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Scalable OFDMA Physical Layer in IEEE 802.16 WirelessMAN

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Hassan Yaghoobi, Intel Communications Group, Intel Corporation

Index words: OFDMA, Scalable, IEEE 802.16, WirelessMAN, subchannel, subcarrier

ABSTRACT

The concept of scalability was introduced to the IEEE 802.16 WirelessMAN Orthogonal Frequency Division Multiplexing Access (OFDMA) mode by the 802.16 Task Group e (TGe). A scalable physical layer enables standard-based solutions to deliver optimum performance in channel bandwidths ranging from 1.25 MHz to 20 MHz with fixed subcarrier spacing for both fixed and portable/mobile usage models, while keeping the product cost low. The architecture is based on a scalable subchannelization structure with variable Fast Fourier Transform (FFT) sizes according to the channel bandwidth. In addition to variable FFT sizes, the specification supports other features such as Advanced Modulation and Coding (AMC) subchannels, Hybrid Automatic Repeat Request (H-ARQ), high-efficiency uplink subchannel structures, Multiple-Input-Multiple-Output (MIMO) diversity, and coverage enhancing safety channels, as well as other OFDMA default features such as different subcarrier allocations and diversity schemes. The purpose of this paper is to provide a brief tutorial on the IEEE 802.16 WirelessMAN OFDMA with an emphasis on scalable OFDMA.

INTRODUCTION

The IEEE 802.16 WirelessMAN standard [1] provides specifications for an air interface for fixed, portable, and mobile broadband wireless access systems. The standard includes requirements for high data rate Line of Sight (LOS) operation in the 10-66 GHz range for fixed wireless networks as well as requirements for Non Line of Sight (NLOS) fixed, portable, and mobile systems operating in sub 11 GHz licensed and licensed-exempt bands.

Because of its superior performance in multipath fading wireless channels, Orthogonal Frequency Division Multiplexing (OFDM) signaling is recommended in OFDM and WirelessMAN OFDMA Physical (PHY) layer modes of the 802.16 standard for operation in sub 11 GHz NLOS applications. OFDM technology has been recommended in other wireless standards such as Digital Video Broadcasting (DVB) [2] and Wireless Local Area Networking (WLAN) [3]-[4], and it has been successfully implemented in the compliant solutions.

Amendments for PHY and Medium Access Control (MAC) layers for mobile operation are being developed (working drafts [5] are being debated at the time of publication of this paper) by TGe of the 802.16 Working Group. The task group's responsibility is to develop enhancement specifications to the standard to support Subscriber Stations (SS) moving at vehicular speeds and thereby specify a system for combined fixed and mobile broadband wireless access. Functions to support optional PHY layer structures, mobile-specific MAC enhancements, higher-layer handoff between Base Stations (BS) or sectors, and security features are among those specified. Operation in mobile mode is limited to licensed bands suitable for mobility between 2 and 6 GHz.

Unlike many other OFDM-based systems such as WLAN, the 802.16 standard supports variable bandwidth sizes between 1.25 and 20 MHz for NLOS operations. This feature, along with the requirement for support of combined fixed and mobile usage models, makes the need for a scalable design of OFDM signaling inevitable. More specifically, neither one of the two OFDM-based modes of the 802.16 standard, WirelessMAN OFDM and OFDMA (without scalability option), can deliver the kind of performance required for operation in vehicular mobility multipath fading environments for all bandwidths in the specified range, without scalability enhancements that guarantee fixed subcarrier spacing for OFDM signals.

The concept of scalable OFDMA is introduced to the IEEE 802.16 WirelessMAN OFDMA mode by the 802.16 TGe and has been the subject of many contributions to the standards committee [6]-[9]. Other features such as AMC subchannels, Hybrid Automatic Repeat Request

(H-ARQ), high-efficiency Uplink (UL) subchannel structures, Multiple-Input-Multiple-Output (MIMO) diversity, enhanced Advanced Antenna Systems (AAS), and coverage enhancing safety channels were introduced [10]-[14] simultaneously to enhance coverage and capacity of mobile systems while providing the tools to trade off mobility with capacity.

The rest of the paper is organized as follows. In the next section we cover multicarrier system requirements, drivers of scalability, and design tradeoffs. We follow that with a discussion in the following six sections of the OFDMA frame structure, subcarrier allocation modes, Downlink (DL) and UL MAP messaging, diversity options, ranging in OFDMA, and channel coding options.

Note that although the IEEE P802.16-REVd was ratified shortly before the submission of this paper, the IEEE P802.16e was still in draft stage at the time of submission, and the contents of this paper therefore are based on proposed contributions to the working group.

MULTICARRIER DESIGN REQUIREMENTS AND TRADEOFFS

A typical early step in the design of an Orthogonal Frequency Division Multiplexing (OFDM)-based system is a study of subcarrier design and the size of the Fast Fourier Transform (FFT) where optimal operational point balancing protection against multipath, Doppler shift, and design cost/complexity is determined. For this, we use Wide-Sense Stationary Uncorrelated Scattering (WSSUS), a widely used method to model time varying fading wireless channels both in time and frequency domains using stochastic processes. Two main elements of the WSSUS model are briefly discussed here: Doppler spread and coherence time of channel; and multipath delay spread and coherence bandwidth.

