A Fairness-Aware Scheduling Algorithm for Industrial Wireless Sensor Networks with Multiple Access Points

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***Abstract*—Real-timeliness and reliability are two basic requirements for industrial wireless sensor networks (IWSNs). In this paper, periodic heterogeneous traffics with delay constraints are concerned in an IWSN with multiple access points (thus forming a redundant star topology). In order to improve the reliability while meeting the real-timeliness and fairness, we propose a fairness-aware scheduling (FAS) algorithm, in which three heuristic rules are first designed based on a novel penalty mechanism. Then, in each slot field devices are classified into six priorities according to the above three rules. Finally, the current slot is allocated to field devices in accordance with their priorities and communication ranges in a space division multiplexing way. A performance study is carried out by simulation, and the results show that the proposed FAS algorithm performs much better than existing works in terms of reliability and fairness.**

***Keywords*-Industrial wireless sensor networks; Transmission scheduling; Real-timeliness; Reliability; Fairness.**

I. Introduction

Industrial wireless sensor networks (IWSNs) outperform traditional wired automation system in terms of flexibility, scalability, and efficiency [1]. As one of the most promising techniques for Industry 4.0, IWSNs are becoming a popular trend in industry applications [2] where rigorous requirements of real-timeliness and reliability are imposed. To address these requirements, recently international standards on IWSNs, including WirelessHART [3], ISA 100.11a [4], WIA-PA [5] and WIA-FA [6], have been released. In typical IWSNs, TDMA scheduling for deterministic performance is performed at the gateway (GW) [7], [8] and in the allocated slot field devices (FDs) report measurements periodically to the GW.

Many contributions have been done on the scheduling of delay-constrained traffics [9]. Joint routing and transmission scheduling problem for reliable real-time communications over lossy networks is studied in [10]-[12]. However, the above researches assume that the traffics are homogeneous, which means that all packets generated in the same collection period have the same deadline [13]. TDMA scheduling schemes for periodic heterogeneous traffics are proposed in [14], [15]. The performance bounds of the convergecast scheduling according to data update rates in cluster-line and cluster-tree topologies are analyzed in [16]. An optimal algorithm which maximizes the transmission reliability is proposed in [17]. Though real-timeliness and reliability are concerned, none of existing researches [10]-[17] consider the fairness in transmission scheduling.

This paper proposes a fairness-aware scheduling (FAS) algorithm for IWSNs with multiple access points (APs). A redundant star topology is considered, wherein the GW has multiple APs and each FD may connect multiple APs in their communication ranges. FDs report heterogeneous traffics with delay constrains to the GW periodically. The uplink packet of one FD is considered successful if one of its associated APs correctly receives the packet. The main contributions of this work are summarized as follows

- We for the first time study the uplink transmission scheduling of periodic heterogeneous traffics for I-WSNs with the redundant star topology, and propose a novel penalty mechanism to balance reliability and fairness.
- We propose an efficient but polynomial algorithm-FAS to generate a fairness-aware schedule. Specifically, with the proposed penalty mechanism, we design three heuristic rules, based on which FDs are classified into six priorities in each slot. The slots are then allocated to field devices in accordance with their priorities and communication ranges.
- Simulation results show that the FAS algorithm achieves much higher reliability and fairness index in comparison to existing works, while guaranteeing the same real-timeliness.

II. Problem Formulation

As illustrated in Fig. 1, this paper considers a redundant star topology of IWSNs. The IWSN comprises one GW, M APs and N FDs. Each FD may communicate with multiple

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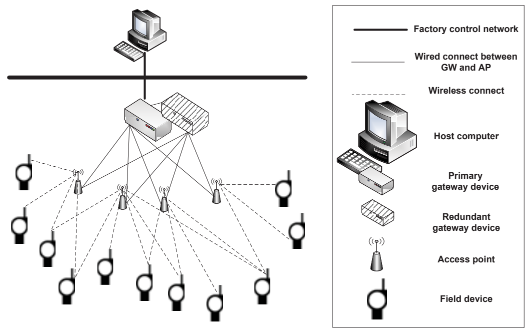

