

# Opportunistic Routing - A Review and the Challenges Ahead

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# Opportunistic Routing - A Review and the Challenges Ahead

**Abstract**—Opportunistic routing (OR) is an upcoming and promising routing technique for wireless multihop networks. The key concepts behind OR is overhearing and cooperation among relaying nodes; therefore, OR works well in wireless multihop networks with higher node density, such as mesh or sensor networks. OR enables multiple routes and dynamic relay selection, thus, it obtains higher link reliability and larger transmission range. This paper reviews the basic concepts and describes components of OR with examples. Current trends, issues and challenges of OR are also discussed.

**Keywords**- wireless networks; routing; opportunistic routing; anypath routing;

## 1. INTRODUCTION

In recent years, wireless networks have already become an important part in our daily life. Though extensive research has been done and new applications continue to emerge for wireless networks, the potential of the wireless medium has not been fully investigated. One main characteristic of the wireless medium is its broadcast nature, i.e. a unicast packet (destined for one specific node) is actually a one-hop broadcast packet to neighbors. Previous routing schemes treat the attribute as a disadvantage, as it induces interference. Opportunistic routing (OR), also called *anypath routing*, is a recently emerging routing technology for wireless networks to take advantage of the broadcast nature. By dynamically selecting from multiple routes, OR can improve link reliability and overall system throughput. The concept of OR can be applied to all kinds of wireless multihop networks, such as ad hoc, mesh, or sensor networks, as long as omni-directional antennas are used. Moreover, the potential of OR has already been confirmed by both theoretical analysis [1-2] and experimental evaluation [3-5].

Currently, research on OR is still under development and problems, such as channel assignment, routing and coordination, are not well investigated. This paper studies and analyzes some existing OR schemes and explores possible issues. It begins with an introduction of basic OR concepts, followed by the differences between OR and other routing approaches. Then, two primary components: coordination and selection of OR mechanisms are discussed. This paper extracts common solutions or improvements to these components from existing OR schemes and describes them in detail. Afterwhich, several current OR protocols are introduced. The opportunities and possible future research directions are identified before the paper concludes.

### 1.1. Traditional routing

*Traditional routing* refers to those routing schemes, which find a path for a given node pair according to various metrics and forward data packets from one intermediate relay node to the next specified relay. These schemes treat wireless links as point-to-point wired links and ignore the unique broadcast nature of the wireless medium. The broadcast nature of the wireless medium allows neighbors to overhear packets; however, overheard packets are dropped even when they are correctly received in traditional routing.

Figure 1 shows two examples of how these dropped packets can be used for enhancing transmission reliability and range. Assume that S is the source, and D is the destination. In Fig. 1(a), R2 is the relay selected by a traditional routing scheme. Suppose that R2 failed to receive a data packet sent by S but R1 and R3 overheard the packet. If they could help R2 forward the packet, a retransmission is saved, i.e. the transmission reliability increases. In Fig. 1(b), R1' is the relay selected by a traditional routing scheme. Though R1' received the data packet correctly, other nodes R2' and R3', which are closer to the destination, may have also correctly received it. If R3' could help forward the data packet, the transmission reaches further and is closer to the destination. In these examples, if overheard packets are well utilized, transmission reliability can be improved and the transmission efficiency can be maximized.

### 1.2. Opportunistic routing

Instead of (pre)selecting a specified relay node at each transmission, OR broadcasts a data packet to a set of relay candidates. Then, relay candidates, who have successfully received the data packet, run a coordination protocol to select the best relay to forward the packet. In other words, OR is conceptually composed of these three steps:

- a) Broadcast a data packet to relay candidates
- b) Select the best relay by using a coordination protocol
- c) Forward the data packet

Consider an example as shown in Fig. 2, where the source S is sending a packet to the destination D through nodes R1, R2 and R3 and the number of each edge indicates the sequence of events. First, S broadcasts a packet. Both R2 and R3 successfully received it but R1 failed. Then, R2 and R3 run a coordination protocol and decide that R2 forwards the packet to D.

Opportunistic routing has the following advantages:

a) Increase reliability

OR transmits a packet through any possible link rather than one specified link. In other words, it acts like OR has additional backup links and the probability of transmission failure is reduced. An experiment in [3] has also shown that OR outperforms traditional routing when loss rates of links are high.

b) Increase transmission range

OR considers all possible links, including good quality short-ranged links and poor quality long-ranged links, within one transmission; therefore, a transmission may directly jump to the farthest relay which successfully receives the packet. Consequently, performance can be improved. Both theoretical analysis [1-2] and experiment results [3-5] have shown that OR has the potential to perform better than traditional routing.

### 1.3. Selection diversity

Compared to traditional routing, one major characteristic of OR is that the next relay is selected dynamically from multiple relay candidates. Another group of routing schemes, called *selection diversity* [6-7], also selects the next relay dynamically; however, these schemes dynamically select one relay from candidates first. Then, the data packet is sent by unicast to the selected relay. Therefore, like traditional routing, these schemes do not utilize overheard packets. In [7], Multiuser Diversity Forwarding (MDF) is proposed to select the next relay according to current link conditions. Before each transmission, a probe is first sent (broadcast) to relay candidates. A candidate can then determine the current link quality according to the received probe and responds with a probe reply accordingly. Based on the replies from candidates, the sender then selects one relay with the best quality. The objective of these selection diversity schemes is to select the next relay according to current conditions. Though these schemes also have multiple relay candidates like OR, they are not opportunistic in nature.

