Project	**IEEE 802.16 Broadband Wireless Access Working Group** <http://ieee802.org/16>
Title	**Ranging Code Design for IEEE 802.16m**
Date Submitted	**2008-5-5**
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Re:	IEEE 802.16m-08/016, "Call for Contributions on Project 802.16m System Description Document (SDD)". In response to the following topics: • Uplink Control Structure
Abstract	The contribution proposes a single OFDM symbol based ranging code design and the associated channel assignment scheme for OFDMA systems. Our design allows an efficient initial ranging method which is capable of detecting single and multiple ranging codes, estimating the corresponding timing offsets and power levels without the aid of side information such as SNR or SINR.
Purpose	For 802.16m discussion and adoption
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Ranging Code Design for IEEE 802.16m

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I. INTRODUCTION

Orthogonal frequency division multiple access (OFDMA) has enjoyed a growing popularity because of its capability to deal with frequency-selective fading, high spectral efficiency, and great flexibility in radio resource allocation. In an OFDMA uplink system the base station (BS) partitions all subcarriers into subsets with disjoint subchannels. To support multiple users simultaneously, the BS assigns different users to transmit on their assigned subsets. To maintain the orthogonality among the subcarriers in such a system, the OFDM signals from all active users should arrive at the BS synchronously. The initial uplink synchronization procedure refers to the process in which ranging subscriber stations (RSSs) adjust their transmission time instants and transmission powers so that at the BS their signals synchronize to the mini-slot boundary of the BS and have almost equal power. A ranging process includes initial ranging and periodic ranging. Any RSS who wants to synchronize to the BS for the first time shall use initial ranging to achieve its desired goals. Periodic ranging is needed to cope with the time-variant nature of a mobile environment. This contribution focuses on the initial ranging process only but an extension to periodic ranging would be straightforward.

As described in [1], a RSS senses a BS, accomplishes downlink synchronization and acquires uplink transmission parameters. Then, it chooses one of the available frequency-domain ranging codes randomly and transmits its ranging symbol twice over two consecutive OFDM symbols with BPSK modulation on the ranging channel in a randomly chosen ranging time-slot. When a BS receives the ranging symbols from several RSSs, it must detect be capable of detecting RSSs based on their ranging codes. After separating colliding codes, the BS will extract the timing information and the associated power for each RSS. The BS then broadcast a ranging response to notify all active RSSs that they should adjust to the corresponding time-slot. The ranging response contains not only the adjustment information (e.g. timing and power adjustments) but also the status information (e.g. success, retransmission). Before receiving the “success” notification, each RSS should adapt its power and timing to satisfy the corresponding adjustment at each iteration. The ranging process shall continue until being notified otherwise.

There are a few investigations [2]-[5] on the initial ranging for the IEEE 802.16e standard [1] or general OFDMA systems. These works fall into two major categories. The first category [2], [3] is based on the ranging codes of [1]. In [2], a frequency domain correlator bank is used to detect the multi-user ranging codes by comparing the correlators’ outputs with a fixed threshold. Since the output statistic is a function of the multi-user interference, which in turn depends on the number of RSSs, the cross-correlations of the ranging codes used, and the corresponding power and noise levels, a fixed detection threshold would not be able to provide robust performance. Fu and Minn [3] suggested using an adaptive threshold for a time-domain correlator bank and, as expected, obtained a better performance.

The second category [4], [5] proposes ranging code structures other than that defined by [1]. Zhuang *et al.* [4] partitions all active RSSs into different groups. Each group is given its specific and non-overlapping subchannels, consisting of consecutive adjacent subcarriers, such that the multiple-period ranging signals from different groups will not interfere with each other within an observation window of a single OFDM symbol. Furthermore, the number of subcarriers within a subchannel is equal to the code duration. As consecutive subcarriers are assigned to an user, diversity is lacking. Frequency-selective fading and propagation delay variation of RSSs increase the ranging complexity and degrade the performance. Fu, Li and Minn [5] suggests an interleaved channel assignment scheme (CAS) to overcome the major drawbacks of the above approache. However, their method requires that multiple-symbol ranging code be used.

