Link Correlation Aware Opportunistic Routing

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Abstract—**By exploiting reception diversity of wireless network links, researchers have shown that opportunistic routing can improve network performance significantly over traditional routing schemes. However, recently empirical studies indicate that we are too optimistic, i.e. diversity gain can be overestimated if we continue to assume that packet receptions of wireless links are independent events. For the first time, this paper formally analyzes the opportunistic routing gain under the presence of link correlation considering the loss of DATA and ACK packets. Based on the model, we introduce a new link-correlation-aware opportunistic routing scheme, which improves the performance by exploiting the diverse uncorrelated forwarding links. Our design is evaluated using simulation where we show (i) link correlation leads to less diversity gain, (ii) and with our link-correlation-aware design; improvement can be gained. We also provide a unique model to generate strings of randomly correlated receptions.**

I. INTRODUCTION

The broadcast nature of wireless networks led to design of opportunistic routing. The basic idea of opportunistic routing is fairly straightforward. Given a source and a destination in a multi-hop wireless network, a set of next-hop candidates are selected and prioritized according to their closeness to the destination. If a packet is successfully received by some of the selected nodes, only the highest priority node among them is chosen as the next-hop forwarder. Unlike in best-path routing, in opportunistic routing, a next-hop is determined opportunistically per-packet.

One distinctive feature of wireless networks that have a strong effect on opportunistic routing is link diversity. The strength of opportunistic routing comes from the diversity of the candidates forwarder's links. Such that when one candidate fails in receiving the forwarded packet, the other candidates are more likely to receive that packet. However, recent works [1][2] have shown that wireless channels are not as diverse they were thought to be. In fact, a phenomena known as link correlation was observed.

Until recently, modeling wireless links had always considered link errors to be independent between neighboring nodes. In such an assumption and given a specific error rate, if a node received a packet in error, it will not have any influence on weather or not its neighbor node receives the packet in error. However, recent works [1][2][3] have shown that correlated shadowing and interference might lead to correlated packet errors between neighboring receivers. Correlated Shadowing is a channel propagation phenomena by which nearby links are often affected by the same shadowers (obstructions) in the environment. As a result, link losses can be correlated. Intra-channel interference caused by external signals in the unlicensed shared spectrum can also lead to link correlations where the interferer's signal can corrupt neighboring links simultaneously. Link correlation has significant effects on diversity based algorithms in wireless networks such as opportunistic routing [4], network coding [5] and collaborative forwarding [6]. Without considering link correlation, modeling and simulating such algorithms often overestimates their performances [2]. However, little research has been done to exploit link correlation to improve the performance of network protocols [1][3][7].

The focus of this work is to improve the performance of opportunistic routing under link correlation by optimizing the forwarder set selection and avoiding duplicate forwarding. Under link correlation, the forwarder selection set algorithm prioritizes selecting uncorrelated nodes to increase the level of diversity while ensuring that neighboring nodes are close enough to each other such that the forwarded packet would be heard and duplicates are avoided.

Our contribution is of three fold:

- We analyze the efficacy of opportunistic routing by defining a new metric that captures the expected number of any-path transmissions under the effect of link correlation and duplication avoidance.
- We design a forwarder set selection algorithm that uses the proposed metric to consider link correlation and improve the performance of opportunistic routing.
- We evaluate our work by using simulation where we developed a unique model to generate correlated links, and use the selection algorithm to show the performance of opportunistic routing under link correlation.

II. DIVERSITY OF OPPORTUNISTIC ROUTING

In this section we introduce the opportunistic routing framework and explain how wireless diversity serves opportunistic routing. We then motivate the reader to the effect of link correlation on the diversity of opportunistic routing.

A. Opportunistic Forwarding Framework

Opportunistic packet forwarding process works as shown in Fig. 1a. Each node selects a subset of its neighbors as candidate next-hops for a destination and assigns a priority

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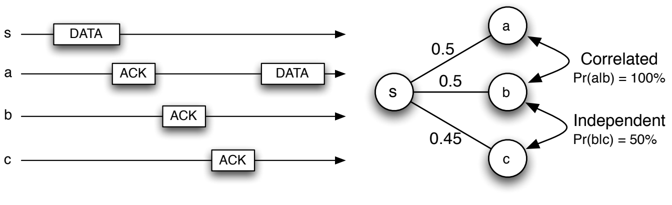


