# OFDM Wireless Communications

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*Abstract* - **Orthogonal frequency division multiplexing (OFDM) is a popular method for high data rate wireless transmission. OFDM may be combined with antenna arrays at the transmitter and receiver to increase the diversity gain and/or to enhance the system capacity on time-variant and frequency-selective channels, resulting in a multiple-input multiple-output (MIMO) configuration. This paper explores various physical layer research challenges in MIMO-OFDM system design, including physical channel measurements and modeling, analog beam forming techniques using adaptive antenna arrays, space–time techniques for MIMO-OFDM, error control coding techniques, OFDM preamble and packet design, and signal processing algorithms used for per-forming time and frequency synchronization, channel estimation, and channel tracking in MIMO-OFDM systems. Finally, the paper considers a software radio implementation of MIMO-OFDM.**

***Keywords— Adaptive antennas, broadband wireless, multiple-input multiple-output (MIMO, orthogonal frequency division multiplexing (OFDM, software radio, space–time coding, synchronization.***

## I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has become a popular technique for transmission of signals over wireless channels. OFDM has been adopted in several wireless standards such as digital audio broadcasting (DAB), digital video broadcasting (DVB-T), the IEEE 802.11a local area network (LAN) standard and the IEEE 802.16a metropolitan area network (MAN) standard. OFDM is also being pursued for dedicated short-range communications (DSRC) for road side to vehicle communications and as a potential candidate for fourth-generation (4G) mobile wireless systems.

OFDM converts a frequency-selective channel into a parallel collection of frequency flat sub-channels. The sub-carriers have the minimum frequency separation required to maintain orthogonality of their corresponding time domain waveforms, yet the signal spectra corresponding to the different subcarriers overlap in frequency. Hence, the available bandwidth is used very efficiently. If knowledge of the channel is available at the transmitter, then the OFDM transmitter can adapt its signaling strategy to match the channel. Due to the fact that OFDM uses a large collection of narrowly spaced sub channels, these adaptive strategies can approach the ideal water pouring capacity of a frequency-selective channel. In practice this is achieved by using adaptive bit loading techniques, where different sized signal constellations are transmitted on the subcarriers.

OFDM is a block modulation scheme where a block of information symbols is transmitted in parallel on sub-carriers. The time duration of an OFDM symbol is times larger than that of a single-carrier system. An OFDM modulator can be implemented as an inverse discrete Fourier trans-form (IDFT) on a block of information symbols followed by an analog-to-digital converter (ADC). To mitigate the effects of inter symbol interference (ISI) caused by channel time spread, each block of IDFT coefficients is typically preceded by a cyclic prefix (CP) or a guard interval consisting of samples, such that the length of the CP is at least equal to the channel length. Under this condition, a linear convolution of the transmitted sequence and the channel is converted to a circular convolution. As a result, the effects of the ISI are easily and completely eliminated. Moreover, the approach enables the receiver to use fast signal processing transforms such as a fast Fourier transform (FFT) for OFDM implementation. Similar techniques can be employed in single-carrier systems as well, by preceding each transmitted data block of length by a CP of length , while using frequency-domain equalization at the receiver.

Multiple antennas can be used at the transmitter and receiver, an arrangement called a multiple-input multiple-output (MIMO) system. A MIMO system takes advantage of the spatial diversity that is obtained by spatially separated antennas in a dense multipath scattering environment. MIMO systems may be implemented in a number of different ways to obtain either a diversity gain to combat signal fading or to obtain a capacity gain. Generally, there are three categories of MIMO techniques. The first aim to improve the power efficiency by maximizing spatial diversity. Such techniques include delay diversity, space–time block codes (STBC) and space–time trellis codes (STTC).The second class uses a layered approach to increase capacity. One popular example of such a system is V-BLAST suggested by Foschini where full spatial diversity is usually not achieved. Finally, the third type exploits the knowledge of channel at the transmitter. It decomposes the channel coefficient matrix using singular value decomposition (SVD) and uses these decomposed unitary matrices as pre- and post-filters at the transmitter and the receiver to achieve near capacity.

