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Distributed Frequency Synchronization for Global Synchronization in Wireless Mesh Networks

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Abstract—In this paper, our focus is to assure a global frequency synchronization in OFDMA-based wireless mesh networks with local information. To acquire the global synchronization in distributed manner, we propose a novel distributed frequency synchronization (DFS) method. DFS is a method that carrier frequencies of distributed nodes converge to a common value by repetitive estimation and averaging step and sharing step. Experimental results show that DFS achieves noteworthy better synchronization success probability than existing schemes in OFDMA-based mesh networks where the estimation error is presented.

Keywords—OFDMA systems; Frequency synchronization; Distributed networks; Multiple groups.

I. Introduction

RECENTLY, OFDMA-based wireless mesh networks have been widely applied in various wireless network such as Wireless Local Area Networks (WLANs), Wireless Metropolitan Area Networks (WMANs), Wireless Personal Area Networks (WPANs), and Wireless Sensor Networks (WSNs). OFDMA-based wireless mesh networks without a center controller substantially improve the network performance and cut down operating cost than the one with a center controller. However, they contain lots of challenges due to the difficulties of collecting network information; In these networks, distributed nodes have to operate with incomplete network information and make local decisions for the optimal transmission and reception. And each node should synchronize with imperfect offset estimation with multiple nodes. To improve the difficulties, a variety of methods have been proposed in literature (see [1], [2], [3], [4], [5], and references therein). Among them, the most powerful and simple method is the consensus synchronization [5]. This mechanism gradually synchronizes a target parameter which is needed to synchronize in the global manner.

In practical systems, each node obtains an estimated offset with a target node instead of exact value and the estimation error leads to the performance degradation. The consensus algorithm in [5] is very effective but vulnerable to estimation error. To minimize the estimation error, we present two solutions; repetitive estimation and sharing estimates. Applying these solutions, we propose a novel frequency synchronization scheme named distributed frequency synchronization (DFS). With only slight cost investment due to the sharing message, DFS significantly improve the synchronization performance.

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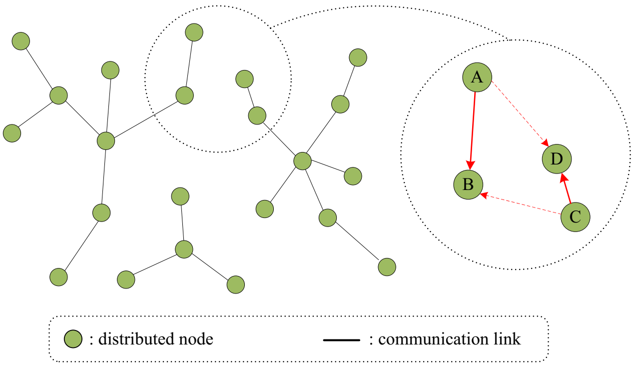


Fig. 1. Illustration of wireless mesh network.

The rest of this paper is organized as follows: In Section II, we introduce system model and describe an issue of frequency synchronization in wireless mesh networks. In Section III, we propose DFS scheme. In Section IV, we confirm the performance of the proposed scheme with simulation results. And in Section V, we present the conclusion.

II. System Model

As shown in Figure 1, wireless mesh network is consisted of lots of distributed nodes and communication links between the nodes. When all nodes in the network directly communicate each other without a center controller, interference between nodes is an inevitable problem. To avoid the interference, scheduling and routing protocols are considered as a solution. However, the interference from asynchronous signal of neighbor nodes is hard to handle by only scheduling and routing techniques. For example, in Figure 1, node A and node C are not in a one-hop neighbour relationship. So, the scheduling and routing protocols allow a simultaneous transmission of these two nodes. Assume that node A transmits a signal to node B, and node C transmits a signal to node D at the same time using the different part of bandwidth. If node A and node C are not perfectly synchronized each other in time and/or frequency domain, node A might interfere node D and node C might interfere node B. This multiple pair synchronization problem is more complex than a single pair synchronization problem and needs a dynamic solution.