We propose a new family of ranging codes and the corresponding CAS which enables a BS to employ a multiple signal classification (MUSIC) based algorithm to detect multiple RSSs and estimate the corresponding timing offsets [6]-[7]. Our design uses only one OFDM symbol and gives robust, excellent multi-user detection and timing estimation performance. Compared with the performance of existing works, our ranging code design and its detection method yield improved performance and greater immunity against the interference from multi-users and frequency selective fading. Side information such as signal-to-noise (power) ratio (SNR) or signal-to-interference-plus-noise ratio (SINR) is not needed.

The rest of this contribution is organized as follows. The ensuing section describes System models. Our ranging signal design is presented in Section III, and proposed ranging method is introduced in Section IV. Simulation results and discussions are reported in Section V. Finally, conclusions are given in Section VI.

Notation: $\lfloor\ \rfloor$ denotes the floor operation. $[i]_M$ represents i modulo M. $(.)^{\mathbf{T}}$ and $(.)^{\mathbf{H}}$ denote transpose and Hermitian operations.

II. CHANNEL ASSIGNMENT AND SYSTEM DESCRIPTION

The same number of subcarriers as that specified in [1] are used for the proposed ranging code structure so that a fair comparison can be made. The proposed frequency domain interleaved-subband channel assignment scheme (IS-CAS) is shown in Fig. 1. Subcarriers are divided into N_{gp} groups with each group having N_b subbands and each subband consisting of N_c consecutive subcarriers such that each group can support a maximum of M RSSs. The bandwidth of a subband is less than the coherent bandwidth to ensure the channel gain of each subcarrier within a subband is approximately the same. On the other hand, the subbands of a group are interleaved so that the frequency spacing between subbands, D_b, is larger than the coherent bandwidth to guarantee that channel responses of subbands are uncorrelated and diversity gain is achieved at the receiving end.

Let S_j be the set of indices of the subcarriers allocated to the jth group and denote by R_{ij} the ith RSS in the jth group which employs the frequency domain ranging code $\{C_{ij}(l) : l = 1, \cdots, N_bN_c\}$. The frequency domain ranging signal $X_{ij}(k)$ for R_{ij} is defined as

$$X_{ij}(k) = \begin{cases} A_{ij}C_{ij}(l), & k \in S_j,\ l = 1, 2, \cdots N_bN_c \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

where $|C_{ij}(l)| = 1$ and A_{ij} is the relative amplitude of R_{ij}.

Consider an operation scenario in which different RSSs are randomly distributed over the coverage of a BS such that their ranging signals arrive at the BS asynchronously. The maximum transmission delay D_{max} (samples) equals to the round-trip propagation delay between the BS and a RSS at the boundary of the cell. To avoid inter subcarrier interference (ICI) and inter symbol interference (ISI), the length of the cyclic prefix (CP), N_g, must be larger than the sum of D_{max} and the maximum delay spread among all uplink ranging channels L (samples). With the CP inserted, the time domain ranging signal for R_{ij} is given by

$$x_{ij}(n) = \begin{cases} x_{ij}(n), & \text{if } n = 0, \cdots, N-1 \\ x_{ij}(n+N), & \text{if } n = -N_g, \cdots, -1 \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Assuming the uplink channels remain static within a symbol duration and ignoring the presence of noise for the moment, we express the received ranging waveform $y_{ij}(n)$ for R_{ij} as

$$y_{ij}(n) = \sum_{l=0}^{L-1} h_{ij}(l) x_{ij}(n-l) \tag{3}$$

where $h_{ij}(l),\ l = 0, \cdots, L-1$ are the associated channel tap weights. The received signal at the BS thus become

$$y(n) = \sum_{j=0}^{N_{gp}-1} \sum_{i=0}^{M-1} y_{ij}(n) + w(n) \tag{4}$$

where $\{w(n)\}$ are independent and identical distributed (i.i.d.) complex circular symmetric Gaussian random variables with zero mean and variance $\sigma_w^2 = E[|w(n)|^2]$.

