Ranging Signal Designs for MIMO-OFDMA Systems

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***Abstract*—In this paper, we propose new ranging signal designs for time-division duplexing multiple input multiple output (MIMO) orthogonal frequency division multiple access (OFDMA) systems. Exploiting the channel knowledge from the downlink channel together with initial power control, we develop three ranging transmission schemes which provide multiuser and multi-antenna diversity gains and significant power saving for the subscriber stations. The advantages of the proposed approach over existing methods in terms of ranging performance, energy saving, and complexity saving are illustrated by analytical and simulation results.**

I. Introduction

Uplink multiuser timing synchronization and power control in orthogonal frequency division multiple access (OFDMA) systems are crucial for avoiding/suppressing interferences and hence maintaining reliable multiuser wireless links. The existing/emerging OFDMA systems such as the IEEE wireless metropolitan area networks (MAN) standards 802.16a/e [1] [2] necessitate a ranging process to address these uplink (UL) synchronization and power control issues.

There are several existing works on initial ranging process of OFDMA systems in the literature [3]–[7]. The ranging methods proposed in [3] and [4] use the ranging signal given in IEEE 802.16-2004 where the randomly chosen ranging codes are transmitted on the same ranging channel. Their common disadvantage is the high computational complexity. The ranging method in [5] achieves low-complexity ranging signal detection by means of a ranging signal design. However, its iterative timing estimator requires high complexity. Recently [6], [7] develop efficient low complexity ranging detector, and timing and power estimators using a new ranging signal design. But the ranging signal design in [6] and [7] requires the cyclic prefix (CP) length $N_g \geq d_{\max} + L - 1$, where $d_{\max}$ is the maximum possible round-trip transmission delay and L is the number of sample-spaced channel taps; and the timing offset estimation performance degrades when the channel delay spread increases, limiting its application to small cell sizes. Furthermore, all these works except [7] address only single input single output (SISO) OFDMA systems.

In this paper, we propose ranging signal designs which provide greater robustness against the channel delay spread and the timing offset, and which can be applied in various cell sizes. We also develop three ranging signal transmission schemes in a MIMO setup. By exploiting multiuser and multi-antenna diversity gains, we develop low-complexity algorithms for multiuser ranging signal detection, timing offset estimation and power estimation for time-division duplexing (TDD) MIMO OFDMA systems. Comparison with the existing methods for IEEE 802.16e in a MIMO setup shows that our approach provides substantial energy saving, complexity reduction, and ranging performance improvement.

II. System Descriptions and Signal Model

Consider a UL $M_T \times M_R$ MIMO OFDMA system with N_r ranging subscriber stations (RSSs), N_d data subscriber stations (DSSs) and N subcarriers. After assigning DC and null subcarriers, the remaining subcarriers are grouped into Q_r ranging subchannels and Q_d data subchannels. Denote the numbers of left and right null subcarriers as γ_{LN} and γ_{RN}, respectively. Each ranging subchannel has γ_r subcarriers and each data subchannel has γ_d subcarriers. The indices of the subcarriers corresponding to the qth ranging subchannel ($q \in \{0, \ldots, Q_r - 1\}$) and the q_dth data subchannel ($q_d \in \{0, \ldots, Q_d - 1\}$) are denoted as $\mathcal{J}_q$ and $\mathcal{K}_{q_d}$, respectively. One UL frame consists of M OFDM symbols where predefined subcarriers over M_r ($\leq M$) OFDM symbols are allocated for the ranging. The ranging time slot index is denoted by t ($t \in \{0, 1, \ldots, \frac{M_r}{M_1} - 1\}$), where M_1 is the number of OFDM symbols per ranging time slot. The OFDM symbol index in a ranging time slot is denoted by m_1 ($m_1 \in \{0, 1, \ldots, M_1 - 1\}$). The antenna indexes of SS and BS are denoted by m_t and m_r, respectively.

Denote $\mathbf{X}_{i,r}^{(m)(m_t)}$ and $\mathbf{X}_{j,d}^{(m)(m_t)}$ as the frequency domain ranging code vector of the ith RSS and the frequency domain data vector of the jth DSS at the mth OFDM symbol interval and the m_tth transmit antenna, respectively. The corresponding kth elements ($k \in \{0, \ldots, N-1\}$) of the m_tth transmit antenna can be expressed as[1]

$$\mathrm{X}_{i,\star}^{(m)(m_t)}(k) = \begin{cases} A_{i,\star}^{(m_t)} C_{i,\star}^{(m_1)}(l), & l = 0, \ldots, \gamma_\star - 1, \\ & k = \mathcal{J}_q(l) \quad \text{(for RSS)} \\ & k = \mathcal{K}_{q_d}(l) \quad \text{(for DSS)} \\ & m = M_1 \cdot t + m_1 \quad \text{(for RSS)} \\ & m = 0, \ldots, M-1 \quad \text{(for DSS)} \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where $C_{i,r}^{(m_1)}(l)$ and $C_{j,d}^{(m)}(l)$ are ranging and data symbols, respectively, with $|C_{i,r}^{(m_1)}(l)| = E[|C_{j,d}^{(m)}(l)|^2] = 1$, and $\{A_{i,r}^{(m_t)}, A_{j,d}^{(m_t)}\}$ are scaling factors.