A maximum speed of 125 km/hr is used here in the analysis for support of mobility. With the exception of high-speed trains, this provides a good coverage of vehicular speed in the US, Europe, and Asia. The maximum Doppler shift [15] corresponding to the operation at 3.5 GHz (selected as a middle point in the 2-6 GHz frequency range) is given by Equation (1).

$$f_m = \frac{v}{\lambda} = \frac{35m/s}{0.086m} = 408Hz \qquad \textbf{Equation (1)}$$

The worst-case Doppler shift value for 125 km/hr (35 m/s) would be ~700 Hz for operation at the 6 GHz upper limit specified by the standard. Using a 10 KHz subcarrier spacing, the Inter Channel Interference (ICI) power corresponding to the Doppler shift calculated in Equation (1) can be shown [16] to be limited to ~-27 dB.

The coherence time of the channel, a measure of time variation in the channel, corresponding to the Doppler shift specified above, is calculated in Equation (2) [15].

$$T_c = \sqrt{\frac{9}{16 \cdot \pi \cdot f_m^2}} = 1.03ms \qquad \textbf{Equation (2)}$$

This means an update rate of ~1 KHz is required for channel estimation and equalization.

The maximum delay spread for fixed broadband wireless is specified by the Stanford University Interim (SUI) channel model [17]. The worst-case rms delay spread corresponding to SUI-6 (Terrain Type A: hilly terrain with moderate-to-heavy tree densities) channel is 5.24 µs. The International Telecommunications Union (ITU-R) Vehicular Channel Model B [18] shows delay spread values of up to 20 µs for mobile environments. The subcarrier spacing design requires a flat fading characteristic for worst-case delay spread values of 20 µs with a guard time overhead of no more than 10% for a target delay spread of 10 µs. The coherence bandwidth of the channel (50% frequency correlation) corresponding to the 20 µs delay spread, given by Equation (3) [15], is shown to be approximately 10 KHz.

$$B_c \approx \frac{1}{5 \cdot \sigma_\tau} = \frac{1}{5 \cdot 20\mu s} = 10KHz \qquad \textbf{Equation (3)}$$

This means that for delay spread values of up to 20 µs, multipath fading can be considered as flat fading over a 10 KHz subcarrier width.

An OFDM system is also sensitive to phase noise and the negative impact of impairment increases for narrower subcarrier spacing, which makes the design more expensive and complex.

The above rationale, based on the coherence time, Doppler shift, and coherence bandwidth of the channel, is the basis for the consideration of a scalable structure where the FFT sizes scale with bandwidth to keep the subcarrier spacing fixed.

Simulation results generated in [6] for a 2.5 MHz channel bandwidth when the FFT size is kept at 2048 shows a considerable amount of degradation in performance plot (Bit Error Rate vs. Signal to Noise Ratio) which is clearly recognizable for 64-QAM and high mobility.

Table 1: OFDMA scalability parameters

Parameters	Values				
System bandwidth (MHz)	1.25	2.5	5	10	20
Sampling frequency (F_s,*MHz*)	1.429	2.857	5.714	11.429	22.857
Sample time (1/F_s,*nsec*)	700	350	175	88	44
FFT size (N_{FFT})	128	256	512	1024	2048
Subcarrier frequency spacing	11.16071429 kHz				
Useful symbol time (T_b=1/ *f*)	89.6 µs				
Guard time (T_g=T_b/8)	11.2 µs				
OFDMA symbol time (T_s=T_b+T_g)	100.8 µs				

Without scalability, performance is reduced or cost is increased for low- and mid-size channel bandwidths.

Table 1 summarizes the main scalability parameters as recommended for adoption in the standard.

Note that in Table 1, the over-sampling factor used is 8/7 (*Fs = floor(8/7 BW/0.008)x0.008*) as globally specified in the standard for all OFDMA operations. The guard time can attain any of the four possible values 1/4, 1/8, 1/16 and 1/32. By setting the value to 1/8 of an OFDM symbol, a maximum of 11.2 µs delay spread can be tolerated with an overhead of around 10%.

WirelessMAN OFDMA supports a wide range of frame sizes (see Table 2) to flexibly address the need for various applications and usage model requirements. With a 2048 FFT size, the number of OFDM symbols in the short frame size, (e.g., 2 ms), will be very small for narrow bandwidths (less than 2 OFDM symbols for 1.25 MHz band) which makes the short frame sizes practically unusable (due to high overhead). Another advantage of scalability is to guarantee a lower bound on the number of OFDM symbols per frame (particularly a problem for small bandwidth and frame sizes).

Table 2: Scalable OFDMA frame sizes

Frame Sizes (msec)	Frame Sizes (OFDM symbols)
2	19
2.5	24
4	39
5	49
8	79
10	99
12.5	124
20	198

In the remainder of this paper, the following items are emphasized as the drivers of scalability and are revisited frequently.

a. Subcarrier spacing is independent of bandwidth.

b. The number of used subcarriers (and FFT size) should scale with bandwidth.

c. The smallest unit of bandwidth allocation, specified based on the concept of subchannels (to be defined later), is fixed and independent of bandwidth and other modes of operation.

d. The number of subchannels scales with FFT size rather than with the capacity of subchannels.

e. Tools are provided to trade mobility for capacity.

Note that fixing the capacity of the subchannel may not be the best choice especially for low-bandwidth systems where typical applications are different in nature.