As shown in Fig. 2, we consider an observation window of width $N + N_g$ samples so that each received RSS signal has contributed N samples of a OFDMA symbol period and that, after discrete Fourier transform, the resulting frequency domain signal is ISI-free.

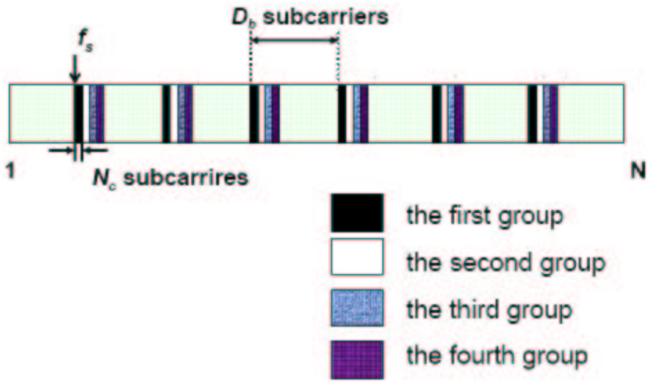

Fig. 1. Interleaved-subband channel assignment scheme for the case, $N_{gp} = 4$ and N_b=6.

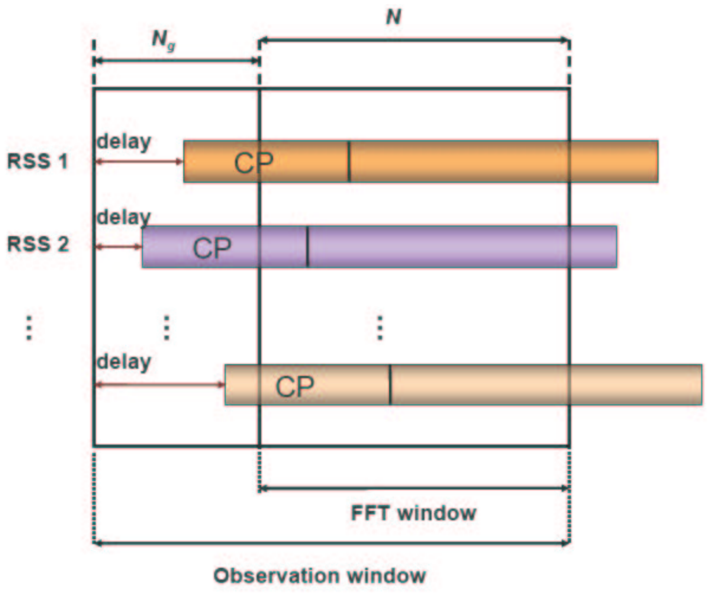

Fig. 2. Time-domain relationships of various arriving RSS signals within a BS observation window.

III. PROPOSED RANGING SIGNAL STRUCTURE

The maximum supported RSSs in one group, M, is set to be $\min\{[N/N_g],\ N_b - 1,\ N_c\}$. In practice, $[N/N_g]$ is usually larger than 2, hence a judicial choice of $\{N_b, N_c\}$ is needed to ensure $M > 2$. Let f_s be the lowest subcarrier index allocated for the ranging codes and for $0 \leq j \leq N_{gp} - 1$ define

$$S_j = \{f_s + jN_c + kD_b + l : 0 \leq k \leq N_b - 1, 0 \leq l \leq N_c - 1\}. \tag{5}$$

Without frequency-synchronization error, the ranging signals from different groups remain orthogonal upon arriving the BS. To distinguish the RSSs in the same group, we let the ranging code, $\{C_{ij}(l)\}$, for the R_{ij} be given by

$$C_{ij}(l) = e^{-j2\pi i[l]_{N_c}/M},\ i = 0,\ 1, \cdots,\ M - 1. \tag{6}$$

In contrast to the CDMA codes used in [1], the above ranging codes have simpler structure and are easier to generate. Such an arrangement also ensures that the overall frequency-domain phase shifts of all RSSs in the same group are non-overlapping over $\left(\frac{2\nu\pi}{M},\ \frac{2(\nu+1)\pi}{M}\right)$, where $\nu = 0,\ 1, \cdots,\ M - 1$, if $N_g \leq N/M$. Hence, the RSSs in the same group can be detected and decoupled easily without using multiple OFDM symbols, giving a better rate and throughput performance.

