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Decentralised ranging method for orthogonal frequency division multiple access systems with amplify-and-forward relays

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Abstract: In this study, a decentralised ranging method for uplink orthogonal frequency division multiple access (OFDMA) systems with half-duplex (HD) amplify-and-forward (AF) relay stations (RSs) is proposed. In the OFDMA systems with HD AF RSs, twice more resources and delays are required as ranging without RS. To reduce the required resources and delays for ranging, the authors propose a two-phase ranging scheme based on the decentralised timing-offset estimation at each ranging mobile station (MS). At the first phase, RS occasionally broadcasts timing reference signal, and at the second phase RS retransmits the collected ranging signals from the MSs. Then, each ranging MSs can individually estimate its own timing offset from the received signals. In the proposed ranging method, the base station does not need to send a timing-adjustment message, and the overhead associated with ranging in the downlink resources, and computational complexity can be significantly reduced without degrading the timing-offset-estimation performance. Moreover, the delay associated with ranging can be maintained as same as ranging without RS.

1 Introduction

To avoid inter-carrier interference in the uplink (UL) resources of orthogonal frequency division multiple access (OFDMA) systems, the signals from all users should arrive at the base station (BS) within a cyclic prefix (CP) range. Since the propagation delays of the mobile stations (MSs) are different, a complex process is required to achieve UL timing synchronisation. This is accomplished by a ranging process to estimate the timing offsets for different MSs at the BS and to adjust their transmission time instants according to the timing-offset adjustment message sent by the BS [1–4].

Recently, to enhance the link quality and to extend the cell coverage of OFDMA-based systems, multihop relay techniques have received considerable attention [5, 6] and are included in the IEEE 802.16-2009 [7], IEEE 802.16 m [8] and LTE-advanced [9] standards. For OFDMA systems with a decode-and-forward relay station (RS), UL signals from multiple MSs within the coverage of the RS should be synchronised at the RS, and the ranging method for the systems without an RS can be applied at the RS [10].

For OFDMA systems with an amplify-and-forward (AF) RS, a ranging method that does not involve an RS can be directly extended [11, 12]. A ranging MS transmits a randomly selected ranging sequence by using the shared UL ranging resources, and an RS relays the ranging sequence to the BS. Then, the BS estimates the time offset of the MS and transmits the timing-adjustment information through a downlink (DL) control message after appropriate channel coding for robust transmission. Finally, the RS relays the control message, and the MS changes its reference time according to the decoded message, if it succeeds to decode the control message. This requires twice the resources as ranging without an RS. To reduce the control overhead and computational complexity, decentralised approaches are popularly considered for relay selection in wireless networks [13, 14]. To reduce the overhead associated with ranging for OFDMA systems with AF RSs, we apply a decentralised approach to the ranging problem with RS. In the proposed method, the estimation process is carried out at each ranging MS instead of at the BS by adopting the following two-phase approach. During the timing-reference-acquisition phase, the RS occasionally transmits a pre-determined reference signal to the MSs, and each MS estimates the arrival time of the reference signal. For arrival time estimation, several methods based on cross-correlation in time or frequency domain [1–4] can be applied, but in this paper, a two-step generalised likelihood ratio test (GLRT) [15]-based detection method is proposed. During the timing-offset-estimation phase, the ranging MSs transmit randomly selected ranging sequences to an RS by using the shared ranging resources, and the RS buffers collected the ranging signals. Then, the RS retransmits the buffered ranging signal, and each ranging MS estimates its own timing offset with respect to the received signals. The proposed GLRT-based detector can be also applied for timing-offset estimation. A comparison of the overheads and simulation results for the proposed scheme and the conventional centralised ranging method in [11] indicates that the proposed method can be used to considerably reduce the DL overhead associated with ranging, without degrading the ranging performance.

In addition, because its own ranging sequence is known at each ranging MS, the ranging sequence identification problem disappears and computational complexity is reduced, which is another important advantage of the proposed method.

2 System model

We consider an OFDMA UL system with a half-duplex (HD) AF RS. Fig. 1 shows the conventional ranging method in an IEEE 802.16j system [11] [IEEE 802.16j standard is a part of IEEE 802.16-2009 standard.] with an RS. The ranging procedures are divided into four time slots. First, the ranging MSs transmit the ranging signal containing the randomly chosen ranging sequence in the pre-determined ranging channel to the RS. A ranging channel is shared by multiple simultaneous ranging MSs based on code division multiple access. Then, the collected ranging signals at the RS are amplified and forwarded to the BS. After the BS receives the ranging signals, it identifies each ranging MS's ranging sequence, estimates the time offset and creates the timing-adjustment message for each ranging MS. Finally, timing-adjustment messages are transmitted from the BS to the ranging MSs through the RS. The detailed timing diagrams and procedures of the conventional ranging method are shown in Fig. 2. Since the BS is equipped with a global positioning system (GPS), it has knowledge of the absolute reference time, $T_{\mathrm{ref},b}$. However, because the RS and the kth ranging MS are not equipped with GPSs, they have delayed reference times $T_{\mathrm{ref},r}$ and $T_{\mathrm{ref},k}$, respectively. In the first time slot, the kth MS transmits the ranging sequence at its reference time $T_{\mathrm{ref},k}$, and the RS receives the ranging sequence after a propagation delay of d_k. In the second time slot, the RS amplifies and forwards the summed ranging sequences. After experiencing a propagation delay of d_{rb}, the ranging sequence of the kth ranging MS is received by the BS at $T_{\mathrm{ref},b} + (T_{\mathrm{ref},k} - T_{\mathrm{ref},b}) + d_k + d_{rb}$, where d_k is the propagation delay between the kth MS and RS and d_{rb} is the propagation delay between the RS and BS. The BS estimates the time offset for the kth user

$$\Delta_{T,k} = T_{\mathrm{ref},k} - T_{\mathrm{ref},b} + d_k + d_{rb} \tag{1}$$