Figure 1. A general redundant star topology

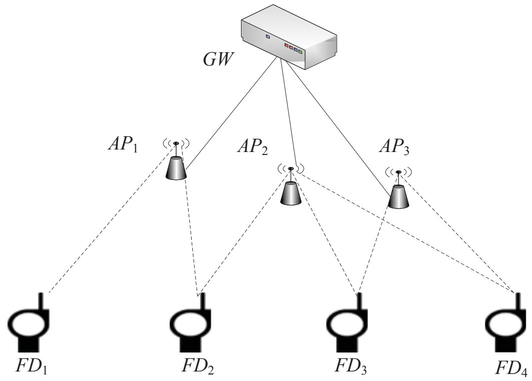

Figure 2. An example of a redundant star topology

APs and at the same time, each AP forms a star topology of multiple FDs. Fig. 2 gives an example redundant star topology with $M = 3$ and $N = 4$.

We use $AP(FD_i)$ to denote the APs which are in the communication range of FD_i $(i = 1, 2, \ldots, N)$. In Fig. 2, $AP(FD_1) = \{AP_1\}$, $AP(FD_2) = \{AP_1, AP_2\}$, $AP(FD_3) = \{AP_2, AP_3\}$, and $AP(FD_4) = \{AP_2, AP_3\}$. c_i is used to denote the number of elements in $AP(FD_i)$, i.e., $c_i = |AP(FD_i)|$. We assume that the packet loss rates for different links are independent and obey Bernoulli distribution. Let $p_{i,r}$ denotes the packet loss rate of the rth $(r = 1, 2, \ldots, c_i)$ link between FD_i and APs.

In our model, time is synchronized and divided into slots of equal length. Each slot allows the transmission of a packet and its associated acknowledgement. In Fig. 2, the slot allocation is performed centrally at the GW, and then the schedule list is delivered to every FD through APs. FDs transmit packets in their buffers to APs when their slots arrive.

The report period of FD_i is T_i which can be different among FDs. In this paper, subperiod and hyperperiod have the similar definition as [17]. A subperiod for FD_i is a report period with T_i slots, and a hyperperiod is defined as a period whose length is H slots, where H is the least common multiple of all subperiods, i.e., $H = \text{lcm}\{T_1, T_2, \ldots, T_N\}$. Therefore, FD_i has $\frac{H}{T_i}$ subperiod in a hyperperiod. $S_{i,m}$ denotes the mth subperiod of FD_i. In the schedule list, FD_i is allocated $x_{i,m}$ slots in $S_{i,m}$. Subperiod and hyperperiod are illustrated in Fig. 3.

There are two ways to increase the reliability in the redundant star topology. First, multiple slots are reserved for a packet transmission. Second, multiple APs are deployed for spatial diversity. Thus, a packet of FD_i fails only when all the reserved slots and all the APs in the communication range of FD_i fail. In $S_{i,m}$, the corresponding failure probability of FD_i is $\prod_{r=1}^{c_i} p_{i,r}^{x_{i,m}}$, where $c_i = |AP(FD_i)|$.

A general method of reserving time slots for the reliable transmission is given as follows

$$R_i = \left\lceil \frac{\ln(1 - p_{succ})}{\ln(\prod_{r=1}^{c_i} p_{i,r})} \right\rceil, \tag{1}$$

where p_{succ} is the reliability requirement by industrial applications, and R_i is the number of slots needed to be allocated to each new arrival packet of FD_i.

In this work, we aim to maximize the reward function $Rwd(X)$, where $X = \{x_{i,m}\}$ $(i = 1, 2, \ldots, N; m = 1, 2, \ldots, H/T_i)$. specifically, we formulate the following optimization problem $\mathscr{P}$

$$\max \quad Rwd(X) = \sum_{i=1}^{N} \sum_{m=1}^{H/T_i} \left(\left(1 - \prod_{r=1}^{c_i} p_{i,r}^{x_{i,m}} \right) + pena\left(x_{i,m}\right) \right) \tag{2a}$$

$$\text{s.t.} \quad x_{i,m} \le T_i, i = 1, 2, \ldots, N, \quad m = 1, 2, \ldots, H/T_i \tag{2b}$$

