TIMING ADJUSTMENT TECHNIQUES TO MITIGATE INTERFERENCE BETWEEN MULTIPLE NODES IN OFDMA MESH NETWORKS

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ABSTRACT

We configure the multiple node interference (MNI) on OFDMA mesh networks and analyze the feature of this MNI as a closed form in terms of timing misalignment between multiple nodes. Based on our analysis, we propose some new timing adjustment techniques to mitigate MNI and verify the difference and superiority of the proposed techniques compared to the ones adopted by cellular OFDMA systems.

Index Terms— OFDMA, mesh network, timing adjustment, SINR analysis

1. INTRODUCTION

Recently, wireless mesh networks have emerged as a promising technology for next-generation wireless networks [1][2] with rapid increase on the demand for higher-speed Internet access from anywhere, which requires high data rate, quality-of-services (QoS) support and enlarged coverage with reliable connectivity. Especially, taking advantage of OFDMA system which granularly utilize the resources, extensive studies are performed over OFDMA mesh networks to realize the potential of this new technology [1]. However, because of the challenges and difficulties presented by the multihop communications over OFDMA mesh networks, OFDMA air interface is not configured as a practical network model [3].

Although lots of researches are performed on OFDMA mesh network to resolve these problems, those researches are mainly focused on MAC layer such as resource allocation, scheduling, while excluding PHY layer issues such as node synchronization, interference management, and so on. However, the researches on PHY layer issues are also essential to configure OFDMA mesh network in practice.

Consequently, we undertake PHY layer issues on OFDMA mesh network, especially the synchronization challenges and interference features in this paper. The main goal of this paper is two-fold: First, we define multiple node interference (MNI) on OFDMA mesh network, which is caused by timing and frequency misalignments between multiple nodes. Then, we quantify the effects of this misalignment on MNI under OFDMA mesh networks with an analytic signal-to-interference-noise ratio (SINR) expression. Next, we clarify the main difference on timing adjustment strategy between cellular based OFDMA systems (e.g., downlink/uplink) and OFDMA mesh network, and propose the timing adjustment criterion to alleviate the performance degradation on mesh networks.

The remainder of this paper is organized as follows: Section 2 describes OFDMA mesh network model considered in this paper and presents the analytic MNI features with respect to timing difference between multiple nodes. We explain the limit of existing adjustment methods and propose new timing adjustment techniques to mitigate SINR degradation due to MNI in Section 3, then observe the performance of OFDMA mesh networks in Section 4. Section 5 concludes this paper.

2. SYSTEM MODEL

Let us consider a generalized OFDMA wireless mesh network employing a total of $N$ subcarriers, where $P$ transmitting nodes communicate with $Q$ receiving nodes simultaneously. Unlike cellular-type of point-to-multipoint (PMP) topology, mesh mode makes each node not only a host but also a router that forwards packets on behalf of others. Consequently, each node can transmit data to multiple nodes as well as receive data from multiple nodes.

Fig. 1 illustrates the OFDMA mesh network scenario considered here. As already declared, the entire network is grouped into transmitting node set $\mathcal{N}_p = \{1, 2, \ldots, P\}$ and receiving node set $\mathcal{N}_q = \{1, 2, \ldots, Q\}$. Since each node can be a host as well as a router in mesh network, transmitter($tx$) $p$ contains different data delivering to different destinations, denoted as $X_{pq}$, $\forall q \in \mathcal{N}_q$ which is the data delivered via the link $L_{pq}$ from $tx$ $p$ to receiver($rx$) $q$.

In order to avoid the subcarrier collision, it is suggested to allocate the subcarriers exclusively. Let us define $\mathcal{S}_p$ as the subcarrier index group assigned to the node $tx$ $p$, and this group is divided into $Q$ subgroups, named $\mathcal{S}_{pq}$, which includes subcarrier indices used at the link $L_{pq}$: $\mathcal{S}_p = \bigcup_{q=1}^{Q} \mathcal{S}_{pq}$ where $\mathcal{S}_{pq} \cap \mathcal{S}_{p'q'} = \emptyset$, $\forall p \neq p' \in \mathcal{N}_p$, $q \neq q' \in \mathcal{N}_q$.

