An Efficient and Effective Regrouping Algorithm for Minimizing Hidden Pairs in 802.11ah Networks

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Abstract: In this paper, a heuristic regrouping algorithm is proposed for 802.11ah networks to minimize the total number of hidden pairs by adopting the regrouping strategy of moving a node to the group with the fewest hidden pairs. The performance evaluation illustrates that our proposed scheme has much better improvement in the decreasing rate of the hidden pairs than a recently related work. In the extreme case of deploying 8,000 nodes in an 802.11ah network, it decreases 97.8% or 99.99% of the hidden pairs. Further, its decreasing rate is very close to the optimal solution of the hidden node problem.

1 INTRODUCTION

The 802.11ah network has been defined by the IEEE 802.11ah Task Group, denoted as TGah shortly. It operates at sub 1 GHz ISM bands with a transmission range up to 1 km for supporting a maximum of 8,192 nodes (Sun et al., 2013). Due to the increasing number of nodes to contend the shared wireless channel, the 802.11ah TGah introduces a grouping-based MAC protocol in the citation (IEEE P802.11ah/D5.0 Draft Standard for Information technology, 2015), where the nodes are partitioned into groups and a non-overlapping period is allocated to each group. Each node contends the shared wireless channel with the nodes within the same group during the allocated period of the group in order to alleviate the contending problem. Therefore, the performance of an 802.11ah network is highly related to how the nodes are partitioned into groups.

Another important challenge in the 802.11ah network is the hidden node problem (Khurana et al., 1998). The problem occurs when two nodes can communicate with a wireless access point, denoted as WAP, i.e., they are within the transmission range of the WAP and vice versa, but they cannot communicate with each other since they are out of the transmission range of each other. In the citations (IEEE Std. 802.11-2007, 2007; Talucci et al., 1997; Wang et al., 2004; Du et al., 2005), the request-to-send/clear-to-send, denoted as RTS/CTS, mechanisms are proposed to solve the problem. However, the RTS/CTS mechanisms incur huge overhead to network bandwidth consuming and lead to performance degradation, especially in an 802.11ah network where up to 8,192 nodes are deployed, the RTS/CTS mechanism overhead problem will become more serious. The analysis results in the citations (Tseng et al., 2003; Yoon et al., 2016) validate the above claim. In the analysis of the citation (Tseng et al., 2003), the probability of any two nodes becoming hidden increases up to 41%, and the expected number of hidden pairs is 1,311,836 for the deployment of 8000 nodes. On the other hand, in the analysis and simulation of the citation (Yoon et al., 2016), the transmission end times of with hidden pairs and without hidden pairs are 85 and 35 msec, respectively. The performance degradation is caused by the huge number of hidden pairs that transmit the RTS/CTS packets for solving the hidden node problem.

In order to alleviate the problems of collision and contention overhead caused by the large number of nodes in an 802.11ah network, the Restricted Access Windows, denoted as RAW, operation is adopted by further partitioning each of beacon intervals into a number of equal-duration slots defined as RAW slots and partitioning the nodes into groups. Each RAW slot is assigned to a group of nodes, where a node

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contends the shared wireless channel with the nodes within the same group during the allocated RAW slot.

Recently, several algorithms in the citations (Zheng et al., 2014; Liu et al., 2014; Park et al., 2014; Yang et al., 2014) have been proposed by adopting the strategy of adjusting the number of contention groups or the duration of a RAW size. Although the above grouping schemes can alleviate the contending problem, but they are very limited to solve the hidden node problem. The reason is that the hidden node problem is not considered into the proposed schemes. For example in the case of the analysis and simulation (Yoon et al., 2016), there are only 20 nodes deployed in an 802.11ah network. The performance degrades seriously from 35 to 85 msec of transmission end times. Especially in an 802.11ah network, the number of the nodes in a group will be hundreds or even thousands. Therefore, taking the hidden node problem into consideration is very necessary in an 802.11ah network.

Several algorithms have been proposed in the literature of the hidden node problem. In the citations (Kim et al., 2013; Nishide et al., 2012; Kim, et al., 2006), the authors have proposed the mechanisms to detect hidden pairs. To the best of our knowledge, the algorithm in the citation (Yoon et al., 2016) presents the first work which aims to minimize the number of hidden pairs in an 802.11ah network. They adopt the regrouping strategy of moving a node suffering the hidden node problem in the current group to a new group where the node has no hidden pair.

