Practical Application of Physical Energy Detection to recognize starvation in 802.11 Wireless Networks

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***Abstract*—In order to prevent a wireless node from corrupting other on-going transmissions, IEEE 802.11 medium access control (MAC) allows the node to access the channel only if the medium is determined to be idle. However, this rule sometimes can lead to extremely low transmission opportunities (i.e. starvation) of nodes owing to unfair carrier sensing induced by complex properties of wireless communication such as hidden/exposed-node topologies, asymmetric channel conditions, and other environmental factors. To share the wireless resource fairly, thus it is necessary for 802.11 nodes to detect the starvation and mitigate it. In this paper we propose a novel starvation detection technique that can identify whether the node is in the flow-in-the-middle (FIM) state by exploiting the physical energy detection mechanism implemented basically in 802.11 devices. In addition, we present a simple strategy that can mitigate the starvation. We show the effectiveness of our scheme via extensive simulations. The results demonstrate that our scheme recognizes the starvation and alleviates it effectively.**

I. INTRODUCTION

Wireless local area networks (WLANs) have grown significantly as the predominant wireless Internet access technology in the last decade. This success of WLANs is fundamentally based on the rapid progress of wireless technologies, particularly the advent of IEEE 802.11 standard. IEEE 802.11 is a prominent standard widely adopted in many wireless networks including large scale wireless mesh networks and ad hoc wireless networks as well as WLANs.

The IEEE 802.11 standard deals with the physical and medium access control (MAC) layers. IEEE 802.11 MAC utilizes CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) in which a wireless node is allowed to access the channel only if the medium is determined to be idle. It prevents the node from corrupting the ongoing transmissions and reduces the collision probability. However, this rule can lead to extremely low transmission opportunities (i.e. starvation) of nodes due to unfair carrier sensing. Let us consider an example case shown in Fig. 1. Node 0 is located in the middle of node 1 and node 2 and can sense the transmissions of node 1 and 2, while node 1 and node 2 are out of carrier sensing ranges from each other and thus their transmissions can overlap randomly at the middle node 0. Therefore, as far as the outer flows (i.e. node 1 and node 2) continue to transmit, node 0 is likely to always sense the channel busy and freeze its transmission attempt thereby suffering from starvation. This problem is referred as the Flow-In-the-Middle (FIM) problem [13]. It is observed that the frequency of severe unfair phenomena increases as the network has became be more dense. In order to share the network resource fairly, therefore, it is necessary for 802.11 nodes to recognize and mitigate the starvation.

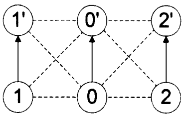

Fig. 1. The Flow-In-the-Middle (FIM) problem

In this paper, we present a novel starvation detection technique that can identify whether the node is in the FIM state by exploiting the physical energy detection mechanism implemented basically in 802.11 devices. The proposed detection technique leverages the fundamental cumulative property of signal strengths where the received signal strength during a reception of signals can vary depending on the number of simultaneous transmissions in the vicinity of the receiver. We also propose a simple method that can mitigate the starvation due to the FIM problem. We show the effectiveness of our scheme via extensive simulations. The results demonstrate that our scheme recognizes the starvation and alleviates it effectively.

The remainder of the paper is organized as follows: In section III, we describe the motivation of this works. Section IV introduces the algorithm to recognize the condition of starvation. Starvation mitigation method is explained in section V. Simulation results are given in section VI. In section II, we discuss related issues. Finally, we conclude this paper in section VII.