IV. RANGING METHOD

Let the timing estimation error for R_{ij} be denoted by $\Delta d'_{ij}$. It was found [8] that whenever $\Delta d'_{ij} \in [-N_g + L - 1, \leq 0]$, $\Delta d'_{ij}$ results in only a cyclic phase shift of the received OFDMA symbol. But if $\Delta d'_{ij}$ is outside $[-N_g + L - 1, 0]$, then the orthogonality among subcarriers is lost and ICI will arise. Our estimate thus assume that the timing offset d_{ij} for R_{ij} is equal to the sum of the transmission delay and the channel group delay. When a RSS receives the timing offset estimate from the BS, it adjusts its timing accordingly and retransmit its ranging code with both cyclic prefix and postfix to avoid loss of orthogonality.

The code structure of (7) and the assumption that the subband bandwidth is smaller than the uplink channel's coherent bandwidth imply that the channel gains within a subband are related by

$$H_{ij}(l+k) \approx H_{ij}(l)e^{-j2\pi k(\frac{i}{M}+\frac{d_{ij}}{N})}, \tag{7}$$

where $k = 0,\ 1, \cdots,\ N_c - 1$.

Let the received frequency domain signal within the jth group be denoted by $Y_j(1), Y_j(2), \cdots, Y_j(N_cN_b)$ and the corresponding channel gains by $H_j(1), H_j(2), \cdots, H_j(N_cN_b)$, $j = 0, 1, \cdots, N_{gp} - 1$. Define the $N_c \times N_b$ matrix $\mathbf{Y_j}$ by

$$\mathbf{Y_j} = \begin{pmatrix} Y_j(1) & Y_j(N_c+1) & \cdots & Y_j(N_c(N_b-1)+1) \\ \vdots & \vdots & \ddots & \vdots \\ Y_j(N_c) & Y_j(2N_c) & \cdots & Y_j(N_cN_b) \end{pmatrix} \tag{8}$$

and the $N_c \times M$ matrix

$$\mathbf{V_j} = \begin{pmatrix} \mathbf{v}_{0j} & \mathbf{v}_{1j} & \cdots & \mathbf{v}_{(M-1)j} \end{pmatrix} \tag{9}$$

where

$$\mathbf{v}_{ij} = \left(1, e^{-j2\pi(\frac{i}{M}+\frac{d_{ij}}{N})}, \cdots, e^{-j2\pi(N_c-1)(\frac{i}{M}+\frac{d_{ij}}{N})}\right)^{\mathbf{T}} \tag{10}$$

and the diagonal matrix

$$\mathbf{A_j} = \begin{pmatrix} A_{0j} & 0 & \cdots & 0 \\ 0 & A_{1j} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A_{(M-1)j} \end{pmatrix}. \tag{11}$$

Then we have

$$\mathbf{Y_j} = \mathbf{V_j A_j H_j} + \mathbf{W_j} \tag{12}$$

where $\mathbf{W_j}$ is a matrix of i.i.d. complex white Gaussian variables with zero mean and variance σ_w^2 and $\mathbf{H}_j$ is given by

$$\mathbf{H}_j = \begin{pmatrix} H_{0j}(1) & H_{0j}(N_c+1) & \cdots & H_{0j}(z) \\ H_{1j}(1) & H_{1j}(N_c+1) & \cdots & H_{1j}(z) \\ \vdots & \vdots & \ddots & \vdots \\ H_{(M-1)j}(1) & H_{(M-1)j}(N_c+1) & \cdots & H_{(M-1)j}(z) \end{pmatrix}. \tag{13}$$

z is equal to $N_c(N_b - 1) + 1$.