The value of $\Delta_{T,k}$ is quantised, and a timing-adjustment message is transmitted to each MS. After decoding the timing-adjustment message, the MS can transmit its signal at $T_{\mathrm{ref},k} - \Delta_{T,k} = T_{\mathrm{ref},b} - d_k - d_{rb}$. Furthermore, after an

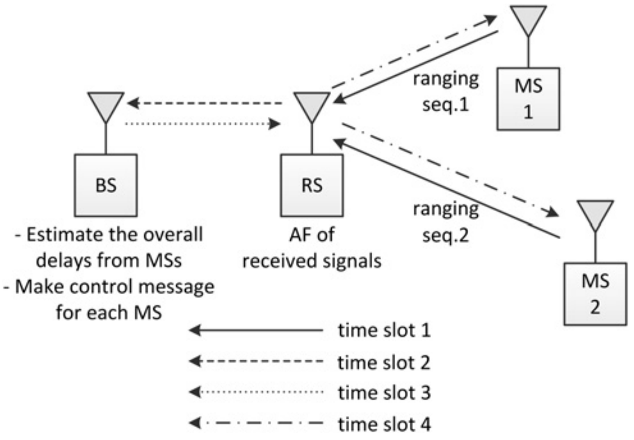

Fig. 1 *Conventional ranging method with AF relay*

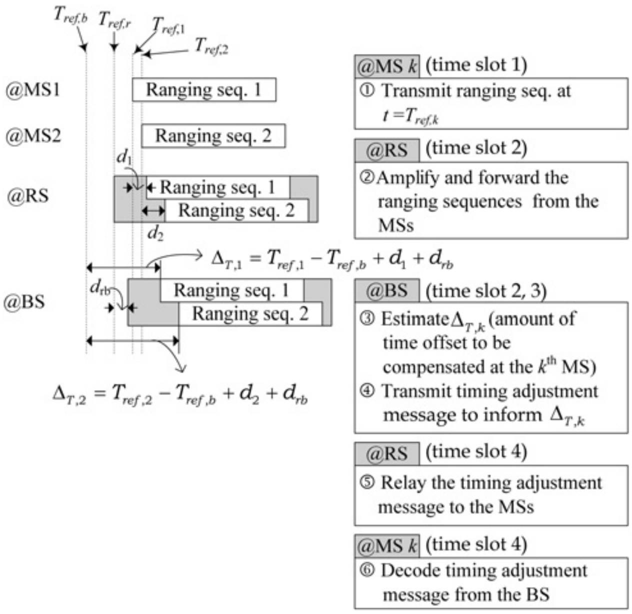

Fig. 2 *Procedures and the detailed timing illustration of the conventional ranging method for OFDMA with AF relay*

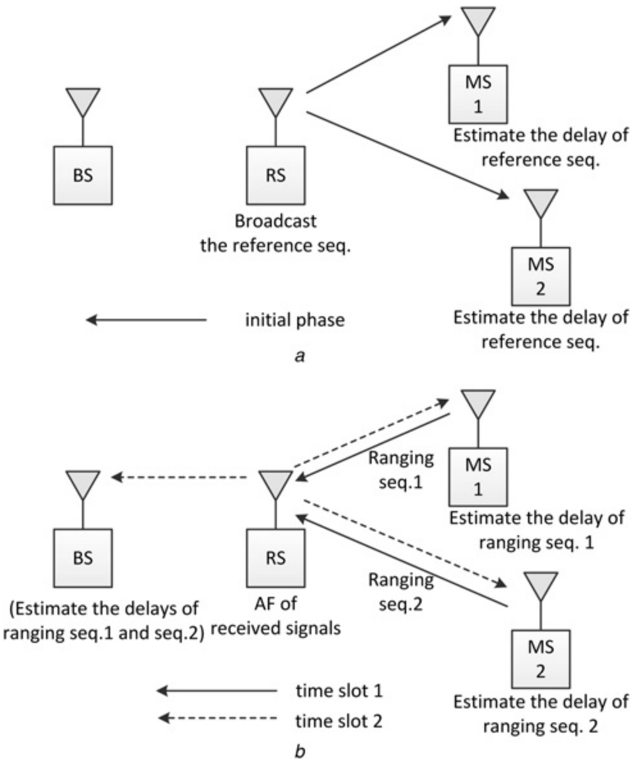

Fig. 3 *Proposed decentralised ranging method*

a Timing-reference-acquisition phase
b Timing-offset-estimation phase

overall propagation delay of $d_k + d_{rb}$, the transmitted signal can arrive at the BS exactly at $T_{\mathrm{ref},b}$ for all MSs.

Fig. 3 shows the proposed ranging method. The proposed method needs only two time slots and an occasional RS reference transmission phase. The specific procedures will be illustrated in Section 3.