II. RELATED WORKS

In [1], Akella et al. have presented a study of the impact of interference in chaotic 802.11 deployments on the performance. Subsequently, many kinds of studies have been suggested to recognize and mitigate starvation. Some of them shows that the starvation can be alleviated by setting the system parameters such as transmission power, channel, carrier sense range, etc to the optimal value. It is one of solutions suggested in [1] to mitigate a starvation that specific node decreases its transmission power when successful transmission at maximum rate continues. In [11], Mhatre et al. have proposed a framework that determines optimum settings for transmit power and carrier sense with the objective of maximizing the network-wide throughput for elastic traffic. Within this framework, they have devised a distributed power control algorithm that uses a Gibbs sampler. Enhance carrier sensing for providing the fairness of system has been proposed in [12]. In [2], [13], authors have proposed the analytical model to characterize throughput of individual flows in multi-hop wireless networks and categorized reasons of starvation. Starvation identification algorithm based on the throughput analysis have been presented in [2]. Reference [11] has proposed another approach using centralized rate-limiting policy in order to solve the problem of starvation. Approaches through minimizing interference among communicating nodes with multichannel have proposed in [14], [15]. However, there are a lot of problems such as limited number of non-overlapped channel, delay of channel changes, and difficult coordination of communicating channel.

III. MOTIVATION

A. Background

In 802.11, each node senses the wireless channel before attempting a transmission. If the received signal strength at a node during channel sensing is greater a certain threshold (referred as "carrier sensing threshold"), the node infers that the wireless channel is currently busy and defers its transmission. The received signal strength is an aggregation of signal strengths from various independent transmitters where each signal strength from a transmitter is determined by the pass loss between the transmitter and receiver. We use the commonly used pass loss model [4] to describe the radio propagation property, which is

$$P_{rx}(j) = \sum_{i}^{N} P_{tx}(i) \left(\frac{\bar{d}}{d(i,j)} \right)^{\omega} \tag{1}$$

where $P_{rx}(j)$ is the received signal strength at node j, N is the number of transmitting nodes around node j, $d(i,j)$ is the distance between node i and j, $\bar{d}$ is the reference distance, ω is the path loss exponent (that typically ranges from 2 to 4), and $P_{tx}(i)$ is the transmission power of node i.

To understand and demonstrate the fundamental cumulative property of signal strengths theoretically expressed in Eq. (1), we have experimented with TIP710CM sensor motes [5] equipped with TinyOS 1.14 [6]. Concretely, the goal of this experiment is to identify the accumulation of signals and its impact on the received signal strength when there are multiple simultaneous transmitters. The topology used in our experiments is shown in Fig. 2. For experiments, we modified the sensor nodes and disabled the functions of Clear Channel Assessment (CCA) and backoff operation. Thus, all the nodes transmit packets continuously without the CCA and backoff operations and the transmitted signals from the transmitting nodes can be overlapped at a monitoring node M where the node M measures (and collects) the received signal strength (RSS) by looking the received signal strength indicator (RSSI) register of CC2420. We repeated the experiment with varying the number of transmitting nodes N from 0 to 4. Note that the number of simultaneously transmitted signals at a certain sampling time of node M may be less than the number of given transmitting nodes due to asynchronous packet transmission time among the nodes. To address this problem, we have used the highest 1.25 percent of RSS values among the eight thousands of measured samples in calculating the average value of received strength for each experiment.

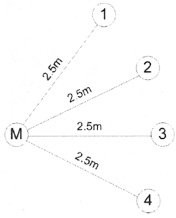

Fig. 2. Topology for experiments

Fig. 3 shows the average received signal strength at node M as a function of transmitting nodes. From the result, we can see that the aggregate signal strength tends to increase linearly as the number of transmitting nodes increases. Our experimental result is consistent with the experiments performed in [7] with 802.11 devices, which have shown that the reception of collided packets at the receiver has a higher RSS value than the solely transmitted packets since the signal of collided packets consists of multiple transmissions.

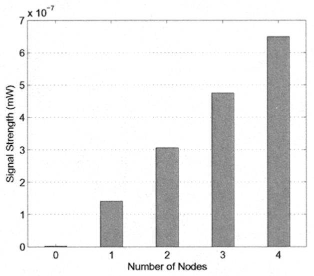

Fig. 3. Average received signal strength as a function of number of transmitting nodes

B. Basic Idea

When a node suffers from starvation, the starvation can be easily detected by the node using its local information such as MAC-layer behavior (i.e. by checking the busy ratio is high or not). However, it is not a easy problem to inter the source of starvation, specially whether the node is in the flow-in-the-middle (FIM) state or not. In this work we are interested in finding a feasible solution that can identify whether the source of starvation is due to the FIM problem or not. To this end, we exploit the physical energy detection mechanism implemented in 802.11 devices.