In this work, we propose another regrouping algorithm for the same purpose as the citation (Yoon et al., 2016). We adopt a distinct regrouping strategy of moving a node to the new group with the fewest hidden pairs to this node. In the performance evaluation of Section IV, the results show that both of the regrouping algorithms are efficient in reducing the numbers of hidden pairs for sparse networks, where the nodes deployed into the network are dozens. Further, our regrouping algorithm achieves fewer hidden pairs than the citation (Yoon et al., 2016). When the networks are dense, for example the nodes deployed into the network are hundreds even more than 8,000, the citation (Yoon et al., 2016) is inefficient. In the case of the deployment of 8,000 nodes, it decreases only 1% of the hidden pairs, which are generated from 802.11ah standard by assigning the nodes randomly into the groups.

On the other hand, our regrouping algorithm is still efficient for dense networks in reducing the numbers of hidden pairs. In the same case of the deployment of 8000 nodes, it decreases 97.8% of the hidden pairs. Even more if we execute the algorithm again by using the output of grouping information obtained in the first execution, the decreasing rate of the hidden pairs is enhanced to 99.99%. Further, the decreasing rate is very close to the optimal solution of the hidden node problem no matter the network is sparse or dense.

2 ILP

In this section, a formal definition of the hidden node problem in an 802.11ah will be given. The following notations in the problem formulation are adopted: The set of nodes is denoted by N and $|N| = n$; the set of groups is denoted by G and $|G| = g$; let $h\_m_{j,k}=1$ /$h\_m_{j,k}=0$ to denote that node j and node k are/are not a hidden pair, where $1 \leq j \leq n$ and $1 \leq k \leq n$. Prior to the problem formulation, the following decision variables are defined: variable $x_{i,j}=1$/$x_{i,j}=0$ is used to denote that node j is/is not assigned to group i; variable $h\_p_{j,k}=1$/$h\_p_{j,k}=0$ is used to denote that a hidden pair of node j and node k is (is not) assigned into the same group, where $1 \leq j \leq n$ and $1 \leq k \leq n$.

The objective is to minimize the total number of hidden pairs assigned into the same groups, i.e., to minimize $\sum_{1 \leq j \leq n} \sum_{1 \leq k \leq n} h\_p_{j,k}$. In the assignment, each node j is required to be assigned to exactly one group, i.e., $\sum_{1 \leq i \leq g} x_{i,j} = 1$. Therefore, constraint (1) is induced. On the other hand, if node j and node k are a hidden pair and they are assigned into the same group i , i.e., $h\_m_{j,k}=1$, $x_{i,j}=1$ and $x_{i,k}=1$, a hidden pair after the assignment is induced by the two nodes and the decision variable $h\_p_{j,k}$ should be equal to 1. Otherwise, $h\_p_{j,k}$ should be equal to 0. Thus, constraint (2) is induced. The 0/1 ILP formulation for the hidden node problem is as follows.

$$\text{Minimize } \sum_{1 \leq j \leq n} \sum_{1 \leq k \leq n} h\_p_{j,k}$$

$$\text{Subject to } \quad \sum_{1 \leq i \leq g} x_{i,j} = 1 \text{ for } 1 \leq j \leq n \qquad (1)$$

$$h\_m_{j,k} + x_{i,j} + x_{i,k} - 2 \leq h\_p_{j,k} \quad \text{for } 1 \leq i \leq g,\ 1 \leq j \leq n \text{ and } 1 \leq k \leq n \qquad (2)$$

$$x_{i,j} \in \{0, 1\} \text{ for } 1 \leq i \leq g \text{ and } 1 \leq j \leq n \qquad (3)$$

$$h\_p_{j,k} \in \{0, 1\} \text{ for } 1 \leq j \leq n \text{ and } 1 \leq k \leq n \qquad (4)$$

3 HEURISTIC REGROUPING ALGORITHM

In this section, a heuristic regrouping algorithm, denoted as MHPA, is proposed for minimizing hidden pairs in 802.11ah networks. The design idea is that a node will be moved from the current group to a new group if its number of hidden nodes can be decreased. In order to minimize the total number of hidden pairs, the node is moved to the new group with satisfying the following two requirements. First, the number of hidden nodes to the node in the new group is less than the number in the current group. Second, the new group has the minimum hidden nodes to the node among the groups satisfied the first requirement.