3 Proposed decentralised ranging method with AF RSs

3.1 Proposed decentralised ranging procedures

The main objective of the proposed ranging method is to estimate $\Delta_{T,k}$ at the MS, without using timing-adjustment messages from the BS. Detailed timing diagrams and procedures of the RS reference sequence and the ranging sequence transmissions are shown in Fig. 4. During the timing-reference-acquisition phase, as shown in Fig. 4*a*, the RS occasionally (e.g. once or twice per second) transmits the RS reference sequence, which is known to the MSs, at absolute time $T_1 = T_{\mathrm{ref},r} - (T_{\mathrm{ref},r} - T_{\mathrm{ref},b}) - d_{rb} = T_{\mathrm{ref},b} - d_{rb}$. A fixed RS can know the reference-time difference ($T_{\mathrm{ref},r} - T_{\mathrm{ref},b}$) and propagation delay d_{rb} through ranging with the BS, and therefore the RS can transmit its RS reference sequence at T_1. Conventional ranging methods for OFDMA systems without RS (e.g. [1–4]) can be used for timing-offset estimation for RS. At the *k*th MS, after a propagation delay of d_k, the RS reference signal is received at $T_{\mathrm{ref},b} - d_{rb} + d_k$. Then, the *k*th ranging MS estimates the delay of the reference sequence, Δ_{k_1}, which is the time offset between the time at which the RS reference sequence is received ($T_1 + d_k$) and the reference time of the *k*th ranging MS ($T_{\mathrm{ref},k}$). The expected value of $\hat{\Delta}_{k_1}$ is given by $T_{\mathrm{ref},k} - (T_{\mathrm{ref},b} - d_{rb} + d_k)$. If we can additionally estimate the round-trip delay between the MS and the RS ($2d_k$) at the second phase, by adding it to $\hat{\Delta}_{k_1}$, the overall estimate of (1) can be obtained. The BSs should not send any signal at the resources for RS reference signal transmission; however, the overhead associated with the first phase is very small owing to its infrequent presence.

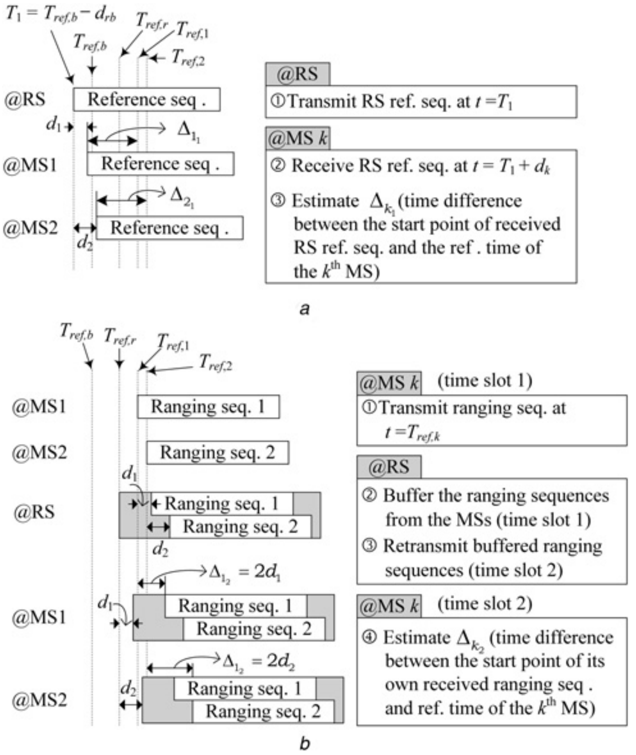

Fig. 4 *Procedures and detailed timing illustrations for the proposed ranging method*

a Timing-reference-acquisition phase
b Timing-offset-estimation phase

The second phase is a timing-offset-estimation phase. Fig. 4*b* shows the timing relationships and procedures related to the ranging sequence transmission and reception at the RS and ranging MSs. In the first time slot, the *k*th MS transmits the ranging sequence at its reference time $T_{\mathrm{ref},k}$, and the RS receives and buffers the summed ranging sequences. In the second time slot, the buffered ranging sequences are amplified and forwarded at the RS. Then, the *k*th ranging MS receives its delayed ranging sequence at $T_{\mathrm{ref},k} + d_k + d_k$ and estimates the round-trip delay $\Delta_{k_2} = 2d_k$. After estimating $\hat{\Delta}_{k_1}$ and $\hat{\Delta}_{k_2}$, which are the estimates of Δ_{k_1} and Δ_{k_2}, respectively, each ranging MS calculates the overall time offset by adding them

$$\hat{\Delta}_{T,k} = \hat{\Delta}_{k_2} + \hat{\Delta}_{k_1} \tag{2}$$

If the two delay estimates of the reference and ranging sequences are correct, the estimated overall delay is given by (1). When the *k*th ranging MS transmits signal $\hat{\Delta}_{T,k}$ before $T_{\mathrm{ref},k}$, the signal is transmitted at an absolute time of $T_{\mathrm{ref},b} - d_k - d_{rb}$, and after a transmission delay of d_k and d_{rb}, the signals from different MSs arrive at the BS at the same absolute time $T_{\mathrm{ref},b}$.