OFDM has been adopted in the IEEE802.11a LAN and IEEE802.16a LAN/MAN standards. OFDM is also being considered in IEEE802.20a, a standard in the making for maintaining high-bandwidth connections to users moving at speeds up to 60 mph. The IEEE802.11a LAN standard

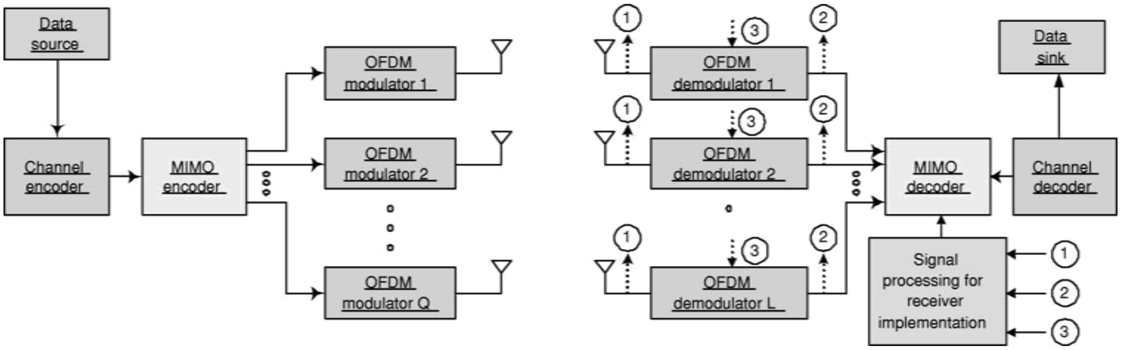

Fig: Q 2 L MIMO-OFDM system, where Q and L are the numbers of inputs and outputs, respectively.

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OFDM has been adopted in the IEEE802.11a LAN and IEEE802.16a LAN/MAN standards. OFDM is also being considered in IEEE802.20a, a standard in the making for maintaining high-bandwidth connections to users moving at speeds up to 60 mph. The IEEE802.11a LAN standard operates at raw data rates up to 54 Mb/s (channel conditions permitting) with a 20-MHz channel spacing, thus yielding a bandwidth efficiency of 2.7 b/s/Hz. The actual throughput is highly dependent on the medium access control (MAC) protocol. Likewise, IEEE802.16a operates in many modes depending on channel conditions with a data rate ranging from 4.20 to 22.91 Mb/s in a typical bandwidth of 6 MHz, translating into a bandwidth efficiency of 0.7 to 3.82 bits/s/Hz. Recent developments in MIMO techniques promise a significant boost in performance for OFDM systems. Broadband MIMO-OFDM systems with bandwidth efficiencies on the order of 10 b/s/Hz are feasible for LAN/MAN environments. The physical (PHY) layer techniques described in this paper are intended to approach 10 b/s/Hz bandwidth efficiency.

This paper discusses several PHY layer aspects broadband MIMO-OFDM systems. All MIMO-OFDM receivers must perform time synchronization; frequency offset estimation, and correction and parameter estimation. This is generally carried out using a preamble consisting of one or more training sequences. Once the acquisition phase is over, receiver goes into the tracking mode. Adaptive analog beam forming approaches can be used to provide the best possible MIMO link.

## II. MIMO-OFDM SYSTEM MODEL

A multicarrier system can be efficiently implemented in discrete time using an inverse FFT (IFFT) to act as a modulator and an FFT to act as a demodulator. The transmitted data are the "frequency" domain coefficients and the samples at the output of the IFFT stage are "time" domain samples of the transmitted waveform. Fig. 1 shows a typical MIMO-OFDM

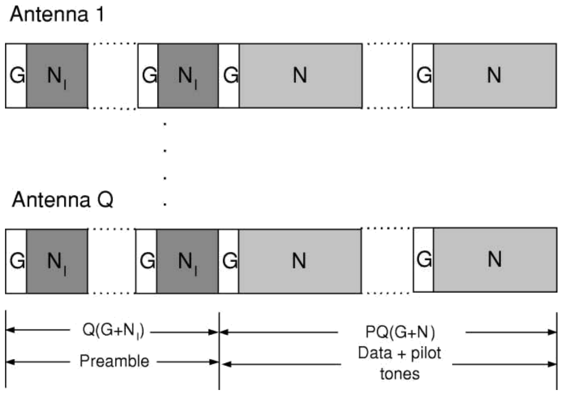
Implementation.