As shown in Fig. 1(b), depending on the propagation delay and timing adjustment parameters, MNI may be reduced at the receiving node (e.g., $rx$ $q$) or may become serious (e.g.,...
Fig. 1. OFDMA mesh network example, two tx nodes and two rx nodes communication scenario

Consequently, in order to prevent or mitigate MNI at the mesh network, at first we should estimate the timing and frequency offsets for each link, and then apply the advanced adjustment strategy to alleviate the performance.

The received symbol at rx q with timing offset over an OFDMA mesh network is described as 

$$y_q[n] = \sum_{p=1}^{P} h_{pq}[n] * x_p[n - \nu_p - \tau_{pq}], n \in [-N_q, N]$$

where * denotes the convolution and $h_{pq}$ means the channel impulse response on link $\mathcal{L}_{pq}$, which connects tx p to rx q. $N_q$ is the length of cyclic prefix, which is assumed to be longer than the maximum channel delay spread $L - 1$. $x_p[n]$ is the transmitted symbol from tx p, and $\tau_{pq}$ means the propagation delay on link $\mathcal{L}_{pq}$. In addition, $\nu_p$ means tx timing adjustment parameter at the tx p for synchronization (see Fig. 1(b)).

The received symbol at the frequency domain is given by 

$$Y_q[k] = \sum_{n=0}^{N_q-1} y_q[n + \mu_q] e^{-j2\pi nk/N},$$

where $\mu_q$ denotes rx timing adjustment parameter at the rx q for synchronization. Now, let us define the effective timing delay at node rx q on link $\mathcal{L}_{pq}$ is denoted as $\theta_{pq} = \nu_p + \tau_{pq} - \mu_q$.

2.1. Interference Features

On OFDMA uplink systems, the multiple access interference (MAI) is only expressed by the timing and frequency offset mismatch between multiple subscriber stations (SSs) since all the SSs share one common base station (BS) to communicate [4][5]. However, all tx nodes communicate with multiple rx nodes simultaneously in the OFDMA mesh network. Thus timing and frequency offset adjustment for one specific link can affect all the other connected links in the network. Therefore, the MNI should be expressed based on the link parameters between tx and rx nodes in the OFDMA mesh network.

Let us define the communication link between tx p and rx q, i.e., link $\mathcal{L}_{pq}$, as the desired link at the receiving node rx q. Then, the interference observed at the node rx q can be classified into four classes as follows:

- **Self-transmitting Self-receiving Node Interference (SSNI):** the interference caused by timing misalignment on the desired link $\mathcal{L}_{pq}$. SSNI may or may not occur. Precisely, there is no SSNI for $0 \leq \theta_{pq} \leq N_q - L + 1$.

Table 1. OFDMA mesh network interference classification

<table>
<thead>
<tr>
<th>Variables</th>
<th>SSNI</th>
<th>SONI</th>
<th>OSNI</th>
<th>OONI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concerned offset parameters</td>
<td>$\nu_p + \tau_{pq}$</td>
<td>$\nu_p + \tau_{pq}$</td>
<td>$\nu_p + \tau_{pq}$</td>
<td>$\nu_p + \tau_{pq}$</td>
</tr>
<tr>
<td>Subcarriers</td>
<td>$x_{pq}$</td>
<td>$x_{pq}'$</td>
<td>$x_{pq}$</td>
<td>$x_{pq}'$</td>
</tr>
</tbody>
</table>

- **Self-transmitting Other-receiving Node Interference (SONI):** the interference caused by timing misalignment on the link $\mathcal{L}_{pq}$. SSNI may occur when the node tx p also delivers the data to the other node rx $q'$.