Figs. 5 and 6 show the mapping between communication resources and time slots described in Figs. 1 and 3, for the conventional and proposed ranging methods in time division duplex (TDD) and frequency division duplex (FDD) frame structures, respectively. In the TDD case, time slot 1 is allocated in UL zone 1, and time slot 2 is allocated in UL zone 2 for both methods. At time slot 2, the RS relays the sum of received signals from ranging MSs and data transmission MSs buffered at time slot 1. Since the operations of the RS are identical for both methods, no additional functionality is required for RS to support the proposed ranging method. In general, UL zones are resources for signal transmission for MSs, but because UL zone 2 is originally idle time for MSs, and the transmitted signal from the RS at time slot 2 can be heard by MSs as well, each MS can estimate its own timing offset by using the received signals at time slot 2. So the required delay for the proposed ranging method is only one frame. As shown in Fig. 3*b*, retransmitted signals from the RS can be also received at the BS, and the BS can estimate timing offsets of ranging MSs. The BS can transmit control message to an MS only for the cases that the BS detects the abnormal status of an MS (e.g. large timing-offset estimation error because of the collision of the ranging sequence) for overall network stability. However, the timing-offset estimation at the BS is not mandatory for the proposed method. In the conventional method, the BS estimates timing offset by using the received signals at time slot 2. Since it takes a few milliseconds processing time to estimate the time offsets and encode control message, time slot 3 for the conventional method cannot allocate at the $(n+1)$th frame. So the time slot 3 for control message transmission is allocated at DL zone 1 of the $(n+2)$th frame, and time slot 4 is allocated at the DL zone 2 of $(n+2)$th frame. Therefore

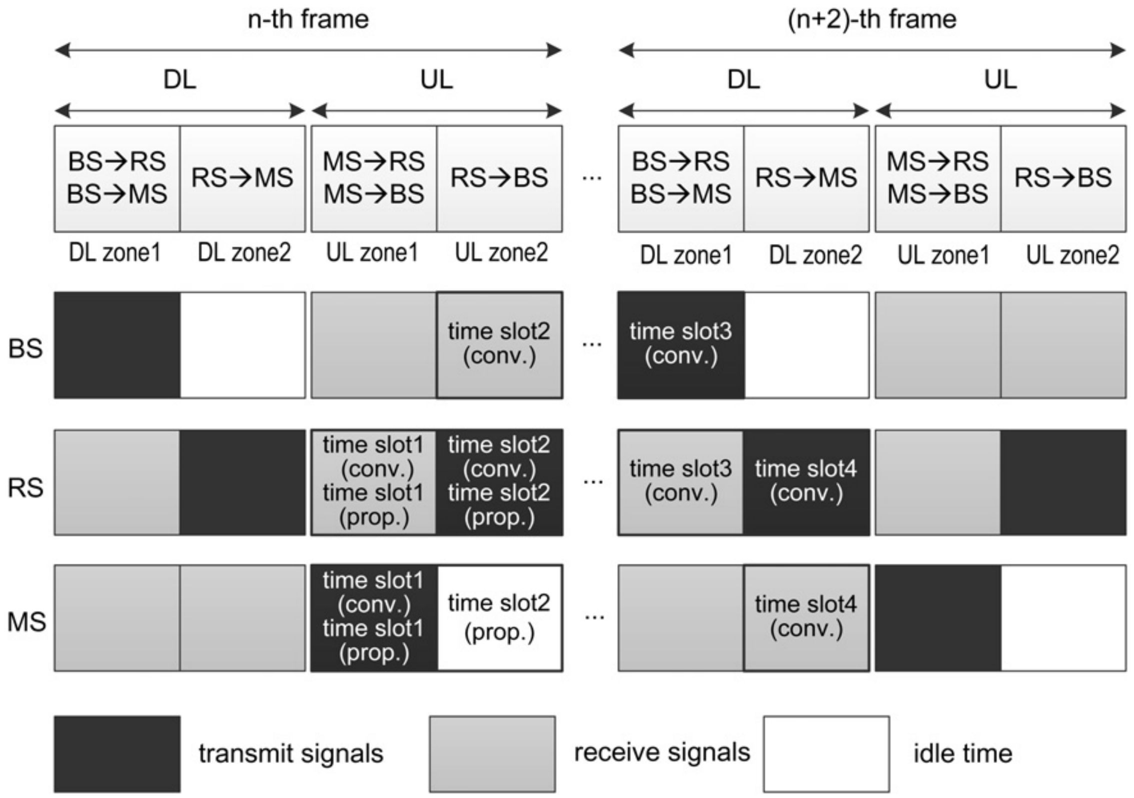

Fig. 5 *Mapping between time slots and communication resources for the conventional ranging method and proposed ranging method in a TDD frame structure*

the total required delay for the conventional method is three frames as shown in Table 1.

In the FDD case, resource mappings of time slots for the conventional method are straight forward, but complex operations at the RS are required to implement the proposed ranging method. The received signals at UL zone 1 of *n*th frame contain both ranging signals and data signals from various MSs, and the received signals corresponding to the time-frequency resources of ranging channel should be forwarded to the MS, but the other signals should be forwarded to the BS for data decoding. So the RS retransmits the all received signal at UL zone 1 of the *n*th frame to the BS by using the resources in UL zone 2. As in the case of TDD, the BS also can estimate the timing offsets of ranging MSs by using the forwarded signals from the RS. In addition, the UL received signals corresponding to the time-frequency resources of ranging channel are extracted and multiplexed with the DL signals at the DL zone 1 of the $(n+1)$th frame from the BS. Then, the RS retransmits the multiplexed signals at the DL zone 2 of the $(n+1)$th frame to the MSs. It should be noted that in order to implement the proposed method in the FDD systems, the BS should not transmit any signal at the resources for forwarded ranging sequence transmission at the RS, and the RS should have additional functions for comparison with conventional AF relays for buffering ranging signals and multiplexing the buffered signals with DL signals from the BS. However, because the time-frequency positions of the ranging resources are periodic and pre-determined, the additional functions for the RS can be implemented with acceptable complexity. As shown in Table 1, the required delay for the proposed ranging is two frames, and the required delay for the conventional ranging is three frames.

