Link-Correlation-Aware Opportunistic Routing in Wireless Networks

Shuai Wang, Anas Basalamah, Song Min Kim, Shuo Guo, Yoshito Tobe, *Member, IEEE*, and Tian He

***Abstract*—Recent empirical studies have shown clear evidence that wireless links are not independent and that the packet receptions on adjacent wireless links are correlated. This finding contradicts the widely held link-independence assumption in the calculation of the core metric, i.e., the expected number of transmissions to the candidate forwarder set, in opportunistic routing (OR). The inappropriate assumption may cause serious estimation errors in the forwarder set selection, which further leads to underutilized diversity benefits or extra scheduling costs. We thus advocate that OR should be made aware of link correlation. In this paper, we propose a novel link-correlation-aware OR scheme, which significantly improves the performance by exploiting the diverse low correlated forwarding links. We evaluate the design in a real-world setting with 24 MICAz nodes. Testbed evaluation and extensive simulation show that higher link correlation leads to fewer diversity benefits and that, with our link-correlation-aware design, the number of transmissions is reduced by 38%.**

***Index Terms*—Opportunistic routing, link correlation, wireless networks, protocol design.**

I. Introduction

OPPORTUNISTIC ROUTING (OR), originally proposed by S. Biswas *et al.* in [1], has great potential to improve the network performance. The basic idea of OR is fairly straightforward. Given a source and a destination in a multi-hop wireless network, instead of preselecting a single specific node to be the next-hop forwarder, a set of candidate forwarders are selected to deliver the packets. Taking advantage of the reception diversity in the candidate forwarder set, OR defers the selection of the next hop for a packet until it acquires knowledge about the set of candidate forwarders that have received that packet.

Since the strength of OR comes from the packet reception diversity of the candidate forwarder set, the candidate selection becomes one of the key issues in OR. The selection of different candidates has a high effect on the performance of OR. Extensive candidate selection algorithms based on the key metric, the expected number of transmissions, have been proposed in the literature [1]–[7]. In these studies, the researchers explicitly or implicitly assume that the wireless links are independent when they estimate the transmission cost from a upstream node to the next-hop candidate forwarder set.

Recent studies [8]–[10], however, provide clear evidence that wireless links are not independent because of cross-technology interference and correlated shadowing. Cross-technology interference, which is caused by the external signal in the unlicensed shared spectrum, can lead to correlated packet losses since the high-power interferer's signal may corrupt nearby low-power links simultaneously. On the other hand, correlated shadowing, a channel propagation phenomenon that nearby links are affected by the same shadower, may also introduce correlated packet losses to wireless networks.

The finding of the link correlation phenomenon has significant impacts on network protocols that utilize concurrent wireless links, which include but are not limited to (i) traditional network protocols such as broadcast [11], multi-cast [12], and multi-path routing [13], or (ii) diversity-based protocols such as opportunistic routing [1]–[3], network coding [14], and hybrid routing [15]. Ignoring this phenomenon may cause serious estimation errors in modeling, which further leads to underutilized benefits or extra costs.

For example, when the packet loss patterns of the candidate forwarders are highly positive correlated (which means that they lose the same packets), the performance of OR is the same as the traditional shortest path protocol (which uses the node with the best link among the candidates), since there are no diversity benefits to exploit from the candidate forwarder set. In this example, ignoring link correlation brings OR no benefits but extra candidate set schedule costs.

Little research has been conducted to exploit link correlation to improve the performance of network protocols [8], [10]. In this paper, we introduce link correlation to improve OR's performance by optimizing the forwarder set selection and avoiding duplicate forwarding. Under link correlation, the forwarder set selection algorithm prioritizes low correlated nodes to increase the level of diversity while ensuring that neighboring

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nodes are close enough to each other such that the forwarded packets would be heard and duplicates are avoided.

In summary, our contributions are as follows:

- We reveal the impact of link correlation upon OR. A novel link correlation aware metric is proposed to capture the expected number of any-path transmissions.
- With the link correlation aware metric, we propose a new candidate forwarder selection algorithm to help OR fully exploit the diversity benefit of the wireless broadcast medium.
- We evaluate our work extensively with testbed implementations and simulations. The experiment results identify the limitation of the traditional OR under the appearance of link correlation. With our link correlation aware design, the number of transmissions of OR is significantly reduced.

The remainder of the paper is structured as follows. Section II reviews the related work. Section III presents the motivation. Section IV introduces the metric, followed by its implementation in Section V. Experiment results from the testbed and simulation are shown in Sections VI and VII. Finally, Section VIII concludes the paper.

II. Related Work

We begin with a brief survey of prior work on opportunistic routing and link correlation.

Opportunistic Routing: The majority of previous studies in OR are devoted to candidate selection [1], [4]–[7], reception acknowledgement [16], forwarder coordination [17], [18], and rate control [19]. In this work we focus on the fundamental issue—the candidate selection in OR. ExOR [1], the primary OR protocol, uses the single path ETX to select candidates, where ETX is the average number of transmissions required to send a packet through a link. The ETX value of a single path is the sum of the ETX for each link in that path. Using the single path ETX as a metric for candidate selection is an approximation since it cannot capture the opportunistic paths. To account for the multiple paths that could be used by the candidates, expected any-path transmission (EAX) [20] is used in [4]–[7] to capture a more accurate expected number of transmissions.

