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Re:	Response to the Call for Contributions on Project 802.16m System Description Document (SDD) (i.e., IEEE 802.16m-08/005).	
Abstract	This contribution proposes the technique of base station cooperation and discusses the associated channel sounding issue for 802.16m system description document (SDD).	
Purpose	To adopt the base station cooperation and the associated channel sounding proposed herein into IEEE 802.16m system description document (SDD).	
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Base Station Cooperation and Channel Sounding

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Introduction

Cell edge performance of IEEE 802.16e systems is typically interference limited. If full frequency reuse is employed, then the average SINR at the cell edge is around 0 dB, i.e., too low for useful communications with OFDM. In order to avoid the interference, fractional frequency reuse (FFR) technology is used in the actual systems. However, FFR schemes decrease the sector throughput (e.g., in the case of 1/3 FFR, max throughput in this sector is limited to 1/3).

To improve the spectral efficiency especially at the cell edge, new transmission schemes have to be introduced. Base Station (BS) cooperation allows to avoid interference at specific locations. In particular, if the BSs cooperate by linear weighting of the transmit signal, the preprocessing is transparent to the MSs (allowing full backward compatibility and low-cost implementation), while tremendously reducing interference. The BS cooperation can be seen as the creation of a “virtual MIMO system”, where the antenna elements of all the collaborating BSs are the elements of the MIMO array that transmits to the MSs, thus taking advantage of additional spatial diversity and increasing system capacity (since each channel use now carries additional information to multiple users)

The main messages of this contribution are the following:

- BS cooperation can reduce interference so much that it doubles or triples the cell-edge throughput.
- BS cooperation can be implemented as a combination of macro-diversity handover (MDHO) and spatial division multiple access (SDMA), both of which are already part of 16e standard.
- Only a minor modification is needed in the training process, which enables the BSs to determine the correct coefficients for linear precoding.

System Overview and Basic Implementation

We consider an IEEE 802.16m system with $\boldsymbol{B}$ base stations (BSs) (each with N_t antennas) and K Mobile Stations (MSs) (each with N_r antennas). In BS cooperation, multiple BSs could collaboratively transmit L_k data streams to MS$_k$. Fig. 1 shows a simple BS cooperation scenario with 2 BSs and 2 MSs. It is assumed that the transmission and particularly zone boundaries from neighboring base stations are synchronized as this is required for cooperation to work correctly. Let us define $\mathbf{H_{bk}}$ ($N_r \times N_t$) as the baseband channel matrix between BS$_b$ and MS$_k$, the singular-value decomposition of which is $\mathbf{H}_{bk} = \mathbf{U}_{bk}\boldsymbol{\Lambda}_{bk}\mathbf{V}_{bk}^{*}$. Let BS$_k$ denote the index of the serving BS of MS$_\mathrm{k}$. The transmit vector for MS$_k$ from BS$_b$ is linearly precoded by the $N_t \times L_k$ matrix $\mathbf{T}_{bk}$ as $\mathbf{x}_{bk} = \mathbf{T}_{\underline{bk}}\mathbf{s}_k(m)$, where $\mathbf{s}_k(m)$ denotes the zero-mean data vector, of size $L_k \times 1$ at time m, meant for MS$_k$. Note that $\mathbf{T}_{bk}$

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$= \mathbf{0}_{Nt\times Lk}$ ($b \neq k$) corresponds to the special case that each BS only serves its own MS, as shown in Fig. 1 (2 BSs and 2 MSs scenario). In order to maximize the per-user transmission information rate, a Gaussian code book is used for the transmit data vectors, with normalized power such that $E\{\mathbf{s}_k(m)\mathbf{s}_k(m)^*\} = I$ and $E\{\mathbf{s}_k(m)\mathbf{s}_l(m)^*\} = \mathbf{0}_{Lk\times Lk}$ (for $k \neq l$).