3.2 Derivation of GLRT-based timing-offset estimates

To estimate Δ_{k_1} and Δ_{k_2}, the two-step maximum-likelihood (ML) detector based on the GLRT [15] is derived [For delay estimation, several methods such as auto-correlation and cross-correlation in the time or frequency domain [1–4] also can be utilised. The relative performance comparison between the proposed and conventional ranging methods is independent of the type of estimate.]. Let N, K, L, $X_{\text{ref}}(n)$ and $X_k(n)$ denote the number of subcarriers, the number of simultaneous ranging MSs sharing the same ranging resources, the length of the time domain channels in samples, the nth subcarrier signal of the RS reference sequence and the ranging sequence of the kth ranging MS, respectively. $\mathfrak{R}\in\{i_1, \ldots, i_{|\mathfrak{R}|}\}$ is the set of ranging channel subcarrier indices, where $|\mathfrak{R}|$ is the number of elements in set $\mathfrak{R}$; P_r and P_k are the power constraints at the RS and the kth ranging MS, respectively.

After CP extraction, an N-point discrete Fourier transform (DFT) of the received signals that contain the RS reference sequence and retransmitted ranging signals is obtained. Then, $|\mathfrak{R}|$-dimensional vectors $\bar{\boldsymbol{Y}}_{k_1}$ and $\bar{\boldsymbol{Y}}_{k_2}$ containing the DFT output at the ranging channel locations are expressed as

$$\bar{\boldsymbol{Y}}_{k_1} = \sqrt{P_r}\boldsymbol{D}_{k_1}\boldsymbol{X}_{\text{ref}}\boldsymbol{B}_1\boldsymbol{h}_{rk} + \bar{\boldsymbol{W}}_{k_1} \tag{3}$$

and

$$\bar{\boldsymbol{Y}}_{k_2} = \alpha\sum_{k=1}^{K}\sqrt{P_k}\boldsymbol{D}_{k_2}\boldsymbol{X}_k\boldsymbol{B}_2\boldsymbol{h}_k + \bar{\boldsymbol{W}}_{k_2} \tag{4}$$

where α is the amplification factor at the RS,

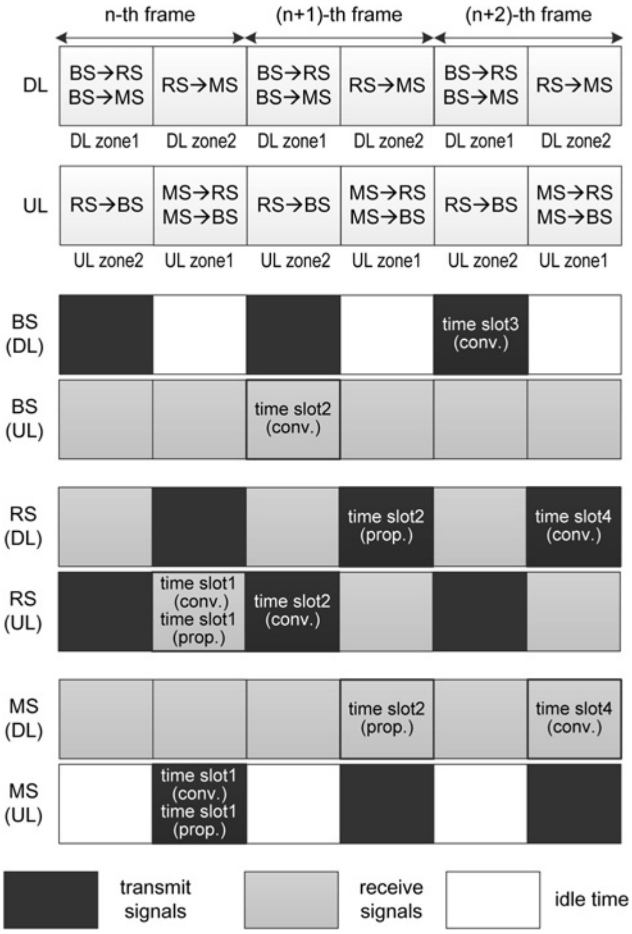

Fig. 6 *Mapping between time slots and communication resources for the conventional ranging method and proposed ranging method in an FDD frame structure*

Table 1 Required delays for the proposed and conventional ranging methods

	Conventional ranging	Proposed ranging
TDD	three frames	one frame
FDD	three frames	two frames