For example, H. Dubois *et al.* propose least-cost opportunistic routing (LCOR) [6] which takes EAX as the metric to select the candidate sets. Similar to the well-known Bellman-Ford algorithm, LCOR exhaustively searches all possible candidates sets to find the paths with minimum transmissions. Its computational cost increases dramatically in dense networks because of the exponentially explosion in the exhaustive search. In minimum transmission selection (MTS) [5], the authors compute the transmission cost with EAX from the destination back to the source, using a dynamic programming formulation analogous to the Dijkstra's algorithm. The authors in [7] investigate the candidate selection with identical maximum candidate set sizes. The result shows that if the maximum number of candidates is not limited, different OR algorithms have almost the same performance. They prove that this assumption is not realistic since a large number of candidates may introduce large schedule overheads and duplicate transmissions.

Our work is different from the previous OR schemes which implicitly or explicitly assume that packet receptions cross multiple receivers are independent when they exploit the diversity benefit of the wireless broadcast medium. We propose a link correlation aware OR scheme to fully exploit the potential diversity benefit.

Link Correlation: Until recently, wireless links were always considered to be independent. Recent studies [8], [9], however, have proven the existence of link correlation. In [9], the authors derive the κ factor that is used to measure the correlation among links. They show how the κ factor could affect diversity based protocols such as OR. The authors of [10] use models to generate link correlations based on distance where negative correlations are not accounted for. They follow a similar approach that developed in the mobile communication literature [21], [22], which is solely based on correlated shadowing. The authors propose a link probing protocol to help collect link correlations, but the protocol does not show how links are selected.

While both [9], [10] briefly mention link correlation in the OR setting, we complement their work by providing (i) detailed analyses of the impact of link correlation on OR, (ii) a correlation aware candidate selection algorithm, (iii) a detailed illustration on how and when link correlation actually helps, (iv) models to generate and simulate link correlation and (v) real implementations to demonstrate the effectiveness of a link correlation aware design.

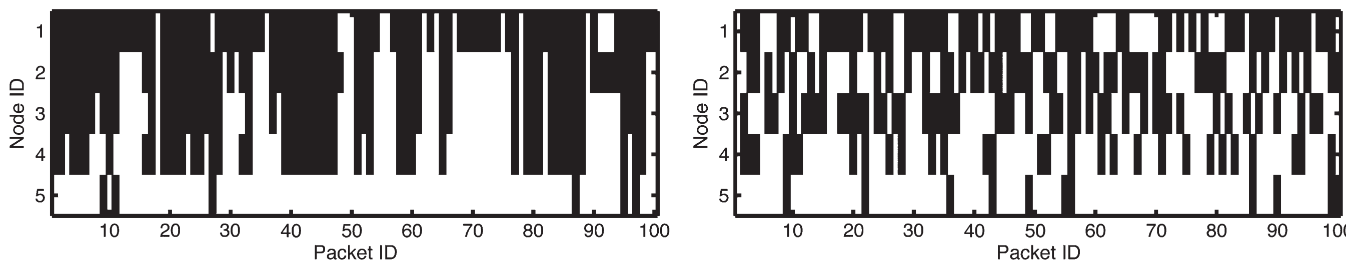
III. Motivation

In this section we first report the existence of link correlation. We then introduce the OR framework and explain how wireless diversity serves OR. Finally, we illustrate the impact of link correlation on the diversity benefit of OR.

A. Existence of Link Correlation

In wireless networks, when a sender transmits a packet, the packet reaches to multiple receivers because of the broadcast medium. Link correlation is a phenomenon that the packet receptions across multiple receivers have certain correlation and are not independent. To verify the existence of link correlation, we conduct an experiment with six MICAz nodes. In the experiment, the sender is placed in the center while the other five nodes are randomly deployed as receivers. The sender broadcasts 1000 packets. Each packet is identified by the sequence number. All the receivers record the reception results through the packet sequence number.

Fig. 1(a) plots the packet reception patterns observed from the testbed. The black bands indicate packet losses while the white bands indicate successful packet receptions. From Fig. 1(a), we find that packet receptions are correlated. Specifically, there are a large number of long black bands which indicate that an individual packet is lost at multiple nodes. When packet receptions are assumed to be independent, we synthetically generate the packet reception pattern which is



(a) Real trace with correlated links

(b) Synthesized traces with independent links

Fig. 1. A comparison between the link correlation and the link independent packet reception pattern where the black band indicates a packet loss: (a) the real trace from a 802.15.4 testbed, and (b) the synthesized independent trace. Compare these two traces, we find that they are quite different. There are many long black bands in the real trace, which indicates that a packet is lost at multiple receivers and packet receptions are correlated.

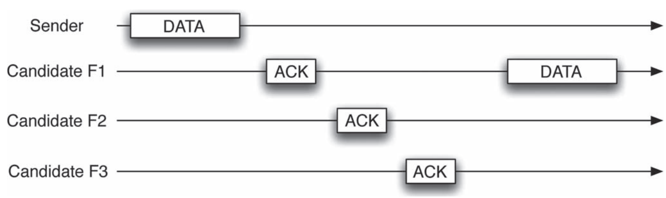


Fig. 2. An example showing the OR operation: candidates defer the ACK according to their priorities and the candidate with the highest priority will send the data first.

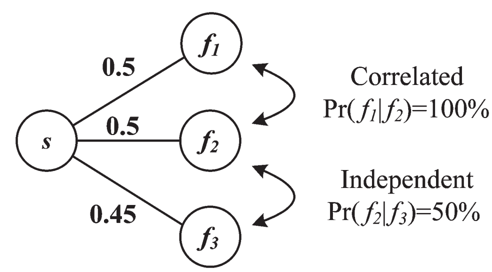


Fig. 3. An OR example with two candidates. When the link independent model is applied, the candidate set $\{f_1, f_2\}$ will be selected since it only counts link quality. Since the candidates f_1 and f_2 are perfect positive correlated, the function of the set $\{f_1, f_2\}$ will be the same as f_1 or f_2. The link correlation aware design will choose $\{f_2, f_3\}$ as the candidate set, which fully exploits the diversity benefit.

shown in Fig. 1(b). The comparison indicates that there exist a big gap between the link independence model and the real link reception patterns. The experiment results reaffirm the observation reported in recent studies [8], [10], [23].