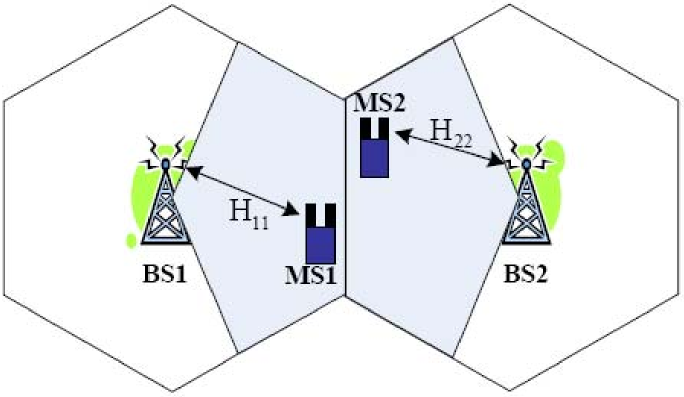

Figure 1 Simple scenario *without* base station cooperation

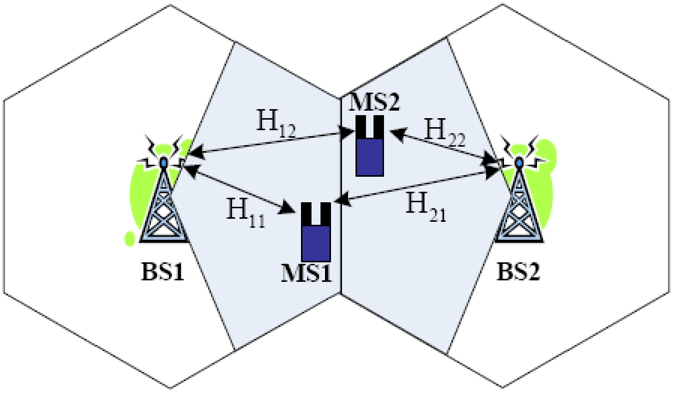

Figure 2 Simple scenario with cooperative Base Stations

For the case of base station cooperation, the received signal at MS_k is given by

$$\mathbf{y}_k(m) = \sum_{b=1}^{B}\mathbf{H}_{bk}\mathbf{x}_{bk}(m) + \sum_{\substack{j=1\\ j\neq k}}^{K}\sum_{b=1}^{B}\mathbf{H}_{bk}\mathbf{x}_{bj}(m) + \mathbf{n}_k(m) = \sum_{b=1}^{B}\mathbf{H}_{bk}\mathbf{T}_{bk}\mathbf{s}_k(m) + \sum_{\substack{j=1\\ j\neq k}}^{K}\sum_{b=1}^{B}\mathbf{H}_{bk}\mathbf{T}_{bk}\mathbf{s}_j(m) + \mathbf{n}_k(m)$$

where $\mathbf{n}_k(m)$ is the additive white Gaussian noise (AWGN) vector with covariance matrix $N0I_{Nr}$. The above equation can be also rewritten as

$$\mathbf{y}_k(m) = \mathbf{H}_k\mathbf{T}_k\mathbf{s}_k(m) + \sum_{\substack{j=1 \\ j\neq k}}^{K} \mathbf{H}_k\mathbf{T}_j\mathbf{s}_j(m) + \mathbf{n}_k(m)$$

$$\text{where } \mathbf{H}_k = [\mathbf{H}_{1k}, \mathbf{H}_{2k}, ..., \mathbf{H}_{\mathrm{B}k}] \text{ and } \mathbf{T}_k = [\mathbf{T}_{1k}^*, \mathbf{T}_{2k}^*, ..., \mathbf{T}_{Bk}^*]^*$$

Equation 1

The goal of base station cooperation is to correctly design the transmitter precoding matrices $\{\mathbf{T}_k, k = 1,2,\ldots K\}$. In this case we wish to maximize the sum rate capacity of the cooperative system. Essentially, if each BS has complete knowledge of all data and channel state information (CSI) e.g. the value of $\mathbf{H}_k$, then significant capacity gains can be realized via precoding. As a result, BSs need to exchange not only their CSI, but also their data streams (via the backbone that has higher bandwidth). Different BSs can then collaboratively and simultaneously transmit data streams intended to different MSs.

We note that the basic building blocks of a cooperative system already exist in the current IEEE 802.16e standard. In BS cooperation, the cooperating base and mobile stations can be grouped into a cooperation set, which is similar to the concept of a *diversity set* in the MDHO. Data transmission during cooperation bears significant resemblance to conventional MDHO, where multiple base stations communicate with one mobile station. Base station cooperation is also similar to conventional SDMA, where one base station communicates with multiple mobile stations. As illustrated in Figure 3, we can view base station cooperation conceptually as a natural extension of MDHO and SDMA. Thus enabling cooperation should require minimal modifications to the existing standard.

