FSA: A Fast Coordination Scheme for Opportunistic Routing

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***Abstract*—Opportunistic Routing (OR) has been considered as one promising technique to overcome the unreliability of the wireless medium by collaborating multiple neighboring receivers/candidates for packet forwarding. A key challenge in OR is how to efficiently coordinate the multiple candidates and ensure only one of them to forward the packet. In this paper, we investigate the existing candidate coordination schemes and propose a"fast slotted acknowledgment" (FSA) to further improve the performance of OR by using single ACK with the help of channel sensing technique. The simulation results show that FSA can reduce the average end-to-end time delay of OR protocols by up to 50% compared with state-of-the-art coordination schemes in light traffic scenarios and can increase the average end-to-end throughput by up to 20% in heavy traffic scenarios.**

I. INTRODUCTION

Routing in multi-hop wireless networks is challenging mainly due to the unreliability of wireless channels [1]. Recently, a new routing paradigm, known as opportunistic routing (OR) [2] [3] has been proposed as a promising approach to take advantage of the broadcast nature of the wireless medium and combat the unreliability of wireless transmissions. The general idea of OR is as follows: at each transmission, the sender chooses multiple rather than one next-hop forwarding candidates at network layer, prioritized by their "distance" to the final destination, and one of the candidates is chosen as the actual relay node at the MAC layer. One important and challenging issue in OR is candidate coordination. That is, in order to avoid duplication, we should ensure that only the "best" receiver of each packet forwards it. However, it is non-trivial to achieve this goal in an efficient way. The existing candidate coordination schemes have some inherent inefficiency such as high time delay at each one-hop transmission, potential duplicate forwarding, etc.

In this paper, we propose a new scheme "fast slotted acknowledgment" (FSA) to further improve the efficiency of OR, which adopts single ACK to confirm the successful reception and suppress other receivers' attempts of forwarding the data packet with the help of channel sensing technique. We also confirm the benefit of our scheme by simulation. The results show that FSA can decrease the average end-to-end delay up to 50% when the traffic is relatively light that all the coordination schemes can still handle and can improve the throughput up to 20% under heavy traffic load where the other coordination schemes are already unable to delivery all the data packets.

The rest of this paper is organized as follows. Section II describes the state-of-the-art coordination schemes in detail. Section III presents FSA's design and analysis, followed by Section IV, where evaluation and analysis of FSA's performance are presented. Section V concludes.

II. EXISTING CANDIDATE COORDINATION SCHEMES

In this section, we review two state-of-the-art candidate coordination schemes: slotted acknowledgement and compressed slotted acknowledgement, and point out their potential vulnerability and inefficiency.

A. Slotted Acknowledgment (SA)

SA is proposed by Biswas and Morris in [2]. It applies a similar acknowledgment scheme as the one used in traditional 802.11, however, requires each candidate who has received the data packet to broadcast an ACK in different time slots according to their priorities. Instead of only indicating the success of reception, each ACK contains the ID of the highest prioritized successful recipient known to the ACK's sender. All the candidates listen to all ACKs before deciding whether to forward the data packet, in case a lower prioritized candidate's ACK reports a higher prioritized candidate's ID. In order to protect all the ACKs from being interrupted by other transmissions, SA extends the Network Allocation Vector (NAV) in the MAC header of the data packet to reserve the channel for longer time. Thus the total coordination time for SA with n candidates is $n \times (T_{SIFS} + T_{ACK})$, where SIFS is short inter frame space [4]. This scheme has a serious vulnerability which makes it fail to work well in some scenarios. Taking one transmission with 3 candidates for example. If the highest prioritized candidate failed to receive the data packet, then the channel will be idle for $2 \times T_{SIFS} + T_{ACK}$ which is obviously greater than DIFS (Distributed Inter Frame Space) [4], during which some other transmitter who does not hear the data packet clearly would send it's own packet, and this packet will collide with the subsequent ACKs from $candidate_2$ and $candidate_3$ as shown in Fig. 1. Since no one hears a clear ACK, both $candidate_2$ and $candidate_3$ will forward the packet, which results in duplication, and the sender also will retransmit the packet unnecessarily. The scenario shown above is not rare, especially under heavy traffic loads.