[1] In the rest of the paper, the subscript $\star$ denotes whether r or d.

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The signals are transmitted through multipath channels. The channels for different SSs are assumed to be independent and quasi-static from the last OFDM symbol of the downlink (DL) frame to the last OFDM symbol of the ranging allocation in the UL frame. The sample-spaced channel impulse response taps (including the transmit and receive filters) for the ith RSS/DSS are denoted by $\{h_{i,\star}^{(m_t,m_r)}(l), l = 0, \ldots, L-1\}$.

At the BS's m_rth receive antenna, the received samples for the ith RSS/DSS are given by

$$y_{i,\star}^{(m_r)}(n) = \sum_{m_t=1}^{M_T} \sum_{l=0}^{L-1} h_{i,\star}^{(m_t,m_r)}(l)\; x_{i,\star}^{(m_t)}(n-l-d_{i,\star}), \tag{2}$$

where $d_{i,r}$ ($d_{i,d}$) are the transmission delays for the ith RSS (DSS).

Then the time domain received signal of m_rth antenna at the BS can be expressed as

$$y^{(m_r)}(n) = \sum_{i=0}^{N_r-1} y_{i,r}^{(m_r)}(n) + \sum_{j=0}^{N_d-1} y_{j,d}^{(m_r)}(n) + \omega^{(m_r)}(n), \tag{3}$$

where $\{\omega^{(m_r)}(n)\}$ are independent and identically-distributed (i.i.d.), circularly-symmetric complex Gaussian noise samples with zero mean and variance σ_ω^2.

III. Proposed Ranging Signal Designs

Consider an OFDMA system with Q_r ranging subchannels, where each ranging subchannel is composed of γ_r adjacent subcarriers over M_1 OFDM symbols (one ranging time slot). The ranging subchannels are spread out over the whole frequency band with approximately equal spacing. The subcarrier assignment for the qth ranging subchannel is defined as

$$\mathcal{J}_q = \{\gamma_{LN} + q \cdot \Delta + l : l = 0, \ldots, \gamma_r - 1\}, \tag{4}$$

where $\Delta = \lfloor \frac{N_{\text{used}}-\gamma_r}{Q_r-1} \rfloor$, $N_{\text{used}} = \gamma_r Q_r + \gamma_d Q_d$, and $\lfloor x \rfloor$ denotes the largest integer not greater than x. Note that $\{\mathcal{J}_q\}$ are disjoint for different values of q.

We propose three ranging signal designs for small, moderate, and large cell-sizes. All three designs have N_c frequency domain orthogonal codes $\{C_c(l) : c, l = 0, 1, \ldots, N_c - 1\}$ (e.g., BPSK modulated Walsh codes) of length N_c each, where c is the ranging code index and l is the orthogonal code element index. Each RSS transmits a ranging code randomly chosen from the above N_c codes on the chosen ranging subchannel defined by $\mathcal{J}_q$ over the randomly chosen ranging time slot. In our proposed scheme, each ranging time slot is equal to M_1 OFDM symbol interval. The total number of ranging opportunities is $N_{\text{total}} = Q_r \cdot N_c \cdot \frac{M_r}{M_1}$ for the proposed designs, but the values of M_1, M_r, and Q_r may be different for different designs. In the following ranging signal design, ν_1 and ν_2 are defined as $\nu_1 = 0, \ldots, \frac{\gamma_r}{2} - 1$ and $\nu_2 = \frac{\gamma_r}{2}, \ldots, \gamma_r - 1$, respectively.

The Ranging Signal Design A: Under the condition of the CP length $N_g \geq d_{\max} + L - 1$ (i.e., small cell-size), we can just use one OFDM symbol per ranging time slot, i.e. $M_1 = 1$. Then the ranging signal for the ith RSS picking the cth ranging code, the tth ranging time slot and the qth ranging subchannel can be expressed as

$$\mathrm{X}_{i,r}^{(m)}(k) = \begin{cases} A_{i,r}C_c(\nu_1), & k \in \mathcal{J}_q(\nu_1),\ m = t, \\ A_{i,r}C_c(\nu_2 - \frac{\gamma_r}{2}), & k \in \mathcal{J}_q(\nu_2),\ m = t, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

where $\gamma_r = 2N_c$.