In this paper, we define the absolute value of the frequency offset between node A and node B as $\varepsilon_{AB} = |f_A - f_B|$, where f_A and f_B are the carrier frequencies of node A and node B respectively. If a link between two nodes has an estimated value of ε less than or equal to the threshold value ε_{th}, the

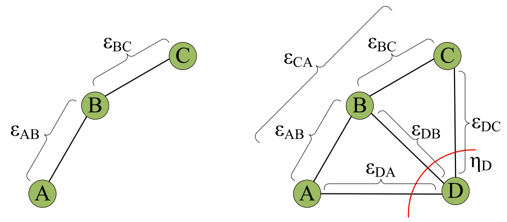


Fig. 2. Example of frequency synchronization in wireless mesh network.

two nodes connected by the link can communicate each other without the interference. Otherwise, the nodes need to control their carrier frequencies in order to avoid the interference. In the rest of this paper, we declare that a link is synchronized when the link has an estimated value of ε less than or equal to ε_{th}. In Figure 2, an entry node D enters into the network formed by pre-existing nodes, node A, node B, and node C. Although pre-existing nodes are already synchronized, that is $\varepsilon_{AB} \leq \varepsilon_{th}$ and $\varepsilon_{BC} \leq \varepsilon_{th}$, node D may not receive all signals from existing nodes without the interference because ε_{AC} may be bigger than ε_{th}. This means that the link-level synchronization does not guarantee the network-level synchronization. Therefore, we define the another factor η in order to guarantee both the link-level synchronization and the network-level synchronization. η_D is defined as the maximum absolute value among frequency offsets of all links in the network consisted by node D and its one-hop neighbor nodes. In other words, $\eta_D = max\{\varepsilon_{DA}, \varepsilon_{DB}, \varepsilon_{DC}, \varepsilon_{AB}, \varepsilon_{BC}, \varepsilon_{CA}\}$.

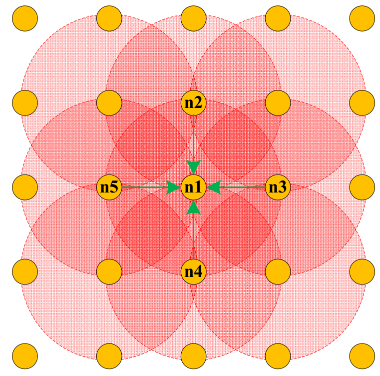
For reliable communication of node D, η_D should be less than or equal to a threshold value, η_{th}. Consequently, all nodes in the distributed network need to be synchronize each other whether they are connected by a link or not in order to guarantee the robust synchronization over a dynamic network topology. The perfect synchronization is achieved when η is zero for all nodes in the network. However, it is almost impossible in practical systems due to the estimation error. To achieve better synchronization, we should reduce the value η as much as possible.

III. Distributed Frequency Synchronization for Wireless Mesh Networks

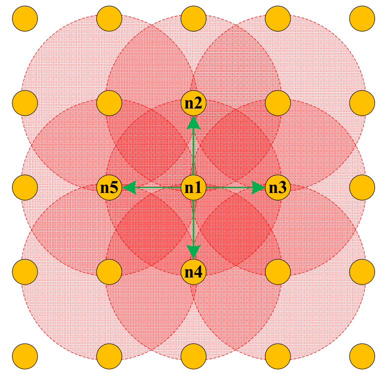
In this section, we introduce DFS which is a scheme for distributed nodes to synchronize each other with very high success probability despite estimation error in OFDMA-based mesh networks. DFS offers the global synchronization with only two simple steps, repetitive estimation and averaging step and sharing estimates step. Moreover, DFS could be applied to not only networks with single group but also networks with multiple groups. We present them in detail as following subsections.

A. Network Entry

Every node initially executes a network entry process [6] to become a member of a network. If an entry node has no neighbour node, it becomes a sponsor node itself. Otherwise, the nearest neighbor node or the node corresponding to maximum received signal power becomes a sponsor node for the entry node. The entry node initially synchronizes its carrier frequency with the sponsor node through the ranging process. For the ranging process, the entry node receives a preamble signal of the sponsor node several times and synchronizes with the sponsor node using the preamble signal. And it transmits a ranging code to the sponsor node. The sponsor node estimates the frequency offset by using the ranging code received from the entry node and responses with a feedback message included the information of corrected offset. The entry node controls its carrier frequency by using the feedback message to reduce estimation error. After the network entry process, the node periodically executes the ranging process and receives preamble signals from neighbor nodes to estimate frequency offsets.