BASICS OF OFDMA FRAME STRUCTURE

There are three types of OFDMA subcarriers:

1. Data subcarriers for data transmission.
2. Pilot subcarriers for various estimation and synchronization purposes.
3. Null subcarriers for no transmission at all, used for guard bands and DC carriers.

Active subcarriers are divided into subsets of subcarriers called subchannels. The subcarriers forming one subchannel may be, but need not be, adjacent. Bandwidth and MAP allocations are done in subchannels.

The pilot allocation is performed differently in different subcarrier allocation modes. For DL Fully Used Subchannelization (FUSC), the pilot tones are allocated first and then the remaining subcarriers are divided into data subchannels. For DL Partially Used Subchannelization (PUSC) and all UL modes, the set of used subcarriers, that is, data and pilots, is first partitioned into subchannels, and then the pilot subcarriers are allocated from within each subchannel. In FUSC, there is one set of common pilot subcarriers, but in PUSC, each subchannel contains its own set of pilot subcarriers.

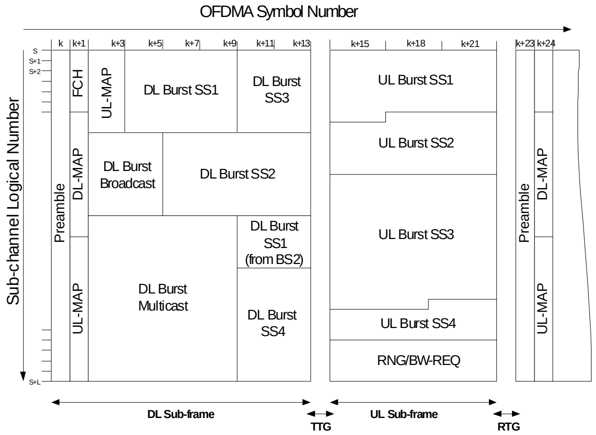

Figure 1: OFDMA frame structure (TDD, PUSC)

In a DL, subchannels may be intended for different (groups of) receivers while in UL, Subscriber Stations (SS) may be assigned one or more subchannels and several transmitters may transmit simultaneously.

The subcarriers forming one subchannel may, but need not be, adjacent. Figure 1 shows the OFDM frame structure for Time Division Duplexing (TDD) mode. Each frame is divided into DL and UL subframes separated by Transmit/Receive and Receive/Transmit Transition (TTG and RTG, respectively) gaps. Each DL subframe starts with a preamble followed by the Frame Control Header (FCH), the DL-MAP, and a UL-MAP, respectively.

The FCH contains the DL Frame Prefix (DLFP) to specify the burst profile and the length of the DL-MAP immediately following the FCH. The DLFP is a data structure transmitted at the beginning of each frame and contains information regarding the current frame; it is mapped to the FCH.

According to the OFDMA specifications, a DL-MAP message, if transmitted in the current frame, shall be the first MAC PDU in the burst following the FCH. An UL-MAP message shall immediately follow either the DL-MAP message (if one is transmitted) or the DLFP. If Uplink Channel Descriptor (UCD) and Downlink Channel Descriptor (DCD) messages are transmitted in the frame, they shall immediately follow the DL-MAP and UL-MAP messages.

Simultaneous DL allocations can be broadcast, multicast, and unicast and they can also include an allocation for another BS rather than a serving BS. Simultaneous ULs can be data allocations and ranging or bandwidth requests.

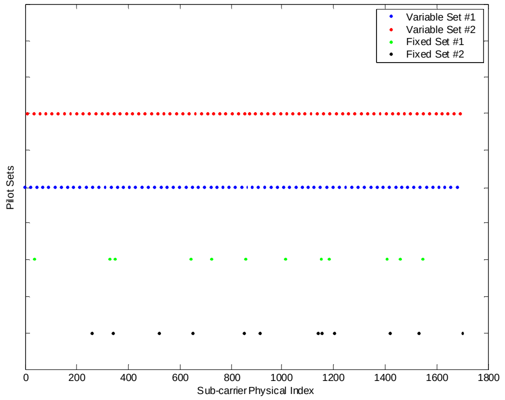

Figure 2: Pilot distribution for FUSC

SUBCARRIER ALLOCATION MODES

There are two main types of subcarrier permutations: distributed and adjacent. In general, distributed subcarrier permutations perform very well in mobile applications while adjacent subcarrier permutations can be properly used for fixed, portable, or low mobility environments. These options enable the system designers to trade mobility for throughput.

In the following section, various subcarrier allocation modes are identified and their main characteristics are summarized.

DL Distributed Subcarrier Permutations: Fully Used Subchannelization (FUSC)

This method uses all the subchannels and employs full-channel diversity by distributing the allocated subcarriers to subchannels using a permutation mechanism. This mechanism is designed to minimize the probability of hits (probably of using the same physical subcarriers in adjacent cells and sectors) between adjacent sectors/cells by reusing subcarriers while frequency diversity minimizes the performance degradation due to fast fading characteristics of mobile environments.

Table 3 summarizes the subcarrier allocation structure parameters. In DL FUSC, there are variable and fixed sets of pilots. The fixed sets are used in all OFDM symbols while the variable sets are divided into subsets that are used in odd and even symbols alternatively. This provides an appropriate tradeoff between allocated power and frequency diversity on pilots for channel estimation. Figure 2 shows the distribution of variable and fixed sets of pilots in the case of 2048 FFT. Pilot sets for other FFT sizes are subsets of those for the 2048 FFT.