Multiple relay candidates and the timing of relay selection are the two main differences between traditional routing, selection diversity and OR. A comparison is shown in Table 1. OR selects the next relay from multiple candidates after data transmission, i.e. a data packet is broadcast to all candidates; therefore, among the three approaches, only OR utilizes overheard data packets.

## 2. REVIEW OF OPPORTUNISTIC ROUTING

This section reviews common components of current OR schemes and describes how they work. OR differs from traditional routing in many aspects: multiple relay candidates and dynamic relay selection after data transmission. *Coordination method* and *candidate selection* are two primary components of OR. Generally, candidate selection schemes determine and arrange candidates in order of priority according to a metric; the order is called *candidate order*. Then, packets are forwarded from lower priority relays (close to source) to higher priority relays (close to destination). In other words, the candidate order is similar to routing tables in traditional routing, and it can be either global or local depending on routing strategies. Typically, a global order is maintained by a source while local orders are distributed among relays. Two examples are shown in Fig. 3 and Fig. 4. When a data packet is broadcasted, a coordination method selects the best candidate, according to the order generated by the candidate selection scheme, to forward the packet and stop others from transmitting. More details are given in the following subsections.

### 2.1. Coordination method

From the sender's point of view, the coordination method is used to pick the best candidate to forward packets; on the other hand, from the candidate's point of view, coordination is used to determine the current status and decide whether to forward overheard packets or not. A good coordination method should select the best relay without duplicate transmissions while using the smallest cost (in terms of time and/or control overhead). Existing coordination methods are divided into three groups based on the mechanism used: *timer*, *token*, and *network coding*. Timer-based coordination is the most straightforward approach and easy to implement, but it may lead to duplicate transmissions. Token-based coordination is mainly used to cope with the duplicate transmissions issue. It can totally prevent duplicate transmissions but at a cost of higher control overheads. Unlike solutions stated above, network coding bypasses the coordination issue, thus no coordination overhead is incurred. However, relays are unaware of the current neighbor status and can lead to other issues such as *redundant packets*, which are not duplicates but do not carry additional useful information.

#### 2.1.1. Timer

To pick out the best relay from a list of eligible candidates, candidates in timer-based coordination method [3, 5, 8] are delayed based on a predefined candidate order before responding. The first one to respond is then selected as the next relay. A general timer-based coordination method behaves as follows:

All candidates are first ordered based on a predefined metric. The order is generated by either a source (global candidate order) or sender (local candidate order), and included in the packet header. After a data packet is broadcasted,

candidates will respond in order, i.e.  $i$ -th priority candidate will respond at the  $i$ -th time slot. A candidate responds at its turn only when it does not hear any responses from others. Therefore, before a candidate responds, it can confirm that all higher priority candidates failed to receive data packets. Once a candidate responds, the candidate is selected as the next relay and the response will prevent others from responding.

In the example of Fig. 4, source  $S$  has candidates  $R1'$  and  $R2'$ , of which  $R2'$  is the better candidate (closer to target  $D$ ) and given the higher priority. After receiving the packet sent from  $S$ , candidates  $R1'$  and  $R2'$  can find the candidate order in the packet header. According to that order,  $R2'$  transmits the data packet in the first time slot while  $R1'$  schedules to transmit in the second time slot. Overhearing the data packet sent from  $R2'$ ,  $R1'$  learned that a better candidate has forwarded the data packet and thus,  $R1'$  keeps silent and the coordination process is completed.

Timer-based coordination has been proposed earlier than the other two methods because it is simple, easy to implement and no other control packet is required. The overheads of the timer-based coordination method are candidate waiting time and candidate order information included in the packet header. To reduce average coordination time, some variants, such as ExOR [3], send multiple data packets within a single coordination cycle and add an additional batchmap in packet header to notify the best receiving candidate of each packet; however, average coordination time is reduced at the cost of larger header size. The main drawback of the timer-based solution is duplicate transmissions because not all candidates are guaranteed to overhear the response from the selected next relay. Fortunately, the issue can be mitigated by proper candidate selection (Section 2.2.). In addition, a special case of combining timer-based coordination with global candidate order, such as ExOR, limits spatial reuse and leads to poor scalability and a waste of capacity.

### 2.1.2. Token

Token-based coordination is first proposed in [9]. In token-based coordination, only the token holder can transmit packets and duplicate transmission is totally prevented but at the cost of extra control packets. The process is summarized as follows:

In token-based coordination, a relay collects overheard packets and transmits them only when a token arrives. Tokens are passed along “connected candidates”, where candidates are ordered in the way such that the  $i$ -th candidate can hear the  $(i+1)$ -th candidate. Tokens are generated from the destination and flow from high priority relays (close to the destination) to low priority relays (close to the source). For a source-destination pair, it is possible to have multiple tokens passing among candidates. As acknowledgment information is included in tokens, a relay has a clear view of what packets higher priority relays have received and transmits only unacknowledged packets.

In the example in Fig. 5, the arrows show how a token flows from destination  $D$  to source  $S$  through candidates  $R1$ ,  $R2$ ,  $R3$  and  $R4$ .  $R5$  is excluded because  $R5$  is not “connected” and therefore cannot receive tokens from  $R4$ . The box next to each node shows its packet collection status: black for acknowledged, gray for collected, and white for empty.  $R2$  has collected all four packets. As a token flows from  $D$  to  $R1$  and arrives at  $R2$ ,  $R2$  learns that packet-2 and packet-3 have been received by higher priority candidates. Then,  $R2$  removes the acknowledged packets (packet-2 and packet-3) and transmits unacknowledged packets (packet-1 and packet-4). Finally,  $R2$  passes the token to  $R3$  and waits for the next token from  $R1$ .