Let $\mathbf{X} = \{X_0 X_1 \ldots X_{N-1}\}$ denote the length-$N$ data symbol block. The IDFT of the data block yield time domain time domain sequence x={x(0),x(1),x(2),……x(N-1) i.e.

$$X_n = \mathrm{IFFT}_N\{X_K\}(n) \qquad (1)$$

To mitigate the effects of channel delay spread, a guard interval comprised of either a CP or suffix is appended to the sequence $\mathbf{X}$. In case of a CP, the transmitted sequence with guard interval is

$$x_n^{9} = x_{(n)N,} \quad ,n=-G,\ldots\ldots-1,0,1,\ldots..N-1 \qquad (2)$$



where $G$ is the guard interval length in samples, and $(n)_N$ is the residue of $n$ modulo $N$. The OFDM complex envelope is obtained by passing the sequence $\mathbf{x}^g$ through a pair of ADCs (to generate the real and imaginary components) with sample rate $1/T$ s, and the analog $I$ and $Q$ signals are up converted to an RF carrier frequency. To avoid ISI, the CP length $G$ must equal or exceed the length of the discrete-time channel impulse response $M$. The time required to transmit one OFDM symbol $T_s = NT + GT$ is called the OFDM symbol time. The OFDM signal is transmitted over the pass-band RF channel, received, and down converted to base band. Due to the CP, the discrete linear convolution of the trans-mitted sequence with the channel impulse response becomes a circular convolution. Hence, at the receiver the initial $G$ samples from each received block are removed, followed by an $N$-point discrete Fourier transform (DFT) on the resulting sequence.

First consider the preamble portion of the OFDM frame. The length-$N_I + G$ preamble sequences are obtained by exciting every $I$th coefficient of a length-$N$ frequency-do-main vector with a nonzero training symbol from a chosen alphabet (the remainder are set to zero). The frequency-do-main training sequences transmitted from the $i$th antenna are $\{S(q)\}_N$, where $q = (c-1)Q + i$ and $c = 1\,2 \ldots Q$ The individual length-$N_I$ time domain training sequences are obtained by taking an $N$-point IDFT of the sequence $\{S_k^{q}\}^{N}_{k-1}$, keeping the first $N_t$ time-domain coefficients and discarding the rest. A CP is appended to each length $N_t$ time-domain sequence. Let $H_{i,j}$ be the vector of sub channel coefficients between the $i$th transmit and the $j$th receive antenna and let $\{R()\}_{N_I - 1}$ be the received sample sequence at the $l$th receiver antenna. After removing the guard interval, the received samples $\{R()\}_{N_I - 1}$ are repeated $I$ times and demodulated using an $N$-point FFT as

$$R_k^{(l)} = \mathrm{FFT}_n\{r^{(l)}\}\,(k) \qquad (3)$$

$$= \sum H_k^{(q,l)} S_k^{(q)} + W_k^{(l)} \qquad (4)$$

where $k = 0 \ldots N-1$. The demodulated OFDM sample matrix $\mathbf{R}_k$ of dimension ($Q \times L$) for the $k$th subcarrier can be expressed in terms of the transmitted sample matrix $\mathbf{S}_k$ of dimension ($Q \times Q$), the channel coefficient matrix $\mathbf{H}_k$ of dimension ($Q \times L$) and the additive white Gaussian noise matrix $\mathbf{W}_k$ of dimension ($Q \times L$) as

$$R_{k,QxL} = S_{k,QxQ\,,}H_{k,QxL} + W_{k,QxL} \qquad (5)$$

where $\mathbf{R}, \mathbf{H}$, and $\mathbf{W}$ can viewed as either a collection of $N$ matrices of dimension $Q \times L$ or as a collection of $Q \times L$ vectors of length $N$.

## III. SPACE–TIME CODING TECHNIQUES FOR MIMO-OFDM

OFDM is an effective and low-complexity strategy for dealing with frequency-selective channels. Roughly speaking, an OFDM transmitter divides the frequency band into $N$ narrow sub channels and sends a different sequence of symbols across each sub channel. When the sub channel bandwidth is sufficiently narrow, the frequency response across each sub channel is approximately flat, avoiding the need for complicated time-domain equalization. In this way, OFDM transforms a frequency-selective channel into a collection of $N$ separate flat-fading channels. In the same way, when an OFDM transmitter is used by each of $Q$ transmit antennas, and an OFDM front-end is used by each of $L$ receive antennas, a MIMO frequency-selective channel is transformed into a collection of $N$ flat-fading MIMO channels, one for each tone, with each having dimension $L \times Q$.