Table 3: DL distributed subcarrier permutation (FUSC)

Parameters	Values				
System bandwidth (MHz)	1.25	2.5	5	10	20
FFT size (N_{FFT})	128	N/A**	512	1024	2048
Number of guard subcarriers	22	N/A	86	173	345
Number of used subcarriers	106	N/A	426	851	1703
Number of data subcarriers	96	N/A	384	768	1536
Number of pilot subcarriers (uses both variable and constant sets)	9*	N/A	42	83	166
Number of subchannels	2	N/A	8	16	32
Subcarrier Permutation	Uses Permutation Type 1 for Tone Distribution (Eq. 107 [20])				

*** variable set only**

**** FFT size of 256 is not supported**

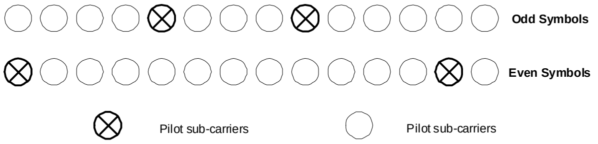

Figure 3: DL PUSC cluster structure

DL and UL Distributed Subcarrier Permutation: Partially Used Subchannelization (PUSC)

According to the OFDMA specification, all OFDMA DL and UL subframes shall start in DL and UL PUSC mode, respectively. In DL PUSC, subchannels are divided and assigned to three segments that can be allocated to sectors of the same cell. The method employs full-channel diversity by distributing the allocated subcarriers to subchannels. A permutation mechanism is designed to minimize the probability of hits between adjacent sectors/cells by reusing subcarriers, while frequency diversity minimizes the performance degradation due to fast fading characteristics of mobile environments.

Table 4 summarizes the parameters of DL PUSC subcarrier allocation. DL PUSC uses a cluster structure, as illustrated in Figure 3, which spans over two OFDM symbols (in time) of fourteen subcarriers, each with a total of four pilot subcarriers per cluster.

Table 5 summarizes the parameters of UL PUSC subcarrier allocation. UL PUSC uses a tile structure, as illustrated in Figure 4, that spans over three OFDM symbols (in time) of four subcarriers, each with total of four pilot subcarriers.

Note that because of the DL and UL, cluster and tile structures are composed of two and three OFDM symbols, respectively; the DL and UL subframe size and the granularity of the DL and UL allocations are also two or three OFDM symbols, respectively.

Table 4: DL distributed subcarrier permutation (PUSC)

Parameters	Values				
System bandwidth (MHz)	1.25	2.5	5	10	20
FFT size (N_{FFT})	128	N/A	512	1024	2048
Number of guard subcarriers	43	N/A	91	183	367
Number of clusters/subchannels	6/3	N/A	30/15	60/30	120/60
Number of used subcarriers	85	N/A	421	841	1681
Number of data subcarriers	72	N/A	360	720	1440
Number of pilot subcarriers	12	N/A	60	120	240
Subcarrier permutation	Uses Permutation Type 1 for Tone Distribution (Eq. 107 [20])				
Cluster renumbering	Activated				

Optional DL Distributed Subcarrier Permutation: Fully Used Subchannelization (OFUSC)

This method employs full-channel diversity by distributing the allocated subcarriers to subchannels using a permutation mechanism designed to minimize the probability of hits between adjacent sectors/cells by reusing subcarriers, while frequency diversity minimizes the performance degradation due to fast fading characteristics of mobile environments.

Table 6 summarizes the parameters of OFUSC subcarrier allocation. In OFUSC, pilots are mapped as specified below, which is different from the assignment in the FUSC mode.

Compared to FUSC mode, the number of used subcarriers in this method is considerably larger (1681 vs. 1729). As a result, compliance with spectral mask requirements, without a change in the over-sampling factor, may be a challenge for this mode.

Table 5: UL distributed subcarrier permutation (PUSC)

Parameters	Values				
System bandwidth	1.25	2.5	5	10	20
FFT size (N_{FFT})	128	N/A	512	1024	2048
Number of guard subcarriers	31	N/A	103	183	367
Number of tiles	24	N/A	102	210	552
Number of subchannels	4	N/A	17	35	92
Number of subcarriers per tile	4	N/A	4	4	3
Number of used subcarriers	97	N/A	409	841	1681
Tile permutation	Uses Permutation Type 2 for Tile Distribution (Eq. 109 [20])				
Subcarrier permutation	Uses Permutation Type 3 for Subcarrier Distribution (Eq. 110 [20])				

Optional UL Distributed Subcarrier Permutation: Partially Used Subchannelization (OPUSC)

This method employs full-channel diversity by distributing the allocated subcarriers to subchannels using a permutation mechanism designed to minimize the probability of hits between adjacent sectors/cells by reusing subcarriers, while frequency diversity minimizes the performance degradation due to fast fading characteristics of mobile environments.

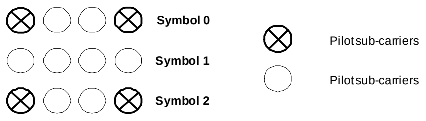

Figure 4: UL PUSC tile structure

Table 7 summarizes the parameters of UL OPUSC subcarrier allocation. UL OPUSC uses a tile structure, as illustrated in Figure 5, that spans over three OFDM symbols (in time) of three subcarriers each with one pilot subcarrier per tile.

