IEEE C802.16m-08/145

Project: IEEE 802.16 Broadband Wireless Access Working Group

Title: Hybrid Precoded CDMA/OFDMA-IC Proposal for 802.16m

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Abstract:
A DFT-precoded CDMA technique is proposed for supporting *event-driven uplink signaling* in 802.16m and in a way that it can coexists with the OFDMA multiple access scheme used for traffic. We describe the different configurations options and elaborate on the BS receiver algorithms necessary to accommodate the scheme. The main advantage of precoded CDMA is the capability of the terminal to autonomously transmit to the BS signaling without resource assignment and de-assignment messages with a link performance superior to OFDMA via frequency domain IC. For traffic, we present the design and performance of OFDMA-IC that can provide *free-riding effects* when OFDMA users with aggressive code rates are scheduled on top of users with less aggressive code rates.

Purpose: To include in the SDD, precoded CDMA as the uplink transmission scheme for event-based signaling as well as to include the hopping options that are required for performing IC for OFDMA traffic in the BS.

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Best Practices in OFDMA Uplink Design (1/2)

Signaling

- Transfer aperiodic uplink PHY/MAC signaling messages without requiring any explicit downlink signaling overhead (e.g UL-MAP) to manage uplink resources. Precoded CDMA is ideally suited for this task.
- Transfer periodic uplink PHY/MAC signaling messages via a persistent OFDMA allocation.
- Achieve virtually zero interruption time for VoIP inter-BS handover. This points to a distributed approach (i.e. terminal centric) on handling RAN mobility. Contrast that to centralized approaches such as found in LTE.
- Minimize the requirements for explicit signaling via the backhaul of messaging required for mobile Tx PSD control (interference control). A distributed approach for Tx PSD control is best and particularly important in IEEE setting as it does not require multiple TGs to be involved in its specification.

Best Practices in OFDMA Uplink Design (2/2)

Traffic

- Consider not only pure Power Amplifier (PA) issues such as PAPR but also the MAC implications. A technique such as SC-FDMA may offer more robust coverage and potentially a higher edge throughput at the expense of MAC inflexibility and performance.
  - OFDMA can flexibly assign resources (tiles) which are disjoint for a given user.
  - SC-FDMA can only perform assignments of a contiguous chunk of bandwidth (tiles that are contiguous).
  - SC-FDMA can only transmit the signaling information inband. For all persistently allocated services such as VoIP, it means that every time signaling needs to be transmitted, the code rate for traffic must be increased, impacting latency and, more importantly, latency variance.
- Allow for opportunistic Interference Cancellation *p*er antenna between a limited number of users that are assigned to different layers within the cell. Layered Superposition with $L = 2$ layers can boost throughput in many scenarios on top of any UL MIMO gains. It also solves the (inherent) to orthogonal uplink fairness issues.

What is Precoded-CDMA ?

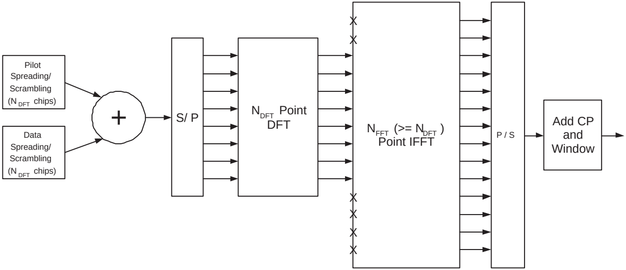
- The specific CDMA flavor that we propose, reuses the OFDM modulation circuitry that is present in the OFDMA transmitter. DFT precoding is applied to the walsh-spread and scrambled CDMA chips and in a localized or distributed fashion, a mapper, maps the precoded chips to the IFFT ports.
- Although DFT-precoding is applied in this paper, more general precoders are equally applicable. On the receive side, after the FFT, the frequency domain signal is further transformed by inverse DFT to get a direct spread CDMA signal. Such a signal processing flow seamlessly integrates the OFDMA and the CDMA components.
- The DFT pre-coded CDMA approach is a fairly general approach as by choosing specific parameters such as spreading factor it can reduce to single-carrier FDMA (SC-FDMA).
- The use of the cyclic-prefix based CDMA approach further makes this approach more robust to delay spread channels, thus improving performance of an interference cancellation based receiver.

