On the Tradeoff between Opportunistic Gain and Coordination Delay of Opportunistic Routing in Wireless Networks

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Abstract—Opportunistic routing has gained much attention in recent years as a means of leveraging the broadcast nature of wireless medium. Most of the previous studies focused only on improving throughput, assuming that Best Effort traffic which is delay insensitive is delivered through opportunistic routing. However, when the delay sensitive traffic is involved, it is necessary to consider both the opportunistic gain and the delay incurred by opportunistic routing at the same time. In this paper, we analyze the relationship between these two factors and through extensive simulations confirm that our analyses are very accurate.

I. INTRODUCTION

One of the intrinsic natures of wireless networks is that wireless medium is shared by a group of nodes in proximity. Such a characteristic has influenced significantly the design of routing protocol as well as medium access control (MAC) for wireless networks. In general, the same approaches used in wired networks have been adopted in the routing protocols for wireless networks with slight modifications regarding the broadcast nature of wireless medium as a hurdle to overcome. In such routing protocols, a transmitter chooses one specific receiver, and transmits a packet until the receiver acknowledges the reception of the packet. Consequently, a considerable amount of research effort has been devoted to the design of routing metric which determines a “proper” receiver [1][2]. To increase the probability of successful reception, a receiver should be close enough to a transmitter. At the same time, the receiver also has to be located sufficiently far away in order to reduce the total number of transmissions required for end-to-end delivery.

On the contrary, in the opportunistic routing paradigm [3], the broadcast nature of wireless medium is considered as an opportunity that can be leveraged to transmit packets. To realize this, a transmitter may have more than one node as receiver. When a packet is transmitted, depending on the instant channel condition, some of these nodes may receive the packet while the others may not. Then, the nodes which received the packet collaborate to decide which node should forward the packet. This coordination process is one of the most crucial factors that affect the performance of the opportunistic routing protocols. If the coordination is carried out inappropriately, the packet may be forwarded by a node which is not a best one to do so. Even worse than that, duplicate forwarding may happen, which undermines the benefit of opportunistic routing.

Meanwhile, to minimize the inevitable signalling overhead for coordination, i.e., the cost for acknowledging the reception of a packet, a majority of opportunistic routing protocols send this information by embedding it in some other packets. Owing to this mechanism, the overhead with respect to airtime usage can be fairly reduced compared to that of sending a standalone ACK (acknowledgement packet). However, it is often neglected in the literatures [4][5] that this mechanism involves a delay in packet forwarding due to the distributed nature of coordination. This is because, in the previous studies, the opportunistic routing protocols were targeted only for Best Effort traffic which is relatively less sensitive to individual packet delay. To the best of our knowledge, the relation between the opportunistic gain and the coordination-induced delay has not been investigated in depth in the literatures.

In this paper, we analyze the relation analytically with some assumptions for the case where delay sensitive traffic is delivered under the opportunistic routing framework. The analysis is validated through extensive simulations. Additionally, we study the effect of some of the assumptions based on the simulation results.

The rest of the paper is organized as follows. In Section II, the considered system model is described in detail. In Section III, we analyze the relation between the opportunistic gain and the coordination-induced delay analytically, which is validated through simulations in Section IV. Finally, we conclude this paper in Section V.

II. SYSTEM MODEL

Unlike in the traditional routing protocols, a transmitter in the opportunistic routing protocols may have more than one node as forwarder candidates, or in short candidates. The list of candidates, called Forwarder Candidate Set (FCS), can be either explicitly specified in a packet to transmit or known to all nodes in advance. The former has an advantage in that it can promptly adapt the FCS to the rapidly changing network condition. On the other hand, the latter can include more nodes in the FCS without incurring additional overhead, thereby fully exploiting the opportunistic gain [4]. In this paper, we assume that the latter is used as in [6].