The Ranging Signal Design B: For a moderate or large cell-size, the timing offset of an unsynchronized RSS plus the channel length can be larger than the CP length N_g, i.e. $d_{\max} + L - 1 > N_g$. In this case, two phase-continuous OFDM ranging symbols (i.e. $M_1 = 2$) are used to absorb large timing offsets, and the ranging code detection is performed based on the second OFDM ranging symbol. The ranging signal B can be expressed as

$$\mathrm{X}_{i,r}^{(m)}(k) = \begin{cases} A_{i,r}C_c(\nu_1)e^{-\frac{j2\pi\mathcal{J}_q(\nu_1)N_g}{N}}, & k \in \mathcal{J}_q(\nu_1),\ m = 2t \\ A_{i,r}C_c(\nu_1), & k \in \mathcal{J}_q(\nu_1),\ m = 2t+1 \\ A_{i,r}C_c(\nu_2 - \frac{\gamma_r}{2})e^{-\frac{j2\pi\mathcal{J}_q(\nu_2)N_g}{N}}, & k \in \mathcal{J}_q(\nu_2),\ m = 2t \\ A_{i,r}C_c(\nu_2 - \frac{\gamma_r}{2}), & k \in \mathcal{J}_q(\nu_2),\ m = 2t+1 \\ 0, & \text{otherwise}, \end{cases} \tag{6}$$

where $\gamma_r = 2N_c$.

The Ranging Signal Design C: To provide greater robustness against the channel delay spread and the timing offset (for a large cell-size), we propose a modified ranging signal design by only using 2 adjacent subcarriers in a ranging subchannel, i.e. $\gamma_r = 2$, and by moving the domain of our orthogonal ranging code design from the frequency domain to the time domain. To absorb large timing offsets, each ranging code is transmitted over two adjacent OFDM symbols in a phase-continuous manner. Hence, the number of ranging OFDM symbols per ranging time slot is $M_1 = 2N_c$. The ranging signal C can be expressed as

$$\mathrm{X}_{i,r}^{(m)}(k) = \begin{cases} A_{i,r}C_c(l)e^{-\frac{j2\pi\mathcal{J}_q(\gamma)N_g}{N}}, & l = 0, \ldots, N_c - 1,\ k \in \mathcal{J}_q,\ m = 2l,\ \gamma = \{0, 1\} \\ A_{i,r}C_c(l), & l = 0, \ldots, N_c - 1,\ k \in \mathcal{J}_q,\ m = 2l+1 \\ 0, & \text{otherwise}. \end{cases} \tag{7}$$

Note that the channel responses within a ranging subchannel of the proposed scheme (e.g., $\gamma_r = 8$ adjacent subcarriers in our Design A/B or $\gamma_r = 2$ in our Design C for an OFDMA system with $N = 1024$ subcarriers) are almost the same. Hence, our ranging signals still maintain orthogonality at the BS (under negligible frequency offsets), while the ranging signals from 802.16a/e suffer from loss of orthogonality due to the channel frequency selectivity.

IV. The Proposed Ranging Transmission Schemes

We consider a TDD OFDMA system. The DL frame in OFDMA systems contains preamble as well as known pilot tones multiplexed with the user data tones. Consequently, each RSS can obtain its UL MIMO channel information from the DL reception. There are many existing works on MIMO transmission schemes with or without channel state information (CSI) at the transmitter side (e.g., [8] and reference therein). All of them assume CSI is available at the receiver which is reasonable for data transmission where preamble provides the required CSI estimates. In contrast, for initial ranging considered in this paper, CSI is unavailable at the BS receiver, while RSS transmitters have CSI knowledge. In the proposed scheme, the ranging signals from different receive antennas are non-coherently combined. The proposed scheme also applies power control such that the received signal power is equal to P_r. We develop three ranging transmission schemes in the following.

Optimal Eigenmode Transmission Scheme: Let $\mathrm{X}^{(m_t)}$ denotes the frequency domain ranging signal transmitted from m_tth antenna, and $\mathrm{H}_q^{(m_t,m_r)}$ denotes the channel gain[2] of qth ranging subchannel between m_tth transmit antenna and m_rth receive antenna. The channel output ISI-free kth subcarrier symbols can be expressed as

$$\mathbf{Y}^T = \mathbf{X}^T \ \mathbf{H}_q, \tag{8}$$

where

$$\mathbf{Y} = [\mathrm{Y}^{(1)}(k), \ldots, \mathrm{Y}^{(m_r)}(k)]^T, \ \mathbf{X} = [\mathrm{X}^{(1)}(k), \ldots, \mathrm{X}^{(m_t)}(k)]^T, \tag{9}$$

and $\mathbf{H}_q$ is an $M_T \times M_R$ channel matrix. For simplicity, we have skipped the subcarrier index in (8) and ignored the noise term. The non-coherently combined received ranging signals can be obtained as

$$|\mathbf{Y}|^2 = \mathbf{Y}^T\mathbf{Y}^* = \mathbf{X}^T\mathbf{H}_q\mathbf{H}_q^H\mathbf{X}^* = \mathbf{X}^T\mathbf{U}\mathbf{\Lambda}\mathbf{V}^*\mathbf{X}^* = P_r. \tag{10}$$

The optimal transmission scheme can be obtained by minimizing the transmission power $|\mathbf{X}|^2$ subject to the fixed received ranging signal power P_r. This is equivalent to choosing $\mathbf{X}$ to maximize $|\mathbf{Y}|^2$ under the constraint of fixed $|\mathbf{X}|^2$, and the solution is [9]

$$\mathbf{X} = U_{\max}, \tag{11}$$

where $U_{\max}$ is the eigenvector of $\mathbf{H}_q\mathbf{H}_q^H$ corresponding to the largest singular value $\lambda_{\max}$. So the optimal transmission scheme transmits on the strongest eigenmode of the best ranging subchannel. The best ranging subchannel is the one with largest singular value among all the ranging subchannels. After obtaining the $U_{\max}$ and the $\lambda_{\max}$ of the best ranging subchannel, the ranging signal defined in Section III is spread by $U_{\max}$ over the transmit antennas. The transmission power is adjusted to $\frac{P_r}{\lambda_{\max}}$ so that the received ranging signal power is P_r. This scheme requires singular value decompositions (SVD) of Q_r matrices with size $M_T \times M_T$, $Q_r - 1$ compare operations, and $M_T N_c$ complex multiplications at each RSS.