DFT-CDMA Configurations

- The pre-coder matrix **F** can be composed of single or multiple DFTs, depending on the pre-coded CDMA configuration, as illustrated in subsequent slides.
- We assume that there are K_z CDMA "zones", each with N_z sub-carriers each such that $K_z\ N_z = N_C$. Here, N_C is the number of CDMA chips per symbol, and is also the total number of sub-carriers allocated for CDMA transmission.

Configuration 1: Single DFT Localized Sub-carrier Allocation

In this configuration, a single DFT is employed. If the DFT outputs are mapped to contiguous sub-carriers, this results in a completely localized CDMA transmission over a given sub-band. Another possibility is for the sub-carrier mapping to be completely distributed. The PAPR here is the same as that of a regular DS-CDMA transmission. Further, the localized zone can hop from one frame to another, in order to provide frequency diversity.



Configuration 2: Multiple DFTs with Localized Sub-carrier Allocation

In this configuration, multiple small-sized DFTs (of dimension N_z) are used to map spread/scrambled chip streams to localized IFFT sub-carriers within a "zone". The zones themselves may be distributed or localized. The receiver for this configuration does not need an equalizer but each symbol has limited frequency diversity. The frequency diversity is obtained over the whole code-block instead.

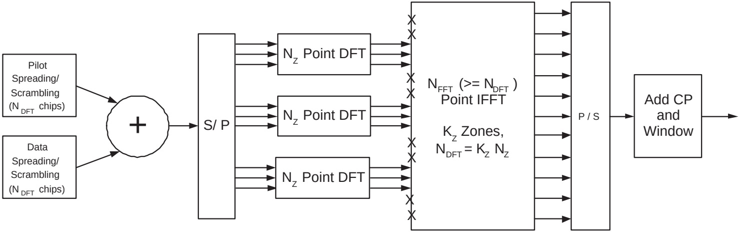


Figure: DFT-CDMA Multiple Zone DFT Option with Distributed Sub-carriers

Precoder Matrix

Option 1 with localized sub-carriers results in $K_z = 1$, and $N_z = N_C$. Option 1 with completely distributed sub-carrier allocation, we have $N_z = 1$, and $K_z = N_C$. In Option 1, the matrix $\mathbf{F}$ is the standard DFT transform matrix $\mathbf{F}_{d,N_C}$ of size N_C:

$$\mathbf{F} = \mathbf{F}_{d,N_C}$$

where $\mathbf{F}_{d,N_C}(k,n) = \frac{1}{\sqrt{N_C}} \exp(-j2\pi(k-1)(n-1)/N_C) \quad ; \quad n, k \in [1, N_C]$. For Option 2, the matrix takes a block diagonal form as follows:

$$\mathbf{F} = \begin{pmatrix} \mathbf{F}_{d,N_z} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{F}_{d,N_z} & \dots & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{F}_{d,N_z} \end{pmatrix}$$

Transmitter Model

We assume that the spreading factor is SF_j, and so the traffic chip vector can be written as:

$$\begin{aligned}\mathbf{x}_{D,j} &= \mathbf{C}_j \ \mathbf{s}_j \qquad (1)\\ \mathbf{C}_j &= \begin{pmatrix} \mathbf{c}_{j,1} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{c}_{j,2} & \dots & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{c}_{j,M} \end{pmatrix}_{N_C \times M}\end{aligned}$$

Here, $\mathbf{c}_{j,m} = [c_{j,m}(1),\ c_{j,m}(2), \dots, c_{j,m}(SF_j)]^T$ is the scrambling/spreading code vector for the m^{th} modulation symbol of length SF_j and $\mathbf{s}_j = [s_j(1)\ s_j(2) \dots s_j(M)]^T$ is the vector of all the modulation symbols that make up one output OFDM symbol. The number of such symbols is $M = \frac{N_C}{SF_j}$.