$\boldsymbol{D}_{k_g} = \mathrm{diag}\left(\left[\mathrm{e}^{-\mathrm{j}2\pi\Delta_{k_g} i_1/N}, \ldots, \mathrm{e}^{-\mathrm{j}2\pi\Delta_{k_g} i_{|\Re|}/N}\right]\right)$, $g \in \{1, 2\}$, are the phase-shift matrices corresponding to delays, $\boldsymbol{X}_{\mathrm{ref}} = \mathrm{diag}([X_{\mathrm{ref}}(i_1), \ldots, X_{\mathrm{ref}}(i_{|\Re|})])$, $\boldsymbol{X}_k = \mathrm{diag}([X_k(i_1), \ldots, X_k(i_{|\Re|})])$, $\boldsymbol{B}_1 \in \mathbb{C}^{|\Re| \times L}$ and $\boldsymbol{B}_2 \in \mathbb{C}^{|\Re| \times (2L-1)}$ are the DFT matrices given by $[\boldsymbol{B}_1]_{m,l} = \mathrm{e}^{-\mathrm{j}2\pi(l-1)i_m/N}$, $m = 1, \ldots, |\Re|$, $l = 1, \ldots, L$ and $[\boldsymbol{B}_2]_{m,l} = \mathrm{e}^{-\mathrm{j}2\pi(l-1)i_m/N}$, $m = 1, \ldots, |\Re|$, $l = 1, \ldots, 2L-1$. In addition, $\boldsymbol{h}_{rk} \in \mathbb{C}^{L \times 1}$ is the L-tap time domain channel vector from the RS to the kth MS, $\boldsymbol{h}_k \in \mathbb{C}^{(2L-1) \times 1}$ is the linear convolution of $\boldsymbol{h}_{rk}$ and $\boldsymbol{h}_{kr}$ (channel from the kth MS to the RS) and $\bar{\boldsymbol{W}}_{k_g} = \left[\bar{W}_{k_g}(i_1), \ldots, \bar{W}_{k_g}(i_{|\Re|})\right]^{\mathrm{T}}$, $g \in \{1, 2\}$, is the DFT output of the time domain complex Gaussian noise with variance $\sigma^2_{w,k}$ at the ranging channel locations. The conditional joint probability density functions of $\bar{\boldsymbol{Y}}_{k_1}$ and $\bar{\boldsymbol{Y}}_{k_2}$ given the delay and channel are as follows

$$f\left(\bar{\boldsymbol{Y}}_{k_1} | \boldsymbol{h}_{rk}, \Delta_{k_1}\right) = \frac{1}{\left(\pi\sigma^2_{w,k}\right)^{|\Re|}} \exp\left\{-\frac{L_1\left(\bar{\boldsymbol{Y}}_{k_1}\right)}{\sigma^2_{w,k}}\right\} \quad (5)$$

and

$$f\left(\bar{\boldsymbol{Y}}_{k_2} | \boldsymbol{h}_k, \Delta_{k_2}\right) = \frac{1}{(\pi\sigma^2)^{|\Re|}} \exp\left\{-\frac{L_2\left(\bar{\boldsymbol{Y}}_{k_2}\right)}{\sigma^2}\right\} \quad (6)$$

where

$$L_1\left(\bar{\boldsymbol{Y}}_{k_1}\right) = \left\|\bar{\boldsymbol{Y}}_{k_1} - \sqrt{P_r}\boldsymbol{D}_{k_1}\boldsymbol{X}_{\mathrm{ref}}\boldsymbol{B}_1\boldsymbol{h}_{rk}\right\|^2 \quad (7)$$

$$L_2\left(\bar{\boldsymbol{Y}}_{k_2}\right) = \left\|\bar{\boldsymbol{Y}}_{k_2} - \alpha\sqrt{P_k}\boldsymbol{D}_{k_2}\boldsymbol{X}_k\boldsymbol{B}_2\boldsymbol{h}_k\right\|^2 \quad (8)$$

and σ^2 is the variance of $\alpha\sum_{m=1, m\neq k}^{K}\sqrt{P_m}\boldsymbol{D}_{m_2}\boldsymbol{X}_m\boldsymbol{B}_2\boldsymbol{h}_m + \bar{\boldsymbol{W}}_{k_2}$. The ML solution for the estimates of Δ_{k_2} and Δ_{k_1} from (5) and (6) is given by

$$\hat{\Delta}_{k_1} = \underset{\Delta_{k_1} \in \Im}{\arg\min}\, L_1\left(\bar{\boldsymbol{Y}}_{k_1}\right) \quad (9)$$

and

$$\hat{\Delta}_{k_2} = \underset{\Delta_{k_2} \in \Im}{\arg\min}\, L_2\left(\bar{\boldsymbol{Y}}_{k_2}\right) \quad (10)$$

where $\Im = \{-d_{\max}, \ldots, d_{\max}\}$. To evaluate (9) and (10), knowledge of $\boldsymbol{h}_{rk}$ and $\boldsymbol{h}_k$ is necessary. Channel vectors $\boldsymbol{h}_{rk}$ and $\boldsymbol{h}_k$ can be estimated as follows

$$\boldsymbol{h}_{rk} = \frac{1}{\sqrt{P_r}}\left(\boldsymbol{B}_1^{\mathrm{H}}\boldsymbol{B}_1\right)^{-1}\boldsymbol{B}_1^{\mathrm{H}}\boldsymbol{X}_{\mathrm{ref}}^{\mathrm{H}}\boldsymbol{D}_{k_1}^{\mathrm{H}}\bar{\boldsymbol{Y}}_{k_1} \quad (11)$$

and

$$\boldsymbol{h}_k = \frac{1}{\alpha\sqrt{P_k}}\left(\boldsymbol{B}_2^{\mathrm{H}}\boldsymbol{B}_2\right)^{-1}\boldsymbol{B}_2^{\mathrm{H}}\boldsymbol{X}_k^{\mathrm{H}}\boldsymbol{D}_{k_2}^{\mathrm{H}}\bar{\boldsymbol{Y}}_{k_2} \quad (12)$$

under the assumption that the delays are known. Vectors $\boldsymbol{h}_{rk}$ and $\boldsymbol{h}_k$ are the ML estimates [16] that minimise $L_1\left(\bar{\boldsymbol{Y}}_{k_1}\right)$ and $L_2\left(\bar{\boldsymbol{Y}}_{k_2}\right)$, respectively. If $\boldsymbol{h}_{rk}$ and $\boldsymbol{h}_k$ in (9) and (10) are replaced by (11) and (12), respectively, (9) and (10) become