$$\sum_{i=1}^{N} \sum_{m=1}^{H/T_i} x_{i,m} \ge H. \tag{2c}$$

There are two parts in objective function (2a). The first part $\sum_{i=1}^{N} \sum_{m=1}^{H/T_i} (1 - \prod_{r=1}^{c_i} p_{i,r}^{x_{i,m}})$ corresponds to the sum of packet success rates of all FDs in a hyperperiod. The second part $pena(x_{i,m})$ is a penalty function accounting for fairness. The detail of $pena(x_{i,m})$ is shown as follows

$$pena(x_{i,m}) = \begin{cases} -\infty, & \text{if } x_{i,m} = 0 \\ 0, & \text{if } 0 < x_{i,m} \le R_i \\ -(x_{i,m} - R_i), & \text{if } x_{i,m} > R_i. \end{cases} \tag{3}$$

The constraint (2b) requires that each packet of FD_i meets its deadline T_i. The constraint (2c) requires that FDs can share slots with each other according to space division multiplexing.

The optimization problem $\mathscr{P}$ (2) is a nonlinear integer programming problem which is inherently NP-hard. To solve

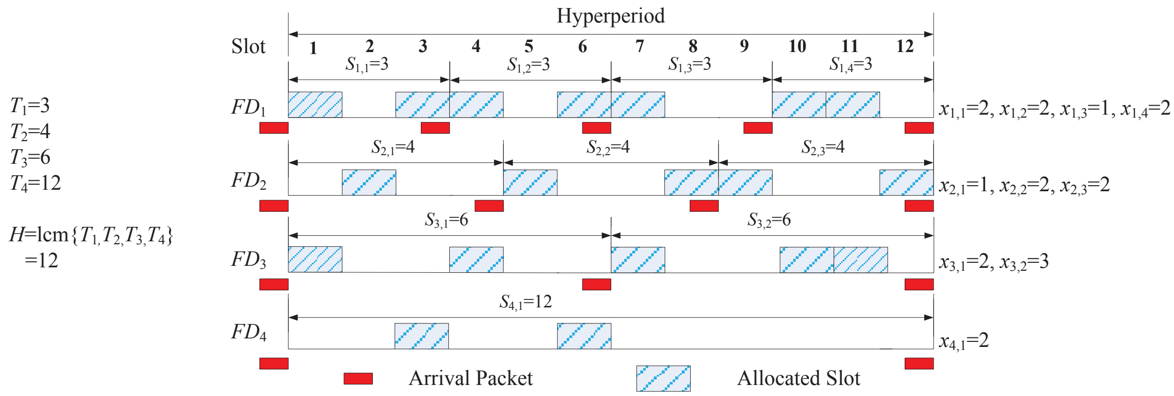

Figure 3. Example of slot allocation in one hyperperiod

problem $\mathscr{P}$ (2), we propose three heuristic rules according to (3) and a heuristic-rules-based FAS algorithm.

III. FAS Algorithm

A. Heuristic Rules

Given a slot t ($t \in \{1,2,\ldots,H\}$), we define $x_{i,m}(t)$ as the number of slots allocated to FD_i from the first slot of $S_{i,m}$ to the tth slot in the hyperperiod. As defined in (3), if no slot or too many slots are given to FD_i, FD_i incurs penalty. Based on this observation, the FAS algorithm proceeds the slot allocation process based upon the following three rules:

Rule 1. In slot t, FDs are grouped into three groups (i.e., G_1, G_2, and G_3) dynamically.

$$FD_i \in \begin{cases} G_1 & \text{if } x_{i,m}(t) = 0 \\ G_2 & \text{if } 0 < x_{i,m}(t) < R_i \\ G_3 & \text{if } x_{i,m}(t) \geq R_i. \end{cases}$$

Property 1. *In slot t, G_i has a higher priority over G_j in obtaining this slot to maximize total reward, if $i < j$.*