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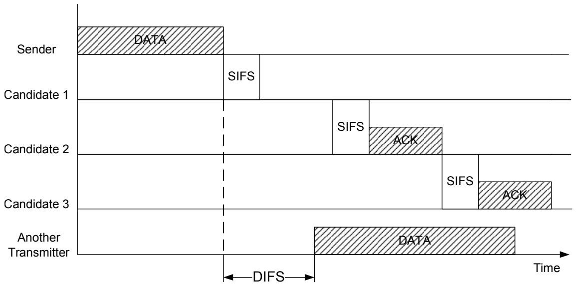


Fig. 1. SA with first ACK missing

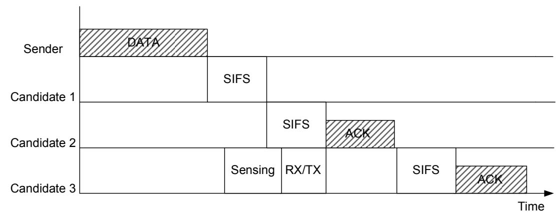


Fig. 2. CSA with the first ACK missing where RX/TX is the turnaround time for radio to change from receive state to transmit state

B. Compressed Slotted Acknowledgment (CSA)

A.Zubow et. al. [5] try to alleviate the potential collision in SA by introducing the channel sensing technique and refine SA to a "compressed slotted acknowledgment". The general idea is as following: With a delay of SIFS after receiving the data packet, the highest prioritized candidate sends out its ACK. From this time point, all other candidates who also successfully received the data packet sense the channel by received signal strength indicator (RSSI), an parameter in PHY layer. If the RSSI value increases significantly within the predefined detecting period determined by the priority, the highest prioritized ACK is considered as sent and they will continue to wait for their corresponding ACK slots before sending their own ACKs. Otherwise, if no such increase in signal strength is observed, the other candidates conclude that the highest priority candidate did miss the data packet. In that case, the second highest prioritized candidate prematurely sends its ACK to compress the channel's idle period to be smaller than DIFS. All the other candidates behave in the same way as before except that all subsequent events happen earlier. Fig. 2 depicts a case with 3 candidates. the use of channel sensing technique makes the SA's fixed ACK slots mechanism more flexible and gives CSA better performance on alleviating the potential collision. However, this detection-based scheme still requires multiple ACKs thus suffers from the same high coordination delay as SA.

III. DESIGN AND ANALYSIS OF FSA

A. Design of FSA

The main objective of FSA is to achieve an agreement between multiple candidates with lower coordination delay than SA and CSA. At the same time, FSA must be robust enough to deal with potential collision and unnecessary retransmission. Since all the inefficiencies in SA and CSA are mainly due to

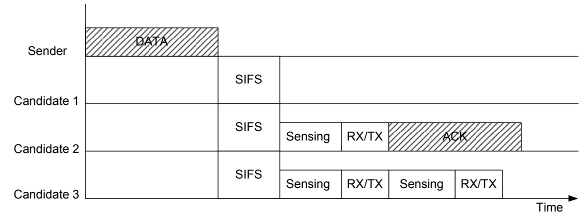


Fig. 3. FSA with the first ACK missing

the use of multiple ACKs, we adopt single ACK in FSA, which will be sent by the highest prioritized candidate in the set of successful receivers. This single ACK plays two roles. On one hand, it informs sender the successful reception, which is the same for SA and CSA; On the other hand, it suppresses all the other lower prioritized candidates' attempts of forwarding the data packet. This is different from the ACKs in SA and CSA schemes which are to help candidates share the information about the reception status. Accordingly, we also choose to use channel sensing technique to detect the appearance of ACK.