$$\hat{\Delta}_{k_1} = \underset{\Delta_{k_1} \in \Im}{\arg\max}\left\{\bar{\boldsymbol{Y}}_{k_1}^{\mathrm{H}}\boldsymbol{D}_{k_1}\boldsymbol{X}_{\mathrm{ref}}\boldsymbol{B}_1\left(\boldsymbol{B}_1^{\mathrm{H}}\boldsymbol{B}_1\right)^{-1}\boldsymbol{B}_1^{\mathrm{H}}\boldsymbol{X}_{\mathrm{ref}}^{\mathrm{H}}\boldsymbol{D}_{k_1}^{\mathrm{H}}\bar{\boldsymbol{Y}}_{k_1}\right\} \quad (13)$$

and

$$\hat{\Delta}_{k_2} = \underset{\Delta_{k_2} \in \Im}{\arg\max}\left\{\bar{\boldsymbol{Y}}_{k_2}^{\mathrm{H}}\boldsymbol{D}_{k_2}\boldsymbol{X}_k\boldsymbol{B}_2\left(\boldsymbol{B}_2^{\mathrm{H}}\boldsymbol{B}_2\right)^{-1}\boldsymbol{B}_2^{\mathrm{H}}\boldsymbol{X}_k^{\mathrm{H}}\boldsymbol{D}_{k_2}^{\mathrm{H}}\bar{\boldsymbol{Y}}_{k_2}\right\} \quad (14)$$

after some manipulation. Finally, the overall estimated delay between the kth ranging MS and BS is obtained as (2).

4 Performance evaluations and discussion

4.1 Simulation results

The timing-estimation performance of the proposed method was compared with that of a conventional method by computer simulations, with the parameters summarised in Table 2. $\Delta_{T,k}$ is randomly selected according to the uniform distribution in the range of $[-d_{\max}, d_{\max}]$, and two adjacent OFDM symbols were used for initial ranging. Since all MSs estimate frequency offset and compensate for it before UL signal transmission, residual frequency offset is not considered. In addition, perfect transmission (0 frame error rate) of the timing-adjustment message for the conventional ranging method is also assumed. In addition, we assume K ranging MSs send different ranging sequences. For the RS reference signal, a randomly selected IEEE 802.16-2009 [7] ranging sequence was transmitted every 0.5 s [When the mobile speed is 120 km/h, and the sampling period is 10 Msamples/second (sps), the shifted sample is ±0.5 in 0.5 s. Thus, the reference-sequence transmission every 0.5 s is sufficient for satisfactory performance.], and $\hat{\Delta}_{k_1}$ was estimated by averaging the four most recently received reference signals. For simplicity, it is assumed that the signal-to-noise ratios (SNRs) of the link from the BS to the RS and that of the link from the RS to the ranging MSs are equal. For both conventional and proposed timing-estimations, the proposed GLRT-based timing-offset estimation method is used.

Table 2 System parameters for performance evaluation

Parameters	Values
system bandwidth	10 MHz
carrier frequency	2 GHz
duplex	TDD
number of subcarriers (N)	1024
CP size (N_g)	128
$d_{\max}$	128
length of ranging sequence ($\lvert\Re\rvert$)	114
the number of ranging sequences (N_{code})	128
number of OFDM symbols for ranging	two symbols/5 ms
residual frequency offset	0
the number of simultaneous ranging MSs (K)	1, 2, 4, 8

Figs. 7 and 8 show the standard deviation of timing estimation errors for the proposed and conventional methods in the case of an ITU-R Pedestrian A channel with a mobile speed of 3 km/h, and Vehicular A channel with a mobile speed of 120 km/h. For all SNR ranges and any number of simultaneous ranging MSs sharing the same ranging channel (K), the performance of the proposed method is comparable with that of the conventional method for both channel environments. This is because the reference-sequence timing estimation is almost perfect because the reference time varies quite slowly, as discussed in the previous section. It should be noted that the estimation error increases with K because the co-channel interference is proportional to K. Performance loss in Vehicular A is observed compared with Pedestrian A channel. This is because the frequency selectivity of Vehicular A channel is higher than Pedestrian A channel, and frequency selectivity leads a loss of code orthogonality.

4.2 Comparisons of required communication resources and computational complexity

We compared the resources required in the conventional and proposed methods according to the TDD and FDD frame structures in Figs. 5 and 6. In accordance with the IEEE 802.16-2009 [7] system parameters, the ranging process is carried out for every frame (5 ms), and the ranging MSs for each frame are different. For the conventional method, we assume that the timing-adjustment message is encoded using a reliable coding and modulation scheme such as the quadrature phase-shift keying (QPSK) 1/12 rate coding. The other parameters are assumed as the values in Table 2. In this case, in the conventional method, approximately 96 samples/5 ms/user (19 200 sps/user) [To represent the ±128 step delay information, 8 bit are required. After QPSK 1/12 encoding, 48 samples are needed. Since two time slots are required to deliver the message information, the final required resources are 96 samples/5 ms/user.] of DL