1In the rest of this paper, we use the term opportunistic gain as a synonym of multi-user diversity gain.
Acknowledgement schemes are indispensable in the opportunistic routing protocols for consensus building on which candidate should take charge of packet forwarding. There are two types of acknowledgement schemes: standalone and piggybacked acknowledgement schemes. In standalone acknowledgement schemes [7], an exclusive opportunity to transmit a standalone ACK is given to each candidate in turn. Such an ACK is transmitted immediately following the preceding data packet. On the other hand, in piggybacked acknowledgement schemes [6][8], an ACK is piggybacked in one or more following packets to transmit. Despite the fact that the ACK should be piggybacked multiple times for reliable delivery, these schemes incur less overhead than standalone acknowledgement schemes. This is because, in general, piggybacked ACKs are transmitted with higher transmission rates than that of a standalone ACK. However, an additional delay is unavoidable due to the consensus building process which is done in a distributed manner. We refer to such a delay as a Coordination Delay (CD) whose mathematical definition will be given in Section III.

When a node receives a packet in piggybacked acknowledgement schemes, it checks whether it is in the FCS by looking up its routing table using the transmitter and destination fields in the packet. To avoid confusion, we refer to the packet in which we are interested as the Packet of Interest (POI) hereafter. In addition, a packet that is transmitted by a candidate and conveys a piggybacked ACK for the POI is referred to as an ACK Conveying Packet (ACP). If the node turns out to be one of the candidates, it retrieves from the routing table its priority for packet forwarding among the candidates. Then, it places the POI on its queue according to the packet classification and scheduling rule. In this paper, we assume that there are two types of traffic: delay sensitive traffic and Best Effort traffic. Packets of delay sensitive traffic are put ahead of those of Best Effort traffic in the queue. Here, our focus lies in investigating the effect of CD when delay sensitive traffic is transported in the opportunistic routing protocols which rely on the piggybacked acknowledgement scheme.

After the POI is enqueued, a timer, called forwarding timer, is created and associated with the POI. The expiration time of the timer is set according to the candidate’s priority. It is only after the timer expires that the POI becomes eligible for transmission. In other words, the POI cannot be transmitted even though it reaches the head of the queue if the timer is still running. Upon the expiration of the timer, the candidate participates in the “forwarding contention”. The candidate is said to “win” the forwarding contention if it actually forwards the POI for the first time among the candidates. The expiration time is assumed to increase linearly with the candidate’s priority. The increment step is denoted by δ.

The value of δ determines how long high priority candidates have an exclusive opportunity to forward the POI, thus winning the forwarding contention. In order to fully enjoy the opportunistic gain, it is necessary to set δ sufficiently large. This is because, by doing so, more chances to win will be given to the high priority candidates which generally have a shorter remaining distance to the destination, i.e., a longer progress distance at this hop. However, δ cannot be indefinitely large since it may cause a long CD as will be shown in Section IV. Hence, there is a tradeoff relation between the opportunistic gain and the CD.

Two mechanisms are introduced in the literatures [6][8] to handle this tradeoff. Firstly, the silent discard is to let a lower priority candidate drop the POI from its queue when it comes to know that one of the higher priority candidates received the POI. To this end, each piggybacked ACK contains the ID of the known highest priority candidate that received the POI. We refer to this ID as the HPC-ID. Due to the distributed nature of the mechanism and the error-prone wireless channel, the candidates may have different information about the HPC-ID.

Upon receiving the POI, a candidate starts to keep track of the HPC-ID and advertises it in every piggybacked ACK. Initially, the HPC-ID is set to the candidate’s own ID. When the candidate overhears an ACP from other candidates, it updates its HPC-ID if the ACK has a higher priority candidate’s ID in the HPC-ID field. Along with the update, it silently discards the POI and cancels its forwarding timer if it didn’t yet. Note that even though the POI is discarded, the candidate continues to send the piggybacked ACKs to ensure the propagation of the up-to-date HPC-ID.

The other mechanism, called the premature timeout, is to allow a candidate to terminate its forwarding timer and join the forwarding contention as soon as it gets to know that none of the higher priority candidates received the POI. This can
be also done by overhearing one or more packets from other candidates. Since ACPs are sent only by the candidates that received the POI, if the candidate overhears a packet without an ACK from one of the higher priority candidates, it can safely conclude that the sender of this packet didn’t receive the POI. If this is true for all the other higher priority candidates, it is advantageous to let the candidate join the forwarding contention immediately in order not to incur an unnecessary delay waiting for the timer’s expiration.