It is easy to see that an SC-FDMA like system results if we choose $SF_j = 1 (or M = N_C)$, i.e., by setting $\mathbf{C} = \mathbf{I}_N$. As a result, the SC-FDMA configuration is a special case of the DFT-CDMA system described here.

Channel Model

In the following, we consider the signal model for a certain desired user, and drop the user index j, considering all the other users to be interference.

The diagonal channel matrix $\mathbf{H}$ in the receiver model (next slide) is expressed as follows. We assume that the sub-carriers used for DFT-Precoded CDMA transmission are from the set $\mathcal{K} = \{k_1, k_2, \ldots, k_{N_C}\} \subset [1, N_{FFT}]$. Further we assume that the m^{th} output of the DFT block is mapped to the sub-carrier k_m, $m = 1, 2, \ldots, N_C$.

Let the impulse response of the channel at symbol i be given by $g(\tau, i) = \sum_{l=0}^{L} g_l(i)\ \delta(\tau - \tau_l)$. Then the frequency-domain sampled (with an FFT of size N_{FFT}) Fourier transform of this signal is:

$$\begin{aligned} G_k(i) &= \sum_{l=0}^{L} g_l(i) \exp(-j2\pi\tau_l k/N_{FFT}) \quad ; \quad \text{and} \\ h_m(i) &= G_{k_m}(i) \quad ; \quad m = 1, 2, \ldots, N_C \quad ; \quad k_m \in \mathcal{K} \end{aligned} \tag{2}$$

Received Signal at Antenna Connector

The received signal can be written as:

$$\begin{aligned}\mathbf{r}(i) &= \mathbf{H}(i)\left[\sqrt{E_P}\,\tilde{\mathbf{x}}_P(i) + \sqrt{E_D}\,\tilde{\mathbf{x}}_D(i)\right] + \mathbf{v}(i)\\ \tilde{\mathbf{x}}_D(i) &= \mathbf{C}_F(i)\,\mathbf{s}(i)\end{aligned}$$

Here, $\mathbf{C}_F(i) = \mathbf{F}\ \mathbf{C}(i)$ is the frequency-domain traffic scrambling code matrix, and $\tilde{\mathbf{x}}_P(i) = \mathbf{F}\ \mathbf{x}_P(i)$ is the frequency-domain pilot scrambling vector, with the following properties:

$$\mathbf{C}_F(i)^\dagger\ \mathbf{C}_F(i) = \mathbf{C}(i)^\dagger\ \mathbf{C}(i) = \mathbf{I}_M \quad ; \quad \|\tilde{\mathbf{x}}_P(i)\|^2 = \|\mathbf{x}_P(i)\|^2 = 1 \qquad (3)$$

and,

$$E\left[\mathbf{c}_m(i)\ \mathbf{x}_P^\dagger(i)\right] = \mathbf{0} \qquad (4)$$

Receiver Model - Channel Estimation

For channel estimation, we consider an example of a "one-shot" estimation across the symbols (in time), followed by an MMSE estimator in the frequency domain. In this structure, assuming that the channel is flat in time over N_{sym} number of symbols over a frame (typically 1ms), we first form an average estimate as follows:

$$\begin{aligned}
\mathbf{y}_P &= \frac{1}{N_{sym}} \sum_{i=1}^{N_{sym}} \mathbf{r}(i) \odot \tilde{\mathbf{x}}_P^*(i) \\
&= \mathbf{A}_P \ \mathbf{h} + \tilde{\mathbf{v}} \quad ; \qquad (5) \\
\mathbf{A}_p &= \mathrm{diag}\left[a_p(1), \ldots, a_p(N_C)\right] \\
a_p(k) &= \sqrt{E_P} \ \mathbf{f}_k^\dagger \left[\frac{1}{N_{sym}} \sum_{i=1}^{N_{sym}} \mathbf{x}_P(i) \ \mathbf{x}_P^\dagger(i) \right] \mathbf{f}_k
\end{aligned}$$

One could further use multiple of such averaged $\mathbf{y}_P$ across multiple frames, but for simplicity we will not consider that here (although the model can be made to take this into account).

