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# A Signal Detection Technique for OFDMA-based Wireless Mesh Networks with TDoAs

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**Abstract**

In this paper, the effect of time difference of arrival (TDoA) is investigated for distributed nodes in OFDMA-based wireless mesh networks (WMNs). In order to minimize the interferences caused by TDoA in WMNs, the optimal starting point of FFT window at the receiver side of a node is derived by maximizing the effective SINR for each subcarrier. Also, a signal detection technique, called two dimensional ordered successive interference cancellation (TD-OSIC), is proposed for WMNs with TDoAs. It was shown via simulation that the proposed technique can achieve effective SINR and BER performances similar to the ideal case (no TDoA), even in WMNs with large TDoAs.

**Index Terms:** Wireless Mesh Networks, TDoA, OFDMA, TD-OSIC

## 1. Introduction

Due to the feature of dynamic self-organization and self-configuration, wireless mesh networks (WMNs) have been actively investigated for many application scenarios such as enterprise networking, tactical information and communication networks, wireless networks for public safety, and broadband metropolitan area networks. WMNs are known to have the advantages of low up-front cost, easy network maintenance, robustness, and reliable service coverage [1][2][3]. One of the prominent challenges in distributed wireless networks is synchronization between nodes, especially when the GPS reference timing signal cannot be used. Distributed synchronization techniques for decentralized wireless networks have been investigated using the exchange information of local timing among neighboring nodes at physical layer [4].

Recently, a single-frequency fully-synchronized WMN was implemented on the Eurecom's OpenAirInterface platform, which targets WiMAX and UMTS LTE-like networks [5]. In [5], orthogonal frequency division multiple access (OFDMA) has been considered as a modulation and multiple access technique for WMNs because it can increase data rates and flexibilities of resource allocation while avoiding the interferences among multi-channels. As in other WMNs, direct communication between mesh routers (MRs) is allowed in the OpenAirInterface platform when the uplink transmission from MR to cluster header (CH) is being performed. The transmission time instant and power of MR are adjusted through a ranging procedure, such as random access in OFDMA-based cellular systems, to minimize multiple access interference (MAI) between CH and MRs in a cluster. Also, network synchronization among adjacent clusters is achieved by cooperation between CH and MR (located at the cluster boundary).

In WMNs, the signals received at the CH are all time-aligned because the uplink signal to be transmitted from each MR in the cluster is time-advanced by the amount of delay between the CH and MR. However, the signals also arrive at the other MRs with time difference of arrival (TDoA) in WMNs. Therefore, the MR can receive not only a desired signal but also undesired signals from adjacent MRs in WMNs with TDoAs, resulting in inter-symbol interference (ISI), inter-carrier interference (ICI), and inter link interference (ILI).

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In recent years, the effective SIR in the presence of imperfect synchronization for OFDMA-based uplink systems has been derived and interference mitigation techniques have been proposed [6][7]. However, there have, thus far, been no report on the effect of TDoA or signal detection techniques for WMNs with TDoAs. In this paper, we propose a signal detection technique for WMNs with TDoAs, called two-dimensional ordered successive interference cancellation (TD-OSIC). It was shown by simulation that the proposed technique can minimize the effect of TDoA in WMNs while providing diversity gain in the process of signal detection and interference cancellation.

## 2. A Signal Detection Technique

In this section, a signal detection technique that can minimize the effect of TDoA at the receiver side is proposed for a WMN with TDoAs. Here, it is assumed that resources for the desired signal ($u=0$) and $u_{\text{th}}$ undesired signal ($1 \le u \le \text{U}$) are allocated to the subcarrier set $\mathbf{k}_u$ in an orthogonal manner to avoid CCI. It is also assumed that 1 desired signal ($u=0$) and U undesired signals arrive at a node under being tested. If we define $\Delta_0$ as the starting point of the FFT window at the node with reference to the starting point of received symbol for the desired signal and $\delta_u$ as the TDoA between the desired symbol and the $u_{\text{th}}$ undesired symbol, the offset between the $u_{\text{th}}$ undesired symbol and the starting point of FFT window at the node is given by $\Delta_u = -\delta_u + \Delta_0$. Then, the signal received at the subcarrier set $\mathbf{k}_0$ in the $m_{\text{th}}$ symbol is composed of the desired signal, interferences, and noise. Here, the interferences can be expressed by ISI and ICI terms caused by $\Delta_0$ in the desired symbol and ILI term caused by $\Delta_u$ in the undesired symbol as follows:

