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CDMA Initial Ranging in OFDMA PHY

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1 Introduction

802.16-2004 defines an initial ranging scheme that is based on transmitting either a single or two CDMA codes over 6 subchannels (8 with optional PUSC). The standard also defines repetition coding and mini-subchannelization as practical means for providing adequate cell coverage - repetition code lowers the per-tone SNR required for decoding, and mini-subchannels reduce the transmission bandwidth (allowing a power-limited SS to transmit more power per tone).

With a single receive antenna at the BS, the detection performance is not acceptable with the single-code 2-symbol scheme, and is only marginal when utilizing the inefficient 4-symbol scheme. The reason for this is two-fold:

- First, the ranging subchannel requires much more bandwidth than typically used by a power-limited SS, leading to reduction of power-per-tone when the ranging signal is transmitted.
- Second, full coherent detection over all subcarriers is possible with data but not with ranging (without resorting to high-complexity algorithms). Note that this problem exists even when there is no contention on the ranging slot.

In addition, the BS may be deployed with multiple receive antennas in order to mitigate the acute misbalance between DL and UL link budget. Unfortunately, it turns out that in such cases, both initial ranging schemes fail with power-limited SSs that use either repetition coding or mini-subchannelization. The situation is more sever than the single-antenna case since with ranging we do not leverage the coherent antenna combining possible with data.

In the next section we present an analysis that showcases the problem following by performance results. Our proposal is outlined in section 5, and two alternatives for text changes are provided in sections6-6.

2 Analysis

In this section we analyze the SNR level required for detecting *a single code with no contention*. Note that the presence of multiple codes over the ranging channel will increase this requirement even further.

3 Detection of a single code in a Rayleigh channel

Let us consider the basic problem of detecting a single code transmitted over a Rayleigh channel in the presence of white Gaussian noise.

3.1 Problem statement

Let $\underline{x} = \{x_1, x_2, \ldots, x_M\}^T$ denote the code vector transmitted over the vector channel. The code element x_i are sent over M subcarriers. For each subcarrier, the received signal, r_i, is given by :

$$r_i = c_i x_i + v_i \qquad 1 \le i \le M \tag{1}$$

Where

c_i is the complex channel response
v_i is the additive noise.
M denotes the number of active subcarriers in the ranging code.

The formalization can also extend to the case where there are multiple receive antennas and/or multiple transmit OFDM symbols. In this case M denotes the number of active subcarriers in a symbol times the number of antennas times the number of OFDMA symbols. For such cases we define N_s to denote the number of OFDMA symbols used for the ranging slot and N_A to denote the number of receive antennas.

We assume that the additive noise v_i is an I.I.D. Gaussian random variable with zero mean and variance N_0.
Next, we assume that the channels are Rayleigh. Let $\underline{c} = \{c_1, c_2, \ldots, c_M\}^T$ define the channel vector. We assume that $\underline{c}$ is a Gaussian random vector with zero mean and autocorrelation matrix R_c.

By defining $\underline{X}$=diag($\underline{x}$), equation (1) can be written as

$$\underline{r} = \underline{X}\,\underline{c} + \underline{v} \tag{2}$$

Here $\underline{r} = \{r_1, r_2, \ldots, r_M\}^T$ and $\underline{v} = \{v_1, v_2, \ldots, v_M\}^T$.

We define E_s as the total energy per one symbol summed over all receive antennas. We then define the signal to noise ratio as:

$$E_s / N_0 = \frac{x^H x}{N_s \cdot N_0} \tag{3}$$

The problem at hand is to detect the known transmitted code $\underline{x}$ over the channel with a prescribed false alarm rate P_{FAR} and to determine the misdetection probability. For this we need to compute the log likelihood ratio

$$\eta(r) = \log \frac{P(\underline{r}|\underline{x})}{P(\underline{r}|\underline{0})} \tag{4}$$

A detection is announced if $\eta(\underline{r}) > \eta_0$, where η_0 is chosen to meet the required P_{FAR}.