The main advantage of this solution is the absence of duplicate transmission. However, the cost of extra control packets makes token-based coordination unsuitable for scenarios when the source-destination pair is too close (such as one or two hops) [9]. Though this solution does not have the waiting time overhead like the timer-based solution, candidates may be idle if no token arrives. Token generation speed at the destination is the key to keep the pipe full. In addition, candidates need to be “connected”; in other words, some relays are filtered out and this reduces the number of relays that can participate in the forwarding process. The impact of this filtering has not been analyzed.

### 2.1.3. Network coding

R. Ahlswede, *et al.* [10] introduced the concept of network coding to routing. When combined with OR, duplicate transmissions can be avoided without coordination by coding packets. A general concept of how network coding is applied to OR is as follows:

When transmitting packets from a source to a destination, a flow between them is divided into batches to code and decode. A batch contains several native packets, which are original packets without coding. Then, the source broadcasts random linear combinations of native packets, and relays forward the linear combinations of received coded packets to the destination. Coded packets are decoded only when the destination has collected enough linearly independent coded packets (e.g. if there are  $m$  native packets in the batch, and the destination has received  $n$  coded packet, where  $n \geq m$ ). Eventually, native packets can be recovered by Gaussian elimination. The process is illustrated by the following example that also shows why coordination is not required.

In Fig. 6, the source  $S$  is transmitting two native packets,  $a$  and  $b$ , to the destination  $D$  through relays,  $R1$  and  $R2$ . First,  $S$  generates two coded packets  $p1$  and  $p2$ , which are linear combinations of  $a$  and  $b$ , and broadcasts them.  $R2$  received both but  $R1$  missed  $p2$ . However, they still generate coded packets and transmit to  $D$  without coordination. With  $p3$  and  $p4$  received,  $D$  can decode and restore  $a$  and  $b$  easily.

This approach for coordination is first proposed by MORE [4]. The main advantage of using network coding is that there is no coordination overhead. However, there remain some concerns and issues, to be discussed as follows:

### 2.1.3.1. Time complexity

One concern is that coding and decoding may incur significant delays. The experiment in [4] uses desktop computers (with Celeron 800MHz CPU) as nodes and can sustain a throughput of 44 Mb/s. Though it has been shown that the combination of OR and network coding can be implemented on low-end PCs, the current approach may not be viable on wireless devices with lower computational capabilities.

### 2.1.3.2. Batch limit

Batch is a basic unit for coding and decoding where the next batch starts only when the current batch has finished. Once a batch is done, a batch-ACK is sent from the destination back to the source by unicast. During this duration, the network is running idle or transmitting redundant packets. To cope with this issue, CodeOR [11] extends the network coding solution with more batches in flight, which is similar to congestion control of batches. SlideOR [12] extends this idea further by dynamically adding new native packets to encode with previous ones so that coded packets are no longer useful only for a specific batch. As a result, network-coding-based OR is now free from batch limits.

### 2.1.3.3 Redundant packets

Redundant packets refer to packets which are not duplicates but do not carry additional information, i.e. linearly dependent packets. Consider the following examples:

In Fig. 7, a source broadcasts one coded packet. If both two relays generate a coded packet immediately, they ( $p_2$  and  $p_3$ ) are obviously linearly dependent. Though they are not duplicate packets, one of them is redundant and does not provide any additional information to the destination.

In Fig. 8, since only two native packets are in the batch, only two linearly independent coded packets are required. Without coordination, it is likely that four relays may generate and transmit four coded packets. Obviously, two of the coded packets are linearly dependent and thus redundant.

From the examples above, it is easy to see that the critical issue of redundant packet is the timing for a relay to generate coded packets. MAC-independent OR and Encoding (MORE) [4] solves this issue by offline prediction according to packet delivery ratio (PDR) between relays. Based on the prediction, relays receive credits (defined by the source) on each packet arrival. After the credit counter reaches a threshold, a coded packet is generated and transmitted. However, the solution cannot prevent redundant packets and the prediction is observed to be incorrect; Koutsonikolas, *et al.* [13] show that the actual number of transmission is often more than twice the predicted number. To reduce redundant packets, Cumulative Coded Acknowledgments (CCACK) [13] utilizes a null-space based (NSB) acknowledgement for network coding. Relays add a hash (vector) in the packet header to disseminate its space information to others. When a relay overhears the hash from its neighbors, the relay can determine if it can generate linearly independent packets for its neighbors or it should stop sending.

Considering the example in Fig. 9, the triple below each node refers to coding vectors of collected coded packets. Coding vectors, which are included in header of coded packets to indicate how the packets are coded, are useful for dependency checking and decoding. In the example shown, only node C holds coded packets that are useful to node A; however, the coding vector, (1,2,1), that node B holds is a linear combination of (1,1,0) and (0,1,1) and thus provides no further information to node A. To help neighbors decide whether to stop generating coded packets or not, node A compresses its space information into a single vector (-1,1,-1), which is orthogonal to all collected coding vectors in A, i.e.  $(-1,1,-1) \times (0,1,1) = 0$  and  $(-1,1,-1) \times (1,1,0) = 0$ . The vector acts as an acknowledgement and is included in coded packets. Once the ACK vector (-1,1,-1) is overheard by a neighbor, the neighbor learns if it has linearly independent packets to node A or not by checking the inner product of its own coding vectors and the overheard ACK vector. If the inner product is zero, which indicates orthogonality, the neighbor stops. As a result, node B in the example knows that it should stop while node C generates another coded packet to node A.