Figure 1 shows the state diagram of the described protocol. In the transition arrows, “E” stands for the event that causes the transition, while “A” represents the action to be taken. An example of the protocol which helps the understanding of the protocol will be given in the following section.

III. ANALYSIS

In this section, we analyze the performance of the opportunistic routing protocol in terms of the opportunistic gain and the CD. For the sake of tractability, we assume the following in our analysis.

- **Slotted p-persistent MAC without collisions.** Each node chooses a random value in [0, 1) at each time slot. Among the nodes with a value less than p which is fixed in the system, one is randomly selected as a “MAC contention” winner. Although this is not the case in practice, we assume that the collision probability is already taken into consideration in the link error probabilities between nodes. The winner transmits a packet from its queue which is eligible for transmission. It is possible that none of the nodes transmit at a certain time slot.

- **Infinitely backlogged queue with Best Effort traffic.** Each node’s queue is infinitely backlogged with Best Effort traffic. As a result, each node always has packets to transmit. When a packet of delay sensitive traffic arrives, it is enqueued at the head of the queue. However, this doesn’t necessarily mean that the packet will be transmitted before any packets of Best Effort traffic as explained in Section II.

- **Successful delivery of piggybacked ACKs.** Piggybacked ACKs are assumed to be delivered without an error. This means that if a higher priority candidate transmits an ACP, all the lower priority candidates overhear it and discard their POIs silently. In Section IV, we will show that the error due to this assumption is not significant in most cases.

- **No premature timeout.** Although it is not difficult to include this feature in our analysis, we omit this feature intentionally to make the analysis clear to understand. It will be also shown in Section IV that when and how much this feature affects the performance.

To help the understanding of our analysis, we use an example topology as shown in Fig. 2. In the figure, there are 5 candidates with node 1 being the transmitter. The number of candidates is denoted by N. Without loss of generality, we assume that the candidates’ priorities are given based on their node indices such that nodes 1 and 5 are the lowest and the highest priority candidates, respectively. The Packet Reception Probability (PRP) of node n, denoted by \( \alpha_n \), determines probabilistically whether a POI transmitted by node 1 is successfully received at node n. Note that \( \alpha_1 = 1 \) by definition. If we assume that node 1 transmits a POI at time slot 0, node 5, the highest priority candidate, can forward the POI from time slot 1 provided that it received the POI. On the other hand, nodes 4, 3, 2, and 1 have to wait \( \delta, 2\delta, 3\delta, \) and \( 4\delta \) time slots, respectively, to participate in the forwarding contention. In Fig. 2, \( \delta \) is set to 5. We suppose that node 5 didn’t receive the POI. As a result, it doesn’t participate in the forwarding contention, which is represented as a gray line in the figure.

Time slots where each candidate can forward the POI is represented by a black solid line. White triangles represent ACPs while the black one stands for the POI forwarding. The reason why node 2 doesn’t win the forwarding contention at time slot 17 is that it overhears an ACP from node 3 at time slot 3, which makes node 2 silently discard the POI.

A. Winning Probability

The probability that node n wins the forwarding contention is denoted by \( P_n \). Now we explain the process of calculating \( P_n \). Firstly, we divide the nodes that received the POI into two groups from the perspective of node n: \( S_h \) and \( S_l \). \( S_h \) is a set of the nodes with a priority higher than node n, whereas \( S_l \) includes the nodes with a priority lower than or equal to node n. Figure 2 shows an example when \( n = 3 \). The nodes in \( S_l \) are also denoted by \( n(k), k = 1, 2, ..., |S_l| \), in descending order of priority, e.g., \( n(1) = 3, n(2) = 2, \) and \( n(3) = 1 \) in Fig. 2.