Table 6: DL distributed subcarrier permutation (optional FUSC)

Parameters	Values				
System bandwidth	1.25	2.5	5	10	20
FFT size (N_{FFT})	128	N/A	512	1024	2048
Number of guard subcarriers	19	N/A	79	159	319
Number of used subcarriers	109	N/A	433	865	1729
Number of data subcarriers	96	N/A	384	768	1536
Number of pilot subcarriers (Npilots)	12	N/A	48	96	192
Number of data subcarriers per subchannel	48	N/A	48	48	48
Number of subchannels	2	N/A	8	16	32
Subcarrier permutation	Uses Permutation Type 3 for Tone Distribution (Eq. 108 [20])				
Pilot subcarrier index	9k+3m+1, for k=0,1,……, Npilots and m=[symbol index] mod 3				

Optional DL and UL Adjacent Subcarrier Permutation: Advanced Modulation and Coding (AMC)

This method uses adjacent subcarriers to form subchannels. When used with fast feedback channels it can rapidly assign a modulation and coding combination per subchannel. The AMC subchannels enable the use of "water-pouring" types of algorithms, and it can be used effectively with an AAS option.

Table 8 summarizes the AMC subcarrier allocation parameters. In AMC, pilots are mapped as specified below.

Table 7: Optional UL distributed subcarrier permutation (OPUSC)

Parameters	Values				
System bandwidth	1.25	2.5	5	10	20
FFT size (N_{FFT})	128	N/A	512	1024	2048
Number of guard subcarriers	19	N/A	79	159	319
Number of used subcarriers	109	N/A	433	865	1729
Number of tiles	36	N/A	144	288	576
Number of tiles per subchannel	6	N/A	6	6	6
Number of data subcarriers per subchannel	48	N/A	48	48	48
Number of subchannels	6	N/A	24	48	96
Subcarrier permutation	Uses Permutation Type 4 for Tone Distribution (Eq. 111 [20])				

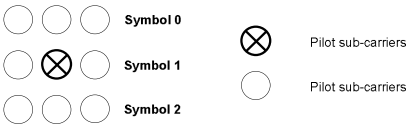

Figure 5: UL OPUSC tile structure

Table 8: UL/DL adjacent subcarrier permutation (optional AMC)

Parameters	Values				
System bandwidth	1.25	2.5	5	10	20
FFT size (N_{FFT})	128	N/A	512	1024	2048
Number of guard sub-carriers	19	N/A	79	159	319
Number of used sub-carriers (Nused)	109	N/A	433	865	1729
Number of pilots (Npilots)	12	N/A	48	96	192
Number of data sub-carriers	96	N/A	384	768	1536
Number of bands	3	N/A	12	24	48
Number of bins per band	4	N/A	4	4	4
Number of subcarriers per bin (8 data +1 pilot)	9	N/A	9	9	9
Number of subchannels	2	N/A	8	16	32
Sub-carrier permutation	None				
Pilot subcarrier index	9k+3m+1, for k=0,1,……, Npilots and m=[symbol index] mod 3				

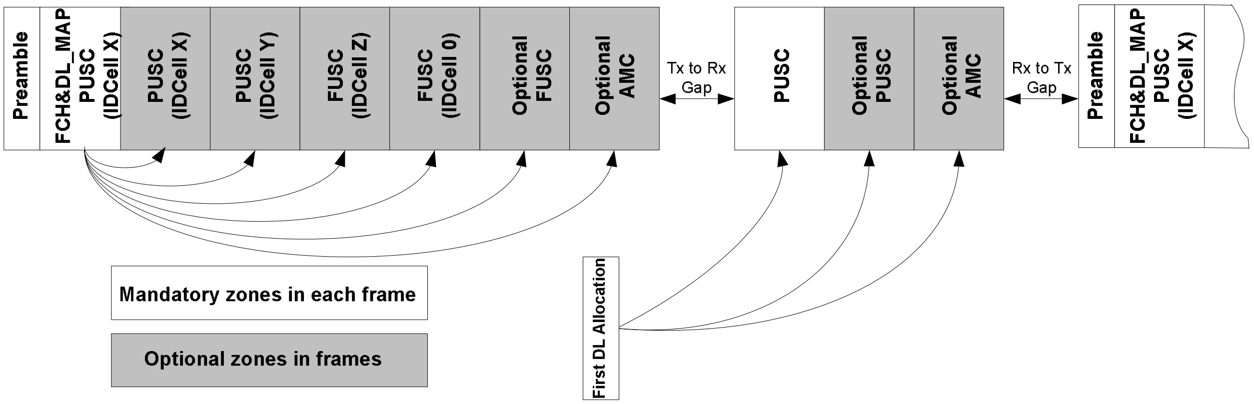

Figure 6: Multiple zones in Uplink and Downlink subframes

Zone Switching

OFDMA PHY also supports multiple subcarrier allocation zones within the same frame to enable the possibility of support for and coexistence of different types of SS's.

Figure 6 illustrates zone switching within the DL and UL subframes. The switching is performed using an information element included in DL-MAP and UL-MAP.