Suboptimal Eigenmode Transmission Scheme: A suboptimal reduced complexity scheme can be obtained by modifying the subchannel selection algorithm as follows. The ranging subchannel with the largest channel power gain, i.e. $\sum_{m_t=1}^{M_T}\sum_{m_r=1}^{M_R}|H_{i,r}^{(m_t,m_r)}|^2$, can be selected as the best ranging subchannel. This scheme requires $Q_r M_T M_R + M_T N_c$ complex multiplications, $Q_r M_T M_R - 1$ real additions and $Q_r - 1$ compare operations, but it only needs one SVD operation on the selected ranging subchannel. These two schemes have almost the same ranging performance except the optimal one has a marginal ranging transmission energy saving over the suboptimal one as will be seen in Section VI.

Single Antenna Selection Transmission Scheme: To further reduce the complexity, we propose a single transmit antenna selection scheme. Each RSS picks the antenna with the best ranging subchannel, i.e. with the largest $\sum_{m_r=1}^{M_R}|H_{i,r}^{(m_t,m_r)}|^2$, and adjusts the transmission power to $\frac{P_r}{\sum_{m_r=1}^{M_R}|H_{i,r}^{(m_t,m_r)}|^2}$ so that the received ranging signal power is P_r. This scheme requires $Q_r M_T M_R$ complex multiplications, $Q_r M_T(M_R - 1)$ real additions and $Q_r M_T - 1$ comparisons.

[2]Average of γ_r adjacent subcarrier channel gains

V. Ranging Signal Detection, Timing and Power Estimation

Each RSS estimates channel power gains by utilizing the DL preamble and the pilots embedded in the subsequent OFDM symbols. The RSS picks the best ranging subchannel according to the adopted ranging transmission scheme, and adjusts the transmission power to achieve the target received ranging signal power P_r. At the BS, the receiver performs ranging code detection, and extracts the timing and power information based on the detection results. Due to the space limitation, we only present the derivations of the ranging signal detection, timing offset estimation and power estimation based on Design B. Those for Design A or Design C can be straightly obtained.

A. Multi-User Ranging Signal Detection

Design B uses two phase-continuous OFDM ranging symbols (symbol index $2t$ and $2t+1$) to absorb large timing offset (i.e., $d_{\max} > N_g - L + 1$). The inter-symbol interference (ISI) can be avoided by using only the $(2t+1)$th OFDM ranging symbol. Then at the BS after the CP removal and the N-point DFT operation, we obtain the ISI-free kth subcarrier symbol of the m_rth antenna at the tth ranging time slot as

$$\begin{aligned} Y^{(2t+1)(m_r)}(k) &= \sum_{i=1}^{N_r} X_{i,r}^{(2t+1)}(k) H_{i,r}^{(m_t,m_r)}(k) \\ &+ \sum_{j=1}^{N_d} X_{j,d}^{(2t+1)}(k) H_{j,d}^{(m_t,m_r)}(k) + W^{(2t+1)(m_r)}(k), \end{aligned} \tag{12}$$

where

$$H_{i,\star}^{(m_t,m_r)}(k) = e^{\frac{j2\pi k d_{i,\star}}{N}} \widetilde{H}_{i,\star}^{(m_t,m_r)}(k), \tag{13}$$

$$W^{(2t+1)(m_r)}(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{N-1} \omega^{(m_r)}((2t+1)(N+N_g) + N_g + l) \ e^{\frac{-j2\pi lk}{N}}. \tag{14}$$

For the m_rth receive antenna, the BS correlates the above frequency domain symbols of every qth ranging subchannel with each fixed phase-compensated cth ranging code as

$$D1_{q,c}^{(t)(m_r)} = \sum_{l=0}^{\frac{\gamma_r}{2}-1} Y^{(2t+1)(m_r)}(\mathcal{J}_q(l)) \ C_c^*(l) \ e^{-\frac{j2\pi\mathcal{J}_q(l)\frac{d_{\max}}{2}}{N}}, \tag{15}$$

$$D2_{q,c}^{(t)(m_r)} = \sum_{l=\frac{\gamma_r}{2}}^{\gamma_r-1} Y^{(2t+1)(m_r)}(\mathcal{J}_q(l)) \ C_c^*(l - \frac{\gamma_r}{2}) \ e^{-\frac{j2\pi\mathcal{J}_q(l)\frac{d_{\max}}{2}}{N}}. \tag{16}$$