CCACK is the first acknowledgement-based solution for OR with network coding that provides a mechanism to stop generating new coded packets; however, the issue of when to generate coded packets is still left open.

## 2.2. Candidate selection

Another component of OR is candidate selection, which is similar to building routing tables in traditional routing. Candidate selection needs to keep track of all possible routes and mark the priority of each route for coordination methods. The task of candidate selection is further divided into two parts: *candidate ordering*, and *candidate filtering*.

### 2.2.1 Candidate ordering

Candidate ordering helps the coordination method find the best route. The best order can be determined using various metrics among all possible orders. In routing, in addition to the traditional distance-vector (hop-count) and link-state

metrics, there are two more recently proposed metrics: expected number of transmissions (ETX) [14] and expected transmission time (ETT) [15]. ETX is good for homogeneous single-radio environments [15] while ETT extends it to multi-rate networks. In particular, ETX is widely used in current OR systems such as ExOR [3], MORE [4], Simple Opportunistic Adaptive Routing (SOAR) [5], and Economy [9]. However, both of these metrics are not suitable for OR because they consider only one route. Reference [16] has shown using OR algebra that OR in combination with metrics such as ETX could degrade performance.

The cost computation is another reason that makes traditional routing metrics unsuitable. When only one route is considered, the route cost from node A to an intermediate node B to the destination can be simply calculated by summing up the cost from A to B and the cost from B to the destination. Due to the possibility of multiple routes in OR, cost computation is no longer straightforward. Currently, cost computation in OR is calculated by adding up the cost from sender S to candidate set SetC (denoted as  $Cost_{S \rightarrow SetC}$ ) and the cost from candidate set to destination D (denoted as  $Cost_{SetC \rightarrow D}$ ). Cost from sender to candidate set is defined by an OR metric such as Expected Anypath Transmission (EAX) [17] or Expected Anypath Transmission Time (EATT) [18] while the cost from candidate set to the destination is the average cost for a given candidate order. EAX is an extension of ETX and can capture the expected number of transmissions required to reach the destination through any route. Similarly, EATT is an extension of ETT that refers to the expected time to send a packet to any next hop under a given rate. A special feature of EATT is that it also takes multi-rate into consideration and utilizes a rate selection algorithm.

Fig. 10 shows an example of how EAX, EATT and  $Cost_{SetC \rightarrow D}$  are computed if the order is  $R2 > R1$ . PDR of link  $S \rightarrow R1$  is 80% and PDR of link  $S \rightarrow R2$  is 90%. The probability that a transmission from S successfully reaches at least one of either R1 or R2 is  $[1-(1-90%)(1-80\%)]$ . Then, its reciprocal is the expected transmission count, EAX. Expected transmission count multiplied by packet transmission time gives the expected transmission time, i.e. EATT. Subsequently, among  $1/[1-(1-90%)(1-80\%)]$  transmissions from S to candidate set {R1, R2}, 90% of them are forwarded by R2 and the remaining  $(1-90\%) \times 80\%$  are forwarded by R1. As a result,  $90\%/[1-(1-90%)(1-80\%)]$  packets are forwarded through R2, which cost  $90\% * Cost(R2 \rightarrow D) / [1-(1-90%)(1-80\%)]$  to destination on average. Summing up all the cost from candidates to destination gives  $Cost_{SetC \rightarrow D}$ , the average cost from the candidate set to destination, as shown in Fig. 10.

A general framework of OR cost calculation is available in [19]; various metrics, such as EAX, can be adopted and candidate sets can be generated by a Bellman-Ford like approach. In addition to EAX or EATT, some OR schemes such as Geographic Opportunistic Routing (GOR) [8, 20-21] considers geographic distance or energy as metric. Under some scenarios, relay nodes are assumed to be aware of their positions. Therefore, routing can be done by selecting the relay, which is geographically closest to the destination, and no routing table is required. For energy constrained scenarios, metrics such as energy per advancement (EPA) [21] focuses on tradeoff between throughput and energy. These types of metrics are especially suitable for sensor networks.

### 2.2.2. Candidate filtering

Candidate filtering removes candidates that may degrade OR performance. Although including more candidates provides more performance gain, the number of candidates should also be limited to minimize overhead and duplicate transmissions. As the candidate list is generally included in the packet header, higher candidate number means higher overhead. Duplicate transmissions occur when candidates are unaware of one another. Including candidates which cannot hear one another in the list may trigger duplicate transmissions. Besides, Zeng, *et al.* [1, 22] found that the performance gain from including more candidates decreases and becomes marginal the number of candidates increases. Therefore, including all possible candidates is unnecessary. The most common approach is to pick candidates based on a metric. Using a given metric, the sender can simply filter out candidates worse than the sender. However, such trivial filtering leads to higher header overhead and more duplicate transmissions as aforementioned issues. Other metrics for candidate filtering include: a) virtual link strength, b) candidate connectivity, c) level of contribution (use in pruning), and d) duplicate probability.

#### 2.2.2.1. Virtual link strength

Filtering by virtual link strength [5] aims to reduce the size of the candidate list in the packet header while achieving high performance gain for OR. Virtual link is the combination of all links from sender to candidates and its strength or PDR is the probability of any candidate receiving data packets. For the example in Fig. 11, if we assume that the PDR of each link is 80%, then PDR of the virtual link if three candidates are included is  $1-(1-80\%)^3=99.2\%$ . The PDR of the virtual link has reached 99% when three candidates are included. Including the remaining candidates only gives minor improvement on reliability, and as a result, those candidates can be filtered out.