(a) repetitive estimation and averaging step

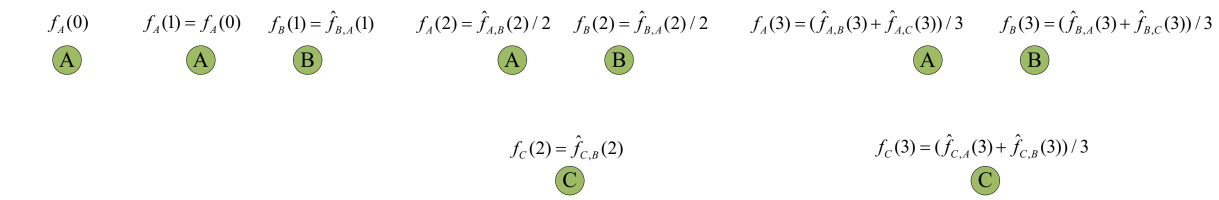


(b) sharing estimates step

Fig. 3. Two steps of DFS for node $n1$.

B. Intra-Group Distributed Frequency Synchronization

For the periodic synchronization, we use the proposed DFS scheme. DFS is consisted of two steps : 1) repetitive estimation and averaging step and 2) sharing estimates step. In Figure 3a, node $n1$ receives sharing messages of neighbor nodes and repetitively estimates frequency offsets with neighbor nodes. The node $n1$ calculates an average value using both the sharing



(a) Time slot 0 (b) Time slot 1 (c) Time slot 2 (d) Time slot 3

Fig. 4. Illustration of DFS operation for each update time slot.

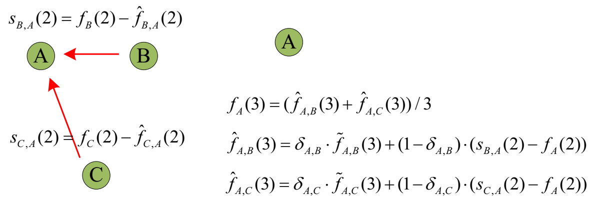


Fig. 5. Example of how node A executes DFS scheme.

messages and repetitive estimated offsets and then controls its own carrier frequency to the average value. In Figure 3b, node $n1$ sends differences between the average from Figure 3a and estimated offsets from neighbors. This value from Figure 3b is used for node $n1$'s neighbor nodes in the next update. Number of neighbor nodes and minimum number for reliable reception could be considered to set up the update period. To prevent a carrier frequency of a node to change during neighbor nodes refer the value, every node updates its own carrier frequency at the same time. It is possible because each node aligns the reference time with neighbor nodes at the network entry process.

Algorithm 1 shows the kth update of node i. In the algorithm, ζ_i is the subset of node i's neighbor nodes where $j \in \zeta_i$, $R_j \geq R_{th}$. R_j is the minimum number of node j's synchronization signal reception. R_{th} is the threshold for reliable reception. $\tilde{f}_{i,j}^{[r]}$ is the estimated frequency offset between node i and node j at the rth reception. And $\tilde{f}_{i,j}$ is the average frequency offset between node i and node j after R_j reception. If node i receives $s_{j,i}$ before the kth update, it calculate $\hat{f}_{i,j}$ with $\tilde{f}_{i,j}$ and $s_{j,i}$. Otherwise, it calculates $\hat{f}_{i,j}$ with $\tilde{f}_{i,j}$ only. f_i is the variation for update of node i. N_{ζ_i} is the number of nodes in ζ_i. $s_{i,j}$ is the sharing message from node i to node j. $\delta_{i,j}$ is a weight parameter where $0 \leq \delta_{i,j} \leq 1$. If node i doesn't receive the sharing message from node j, $\delta_{i,j}$ should be one. Initially, $s_{i,j}(0) = 0$ and $f_i(0) = 0$ for all node i and node j.

