OFDM for High Data Rate, High-Mobility, Wide-Area Wireless Communications

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ABSTRACT

In recent years, there has been considerable growth in interest in wireless access to wide area data networks at high data rates. This growth has been fuelled by the simultaneous development of the high-speed wired data networks (e.g., the Internet), wide-spread availability of powerful mobile computing devices, rapidly dropping prices for increasingly sophisticated electronic devices, plus the global deployment of wireless voice systems. High-mobility wireless data access at near-LAN rates is likely to be an attractive option. The harsh cellular radio environment creates significant challenges when trying to provide access at high data rates, especially if high-mobility and wide-area availability are expected - even more so when considering the constraints placed on the system design by terminal size and power constraints. This paper describes research into Orthogonal Frequency Division Multiplexing (OFDM) techniques addressing high data rate access in representative mobile cellular-like environments.

1. INTRODUCTION

A few years ago, high-speed access to the few specialized wired data networks that existed was exclusively available to large organizations. Today, small businesses and end users routinely access the Internet at 1 Mb/s and faster through DSL and cable modem networks. The computing power of today's palm-size PDA or a notebook-size computer recently required a room full of hardware. Mobile voice communications taken for granted in today's cellular telephones was, until recently, too bulky and expensive for all but a small handful of users. All of these trends will continue and have fuelled the interest in access to wide area data networks at high data rates with the convenience of high-mobility wireless access.

While high-mobility, fast wireless network access is very attractive, designers must address the harshness of the radio environment. Available spectrum is limited. Multipath dispersion, fading, power restrictions, and system complexity create further challenges, especially for small, battery operated, portable terminals.

This paper and related research[1][2][3] focus on the downlink - the path *from* the network *to* the end user. First, there are systems-level reasons for this. Client-server communications dominates computing applications today. The bulk of the traffic flows from the server to the client, with a few user keystrokes or mouse clicks generating large amounts of multimedia server traffic. Even for users creating substantial uplink traffic, there are generally more traffic *consumers* than *generators*. In aggregate, downlink flows dominate.

Terminal implementation issues provide a second reason to study the downlink. Generally, the portable or handheld devices envisioned (e.g., PDAs, notebook PCs or handsets), will be battery powered. Increasing uplink data rates by orders of magnitude requires increases in portable transmit power to meet the link budget, a major challenge with foreseeable battery technology. However, readily applicable downlink techniques can attain the high peak data rates desired.

The remainder of this paper is organized as follows: First, a general overview of OFDM is presented. We then describe the parameters of representative OFDM systems. An OFDM system appropriate for high data rate, high-mobility applications is described. We conclude by describing future directions for this work.

2. OFDM BACKGROUND

Four major impairments to the operation of wireless communications networks are: delay spread, noise, interference, and channel variation. Noise and interference are managed by appropriate budgetting of link margin and frequency reuse, but delay spread is inherent to the outdoor multipath environment. Channel variation is likewise inherent to outdoor mobile operation, with the speed of variation directly related to vehicle velocity and operating frequency.

Two system parameters dictate achievable data rates: symbol rate and transmit constellation complexity. Unfortunately, both are constrained by the wireless channel. A complex constellation with a large number of potential transmitted signals makes the signal more susceptible to channel noise and interference. Efficiently implementing a complex constellation requires amplitude variation, increasing susceptability to path loss and rapid fading.

The channel similarly limits symbol rate. Scarce RF spectrum restricts the emitted bandwidth. The dispersive multipath channel also limits the signalling rate. With the multipath delay in a typical urban environment, delayed copies of a transmit pulse arrive microseconds after the original signal. Severe intersymbol interference (ISI) occurs when the transmit symbol interval is not substantially longer than the delay spread. ISI is countered by channel equalization, but rapid variation of the mobile channel complicates this. High symbol rates require long equalizers with high-speed signal processing, even for known channels.