The above phase-compensation is equivalent to shifting the sample space of the possible timing offsets from $\{0, 1, \ldots, d_{\max} - 1\}$ to $\{-\frac{d_{\max}}{2}, \ldots, 0, \ldots, \frac{d_{\max}}{2}\}$, which in turn reduces the detrimental effect of timing offsets in ranging performance, providing a better performance than the detector presented in [7]. For simplicity, we drop the ranging code index c and the ranging time slot index t. Then the decision variable D_q for the RSS detection at the qth ranging subchannel is defined by combining the correlator outputs of the M_R receive antennas as

$$D_q = \sum_{m_r=1}^{M_R} \left(|D1_q^{(m_r)}|^2 + |D2_q^{(m_r)}|^2\right). \tag{17}$$

The probability density function (PDF) f_{D_q} for 0 and 1 RSS cases are, respectively, central and non-central Chi-square with $n = 4M_R$ degrees of freedom. Then the presence or

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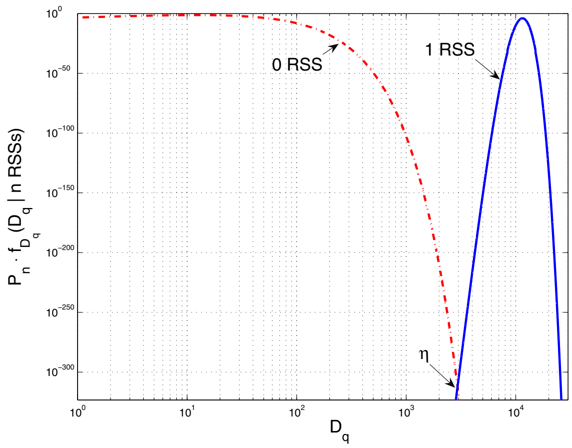

Fig. 1. The PDFs of the ranging code detection decision variable

absence of the ranging code on a ranging opportunity (denoted by $n_{\text{RSSs}} = 1$ or 0, respectively) is determined by

$$n_{\text{RSS}} = \underset{n=0,1}{\text{argmax}}\{P_n \cdot f_{D_q}(D_i \mid n \text{ RSSs})\}, \tag{18}$$

where $\{P_n\}$ representing the probability of n RSSs in the same ranging opportunity can be replaced with pre-defined design values. Fig. 1 shows $P_n \cdot f_{D_q}(D_q)$ for 0 and 1 RSS at a ranging opportunity, from which the detection threshold can be determined as

$$n_{\text{RSS}} = \begin{cases} 0, & \text{if } D_q < \eta \\ 1, & \text{else,} \end{cases} \tag{19}$$

where η is the crossover point of $P_0 \cdot f_{D_q}(D_q \mid 0 \text{ RSS})$ and $P_1 \cdot f_{D_q}(D_q \mid 1 \text{ RSS})$.

B. Timing Offset Estimation

We can utilize the ranging signal detection results to perform the timing offset estimation. $D1_q$ and $D2_q$ for the collision-free ($n_{\text{RSS}} = 1$) ith RSS with corresponding ranging channel response $\widetilde{H}_{i,r}(\mathcal{J}_q(l))$ can be approximated by

$$D1_q^{(m_r)} \approx B_1^{(m_r)} \left(\sum_{l=0}^{\frac{\gamma_r}{2}-1} e^{\frac{j2\pi(\epsilon_i - \frac{d_{\max}}{2})\mathcal{J}_q(l)}{N}} \right) + \widetilde{W}_{1,i}, \tag{20}$$

$$D2_q^{(m_r)} \approx B_2^{(m_r)} e^{\frac{j2\pi(\epsilon_i - \frac{d_{\max}}{2})\frac{\gamma_r}{2}}{N}} \left(\sum_{l=0}^{\frac{\gamma_r}{2}-1} e^{\frac{j2\pi(\epsilon_i - \frac{d_{\max}}{2})\mathcal{J}_q(l)}{N}} \right) + \widetilde{W}_{2,i}, \tag{21}$$

where $B_1^{(m_r)} \approx B_2^{(m_r)} = A_{i,r}\widetilde{H}_{i,r}^{(m_r)}(\mathcal{J}_q(l))$, ϵ_i is the timing offset of the ith RSS, and $\{\widetilde{W}_{1,i}, \widetilde{W}_{2,i}\}$ are i.i.d. zero-mean complex Gaussian random variables with a variance of $\sigma_w^2\gamma_r/2$. Since $B_1^{(m_r)} \approx B_2^{(m_r)}$, the timing offset (an integer in the unit of samples) for the ith RSS can be estimated by coherently combining the outputs of the M_R receive antennas as

$$\hat{\epsilon}_i = \text{round}\Big\{ \frac{N \cdot \text{angle}\{\sum_{m_r=1}^{M_R} D2_q^{(m_r)}(D1_q^{(m_r)})^*\}}{\pi\gamma_r} + \frac{d_{\max}}{2} \Big\}. \tag{22}$$

Since $0 \le \epsilon_i \le d_{\max}$, for occasional cases of $\hat{\epsilon}_i > d_{\max}$, we can set $\hat{\epsilon}_i = d_{\max}$. The above estimator provides a significant complexity reduction over the existing methods [3]–[5].