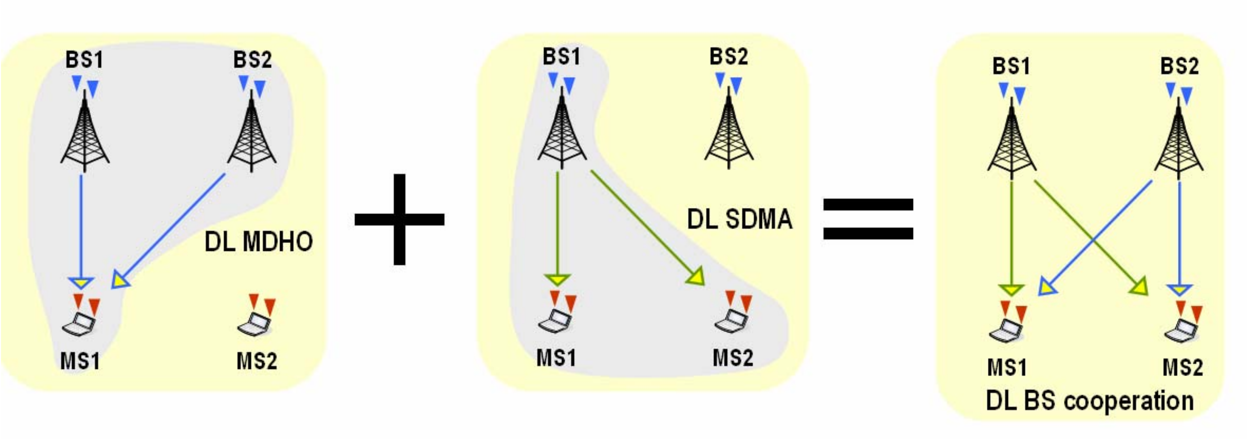

Figure 3 Base Station Cooperation viewed conceptually as a combiniation of MDHO and SDMA

Simulation Results

We have simulated the downlink of an urban micro-cell 1]network that consists of two cells, each with 1BS and 1 MS (as in Fig. 1). $N_t = N_r = 2$, $L_k = L = 2$, and equal transmission power for each BS. Although our interest is frequency selective channels, results for Rayleigh flat fading are also shown for the completeness and comparison.

A. Rayleigh flat fading

We first consider Rayleigh flat fading channels. We use the same simulation conditions as in [2]: The inter-BS distance is 500m. MSs are uniformly distributed in a limited cell area so that any MS is at least 150m from its serving BS. The path-loss coefficient for all the BS-MS channels is 2.0 (free-space propagation) up to distance of 30m and increases to 3.7 thereafter. Without loss of generality, the channel path-loss values are normalized with respect to the largest in-cell path-loss in the cell. Channel errors are modeled as zero-mean complex Gaussian random variables, with the same variance as the AWGN. Figure 4 compares the sum rate capacity of the 2 BS 2 MS system for the case of cooperation and non-cooperation.