3.2 The Optimal Detector

We begin by writing

$$P(\underline{r}|\underline{X}) = \int P(\underline{r}|\underline{X},\underline{c})P(\underline{c})d\underline{c} \qquad (5)$$

Now according to the assumptions in the previous section:

$$P(\underline{r}|\underline{X},\underline{c}) = \frac{1}{N_0^M \pi^M}\exp\left(-\frac{1}{N_0}\left\|r-\underline{X}\,\underline{c}\right\|^2\right) \qquad (6)$$

and

$$P(c) = \frac{1}{|R_c|\pi^M}\exp\left(-\underline{c}^H R_c^{-1}\underline{c}\right). \qquad (7)$$

Here |.| denotes the determinant operator. We assume that R_c is perfectly known. This is not a trivial assumption. For instance in OFDM timing offset will modify the phase of the elements of R_c. However we ignore this effect in the analysis.

From (6)- (8) we obtain

$$P(\underline{r}|\underline{X}) = \frac{|D|}{N_0^M \pi^M}\exp\left\{r^H X D^{-1}\ X^H r - \frac{1}{N_0} r^H r\right\} \qquad (9)$$

where

$$D = \left(\frac{1}{N_o}X^H X + R_c^{-1}\right)^{-1} \qquad (10)$$

Using (9) we can compute the likelihood ratio. For the case of no signal *X=0* and so

$$\eta(\underline{r}) = \underline{r}^H XDX^H r \overset{?}{>} \eta_0 \qquad (11)$$

where some additive factors were absorbed into η_0.

Since the code symbols are of equal magnitude, condition (11) can be somewhat simplified. Defining |xi|=const and

$$\underline{y} = \underline{r}\,\underline{X}^H \qquad (12)$$

we arrive at:

$$\eta(\underline{y}) = \underline{y}^H \underline{B}\,\underline{y} \qquad (13)$$

where

$$\underline{B} \equiv \left(\frac{1}{M}\frac{E_s \cdot N_s}{N_0} I_{MxM} + R_c^{-1}\right)^{-1} \qquad (14)$$

3.3 A sub-optimal solution for the tiled case.

In this section we consider the detector for the specific case of tiled signals.
Let us look at the time representation of the channel. Let *h(t)* denote the channel impulse response. Let *P(t)* denote the channel delay profile, so that:

$$E\{h^*(t_1)h(t_2)\} = P(t_1)\delta(t_1 - t_2) \quad (15)$$

Now the (k,ℓ) element of R_c is given by

$$R_c(k,\ell) = F^{-1}\{P\{t\}\}\Big|_{f=(k-\ell)\Delta f} \quad (16)$$

Where F^{-1} is the inverse Fourier transform and Δf is the subcarrier spacing.

Now we consider the specific case of the 802.16-2004 waveform. The ranging signal is composed of 144 subcarriers arranged in 36 tiles of 4 subcarriers for the case of PUSC, and in 48 tiles of 3 subarriers for the case of Optional PUSC. The tiles are spread across the allocated bandwidth according to a permutation formula (with Optional PUSC, the tiles are spread over 1/3 of the bandwidth).

We make the following simplifying assumptions:

- For the PUSC permutation, the channel is uncorrelated from tile to tile. Assuming 10MHz bandwidth, the spacing between the ranging tiles is 260KHz on average. The permutation may cause some tiles closer to other, however we do not assume that this is the case. In many practical channels this indeed leads to uncorrelated tiles.

- For the Optional PUSC permutation, we break the tile sequence in frequency into consecutive triplets, and assume that the channel is completely correlated within a tile triplet, and uncorrelated between different triplets. This may be partly justified by the fact that for 10MHz bandwidth, the spacing between tiles is a mere 67KHz.

- The channel response is completely correlated between subcarriers of the same tile, and between same subcarriers of consecutive OFDMA symbols.

- Channels realizations are uncorrelated between the antennas.

Let:
N_t denote the number of tiles.
S denote the number of subcarriers within a tile
N_A denote the number of antennas,
N_s denote the number of OFDMA symbols.

Here $M=N_t * S * N_A * N_s$.

Under the above assumptions we can coherently combine subcarrier groups of same tile, possibly in different symbols. Let the vector $\underline{z} = \{z_1, z_2, \ldots, z_{Nt*NA}\}$ denote the result of this coherent combining operation, namely:

$$z_n = \sum r_i x_i^H \qquad (17)$$

where the sum in (17) is over the $S*N_s$ subcarriers of the same tile.