C. RSS Power Estimation

If only one ranging code is detected on a ranging sub-channel in a ranging time slot, define

$$P1_q^{(m_r)} = \frac{2}{\gamma_r} \sum_{l=0}^{\frac{\gamma_r}{2}-1} Y^{(2t+1)(m_r)}(\mathcal{J}_q(l)) C_c^*(l) e^{\frac{-j2\pi\hat{\epsilon}_i\mathcal{J}_q(l)}{N}}, \tag{23}$$

$$P2_q^{(m_r)} = \frac{2}{\gamma_r} \sum_{l=\frac{\gamma_r}{2}}^{\gamma_r-1} Y^{(2t+1)(m_r)}(\mathcal{J}_q(l)) C_c^*(l - \frac{\gamma_r}{2}) e^{\frac{-j2\pi\hat{\epsilon}_i\mathcal{J}_q(l)}{N}}. \tag{24}$$

If there are more than one distinct ranging code detected on a ranging sub-channel in a ranging time slot, define

$$P1_q^{(m_r)} = \frac{2}{\gamma_r} D1_q^{(m_r)}, \quad P2_q^{(m_r)} = \frac{2}{\gamma_r} D2_q^{(m_r)}. \tag{25}$$

Then the power estimator is given by

$$\hat{P} = \sum_{m_r=1}^{M_R} \frac{\left(|P1_q^{(m_r)}|^2 - \frac{\sigma_w^2}{\frac{\gamma_r}{2}}\right) + \left(|P2_q^{(m_r)}|^2 - \frac{\sigma_w^2}{\frac{\gamma_r}{2}}\right)}{2}, \tag{26}$$

where the noise variance σ_w^2 is assumed to be known (can be measured or estimated easily).

VI. Performance Evaluation

A. System Parameters

The ranging code detector and timing estimator in [3] with the ranging signals from the IEEE 802.16e are used as the reference method for comparison. Both proposed method and reference method are simulated in a TDD MIMO OFDMA system. The system simulation parameters are summarized in Table I.

The system parameters are the same for the proposed ranging method and the reference ranging method. The difference is the ranging channel setup. Q_r is equal to 18 for Design B and 72 for Design C. For the reference method, each RSS transmits one selected CDMA code and its gradual phase rotated version on the single ranging channel that consists of 144 spread-out subcarriers over two consecutive symbols. In order to reduce the simulation time for the reference method, we use only 32 codes (equal to the considered maximum number of RSSs) and we assume there is no collision in the reference method. Since there is no power estimator provided in [3], we assume perfect power estimation (hence yielding slightly optimistic results) for the reference method. For simplicity in evaluation, we assume that all N_r RSSs attempt their ranging simultaneously at the first ranging frame, there are no new RSSs until their ranging processes are completed, and the collided RSSs retry their ranging in the next frame.

For the reference method, each RSS transmits the same selected CDMA code on both antennas. At the BS, the outputs of both receive antennas are non-coherently combined for the ranging code detection and the timing offset estimation. The initial ranging transmission power of each transmit antenna on each ranging subcarrier is set 10 dB above the noise power (σ_w^2) on a subcarrier. Therefore, the total ranging transmission power of each transmit antenna over 144 ranging subcarriers normalized by σ_w^2 is 10 $\log_{10}(1440)$ dB. In the proposed method, the target received total ranging signal power of an RSS is set the same as the statistical average of the total received ranging signal power of an RSS in the reference method, i.e., $P_r/2\sigma_w^2 = 1440/8$.

B. Simulation Results and Discussions

The proposed designs outperform the reference method. Due to the space limitation, we mainly present the simulation results for Design B based on the ITU pedestrian B (Ped B) and vehicular A (Veh A) multipath channels [10], which are the same simulation environments used in WiMAX system evaluation methodology [11].

For Design B, three proposed transmission schemes are evaluated. Due to the power control, the ranging performance of these three transmission schemes are almost the same except the optimal and suboptimal eigenmode transmission schemes provide marginal ranging transmission energy savings over the single antenna selection transmission scheme. Hence for the proposed method, we only present the results of the single antenna selection transmission scheme in all figures except Fig. 6 due to space limitation.

Fig. 2 shows the probabilities of missed detection P_{miss} and false alarm P_{false} in moderate cell size environments on both Ped B and Veh A channels. The P_{miss} is defined as $E[\frac{D_m}{N_r}]$ where D_m is the number of RSSs whose transmitted ranging signals are not detected at the BS and N_r is the total number of RSSs. The P_{false} is defined as $E[\frac{D_a}{N_{\text{total}}-N_r}]$ where D_a is the number of ranging signals which are detected at the BS but are not transmitted from any RSSs. The proposed method performs much better than the reference method. The reference method's performances substantially degrade as the number of the RSSs increases.