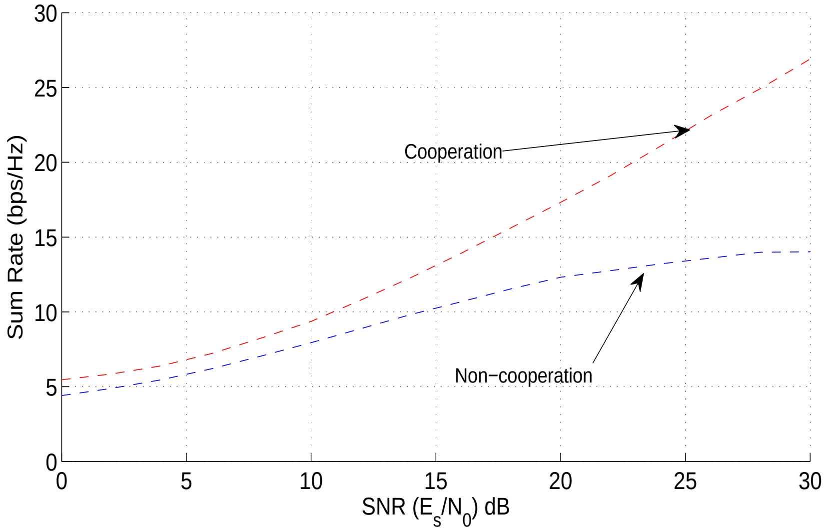

Figure 4 sum rate capacity over rayleigh channels

In non-cooperative system, CSI exchange is not available. It is assumed that each BS still has knowledge of CSI of its own MS (i.e., $\mathbf{H}_{kk}$), the optimal precoding matrices to maximize the sum rate can be calculated based on the eigen-beamforming and equal power allocation on each data stream to each MS. In other words, the eigenvectors of the input covariance matrix $(\mathbf{T}_{\mathrm{kk}})^{*}\mathbf{T}_{\mathrm{kk}}$ are the first L_{k} columns of $\mathbf{V}_{kk}$, where $\mathbf{H}_{kk} = \mathbf{U}_{kk}\mathbf{\Lambda}_{kk}V_{kk}^{*}$, every singular value of $\mathbf{T}_{kk}$ equals P^{tx}/L_k. We see from Figure 4 that the gain from cooperation ranges from 2dB at low SNR to over 10dB at higher SNRs.

B. Frequency-selective fading

We also considered a simple but typical scenario of WiMax systems. Where channels are frequency selective, and modeled as in the EVM [1]. The inter-BS distance is 1,500m. MSs are uniformly distributed in a limited cell area so that any MS is at least 500m from its serving BS. Other simulation parameters are summarized in Table I. Without loss of generality, the channel path-loss values are normalized with respect to the largest in-cell path-loss in the cell. Channel errors on OFDM subcarriers are modeled as zero-mean complex Gaussian random variables, with same variance with AWGN. Results for the non-cooperative case and cooperative case are shown in Figure 5. Again we see significant gains from the cooperation which indicates that base station cooperation can be highly effective in IEEE 802.16m.

Table 1 WiMAX simulation parameters

FFT Size	1024
CP length	1/8
OFDM Symbol Duration	102.86 us
Frame length	5 ms
DL frame length	30 OFDM Symbols
Carrier Frequency	2.5 GHz
Bandwidth	10 MHz
Sampling Frequency	11.2 MHz
Subcarrier Allocation mode	AMC 1 x 6
Channel Model	Urban Macro-cell
MS velocity	5 m/s

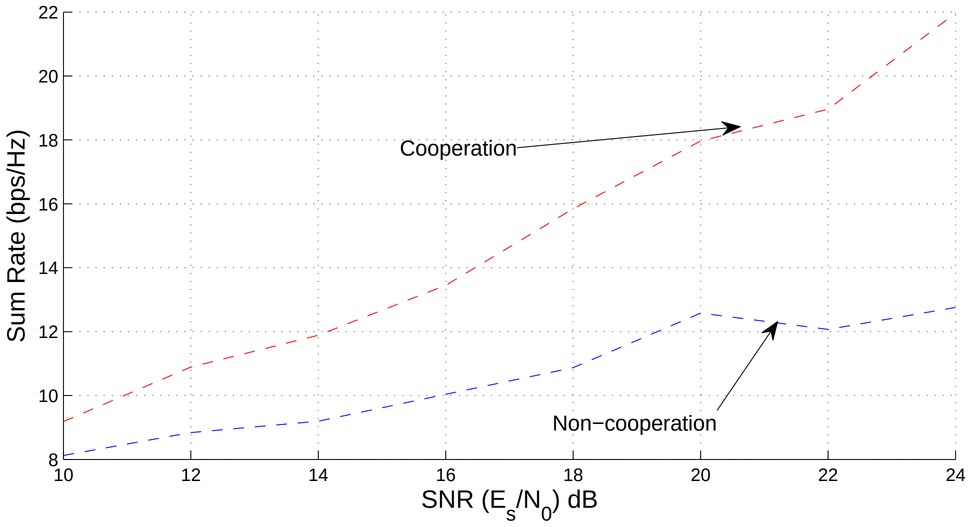

Figure 5 Sum Rate v. SNR for frequency selective (Urban-Macro) channels

Channel Estimation

In general, we note that in order to compute the precoding matrices the transmitter must have knowledge of the channels seen at the receiving MSs. The goal of this section is to determine the impact of imperfect channel knowledge on the achievable capacity of a cooperative system.