DL and UL subframes both start in PUSC mode where groups of subchannels are assigned to different segments by the use of dedicated FCH messages. The PUSC subcarrier allocation zone can be switched to a different type of subcarrier allocation zone through a directive from the PUSC DL-MAP. Figure 6 shows the zone switching from the perspective of a PUSC segment. In the figure, the PUSC FCH/DL-MAP for a segment with *IDCell X* is followed with another possibly data PUSC zone for *IDCell X*. A PUSC zone for another sector/cell with *IDCell Y* (*Y* in general is different from *X*) is allocated next. An FUSC zone for *IDCell Z* is shown next in the figure. Note that *IDCell Z* may be the same as *IDCell X* which means that a PUSC to FUSC switching is scheduled within the segment for Frequency Reuse One operations. A switching to *IDCell 0* can be planned for all network broadcast operations.

Optional PUSC, FUSC, and AMC zones in DL subframes and optional PUSC and AMC zones in UL subframes can be similarly scheduled. Allocation of AMC zones enables the simultaneous support of fixed, portable, and nomadic mobility users along with high mobility users (supported in PUSC/FUSC zones).

DIVERSITY OPTIONS

OFDMA PHY supports AAS and also a set of second-, third-, and fourth-order transmit diversity options.

With the AAS option, the system uses a multiple-antenna transmission to improve the coverage and capacity of the system while minimizing the probability of outage through transmit diversity, beam forming, and null steering.

Transmit diversity options consist of a comprehensive set of methods based on second- or fourth-order diversity in DL and second-order diversity in UL that can be flexibly chosen to tradeoff capacity and coverage. The set includes both closed- and open-loop options and also supports Spatial Multiplexing (SM) for maximum spectral efficiency.

Advanced Antenna Systems

Two optional AAS modes are supported in OFDMA PHY: Diversity-Map Scan and Direct Signaling Method. Diversity-Map Scan supports both diversity (FUSC and PUSC) and adjacent (AMC) subcarrier permutation options. The Direct Signaling Method supports adjacent subcarrier permutation with less overhead in control signaling.

We now discuss the Diversity-Map Scan option when applied to the AMC subcarrier allocation method.

Figure 7 shows the AAS Diversity Map Zone within a frame. The DL subframe includes a non-AAS section and an AAS section specified by information elements provided in the DL MAP.

Within the AAS zone, subchannel numbers *4* and *N-4* (N is the index for the last logical subchannel) are allocated to the AAS DL MAP where a pointer to a beamformed broadcast DL MAP is specified. The broadcaset DL MAP provides beamformed private DL and UL MAPs for AAS users. The figure illustrates a four-antenna configuration where the AAS preamble and AAS DL MAPs structure are repeated multiples of four times to support the corresponding four groups of users.

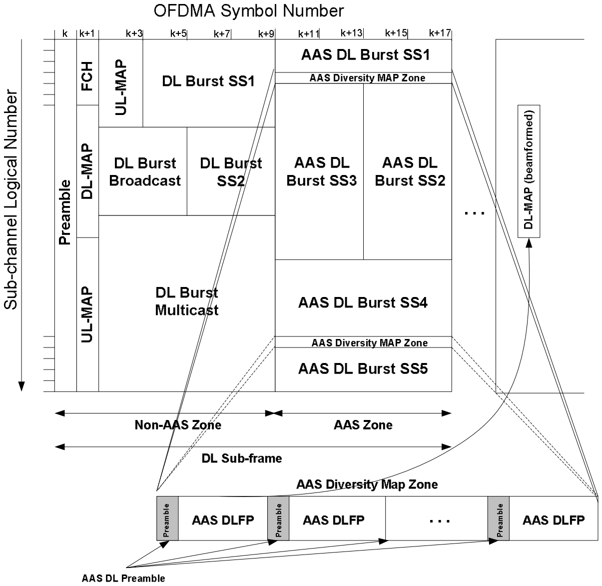

Figure 7: AAS diversity MAP zone

Within the AAS zone, the AAS BS specifies allocations to be used for SS Ranging. In TDD mode, the BS can extract the channel information required for beam forming from the Ranging Request messages received from the SS's. In FDD mode, beam forming is done through the AAS Feedback Request and Response messages where channel response information along with mean Received Signal Strength Indicator (RSSI) and Carrier to Interference plus Noise Ratio (CINR) are reported back to the BS by the SS.

Transmit Diversity

OFDMA mode supports second-, third- and fourth-order transmit diversity options in DL and second-order transmit diversity in UL. All diversity options are applicable to both diversity and adjacent subcarrier permutations.

Space Time Coding (STC) based on Alamouti algorithm [19] and Frequency Hopping Diversity Code (FHDC) are two options for second-order diversity in DL. Although not specified by the standard, the number of receive antennas can be specified depending on the performance required.

Second-Order STC

Second-order STC in DL supports coding rates of 1 and 2 using the following two transmission format matrices.

$$A = \begin{bmatrix} S_i & -S_{i+1}^* \\ S_{i+1} & S_i^* \end{bmatrix}$$ **Equation (4)**

$$B = \begin{bmatrix} S_i \\ S_{i+1} \end{bmatrix}$$ **Equation (5)**

Here S_k's are OFDM symbols in the frequency domain right before IFFT operation.