Channel Estimation

The vector **h** is the frequency domain channel values at the sub-carriers that are mapped in a given configuration. The channel estimate in the frequency domain is now constructed as another linear weighting over the vector $\mathbf{y}_P$, using for example, an MMSE criterion. Thus,

$$\begin{aligned} \hat{\mathbf{h}} &= \mathbf{W}_{mmse}\ \mathbf{y}_P \qquad (6) \\ \mathbf{W}_{mmse} &= \left[\mathbf{I} - \mathbf{R}_v\ \mathbf{R}_{y_p}^{-1}\right] \end{aligned}$$

where $\mathbf{R}_x$ refers to the correlation matrix of the random vector $\mathbf{x}$. In practice, this correlation matrix is adapted using samples of the random vector.

Traffic Demodulation

In general, we require an equalizer to demodulate the traffic symbols. To this end, we consider a linear equalizer of the form:

$$\begin{aligned} \hat{\mathbf{s}}(i) &= \mathbf{L}\ \mathbf{r}(i) \qquad (7) \\ \mathbf{L}_{mmse} &= \sqrt{E_D}\ \mathbf{C}_F^{\dagger}\ \hat{\mathbf{H}}^{\dagger}\ \left[E_D\ \hat{\mathbf{H}}\ \mathbf{C}_F\ \mathbf{C}_F^{\dagger}\ \hat{\mathbf{H}}^{\dagger} + \mathbf{R}_v\right]^{-1} \end{aligned}$$

The zero-forcing (ZF) equalizer is of the form:

$$\mathbf{L}_{zf} = \left[\mathbf{C}_F^{\dagger}\ \hat{\mathbf{H}}^{\dagger}\ \ \hat{\mathbf{H}}\ \mathbf{C}_F\right]^{-1}\ \mathbf{C}_F^{\dagger}\ \hat{\mathbf{H}}^{\dagger}$$

If the channel is not highly frequency selective (or the localized bandwidth of transmission is small compared to the coherence bandwidth of the channel), we can implement a simpler correlation based receiver that is obtained by doing channel derotation followed by an IFFT and despreading/de-scrambling this “time-domain” signal:

$$\mathbf{L}_{corr} = \mathbf{C}^{\dagger}\ \mathbf{F}^{\dagger}\ \hat{\mathbf{H}}^{\dagger}$$

Traffic Demodulation

When the channel is truly flat in frequency and the interference is not correlated in frequency, both the MMSE and ZF solutions will result in the correlator receiver, as expected.

As a special case of an SC-FDMA like system when we set $\mathbf{C} = \mathbf{I}_{N_C}$, we have (with $\mathbf{R}_v = \sigma_v^2 \ \mathbf{I}$):

$$\begin{aligned} \hat{\mathbf{s}}(i) &= \sqrt{E_D} \ \mathbf{F}^{\dagger} \ \hat{\mathbf{H}}^{\dagger} \ \hat{\mathbf{D}} \ \mathbf{r}(i) \\ \hat{\mathbf{D}} &= \mathrm{diag}[d_1, d_2, \ldots, d_{N_C}] \end{aligned} \tag{8}$$

where $d_k = \frac{1}{E_D |h_k|^2 + \sigma_v^2}$ for an MMSE equalizer and $d_k = \frac{1}{|h_k|^2}$ for a ZF equalizer. With $d_k = 1$, we obtain a correlator receiver in this case.