#### 2.2.2.2. Candidate connectivity

To prevent coordination failure when candidates cannot communicate with (hear) one another, systems such as SOAR [5] and Economy [9] select “connected” candidate sets. For any two candidates  $c_i$  and  $c_j$  in a connected candidate set, PDR of the link connecting  $c_i$  to  $c_j$  must be higher than a predefined threshold. After connected candidate sets are found, these sets are then evaluated by a given metric to find the best set and order. For the example in Fig. 12, four candidates are

available for S, namely, R1, R2, R3, and R4, but R1 and R4 cannot hear each other. If R1 and R4 are in the same candidate set concurrently, coordination may fail and trigger duplicate transmissions. Therefore, candidate sets, which include both R1 and R4, such as {R1, R2, R3, R4} or {R1, R2, R4} are not considered.

### 2.2.2.3. Pruning

Pruning [4, 13] is used to further remove useless candidates based on their level of contribution to the forwarding process during execution. Removing candidates with poor contributions saves coordination time and overhead. Previously, candidates are filtered by considering static information such as PDR; however, such offline calculation could be inaccurate [13]. Therefore, it would be better to filter candidates based on actual performance online. In MORE [4] and CCACK [13], each candidate is given a predicted number of transmissions for a flow. If a candidate does not perform at least 10% of the overall predicted transmissions, the candidate is pruned; i.e. the candidate does not participate further and stops forwarding data packets for the flow.

### 2.2.2.4. Duplicate probability

Unlike other filtering approaches, this solution directly calculates the duplicate transmission probability and filters out candidates with high probabilities. Modeling OR with Markov chains was first proposed for error rate calculation in [23]. Deng, *et al.* [24] modeled ACK transmission in OR using a discrete-time finite-state Markov chain model. For a given candidate order, it returns the duplicate probability triggered by a specific candidate. If the probability is higher than a threshold, the candidate is removed. For duplicate prevention, filtering by duplicate probability is more accurate and better than other measures such as connectivity.

### 2.2.3. Other influencing factors

In addition to candidate order and filtering, there are other factors that influence candidate set and order: a) coordination overhead, b) spatial correlation, and c) bit rate selection.

#### 2.2.3.1. Coordination overhead

In the timer-based coordination method, the best candidate is always given the highest priority; however, Zeng, *et al.* [8] pointed out that it is not always the best case if coordination overhead is taken into consideration. This is because good candidates with low PDR increase coordination time, and thus reduce throughput. Expected One-hop Throughput (EOT) [8] has been proposed to capture the tradeoff between the benefit (advancement) and cost (coordination time). EOT indicates the expected advancement per second for a given candidate order, and it is calculated by dividing the average advancement with the average time. Advancement means how far a packet may jump by selecting a candidate/link. A simplified version of Fig. 1(b) is considered to demonstrate the concept as shown in Fig. 13.

In Fig. 13, S is the source and, R1' and R2' are candidates. The number of each link refers to the transmission probability. The number next to S/R1'/R2' refers to ETX to the destination; therefore, advancement of a link is obtained by the difference of the ETX of two nodes (e.g. advancement for S to R1' is  $4.1 - 3 = 1.1$ ). Time is the coordination cost under timer-based coordination. Fig. 14 shows the expected throughput (advancement/time) of order R1' > R2' and R2' > R1'. The example shows that giving the best candidate (R2') higher priority does not lead to higher throughput.

Although the metric EOT has been proposed for routing based on geographic distance, the concept of considering coordination overhead can also be applied to other metrics.

#### 2.2.3.2. Spatial correlation

The calculation of OR metrics such as EAX or EATT requires the PDR of each link, and the PDR of links is assumed to be independent. However, Zubow, *et al.* [25] observed that a spatial correlation exists when the distance between relays is less than two meters. In other words, the probability of multiple link failures can no longer be calculated by simply multiplying error rates. An approach to calculate a more accurate PDR using a table to track all probes has been proposed [25].

Table 2 shows probing results between a source and its neighbors {R1', R2', R3'} in Fig. 1(b). From the table, the PDR to R1' can be calculated as  $2/5 = 40\%$ . In OR metric calculation, one may need to know the probability when both R1' and R2' failed but R3' succeeded. If links are assumed to be independent, the probability is  $(1 - 0.4) \times (1 - 0.6) \times 0.2 = 4.8\%$ . However, the probability when both R1' and R2' failed is  $2/5 = 40\%$  from the table rather than  $(1 - 0.4) \times (1 - 0.6) = 24\%$ . Under the two cases (probe-2 and probe-5), R3' has a 50% chance to succeed. Therefore, the probability when both R1' and R2' failed but R3' succeeded is  $40\% \times 50\% = 20\%$  if spatial correlation is taken into consideration.

Like coordination overhead, the spatial correlation factor can be incorporated with other metrics previously discussed.

#### 2.2.3.3. Bit rate selection

Transmitting with higher bit rates can increase throughput to a specific relay at a cost of higher error probabilities to other neighbors. In other words, multi-rate selection increases link throughput but also poses a new challenge to OR: the tradeoff between number of candidates and link throughput. Reference [18] observes that the distribution of optimal

transmission rates is not concentrated at any particular rate; therefore, multi-rate transmission is one of necessary consideration for high performance OR. ETT-RCA [23] models OR with Markov chain to calculate packet error rate. Then, the expected transmission time of a given candidate set under a given rate can be generated; the best candidate set with the best rate is then evaluated and picked based on the expected transmission time. The performance gain from bit rate selection in OR is also studied in [18], and what makes bit selection challenging in OR is time complexity. If there are  $N$  relays from source to destination and  $R$  possible rates available, it is nontrivial to determine the best rate and order from  $(N!)(R^N)$  possible combinations. Therefore, Shortest Multirate Anypath First (SMAF) [18] is proposed to pick the best order and rate for all relays to a specific destination. SMAF, similar to the Dijkstra algorithm, takes polynomial-time (to number of nodes) and is proven to be optimal.