(a) Opportunistic Routing Oppertation (b) Correlated Links

Fig. 1. Opportunistic Routing Diversity

to each of the candidates. When a sender transmits a packet, it includes this ordered selection set in its headers. Each candidate that received the packet responds with an ACK, but in order to avoid feedback implosion, candidates defer their ACKs according to their priorities. Because candidates are likely to hear each others ACKs, candidates should include in their ACKs a list of higher priority candidates they received ACKs from. Only the highest priority candidate forwards the packet to the next hop. Other candidates refrain from forwarding the packet as long as they overheard a higher priority ACK. Duplicate forwarding by more than one candidate could happen if a lower priority candidate can not hear an ACK from a higher priority candidate. The forwarding process is repeated by sender as long as it does not receive an ACK from any of the candidates. ExOR [4], the primary opportunistic routing protocol, uses single path ETX to select candidates, such that only candidates with lower ETX than the sender are selected and incrementally prioritized. ETX is the average number of transmission required to send a packet in a link, and the ETX of a single path is the sum of the ETX for each link in that path. Using single path ETX as a metric for candidate selection does not capture the opportunistic paths from a candidate to the destination. To account for the multiple paths, Anypath ETX (EAX) was proposed to capture a more accurate expectation of the number of transmissions [8][9][10].

B. Diversity of Opportunistic Routing

When the diversity of the links is not accounted for, all the previously mentioned selection methods do not capture the full potential of opportunistic routing. The following sections will demonstrate the effect of diversity on opportunistic routing.

1) Diversity without Link Correlation: The strength of opportunistic routing comes from the diversity of the candidates forwarders' links. Such that when one candidate fails in receiving the forwarded packet, the other candidates are more likely to receive that packet. In the example in Fig.1b, if node a fails to receive the packet, candidate b will probability receive the packet. Similarly if b lost the packet as well, c will probably receive the packet. In other words, since links are diverse, it becomes less probable that all candidates will lose the packet. Let s be the source sending a packet to a destination d.

We will mathematically demonstrate the effect of diversity using the example in Fig. 1b. Suppose $F_{s,d}$ is the set of candidate next-hop forwarders from s to d, and f_i is the candidate with priority i (with 1 being the highest). Assume that the packet delivery probability from s to f_i is $p_{s,i}$ and ACK delivery probability from f_i to s is $p_{i,s}$. The figure shows an example of forwarding set selection where we have a maximum set size of 2. i.e. no more than 2 nodes are allowed to be forwarders. Let us start by selecting one node. The expected number of transmissions required for Candidate a or b to receive a packet from s is $1/p_{s,a} = 1/p_{s,b} = 1/0.5 = 2$. Similarly, the expected number of transmissions required for node c is $1/p_{s,c} = 1/0.45 = 2.222$. Obviously selecting node a or b would be our best choice. Now consider the case where a second node is added to the candidate set, the expected number of transmissions needed for receiving of a packet from a source s to at least one of the given the candidates a, or b, as follows:

$$ex(s, F_{s,d}) = \frac{1}{1 - \prod_i (1 - p_{s,i})} \tag{1}$$

in our example ex is equal to 1.33333. Similarly, the expected number of transmissions needed for receiving of a packet from a source s to at least one of the given the candidates a, or c, is 1.379. We get a similar result if we select b and c. As a result, assuming link independence, selecting nodes a and b as our forwarders will be our best choice in reducing the cost of transmissions. This independent model shows that with the addition of a second candidate the diversity of the links helps to reduce the expected number of transmissions.

2) Diversity with Link Correlation: If links are not independent, we can calculate the expected number of transmissions as:

$$\alpha_0 = \frac{1}{1 - Pr(\overline{E_{s,1}}, \overline{E_{s,2}}, ..., \overline{E_{s,n}})} \tag{2}$$

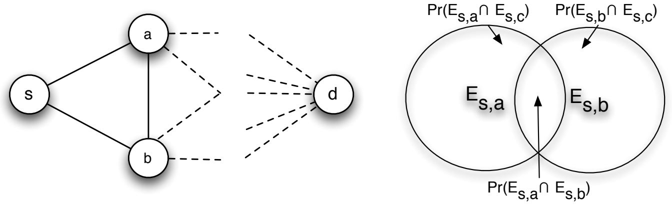
where $E_{s,i}$ is event that a packet is successfully received by forwarder f_i in one transmission. Going back to the example in Fig. 2b, if links from s to candidates a and b are 100% correlated, $Pr(\overline{E_{s,a}}, \overline{E_{s,b}})$ equals 0.5. Thus, E reduces to 2. As a result, with link correlation awareness, Selecting nodes b and c is the best choice. The assumption of link independence overestimated the true diversity of links.