Traditional space–time codes were designed to extract spatial diversity from a flat-fading MIMO channel, and are not generally effective at extracting the additional *frequency* (or multipath) diversity of a frequency-selective fading channel. Quantitatively, the maximum achievable diversity order is the product of the number of transmits antennas, the number of receiver antennas, and the number of resolvable propagation paths (i.e., the channel impulse response length),To achieve this full diversity requires that the information symbols be carefully spread over the tones as well as over the transmitting antennas. A *space-frequency* code—or more generally, a space–time-frequency code—is a strategy for mapping information symbols to antennas and tones as a means for extracting both spatial and frequency diversity.

Space-frequency codes based directly on space–time codes (with time reinterpreted as frequency) have been proposed, but they fail to exploit the frequency diversity of a frequency-selective fading MIMO channel. A simple method for transforming any full-diversity space–time code into a full-diversity space-frequency code has recently been proposed, at the expense of a reduced rate.

In the remainder of this section we highlight two approaches to space–time processing for MIMO-OFDM. The first is a combination of delay-diversity and OFDM known as multicarrier delay-diversity modulation, while the second is a closed-loop system with channel knowledge at the transmitter.

## IV. Error Correction Coding for MIMO-OFDM

There are many possible error control strategies in MIMO-OFDM systems. In this section we highlight some of the methods that have been proposed. At this writing this is a very active and rapidly evolving research area. As in any system there are important performance-complexity tradeoffs; however, we do not address those here. Further-more, depending on the application, the desired BER may result in the need for only minimal or no error correction; namely, the modulation code might be sufficient to provide the needed BER, for example, $10_{-3}$. However, if either near capacity performance or a very low BER is required (e.g., $10_{-6}$ to $10_{-12}$), a powerful error control code is needed. From this perspective much of the recent work has focused on the use of iteratively decodable codes such as turbo codes and low-density parity check (LDPC) codes. As turbo codes are special cases of LDPCs, we focus on those. Also, we start our description with single-input single-output (SISO) channels as many practical error control strategies for MIMO systems will be designed for SISO channels and then mapped to MIMO channels

## V. Antenna and Beam Selection

The cost of the MIMO-OFDM system is largely driven by the number of transmit and receive chains, for example, each receiver chain includes frequency conversion, IF filtering, and analog-to-digital conversion. The circuits performing these functions must be replicated $L$ times if a MIMO receiver has $L$ receive branches. However, it is possible to have the spatial diversity and interference suppression benefits of many more antennas than full receiver chains through the use of antenna or beam selection. In this section, we consider antenna and beam selection, give a summary of a low-complexity selection algorithm for OFDM, and show some results for measured channels that compare antenna to beam selection.

### *A. Antenna Selection*

Transmit antenna selection for MIMO has been previously considered for flat-fading MIMO links in the absence of interference and with interference .In the no-interference works, the selection criterion was based on average SNR criteria. Three-select-two antenna selection appeared to give a second-order diversity gain for zero-forcing spatial multiplexing receivers, and produced vector symbol error rates that matched that of the 2 by 2 maximum likelihood receiver without selection. For space–time block coding, selection of two transmit antennas from five to ten antennas, assuming two receive antennas, provided an SNR gain of 2 to 3 dB. For the flat-fading channel with interference, Blum and Winters show about a 7-dB improvement for 8-select-2 diversity at both ends of the link, assuming one or two interference data streams and simulated i.i.d. MIMO channels.

The MIMO selection diversity gain comes with a price: the switch that performs the antenna selection requires a non-trivial design and has a non-negligible insertion loss. For example the 8-select-2 switch has an insertion loss of 3.15 dB. In a transmitter, the insertion loss reduces the radiated power. In a receiver, the insertion loss degrades the SNR. The degradation can be made negligible by placing low-noise amplifiers between the antenna elements and the switch. However, this addition can add significant expense to the receiver. On the other hand, the degradation in SNR may not be important if the receiver performance is limited by interference.

The gain from antenna selection for OFDM-MIMO may not be as large as it is for the flat-fading channel because the best selection of elements is likely to change with frequency. While subcarrier-dependent antenna selection is not considered here, since our goal is for the solution to have a certain limited number of transmit and receive chains.