A. Multi-user Ranging Signal Detection and Timing Offset Estimation

The covariance matrix of $\mathbf{Y_j}$ defined by

$$\mathbf{\Phi_j} = \frac{\mathbf{1}}{N_b} \mathbf{Y_j} \mathbf{Y_j}^{\mathbf{H}}. \tag{14}$$

is a Hermitian matrix whose eigenvalues values are non-negative. Let $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_{N_c}$ be the N_c eigenvalues of $\mathbf{\Phi}_j$ in descending order. When there are κ_j RSSs in the jth group, $\kappa_j \leq M$, we have $N_c - \kappa_j$ basis vectors which span the null space $\mathbf{U_{wj}}$ and can be obtained by performing singular value decomposition (SVD) of $\mathbf{\Phi_j}$. An estimate $\hat{d}_{ij}$ of the timing offset associated with R_{ij} corresponds to one of the largest κ_j local maximum of

$$\frac{\|\alpha^{\mathbf{H}}(d)\alpha(d)\|}{\|\alpha^{\mathbf{H}}(d)\mathbf{U}_{wj}\mathbf{U}_{wj}^{\mathbf{H}}\alpha(d)\|} \tag{15}$$

where $\alpha(d) = [1,\ e^{-j2\pi d/N}, \cdots,\ e^{-j2\pi d(N_c-1)/N}]^{\mathbf{T}}$.

The vector $\hat{\mathbf{d}} = (\hat{d}_{1j}, \hat{d}_{2j}, \cdots, \hat{d}_{Mj})^T$ which represents the delay estimates of the delays of the active RSSs in the jth group is obtained by using the received samples in one OFDMA symbol and following the steps given below.

1) Arrange the received frequency domain samples in matrix form $\mathbf{Y_j}$. Set $\hat{\kappa}_j$ equal M.
2) Apply SVD to $\mathbf{\Phi_j}$ to find the $N_c \times \hat{\kappa}_j$ matrix $\hat{\mathbf{U}}_{\mathbf{wj}}$.
3) Find the largest $\hat{\kappa}_j$ peaks of (15) to estimate $\hat{\mathbf{d}}$ for $\hat{\kappa}_j$ RSSs. Check the $\hat{\kappa}_j$ peaks' values with the threshold, $\eta(N_c,\ N_b,\ \hat{\kappa}_j)$. If there exist l peaks below the threshold, $\hat{\kappa}_j \leftarrow \hat{\kappa}_j - l$ and go back to the step 2.

B. *Power Estimation*

Rewriting (12) as

$$\mathbf{Y}_j = \hat{\mathbf{V}}_j(\hat{\mathbf{d}})\mathbf{P}_j + \mathbf{W_j}, \tag{16}$$

where $\mathbf{P}_j = \mathbf{A}_j\mathbf{H}_j$ and $\hat{\mathbf{V}}_j(\hat{\mathbf{d}})$ is obtained by replacing the delays in (10) by their estimated version $\hat{\mathbf{d}}$. The LS estimate $\hat{\mathbf{P}}_\mathbf{j}$ can be obtained by

$$\hat{\mathbf{P}}_j = \hat{\mathbf{V}}_j^{\dagger}(\hat{\mathbf{d}})\mathbf{Y}_j, \tag{17}$$

where $\hat{\mathbf{V}}_j^{\dagger}(\hat{\mathbf{d}}) = \left[\hat{\mathbf{V}}_j^{\mathbf{H}}(\hat{\mathbf{d}})\hat{\mathbf{V}}_j(\hat{\mathbf{d}})\right]^{-1}\hat{\mathbf{V}}_j^{\mathbf{H}}(\hat{\mathbf{d}})$. The power of the ith RSS in the jth group can be represented as

$$P_{ij} = N_c\mathbf{P_{ij}}\mathbf{P_{ij}^H} \tag{18}$$

where $\mathbf{P_{ij}}$ denote the row vector in $\hat{\mathbf{P}}_j$ corresponding to the ith RSS in the jth group. Note that neither channel knowledge nor noise spectrum density are required in the proposed algorithm.