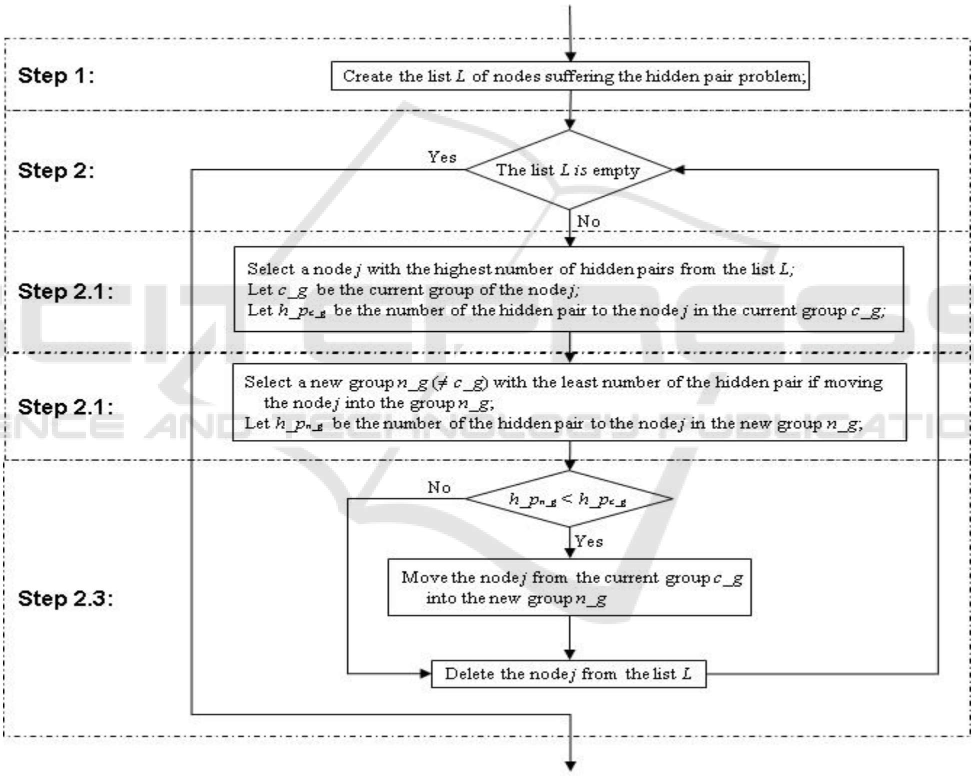

Figure 1: Flow chart of MPHA.

3.1 System Model and Hidden Pair Detection

We consider an 802.11ah network with n nodes and a single WAP, where all the nodes are uniformly distributed within the WAP coverage with no mobility. In 802.11ah, a beacon interval is divided into several RAWs. The nodes operate in power save mode and periodically wake up at the beginning time that is the target beacon transmission time, denoted as TBTT, of every beacon interval to listen to the beacon frame from the WAP. The beacon frame contains the information that the nodes are assigned to the groups, the start timing and duration of each RAW, and the buffered packets for the nodes. Then, each node enters sleep state and wakes up at its assigned group's RAW. To receive a packet, each node transmits a power-save poll, denoted as PS-Poll, frames to the WAP. Otherwise, it goes back to sleep state until the next TBTT. If the node receives an ACK frame from the WAP after transmitting the PS-Poll frame, it enters sleep state again and wakes up to receive the buffered packet at its assigned group's RAW. Otherwise, it retransmits the PS-Poll frame again.

To detect the hidden pairs, the method in the citation (Yoon et al., 2016) is used. In the citation (Yoon et al., 2016), the hidden relation between every two nodes is obtained by PS-Poll transmission time. Let t_j and t_k denote the start time of the first PS-Poll frame transmission at node j and node k, respectively. And, $t_{PS\text{-}Poll}$ denotes the duration of the PS-Poll frame transmission. The two node j and node k are a hidden pair if the following condition is met:

$$\mathcal{E} < | t_j - t_k | < t_{PS\text{-}Poll} \quad (5)$$

where $\mathcal{E}$ is a small timing variable to cover the propagation delay and clock drift offset between nodes. According to equation (5), the value of element $h\_m_{j,k}$ for node j and node k can be obtained.

3.2 MHPA

The proposed algorithm MHPA regroups the nodes in 802.11ah networks for minimizing hidden pairs. Based on this consideration, MPHA regroups the nodes by using element $h_m_{j,k}$s that are obtained by the method of the citation (Yoon et al., 2016) during each TBTT. Whether a node j and a node k suffer from the hidden node problem can be validated by using the element $h\_m_{j,k}$. If the two nodes are grouped into the same group and the element $h\_m_{j,k}$ equals to 1, they are a hidden pair in the 802.11ah network.

The flow chart of MHPA is shown in Figure 1. In Step 1, MHPA initially defines the list L of nodes that suffer from the hidden node problem. In Step 2, the while-loop is executed until the list L is empty. In each iteration of Step 2, a node j that has the highest number of hidden pairs in the list L is determined in Step 2.1. Let c_g be the current group of the node j, and $h\_p_{c\_g}$ be the number of the hidden pairs to the node j in the current group c_g.