Proof: Assuming that in slot t, FD_i, FD_j, and FD_k are in S_{i,m_i}, S_{j,m_j}, and S_{k,m_k}, respectively. FD_i, FD_j, and FD_k are grouped into G_1, G_2, and G_3 according to **Rule 1**, respectively. Without causing ambiguity, we write $x_{i,m_i}(t)$, $x_{j,m_j}(t)$, and $x_{k,m_k}(t)$ as x_i, x_j, and x_k and define

$$F_i(x_{i,m_i}(t)) \triangleq 1 - \prod_{r=1}^{c_i} p_{i,r}^{x_{i,m_i}(t)} + pena(x_{i,m_i}(t))$$
$$= 1 - \prod_{r=1}^{c_i} p_{i,r}^{x_i} + pena(x_i)$$

To prove **Property 1**, two cases are discussed. We use "$G_i > G_j$" to denote that G_i has a higher priority over G_j in obtaining slot t.

Case 1: $G_1 > G_2$

If we allocate slot t to FD_i, the gain of $Rwd(X)$ is

$$\Delta_i = F_i(x_{i,m_i}(t)+1) - F_i(x_{i,m_i}(t))$$
$$= F_i(1) - F_i(0)$$
$$= (1 - \prod_{r=1}^{c_i} p_{i,r}^{1} + 0) - (0 - \infty)$$
$$= \infty.$$

Similarly, we can calculate Δ_j by allocating slot t to FD_j

$$\Delta_j = F_j(x_{j,m_j}(t)+1) - F_j(x_{j,m_j}(t))$$
$$= F_j(x_j+1) - F_j(x_j)$$
$$= (1 - \prod_{r=1}^{c_j} p_{j,r}^{(x_j+1)} + 0) - (1 - \prod_{r=1}^{c_j} p_{j,r}^{x_j} + 0)$$
$$= (\prod_{r=1}^{c_j} p_{j,r})^{x_j} * (1 - \prod_{r=1}^{c_j} p_{j,r})$$
$$< \infty.$$

Obviously, we have $\Delta_i > \Delta_j$, which means $G_1 > G_2$.

Case 2: $G_2 > G_3$

Similar to case 1, we have

$$\Delta_j = (\prod_{r=1}^{c_j} p_{j,r})^{x_j} * (1 - \prod_{r=1}^{c_j} p_{j,r}) > 0.$$

As for Δ_k, two subcases should be taken into account.

Case 2.1: $x_{k,m_k}(t) = R_k$

If we allocate slot t to FD_k, the gain of $Rwd(X)$ is

$$\Delta_k = F_k(x_{k,m_k}(t)+1) - F_k(x_{k,m_k}(t))$$
$$= F_k(x_k+1) - F_k(x_k)$$
$$= ((1 - \prod_{r=1}^{c_k} p_{k,r}^{(x_k+1)}) - ((x_k+1) - R_k)) - (1 - \prod_{r=1}^{c_k} p_{k,r}^{x_k})$$
$$= (\prod_{r=1}^{c_k} p_{k,r})^{R_k} * (1 - \prod_{r=1}^{c_k} p_{k,r}) - 1$$
$$< 0 \ (c_k \in \mathbb{N}_+).$$

Case 2.2: $x_{k,m_k}(t) > R_k$

Similarly, we can calculate Δ_k by allocating slot t to FD_k

$$\Delta_k = F_k(x_{k,m_k}(t)+1) - F_k(x_{k,m_k}(t))$$
$$= F_k(x_k+1) - F_k(x_k)$$

$$= ((1-\prod_{r=1}^{c_k} p_{k,r}^{(x_k+1)}) - ((x_k+1)-R_k)) - ((1-\prod_{r=1}^{c_k} p_{k,r}^{x_k}) - (x_k - R_k))$$
$$= (\prod_{r=1}^{c_k} p_{k,r})^{x_k} * (1-\prod_{r=1}^{c_k} p_{k,r}) - 1$$
$$< 0 \ (c_k \in \mathbb{N}_+).$$

Finally, we have $\Delta_j > \Delta_k$, which means $G_2 > G_3$.

In summary, $\Delta_i > \Delta_j > \Delta_k$, i.e., $G_1 > G_2 > G_3$. This completes the proof of **Property 1**.