B. Opportunistic Forwarding Framework

The opportunistic packet forwarding process is shown in Fig. 2. The sender selects a subset of nodes as candidate next-hops and assigns a priority to each of them. When the sender transmits a packet, it includes the ordered candidate forwarder set in its headers. Each candidate that receives the packet responds with an ACK. To avoid the feedback implosion, candidates defer their ACKs according to their priorities in a TDMA-like approach. Since the candidates are likely to hear each other's ACK, they should include in their ACKs a list of higher priority candidates. In OR, only the candidate with the highest priority forwards the packet to the next hop. Other candidates refrain from forwarding the packet as long as they overhear a higher priority ACK. Duplicate forwarding by more than one candidate could happen if a lower priority candidate cannot hear an ACK from a higher priority candidate. The whole forwarding process is initiated again by the sender as long as it does not receive an ACK from any candidates.

C. Diversity Benefits in OR

Without considering link correlation, the previously OR schemes do not fully capture the diversity benefit of the wireless broadcast medium. The following section will demonstrate the impact of diversity on OR.

Diversity With Link Independence Model: The strength of OR comes from the diversity of the candidates' packet receptions. In OR, when one candidate fails in receiving a packet, the other candidates may receive the packet. In the example in Fig. 3, if node f_1 fails to receive a packet, candidate f_2 may receive the packet. Similarly if f_2 loses the packet as well, f_3 may probably receive it. In other words, the probability that all candidates lose the packet becomes quite low because of the packet reception diversity among multiple candidates.

The optimistic view of diversity comes from the assumption that the packet receptions cross multiple wireless links are independent. Under such an assumption, the packet loss in a receiver has no relationship with the packet losses in other receivers.

Let s be the source and d be the destination. 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 priority). Assume that the packet delivery probability from s to f_i is p_{s,f_i}, and the ACK delivery probability from f_i to s is $p_{f_i,s}$.

We now mathematically demonstrate the impact of diversity upon OR with the example in Fig. 3. In the example, the size of the candidate set is set to be two, i.e., no more than two nodes are allowed to be candidate forwarders. Let us start by selecting the first forwarder. The expected number of transmissions required for candidate f_1 or f_2 to successfully receive a packet from s is $1/p_{s,f_1} = 1/p_{s,f_2} = 1/0.5 = 2$. Similarly, the expected number of transmissions required by node f_3 is $1/p_{s,f_3} = 1/0.45 = 2.22$. Obviously selecting node f_1 or f_2 would be the optimal choice. Now consider the case that a second node is added to the candidate set. The expected number of transmissions for receiving one packet from s to at least one of the two candidates is given by

$$E(s, F_{s,d}) = \frac{1}{1 - \prod_i^2 (1 - p_{s,f_i})}. \quad (1)$$

In the example, $E(s, F_{s,d})$ with candidate set $\{f_1, f_2\}$ equals 1.33. Similarly, $E(s, F_{s,d})$ with candidate set $\{f_1, f_3\}$ or $\{f_2, f_3\}$ is 1.38. As a result, under link independence model, selecting nodes f_1 and f_2 as our forwarders will be the best choice in reducing the transmission cost.

Diversity With Link Correlation Model: If links are not independent, the expected number of transmissions for delivering one packet to at least one of the two candidates is given by

$$E(s, F_{s,d}) = \frac{1}{1 - Pr\left(\overline{E_{s,f_1}}, \overline{E_{s,f_2}}\right)}, \quad (2)$$

where $\overline{E_{s,f_i}}$ is the event that a transmission from source s is lost at forwarder f_i. In the example in Fig. 3, the links from s to f_1 and f_2 are 100% correlated. $Pr(\overline{E_{s,f_1}}, \overline{E_{s,f_2}})$ equals 0.5. Thus, $E(s, F_{s,d})$ with candidate set $\{f_1, f_2\}$ turns out to be 2, which is greater than $E(s, F_{s,d})$ with candidate set $\{f_2, f_3\}$ (i.e., 1.38). As a result, selecting nodes f_2 and f_3 as candidates is the best choice under link correlation model. From this example, we find that the link independence assumption overestimates the real diversity of wireless links. In the following section, we further analyze the OR framework under the impact of link correlation.

IV. Link Correlation Metric

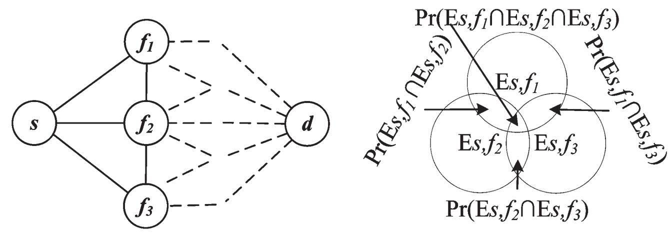
In this section we analyze OR under the existence of link correlation. We explore the impact of link correlation on the candidate set selection process and reveal how link correlation awareness improves the performance of OR. Finally we propose a novel link correlation aware opportunistic routing.