- **Other-transmitting Self-receiving Node Interference (OSNI):** the interference caused on the link $\mathcal{L}_{pq}$.

- **Other-transmitting Other-receiving Node Interference (OONI):** the interference caused on the link $\mathcal{L}_{pq}$.

This is generalized MNI classification for OFDMA mesh network. Thus, depending on subcarrier allocation strategy and link connectivity [2], the MNI term can be described for various kinds of OFDMA mesh network. The detailed parameters to dominate the interference are classified in Table 1.

2.2. Received Signal to Interference Noise Ratio (SINR)

Based on the interference classification, the received SINR at rx q on the k-th subcarrier ($k \in S_{pq}$) is expressed as

$$\text{SINR}_q[k] = \frac{E_q^2[k]}{\sum_{W \in \{\text{SSNI,SONI,OSNI,OONI}\}} \sigma_{q,W}^2[k] + \sigma_n^2}.$$  

where $E_q^2[k]$ is the desired signal power at the k-th subcarrier, and $\sigma_{q,\text{SSNI}}^2[k]$, $\sigma_{q,\text{SONI}}^2[k]$, $\sigma_{q,\text{OSNI}}^2[k]$, and $\sigma_{q,\text{OONI}}^2[k]$ denote the variances of SSNI, SONI, OSNI, and OONI observed at the k-th subcarrier, respectively, and $\sigma_n^2$ is the noise variance. The detailed derivations are shown in the Appendix.

Let us define $\gamma_m(k,n_L,n_U)$ as the normalized orthogonal sufficiency to evaluate the orthogonality degradation caused by timing and frequency offset misalignment as follows:

$$\gamma_m(k,n_L,n_U) = \frac{1}{N} \sum_{n=0}^{n_U-1} e^{j2\pi(m-k+n_L-n_U)} u(n_U - n_L),$$

where $u(n)$ is the unit step function, $k \in S_{pq}$ and $m \in S_{ph}$.  

3. TIMING ADJUSTMENT FOR MNI MITIGATION

3.1. Tx Node Timing Adjustment Strategy

Typically in OFDMA uplink systems, the base station (BS) (rx) forwards timing adjustment feedback to each subscriber stations (txs) in order to adjust timing offset and align at the BS [6]. However, it is very difficult to apply this timing adjustment strategy for OFDMA mesh network since the timing adjustment for specific rx node can cause the timing misalignment for all the other rx nodes.
If it is highly required to use tx timing adjustment in the system, then the artificial timing adjustment at tx, \( \nu_p \), should satisfy the following condition in order to eliminate all the MNI for given propagation delays, \( \tau_{pq} \):

\[
\max_p(\theta_{pq}) - \min_p(\theta_{pq}) \leq N_q - L + 1, \forall q \in N_q. \tag{3}
\]

In order to obtain \( \nu_p \)'s to satisfy the condition (3), each tx node should know all \( \tau_{pq} \)'s as well as all the other tx nodes timing adjustment \( \nu_p \)'s. Therefore, the fusion center should be required to collect all the information, calculate the proper \( \nu_p \)'s and distribute the achieved parameters, but it requires too much complexity and feedback burden. Moreover, there are some unaffordable cases not to obtain the proper \( \nu_p \)'s depending on the given \( \tau_{pq} \). Consequently, the timing adjustment method used in OFDMA uplink system is no longer attractive to mitigate the MNI over OFDMA mesh networks.

3.2. Rx Node Timing Adjustment Strategy

Unlike OFDMA downlink systems, it is addressed in OFDMA mesh network that the existing synchronization methods which use the exact timing offset for tx, \( q \), i.e., \( \mu_q = \tau_{pq} \), does not guarantee the best performance any more since the desired link \( \mathcal{L}_{pq} \) still can be disturbed by other links \( \mathcal{L}_{p'q}, \forall p' \in N_p \) because of the timing misalignment between links. There are other synchronization points to enable better performance according to the distribution of timing offset. Therefore, even though we estimate very accurate timing offsets for all links [6], it should be performed finding the best timing adjustment \( \theta_{pq} \), which is not the exact timing offset of the desired link but the compromised offset from all the links, to minimize MNI. Using the derived analytic SINR expression in (1), we propose two rx timing adjustment strategies to improve the performance in the following.