V. SIMULATION RESULTS

A. *System parameters and assumptions*

The OFDMA system parameter values used in the simulations and reported in this section are the same as those defined in [1] and [9]. The uplink bandwidth is 10 MHz, and the subcarrier spacing is 10.9375 KHz. The number of subcarriers used for initial ranging is 144. For the proposed ranging structure N_c=6, N_b=6, N_{gp}=4 and D_b=140. The modified ITU Vehicular A channel model with 24 paths is used and the sampling interval, T_s, is 89.285 ns. The number of sample-spaced channel taps, L, is set to be 30. We consider a cell size of radius 5 km so that the round-trip delay d_{max}=33.34 μs = 373 samples. $N_g = 512$ samples is assumed to satisfy the condition $N_g > d_{max} + L$. Each group can support M RSSs, where M=2. Thus the maximum number of RSSs in one time slot is equal to 8. The speed of each RSS is 120 km/hr and carrier frequency is 2.5 GHz, hence the normalized residual frequency offsets of RSSs are assumed to be i.i.d. within the range [-0.05,0.05]. Some or all of the following RSS distributions are considered in each figure. They are (i) 1 RSS, (ii) 2 RSSs in 1 group, (iii) 2 RSSs in 2 groups, (iv) 4 RSSs in 4 groups, (v) 4 RSSs in 2 groups and (vi) 8 RSSs within one ranging time-slot.

B. Multi-User detection performance

Fig. 3 shows the probability of correct detection (P_D) performance versus the average SNR. It can be seen that P_D is close to 1 even if SNR is as small as -10 dB. The performance degrades sightly if there are two RSSs in the same group. When SNR is larger than -7 dB, the performance loss is less than 0.005. It is clear that the performance of the proposed ranging signal and algorithm is insensitive to the RSSs' interference and residual frequency offsets.

Fig. 4 plots the probability of false alarm (P_F) as a function of the average SNR. We find that at high SNR, the RSSs in the different groups do not cause an increase of false alarm probability even if the residual frequency offset is nonzero. At lower SNR, the false alarm probability for the case when there is only one RSS per group will be higher than that if there are more than one RSS in each group due to the use of the same group of subcarriers. Both signal and null spaces are influenced by strong noise. When the SNR exceeds 5 dB, the noise effect becomes insignificant. However, even if SNR is smaller than 5 dB, the false alarm probability is always less than 0.02.

C. Performance of timing estimate

Fig. 5 shows the performance of timing jitter, defined as the root mean squared error of the timing offset estimator, as a function of the average SNR for various RSS distributions. In each simulation run, the transmission delays are taken randomly from the interval $[0, d_{max}]$. It can be observed that one RSS in one group yields better performance than two RSSs in one group. The performance loss, however, is but one sampling interval. After each RSS has adjusted its timing offset, the BS can increase the number of RSSs in one group to support more RSSs provided that the dimension of the null space is larger than one.

D. Power estimator performance

Fig. 6 shows the normalized MSE performance of our power estimation scheme as a function of average SNR. The performance of the power estimate is rather insensitive to the number of RSSs and suffers little or no performance loss in the presence of a residual frequency offset. The MSE curves flatten out at high SNR's due to the limitation of the approximation (7).