We define the expected number of any-path transmissions needed for reliably delivering a packet from the source s to the destination d, given the candidate set $F = \{f_1, f_2, \ldots, f_n\}$ with the link correlation awareness, as $E(s, F, d)$. In our design, the computation of $E(s, F, d)$ is recursive and is executed at individual nodes independently. At the receiver d, obviously, $E(s, F, d)$ is zero. The key idea is to radially calculate $E(s, F, d)$ starting from the destination d outward to the rest of the network. Specifically, we calculate $E(s, F, d)$ as follows:

$$E(s, F, d) = \alpha + \beta, \quad (3)$$

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

Three-Candidate Case: We start by considering the 3-candidate case in Fig. 4, where the receptions of candidate f_1, f_2 and f_3 are partially correlated. Fig. 4(b) shows the Venn diagram representing the events that candidates successfully receive a transmission from the sender. E_{s,f_i} is the event that a packet is successfully received by forwarder f_i with one transmission. The intersection areas represent the correlated events. For example, $E_{s,f_1} \cap E_{s,f_2}$ represents the correlation between event E_{s,f_1} and E_{s,f_2}. Let α_0 be the expected number of transmissions for s to successfully deliver a packet to the candidate set. α_0 is the inverse of the total area in Venn diagram, which is given by



(a) Topology (b) Joint Reception

Fig. 4. Three-candidate case example: (a) the topology; (b) the Venn diagram of the candidate's packet reception.

$$\begin{aligned} \alpha_0^{-1} = & p_{s,f_1} + p_{s,f_2} + p_{s,f_3} - Pr\left(E_{s,f_1}, E_{s,f_2}\right) \\ & - Pr\left(E_{s,f_1}, E_{s,f_3}\right) - Pr\left(E_{s,f_2}, E_{s,f_3}\right) \\ & + Pr\left(E_{s,f_1}, E_{s,f_2}, E_{s,f_3}\right). \end{aligned} \quad (4)$$

To calculate α, we need to count in the lost ACKs from each candidate to s by multiplying each term in Eq. (4) with the probability of successfully receiving the ACK. We thus have

$$\begin{aligned} \alpha^{-1} = & p_{s,f_1} p_{f_1,s} + p_{s,f_2} p_{f_2,s} + p_{s,f_3} p_{f_3,s} \\ & - Pr\left(E_{s,f_1}, E_{s,f_2}\right) p_{s,f_1} p_{s,f_2} \\ & - Pr\left(E_{s,f_1}, E_{s,f_3}\right) p_{s,f_1} p_{s,f_3} \\ & - Pr\left(E_{s,f_2}, E_{s,f_3}\right) p_{s,f_2} p_{s,f_3} \\ & + Pr\left(E_{s,f_1}, E_{s,f_2}, E_{s,f_3}\right) p_{s,f_1} p_{s,f_2} p_{s,f_3}. \end{aligned} \quad (5)$$

When the candidate f_1, f_2 or f_3 succeeds in receiving a packet, it will take over the forwarding process as long as it does not receive an ACK from a higher priority candidate. For candidate f_1, it forwards a packet as long as it receives it since f_1 has the highest priority. We thus have

$$\beta_{f_1} = \alpha_0 \cdot \left(E(f_1, F, d) \cdot (1 - \gamma_{f_1})\right), \quad (6)$$

where α_0 is multiplied because of the implicit condition that at least one of the candidates has received the packet, and γ_{f_1} is the probability that candidate f_1 will not take the forwarding process, which equals $1 - p_{s,f_1}$. For the lowest priority candidate f_3, the forwarding process will not happen when f_3 fails to receive a packet, or when an ACK is received from f_1 or f_2. The probability that candidate f_3 will not take the forwarding process γ_{f_3} can be calculated as follows:

$$\begin{aligned} \gamma_{f_3} = 1 - p_{s,f_3} + p_{f_1,f_3} Pr\left(E_{s,f_3}, E_{s,f_1}\right) \\ + p_{f_2,f_3} Pr\left(E_{s,f_2}, E_{s,f_3}\right). \end{aligned} \quad (7)$$

For candidate f_2, an ACK could be received explicitly from candidate f_1 or implicitly from candidate f_3 when f_3 receives the packet from s and the ACK from f_1. γ_{f_2} is thus given by

$$\gamma_{f_2} = 1 - p_{s,f_2} + p_{f_1,f_2} Pr\left(E_{s,f_1}, E_{s,f_2}\right) + (1 - p_{f_1,f_2}) \cdot p_{f_1,f_3} p_{f_3,f_2} Pr\left(E_{s,f_1}, E_{s,f_2}, E_{s,f_3}\right). \quad (8)$$

Similar to (6), we now obtain β_{f_2} and β_{f_3} where γ_{f_2} and γ_{f_3} can be calculated with Eqs. (7) and (8). Finally, β is the sum of β_{f_1}, β_{f_2} and β_{f_3}.

n-Candidate Case: We now extend the problem to n candidates. It turns out to be an inclusion-exclusion where we should sum the probabilities of individual links but remove the overlapped intersection:

$$\alpha = \frac{1}{\sum_{k=1}^{n} (-1)^{k-1} Pr(f^k)}, \quad (9)$$

where $f^k \subset F = \{f_1, \ldots, f_n\}$ is any candidate forwarder set with size k, and $Pr(f^k)$ is the probability that the k candidate forwarders successfully receive a packet and send back the ACK. $Pr(f^k)$ is calculated as follows:

$$Pr(f^k) = \sum_{f^k \subset F} Pr\left(E_{s,f_1^k}, \ldots, E_{s,f_k^k}\right) \prod_{i}^{k} p_{f_i^k,s}. \quad (10)$$