### 3. OVERVIEW OF CURRENT OR PROTOCOLS

Before performance gain of OR drew great attention, there were a few research efforts that adopted the same concepts as OR but for different purposes. Contention-based forwarding (CBF) [20] operates similar to timer-based OR. However, the focus of CBF is to get more accurate location information for geographic routing in mobile ad hoc networks and the performance gain of OR has not been discussed.

In 2005, the first OR scheme, ExOR [3], focusing on performance gain is proposed and implemented. To cope with the acknowledgement and the coordination issue, ExOR adopts batch transmission; 10 to 100 packets are collected in a batch to transfer and the next batch starts only when the current batch has completed. One main achievement of ExOR is to show that the concept of OR indeed works better than traditional routing. However, without proper transmission control, the pipe between source and destination is not fully utilized, and the design also induces duplicate transmission.

After ExOR, another timer-based OR technique, SOAR [5], has been proposed for better transmission control and duplicate prevention. The main feature of SOAR is that the candidate set is generated by both source and relays. A source picks default candidates (by traditional routing) and each relay dynamically adds a few local neighbors, which do not lead to duplicate transmissions, into the candidate set. SOAR was implemented and compared with ExOR and the results showed that SOAR outperforms ExOR especially as the number of flows grows.

In addition to proposing a timer-based solution, MORE [4] is the first work to adopt network coding as the coordination method in 2007. MORE has been implemented on low-end PCs to show that network coding is feasible. Though bypassing the coordination issue, MORE introduces more issues such as batch limits and redundant packets. Fortunately, supporting techniques, such as CodeOR [11] and SlideOR [12], free network-coding-based-OR from batch limits. Due to the lack of acknowledgement in MORE, relays do not know when to stop transmitting, hence triggering redundant packets. CACK [13] uses NSB acknowledgement to give relays their neighbors' status in network-coding-based OR. However, the issue of when to generate coded packet is still left open.

Economy [9] is the only OR protocol which adopts token-based coordination. The main advantage of Economy and token-based coordination is the absence of duplicates. Observations from simulations showed that Economy uses fewer transmissions to deliver a packet to the destination. With benefit from OR and free from duplicates, the number of transmissions required to deliver packets to the destination (by source and all relays) is much lower than that of ExOR and is even lower than the number of hops of the best route selected by traditional routing. However, Economy is lacking in testbed experiment and analysis on the token-passing path.

GOR [8, 21] is used in geographic routing scenarios and adopts timer-based coordination with local candidate order. GOR improved CBF by proposing a new candidate selection scheme, EOT, which considers the coordination overhead. However, the issue of duplicate transmissions, induced by timer-based coordination, is not discussed. Table 3 summarizes the key features of the OR schemes discussed above.

### 4. CHALLENGES AND OPEN ISSUES

Despite the potential benefits that OR can bring to wireless networks, prevailing challenges remain and more research is needed to improve OR. In this section, we discuss some of the challenges faced by OR and the open issues that are yet to be addressed.

#### 4.1. Coordination method

##### 4.1.1. Token-based coordination

Token-based coordination is free from duplicates and is superior in scenarios such as grids. The token-passing path significantly influences its performance; however, the impact of the path selection has not been analyzed yet and solutions to select the optimal token-passing path(s) are also lacking.

##### 4.1.2. Network coding coordination

Though network coding coordination has the potential to achieve zero overhead, coding time and redundant packets are the main issues. It has been shown that the combination of network coding and OR can be implemented on low-end PCs



[4], but it still cannot be deployed on existing wireless networking devices. In other words, for existing wireless mesh networks upgrading from traditional routing to OR, network coding coordination is not an option. Regarding the issue of redundant packets, the timing of coded packet generation is critical. Previous solutions based on offline prediction are inaccurate [13]; as a result, the effect of redundant packets may be even greater. The issue of when to generate coded packets certainly requires further analysis.

#### 4.1.3. Theoretical comparison

Timer-based coordination incurs waiting time. Token-based coordination is free from duplicates but requires additional control packets. While network coding coordination has the potential to achieve zero overheads, various other issues remain. It is hard to determine which coordination method is the best; therefore, theoretical performance comparison (using theoretical bounds that consider their costs) among the three coordination methods is useful and important. The comparison may provide insights as to which one has the potential to be the best, or point out suitable scenarios for each coordination method.

#### 4.2. Candidate selection

While many candidate selection schemes have been proposed, there is a lack of integration of different desirable features. Typically, filtering and ordering metrics are applied separately such that the outcome is not optimized. For example, filtering by duplicate probability removes candidates that trigger duplicate transmissions after the best candidate order has been generated using a given metric. Although both approaches aim for the same goal of improving performance, the outcome may not necessarily be the best as the second phase filtering can also change the optimized candidate order that has been previously generated using the metric in the first phase. Hence, to get an optimized candidate order, an integrated approach taking all desired features, such as duplicate probability and virtual link strength, into consideration is highly recommended.