For the above assumptions the detector (11) is

$$\eta(\underline{z}) = \underline{z}^H \underline{z} \qquad (18)$$

In the case that the signal is not transmitted, $\underline{z}^H z$ is centric chi square with $2*N_t*N_A$ degrees of freedom. The variance of z_n is $S*N_s*N_0$. In the case the signal is transmitted, $\underline{z}^H z$ is non–centric chi square with $2*N_t*N_A$ degrees of freedom and non-centrality parameter of $N_t*N_A*(E_s*N_s/M)*(S*N_s)^2$. z_n has variance of $S*N_s*N_0$. Recall that E_s denotes the signal energy over <u>one</u> symbol and over <u>all</u> antennas.

4 Results

4.1 UL PUSC

Let us consider a power-limited SS at the cell edge able to decode QPSK rate ½ when transmitting over a 2-tile mini-subchannel (8 active subcarriers per symbol).

Assuming that the post-combining C/I level for QPSK ½ is 4dB, we have E_s/N_0 = 4+10*log$_{10}$(8) = 13dB, with energy summed over all receive antennas.

In Figure 1, we set the threshold η_0 so that P_{FAR} = 1% and consider the misdetection rate for 1, 2, and 4 receive antennas as a function of E_s/N_0. The dashed vertical line represents the required E_s/N_0 for the above SS. '1 code' is the initial ranging scheme that uses 2 OFDMA symbols, '2 codes' refers to initial ranging over 4 OFDMA symbols.

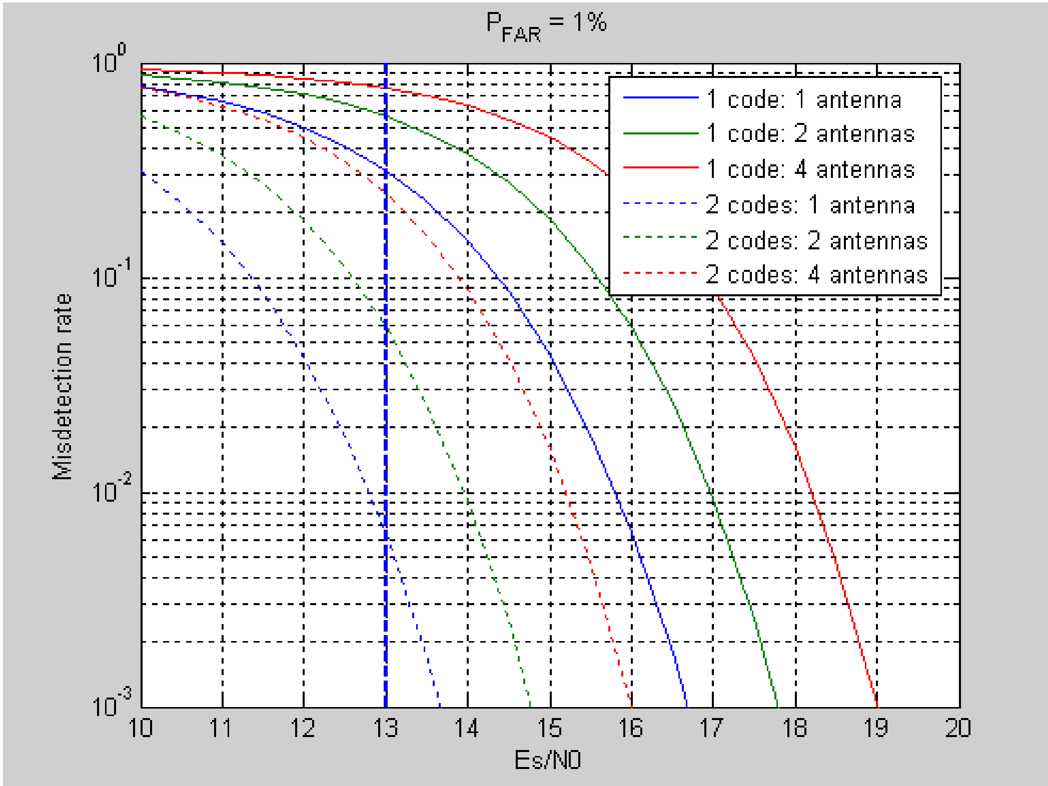

Figure 1 – Initial ranging with PUSC: Misdetection probability for false alarm rate of 1%

4.2 UL Optional PUSC

We repeat the same analysis for optional PUSC. For the same assumptions, the required E_s/N_0 is $4+10*\log_{10}(6) = 11.8$dB, with energy summed over all receive antennas.