Special Case: Equation (9) includes the special link independence case. When wireless links are independent, we have

$$Pr\left(E_{s,f_1^k}, \ldots, E_{s,f_k^k}\right) = \prod_{i}^{k} p_{s,f_i^k}.$$

And $Pr(f^k)$ in Eq. (10) turns out to be

$$Pr(f^k) = \sum_{f^k \subset F} \prod_{i}^{k} p_{s,f_i^k} p_{f_i^k,s}.$$

For the candidates which have received the packet from the transmitter, the expected number of transmissions to forward the packet to the next hop is calculated as follows:

$$\beta = \alpha_0 \cdot \sum_{i=1}^{n} \left(E(f_i, F, d) \cdot (1 - \gamma_{f_i})\right). \quad (11)$$

where γ_{f_i} is the probability that candidate f_i does not forward the packet. To calculate γ_{f_i}, we need to consider three cases: (i) candidate f_i loses the packet, (ii) candidate f_i receives an direct ACK from a higher priority candidate, and (iii) the candidate receives an indirect ACK through a low priority candidate. Compared with the first two cases, the third case can be ignored since it rarely happens. γ_{f_i} thus can be calculated using the following equation:

$$\gamma = (1 - p_{s,f_i}) + \sum_{k=1}^{j<i} (-1)^{k-1} Pr(f^k). \quad (12)$$

Equation (12) consists two parts, i.e., $(1 - p_{s,f_i})$ and $\sum_{k=1}^{j<i} (-1)^{k-1} Pr(f^k)$. The first part represents the first case. $\sum_{k=1}^{j<i} (-1)^{k-1} Pr(f^k)$ describes the second case, which represents the union of the probability of each higher priority candidate in receiving the packet and sending back the ACK.

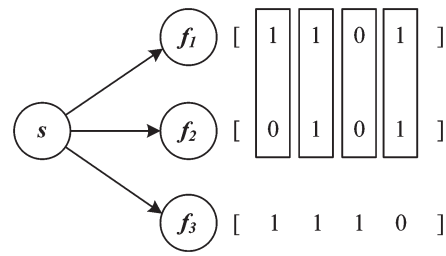


Fig. 5. An example of calculating s's $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$ for $\{f_1, f_2\}$.

V. Implementation

In this section, we introduce the implementation detail of the link correlation aware metric $E(s, F, d)$. The calculation of $E(s, F, d)$ finally goes to find the link quality (i.e., p_{s,f_i} and $p_{f_i,s}$) and the link correlation (i.e., $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$). Suppose each receiver maintains a packet reception report (e.g., [1101]) recording the reception status of a fixed number (e.g., 4) of most recent packets. With the reception report, the link quality is given simply by the number of 1s in the reception report divided by the length of reception report. The calculation of $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$ deserves a little more explanation. Here we use an example to show how to calculate $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$. Assume a reception report of length L, we have

$$Pr\left(E_{s,f_1^k}, \ldots, E_{s,f_k^k}\right) = \frac{1}{L} \sum_{j=1}^{L} B_{f_1}(j) \,\&\cdots\&\, B_{f_k}(j), \quad (13)$$

where $B_{f_i}(j)$ is a bit representing the candidate f_i's reception status of the jth packet. $B_{f_i}(j) = 1$ represents candidate f_i receives the packet, otherwise $B_{f_i}(j) = 0$. For example, in Fig. 5, the sender s has three candidates. We calculate s's $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$ when k equals two, i.e., $Pr(E_{s,f_1^2}, \ldots, E_{s,f_2^2})$. Suppose the reception report of candidate f_1 is [1101], which indicates that f_1 receives the 1st, 2nd, and 4th packets and misses the 3rd packet. When the sender s receives the reception reports from the candidates, it uses Eq. (13) to calculate $Pr(E_{s,f_1^2}, \ldots, E_{s,f_2^2})$, i.e.,

$$Pr\left(E_{s,f_1^2}, E_{s,f_2^2}\right) = \frac{1}{4}(1\&0 + 1\&1 + 0\&0 + 1\&1) = 50\%.$$

A. Metric Overhead

Computational Cost: In OR, having a large set of candidates may reduce the number of transmissions from the source to the destination. On the other hand, it may bring serious problems of increasing the schedule overhead among candidates as well as the chance of duplicated transmissions, which may reduce the efficiency of OR. Moreover, the computational cost of searching the optimal candidate set increases

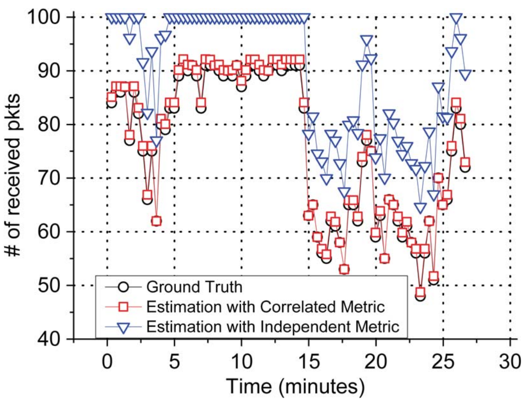


Fig. 6. Received pkts versus Estimation with our link correlation metric α_0 and the link independent metric ETX: the estimation with the link correlation metric closely follows the real one while the link independent metric overestimates the number of received packets.

dramatically due to the exponentially increased combination [6], [7]. In practice, the number of candidates that can be used is set to a small number, e.g., 4. Therefore, the computation cost of our metric is low due to the small size of the candidate set.

Communication Cost: Our metric needs to calculate link quality and link correlation which may change over time. We now discuss the overhead for maintaining the metric accurate. We conduct an experiment in a dynamic scenario. In the experiment, the sender transmits packets every 0.2 seconds while the packet reception report is sent in every 20s. The total number of packets sent is 8000. The candidates keep track of the received packets through the packet sequence numbers.

The main communication overhead of our metric comes from the reception reports which are used to calculate link quality and $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$. The required information for link quality and $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$ is exactly the same, i.e., the reception report. It not only helps to calculate link quality, which only uses the bit information in rows in Fig. 5, but also provides information of links' relationship, i.e., the bit information in columns in Fig. 5.