Traffic Demodulation

The correlator receiver is of interest since it is also the optimal solution in the configuration outlined in Option 2. This results because the matrix $\mathbf{F}$ is made up of multiple small DFT matrices, each of a small dimension N_z. Assuming that the channel is frequency-flat over a CDMA zone with $SF \leq N_z$, it follows that the effective receiver matrix is block diagonal:

$$\mathbf{L}_{opt} = \begin{pmatrix} h_1^* \ \mathbf{C}_1^\dagger \ \mathbf{F}_{d,N_z}^\dagger & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & h_2^* \ \mathbf{C}_2^\dagger \ \mathbf{F}_{d,N_z}^\dagger & \dots & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & h_{N_z}^* \ \mathbf{C}_{N_z}^\dagger \ \mathbf{F}_{d,N_z}^\dagger \end{pmatrix}$$

Performance Results - Assumptions

Link level performance of a DFT-pre-coded CDMA system is shown below for the following simulation parameters:

Parameter	Value
Configuration	Configuration 2
System BW	5 MHz
Precoded CDMA Zone BW	1/4 of System Bandwidth
frame	1.6667 ms
Number of OFDMA symbols per frame	20
N_{FFT}	512
Number of CDMA Tones N_C	92
Number of CDMA Tones per Zone N_z	4
Number of CDMA Zones K_z	23
Transport Formats	128/256 bits
Power Control Method	Ack/Nack based
Target PER	10^{-2}
Termination Target	4
Number of HARQ Processes	4

Performance Results - Transport Formats

The transport format table that is used for the precoded CDMA transmissions consists of small block sizes, inline with the notion of carrying low-rate (and possibly delay-sensitive) signaling on the CDMA zones.