III. CORRELATION AWARE OPPORTUNISTIC ROUTING

In this section we analyze the opportunistic routing model under the existence of link correlation. Then we explore the impact of link correlation on the set selection process, and explain how link correlation awareness can improve the performance of opportunistic routing.

A. Model Analysis

We define the expected number of any-path transmissions needed for reliable delivery of a packet from a source s to a destination d, given the candidate set F with link correlation awareness, as $cEAX(F, s, d)$. Our model for computing $cEAX$ values is recursive and can be executed at individual nodes independently. At the receiver d, obviously, $cEAX$ is zero. The main idea is to radiate calculated $cEAX$ of every node starting from d outward to the rest of the network.



(a) Topology (b) Joint Receiption

Fig. 2. Two-node case example

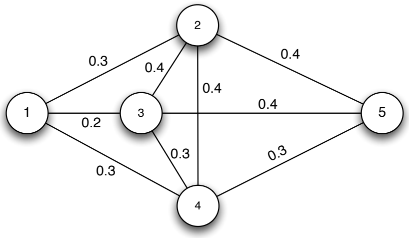


Fig. 3. Example

We calculate $cEAX$ values as follows:

$$cEAX(F, s, d) = \alpha + \beta \tag{3}$$

where α captures the expected number of transmissions for successfully transmitting a packet from s to at least one of the candidate next-hops and getting at least one acknowledgment back to s, and β captures the expected number of transmissions for delivering the packet in turn from those candidates to the destination.

Since our objective is to study the performance of opportunistic routing under link correlation, in the following analysis, we limit the size of the selection set size to two candidates as in Fig. 2, where the receptions of candidates a and b are partially correlated. Fig. 2b shows a Ven diagram representing the events where candidates successfully receive a transmissions from the sender, where $E_{s,i}$ is event that a packet is successfully received by forwarder f_i in one transmission. The intersection areas between events represent the correlated events between them such that the correlation between events $E_{s,a}$ and $E_{s,b}$ is represented by $E_{s,a} \cap E_{s,b}$. Now we calculate the expected number of transmissions for successfully receiving a packet from s, α_0 as the inverse of the probability of the total area:

$$\alpha_0 = \frac{1}{p_{s,a}+p_{s,b}-Pr(E_{s,a},E_{s,b})} \tag{4}$$

where the total area should include and exclude duplicate counting of joint areas. Finally, to calculate α we need to account for the lost ACKs from each candidate to s by multiplying each term with the probability of successfully receiving the ACK.

$$\alpha = \frac{1}{p_{s,a}^2+p_{s,b}^2-Pr(E_{s,a},E_{s,b})p_{s,a}p_{s,b}} \tag{5}$$

If any of the candidates a or b succeeds in receiving the packet, it will take over the forwarding process as long as it does not receive an ACK from a higher priority candidate. If this happens, we need to account for the cost of forwarding the packet from the candidate to the destination. Since candidate a has the highest priority, it will forward the packet as long as it receives it:

$$\beta_a = \alpha_0 \cdot \big(cEAX(F, a, d) \cdot (1 - \gamma_a)\big) \tag{6}$$

where α_0 is used because of the implicit condition that at least one of the candidates have received the packet, and γ_a is the probability that candidate a fails to receive the packet, and it is equal to $1 - p_{s,a}$. For the lower priority candidate b, the forwarding process will not happen when b fails to receive the packet, or when an ACK is received from a:

$$\gamma_b = 1 - p_{s,b} + p_{a,b}Pr(E_{s,b}, E_{s,a}) \tag{7}$$

Using (7) we can obtain β_b similar to (6). Finally β is the sum of β_a and β_b.

B. Selection Algorithm

The calculation of the $cEAX$ metric can be done for any given set of candidate forwarders, but which set should be selected? This section describes the algorithm that we use to select candidate forwarders. The simple idea is to select candidates that have good link qualities from the sender and prioritize them according to their $cEAX$ costs to the destination such that when a candidate with lower $cEAX$ costs to the destination opportunistically receives the packet, it has a better chance of delivering it. One important thing to account for during this selection process is the correlation between selected nodes. Fortunately, our calculation of the $cEAX$ metric accounts for this correlation.

We extend the algorithm in [8] to support link correlation. The extended algorithm is shown in Algorithm 1. Before running the algorithm on node s, all the $cEAX$ values of the possible candidates should have been obtained. We start by initializing the initial candidates set $\hat{F}$ by only adding nodes having smaller ETX values to the destination. By this step we are creating a Directed Acyclic Graph to the destination and eliminating candidates having higher ETX (Lines 1-6).