### *B. Beam Selection*

An alternative selection approach for OFDM-MIMO is to select beams instead of selecting antennas. Fig. 15 shows antenna selection (top) and beam selection (bottom) architectures, both incorporating 4-select-2 switches. Beam se-lection is motivated by the observation that multipath angles are often clustered. The cluster angles are not expected to be very frequency dependent, so the best selection of beams should not change much with frequency.

interference. Moreover, analog beam forming circuits, such as the Butler matrix are inexpensive compared to the switch at microwave frequencies because they can be implemented in stripline. Therefore, the percentage increase in cost to have beam selection should be small. Like the switch, the beam former has an insertion loss (2.26 dB for the eight-beam Butler matrix in so its effects must be more than overcome to justify its use. Two-beam selection for array receivers over simulated clustered indoor

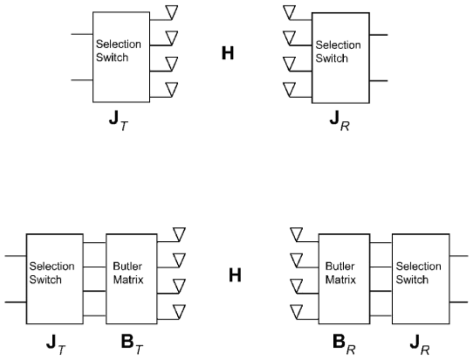


Fig: Antenna selection and beam selection architectures.

channels have indicated that four eight-element linear arrays, placed end to end in a square configuration to provide 360° azimuth coverage, yield an almost 6-dB SNR improvement compared to two fixed omnidirectional antennas when the two beams are processed by a joint decision-feedback equalizer. When the same beam-selection configuration is simulated for space–time block-coded OFDM, an SNR improvement of approximately 5 dB is obtained without interference, and an SIR improvement of more than 16 dB is obtained with interference.

## VI. MEDIUM ACCESS CONTROL

Although not the focus of this paper, MAC protocols are essential for effective broadband wireless access. MAC protocols for OFDM can be based on time division multiple access (TDMA), where all the OFDM subcarriers are used at once. Such protocols are used in IEEE802.11a and IEEE802.16a, for example. An alternative is to used OFDMA or clustered OFDM, where each connection uses a subset of the OFDM subcarriers. Such an approach is used in some operating modes of IEEE802.16a. MAC protocols generally must support hundreds of end-user terminals that demand a mixture of services ranging from traditional voice and data, internet protocol (IP) connectivity, multimedia and real time applications such as voice-over IP (VoIP). The sup-port of these services requires a MAC protocol that handles both continuous and bursty traffic with quality-of-service (QoS) guarantees that depend on the application. The issues of transport efficiency are addressed at the interface between the MAC and PHY layers, and the actual throughput that is achieved is highly dependent on the choice of MAC protocol. For example, the MAC adjusts PHY layer parameters such as the type of modulation and coding employed to meet QoS and link availability requirements. Addition information on typical MAC related issues are available in a variety of sources including the IEEE802.16a standard.

## X. SOFTWARE RADIO IMPLEMENTATION

The proliferation of high-performance DSP cores, FPGAs, and application-specific integrated circuits (ASICs)—as well as the current trend toward system-on-a-chip (SoC) integration—are bringing the software radio paradigm closer to practical realization. While advances in these key technology areas—and other areas such as wideband A/Ds, low-power circuit technology, and wideband amplifiers—are critical in the evolution of software radio, technology today allows one to begin to discover and appreciate the great promise that software radio holds. Current trends in the wireless telecommunications industry are steering toward advanced applications requiring wider bandwidth, which will place increasing processing loads upon future SDR implementation architectures.

Faculty at Georgia Tech are collaborating to develop a high bandwidth, high data rate wireless gateway using advanced technologies including software radio, smart antennas, MIMO-OFDM, advanced FECs, and higher layers that support quality of service. A key component in the research is the implementation of the techniques in a programmable testbed at the GT Software Radio Laboratory. In this paper, we focus on a description of the physical layer and on the implementation of MIMO-OFDM in the testbed.

In the first part of this section, we describe the design and performance of the software-radio testbed, which was developed using commercial components to implement programmable transceivers for wireless communications. The system provides a useful vantage point for empirical exploration of issues related to software radio implementation. We describe the major hardware components, the algorithm flow through the system, and the implementation performance for MIMO-OFDM.

## VII. CONCLUSION

This paper has discussed a number of PHY layer issues relevant for the implementation of broadband MIMO-OFDM systems. We have discussed in detail the peculiar issues relating to MIMO-OFDM synchronization and channel estimation. We then discussed space–time coding strategies for closed loop MIMO-OFDM systems where knowledge of the channel is available at the transmitter. Error correction coding was discussed with an emphasis on high-rate LDPC codes. Adaptive analog beam forming techniques were discussed that can provide the best possible MIMO channel environment. Finally, the paper discussed a software radio test bed at Georgia Tech for MIMO-OFDM.

## ACKNOWLEDGMENT

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