The FSA works as follows: Each candidate waits for $T_{SIFS} + (n-1) \times T_{Sensing\_Slot}$ before deciding whether it should broadcast ACK, where n is its priority order in the candidate set. So with a time delay of SIFS after the data packet was received, the highest prioritized candidate sends out an ACK. From that point in time, all the other candidates detect the channel for a $T_{Sensing\_Slot}$ time which consists of $T_{Sensing}$ and RX/TX to tell whether they detect this ACK. If the answer is positive, they stop detecting the channel and simultaneously suppress their own attempts of sending ACK and forwarding the data packet. Otherwise, they think the highest prioritized candidate missed the data packet and the second highest priority candidate takes the responsibility of sending ACK in the beginning of the second $T_{Sensing\_Slot}$ and all the remaining lower priority candidates continue to monitor this second ACK. The coordination process goes on like that until some successful receiver finally sends out an ACK. An example of a transmission with 3 candidate nodes is illustrated in Fig. 3.

During this one-hop transmission, $candidate_1$ failed to receive the packet. Thus the $candidate_2$ and $candidate_3$ detect nothing in the first $T_{Sensing\_Slot}$ time. then $candidate_2$ thinks itself is the highest successful receiver and sends ACK at the beginning of the second $T_{Sensing\_Slot}$. $candidate_3$ detects this ACK and immediately suppresses itself. The total coordination time for FSA with n candidates is: $T_{SIFS} + T_{ACK} + (n-1) \times T_{Sensing\_Slot}$ compared with SA and CSA's $T_{SIFS} + n \times T_{ACK}$. Since the $T_{Sensing\_Slot}$ is far less than T_{ACK} (for 802.11b, the former is 20 micro-seconds while the latter is more than 200 micro-seconds), FSA can significantly reduce the time cost for candidate coordination.

B. Analysis

The key difference of FSA from SA and CSA is that it uses single ACK to suppress other potential forwarders and acknowledge the sender. It only needs to obtain some raw information such as whether some packet is transmitting rather than more detailed information like the content of the packet with the help of channel sensing technique. At first sight, FSA seems to be less reliable. However, just because those information required by FSA is raw, they can be got more easily and reliably which makes the whole scheme more reliable. Suppose one transmission with two candidates A and B where A possesses higher priority and both candidates got the data packet. If the link between A and B is not good when A is transmitting its ACK, then the ACK received by B maybe corrupted. In SA and CSA coordination schemes, node B needs to get the ID of the highest priority successful recipient known to the ACK's sender (in the case it is A itself) from received ACK. However, with this corrupted ACK, B will fail to do that and consider itself as forwarder which leads to the result of duplicate forwarding and unnecessary retransmission. However, in FSA, B just need to know the happening of transmission and don't care about the detailed content within the received packet. This information can be got reliably even under bad link because the fluctuation of link state has far less impact on the average signal strength than each single bit of the transmitting packet. thus FSA is more robust in this case.

Another seemingly weakness of FSA is that single ACK would attenuate the reliability between the sender and candidate set. However, it is also not true because of the following reasons. (1) If the data packet which is generally longer than ACK and sent in higher rate has already been received by the corresponding candidate successfully, the subsequent ACK sent along reverse direction in a lower rate (1Mbps for 802.11b) will be received by the sender successfully with very high probability [6]. (2) The other ACKs except the first one in SA and CSA are sent in relatively long intervals (several ACK slots) after receiving the data packet. For the good links, the first ACK has already achieved almost 100% reliability, thus there is no space for improving; For more variable links, the link states may have already changed at that time. Then the probability that those following ACKs being received correctly by the sender is much smaller than the first one [6]. So the improvement of reliability provided by those extra ACKs is also quite limited. In another word, single ACK is already strong enough and multiple ACKs are not indispensable.