Again we set the threshold η_0 so that $P_{FAR} = 1\%$ and consider the misdetection rate. The figure below shows the misdetection rate for 1, 2, and 4 receive antennas as a function of E_s/N_0. The dashed vertical line represents the required E_s/N_0 for the above SS. '1 code' is the initial ranging scheme that uses 2 OFDMA symbols, '2 codes' refers to initial ranging over 4 OFDMA symbols.

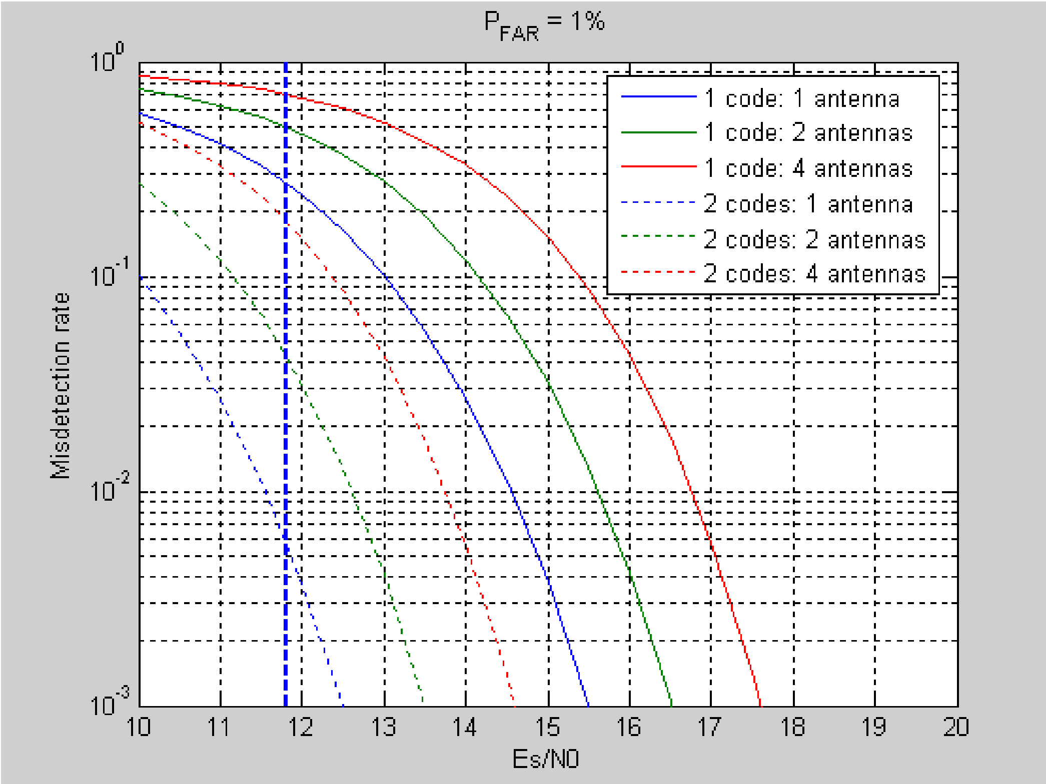

Figure 2 - Initial ranging with Optional PUSC: Misdetection probability for false alarm rate of 1%

4.3 Conclusions

The following can be concluded from the above analysis:

- The single-code initial ranging scheme fails: misdetection rate is above 25-30% with 1 receive antenna, and close to 70-80% with 4 receive antennas.
- The two-code initial range scheme leads to 0.7% misdetection rate with 1 antenna, 5%-6% with 2 antennas, and 20%-25% misdetection probability with 4 antennas.
- The results are **optimistic** in the sense that they do not consider multiple code hypotheses or code contention.

Initial ranging fails for users that require repetition or 1/3 mini-subchannelization, when more than 1 receive antenna is used at the BS. Performance is marginal with a single antenna.

5 Outline of proposed solution

Increasing the power received per bit is one way to reduce the misdetection rate. This can be achieved by halving the bandwidth occupied by the 1-code initial ranging scheme and extending the transmission in time. Due to the diversity nature of the PUSC and optional PUSC permutations, a high frequency diversity order is maintained even after the bandwidth is halved.