□

Rule 2. In slot t, FDs in G_i $(i = 1,2,3)$ are classified into two categories, i.e., CG_1 and CG_2. As for FD_i, which is a member of G_i, if $\exists m \in \mathbb{N}_+$ and $m * T_i = t$, then FD_i belongs to CG_1 of G_i; otherwise, FD_i belongs to CG_2 of G_i. CG_1 has a higher priority than CG_2 to get slot t.

This rule is based on the consideration that if an AP is in CG_1, then slot t will be its last chance to get one more slot in $S_{i,m}$. On the contrary, APs in CG_2 have other chances after slot t, as a result of which the former has a more urgent need for slot t.

Rule 3. In slot t, the reward gain Δ_i are obtained for all FDs in (G_i, CG_j) $(i = 1,2,3; j = 1,2)$, i.e., the jth category of the ith group. Then slot t is allocated the FD who has the largest gain.

Based on above three rules, we can get six priorities, and each FD belongs to one of the six priorities.

B. FAS Algorithm

The FAS algorithm is proposed according to the above three rules. Two phases, the classification phase and the selection phase, are considered in each slot. During the classification phase, each FD is classified into one of the six priorities set_i $(i = 1,2,\ldots,6)$. In the selection phase, we build a set S_k whose elements do not collide with each other, in other words, if $FD_i \in S_k$ and $FD_j \in S_k$, then $AP(FD_i) \cap AP(FD_j) = \emptyset$. The detail of the FAS algorithm is as follows:

Algorithm 1: FAS

Input: $\vec{T} = [T_i], \vec{c} = [c_i], \vec{p} = [p_{i,r}], \vec{R} = [R_i]$
Output: schedule list
H =lcm$\{T_1, T_2, ..., T_N\}$;
for *t=1 to H* **do**
  $(set_1, set_2, set_3, set_4, set_5, set_6) = Classification(t, \vec{T})$; // classify FDs into six priorities
  $S_0 = \emptyset$;
  for *k=1 to 6* **do**
    $S_k = Selection(set_k, S_{k-1})$; // select FDs from set_k, then add them to S_{k-1}
  allocate slot t to $FD_i \in S_6$;
return schedule list.

In the first phase of the FAS algorithm, FDs are classified into six priorities according to $x_{i,m}(t)$. The details are illustrated in Algorithm 2. In slot t, Algorithm 2 classifies FDs into three groups according to **Rule 1**, and in each group, FDs are classified into two categories according to **Rule 2**. As a result, each FD belongs to one of the six priorities.

In the second phase, proper FDs are selected from the six priorities. The details are summarized in Algorithm 3. For a non-empty priority set_k, Algorithm 3 first calculates the gain Δ_i, which equals to the difference of reward value between allocating slot t to FD_i and not. Then Algorithm 3 sorts the $FD_i \in set_k$ in a descending order of Δ_i, and after that, set_d is obtained. By fully considering space division multiplexing, Algorithm 3 adds FD_i in set_d to S_k one after another if FD_i does not have common APs with any FDs in S_k. In the same way, Algorithm 3 deals with all priorities, then we get S_6.

Fig. 3 gives an example illustrating the FAS algorithm, where we assume that $p_{succ} = 99.99\%$ and packet loss rates for all links are 10% based on the example topology in Fig. 2.

Algorithm 2: Classification

Input: $t, \vec{T}$
Output: $\vec{set} = [set_i]$
1 $set_i = \emptyset, i = 1,2,\ldots,6$
2 **for** *i=1 to N* **do**
3   $m = \lceil \frac{t}{T_i} \rceil$;
4   **if** $x_{i,m}(t) = 0$ **then**
5   **if** $t\%T_i = 0$ **then**
6       $set_1 = set_1 \cup FD_i$; // priority 1
7   **else**
8       $set_2 = set_2 \cup FD_i$; // priority 2
9   **else if** $0 < x_{i,m}(t) < R_i$ **then**
10   **if** $t\%T_i = 0$ **then**
11       $set_3 = set_3 \cup FD_i$; // priority 3
12   **else**
13       $set_4 = set_4 \cup FD_i$; // priority 4
14   **else**
15   **if** $t\%T_i = 0$ **then**
16       $set_5 = set_5 \cup FD_i$; // priority 5
17   **else**
18       $set_6 = set_6 \cup FD_i$; // priority 6
19 **return** $\vec{set}$.