In contrast to single carrier systems, OFDM counters the high-mobility outdoors channel by transmitting a simple constellation at low symbol rates. In this way, the OFDM signal is inherently resistant to noise, interference, and delay spread.

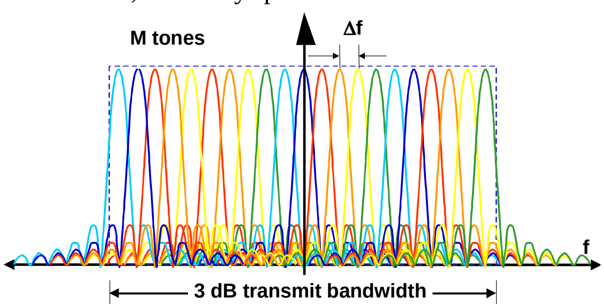

Figure 1 - OFDM spectrum

Low symbol rates and simple constellations would appear to restrict attainable data rates for OFDM. By transmitting a large number of separate carriers, each conveying a low data rate stream, OFDM can attain high data rates. By properly choosing the symbol duration and carrier spacing, efficient modulation and demodulation of the signal is possible. In particular, using the Fast Fourier Transform (FFT), efficient transmitter and receiver structures are easily attained. Figure 1 illustrates a representative spectrum for an OFDM signal. The carrier spacing, Δf, is small compared to the frequency selective fading effects so it appears that each carrier experiences "flat fading."

Figure 2 illustrates a block diagram for a typical OFDM transmitter. User data is coded, interleaved, and combined with appropriate control and signalling signals. The resulting bit stream modulates a series of carriers. Here, modulation simply maps groups of bits to a series of constellation points, represented as complex numbers input to the Inverse FFT. The IFFT transforms the modulated carriers into a sequence of time domain samples. The IFFT size is generally a power of two for efficiency. Since the number of modulated carriers must be smaller than the size of the FFT to make the analog reconstruction filters realizable, the "higher frequency" carriers are set to zero.

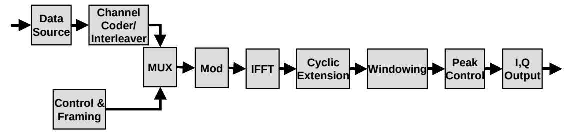

Figure 2 - OFDM transmitter

If the time samples were transmitted at this point, the OFDM signal would not be resistant to delay dispersion and ISI. Delayed versions of previous symbols would mix with the current symbol to degrade the demodulated carriers. The OFDM transmitter adds a "cyclic extension" to the transmitted samples to counter this. Successive samples are copied from the beginning (and/or end) of the transformed samples to the end (and/or beginning) of the block. Any set of N (N is the FFT size) successive samples drawn from the block can be transformed back to the original modulated carriers with only a phase shift, due to the time shifting property of the FFT. Generally, the overall length of the cyclic extension is chosen to exceed the maximum expected delay spread on the channel.

Additional time domain processing performed by the OFDM transmitter includes windowing and peak control. Windowing is necessary to constrain the transmitted signal to the minimum necessary bandwidth needed for the set of transmitted carriers. By controlling the rise and fall times of the transmitted signal, little more than the bandwidth needed for the collection of transmitted carriers is needed.

The OFDM waveform is equivalent to the summation of a large number of sinusoids of arbitrary amplitude and phase. As such, it may theoretically attain high peak levels, relative to the RMS value. While very high peak levels are rarely attained, peak control is needed to minimize linear power requirements of the transmit amplifiers. Peak clipping, followed by waveform filtering often suffices to minimize the worst case peak-to-average.

The OFDM receiver shown in Figure 3 follows the structure of the OFDM transmitter directly. IQ baseband analog signals or digital IF signals are input to the receiver. A complex baseband rotator removes carrier offset caused by transmit and receiver local oscillators differences. After selecting an appropriate sequence of N samples, the time domain waveform is converted to the frequency domain by the FFT. With the correct timing instant, the individual carriers are demodulated and the bit stream deinterleaved and decoded. This OFDM receiver structure performs quite efficiently when compared to equalized single carrier systems and other techniques[4].