3.2.1. Maximize Average SINR

\[
\mu_{q,\text{avg}} = \arg \max_{\mu_q} \frac{1}{|\mathcal{S}_{pq}|} \sum_{k \in \mathcal{S}_{pq}} \text{SINR}_k[\mu_q] \tag{4}
\]

Since SINR[\mu_q] of the function of \( \mu_q \), the best timing adjustment parameter can be obtained by using the analyzed SINR expression. Intuitively, this method is applied to maximize the average capacity on the link \( \mathcal{L}_{pq} \).

3.2.2. Maximize Minimum SINR

\[
\mu_{q,\text{maxmin}} = \arg \max_{\mu_q} \min_{k \in \mathcal{S}_{pq}} \text{SINR}_k[\mu_q] \tag{5}
\]

This adjustment technique picks up \( \mu_q \) which maximizes the minimum SINR. This strategy is appropriate to minimize the average bit error rate (BER) on the link \( \mathcal{L}_{pq} \) since BER is dominantly determined by the weakest SINR.

4. SIMULATION RESULTS

We evaluate the performance of the proposed rx timing adjustment techniques in terms of SINR. Let us consider the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{SINR comparison with respect to maximum propagation delay, \( \tau_{pq} \)}
\end{figure}

OFDMA system parameters as \( N = 64, N_q = 8, L = 4 \) and mesh network with \( P = 2, 4 \) and \( Q = 4 \) nodes.

Fig. 2 shows the SINR performance of(rx timing adjustment) methods when \( \tau_{pq} \)'s are uniformly distributed within \( [0, \tau_{\text{max}}] \) when \( \tau_{\text{max}} \) is denoted as the maximum timing offset. As shown in the figure, the proposed timing adjustment techniques \( \mu_{q,\text{avg}} \) and \( \mu_{q,\text{maxmin}} \) outperform both exact timing \( \mu_q = \tau_{pq} \) and no timing \( \mu_q = 0 \) adjustment cases. In addition, it is observed that the SINR improvement using the proposed adjustment techniques is more prominent as \( \tau_{\text{max}} \) increases. It means the usage of the proposed adjustment is more important for the system with large network size.

In addition, we compare the SINR performance for different subcarrier allocation schemes. Since the MNI feature is quite different depending on what the allocation scheme is used in the mesh network, it is also important to allocate subcarriers smartly in order not to cause too much MNI. As shown in the figure, basically exclusive subband allocation scheme shows better SINR performance compared to random allocation since only edge subcarriers are dominantly sacrificed by interference invasion on subband allocation [5]. In addition, as the number of active nodes is increased from \( P = 2 \) to \( P = 4 \), the SINR performance is severely decreased. It means that, in the heavy network, it is more crucial to find the best \( \mu_{q,\text{avg}} \) parameters to mitigate MNI.

Fig. 3 describes the BER performance of the desired receiver according to the maximum timing offset \( (\tau_{\text{max}}) \). The timing adjustment \( \mu_{q,\text{avg}} \) and \( \mu_{q,\text{maxmin}} \) are applied in the simulation from the analysis for given timing offsets \( \tau_{pq} \). As depicted in the figure, the proposed timing adjustment techniques outperform the other existing methods since the appropriate timing adjustment parameter \( \mu_q \) is chosen to minimize MNI, and the performance difference becomes bigger as the maximum timing offset increases, which means that the proposed timing adjustments can maintain the performance by
alleviating the degradation caused by MNI. In addition, the BER performance difference is negligible between μ_q.avg and μ_q.maxmin even though the criteria are different, so we can pick up either scheme which has the lower complexity for implementation.