Figure 4 shows a simple example of Algorithm 1. At the time slot 0, node A establishes an initial network. At the time slot 1, node B enters into the network by performing the network entry process. At the time slot 2, node A and node B perform the DFS process and node C enter into the network. At the time slot 3, node A, B, and C perform the DFS process and all nodes, A, B, and C, periodically perform the DFS process at the following slots. In more detail, Figure 5 shows how node A use the sharing messages from node B and node C for offset estimation.

Algorithm 1 Distributed Frequency Synchronization (DFS)

1: **for** every $j \in \zeta_i$ **do**
2: Calculate $\tilde{f}_{i,j}(k) = \dfrac{\sum_{r=1}^{R_j} \tilde{f}_{i,j}^{[r]}(k)}{R_j}$
3: Calculate
$\hat{f}_{i,j}(k) = \delta_{i,j} \cdot \tilde{f}_{i,j}(k) + (1 - \delta_{i,j}) \cdot (s_{j,i}(k-1) - f_i(k-1))$
4: end **for**
5: Calculate $f_i(k) = \dfrac{\sum_{j \in \zeta_i} \hat{f}_{i,j}(k)}{N_{\zeta_i} + 1}$
6: **for** every $j \in \zeta_i$ **do**
7: Calculate $s_{i,j}(k) = f_i(k) - \hat{f}_{i,j}(k)$
8: end **for**

C. Inter-Group Distributed Frequency Synchronization

For multiple group networks, an additional synchronization technique is needed when different groups are approaching each other even if all nodes in the each group are accurately synchronized to a common value. We name it inter-group DFS. The inter-group DFS is similar with the intra-group DFS except one point that the inter-group DFS uses the priority of groups. Figure 6 illustrates a scenario that two groups get close each other and node C position in the intersection area between an inferior group and a superior group. Since node X and node Z are members of the superior group, node C refers only preamble signals of node X and node Z. After node C synchronizes with the superior group, node C propagates the carrier frequency of superior group to inferior group by performing the DFS process.

IV. Simulation Results

For the simulation, we use the preamble signal in IEEE 802.16m [7] as a synchronization signal. We set system parameters as follows, $R_{th} = 3$, $\delta_{i,j} = 0.5$ for all node i and node j. We use RMa, LoS channel model in [8]. One-hop distance is $10km$ (SNR=8.47dB), the velocity between node is $120km/h$. To establish networks, we drop nodes one by one at an interval of DFS update in the $40km \times 40km$ square simulation plane. We simulate three node distributions. We position nodes randomly and perform the simulation 50,000

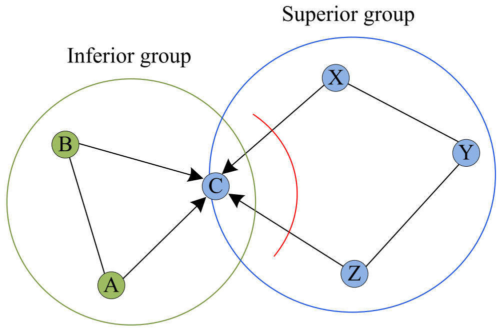


Fig. 6. Example of DFS for multiple group networks.

times for each case. In the first distribution, total number of nodes in the network is 20 and the average number of one-hop nodes is 3. In the second distribution, total number of nodes in the network is 35 and the average number of one-hop nodes is 5. In the third distribution, total number of nodes in the network is 55 and the average number of one-hop nodes is 8. We define the synchronization success when it synchronizes not only a target node but also neighbor nodes within less than 1% subcarrier spacing (η is less than 1%). The 1% threshold value is reasonable enough in the aspect of bit error ratio (BER) [9].

For performance comparison, we use the sponsor-based frequency synchronization (SFS) and the consensus-based frequency synchronization (CFS). SFS is a traditional scheme in cellular systems. In the system using SFS, each node synchronizes with only its sponsor node. CFS is a modified synchronization scheme for frequency synchronization based on the consensus clock synchronization method in [5]. For more accurate synchronization, we apply a repetitive offset estimation technique to both SFS and CFS.