The proposed alternative initial ranging scheme is as follows. Consider the existing 1-code configuration, in which the single 144-bit code is transmitted over 6 (or 8 with optional PUSC) subchannels and repeated over 2 symbols. The proposal is to transmit this single 144-bit code over 3 subchannels (4 with optional PUSC) and 4 symbols:

- Bits 0-71 are transmitted on symbol 1 and repeated on symbol 2;
- Bits 72-143 are transmitted on symbol 3 and repeated on symbol 4.

As a consequence, the ranging slot will have the same time duration as the current 2-code initial ranging scheme, however it will use half the bandwidth. Note that the same time/frequency resources as in the current 1-code scheme are utilized.

The proposal is depicted in the figure below.

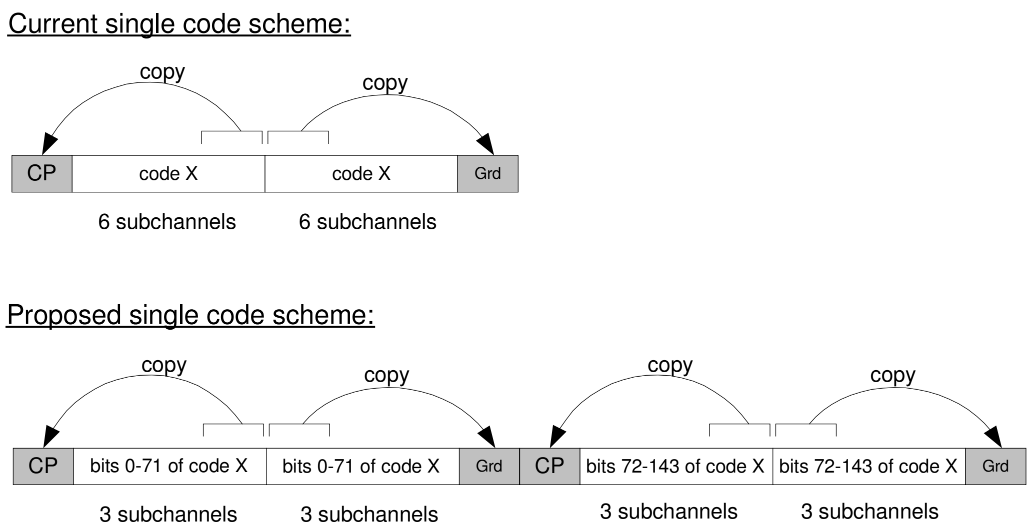

Figure 3 – Outline of proposed change

The figure below compares the misdetection rate of the proposed single-code scheme with the current single-code scheme, for PUSC ('1 code (alt)' refers to the proposed scheme).