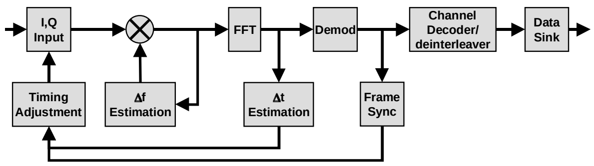

Figure 3 - OFDM Receiver

Coding across the OFDM carriers creates a signal that is very robust against the frequency selective fading that might impair or prevent reception of any single carrier. In fact, within the limits of the cyclic extension, coding in frequency complements delay dispersion to create frequency diversity, improving the performance of an OFDM system[5]. By time interleaving across several blocks, short bursts of noise, interference, or rapid fading are also mitigated.

3. EXAMPLE OFDM SYSTEMS

Two existing standards serve as excellent examples of practical OFDM systems addressing somewhat different environments. IEEE 802.11a[6] defines a protocol for indoor high-speed wireless LANs. The European terrestrial digital video broadcast (DVB-T) standard[7] defines an OFDM link for the wide-area environment and addresses high-mobility applications.

User data rate:	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Modulation:	BPSK, QPSK, 16QAM, 64QAM
Coding rate:	1/2, 2/3, 3/4
Data subcarriers:	48
Pilot subcarriers:	4
FFT size:	64
Symbol duration:	4 µs
Guard interval:	800 ns
Subcarrier spacing:	312.5 kHz
3 dB bandwidth:	16.56 MHz
Channel Spacing:	20 MHz
Carrier frequency:	~5 GHz

Figure 4 - 802.11a Wireless LAN parameters

Figure 4 lists some important parameters of 802.11a. First, by using 48 data-bearing subcarriers, very high data rates are achieved. Since 802.11a is intended for indoors or, at most, local campus-like operation, the guard time (mostly of cyclic extension), is only 800 ns. If the RMS delay spread is roughly half the guard interval, 802.11a should resist about 400 ns delay spread. This equates to a 400 foot path length difference, representative of an indoor environment. Outdoor reflections from buildings, vehicles, terrain, etc., would create much greater path length differences.

Varying distances between 802.11a stations create significant channel quality differences. 802.11a supports link adaptation to attain maximum throughput. A 10:1 range in link throughput is possible with rate-1/2 coding and BPSK on the worst channel or rate-3/4 coding and 64QAM on the best.

Size, power and cost constraints of a PCMCIA card implementation mean that small, low-cost oscillators must determine the 802.11a modem's carrier frequency. Carrier frequency accuracy becomes an important design issue, especially at 5 GHz where 802.11a wireless LANs operate. Fortunately, a 312.5 kHz carrier spacing relaxes oscillator precision to 20 ppm.

User data rate:	4.98 - 31.67 Mbps
Modulation:	QPSK, “16QAM”, “64QAM”
Coding rate:	(1/2, 2/3, 3/4, 5/6, 7/8) + RS(204,188)
Data subcarriers:	1512
Pilot subcarriers:	193
FFT size:	2048
Symbol duration:	231 - 280 µs
Guard interval:	7 - 56 µs
Subcarrier spacing:	4.464 kHz
3 dB bandwidth:	7.61 MHz
Channel Spacing:	8 MHz
Carrier frequency:	~500 MHz

Figure 5 - A subset of DVB-T parameters

Figure 5 shows the corresponding parameters for the "2k mode" of the DVB-T system. Because of the outdoor of operation of DVB-T, much larger expected delay spread requires much longer guard times. Macrodiversity in Single Frequency Networks (multiple transmitters sending the same information on the same frequency) fills in coverage areas, but creates large artificial delay spread. Thus, DVB-T must support up to 56 µsec guard times. Longer guard times require longer blocks to maintain reasonable link efficiencies. Since the active interval of the block is the inverse of the carrier spacing, this translates directly into the smaller 4.464 kHz carrier spacing. With a longer symbol duration, DVB-T needs many more carriers to attain data rates comparable to 802.11a.