Figure 7 and Figure 8 show the synchronization success probability of SFS, CFS, and DFS in two distributions. In the both figures, CFS outperforms SFS since it has more chance to recover synchronization failure by using all estimated offsets with neighbor nodes without relying on only one sponsor node. And DFS outperforms CFS because it improves the reliability by using the sharing message.

We further investigate the convergence speed of synchronization when a new node enters into a network after the network was already synchronized, in Figure 9. The performance temporarily decreases due to the new node but the performance increases again after a few updates. This value is smallest with DFS scheme.

V. Conclusion

DFS is the method of global frequency synchronization by estimating frequency offsets with neighbor nodes repetitively and sharing the estimates in OFDMA-based wireless mesh networks. In OFDMA-based wireless mesh networks where the estimation error is presented, DFS provides the superior synchronization performance. With only slight cost investment due to the sharing messages, DFS could be applied in various wireless networks and eventually improve the network performance.

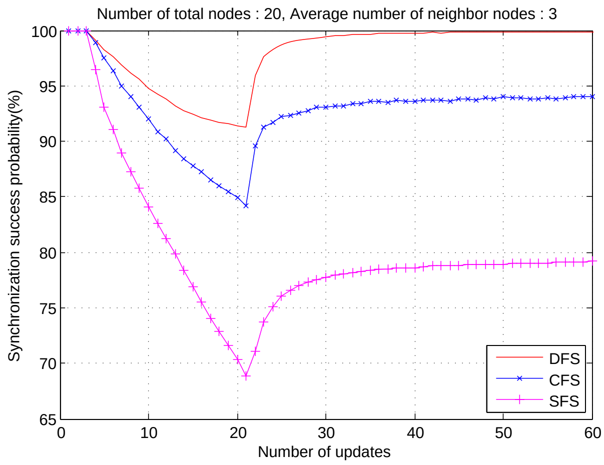


Fig. 7. Synchronization success probability comparison with the first node distribution.

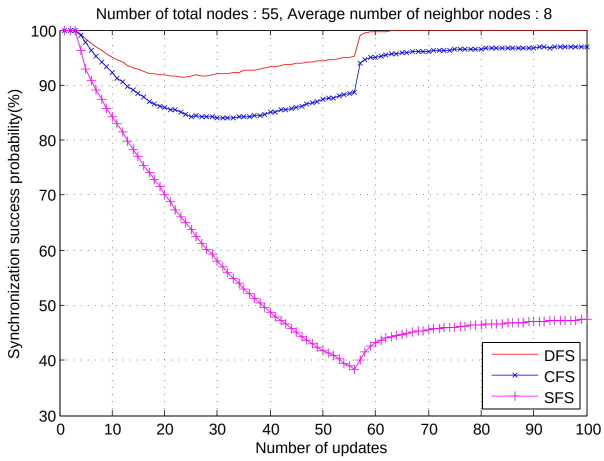


Fig. 8. Synchronization success probability comparison with the third node distribution.

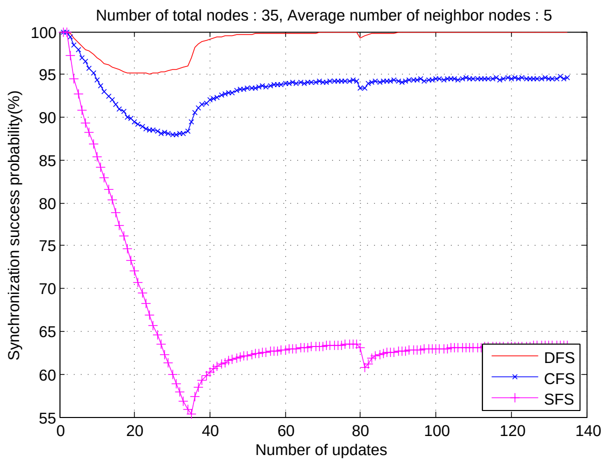


Fig. 9. Synchronization success probability comparison when a new node enter into the network after the network was already synchronized with the second node distribution.

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