C. Time Complexity

First, the time complexity of Algorithm 2 is $\mathbb{O}(N)$ which is dominated by the loop (lines 2∼18). Then, in Algorithm 3, the first outer loop (lines 2∼3) has a time complexity

Algorithm 3: Selection

Input: set_k, S_{k-1}
Output: S_k
1 **if** $set_k \neq \emptyset$ **then**
2 **for** $FD_i \in set_k$ **do**
3   calculate the gain Δ_i;
4 obtain set_d by sorting $FD_i \in set_k$ in a descending order;
5 **for** $FD_i \in set_d$ **do**
6   $isCollide = false$; // set a flag to indicate collision
7   **for** $FD_k \in S_k$ **do**
8   **if** $AP(FD_i) \cap AP(FD_k) \neq \emptyset$ **then**
9     $isCollide = true$;
10   break;
11   **if** $isCollide = false$ **then**
12    $S_{k-1} = S_{k-1} \cup FD_i$;
13 $S_k = S_{k-1}$;
14 **return** S_k.

of $\mathbb{O}(N)$ and the second outer loop (lines 5∼12) has a time complexity of $\mathbb{O}(N^2)$. To sort $FD_i \in set_k$ we use the fast sorting algorithm whose time complexity is $\mathbb{O}(N\log N)$. Therefore, the total time complexity of Algorithm 3 is $\mathbb{O}(N^2)$. As the FAS algorithm is composed of two phases, the time complexity of FAS, T_{FAS}, is given by

$$T_{FAS} = H \cdot (\mathbb{O}(N) + \mathbb{O}(N^2)) = \mathbb{O}(HN^2).$$

IV. Performance Evaluation

In this section, we evaluate the performance of the FAS algorithm through numerical simulations by using Matlab. We compare the FAS algorithm with the OPT_SLOT algorithm proposed in [17] in terms of reliability and fairness. As OPT_SLOT is not specially designed for multiple *AP*s scenarios, we modify OPT_SLOT to its multiple *AP*s version, OPT_SLOT_APs, to perform a fair comparison. Following FAS, OPT_SLOT_APs gives n times the transmission chances to FD_i if there are n *AP*s in the communication range of FD_i.

We simulate eight scenarios where the number of *AP*s ranges from one to eight, so as to investigate how the number of *AP*s impacts the performance of algorithms. Without loss of generality, in each scenario, we arbitrarily choose six network setups with different values of N and T_i, as described in Table I. In each network setup, we run 1000 simulations. In each simulation, we set $p_{succ} = 99.99\%$ and randomly generate a network topology, where packet loss rates for each link are uniformly distributed in [0.2,0.8]. The duration of one simulation is 1000 hyperperiods.

Table I
Network Setups

Group_ID	N	T_i
G_1	5	[6,9,12,10,8]
G_2	5	[20,15,5,6,9]
G_3	8	[6,9,12,10,8,15,20,18]
G_4	8	[20,15,5,6,9,15,20,10]
G_5	12	[6,9,12,10,8,15,20,18,20,30,25,20]
G_6	12	[20,15,5,6,9,15,20,10,24,18,25,20]

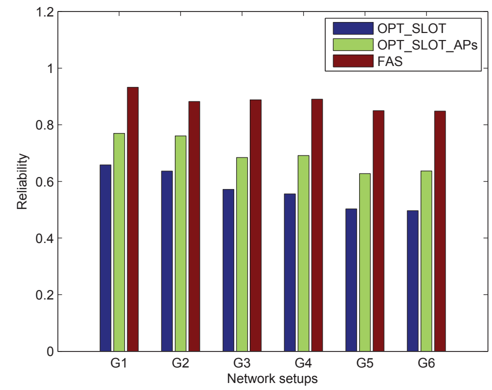

Figure 4. Comparison on reliability of three algorithms with different network setups