TF	Block Size	Number of SF=4 Codes	TPR (dB)
2	128	1	1
3	256	1	4

Performance Results - Required E_c/N_t

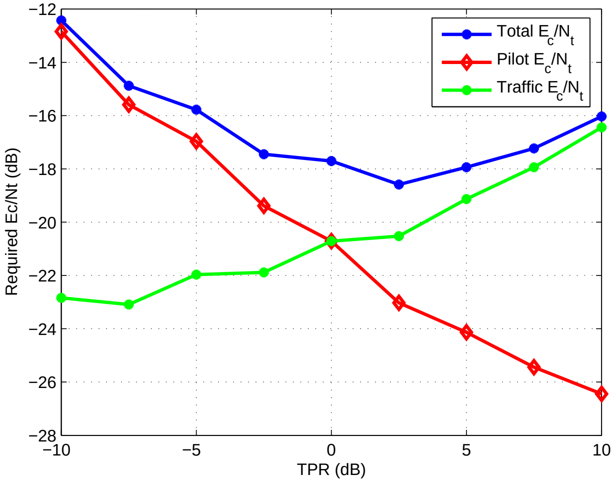


Figure: TPR Optimzation for Ped. A 3km/h channel with reference TF of 128 bits

Performance Results - Required E_c/N_t

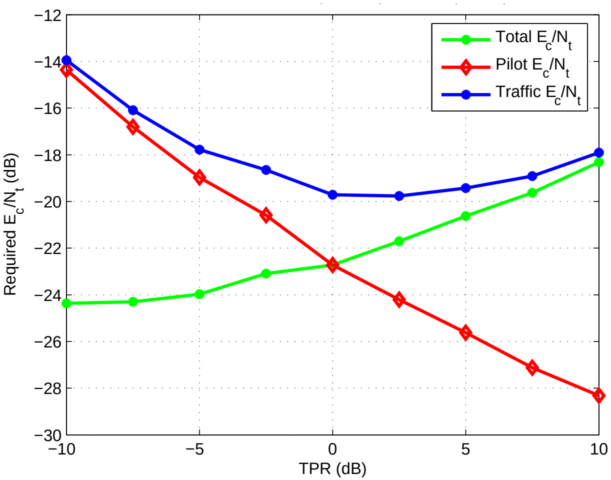


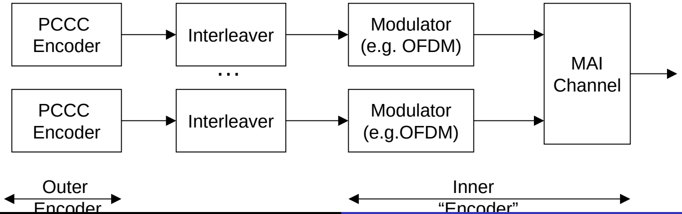
Figure: TPR Optimzation for Veh. A 120km/h channel with reference TF of 128 bits

OFDMA-IC Concept

- Layered Superposition, allows the reuse of uplink resources without using any spatial degrees of freedom.
- The degrees of freedom that we exploit are obtained from the differences in the codeword structure between near and far user-sets or layers.
- In this respect, LS-OFDMA complements SDMA schemes in that in a base station with multiple receive antennas SDMA and LS-OFDMA can simultaneously exploit codeword dimensions and spatial dimensions. Codeword dimensions can be made robust via a number of techniques such as:
    - Differences in code rate after puncturing and/or repetition. This is automatically achieved by assignment of different modulation and coding schemes to interfering users.
    - User-specific scrambling the channel encoder output or equivalently,
    - Allowing for user-specific offsets in the addressing of channel interleaver look-up tables.
    - Frequency hopping patterns.

OFDMA-IC Layers

- The base station broadly divide users in terms of layers based on achievable spectral efficiency (SE) estimates. For example, it is straightforward to define two layers: a high SE layer that would include users that are closer to the base station and a low SE layer for users that are at the cell edge.
- Within the layer, the base station allocates orthogonal resources to the multiplexed users. Between layers the base station allows cross-layer interference by allocating the same resources to all layers. In the case of two layers the pilot patterns are orthogonal, allowing for channel estimates without the inter-layer interference.



Cross-Layer Hopping

A couple of options exist at the disposal of the operator.

- In the **independent cross-layer hopping** option shown pictorially in the next slide, each layer is hopping independently from the other layers. Because of the layer hopping, the interfering symbols from the other layer do not form a valid code-words.
- This helps during the single-user decoding and achieves faster convergence. In addition, when one user from an earlier layer terminates, the interference to a bunch of users on the other layers is reduced, improving their effective code-rate (decodability).
- In other words, the effects of a single user decoding are amortized over a range of users on the other layers, which is desirable from a fairness point of view. The interference variability between the users in the subsequent layers is reduced this means that the rate predictability for those users is easier and more accurate.

Independent Cross-Layer Hopping

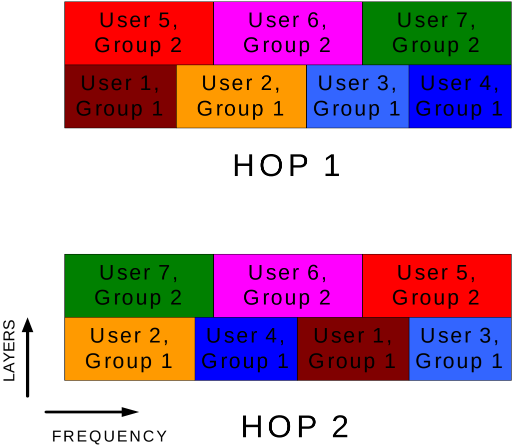
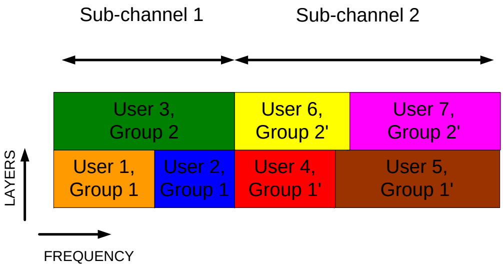


Figure: Independent Layer Hopping Option

Coordinated Cross-Layer Hopping

- In the **coordinated cross-layer hopping** we plan the interfering users such that each user interferes with the same set of users all the time (until it is terminated). The idea is to have a joint decoder for the typically small number of users that iteratively goes across all the users and improves the LLRs of all users jointly. With independent hopping and SIC reception, users did not see any decoding benefit till an earlier layer user decoded successfully. In the joint decoding approach, all users see incremental improvements in LLR as the iterations increase.