The received signal strength during a packet reception is shown to be fairly constant while noise has significant variance in channel energy – this was already well approved through many prior experiments (e.g. see Fig. 2 in [8]).

This means that the significant variation of received signal strength will not appear unless the number of simultaneous packet transmissions changes in the vicinity of the receiver during the packet reception. In other words, a wide variation of received signal strength implies a change of the number of simultaneous transmissions as discussed in the previous section. With this observation, let us consider a starving node in the FIM topology, for example, node 0 in Fig. 1. The main feature of a starving node due to the FIM problem is that the node suffers from the randomly overlapped transmissions of outer flows as explained in Section I. Thus, if the starvation of a certain node is caused by the FIM problem, the received signal strength at the node can vary significantly during a single busy detection period due to the change of outer nodes' simultaneous transmissions as shown in Fig. 4. Here, we have noted that the variation difference of the received signal strength will be larger than the carrier sense threshold (CS_{th}) because node 1 and 2 are located in the carrier sense range of node 0 in the FIM topology. In this paper, we utilize the number of changes in the measured received signal strength which drops or rises larger than CS_{th} to recognize the FIM starvation.

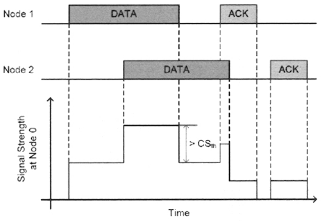

Fig. 4. A variation of aggregate received signal strength at a starving node in a FIM topology

IV. STARVATION RECOGNITION WITH PHYSICAL ENERGY DETECTION

As mentioned above, it can imply for a node that there are more than two nodes transmitting simultaneously in its vicinity it if the aggregate received signal strength for incoming signals changes sharply larger than the degree of CS_{th}. In this work we note that the number of such sharp changes in the received signal strength, n, during a packet reception period can be used to infer the number of neighboring nodes which cannot sense each other and can transmit simultaneously. In other words, we can conclude that a node is in the condition of FIM if the node experiences the sharp change frequently, in particular, the value of n is larger than or equal to 2.

In addition, changes in the received signal strength can be caused by various type of packets such as DATA, ACK, RTS, CTS, etc. However, overlapping transmissions are mainly due to DATA packet. Thus, we count a change after holding specific signal strength for T_{ack} in order to estimate the value of n (T_{ack} means the required time to transmit ACK). If there is fluctuations of channel, a sampling method for T_{ack} can be adopted to mitigate misbehavior caused by them.

Even though some nodes can carrier sense each others, collisions can cause that n become larger than 1. To prevent misbehavior due to collisions, we define the threshold γ. A node regards itself as starving when it satisfies the condition more than γ times. Simulation results of section VI-A show that this algorithm can recognize the condition of FIM successfully.

Algorithm 1 Starvation Recognition

```
Notation : $P_{recv}$ is the aggregate signal strength
Before trying to transmit, $n \Leftarrow 0$ and $\alpha \Leftarrow 0$
while defering or doing backoff in order to transmit do
  if $P_{recv}$ increases then
    if $n \geq 2$ then
      $\alpha = \alpha + 1$
    end if
    if $P_{recv} \geq CS_{th}$ then
      $n \Leftarrow 1$
    else
      $n \Leftarrow 0$
    end if
  else if $P_{recv} \geq CS_{th}$ & decreases larger than $CS_{th}$ & held for longer than $T_{ack}$ before decrease then
    $n \Leftarrow n + 1$
    if $\alpha > \gamma$ then
      $\alpha \Leftarrow 0$
      Alarm FIM
    end if
  end if
end while
```

V. SELF-INTERVENTION OF STARVING NODES

In this section, we devise the self-intervention method of starving nodes. Since interventions ignoring carrier-sense can make significant problems of the system, we should adopt a conservative approach. Thus, our method cannot achieve an absolute fairness but an alleviation of starvation.