Fig. 3 shows the probability distribution of the number of frames required for an RSS to complete a successful ranging. For the 32 RSSs case in Ped B channel, the simulation results show that about 91% of the RSSs in the proposed method (75% in the reference method) can finish the ranging process in two frames. The percentage of RSSs that can finish ranging in two frames is smaller in Veh A channel than in Ped B channel due to the faster time variation of Veh A channel. About 70% of the RSSs in the proposed method (54% in the reference method) can finish the ranging process in two frames.

Fig. 4 presents the advantage of the proposed method over the reference method in terms of the average number of frames required to complete a successful ranging versus the number of RSSs for 6 DSSs and 12 DSSs on both Ped B and Veh A channels. Both methods are insensitive to DSS interference, but the average number of ranging frames required for the reference method increases with the number of RSSs, while the corresponding performance of the proposed method is robust to RSS interference. The advantage of the proposed method also translates into smaller latency at the network entry.

The standard deviations of the timing offset estimation versus the number of RSSs are presented in Fig. 5 for Veh A channel with 6 DSSs and 12 DSSs. The true timing offsets for RSSs and DSSs are taken randomly from the interval $[0, d_{\max,\text{r}}]$ and $[0, d_{\max,\text{d}}]$, respectively. The simulation results show that both methods are robust to the DSS interference.

Fig. 6 presents the average total normalized ranging transmission energy required for an RSS to finish its ranging process. The proposed method cuts down the ranging energy consumption at an RSS to approximately $\frac{1}{4}$ of that required in the reference method. The average total normalized ranging transmission energy of the optimal eigenmode transmission scheme is also included in Fig. 6.[3] The optimal eigenmode transmission scheme provides only marginal ranging transmission energy saving over the single antenna transmission scheme. Hence the single antenna selection transmission scheme is recommended due to its complexity saving.

VII. Conclusions

We have presented ranging signal designs and ranging transmission schemes for MIMO-OFDMA systems that take advantage of multiuser and multi-antenna diversities. By means of ranging signal designs, the proposed approach achieves multiuser diversity gain and significant power saving while facilitating efficient low-complexity algorithms for multiuser ranging signal detection, timing offset estimation and power estimation. The proposed ranging method achieves significant gains in ranging signal detection and synchronization performance, latency reduction at the network entry, energy saving at the subscriber stations, and complexity reduction over the existing ranging methods while utilizing the same amount of time and frequency resources.

References

[1] *Broadband Wireless Access: IEEE MAN standard*, IEEE LAN/MAN Standards Committee IEEE 802.16a, 2003.

[2] *Broadband Wireless Access: IEEE MAN standard*, IEEE LAN/MAN Standards Committee IEEE 802.16e, 2005.

[3] J. Krinock, M. Singh, M. Paff, Vincent, A. Lonkar, L. Fung, and C.-C. Lee, "Comments on OFDMA ranging scheme described in IEEE 802.16ab-01/01r1," Document IEEE 802.16abc-01/24.

[4] X. Fu and H. Minn, "Initial uplink synchronization and power control (ranging process) for OFDMA systems," in *Proc. IEEE GLOBECOM*, vol. 6, Nov. 29-Dec. 3 2004, pp. 3999–4003.

[5] X. Fu, Y. Li, and H. Minn, "A new ranging method for OFDMA systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 659–669, Feb. 2007.

[6] J. Zeng and H. Minn, "A novel OFDMA ranging method exploiting multiuser diversity," in *Proc. IEEE GLOBECOM*, 26-30 Nov. 2007, accepted.

[7] ——, "Diversity exploiting MIMO-OFDMA ranging," in *Proc. 6th International Conference on Information, Communications & Signal Processing*, 2007, pp. 1–5.

[8] A. Molisch and M. Win, "MIMO systems with antenna selection," *IEEE Microwave Magazine*, vol. 5, no. 1, pp. 46–56, Mar 2004.

[9] R. A. Horn and C. R. Johnson, *Matrix Analysis*. Cambridge University Press, 1990.

[10] *Recommendation ITU-R M.1225: Guidelines for evaluation of radio transmission technologies for IMT-2000*, Std., 1997.

[11] WiMAX system evaluation methodology. Version 1.0. WiMAX Forum.

[3]The transmission energy of the suboptimal eigenmode transmission scheme is very close to the optimal one, so the results of suboptimal one are skipped in order not to overcrowd the figure.

TABLE I
SIMULATION PARAMETERS

Carrier frequency	2.5 GHz
System channel BW	10 MHz
Sampling frequency	11.2 MHz
FFT size N	1024
CP length N_g	128
BS-to-BS distance	3 km
Maximum RSS timing offset $d_{\max,\mathrm{r}}$	112 samples
Maximum DSS timing offset $d_{\max,\mathrm{d}}$	32 samples
Sub-carrier spacing	10.94kHz
Number of guard subcarriers, left	92
Number of guard subcarriers, right	91
Number of used subcarriers	840
Number of OFDM symbols in one frame	48
DL/UL Partition	29 : 18 (1 TTG)
Number of OFDM symbols allocated for ranging	8
Modulation	BPSK for RSS
	QPSK for DSS
Number of data subcarriers per subchannel	48
Mobile speed in Ped B channel	3 km/hr
Mobile speed in Veh A channel	60km/hr
Timing requirement	32 Samples
Power requirement	9.4 dB
Residual normalized frequency offsets	$[-0.02, 0.02]$