To collect reception reports, we adopt the free piggyback mechanism with normal traffic data, which has been already applied by the existing protocols [24] to measure link quality or to improve the robustness of the routing structure. The binary reception report is small and is much less frequently transmitted, therefore the overhead occupies a tiny fraction (0.9%) of the total energy cost according to our measurements.

B. Metric Accuracy

We run our experiments in a period of 30 minutes, during which reception reports (0.9% overhead) are used to fresh link quality and $Pr(E_{s,f_1^k}, \ldots, E_{s,f_k^k})$ values. Fig. 6 compares the real values with the estimates using our link correlation metric α_0 and the link independent metric ETX. From Fig. 6, we find that α_0 is accurate over time and the number of received packets by the forwarder set (during 20s) closely follows the number of sent packets (i.e., 100) divided by α_0.

From Fig. 6, we also find that the link independence metric always overestimates the number of received packets. This is because in the testbed environment, the links are positive correlated because of cross-technology interference and correlated shadowing [8]–[10]. Under such an environment, the forwarders in the candidate set lose similar packets. With the link independence assumption, when one forwarder fails to receive a packet, others may have a better chance of receiving it. This optimistic view thus leads to an overestimate of diversity benefit and transmission efficiency.

Algorithm 1 CANDIDATES SELECT(s, d, set size)

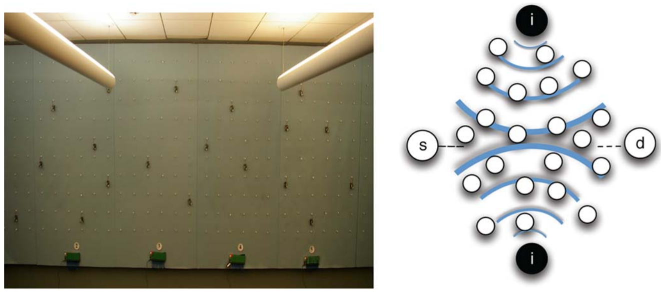
1: $F \Leftarrow \emptyset; \hat{F} \Leftarrow \emptyset; m_p \Leftarrow \infty; m_c \Leftarrow \infty$
2: **for all** $v \in N(s)$ **do**
3:   **if** ETX$(v,d) <$ ETX(s,d) **then**
4:     $\hat{F} \Leftarrow \hat{F} \cup v$
5:   **end if**
6: **end for**
7: **while** $|F| < setsize$ **do**
8:   $cand \Leftarrow \arg\min_{c \in \hat{F}} E(s, F \cup c, d)$
9:   $m_c \Leftarrow E(s, F \cup cand, d)$
10:   **if** $m_c < m_p$ **then**
11:     $F \Leftarrow F \cup cand; \hat{F} \Leftarrow \hat{F} \setminus cand$
12:     $m_p \Leftarrow m_c$
13:   **else**
14:     $E(s, F, d) \Leftarrow m_p$; break
15:   **end if**
16: **end while**

C. Metric Embedding

This section describes how we integrate the link correlation aware metric $E(s, F, d)$ into OR to select the candidate forwarder set. The key idea is to select candidates with good link quality and prioritize them according to the $E(s, F, d)$ value. The design is specified by the pseudo code in Algorithm 1. We initialize the candidate set $\hat{F}$ by adding nodes with smaller ETX values. At this step, we create a directed acyclic graph from the source s to the destination d and eliminate candidates which have higher ETX values (Lines 1–6). In lines 7–16, we loop through the initial candidate set and find the candidate with the minimum $E(s, F, d)$ value. We add the node to our candidate set F and remove it from the initial set $\hat{F}$. We loop the above procedures until we find enough candidates to meet the predesigned set size.

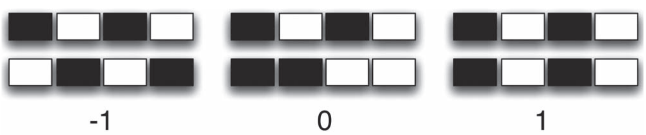
VI. Testbed Experimentation

In the real world environment, interference exits everywhere because of the massive number of uncontrollably deployed wireless devices sharing the same unlicensed spectrum. In the testbed experiment, we adopt interferers to introduce negatively correlated, positively correlated and uncorrelated links. We investigate the effect of various correlation degrees on the performance of our design.



(a) (b)

Fig. 7. The testbed with 24 MICAz nodes. (a) Physical deployment. (b) Logical topology.



(a) (b) (c)

Fig. 8. The interference pattern which is used to generate link correlation. (a) Negative correlated. (b) Uncorrelated. (c) Positive correlated.

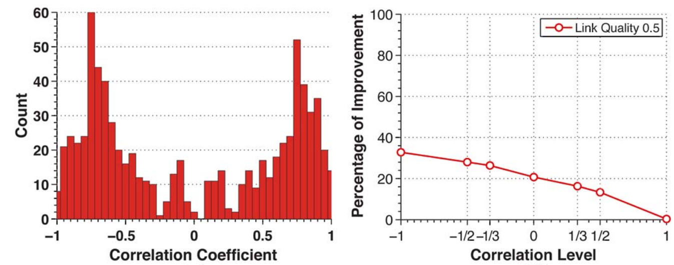
A. Generating Correlated Links

We deploy 24 MICAz nodes in our indoor 24 feet by 8 feet testbed, as shown in Fig. 7(a). It forms a simple two-hop network as shown in Fig. 7(b), where we have one source s, one destination d, two interferers, and a set of 20 candidate forwarders. The two interferers are placed randomly within a pool of forwarders. They are used to create interference of various patterns. Fig. 8 shows selected examples of interference patterns which may further lead to different degrees of link correlation.