While 802.11a is intended for bursty packet communications, DVB-T uses a continuous downlink, so multi-block coding and interleaving can improve system error rates. With more carriers and longer frames, a complex matrix of pilot carriers is used to allow accurate channel estimation.

4. OFDM PARAMETERS FOR 4G

The design of an OFDM system assumes essentially no frequency selective fading within a carrier, so equalization is not needed. In an outdoor environment, where several microseconds of delay spread are likely, this assumption would obviously be violated in

802.11a, with the 312.5 kHz carrier spacing. Secondly, it is assumed that the channel is relatively stable within a symbol. For high vehicle velocities, several hundred microsecond long symbols violate this assumption - doppler rates approach several hundred hertz. Our research shows that there is a "sweet spot" for carrier spacing of several kilohertz; we have focussed on this range for wide-area high-mobility applications.

User data rate:	2.56 - 8.96 Mbps
Modulation:	QPSK, 16QAM
Coding rate:	1/2 - 7/8
Data subcarriers:	512 (average) (128, 256, 384 optional)
Pilot subcarriers:	128 (average) (32, 64, 96 optional)
FFT size:	1024
Symbol duration:	200 µs
Guard interval:	40 µs
Subcarrier spacing:	6.25 kHz
3 dB bandwidth:	4 MHz (1, 2, 3 MHz optional)
Channel Spacing:	5 MHz (1.25 MHz optional)
Carrier frequency:	~2 GHz

Figure 6 - OFDM parameters for 4G

Available spectrum is always a concern for wireless system deployment. OFDM, as other techniques, benefits from frequency diversity inherent in wideband operation yet, often only 5 MHz or less is available. Here, the multicarrier nature of OFDM lends itself well to flexible bandwidth assignment - experiments[8] have shown good performance in less than 1 MHz. This, plus the portable power burden of wider band operation drive the assumed 5 MHz channelization. Figure 6 lists a set of representative parameters for an OFDM system we have defined for 4th generation wireless networks. Research convinces us that 2.5 to 5 Mbps is readily attainable, with peak rates of almost 10 Mbps for a sizable fraction of high-mobility users.

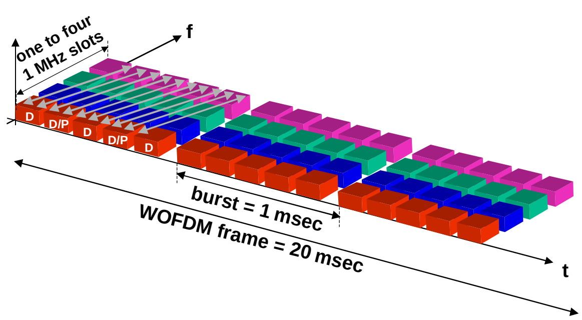

Figure 7 - OFDM frame

As described earlier, time interleaving and frequency coding work together to maximize link reliability. Figure 7 illustrates the time and frequency relationship of an OFDM frame. One to four 1 MHz bands are used for OFDM carriers, organized as several OFDM symbols in a 1 millisecond burst, containing data and pilot carriers, coded in time and frequency. With a packet mode downlink, time slots can be assigned to multiple base stations as traffic dictates. This TDMA mode balances the typical user's need for low average data rates against the value of a high peak data rate. It also offers the opportunity for power savings at the mobile, only requiring receiver processing for control messages and traffic for the specific terminal.

5. CONCLUSION

This paper has described considerations for an OFDM modem intended for asymmetric high data rate wireless network access in wide-area, high-mobility applications. Simulations and real-time prototypes have demonstrated the viability of this approach. Other research[9] has shown the potential to extend these results to much higher data rates with multiple-input multiple-output (MIMO) smart antenna techniques. Peak data rates of up to 40 Mbps in the wide-area, high-mobility environment appear quite feasible with four base antennas and four mobile antennas.

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