#### 4.3. Multi-flow rate control

As it has been reported that TCP congestion control is not suitable for multi-hop wireless networks [26], several solutions have been proposed to cope with it. For OR, few rate control solutions, such as, in SOAR [5] and CCACK [13, 27], have been proposed. As these solutions have been evaluated mainly by simulations with some testbed experimentations, more theoretical studies on rate control for OR are required.

#### 4.4. Power control with proper bit-rate selection

Power control is a critical issue in wireless networks. From previous studies, a variable-range transmission approach supported by power control can outperform a fixed-range transmission approach in terms of power savings and increased capacity [28]; besides, it has been shown that performance improvements of more than 100% can be achieved with power control over ordinary non-power-controlled 802.11 networks [29]. Therefore, supporting OR by power-control is desirable.

With power control, transmitting with higher power increases PDR and transmission range so that higher bit-rate is achievable and more candidates are available for OR; however, it also induces larger interference areas and degrades the performance of neighboring transmissions. Previous work focuses on bit-rate selection for OR [18], which affects only the candidate set of the sender itself. Power control in OR affects not only the sender itself, but also changes suitable bit-rate and candidate sets of neighboring transmissions, i.e. a tradeoff between local and global throughput. It is desirable to have power control for OR so that sufficient candidates are covered while interference range is minimized.

#### 4.5. Multi-channel scenario

Another popular solution to improve the capacity of wireless networks is the multi-channel multi-interface approach. OR relies on overhearing; in contrast, the multi-channel approach improves capacity by reducing overhearing and the resulting interference from neighbors. In other words, fewer candidates are available for OR in a multi-channel scenario. The pertinent question then is whether OR can still achieve the same level of efficiency in multi-channel scenarios. This has been addressed in a recent study [22] that analyzed the end-to-end capacity of OR in a multi-channel scenario using linear programming and found that OR can indeed achieve better performance with even lesser radio resources. Furthermore, Zubow, *et al.* [30] showed similar simulation results that the overall throughput increases proportionally to the increase in number of channels. The work also pointed out that with multiple candidates acting as backup links, OR has the advantage to overcome the deafness problem, where nodes cannot communicate with each other because they operate on different channels. Though OR in multi-channel scenario is promising, the channel assignment strategy for OR is still an open research problem.

#### 4.6. Deployment of OR

Numerical and simulation results have shown the potential of OR, but the appropriate network topology to be adopted for deployment has not been examined yet. The need for OR deployment can be discussed in two aspects: a) building a new wireless mesh network, and b) transitioning from existing wireless mesh networks.

Due to the properties of OR, traditional deployment strategies may not achieve the best tradeoff between performance and cost (number of relays), i.e. cost-performance ratio for constructing a wireless mesh network. Besides, even in a planned and optimized wireless network for traditional routing, OR is still beneficial as long as link quality is not perfect (i.e., varies over time due to changing environmental conditions) and multiple relays are available. Therefore, it would be necessary to analyze how to place nodes within a network to achieve higher performance or deploy a wireless mesh network that can achieve comparable performance with fewer nodes.

Though existing wireless mesh networks can be easily modified to take advantage of OR by updating their firmware, the main challenge is that those nodes are mostly unmovable and therefore the network topologies may not be easily reorganized. As a result, there is a need to determine if it is beneficial to implement OR using the current network deployment. Alternatively, we can also evaluate how the current topology can be minimally modified (by adding or moving a few nodes) to derive performance gains from OR. Consequently, a transition strategy is therefore necessary to incorporate OR into existing wireless mesh networks.

#### 4.7. Combination OR with Selection Diversity (SD)

Though SD does not benefit from overheard packets as OR, it is possible and beneficial to put them together. SD is shown to have great impact on performance in slow fading channel conditions with multirate support [23]. While sending probes to detect channel quality incurs additional overhead, adjusting to appropriate bitrate makes the cost worthwhile. However, in fast fading channel conditions, the channel condition information of SD is out of date and the performance of SD drops significantly due to probing overhead. In contrast, with multiple backup links and without probing cost, OR outperforms SD in fast changing channel conditions. In short, under multirate scenarios SD is suitable for slow fading channel conditions while OR is good for fast fading channel conditions. Naturally, it is attractive to put OR and SD together. Hybrid Opportunistic Routing (HOR) [23] multicasts probes to the candidate set and then adjusts the candidate set and bitrate accordingly. However, such a combination also includes the drawbacks of OR and SD, namely, coordination cost and probing cost, and thus the usage of this combination is limited. Besides, only trivial one-hop throughput is evaluated in the work [23]. It is desirable to have further analysis on the combination of OR with SD or design an algorithm to switch between OR and SD.

## 5. CONCLUSIONS

Opportunistic routing, which is a new routing paradigm for wireless multihop networks, exploits the salient broadcast nature of wireless communications. In this paper, we have provided a review of the research done on OR. Some key challenges in OR that need to be further researched on are addressed and we hope that this will stimulate more research in this area.