The periods when node n can forward the POI are divided into \( L_1, L_2, ..., L_{|S_l|} \). \( L_k \) is the period where node \( n(k) \) is the lowest priority node that can join the forwarding contention. The number of contending nodes in \( L_k \), including node n, ranges from \( |S_h| + 1 \) to \( |S_h| + k \). Then, \( P_n \) can be expressed as a product of five terms described in the following. First of
all, in order for node $n$ to win the forwarding contention in $L_k$ among $|S_h| + i$ $(1 \leq i \leq k)$ contending nodes, the nodes with a higher priority than $n_{(i)}$ should not transmit neither the POI nor an ACP until the beginning of $L_k$. This probability is calculated as

$$P_n^{(1)} = q^{(N - n_{(k)})\delta((|S_h|+i-1))},$$

(1)

where $q$, the probability that a node does not transmit at a certain time slot, can be obtained as

$$q = 1 - \sum_{j=1}^{N} \frac{1}{j} \left[p \left(\frac{N-1}{j-1}\right)(1-p)^{N-j}p^{j-1}\right]$$

$$= 1 - \frac{1 - (1-p)^N}{N}.$$  

(2)

To make the nodes with a lower priority than $n_{(i)}$ silently discard the POI, $n_{(i)}$ should transmit at least one ACP during $(N - n_{(i)})\delta$. This probability is

$$P_n^{(2)} = \begin{cases} 1 - q^{(N - n_{(i)})\delta}, & i < k, \\ 1, & i = k. \end{cases}$$

(3)

In (3), $P_n^{(2)} = 1$ for $i = k$ since $n_{(i)}$ is the lowest priority node that can contend for packet forwarding in $L_k$. In other words, there is no need to impose this constraint.

Next, $n_{(i)}$ should not transmit from $L_i$ to $L_{k-1}$, which is expressed as

$$P_n^{(3)} = \begin{cases} \sum_{j=1}^{k-1} q^{(N - |S_h| + i)}j, & i < k, \\ 1, & i = k. \end{cases}$$

(4)

Again, $P_n^{(3)} = 1$ for $i = k$ due to the same reason as above.

Until now, we calculated the probability that $|S_h| + i$ nodes come to contend for packet forwarding in $L_k$. Since each of these nodes has an equal chance to win from this moment on, the probability is

$$P_n^{(4)} = \frac{1}{|S_h| + i}.$$ 

(5)

Finally, the probability that the forwarding contention will end in $L_k$ is expressed as

$$P_n^{(5)} = \begin{cases} 1 - q^{|S_h|(|S_h|+i)}, & k < |S_l|, \\ 1, & k = |S_l|. \end{cases}$$

(6)

Here, $P_n^{(5)} = 1$ for $k = |S_l|$ since it is the last period which continues until the forwarding contention is over.

Now we can calculate $P_n$ summing the product of $P_n^{(1)}$ to $P_n^{(5)}$ over all the periods $L_1$ to $L_{|S_l|}$ and all the possible number of contending nodes in a certain period as follows:

$$P_n = \sum_{S_h, S_l} \left\{ \sum_{|S_l|} P_n^{(4)} \sum_{k=1}^{i} P_n^{(5)} \right\}$$

(7)

where

$$P[S_h, S_l] = \prod_{m \in S_h \cup S_l} \alpha_m \prod_{m \notin S_h \cup S_l} (1 - \alpha_m)$$

(8)

and $P_n^O = \prod_{j=1}^5 P_n^{(j)}$. In the right-hand side of (7), the first and overall summation means the enumeration of all possible cases in terms of PRP. In the summation, the probability of each case, i.e., $P[S_h, S_l]$, is multiplied to the probability that node $n$ wins the forwarding contention in the case.

B. Progress Distance and Coordination Delay

With the calculated winning probability, it is straightforward to obtain the expected progress distance of the POI transmission, denoted by $D$, as follows:

$$D = \sum_{n=1}^{N} P_n D_n,$$ 

(9)

where $D_n$ denotes the distance from the transmitter to node $n$.

The CD is defined as the time difference from when a node wins the MAC contention for the first time to when it wins the forwarding contention by forwarding the POI. This implies that the CD can be calculated only for the forwarding contention winner. To calculate the expected CD, we first consider the “winning time slot” which is the time slot when a node wins the forwarding contention. When $m$ nodes contend during a period of $l$ time slots and the contention must end in the period, i.e., at least one transmission should occur, the expected winning time slot can be calculated as

$$w(m, l) = \frac{\sum_{j=1}^{l} j \cdot q^{(j-1)m} \cdot (1-q^m)}{1 - q^m}. $$

(10)