In (lines 7-16) we loop through initial candidates and obtain the candidate with the minimum $cEAX$ value, and add that node to our candidate set F and remove it from the initial set $\hat{F}$. We loop again through remaining nodes in the initial set and obtain the candidate with the minimum $cEAX$ value along with the nodes in the candidate set. It is important to note that candidates are ordered by $cEAX$ cost to the destination.

The differences in candidate selection based on correlation aware and correlation unaware selection is illustrated using Fig 3. In this example, node 5 is the destination and all other nodes use Algorithm 1 to select their candidate sets to the

Algorithm 1 Candidate Selection SELECT(s,d,setsize)

```
$F \Leftarrow \emptyset; \hat{F} \Leftarrow \emptyset; m_p \Leftarrow \infty; m_c \Leftarrow \infty$
for all $v \in N(s)$ do
    if $\mathrm{ETX}(v,d) < \mathrm{ETX}(s,d)$ then
        $\hat{F} \Leftarrow \hat{F} \cup v$
    end if
end for
while $|F| < setsize$ do
    $cand \Leftarrow \underset{c \in \hat{F}}{\mathrm{argmin}} cEAX\ (F \cup c, s, d)$
    $m_c \Leftarrow cEAX\ (F \cup cand, s, d)$
    if $m_c < m_p$ then
        $F \Leftarrow F \cup cand; \hat{F} \Leftarrow \hat{F} \backslash cand$
        $m_p \Leftarrow m_c$
    else
        $cEAXcost(s) \Leftarrow m_p$; break
    end if
end while
$\{F \Leftarrow F$ ordered by $cEAXcost\}$
```

TABLE I
A COMPARISON BETWEEN cEAX AND EAX METRICS

	2	3	4	2,3	3,2	2,4	4,2	3,4	4,3
cEAX	5.8	7.5	6.25	**4.53**	4.53	5.84	6.26	4.78	4.78
EAX	5.8	7.5	6.25	4.75	4.75	**4.64**	4.72	5.06	5.12

destination. Also each node should select at most 2 nodes as candidate forwarders. For simplicity of presentation we also assume that the feedback packets are always received. Now lets focus on node 1. Node 1 looks up the ETX values for its direct neighbors towards the destination and finds that it has the largest value. It initializes its initial sets with nodes 2,3 and 4. Before we can calculate the $cEAX$ values for node 1, the $cEAX$ values for 2,3 and 4 must be calculated. By looping through the initial candidates, node 1 finds that node 2 has the lowest $cEAX$ value so node 2 is added to the candidate set. Node 1 loops through the remaining nodes (3 and 4) and tests the $cEAX$ with the current candidate set (node 2). Node 1 checks that adding node 3 results in the smallest $cEAX$ value, and adds it to the candidate set. Because the maximum set size is 2, node 1 terminates the algorithm.

Table I shows the estimated number of transmissions with and without considering correlations for all possible combinations of node 1's forwarders. When selecting nodes 2 and 3 as candidates, node 1 would require 4.53 transmissions to send a packet to node 5. Now if the correlation unaware selection had been used, nodes 2 and 4 would have been selected as candidates. This is because when calculating candidate sets merely based on link qualities, the estimated number of transmissions is 4.64, which is incorrect since nodes 2 and 4 are correlated thus the number of transmissions is 5.84.

IV. SIMULATION

In this section we describe the correlation generation model and simulate the correlation aware selection.

A. Model for Generating Correlated Links

Given any network topology, we generate correlated links as correlated multi-variate bernoulli random numbers. We use the sampling algorithm for correlated Bernoulli random variables, described in [11]. Link correlations can either be positive or negative depending on the possible causes that affect inter-link reception. To accommodate for such correlations, in our simulations we create a correlation matrix with Σ_{ij} randomly selected from $[-1, 1]$. We generate a string of 10,000 sequences for each sender to capture the correlated events.

B. Simulation Setup

We randomly generate network graphs to evaluate our design. In the simulation, we set the number of nodes to be 50. The density of the topology is selected such that we have enough forwarding candidates and hops to the destination. The nodes are uniformly distributed in the plane and edges are added according to probabilities that depend on the distances between the nodes. Each node sends 10,000 packets to the destination, and we record the number of transmissions required to receive that packet. In the following simulations, we assume that the ACK packet size is always received, given that ACK packets are much smaller than Data packets. In our experiment, the generated link qualities randomly vary from 0.0 to 0.5, and the selection algorithm selects at most 2 candidates.