We use the maximum transmission power, i.e., 0 dBm, to make sure that the links from the forwarders to the destination d are perfect. For the links from the source s to the candidate forwarders, the transmission power is controlled carefully to introduce the packet loss in the presence of the interference signal. The source s sends packets with 2-byte data payload in every 0.2 s. In the default setting, the source node keeps on sending packets until the destination returns an ACK. We use 802.15.4 channel 26 to avoid the effect of Wi-Fi interference.

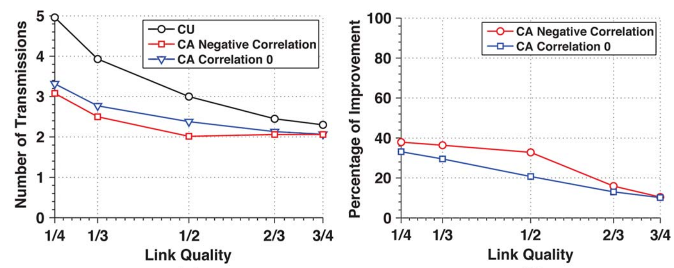
B. Performance Evaluation

In this section, we compare the performance of OR with and without considering link correlation. We use "CA" to represent the link correlation aware OR. "CU" means the traditional correlation unaware OR. The size of forwarder set is two. In the experiment, we maintain the link quality from the source to candidate forwarders to be almost the same. In the correlation unaware OR, two forwarders which are the most positively correlated are selected. In correlation aware OR, we select forwarders with different degrees of link correlation. The experiment results are the average values taken from 1000 samples. In the following, we show the performance results of the correlation aware and unaware design on the number of transmissions, energy consumption, and delivery ratio.



(a) (b)

Fig. 9. The impact of correlation level. (a) Correlation distribution. (b) Performance improvement.



(a) (b)

Fig. 10. The impact of link quality. (a) Number of transmissions. (b) Percentage of improvement.

C. Results on Transmissions

Varied Correlation Levels: We start off by showing the impact of link correlation degree on OR. To focus on the effect of link correlation, link quality is kept constant at 0.5. Fig. 9(a) plots the distribution of pairwise link correlations in the presence of the interference pattern of Fig. 8(a). The achievable performance gain of the correlation aware OR is shown in Fig. 9(b). From the figure, we find that OR obtains the maximum 33% improvement, when negatively correlated forwarders are selected. That's because when one forwarder fails to receive a packet, the other is very likely to receive it under negative correlated link correlation. We also find that the improvement decreases when the correlation level increases and there are no improvement at all when the links are perfectly correlated. That's because when the packet receptions of the candidate are highly correlated, link quality becomes the only factor affecting the selection process, and no diversity benefits can be exploited.

Varied Link Qualities: In this experiment, we investigate the impact of link quality on our design. The results are shown in Fig. 10 where Fig. 10(a) shows the number of transmissions needed by correlation aware and correlation unaware designs and Fig. 10(b) shows the corresponding improvement percentage introduced by our correlation aware design. From the figures, we find that the correlation aware scheme obtains significant improvement when link quality is low. For example, the link correlation aware OR obtains the best performance—an improvement of 38% under 1/4 link quality. In the environment where we introduce independent interferences, we observe that the performance gain of our design is still significant, and its performance gain is lower than the negative link correlation scenario.

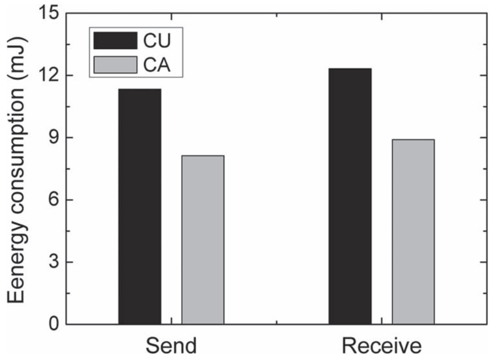


Fig. 11. Energy consumption.

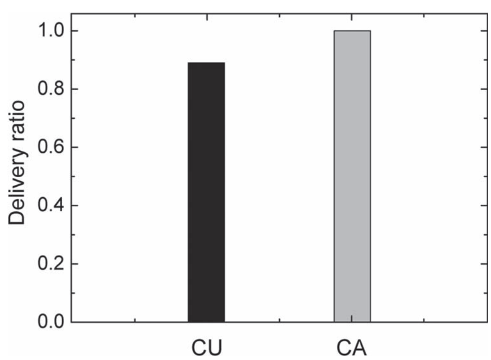


Fig. 12. Delivery ratio.

D. Results on Energy Consumption

Fig. 11 plots the experiment results of the correlation aware and unaware designs on energy consumption from both sending and receiving aspects. From the figure, we can see that on average the sender takes 11.34 mJ, including Clear Channel Assessment (CCA) and transmitting operations, to deliver one packet to the destination with correlation unaware OR. With our correlation aware design, this part energy consumption deduces to 8.13 mJ, which thus saves 28.3% energy consumption. At the receiver side, the energy consumption for CU is 12.33 mJ while it's 8.90 mJ for CA. This part energy consumption includes listening and receiving. Our design improves 27.8% energy efficiency.

E. Results on Delivery Ratio

In the default setting, we retransmit as many packets as possible until the source node receives an ACK from the destination. In this experiment, we limit the maximum number of retransmissions to three. The experiment result is shown in Fig. 12. From the figure, the reliability of CA, and CU is 100%, and 89%, respectively. With the packet reception correlation information, our design helps opportunistic routing find the suitable candidate forwarders and save the number of retransmissions.

VII. Simulation Evaluation

In this section, we evaluate our link correlation aware design in simulations with various network settings.