The previous section considered that the precoding matrices were computed under perfect channel knowledge. However, under the condition that the distance from the mobile station to the cooperating base stations are on the same order, which is typical for base station cooperation, the interference from the adjacent base station while performing channel estimation is non-negligible. In legacy IEEE802.16e systems channel estimation is performed during the transmission of preamble, midambles and/or during data transmission using pilot tones. Each channel sounding signal contains PN sequence, $\{c_{b,P}\}$ unique to each base station. Since for a cooperative system to operate correctly the transmissions from BSs need to occur simultaneously, a certain amount of interference (self-interference) is expected during channel estimation. This interference is due to the non-orthogonality of the channel sounding signals among the base stations.

To analyze this interference, consider again a simple system with two BSs cooperating to deliver information to two MSs near the cell edge. We consider the following System parameters:

- N: number of subcarriers in the orthogonal frequency division multiplexing (OFDM) systems;
- L: number of taps in the tap delay model of frequency selective fading channels;
- P: number of pilot symbols in a frame;
- K: number of subcarriers between adjacent pilot symbols.
- $\mathbf{h}_i$: column vector of dimension L x 1 consists of L channel taps for the channel from base station to user i in the time-domain

During the channel sounding (which can occur during the transmission of preambles, midambles, or data with pilots) the receiver computes a channel estimate based on the received signal

$$\mathbf{Y} = \sum_{b=1}^{2} \begin{bmatrix} c_{b,0} & & \\ & \ddots & \\ & & c_{b,P-1} \end{bmatrix} \mathbf{F}\mathbf{h}_b + \mathbf{n}$$

Equation 2

Where $\mathbf{n}$ is the $P\times 1$ complex noise vector on the pilot subcarriers and $\mathbf{F}$ is a $P\times L$ DFT matrix given by

$$\mathbf{F} = \begin{bmatrix} w^0 & w^0 & w^0 & \cdots & w^0 \\ w^0 & w^K & w^{2K} & \cdots & w^{(L-1)K} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ w^0 & w^{(P-1)K} & w^{(P-1)2K} & \cdots & w^{(P-1)(L-1)K} \end{bmatrix} \text{ with } w = \exp(-j2\pi/N) = \exp(-j2\pi/(KP))$$

Equation 3

The goal of the receiver is to estimate the channels $\mathbf{H}_b$, $b = 1,2$, from the sounding signaling. Note that $\mathbf{H}_b$, is the frequency response of the channel which is the Fourier transform of $\mathbf{h}_b$. Suppose the mobile station performs least-square (LS)

estimate for both of the downlink channels. Without loss of generality (WLOG), we focus on the estimate of $\mathbf{H}_1$. The sufficient statistics for the estimate of $\mathbf{H}_1$ can be expressed as

$$Y_1 = Fh_1 + \begin{bmatrix} c_{1,0}c_{2,0} & & \\ & \ddots & \\ & & c_{1,P-1}c_{2,P-1} \end{bmatrix} Fh_2 + \begin{bmatrix} c_{1,0} & & \\ & \ddots & \\ & & c_{1,P-1} \end{bmatrix} n = Fh_1 + \begin{bmatrix} c_{1,0}c_{2,0} & & \\ & \ddots & \\ & & c_{1,P-1}c_{2,P-1} \end{bmatrix} Fh_2 + n_1$$

Equation 4

Note that the noise vector $\mathbf{n}_1$ has the same characteristics as the noise vector $\mathbf{n}$. The LS estimate of $\mathbf{h}_1$ is then given by

$$\hat{h}_1 = (F^*F)^{-1}F^*Y_1 = h_1 + (F^*F)^{-1}F^* \begin{bmatrix} c_{1,0}c_{2,0} & & \\ & \ddots & \\ & & c_{1,P-1}c_{2,P-1} \end{bmatrix} Fh_2 + (F^*F)^{-1}F^*n_1$$

Equation 5

The second term in the far right hand side of the above equation is actually the interference from base station 2 when doing channel estimation for base station 1. If the PN sequences are not orthogonal to each other and the fading is not frequency flat, the interference level can be substantial.

We compare the performance of two base station cooperation systems as follows. In the first system, the channel gains of the downlink channels are assumed to be perfectly known at the base station. The corresponding system throughput of the cooperation system as a function of signal to noise ratio (SNR) is plotted as a dashed line in Figure 6In the second system, we assume that the channel gains of the downlink channels are actually estimated using the least-square (LS) estimator analyzed in this section. In this setting, both of the base stations which participate in the cooperation will send their midambles for the MIMO zone simultaneously through 2 transmit antennas. Each base station is equipped with a unique base station ID specified by IEEE 802.16e and each transmit antenna of the same base station has a different midamble sequence. The transmitted power of the preambles from the two base stations are the same.