The real potential vulnerability of FSA is its dependence on the precision of channel sensing technique. For example, if the detecting node considered some other interferences to be ACK sent by some higher priority candidate, it will falsely suppress itself from forwarding the packet. It is also possible that in some situation the detecting node fails to sense the transmission of ACK from higher priority candidate and then send its own ACK which will collide with the transmitting one. However, this dependence problem can be greatly alleviated through careful design of the scheme. For the first case, we make the whole coordination process highly synchronized and also introduce more precise channel sensing technique (see details in following subsection). Thus such probability will be constrained in a rather low level. Even this scenario indeed happened, the consequence is just that those lower priority detecting candidates suppress themselves "over cautiously" and cause the sender's unnecessary retransmission, which will not cause big trouble. For the second case, just as we describe in the beginning of this section, this possibility will be very low because the presence of transmission is just some kind of raw information that could be got very reliably. If this case really happened, the consequence will be duplicate forwarding besides unnecessary retransmission. However, we should notice that this false detection has the same consequence in CSA scheme, which means FSA will not introduce extra chance for duplicate forwarding in the worst case.

C. More on Channel Assessment Techniques

Carrier Sensing Multiple Access (CSMA) is the de-facto medium access control protocol for 802.11 WLAN. Such sensing mechanism is called clear channel assessment (CCA) [4]. Generally speaking, CCA performance could be characterized by a pair of parameters:(P_d and P_{fa}) where P_d refers to the probability of detecting the channel to be busy when the channel is indeed busy and P_{fa} refers to the probability of detecting the channel to be busy when the channel is actually idle. There is an inherent trade-off between P_d and P_{fa} with the constraint of limited detection time [7]. CCA module can be implemented in two ways:Energy detection (ED) and Preamble detection (PD). ED-based CCA integrates the square of the incoming signal from the radio front end during the CCA window to get an average signal strength, then compares it with a predefined threshold level which represent the normal background noise and make a judgment. PD-based CCA tries to use the correlation of well-knowned preambles with the received signal to detect the presence of packet, thus has a more enhanced reliability. In FSA we choose PD-based CCA technique because it is more precise and its main disadvantage, which is highly energy cost, can be avoided in the scenario of coordination in OR protocols.

IV. Simulation Results and Evaluation

In this section, we evaluate and compare the performance of FSA with SA and CSA. We also introduce a perfect detection-based scheme, IDEAL, as the baseline for comparison. The IDEAL scheme is the same as FSA, except that all the ACKs in IDEAL is 100% reliable and the detection judgement is 100% precise. Since our focus is on the efficiency of different coordinagtion schmes given the same candidate set and the corresponding forwarding priorities, we use an existing candidate selection algorithm based on node's geographic locations and adopt the local metric opportunistic effective one-hop throughput (OEOT) [8] to select candidates.

Because the existing popular network simulators, such as NS-2, OPNET, GloMoSim, have not implemented the PHY layer's function like energy integration or matched filter module currently, we have to do some modification to the PHY layer and make the detection judgment based on the following probability model. We define the CCA error floor [7] at the optimal threshold, which can be achieved by equating $1 - P_d$ and P_{fa} where P_d is detection possibility and P_{fa} is the false alarm possibility. Then the CCA error floor for ED-based

TABLE I
SIMULATION PARAMETERS

Simulation Parameter	Value
number of nodes	50
stationary or dynamic	stationary
data transmission rate	11Mbps
ACK transmission rate	1Mbps
Retry limit	5
Collision window	31..1023
Radio sensing threshold for data	-100dbm
Radio receiving threshold for data	-83dbm
Radio sensing threshold for ACK	-100dbm
Radio receiving threshold for ACK	-91dbm
pathloss model	two-ray
fading mode	rician
rician k factor	4
radio reception SNR	10
Hello packet intervial	1s
Size of candidate set	3
CCA window	15μs
SIFS	10μs
Radio receive/transmit turnaround time	5μs

CCA and PD-based CCA can be expressed in terms of the Q function [9], where N is the number of independent samples within the CCA window:

$$P_{CCA\_ef\_ed} = Q(\sqrt{N}\frac{SNR}{1+\sqrt{1+2SNR}})$$

$$P_{CCA\_ef\_pd} = Q(\sqrt{\frac{N}{2}SNR})$$

We define the following performance metrics.