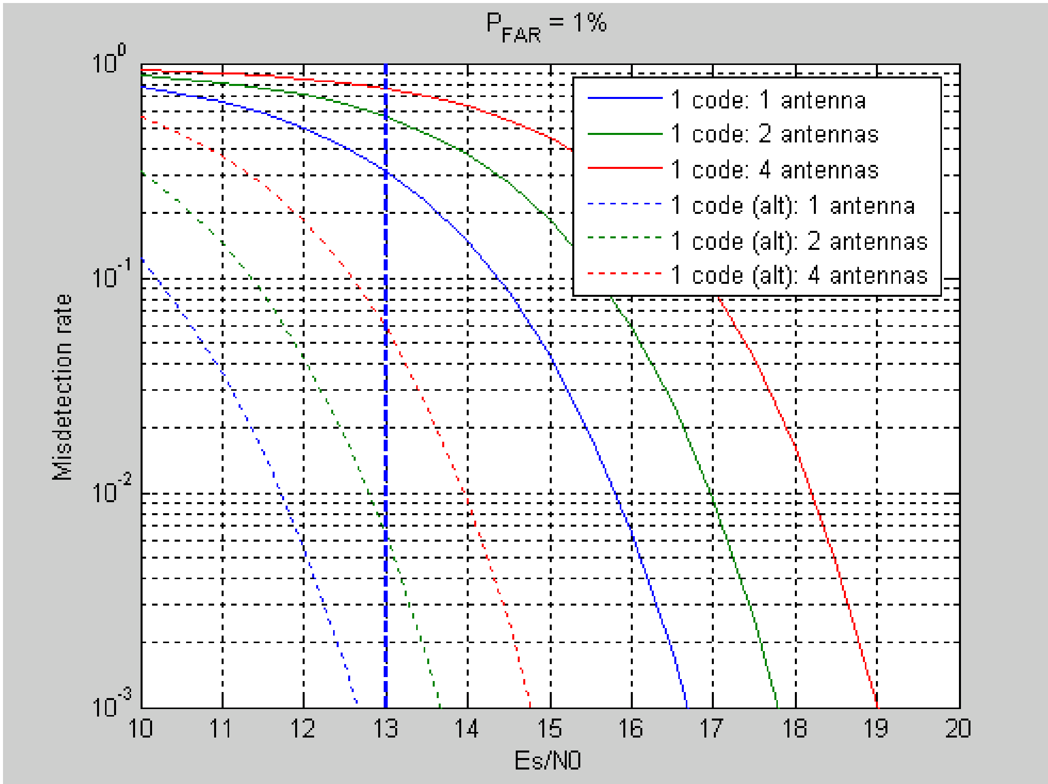

Figure 4 – Comparison of the current single code scheme with the proposed one, PUSC permutation.

The figure below makes the same comparison for Optional PUSC.

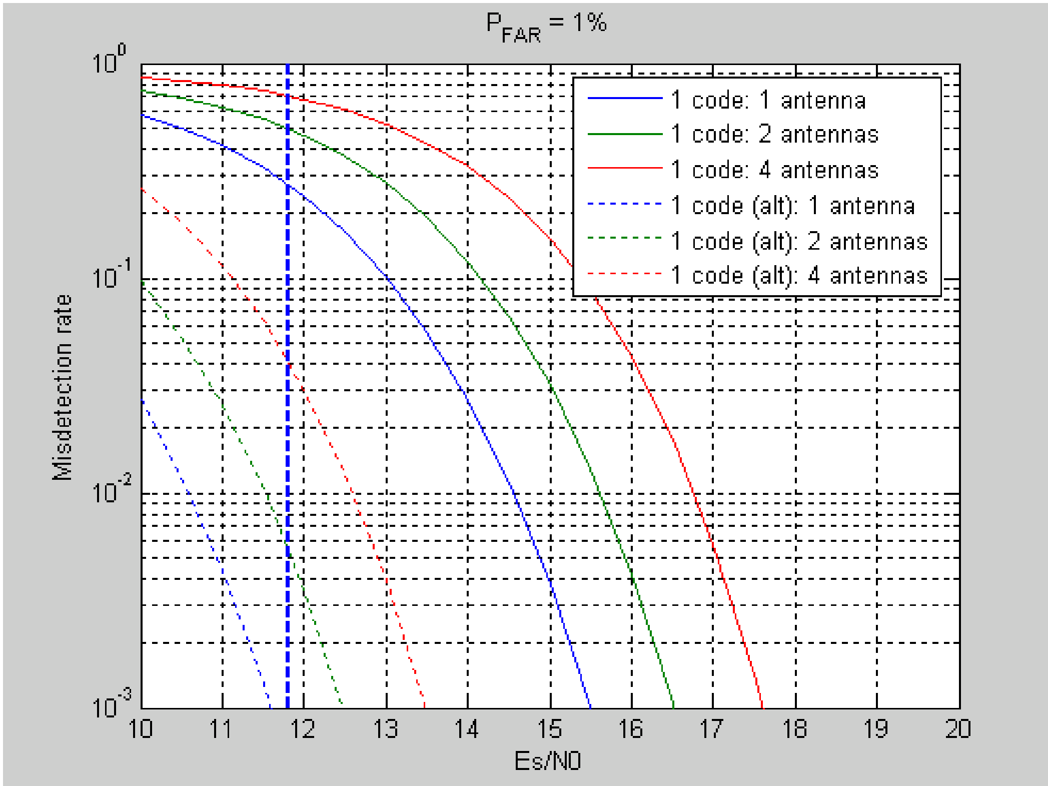

Figure 5 – Comparison of the current single code scheme with the proposed one, Optional PUSC permutation.

For the same misdetection rate, the alternative 1-code scheme provides a gain of 4dB relative to the current scheme, occupies the same frequency-time resources, and still maintains a high frequency diversity order.