The optional STC transmit diversity is also supported in UL using the transmission format matrix A of Equation (4). Matrix B of Equation (5) can be used by two SS's in a collaborative special multiplexing mode.

Fourth-Order STC

The fourth-order transmit diversity in DL supports rates 1, 2, or 4 using the following transmission format matrices A, B, and C, respectively.

$$A = \begin{bmatrix} S_i & -S_{i+1}^* & 0 & 0 \\ S_{i+1} & S_i^* & 0 & 0 \\ 0 & 0 & S_{i+2} & -S_{i+3}^* \\ 0 & 0 & S_{i+3} & S_{i+2}^* \end{bmatrix}$$ **Equation (6)**

$$B = \begin{bmatrix} S_i & -S_{i+1}^* & S_{i+4} & -S_{i+6}^* \\ S_{i+1} & S_i^* & S_{i+5} & -S_{i+7}^* \\ S_{i+2} & -S_{i+3}^* & S_{i+6} & S_{i+4}^* \\ S_{i+3} & S_{i+2}^* & S_{i+7} & S_{i+5}^* \end{bmatrix}$$ **Equation (7)**

$$C = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix}$$ **Equation (8)**

Here, S_k's are OFDM symbols in the frequency domain right before the IFFT operation.

Third-Order STC

The third-order transmit diversity in DL supports rates 1, 2, or 3 using the following transmission format matrices A, B, and C, respectively.

$$A = \begin{bmatrix} \tilde{S}_1 & -\tilde{S}_2^* & 0 & 0 \\ \tilde{S}_2 & \tilde{S}_1^* & \tilde{S}_3 & -\tilde{S}_4^* \\ 0 & 0 & \tilde{S}_4 & \tilde{S}_3^* \end{bmatrix}$$ **Equation (9)**

$$B = \begin{bmatrix} \tilde{S}_1 & -\tilde{S}_2^* & \tilde{S}_5 & -\tilde{S}_6^* \\ \tilde{S}_2 & \tilde{S}_1^* & \tilde{S}_6 & \tilde{S}_5^* \\ \tilde{S}_7 & \tilde{S}_8 & \tilde{S}_3 & \tilde{S}_4 \end{bmatrix}$$ **Equation (10)**

$$C = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$ **Equation (11)**

In Equations (9) and (10), we have

$$\begin{aligned} \tilde{S}_1 &= S_{1I} + S_{3Q} \\ \tilde{S}_2 &= S_{2I} + S_{4Q} \\ \tilde{S}_3 &= S_{3I} + S_{1Q} \\ \tilde{S}_4 &= S_{4I} + S_{2Q} \\ \tilde{S}_5 &= S_{5I} + S_{7Q} \\ \tilde{S}_6 &= S_{6I} + S_{8Q} \\ \tilde{S}_7 &= S_{7I} + S_{5Q} \\ \tilde{S}_8 &= S_{8I} + S_{6Q} \end{aligned}$$ **Equation (12)**

where $\theta = (\tan^{-1} 2)/2$, $S_k = S_{kI} + j \cdot S_{kQ}$, $S_k = X_k \cdot e^{j\theta}$ for $k = 1,2,\cdots,8$ and X_k's are OFDM symbols in the frequency domain right before the IFFT operation.

Precoding

A general KxL precoding matrix W is specified to be applied to the output X of any second-, third- or fourth-order diversity option mentioned earlier. This way an L *th* order output vector Z of the STC block is transformed into a final K *th* order vector for transmission on antennas.

$$Z = W \cdot X$$ **Equation (13)**

Precoding can be performed either in closed-loop or open-loop form. In the case of open-loop, the BS weights the transmission according to the channel measurement performed on the UL signal, where a reciprocity assumption can be made for a TDD mode, for example. In the case of closed-loop, BS uses the Channel Quality Indications feedback from the SS.

RANGING IN OFDMA

The OFDMA PHY specifies a ranging allocation that can be used for ranging as well as bandwidth request. Initial and periodic ranging processes are supported to synchronize the SS's with the BS at the initial network entry and also periodically during the normal operation. Bandwidth request mechanism is supported so that SS's can request UL allocations for transmission of data to the BS. A set of 256 special pseudo-noise 144 bit-long ranging codes are divided into three groups for Initial Ranging, Periodic Ranging, and Bandwidth Requests, such that the BS can determine the purpose of the received code by the subset to which the code belongs. One or more groups of six adjacent subchannels are allocated to ranging where the ranging codes are BPSK modulated to the allocation. The SS randomly selects one code from the allocated set of codes and transmits back to the BS through ranging allocation. Different SS's can collide on their ranging and/or bandwidth requests and the BS is still able to receive simultaneous requests.

To process an Initial Ranging request, a ranging code is repeated twice and transmitted in two consecutive OFDM symbols with no phase discontinuity between the two OFDM symbols (see Figure 8). This way, the BS can properly receive the requests from un-ranged SS's with a larger value of synchronization mismatch when the first attempt is made to enter the network. The SS can optionally use two consecutive ranging codes transmitted during a four-OFDM symbol period (see Figure 9). This option decreases the probability of failure and increases the ranging capacity to support larger numbers of simultaneous ranging SS's while at the same time it further increases the capability of the system to support larger numbers of synchronization mismatches.