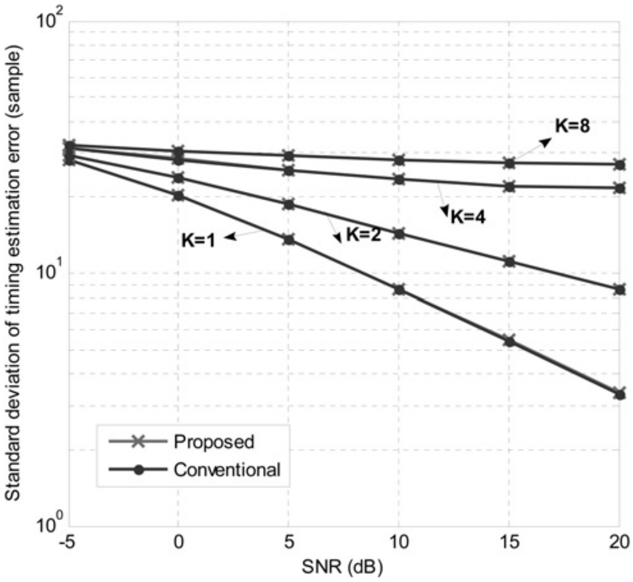

Fig. 7 *Standard deviation of timing estimation error for the conventional and proposed methods in the case of an ITU-R Pedestrian A channel at 3 km/h*

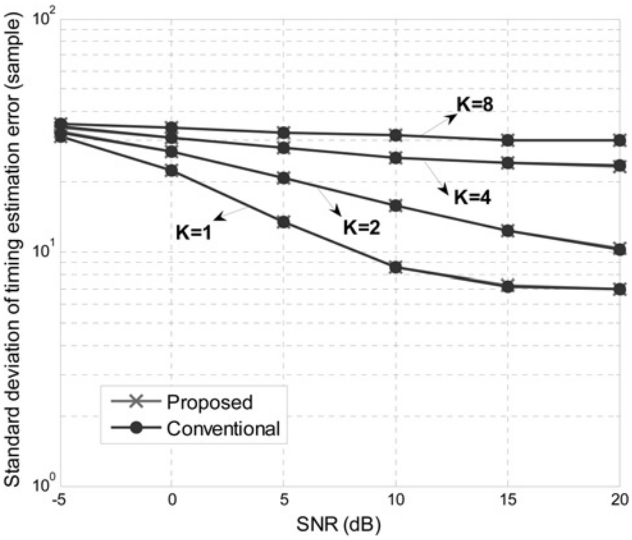

Fig. 8 *Standard deviation of timing estimation error for the conventional and proposed methods in the case of an ITU-R Vehicular A channel at 120 km/h*

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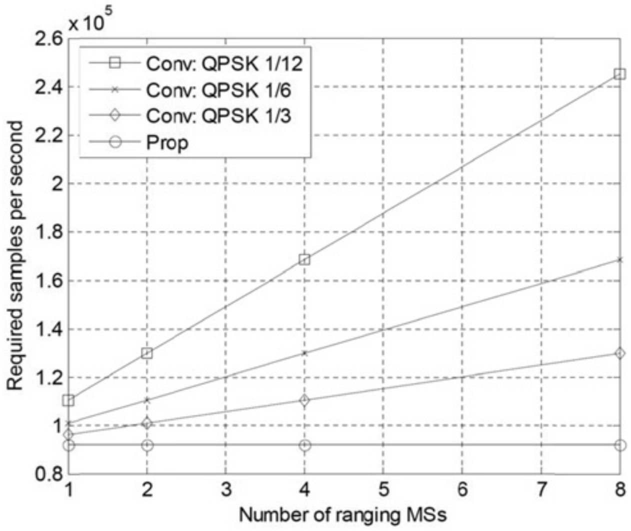

Fig. 9 *Comparison of the number of required samples per second for the conventional and proposed methods*

resources are required for timing-adjustment-message transmission and 456 samples/5 ms (91 200 sps) of UL resources are required for ranging-sequence transmission in both TDD and FDD cases. However, in the proposed method, 456 sps of DL resources are required for the RS reference-sequence transmission, 456 samples/5 ms (91 200 sps) of UL resources are required in TDD, 228 samples/5 ms (45 600 sps) of DL and UL resources are required in FDD for ranging-sequence transmission. When the number of simultaneous ranging MSs is varied from 1 to 8, the amount of resources required in the proposed method varies from 83 to 37% of that required in the conventional centralised method. In Fig. 9, the sum of required DL and UL resources are compared in terms of the number of simultaneous ranging MSs (K) and various message coding rates. Since the proposed method does not require a timing-adjustment message, the amount of resources required in the proposed method does not increase as the number of ranging MSs increases. However, the amount of resources required in the conventional method increases with the number of ranging MSs because the timing-adjustment messages are different for all ranging MSs.

In addition, computational complexity for timing-offset estimation is compared. In the conventional method, the BS does not know the ranging code, and it should correlate for all possible ranging sequences and time offsets. Therefore the computational complexity is proportional to $|\Im|N_{\text{code}}$, where $|\Im|$ is the number of timing-offset candidates, and N_{code} is the number of ranging sequences; however, the computational complexity does not increase as K increases. In the proposed method, because each MS knows its own ranging sequence, the reference signal from the RS, the computational complexity for each MS is proportional to $2|\Im|$, and total computational complexity for all K users is proportional to $2K|\Im|$. In general, N_{code} is much larger than $2K$, and the computational complexity of the proposed ranging method is much less than the conventional method.

5 Conclusions

A decentralised ranging method for an OFDMA system with an AF RS was proposed. In the proposed method, only two time slots in addition to those required for the occasionally transmitted reference sequence are necessary for the ranging. Thus, the total amount of resources required is significantly reduced, and for a greater number of ranging MSs, greater resource saving can be expected without degrading the performance.

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