6 Detailed Text Changes

[Add a new section 8.4.5.4.xx:]

8.4.5.4.xx Extended CDMA-Ranging IE

The extended CDMA-Ranging IE may be used to define additional types of CDMA-ranging regions. See section 8.4.7.1. The format of the IE is described in table XXX

Table XXX — Extended CDMA-Ranging IE format

Syntax	**Size**	**Notes**
STC_ZONE_IE() {		
Extended-2 UIUC	4	Extended_CDMA_RANGING = 0x0A
Length	8	Length
OFDMA Symbol offset	8	
Subchannel offset	7	
No. OFDMA Symbols	7	
No. Subchannels	7	
Ranging Method	2	0b00: Initial ranging type B over four symbols 0b01 – 0b11: Reserved
Dedicated ranging indicator	1	0: the OFDMA region and Ranging Method defined are used for the purpose of normal ranging 1: the OFDMA region and Ranging Method defined are used for the purpose of ranging using dedicated CDMA code assigned in the MOBPAG-ADV message.
Reserved	4	Shall be set to zero
}		

[Modify table 302h in section 8.4.5.4.21 as follows]

Ranging Method	~~2~~ 3	0b000 - Initial Ranging over two symbols 0b001 - Initial Ranging over four symbols 0b010 - BW Request/Periodic Ranging over one symbol 0b011 - BW Request/Periodic Ranging over three symbols 0b100 - Initial ranging type B over four symbols 0b101 – 0b111: Reserved
~~***Reserved***~~	~~1~~	~~Shall be set to zero~~
}		

[Modify first paragraph of 8.4.7 as follows:]

When used with the WirelessMAN-OFDMA PHY, the MAC layer shall define a single ranging channel. This ranging channel is composed of one or more groups of six adjacent subchannels (except in the case of four-symbol initial ranging of type B, where each group is comprised of three adjacent subchannels), where the groups are defined starting from the first subchannel. Optionally, ranging channel can be composed of eight adjacent subchannels (except in the case of four-symbol initial ranging of type B, where each group is comprised of four adjacent subchannels) using the symbol structure defined in 8.4.6.2.5. The indices of the subchannels that compose the ranging channel are specified in the UL-MAP message. Users are allowed to collide on this ranging channel. To effect a ranging transmission, each user randomly chooses one ranging code from a bank of specified binary codes. These codes are then BPSK modulated onto the subcarriers in the ranging channel, one bit per subcarrier (subcarriers used for ranging shall be modulated with the waveform specified in 8.4.7.1/8.4.7.2 and are not restricted to any time grid specified for the the data subchannels).

[Add the following text and figure before the end of section 8.4.7.1]

A four-symbol initial-ranging transmission of type B is defined as follows. The first half of the ranging code is transmitted in the 1^{st} symbol and repeated in the 2^{nd} symbol with no phase discontinuity. The second half of the ranging code is transmitted in the 3^{rd} symbol and repeated in the 4^{th} symbol, again with no phase discontinuity. A time-domain illustration of the type C initial-ranging transmission is shown in Figure 240a.

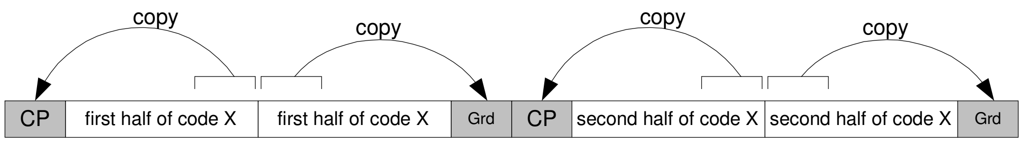

Figure 240a - Initial-ranging transmission type B for OFDMA, using a single code over four consecutive symbols

[Modify the 2^{nd} paragraph of 8.4.7.3 as follows:]

The binary ranging codes are subsequences of the pseudonoise sequence appearing at its output C_k. The length of each ranging code is 144 bits. These bits are used to modulate the subcarriers in ~~a~~ each group of adjacent subchannels (see section 8.4.7.2). ~~six (eight for the permutation defined in 8.4.6.2.5) adjacent subchannels.~~ The index of the lowest numbered subchannel in ~~the~~ each group of subchannels ~~six (eight for the permutation defined in 8.4.6.2.5)~~ shall be an integer multiple of the number of subchannels in the group ~~six (eight for the permutation defined in 8.4.6.2.5)~~. Each group of ~~The six (eight for the permutation defined in 8.4.6.2.5)~~ subchannels is ~~are~~ called a ranging subchannel. The ranging subchannel is referenced in the ranging and Bandwidth Request messages by the index of lowest numbered subchannel.