$$y_m\left(k \mid \Delta_0\right) = \underbrace{y_{m,0}\left(k,0 \mid \Delta_0\right)}_{\text{desired signal and ISI caused by } \Delta_0} + \underbrace{\sum_{k' \in \mathbf{k}_0, k' \neq k} y_{m,0}\left(k', k-k' \mid \Delta_0\right)}_{\text{ICI caused by } \Delta_0}$$
$$+ \underbrace{\sum_{u=1}^{U} \sum_{k' \in \mathbf{k}_u} y_{m,u}\left(k', k-k' \mid \Delta_u\right)}_{\text{ILI caused by } \Delta_u} + \underbrace{z_m(k)}_{\text{AWGN}} \quad \text{for } k \in \mathbf{k}_0 \tag{1}$$

where $y_{m,u}(k, \nabla \text{k} | \Delta_u)$ is defined as

$$y_{m,u}\left(k, \nabla k \mid \Delta_u\right) = \sum_{l=0}^{L_u - 1} h_{m,u,l} x_{m,u}\left(k, \nabla k \mid \Delta_u - l\right) \text{ for } k \in \mathbf{k}_u \tag{2}$$

where $h_{m,u,l}$, $L_u$, and $\nabla \text{k}$ denote the channel coefficient of the $l_{\text{th}}$ multipath for the $m_{\text{th}}$ symbol transmitted from the $u_{\text{th}}$ transmitter, the number of multipath components, and $k-k'$, respectively. Also, $x_{m,u}(k, \nabla \text{k} | \Delta_u)$ denotes the interference term affecting the $(k+\nabla \text{k})_{\text{th}}$ subcarrier due to the $u_{\text{th}}$ signal with $\Delta_u$ sample offsets at the $k_{\text{th}}$ subcarrier. Then, the power of desired signal, ISI, ICI, and AWGN, at the $k_{\text{th}}$ subcarrier ($k \in \mathbf{k}_0$) can be expressed as follows:

$$\sigma_D^2\left(k \mid \Delta_0\right) = \sigma_D^2\left(\Delta_0\right) = \sum_{l=0}^{L_0-1} \sigma_{h_0}^2(l) \sigma_{x_0}^2\left(0 \mid \Delta_0 - l\right) \tag{3}$$

$$\sigma_{ISI}^2\left(k \mid \Delta_0\right) = \sigma_{ISI}^2\left(\Delta_0\right) = \sum_{l=0}^{L_0-1} \sigma_{h_0}^2(l)\left(1 - \sigma_{x_0}^2\left(0 \mid \Delta_0 - l\right)\right) \tag{4}$$

$$\sigma_{ICI}^2\left(k \mid \Delta_0\right) = \sum_{k' \in \mathbf{k}_0, k' \neq k} \sum_{l=0}^{L_0-1} \sigma_{h_0}^2(l) \sigma_{x_0}^2\left(k-k' \mid \Delta_0 - l\right) \tag{5}$$

$$\sigma_{ILI}^2\left(k \mid \Delta_0\right) = \sum_{u=1}^{U} \sum_{k' \in \mathbf{k}_u} \sum_{l=0}^{L_u-1} \sigma_{h_u}^2(l) \sigma_{x_u}^2\left(k-k' \mid \Delta_0 - \delta_u - l\right) \tag{6}$$

$$\sigma_Z^2\left(k; \Delta_0\right) = \sigma_Z^2 = E\left[z_m(k) z_m^*(k)\right] \tag{7}$$

where $\sigma_{h_u}^2(l)$ denotes the variance of the $l_{\text{th}}$ multipath channel for the $u_{\text{th}}$ transmitter. Also, $\sigma_{x_u}^2(\nabla k_u | \Delta_u)$ denotes the averaged interference power of $x_{m,u}(k, \nabla \text{k} | \Delta_u)$ caused by $\Delta_u$ sample offsets of the $u_{\text{th}}$ signal and can be expressed differently depending on the value of $\Delta_u$ as follows:

(i) $-G \le \Delta_u \le 0$

$$\sigma_{x_u}^2\left(\nabla k_u \mid \Delta_u\right) = \begin{cases} 1, & \nabla k_u = 0 \\ 0, & \nabla k_u \neq 0 \end{cases} \tag{8}$$