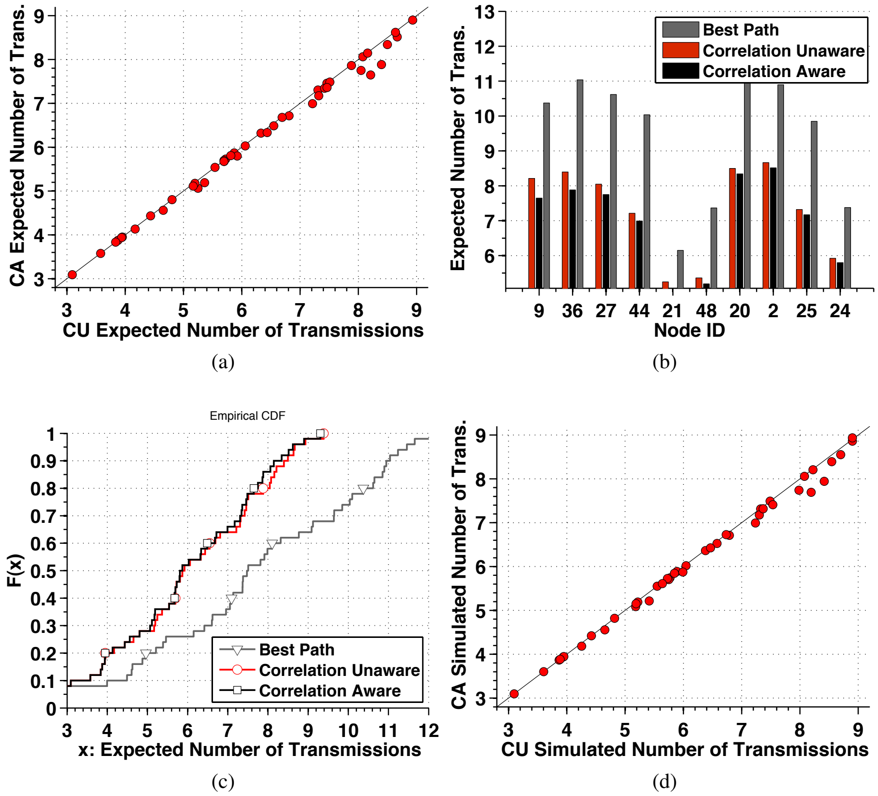
C. Simulation Results

Fig. 4 represents the results from the first experiment. We can see a scatter plot for the expected number of transmissions for Correlation Aware (CA) and Correlation Unaware (CU) in Fig.4a. Most of the points fall below the diagonal line meaning that there is an improvement for most of the nodes when using CA. An empirical CDF shown in Fig. 4c shows that 80% of the nodes show less than 7.6 (8.0) expected number of transmissions with CA (CU). The space between the lines indicate the expected improvement. Fig. 4b shows a sample of 10 nodes sorted by their improvement in number of transmissions. Note that the performance is always similar or better. So using CA never reduces the performance.

To confirm the applicability of the expected results, we ran a simulation using OMNeT++ and the Castalia Framework. We use the correlated traces generated in the previous section to sample transmission success or failure events. Results on Fig. 4d are accurate enough to represent our findings.

V. RELATED WORKS

The objective of candidate selection for opportunistic routing protocols can be for purposes of energy efficiency [12] or implementation simplicity [4], or transmission cost [8][9][10]. In this work we are interested in optimizing the channel diversity which is the reason behind the opportunistic routing gain. Until recently, modeling wireless links had always considered link errors to be independent. Recent works such as [1][2] have proven the existence of link correlation. In [2], the authors derived the κ factor that is used to measure correlation between links, they showed how the κ could affect diversity based protocols. The authors of [3] used models to generate link correlations based on distance where negative correlations are not accounted for. They followed an approach similar that



(a)

(b)

(c)

(d)

Fig. 4. Simulation results for a random network topology with link qualities between 0.0-0.5

developed for the mobile communication literature [13] which is solely based on correlated shadowing. While both of [2][3] briefly mention link correlation on the opportunistic routing setting, we complement their work by providing a detailed analysis of correlation aware opportunistic routing under the link correlation effect, and demonstrating the performance improvement using simulation.

VI. CONCLUSION

In this paper we extensively studied the effects of link correlation on the performance of opportunistic routing. We provided a detailed analysis of the opportunistic routing framework under the influence of link correlation. We then developed a metric and a selection algorithm to help diversifying opportunistic links, thus improving the performance. We evaluated our work with simulation. The results indicate the effectiveness of our design in capturing the full advantage of opportunistic routing. Our future work include studying the performance limits as well as extending our analysis to multiple forwarders. We also plan to perform an extensive experimental evaluation using our WSN testbed.

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