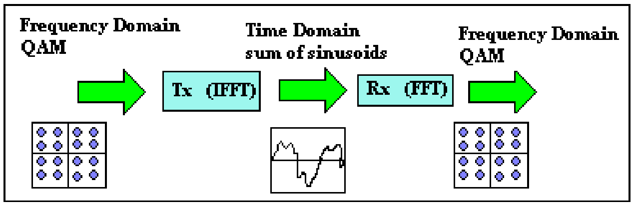


Fig. 3 FFT & IFFT diagram

One of the most important properties of OFDM transmissions is the robustness against multipath delay spread. This is achieved by having a long symbol period, which minimizes the ISI. The level of robustness, can infact is increased even more by the addition of a guard period b/w transmitted sym's. The guard period allows time for multipath sig's from the pervious symbol to die away before the information from the current symbol is gathered. The most effective guard period to use is a cyclic extension of the symbol. If a mirror in time, of the end of the symbol waveform is put at the start of the symbol as the guard period, this effectively extends the length of the symbol, while maintaining the orthogonally of the waveform. Using this cyclic extended symbol the samples required for performing the FFT (to decode the sym), can be taken anywhere over the length of the sym. This provides multipath immunity as well as sym time synchronization tolerance. If the delay spread is longer then the guard interval then they begins to cause ISI. However, provided the echo's are sufficiently small they do not cause significant problems. This is true most of the time as multipath echo's delayed longer than the guard period will have been reflected of very distant objects. Other variations of guard periods are possible. One possible variation is to have half the guard period a cyclic extension of the symbol, as above, and the other half a zero amplitude signal. This will result in a signal as shown in Fig.4.

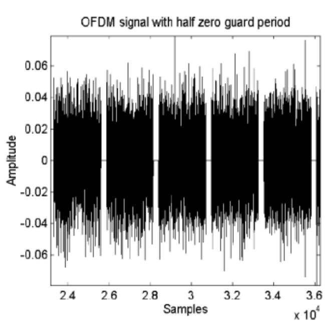


Fig. 4. Section of an OFDM signal showing 5 symbols, using a guard period which is half a cyclic extension of the symbol, and half a zero amplitude signal.

Adaptive OFDM Downlink

We assume the use of FDD, and of a base station infrastructure with sectored antennas. User terminals are in this paper assumed to have only one antenna. The available downlink bandwidth within a sector (cell) is assumed to be slotted in time. Each slot of duration T is furthermore partitioned into *time-frequency bins* of bandwidth Δfb. We here assume $T = 0.667$ ms and $\Delta fb = 200$ kHz, which is appropriate for stationary and vehicular users in urban or suburban environments. We also assume a subcarrier spacing of 10 kHz, a cyclical prefix of length 11μs and an OFDM symbol period (including cyclic prefix) of $Ts = 111\mu$s. Thus, each bin of 0.667 ms × 200 kHz carries 120 symbols, with 6 symbols of length 111μs on each of the 20 10 kHz subcarriers. Of these 120 symbols, 12 are allocated for training and downlink control, leaving 108 payload symbols, see Fig. below. During slot j, each terminal predicts the signal to interference and noise ratio (SINR) for all bins, with a prediction horizon mT that is larger than the time delay of the transmission control loop. All terminals then signal their predicted quality estimates on an uplink control channel. They transmit the suggested appropriate modulation formats to be used within all bins of the predicted time slot $j + m$. A scheduler that is located at the base station then allocates these time-frequency bins exclusively to different users and broadcasts its allocation decisions by using some of the downlink control symbols. In the subsequent downlink transmission of slot $j + m$, the different modulation formats used in different bins are those which were suggested by the appointed users. For the payload symbols, we utilize an adaptive modulation system that uses 8 uncoded modulation formats: BPSK, 4- QAM, 8-QAM, 16-QAM, 32-QAM 64-QAM, 128-QAM, and 256-QAM, with constant transmit power . The use of 256- QAM requires SNR $\geq$ 30 dB, and a correspondingly low channel estimation error. The 12 pilots and control symbols are located within each bin as indicated by Fig. 1. They are assumed to use 4-QAM and can be detected by all users within the sector. (The sector boundary is defined as the range at which 4-QAM symbols can on average be detected with low probability of error.) The spacing between pilots in time, 0.666 ms, corresponds to 0.115 wavelengths at 1.9 GHz carrier frequency and 100km/h vehicle speed. Pilot symbols are transmitted over every fifth subcarrier, in the following denoted *pilot subcarriers*. Their spacing in frequency, 50 kHz, is designed to be adequate to handle the frequency selectivity encountered in suburban propagation environments. Thus, all active users must estimate the channel within the whole bandwidth. The channel estimates are used for two purposes: In bins addressed to a user, the payload symbols are de-rotated for coherent detection. Channel estimates for all bins are furthermore used by the predictor.