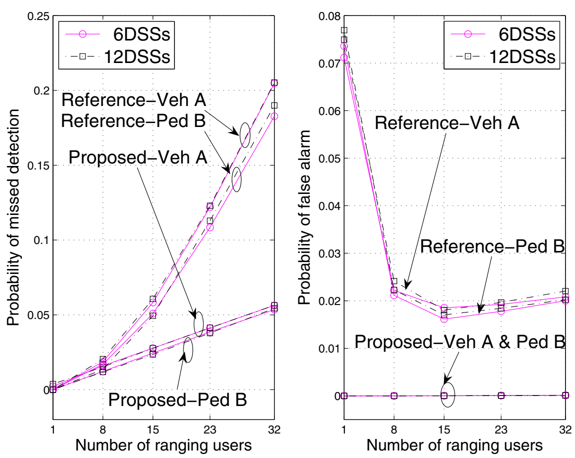

Fig. 2. The probabilities of missed detection and false alarm at the first ranging frame (SNR=10 dB)

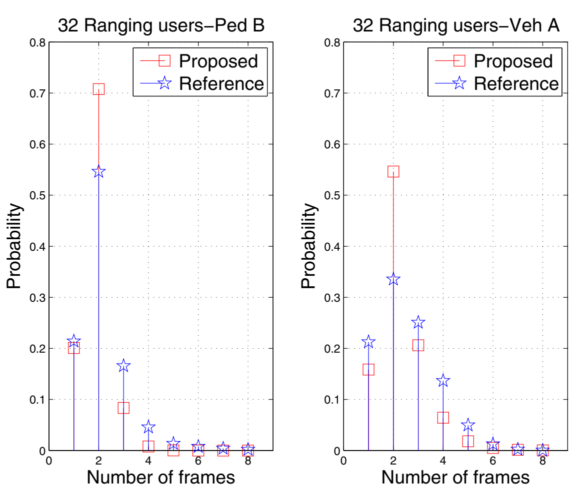

Fig. 3. The probability distribution of the number of frames required for a successful ranging (SNR=10 dB)

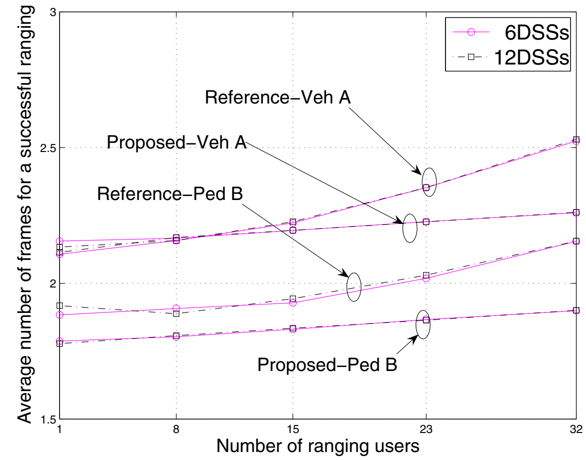

Fig. 4. Average number of frames required to complete a successful ranging (SNR=10 dB)

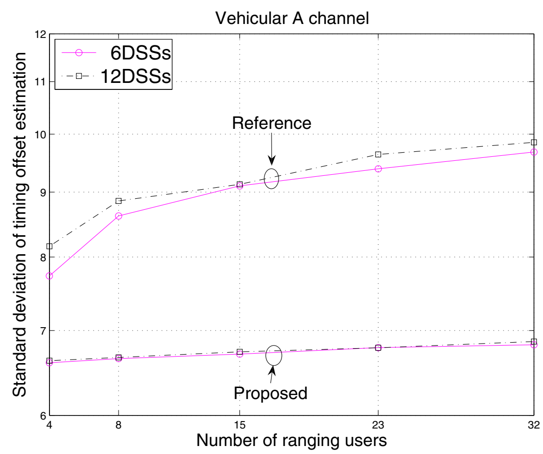

Fig. 5. Timing offset estimation performance comparison (SNR=10 dB)

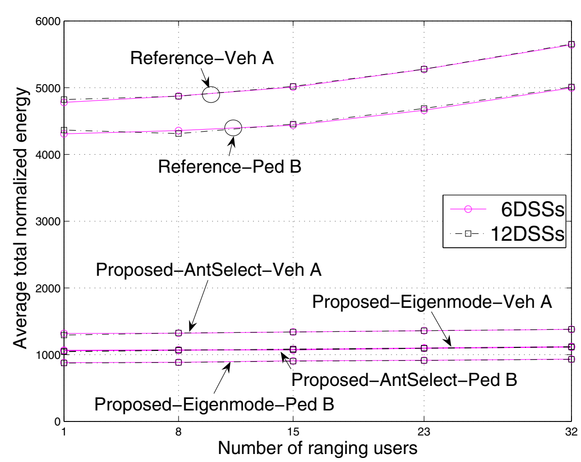

Fig. 6. Average total normalized ranging transmission energy required for a successful ranging (SNR=10 dB)