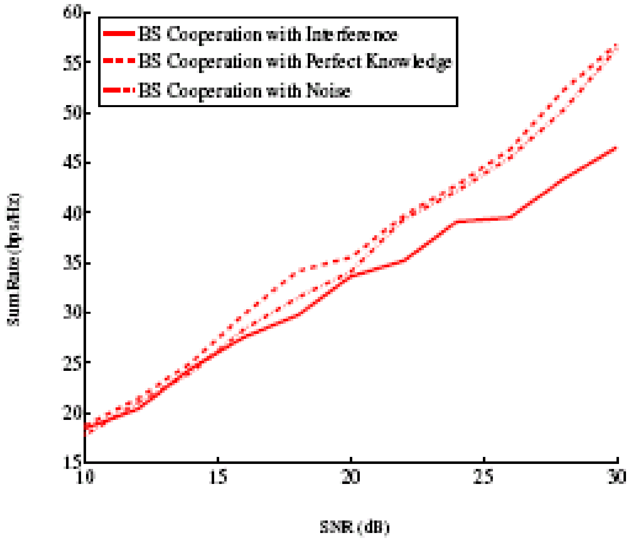

Figure 6 Sum Rates of cooperation with imperfect channel estimation.

The effects of the channel estimation errors on the system performance are clearly shown in Figure 6. The solid line shows the actual system throughput of the base station cooperation system as a function of SNR.

There are two interesting observations.

- First, there is a large gap in terms of sum rate between the perfect channel knowledge and channel estimation in the presence of interference.
- Second, as the SNR increases, unlike the noninterference system, the gap actually increases and the throughput of base station cooperation under channel estimation errors quickly hits a floor. This is because at large SNRs the base station cooperation system is actually operating in the interference-limited regime.

These observations lead us to consider the modification of the channel sounding in IEEE 802.16m. The task group should consider the design of channel sounding techniques that maintain orthogonality among the BSs that are cooperating to deliver data to multiple MSs. This orthogonality can be easily achieved in time, by interleaving midamble symbols, so that a receiver can estimate each channel without interference from other BSs. This is illustrated in Figure 7. This scheme has the drawback of some minor increased overhead, but the capacity gains from cooperation clearly out weigh the overhead. Essentially, this amounts to interleaving midambles so that they are not necessarily transmitted simultaneously from each BS. This requires a modification to the existing frame structure that would increase the number of midamble symbols so that the time interleaving can be accomplished. Alternatively, the orthogonality can be maintained in the frequency domain by dividing the available subcarriers in midamble symbols. Each cooperating base station can then use an orthogonal subset of subcarriers when transmitting its channel sounding sequence.

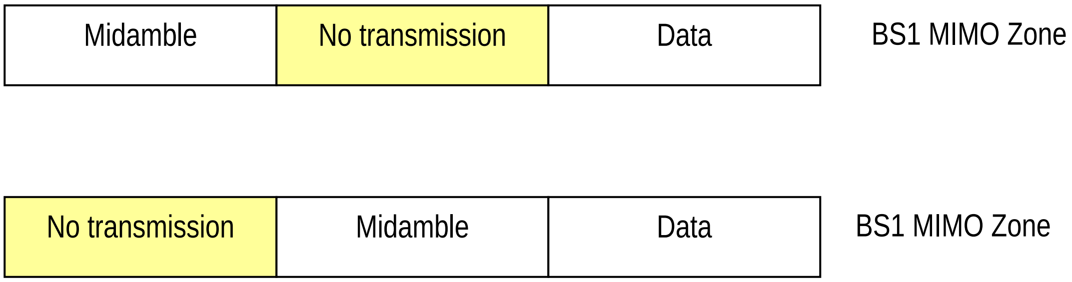

Figure 7 Example of time orthogonal midamble transmission

References

[1] IEEE 802.16m-008/004, “802.16m Evaluation Methodology”

[2] H. Zhang, N.B. Mehta, A.F. Molisch, J. Zhang and H. Dai, “Asynchronous Interference Mitigation in Cooperative Base Station Systems,” *IEEE Trans. Wireless Communications*, accepted in 2007.