We aim to move the node j from the current assigned group into another new group if the number of hidden nodes can be decreased. In order to minimize the total number of hidden pairs, the new group is determined by selecting the one with the minimum hidden nodes to the node j among the all groups in Step 2.2. Let n_g, where $n\_g \neq c\_g$, be the new group with the least number of the hidden pairs, and $h\_p_{n\_g}$ be the number of the hidden pairs to the node j in the new group n_g. In Step 2.3, the node j is moved to the new group n_g if the number of hidden nodes to it can be decreased, i.e., $h\_p_{n\_g} < h\_p_{c\_g}$.

Lemma 1. The time complexity of MHPA is $O(n^3)$.

Proof. To create the list L in Step 1 can be done in $O(n^2)$, where n is the number of the nodes in a 802.11ah network. The while-loop in Step 2 can be done in $O(n)$. In Step 2.1, to determine the number of hidden pair for a node by using the hidden pair relation matrix H_M with n^2 elements can be done in $O(n)$. The time complexity of selecting the node with the highest number is $O(n^2)$. In Step 2.2, to select a group from the g groups b can be done in $O(gn^2)$. In Step 2.3, the time complexity is $O(1)$. Since the group number g is much smaller than the node number n, the overall time complexity of MHPA is $O(n^3)$.

4 PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed algorithm MHPA with the 802.11ah standard denoted as Random and the algorithm denoted as HNRP proposed in the citation (Yoon et al., 2016). The number of hidden pairs is used as the metric to evaluate the performance of MHPA, Random, and HNRP. In Section 2, we formulate the hidden node problem in 802.11ah as a 0/1 ILP, which can be well solved by a branch-and-bound algorithm (Geoffrion et al., 1972). We use Opt to denote the 0/1 ILP solved by such a branch-and-bound algorithm. Opt can serve as a benchmark for evaluating the performance of MHPA.

According to the 802.11ah standard, where the transmission range is up to 1 km for supporting a maximum of 8,192 nodes, we model an 802.11ah network with a WAP whose transmission range is 1 km. Within the network, the WAP is placed at the center of a 1500m×1500m area, and the numbers of nodes are varied from 10 to 8000. The nodes are placed randomly within the area. The modelled networks are divided into sparse networks and dense networks. The numbers of the nodes in the sparse networks are varied from 10 to 50, and those in the dense networks are varied from 500 to 8000. Since the performance of MHPA, Random, and HNRP heavily depends on the position of the nodes, the simulations are performed 50 times with random node distribution, and the results are averaged.

Figure 2 shows the numbers of hidden pairs of Random, HNRP, MHPA, and Opt in sparse networks. When the node number is increased to 50, the number of hidden pairs of Random is increased to 57. The results in Figure 2 validate that both HNRP and MHPA are efficient in reducing the numbers of hidden pairs. In case of 50 nodes, HNRP decreases the number of hidden pairs to 30, MHPA decreases it to 5. MHPA is more efficient than HNRP in reducing the number of hidden pairs, and its number of hidden pairs is very close to that obtained in Opt.

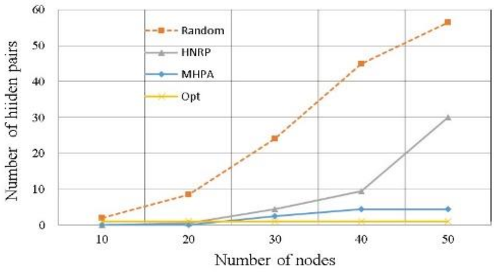

Figure 2: Number of hidden pairs of Random, HNRP, MHPA, and Opt in sparse networks.

In Figure 3, the numbers of hidden pairs of Random, HNRP, MHPA, and Opt are obtained in dense networks, where the numbers of nodes are increased from 500 to 8,000. The results of Figure 3 show that the numbers of hidden pairs of Random are increased from 6,311 to 1,582,613 while the numbers of nodes are increased from 500 to 8,000. It is consistent with the analysis of the citation (Tseng et al., 2003), where the number of hidden pairs of Random is 1,311,836 for the deployment of 8000 nodes.

Although HNRP is efficient for sparse networks in reducing the numbers of hidden pairs, it is inefficient for dense networks. The results of Figure 3 show that the numbers of hidden pairs of HNRP are changed from 6,300 to 1,566,786 while the numbers of nodes are increased from 500 to 8,000. It presents that the efficiency of HNRP is very limited in reducing the numbers of hidden pairs for dense networks. The inefficiency of HNRP is derived from the regrouping strategy of HNRP. The regrouping strategy moves a node suffering the hidden node problem in the current group to the new group where the node has no hidden pair. When the probability of any two nodes becoming a hidden pair is low, i.e., the network is sparse, it is easy to find such a new group. Whereas, the probability is high, i.e., the network is dense, the probability of finding such a new group is very low. The results of Figure 2 and Figure 3 validate the above claim.