When a node recognizes the condition of FIM based on our recognition algorithm, it starts transmitting after waiting for T_{ack} in order to protect one flow at least. Intervention successes decrease the threshold γ until it is larger than or equal to 2. If successful intervention do not occur until specific timer β expires, the threshold γ is set to default value. With this approach, starving nodes can intervene more aggressively when their intervention is successful. If interventions cause significant disturbance of other transmission, decrease of other nodes' transmission results in infrequent occurrence of FIM alarms, so that timer β will be expired and threshold γ is set to default. It prevents too aggressive intervention of starving nodes when it make significant disturbance to the system.

Traditional post-backoff operation of intervening nodes after successful interventions can result in the unfairness of other nodes due to EIFS operation. In order to give intervening node a penalty, post-backoff of intervening nodes operates with EIFS value. In addition, the reason of unsuccessful interventions is that ignoring the channel status results in a collision. In this case, increasing of CW at intervening nodes aggravates starvation of themselves. Thus, CW does not increase though a transmission failure occurs after a intervention. If an intervention disturb flows which make the intervening node starve, freezing CW results that retransmission of the intervening node could avoid the condition of FIM. Algorithm 2 is the proposed scheme for self-intervention.

Algorithm 2 Self-Intervention

```
INIT : $\gamma \Leftarrow$ Maximum $\gamma$
loop
  if FIM-alarm occured then
    After $T_{ack}$, Transmit data frame
  end if
  if the intervening packet is transmitted successfully then
    Do post-backoff with EIFS
    if $\gamma > 2$ then
      $\gamma \Leftarrow \gamma - 1$
    end if
    Start timer $\beta$
  else
    try to retransmit without increasing CW
  end if
  if timer $\beta$ is expired then
    $\gamma \Leftarrow$ Maximum $\gamma$
  end if
end loop
```

VI. PERFORMANCE EVALUATION

In this section, we show the effectiveness of our schemes using the ns-2 simulator [9]. In simulations, we consider 15 random topologies where each topology consists of 15 flows which are randomly deployed in the 1500m×1500m space. The distance of each flow is set randomly in the range of [30m, 250m]. All the flows are assumed to be saturated with UDP packets. The simulation parameters are listed in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Propagation Model	TwoRayGround
Simulation Time	30 sec
Transmission Range	250m
Carrier Sense Range	500m
Packet Size	1500bytes
Basic rate	1Mbps
Data rate	11Mbps
Maximum γ	5
Timer β	0.05sec

A. Accuracy of Starvation Recognition

First, we evaluate the accuracy of our recognition scheme. For the evaluation of detection accuracy, we introduce a metric of *true alarm ratio*. We define an alarm detecting starvation correctly as "true alarm" where a flow is regard as being starved when its throughput is lower than its minimum expected reference throughput. The *true alarm ratio* is defined as the ratio of the number of true alarms to the total number of alarms. Here, we define the reference throughput $S_{ref,i}$ of node i as the throughput obtained under the hypothesis that the node obtains a fair share of the full channel throughput S when contending with its neighbor nodes, which is

$$S_{ref,i} = \frac{S}{\text{the number of neighbors} + 1} \tag{2}$$

Fig. 5 represents the throughput of each flow and the number of their alarms in the simulation topology 1. As shown in Fig. 5, alarms are shown to be occurred frequently at starving nodes. However, the number of alarms in flow 13 is small even though it suffers from starvation. This is because that the cause of flow 13's starvation was not the FIM problem but the hidden node problem [2]. Note that our scheme focuses only on detecting the starvation due to the FIM problem and it does not activate an alarm for other types of starvation. Table II shows the *true alarm ratio* for each random topology.