5. CONCLUSION

We declare four different kinds of MNI in OFDMA mesh network and analyze the feature of MNI in terms of timing and frequency misalignments. Unlike the timing adjustment techniques on cellular-based OFDMA systems, the compromised timing adjustment (not the exact timing offset compensation) should be performed at the receiver in order to alleviate the MNI on OFDMA mesh networks. By exploiting analyzed SINR expression, we proposed the new timing adjustment criterion to maximize the performance on mesh network without big burden on complexity and feedback. Simulation results verify the proposed timing adjustment techniques at the receiver outperform the exact timing compensation techniques, and the performance improvement by the proposed adjustment is more significant as the system is more crowded or the network size grows. The proper timing adjustment can be usefully extended for complex subcarrier and different power allocation in OFDMA mesh network since it can support arbitrary subcarrier and power allocation techniques.

6. APPENDIX

If the timing adjustment θpq is given at the node rx q, it is determined to calculate the interference from the current symbol (CS), previous symbol (PS), and next symbol (NS), respectively. Based on [4], we unified the variables and refined the functions in order to express MNI for all cases in OFDMA mesh network. Let us define n_ab,L(l) and n_ab,U(l) as follows:

\[ n_{ab,L}(l) = \theta_{ab} + (\mu_a - \mu_q) + l - N_y \]
\[ n_{ab,U}(l) = \theta_{ab} + (\mu_a - \mu_q) + l + N - 1. \]

Then, the lower and upper sample bounds of CS within FFT window is described as \( n_{ab,L}(l) = \max(0, n_{ab,L}(l)) \) and \( n_{ab,U}(l) = \min(N - 1, n_{ab,U}(l)) \). Then, the amount of node interference caused by CS, PS and NS can be given by

\[ \Gamma_{ab,CS}[k] = \sum_{m \in S_{ab}} \sum_{l=0}^{L-1} |\gamma_{mk}(n_{ab,L}(l), n_{ab,U}(l))|^2 \] (6)
\[ \Gamma_{ab,PS}[k] = \sum_{m \in S_{ab}} \sum_{l=0}^{L-1} |\gamma_{mk}(0, n_{ab,L}(l) - 1)|^2 \] (7)
\[ \Gamma_{ab,NS}[k] = \sum_{m \in S_{ab}} \sum_{l=0}^{L-1} |\gamma_{mk}(n_{ab,U}(l) + 1, N - 1)|^2. \] (8)

The normalized total interference on link \( L_{pq} \) is denoted as

\[ \Gamma_{ab,T}[k] = \Gamma_{ab,CS}[k] + \Gamma_{ab,PS}[k] + \Gamma_{ab,NS}[k]. \] (9)

Then, the explicit analysis for the variances is given by

\[ E^2_{pq} [k] = \mathcal{E}_{pq} \sum_{l=0}^{L-1} |\gamma_{kk}(n_{pq,L}(l), n_{pq,U}(l))|^2 \] (10)
\[ \sigma^{2}_{q,SSNI}[k] = \mathcal{E}_{pq} \times \Gamma_{pq,T}[k] - E^2_{pq}[k] \] (11)
\[ \sigma^{2}_{q,SONI}[k] = \sum_{q' \neq q} \mathcal{E}_{pq'} \times \Gamma_{pq',T}[k] \] (12)
\[ \sigma^{2}_{q,OSNI}[k] = \sum_{p' \neq p} \sum_{q' \neq q} \mathcal{E}_{pq'} \times \Gamma_{p'q',T}[k]. \] (13)
\[ \sigma^{2}_{q,ODNI}[k] = \sum_{p' \neq p} \sum_{q' \neq q} \mathcal{E}_{pq'} \times \Gamma_{p'q',T}[k]. \] (14)

where \( \mathcal{E}_{pq} \) is defined as the transmission energy at link \( L_{pq} \).

7. REFERENCES