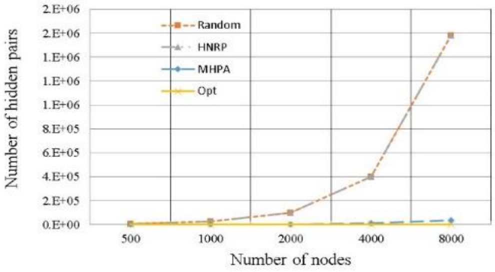

Figure 3: Number of hidden pairs of Random, HNRP, MHPA, and Opt in dense networks.

On the other hand, the results of Figure 3 show that MHPA is also efficient for dense networks in reducing the numbers of hidden pairs. When the numbers of nodes are increased from 500 to 8,000, the numbers of hidden pairs of MHPA are varied from 504 to 35,061. In the case of the deployment of 8000 nodes, MHPA decreases the number of hidden pairs from 1,311,836 obtained in Random to 35,061. It decreases 97.8% of the hidden pairs, whereas HNRP decreases only 1%. The results of Figure 2 and Figure 3 show that MHPA is efficient in reducing the numbers of hidden pairs not only for sparse networks but also for dense networks. The efficiency of HNRP is derived from that we adopt a distinct strategy of regrouping. Our regrouping strategy moves a node suffering the hidden node problem in the current group to the new group where the node has the fewest hidden pairs.

Although MHPA reduces a large number of the hidden pairs and has much better performance than HNRP, there is a performance difference between HNRP and Opt as showed in the results of Figure 4. The performance difference decreases as the number of the nodes, especially in the case of 8000 nodes. Due to that the time complexity of MHPA is $O(n^3)$ as showed in Lemma 1, i.e., executing MHPA is not time-consuming, we further decrease the number of the hidden pairs by executing MHPA again, denoted as MHPA-2. The output of grouping information obtained in the first executing MHPA is used as the input information of executing MHPA-2.

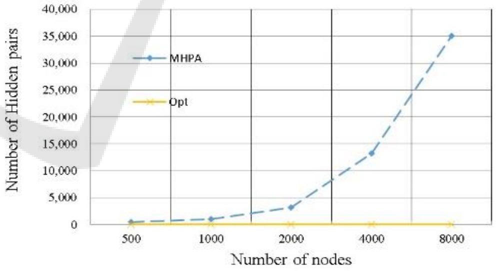

Figure 4: Number of hidden pairs of MHPA and Opt in dense networks.

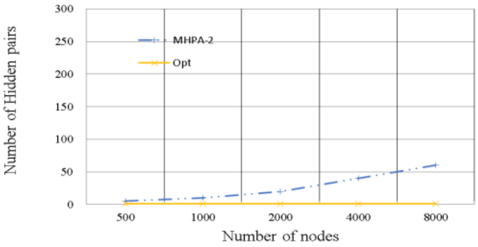

Figure 5: Number of hidden pairs of MHPA-2 and Opt in dense networks.

The results of executing MHPA-2 are showed in Figure 5. In the case of the deployment of 8000 nodes, MHPA-2 further decreases a large number of hidden pairs, where the hidden pair number is decreased from 35,061 obtained in MHPA to 60. The decreasing rate of the hidden pairs is enhanced from 97.8% to 99.99%. The hidden pair number 60 is very close to the number, which is the optimal solution of the hidden node problem, obtained by Opt. The performance effect caused by the remaining only 60 hidden pairs to an 802.11ah network with 8000 nodes will be very limited.

5 CONCLUSIONS

This paper has introduced a distinct regrouping algorithm MHPA for 802.11ah networks. We evaluate the performance of the proposed algorithm MHPA with the other two algorithms Random and HNRP. The results of the performance evaluation show that both of MHPA and HNRP are efficient for sparse networks in reducing the hidden pairs; in addition, MHPA achieves fewer hidden pairs than HNRP. When the networks are dense, MHPA achieves much fewer hidden pairs than HNRP. In the case of the deployment of 8,000 nodes, MHPA decreases 97.8% of the hidden pairs, whereas HNRP decreases only 1% of the hidden pairs. Even more if MHPA is executed again, the decreasing rate is enhanced to 99.99%. Further, the decreasing rate of MHPA is very close to the optimal solution obtained in Opt no matter the network is sparse or dense.

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