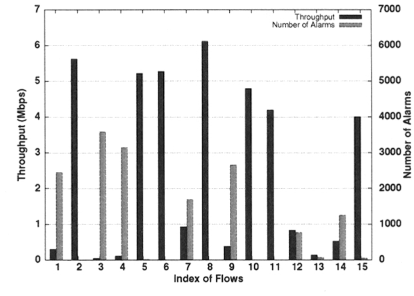

Fig. 5. Throughput and the number of alarms at Random Topology 1

TABLE II
TRUE ALARM RATIO

Topology index	*true alarm ratio*
1	1.00
2	0.93
3	1.00
4	0.96
5	0.82
6	0.98
7	0.88
8	1.00
9	0.63
10	0.93
Average	0.91

B. Self-intervention

We have performed simulations with same setting in section VI-A. The key values which determine the degree of intervention are γ and timer β. We have selected them which can achieve the best performance among experiments. To quantify the enhancement of fairness, we adopt the fairness index, i.e.,

$$F = \frac{\left(\sum_{i=1}^{N} \frac{S_i}{S_{ref,i}}\right)^2}{N \sum_{i=1}^{N} (\frac{S_i}{S_{ref,i}})^2} \tag{3}$$

, where S_i is the throughput of ith flow. F is a value between 0 and 1, and the maximum value of 1 is achieved if all N flows receive expected throughput $S_{ref,i}$.

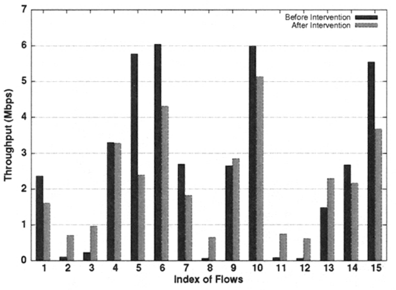

Fig. 6. Throughput changes of Random Topology 2

TABLE III
STATUS OF RANDOM TOPOLOGY 2

Flow Index	Throughput (Mbps)		
	Before	After	$S_{ref,i}$
1	0.104	0.710	2.039
2	2.356	1.609	2.039
3	0.230	0.962	1.020
4	3.295	3.276	3.058
5	5.766	2.386	1.223
6	6.039	4.312	2.039
7	2.688	1.824	2.039
8	0.062	0.656	1.020
9	2.651	2.845	2.039
10	5.989	5.134	3.058
11	0.080	0.748	1.020
12	0.064	0.618	1.020
13	1.481	2.295	1.529
14	2.671	2.163	1.529
15	5.541	3.677	2.039

Figure 6 and Table III show changes of each flow's throughput and status after self-intervention at topology 2. We could find that the throughput of flow 2,3,8,11 and 12 in starvation increases with self-intervention. Due to the conservative intervention, enhancements of throughput seems to be insignificant. However, starving flows could obtain near $S_{ref,5}$ throughput due to interventions. In case of flow 5, its throughput decreased largely since other nodes' starvation gave it more transmission opportunity before self-intervention. As shown Table III, the throughput of flow 5 approached its expected throughput $S_{ref,i}$ after interventions. Changes of fairness index for each topology is shown in Table IV. For the average, self-intervention increases fairness by about 30%.

VII. CONCLUSION

This paper suggests a recognition method of starvation considering energy detection in the physical layer. First, we verify aggregate signal strength is proportional to the number of transmitting neighbors via simple experiments. Then, we show that the condition of starvation can be detected with the observation of signal strength variation during deferring or backoff operation through simulations. Based on our proposed recognition scheme, we propose simple mitigation method of starvation. Simulation results show that our simple approach can mitigate starvation and improve a fairness of system successfully.

TABLE IV
CHANGES OF FAIRNESS INDEX

Topology Index	Fairness Index	
	Before	After
1	0.53	0.84
2	0.52	0.75
3	0.61	0.80
4	0.67	0.81
5	0.81	0.89
6	0.60	0.91
7	0.59	0.77
8	0.54	0.64
9	0.74	0.80
10	0.59	0.81
Average	0.62	0.80

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