- Throughput: the ratio of the number of received bits to the whole session time.
- Delay: the per packet end-to-end time delay from the packet being sent out until it reaches the destination.
- Packet deliver ratio: the number of successfully received packets over the number of sent packets.
- Duplicate deliver ratio: the number of duplicate packets received at all the destinations over the total number of received packets.
- Retransmission ratio: the transmission number needed for a successful one-hop forwarding.

The simulation results of all metrics except for the number of transmissions are averaged over 25 flows under 5 simulation runs with different seeds.

A. Simulation Setup

We developed a simulation environment with Glomosim. the MAC protocol is based on 802.11b, however, with some modifications. Since the source code of SA and CSA schemes are not publicly available, we implemented our own version. Table I lists all the related simulation parameters. All these 50 nodes are randomly uniformly distributed in a $d \times d$ m^2 square region where d=1400,1500,...,1800. The corresponding average number of neighbors per node are 12.42, 10.90, 9.65, 8.60, 7.79.

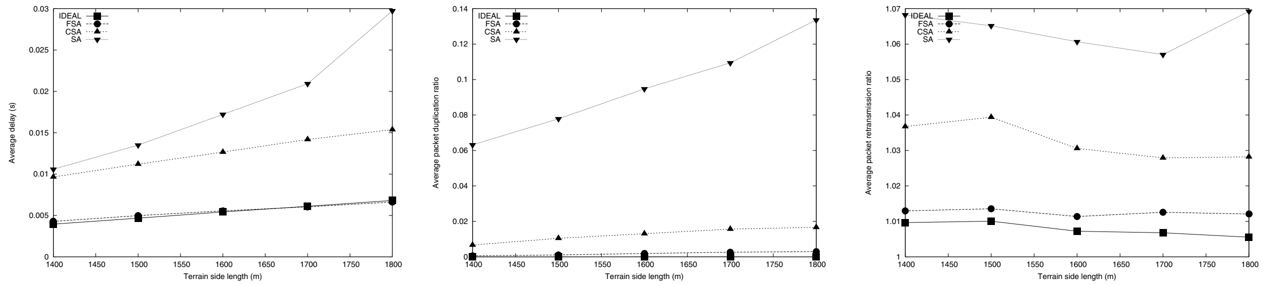
We randomly choose 25 communication pairs in the network. The sources are CBR (constant bit rate) and each packet being 512 bytes long. UDP is used in transportation layer. Each communication session lasts 120 seconds. Before all the transmissions start, the simulation environment will go through a 30 seconds' warm-up phase, during which each node sends out "Hello" packet periodically to learn the neighbors information and this learning process lasts through the simulation.

B. Simulation Results and Evaluation

1) Delay: Fig. 4(a) shows the average per packet end-to-end time delay of SA, CSA, FSA and IDEAL. In order to make a fair comparison, we set the packet interval of all the data flows to be 120 milliseconds which promises all the schemes can handle the traffic demand (in this case, all the protocols achieve 100% delivery ratio and almost the same average per flow throughput of 34k bps). We see that SA has highest delay value under all terrain side lengths and CSA performs some better. FSA achieves far lower time delay than these two schemes and very close to the performance of IDEAL, which has the lowest delay value. From this result, Firstly, we can get the conclusion that the use of channel sensing technique indeed can alleviate the potential collision problem caused by the ACK's unexpected missing. Secondly, we observe that FSA achieves less than half time delay of CSA under all the terrain side lengths. This reduction in time delay can be mainly attributes to the design of single ACK.

2) Duplicate deliver ratio and Average retransmission ratio: The per packet duplicate ratio shown in Fig. 4(b) and average retransmission ratio shown in Fig. 4(c) can further demonstrate that FSA is more reliable. In Fig. 4(b), we see that of all the data packets received successfully by the destinations of these data flows, there are approximately 6%-14% duplicated ones for SA and 0.4%-2% for CSA under different terrain side lengths. However, the duplicate ratios for FSA are almost zero under all terrain side lengths, which are very close to the performance of IDEAL. This confirms our analysis in section III-B which concludes that the probability for candidates in FSA to miss the presence of a higher priority candidate'ACK and result in duplicate forwarding is very low, but the probability for candidates in CSA to receive corrupted ACKs from other candidates and leads to duplicate forwarding is not negligible. In Figure 4(c), we see that IDEAL achieves an average retransmission ratio of approximately 1.01 under all terrain side lengths. Since the ACKs in IDEAL scheme are exempt from fading or interference, the only reason for retransmission in IDEAL is because all the candidates fail to receive the data packet. Such low retransmission ratio shows that OR schemes with multiple candidates indeed can greatly increase the forwarding reliability. We also notice that FSA's performance is close to the IDEAL, with an average higher ratio of 0.5%. This shows that the use of single ACK in FSA already could achieve very good performance on promising the reliability between sender and the candidate set and multiple ACKs are not necessary.