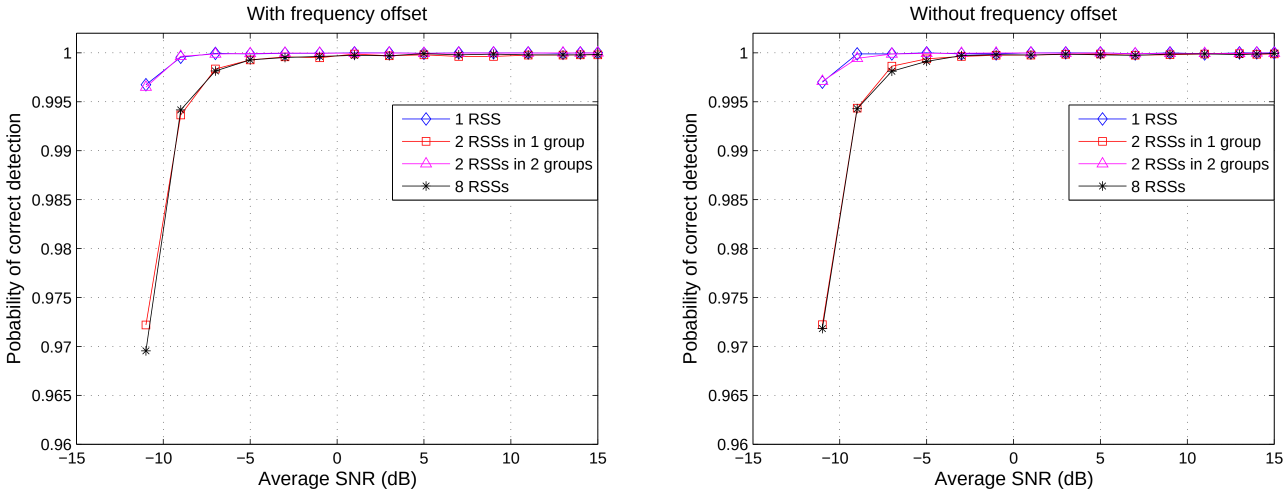

Fig. 3. Detection probability performance as a function of average SNR.

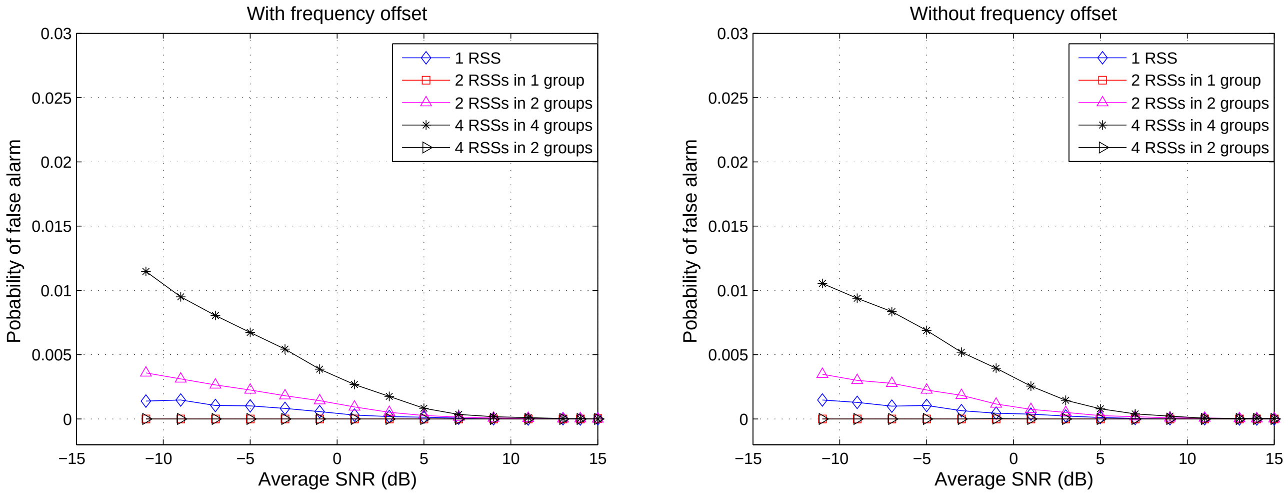

Fig. 4. Probability of false alarm as a function of average SNR.

VI. CONCLUSION

We propose a single OFDM symbol based ranging signal structure for initial ranging in a wireless mobile OFDMA system. An efficient and robust ranging algorithm is presented which requires no side information about the noise power spectrum density nor powers of active RSSs. The proposed ranging scheme is based on the idea of projecting the received multiple ranging signals onto the null space and can also be extended for use in periodic ranging process in a