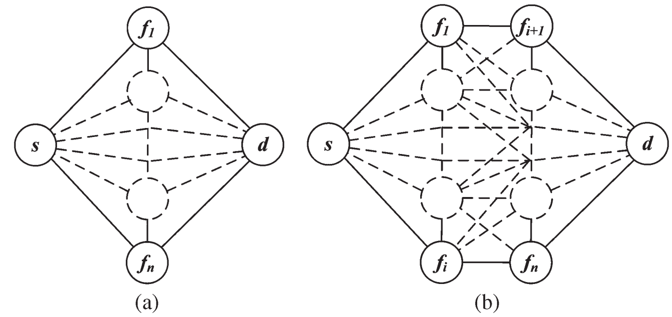


Fig. 13. The topologies used to investigate the effect of link correlation awareness: (a) Single-hop and (b) Multi-hop.

A. Link Correlation Generation Model

We generate correlated links using the sampling algorithm for correlated Bernoulli random variables, described in [25]. The inputs of the algorithm are the mean and the covariance matrix of the joint Bernoulli distribution. It then uses a dichotomized multivariate Gaussian distribution to sample the multivariate Bernoulli distribution. We need to choose the covariance matrix carefully since it cannot be always associated with a valid Bernoulli distribution. We thus use the algorithm in [26] to obtain the closest admissible matrix. The algorithm converts the inadmissible matrix using an iterative projection algorithm into the closest unique admissible matrix in the Euclidean norm.

Link correlation can be either positive or negative depending on the possible cause that affects the inter-link reception. To accommodate such correlations, we create a correlation matrix with the covariance matrix randomly selected from $[-1, 1]$. We generate a string of 10,000 sequences for each sender to capture the link correlation. We then run simulations on OMNeT++ and the Castalia Framework using the generated correlated traces to sample transmission success or failure events.

B. Simulation Setup

We randomly generate different network topologies using the Waxman model [27], where the nodes are uniformly distributed in the plane and edges are added according to the probability that depends on the distance between the nodes. The network size is 50. We consider both the single-hop and multi-hop scenarios. The logical topologies are shown in Fig. 13, where a sender s has n initial candidate forwarders to the destination d. The sender s transmits 10,000 packets to the destination d.

OR obtains significant benefit when link qualities are low. That's because when link quality is high, the forwarder set is not so necessary and its function is almost the same as the best link. The performance of OR is quite close to the traditional shortest path routing under such scenarios. In the following simulations, we mainly focus on low link quality scenarios. Both the links from the source to the forwarder set and the links from the forwarder set to the destination are set to be lossy. In our experiments, the default size of the candidate forwarder set is two.

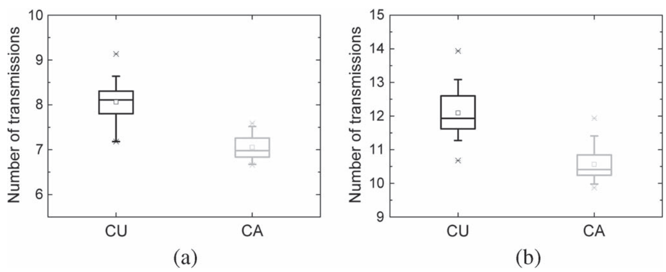


Fig. 14. Main simulation results in single-hop and multi-hop scenarios. (a) Single-hop scenario. (b) Multi-hop scenario.

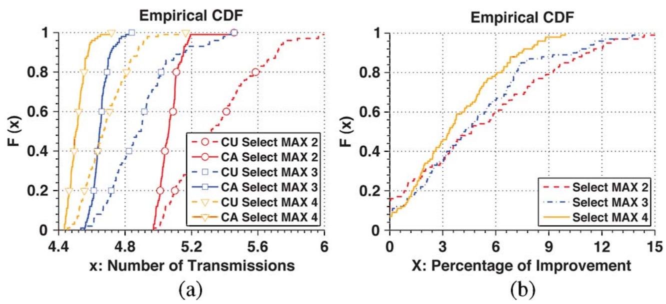


Fig. 15. The impact of forwarder set sizes. (a) The CDF of the number of transmissions. (b) The CDF of the percentage of improvement.

C. Main Performance Results

The main experimental results in both single-hop and multi-hop scenarios are shown in Fig. 14. The box plot in Fig. 14(a) shows the experiment result in the single-hop scenario where the average number of transmissions with CA is 7.05, which is much less than CU's 8.06. The CA design obtains the improvement because it replaces the candidates selected by previous link independent metric when it finds more diversity benefits can be exploited. The performance of the two algorithms in the multi-hop scenario is shown in Fig. 14(b), where a similar result, i.e., a 15% improvement, is observed.

D. Impact of Candidate Set Sizes

In this experiment, we examine the performance of our design with different candidate set sizes. We investigate the cases with 2, 3, and 4 candidates. The results are shown in Fig. 15. From Fig. 15(a) we can see that increasing the size of the candidate set would improve the performance of OR with or without correlation awareness. This happens because the more links we have, the more diverse we can exploit. From Fig. 15(b), we find that the percentage of improvement of our design is reduced when we add more nodes since little improvement room is left when we have enough candidates.

VIII. Conclusion

This paper extensively studies the impact of link correlation on the performance of OR. We provide a detailed analysis of the OR framework under the influence of link correlation. We find that diversity benefit is overestimated when we assume that packet receptions of wireless links are independent. A link correlation aware metric is thus proposed to improve the performance of OR by selecting the nodes with diverse low correlated links as forwarder candidates. We evaluate our work with testbed implementation and extensive simulations. The experiment result affirms the efficiency of our design in capturing the full advantage of OR.

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