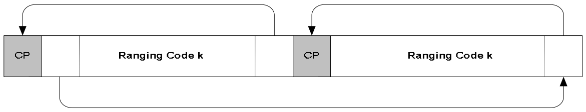

Figure 8: Initial ranging transmission

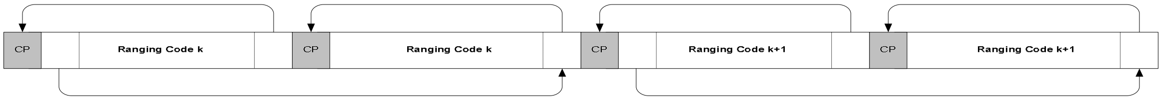

Figure 9: Initial ranging using two ranging codes

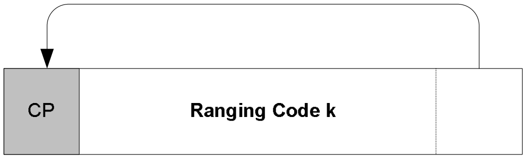

Figure 10: Periodic ranging and bandwidth request transmission

For Periodic Ranging or Bandwidth Requests, the options are either to use one or three consecutive ranging codes transmitted during a one or three OFDM symbol period (see Figure 10 and Figure 11). In the case of three ranging codes, the probability of failure decreases at the same time as the ranging capacity increases, to support larger numbers of simultaneous ranging SS's.

CHANNEL CODING

A detailed discussion of channel coding options in OFDMA PHY is beyond the scope of this paper; only a brief summary of the supported mandatory and optional modes are given here.

Based on terminology used in WirelessMAN OFDMA PHY, channel coding consists of Randomization, Forward Error Correction (FEC), bit interleaving, and modulation. Repetition code is used on various control messages to further enhance the error correction performance of the system. Repetition codes of 2, 4, or 6 are implemented by utilizing multiple subchannels.

Randomization is performed on both UL and DL data. The data are randomized using a PN sequence generator with a polynomial of degree 15 that is reinitialized at the beginning of each FEC block with a seed, which is a function of the OFDM symbol offset (from the start of the frame) and the starting subchannel number corresponding to the FEC block.

The OFDMA PHY supports mandatory tail-biting Convolutional Coding and three optional coding schemes: Zero Tailing Convolutional code, Convolutional Turbo code along with H-ARQ, and Block Turbo code.

The tail biting is implemented by initializing the encoders memory with the last data bits of the FEC block being encoded, and the zero tailing is implemented by appending a zero tail byte to the end of each burst.

H-ARQ mitigates the effect of impairments due to channel and external interference by effectively employing time diversity along with incremental transmission of parity codes (subpackets in this case). In the receiver, previously erroneously decoded subpackets and retransmitted subpackets are combined to correctly decode the message. The transmitter decides whether to send additional subpackets, based on ACK/NAK messages received from the receiver.

Bit interleaving is performed on encoded data at the output of FEC. The size of the interleaving block is based on the number of coded bits per encoded block size. The interleaving is performed using a two-step permutation process. The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second permutation ensures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation, thus avoiding long runs of lowly reliable bits.

CONCLUSION

The IEEE 802.16 WirelessMAN OFDMA supports a comprehensive set of system parameters and advanced optional features for mobile, portable, and fixed usage models. Scalability enables the technology to operate optimally in different usage scenarios.

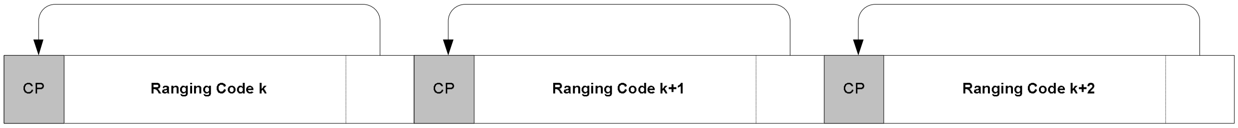

Figure 11: Periodic ranging and bandwidth request transmission using three codes

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AUTHOR'S BIOGRAPHY

Hassan Yaghoobi received a B.S. degree from Sharif University of Technology, Tehran, Iran, in 1989 and M.S. and Ph.D. degrees from the University of Maryland, in 1993 and 2000, respectively, all in Electrical Engineering. His academic research interests include nonlinear control theory, communications theory, and digital signal processing.

Hassan's industrial experience includes communications systems engineering, silicon design/functional definition, and standards development in the area of broadband communications. Since 2000, he has been working at Intel Corporation. As an engineer for Intel's Broadband Product Group, he worked on silicon functional definition, algorithm design, system design verification, and validation of various cable modem products. He represented Intel at the DOCSIS2.0 Radio Frequency Interface Specification (RFI) and Acceptance Test Plan (ATP) standard committees at Cablelabs. Hassan is currently working as a Strategic Technologist for Intel's Broadband Wireless Division working on product definitions of Intel's 802.16d/e silicon solutions. He is a member of the IEEE 802.16 and 802.20 working groups. He also serves as secretary of the sub 11 GHz Technical Working Group for the WiMAX forum, an industry group focused on interoperability of systems that conform to the IEEE 802.16 standard. Prior to Intel, he worked on design and modeling of wireless terrestrial and satellite receivers for Stanford Telecom and on RF network design of mobile wireless systems for LCC international. His e-mail is hassan.yaghoobi at intel.com.

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