ISIC

In the coordinated case, an Iterative Soft Interference Canceller (ISIC) can be used as a Joint Detector. Independent single user channel decoders feedback extrinsic information regarding the *coded bit* of each user that will enable to Joint Maximum A Posteriori (JMAP) Soft Input Soft Output (SISO) detector to separate the two user signals.

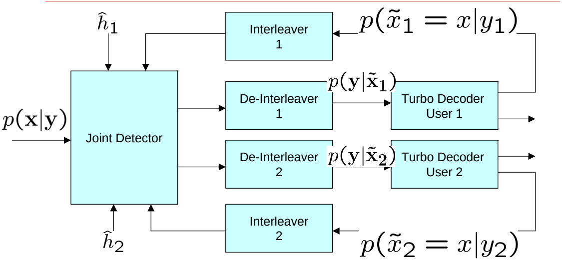


Figure: ISIC Signal Flow Diagram for 2 Users

ISIC Results

A two-user LS-OFDMA system without HARQ was simulated for AWGN channels as a proof of concept for the ISIC receiver. CRC-based power control for a target PER (10%) is included. Multiple scenarios were simulated with varying outer and inner iterations such as the total number of iterations is limited to $N_{outer}x(N_{turbo} - N_{outer})$ where $N_{turbo} = 8$.

1. Scenario one is the superposition of QAM-16 $r_1 = 1/2$ and QPSK $r_2 = 1/5$ with $A_1 = 128$ and $A_2 = 128$ bits block size respectively.
2. The second scenario was the superposition of QPSK $r_1 = 1/5$ and QPSK $r_2 = 1/5$ with $A_1 = 128$ and $A_2 = 128$ bits block respectively.
3. The third scenario differs from the second scenario in that a user specific offset in the interleaving pattern is introduced.
4. The forth scenario is the superposition of QAM-16 $r_1 = 1/2$ and QPSK $r_2 = 1/5$ with $A_1 = 1024$ and $A_2 = 128$ bits block size respectively.
5. The fifth scenario is the superposition of QPSK $r_1 = 3/4$ and QPSK $r_2 = 1/5$ with $A_1 = 1024$ and $A_2 = 128$ bits block respectively.
6. The sixth scenario refers to a no-cancellation receiver i.e. the receiver that does not have the J-SISO in the frontend.

ISIC Results

Table: OFDMA-IC in AWGN Results (PER Target = 10%)

Scenario	**Req.** E_s/N_t **(dB)** Layer 1	**Req.** E_s/N_t **(dB)** Layer 2
1	5.84 /6.98	1.42/-3.38
2	13.07	11.65
3	-0.17	-0.14
4	9.57 / 6.79	4.64 / N/A
5	5.64	-0.85
6	10.34	7.81

In some scenarios two values are mentioned separated by "'/"'. The first corresponds to the case of superposition while the second corresponds to the result of the corresponding layer if no superposition is present i.e. no other layer to interfere.

Conclusions

- It is absolutely critical to design 802.16m such that it can have the potential to differentiate in the marketplace especially when compared to LTE.
- We provided a first principles view of the uplink and suggest that precoding together with superposition in both signaling (CDMA) and traffic (OFDMA-IC), paired with a distributed (i.e. terminal centric) interference control architecture can satisfy 802.16m differentiation requirements.
- We also provided our views regarding SC-FDMA (the choice of LTE) and why it should not be selected for 802.16m. We provide comparative link level results between SC-FDMA and OFDMA in C80216-08_146.