(ii) $0 < \Delta_u \le N$

$$\sigma_{x_u}^2\left(\nabla k_u \mid \Delta_u\right) = \begin{cases} \left(N^2 - \Delta_u\right)^2 / N^2, & \nabla k_u = 0 \\ \dfrac{2}{N^2} \dfrac{1 - \cos\left(2\pi \Delta_u \nabla k_u / N\right)}{1 - \cos\left(2\pi \nabla k_u / N\right)}, & \nabla k_u \neq 0 \end{cases} \tag{9}$$

(iii) $-(N+G) < \Delta_u < -G$

$$\sigma_{x_u}^2\left(\nabla k_u \mid \Delta_u\right) = \begin{cases} \left(N + G + \Delta_u\right)^2 / N^2, & \nabla k_u = 0 \\ \dfrac{2}{N^2} \dfrac{1 - \cos\left(2\pi\left(\Delta_u + G\right) \nabla k_u / N\right)}{1 - \cos\left(2\pi \nabla k_u / N\right)}, & \nabla k_u \neq 0 \end{cases} \tag{10}$$

where $N$ and $G$ denote the total number of subcarriers in the FFT and samples in the guard interval, respectively.

Then, the effective SINR at the $k_{\text{th}}$ subcarrier ($k \in \mathbf{k}_0$) and the corresponding BER for $M$-QAM over Rayleigh fading channel are given by

$$\eta\left(k \mid \Delta_0\right) = \frac{\sigma_D^2\left(\Delta_0\right)}{\sigma_{ISI}^2\left(\Delta_0\right) + \sigma_{ICI}^2\left(k \mid \Delta_0\right) + \sigma_{ILI}^2\left(k \mid \Delta_0\right) + \sigma_Z^2} \tag{11}$$

$$P_{M,e}\left(k \mid \Delta_0\right) = \frac{2}{\log_2^M}\left(1 - \frac{1}{\sqrt{M}}\right)\left(1 - \sqrt{\frac{\eta\left(k \mid \Delta_0\right)}{\eta\left(k \mid \Delta_0\right) + 2(M-1)/3}}\right) \tag{12}$$

From (12), one can see that the BER performance varies depending on the subcarrier position and the starting point of the FFT window. The optimal starting point of the FFT window that minimizes the BER at the $k_{\text{th}}$ subcarrier can be found by locating the point that maximizes the effective SINR at the subcarrier. The optimal starting point can be derived using inequality properties as follows:

$$\begin{aligned}\Delta_{0,k}^{*} &\triangleq \arg\min_{\Delta_0}\left\{P_{M,e}\left(k\mid\Delta_0\right)\right\}\\ &=\arg\max_{\Delta_0}\left\{\left(3+2\left(M-1\right)/\eta\left(k\mid\Delta_0\right)\right)^{-1}\right\}\\ &=\arg\max_{\Delta_0}\left\{\eta\left(k\mid\Delta_0\right)\right\}\end{aligned} \tag{13}$$

In the proposed signal detection technique, the optimal starting point of the FFT window for each subcarrier is first determined by (13) to minimize error propagation in the process of interference cancellation. Then, the interference terms due to the TDoA are subtracted in descending order from the subcarrier with the highest effective SINR. In the proposed TD-OSIC technique, the interferences (ISI and ICI) caused by the desired user and other users are cancelled in both the time- and frequency-domain as follows:

$$\hat{\mathbf{y}}_m\left(\Delta_{0,k}^{*}\right)=\underbrace{\overbrace{\mathbf{y}_m\left(\Delta_{0,k}^{*}\right)-\mathbf{H}_{m,0}^{e}\left(\Delta_{0,k}^{*}\right)\hat{\mathbf{x}}_{m,0}}^{\text{ICI cancellation}}-\mathbf{H}_{m,0}^{i}\left(\Delta_{0,k}^{*}\right)\hat{\mathbf{x}}_{m,0}^{i}}_{\text{ISI cancellation}}\in\mathbb{C}^{N} \tag{14}$$

where

$$\mathbf{y}_m\left(\Delta_0\right)=\sum_{u=0}^{U}\left\{\mathbf{H}_{m,u}^{e}\left(\Delta_0-\delta_u\right)\mathbf{x}_{m,u}+\mathbf{H}_{m,u}^{i}\left(\Delta_0-\delta_u\right)\mathbf{x}_{m,u}^{i}\right\}+\mathbf{z}_m \tag{15}$$