A. Reliability

In this subsection, the comparisons on three algorithms are evaluated under different scenarios. First, we fix the number of *AP*s, and compare the packet success rates of above three algorithms under six groups, respectively. As shown in Fig. 4, five *AP*s are considered, FAS significantly outperforms the other two algorithms. Then to study how the number of *AP*s impacts the reliability, we fix the group (G_4) and increase the value of M. As shown in Fig. 5, the packet success rates of FAS and OPT_SLOT_APs grow with the increase of the value of M while OPT_SLOT's does not. This is because FAS and OPT_SLOT_APs give full considerations to the characteristic of multiple *AP*s in the network while OPT_SLOT does not. We can also see from the Fig. 5 that the gap is enlarging between FAS and OPT_SLOT_APs with the increase of the value of M, which is because FAS takes space division multiplexing into consideration while OPT_SLOT_APs does not.

B. Fairness

To evaluate the fairness of transmission scheduling, the Jain's fairness [18] is exploited

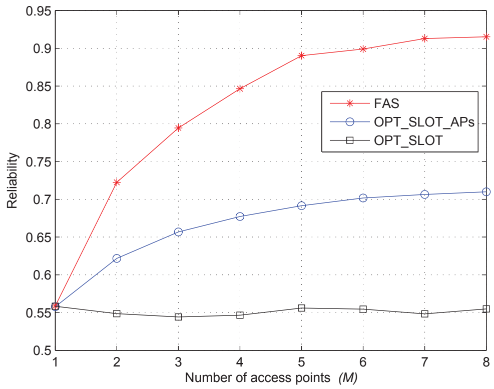

Figure 5. Comparison on reliability of three algorithms for different values of M

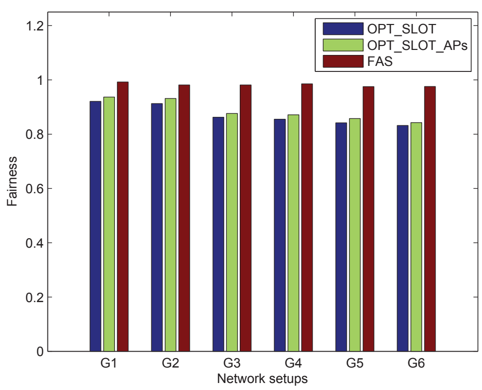

Figure 6. Comparison on fairness of three algorithms with different network setups

$$Fairness = \frac{\left(\sum_{i=1}^{N} RA_i\right)^2}{N\sum_{i=1}^{N} RA_i^2} \tag{4}$$

where RA_i is defined as the packet success rate of FD_i in a long run.

As Fig. 6 shows, five APs are considered, and FAS can get better fairness than the other two algorithms. Then to study how the number of APs impacts the fairness, we fix the group (G_4) and increase the value of M. As Fig. 7 shows, the fairness of FAS is becoming better with the increase of the value of M. This is because multiple APs and space division multiplexing give more transmission chances to FDs in one slot, and if one FD obtains enough transmission chances, it will leave remaining chances to others, which is guaranteed by the penalty function (3).

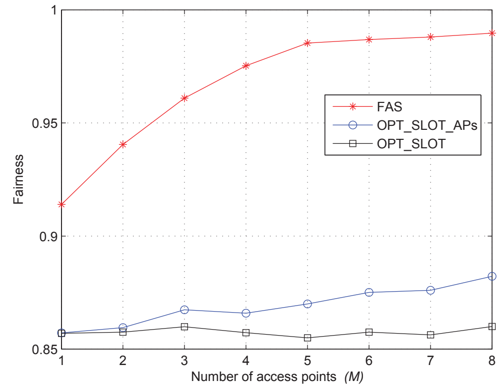

Figure 7. Comparison on fairness of three algorithms for different values of M

V. Conclusion

In this paper, we have studied the transmission scheduling of periodic heterogeneous traffics in IWSNs with multiple APs. First, a novel penalty mechanism has been proposed to balance reliability and fairness. Second, three heuristic rules have been designed based on the penalty mechanism. Finally, a FAS algorithm has been proposed, which allocates current slot to FDs according to their priorities and communication ranges in a space division multiplexing way. Simulation results have demonstrated that the FAS algorithm can yield higher reliability and better fairness than existing schemes.

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