Kalman channel estimation

Theoretically, the Kalman Filter is an estimator for what is called the *"linear quadratic problem"*, which focuses on estimating the instantaneous "state" of a linear dynamic system perturbed by white noise. Statistically, this estimator is optimal with respect to any quadratic function of estimation errors. In practice, this Kalman Filter is one of the greater discoveries in the history of statistical estimation theory and possibly the greatest discovery in the twentieth century. It has enabled mankind to do many things that could not have been done without it, and it has become as indispensable as silicon in the makeup of many electronic

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systems. In a more dynamic approach, controlling of complex dynamic systems such as continuous manufacturing processes, aircraft, ships or spacecraft, are the most immediate applications of Kalman filter. In order to control a dynamic system, one needs to know what it is doing first. For these applications, it is not always possible or desirable to measure every variable that you want to control, and the Kalman filter provides a means for inferring the missing information from indirect (and noisy) measurements. Some amazing things that the Kalman filter can do is predicting the likely future courses of dynamic systems that people are not likely to control, such as the flow of rivers during flood, the trajectories of celestial bodies or the prices of traded commodities.

Implementation of OFDM System

An OFDM system was modeled using MATLAB to allow various parameters of the system to be varied and tested. The aim of doing the simulations was to measure the performance of OFDM under different channel conditions, and to allow for different OFDM configurations to be tested. The OFDM system was modeled using Matlab and is shown in Fig.5**.** A brief description of the model is provided below.

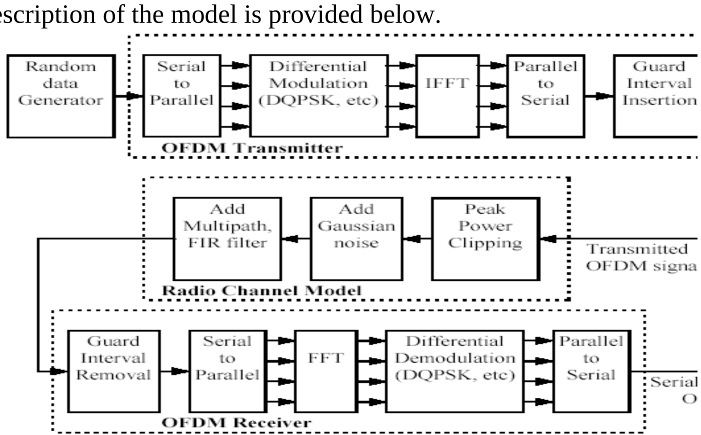

Fig. 5. OFDM Model used for simulations

Almost any hardware system can be simulated in a software environment to help eliminate bugs and tweak settings. An OFDM system is no exception to this statement. There are many features of an OFDM system that are more easily manipulated in a software situation. A very powerful and useful engineering software package is MATLAB by Math Works. MATLAB can be used to simulate common engineering systems including hydraulics, aeronautics, GPS, and communications. It also has many useful digital signal processing functions and features, which will prove to be useful in an OFDM simulation. The first step in the development of any software is the making of a simple overall flowchart shown in Fig.6 is the MATLAB flowchart of an OFDM system.