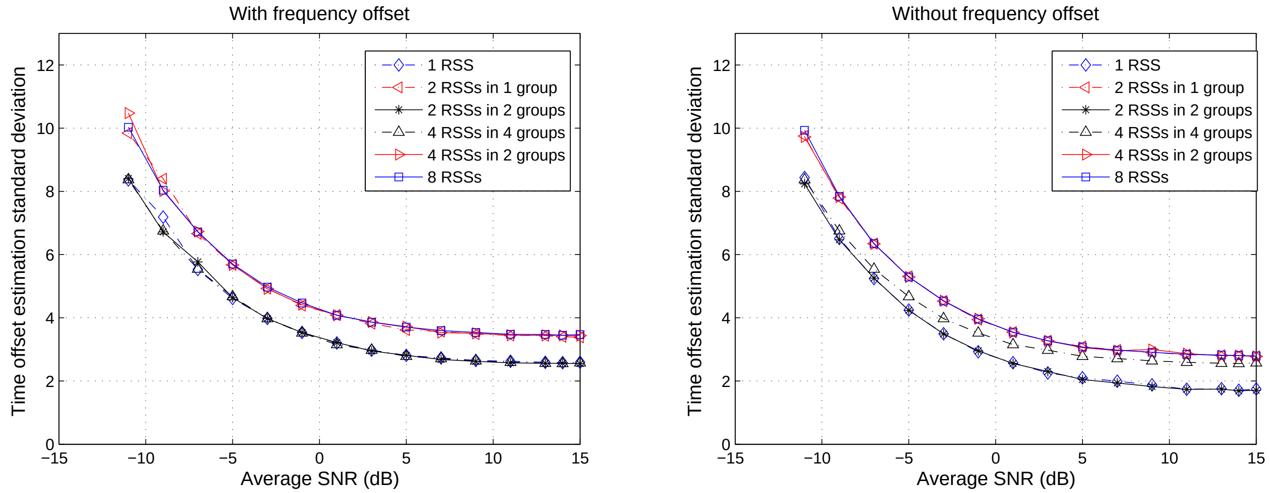

Fig. 5. Timing jitter behavior as a function of average SNR

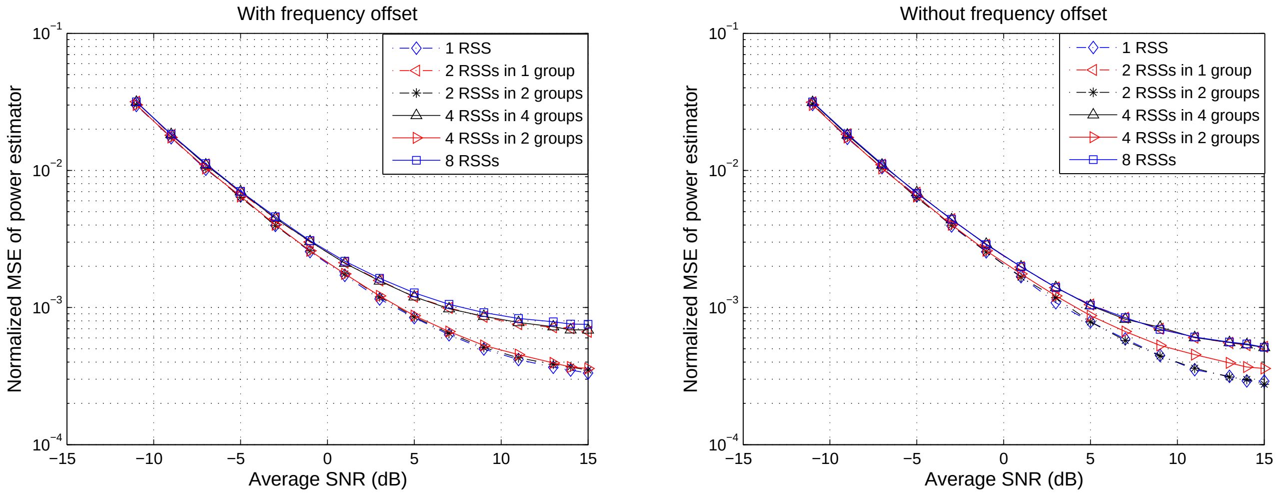

Fig. 6. Normalized MSE performance of the proposed power estimate.

similar OFDMA system. The simulation results demonstrate that the proposed method is more robust to multipath fading and multiuser interference than those using the frequency domain CDMA ranging codes as defined in [1].

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