3) Packet delivery ratio and Throughput: In order to evaluate the throughput performance of all the schemes, we set the packet interval of all data flows to be 70 milliseconds, which makes a relatively heavy traffic load. The results are shown in Fig. 5. From Fig. 5(a) we see that SA and CSA are unable to

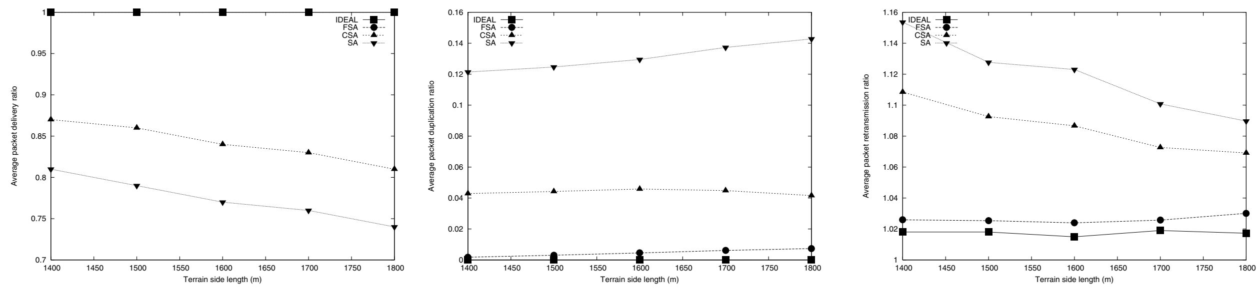


(a) average per packet end-to-end time delay

(b) average per packet duplicate ratio counted in the final receivers

(c) average one-hop retransmission ratio

Fig. 4. simulation results with packet interval of 120 milliseconds



(a) average per flow delivery ratio

(b) average per packet duplicate ratio counted in the final receivers

(c) average one-hop retransmission ratio

Fig. 5. simulation results with packet interval of 70 milliseconds

handle the traffic demand and can only achieve packet delivery ratio of 87% - 81% and 81% - 74% respectively under different terrain side lengths. However, FSA still performs well and achieves 100% delivery ratio under different terrain sizes, just like IDEAL. Since our throughput metric is the ratio of the number of received bits to the whole session time and all the schemes have the same simulation time, thus the throughput is proportional to the packet delivery ratio. The simulation shows that FSA and IDEAL can achieve a throughput of approximately 54k bps, with an average gain of 12.5%-20% compared with CSA's throughput under different terrain side lengths. The reason behind is that FSA takes less medium time in each hop's transmission and thus possesses a higher throughput capacity and the traffic demand in this setting is still within its capacity range. The time delay of SA and CSA in this setting is as high as 6-10s which is due to the fact that the traffic demand is beyond the throughput capacity of these two schemes, which cause each packet to suffer a long waiting time in the packet queue of every intermediate relay node. This long queueing delay reversely further aggravates the duplicate and retransmission problems, which can be observed in Figure 5(b) and Figure 5(c).

V. Conclusion and Future Work

In this paper, we comprehensively analyze the coordination problem in opportunistic routing and based on these analysis, propose a new coordination scheme"fast slotted acknowledgment" which is fully rely on the detection approach to meet an agreement between multiple candidates. we also compare FSA with those state-of-the-art schemes and simulation results show that it achieves better performance in all the metrics, especially in time delay.

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