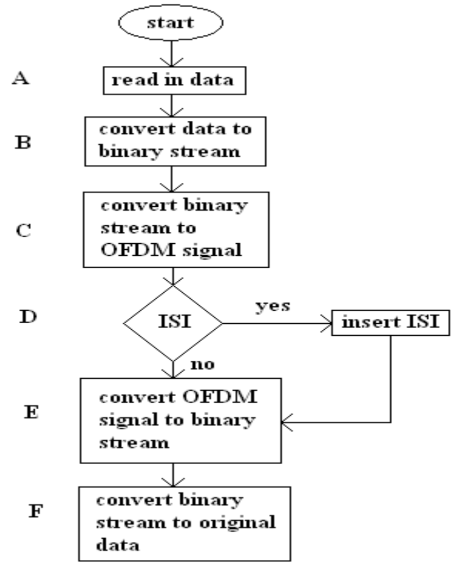

Fig.6. Overall flowchart of OFDM system in MATLAB

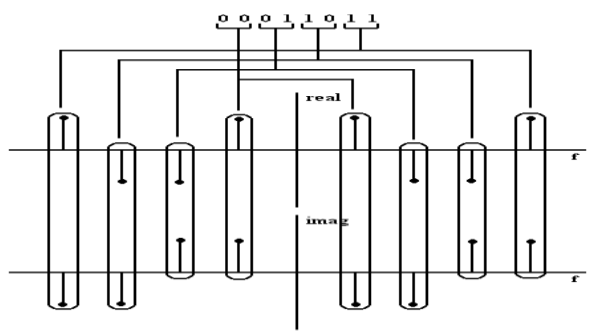

Fig. 7. Construction of OFDM waveform in frequency domain

An advantage of the OFDM scheme is that it naturally combats inter-symbol interference while still allowing a high data rate. In order to fully understand this, we will first take a look at a traditional wireless transmission as seen in Fig. 8.

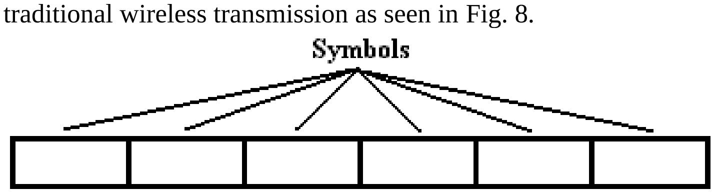

Fig.8. Traditional symbol transmission

In a traditional transmission, if the system was to have a high data rate the symbol length would have to be short thus making the rate high as seen in the Fig. 8. The problem with this technique is that in wireless transmission, inter symbol interference presents a huge problem when short symbols are used. As seen in Fig. 9. Even small ISI consumes much of the actual symbol. In this example, ISI consumes roughly one third

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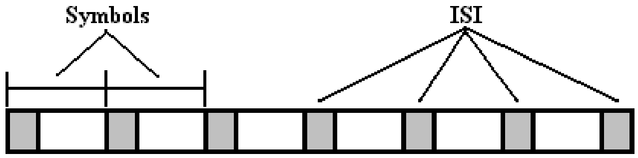
of each symbol. Therefore, a large portion of the actual information is corrupted.



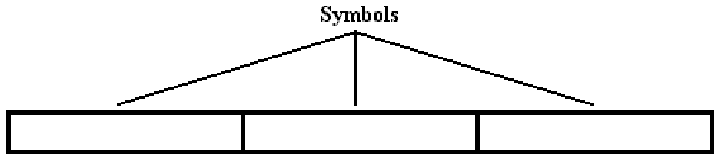


Fig.9. Traditional symbol transmission with ISI

Fig. 10. OFDM symbol transmission

In an OFDM transmission, the symbols do not need to be short to produce a high data rate. This is illustrated in Fig 5.19. Recall that in an OFDM transmission, the information is represented in the frequencies of the symbol and not the symbol itself. Therefore, the symbol may be very lengthy but can still can a large amount of information in its component frequencies.

V. CONCLUSION

The purpose of this work was to give some insight into the power of the OFDM transmission scheme. It has discussed not only the transmission scheme itself, but also some of the problems that are presented in mobile communications as well as the techniques to correct them. Digital Communications is a rapidly growing industry and Orthogonal Frequency Division Multiplexing is on the forefront of this technology. OFDM will prove to revolutionize mobile communications by allowing it to be more reliable and robust while maintaining the high data rate that digital communications demands.

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