Here, $\mathbf{y}_m(\Delta_0)$ denotes the $m_{\text{th}}$ signal vector, which is composed of the signals received from adjacent nodes in the frequency domain when the starting point of FFT window is set to $\Delta_0$. Also, $\mathbf{x}_{m,u}$ and $\mathbf{x}_{m,u}^{i}$ denote the signal vector transmitted from the $u_{\text{th}}$ node at the $m_{\text{th}}$ symbol period and the signal (ISI) vector at the $(m-1)_{\text{th}}$ or $(m+1)_{\text{th}}$ symbol period, respectively, all in the frequency domain. The vector $\mathbf{x}_{m,u}^{i}$ becomes $\mathbf{x}_{m-1,u}$ or $\mathbf{x}_{m+1,u}$ depending on the situation, where the ISI occurred is due to either the previous symbol or next symbol. The components not included in the subcarrier set $\mathbf{k}_u$ are set to zero in the vector $\mathbf{x}_{m,u}$. The vector $\mathbf{z}_m$ denotes the AWGN in the frequency domain. Also, $\mathbf{H}_{m,u}^{e}(\Delta_{0,k}^{*})$ and $\mathbf{H}_{m,u}^{i}(\Delta_{0,k}^{*})$ represent the effective channel and interference channel matrices for the $m_{\text{th}}$ symbol received from the $u_{\text{th}}$ node, respectively, when the receiver has the optimal starting point of FFT at the $k_{\text{th}}$ subcarrier. $\hat{\mathbf{x}}_{m,0}$ denotes the vector composed of the previously detected signals from the $m_{\text{th}}$ desired OFDM symbol, and $\hat{\mathbf{x}}_{m,0}^{i}$ denotes the vector of the previously detected signals from the $(m-1)_{\text{th}}$ or $(m+1)_{\text{th}}$ desired OFDM symbol, all in the frequency domain.

When $-G\leq\Delta_u< L_u-G-1$, $\mathbf{x}_{m,u}^{i}$, $\mathbf{H}_{m,u}^{e}(\Delta_u)$, and $\mathbf{H}_{m,u}^{i}(\Delta_u)$ in (14) and (15) are given by $\mathbf{x}_{m-1,u}$, $\mathbf{F}(\mathbf{H}_{m,u}-\mathbf{H}_{m-1,u})\mathbf{F}^{\text{H}}\mathbf{W}$, and $\mathbf{F}\mathbf{H}_{m-1,u}\mathbf{F}^{\text{H}}$, respectively. Here, $\mathbf{A}^{\text{H}}$ denotes the Hermitian matrix of $\mathbf{A}$. $\mathbf{F}$ and $\mathbf{W}$ denote the DFT matrix whose $(k,n)_{\text{th}}$ entry is $e^{-j2\pi nk/N}$ and a diagonal matrix whose $k_{\text{th}}$ diagonal entry is $e^{-j2\pi Gk/N}$, respectively. Also, $\mathbf{H}_{m,u}$ is a circulant matrix whose $\Delta_{u\,\text{th}}$ column is $\left[h_{m,u,0},h_{m,u,1},\cdots,h_{m,u,L_u-1}\mathbf{0}_{1,N-L_u}\right]^{\text{T}}$. $\mathbf{0}_{k,n}$ and $\mathbf{A}^{\text{T}}$ denote the zero matrix with a size of $k\times n$ and the transpose matrix of $\mathbf{A}$, respectively. $\mathbf{H}_{m-1,u}$ is the interference channel matrix including ISI and ICI caused by the previous symbol, and is given by

$$\mathbf{H}_{m-1,u}=\begin{bmatrix}\mathbf{0}_{N,N-L_u+G+\Delta_u+1} & \begin{matrix}h_{m,u,L_u-1} & h_{m,u,L_u-2} & \cdots & h_{m,u,G+\Delta_u+1}\\ 0 & h_{m,u,L_u-1} & \ddots & \vdots\\ \vdots & \ddots & \ddots & h_{m,u,L_u-2}\\ 0 & \cdots & 0 & h_{m,u,L_u-1}\\ & \mathbf{0}_{N-L_u+G+\Delta_u+1,L_u-G-\Delta_u-1} & & \end{matrix}\end{bmatrix} \tag{16}$$

Unlike the conventional signal detection techniques ($\Delta_{0,k}^{*}=0,\forall k\in\boldsymbol{k}_0$), the interferences caused by desired symbols may exist due to $\Delta_{0,k}^{*}\neq 0$ in the proposed technique. The effects of interferences caused by desired and undesired symbols are minimized in the proposed approach by finding the optimal starting point of FFT window for each subcarrier using (13), re-ordering the subcarrier index according to the effective SINR using (11), and canceling the interferences in both the time- and frequency-domain using (14).