Considering the fact that each node has to wait until its timer expires before transmitting the POI, we obtain the expected winning time slot in our context as follows:

$$W_{CD} = \sum_{n=1}^{N} \left\{ \sum_{S_h, S_l} \left[ \sum_{k=1}^{l} \sum_{i=1}^{k} P_n^{O} \times \left\{ w(|S_h| + i, L_k) + (N-n)\delta \right\} \right] \right\}.$$ 

(11)

Therefore, the CD is given as

$$T_{CD} = W_{CD} - \frac{1}{1-q}.$$ 

(12)

IV. SIMULATION RESULTS

To evaluate the validity of our analysis, we present some simulation results in this section. Figure 3 depicts the used topology and PRP function. In Fig. 3(a), a total of $N$ nodes are located in a sector where $N$ varies with the simulation scenario. All the nodes are uniformly distributed in the sector except for the transmitter which is located at the vertex of the sector. The priority of each node is determined in descending order of the distance from the transmitter such that the farthest node becomes the highest priority candidate. The channel access probability is given as $p = 1/N$ for each scenario. The PRP function in Fig. 3(b) is taken from [9] which is based on IEEE 802.11g physical layer. Every point in the following graphs is an average of 100 randomly generated scenarios, each of which runs 5,000 times.
Fig. 3. Simulation setup. (a) Topology. (b) PRP function.

Fig. 4. The progress distance and the hop delay with varying $\delta$. The hop delay is defined in (11), the number of nodes is fixed as 10.

A. Validity of Analysis

The comparison between the analysis and the simulation results with varying factors such as $\delta$, the number of nodes, are given in Figs. 4 to 6. In the figures, lines represent the analysis results while markers are corresponding to the simulation results. Instead of the CD, we depict in Figs. 4 and 6 the average hop delay which is the sum of the channel access delay and the CD as in (11). This is to rule out the effect of $p$ and examine the CD from the perspective of end-to-end delay which is an accumulation of several hop delays. Throughout the figures, it is exhibited that our analysis is very accurate.

B. Impact of ACK Delivery Failure

In our analysis, we assumed that piggybacked ACKs are delivered without an error. However, in practice, ACPs which convey the ACKs are vulnerable to channel errors and collisions. This may cause duplicated and/or suboptimal POI forwarding due to the inconsistent information about the HPC-ID across the candidates. Figures 7 and 8 show the impact of such ACK delivery failures on the performance. The y-axis in the figures means the error ratio which is calculated as $|1 - X^{(\text{anal})}/X^{(\text{sim})}|$ where $X^{(\text{anal})}$ and $X^{(\text{sim})}$ represent either the progress distance or the hop delay for the analysis and the simulation results, respectively. To see how severely the

Fig. 5. Effect of the number of nodes on the progress distance.

Fig. 6. Effect of the number of nodes on the hop delay with the premature timeout disabled.

Fig. 7. Impact of ACK delivery failures on the progress distance.
ACK delivery failures affect the performance in the case where candidates are located far from each other, we increased the angle of the sector in Fig. 3 to $150^\circ$. In the figures, “AVG” and “MAX” show the average and the maximum error ratio of each metric. As shown in the figures, even the maximum error ratio is less than 10% owing to the efficient HPC-ID propagation mechanism. This implies that the error due to the assumption of successful ACK delivery is not significant in most cases.

C. Effect of Premature Timeout

The effect of the premature timeout on the hop delay is depicted in Fig. 9. As expected, the performance gain in terms of the hop delay begins to appear as $\delta$ increases. Also, it is observed that the effect is more apparent when the number of nodes is small. This is because the probability that the premature timeout occurs is larger when there are a smaller number of nodes. Recall that in order for the mechanism to work, all the higher priority nodes should transmit at least one packet. Although not shown in the figure, we observed that the average progress distance remains almost the same regardless of the premature timeout.

V. CONCLUSION

In this paper, we studied the performance of the opportunistic routing protocol that relies on the piggybacked acknowledgement scheme. To see the relationship between the opportunistic gain and the coordination delay, we analyzed the protocol probabilistically with some assumptions. Although these assumptions were made for the sake of tractability, the extensive simulation results revealed that the error caused by these assumptions is not significant, thus validating our analysis. Additionally, we showed the effect of the premature timeout mechanism on the hop delay through the simulation.

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