## 3. Simulation Results

In this section, performances of the proposed signal detection technique for a WMN with TDoA are evaluated by computer simulation. Parameters for simulation are set to $N=256$, $G=32$, and $L_u=33$. It is assumed that the channel impulse response has an exponentially decaying power delay profile.

In Fig. 1, effective SINR performances of the proposed technique for adjusting the starting point of the FFT window in (13) are compared with those of the conventional one when TDoA and DUR vary. Here, the number of subcarriers allocated to desired node, $K_0$, is set to 32 or 128, and the rest of the subcarriers $N-K_0$ are allocated to the other nodes. SNR is set to 20dB. From this figure, one can see that effective SINR performances are almost identical regardless of DUR and $K_0$ when the proposed approach is applied. Also, the amount of performance degradation in the effective SINR for $\delta_1=-20$ is less than 1.5dB compared with the case of $\delta_1=0$. On the other hand, the effective

SINR performances of the conventional technique ($\Delta^*_{0,k}= 0, \forall k \in \boldsymbol{k}_0$) decrease significantly as DUR or $K_0$ decreases. The effective SINR performances also decrease as TDoA increases. From this figure, one can see that the proposed technique can enhance the effective SINR significantly in a WMN with TDoAs.

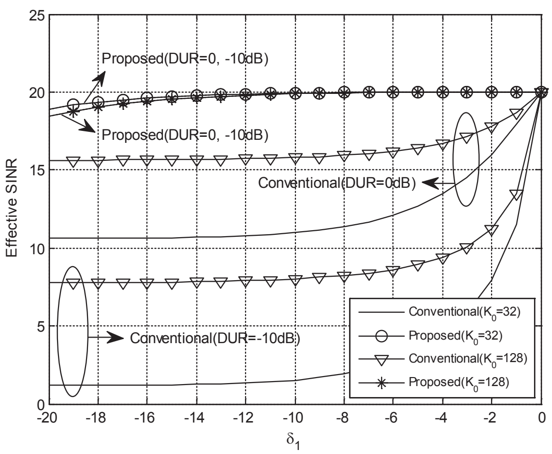


**Fig. 1.** Effective SINR vs. TDoA

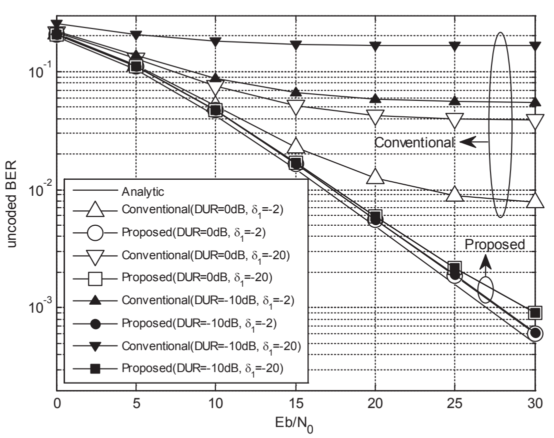


**Fig. 2.** BER performance comparison of signal detection techniques for a WMN with TDoA

In Fig. 2, BER performances of the proposed TD-OSIC signal detection technique are compared with the conventional one (OSIC). Here, parameters for simulation are set to $K_0 = 32$, $\delta_1 = -2$ or $-20$, and DUR is 0dB or -10dB. Also, 16QAM modulation and zero-forcing detection for initial value are used. From this figure, one can see that the proposed technique has the same performance regardless of DUR and has only about a 0.5dB gap at a BER of $10^{-3}$ compared with the analytic one, when $\delta_1 = -2$. On the other hand, error floors occur in most cases of the conventional technique. The BER performances of the conventional technique decrease as DUR or $\delta_1$ decreases. From this figure, we can see that the proposed technique can minimize the interferences caused by TDoA in a WMN with a large TDoA and low DUR.

## 4. Conclusion

In this paper, we investigated the effect of TDoA for distributed nodes in OFDMA-based WMNs and proposed a signal detection technique for WMNs with TDoAs. Through simulation results, it was shown that a significant performance loss may occur due to the interferences (ISI, ICI, ILI) caused by TDoA in a WMN and the effective SINR and BER performances similar to the ideal situation (no TDoA) can be achieved in a WMN with a large TDoA by applying the proposed TD-OSIC signal detection technique.

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