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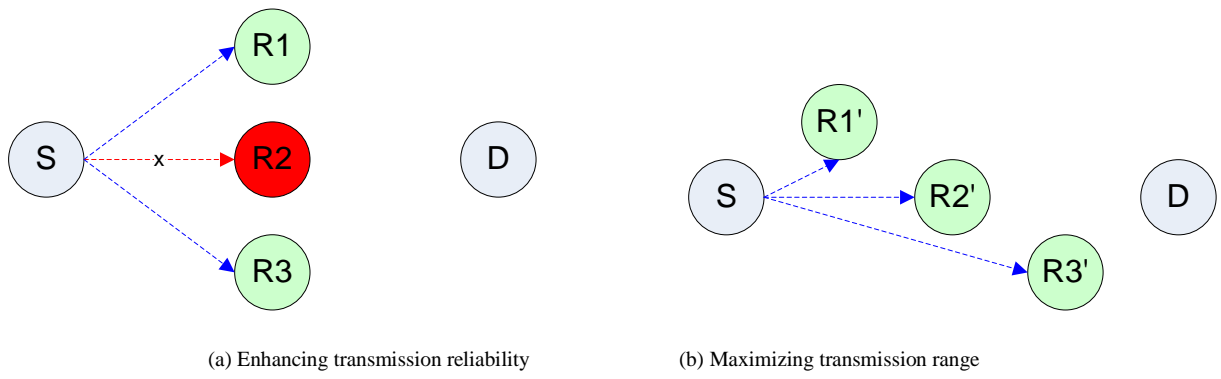


Figure 1. How overhead packets could be utilized

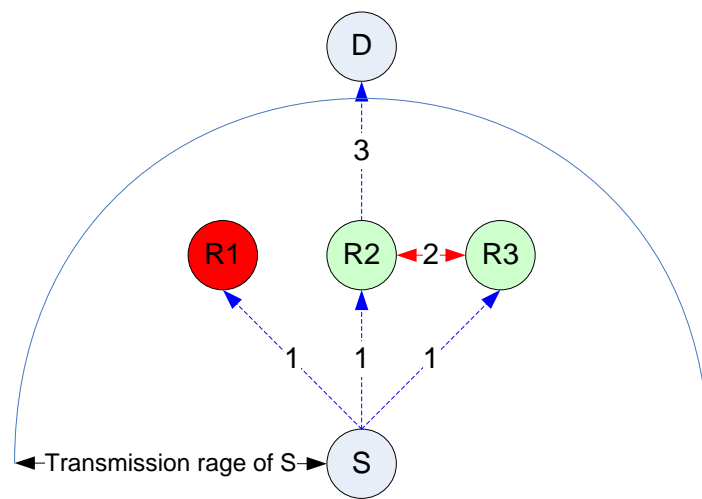


Figure 2. How OR works

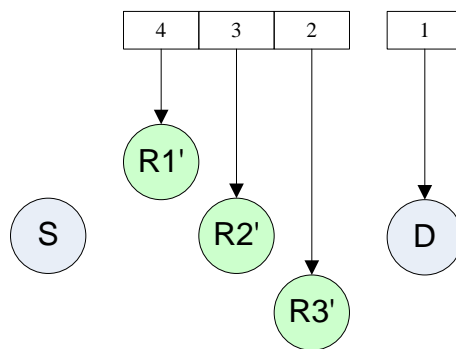


Figure 3. Global candidate order

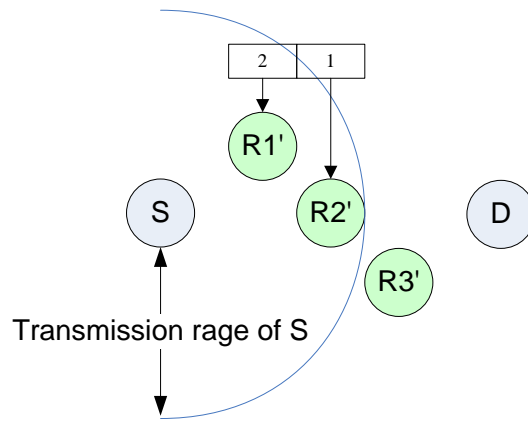


Figure 4. Local candidate order

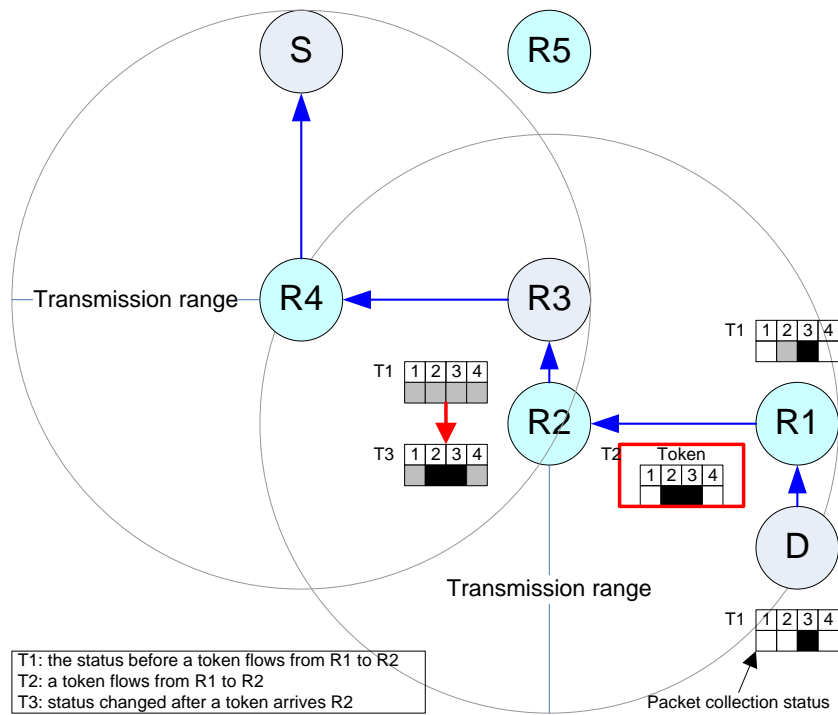


Figure 5. Token-based coordination method

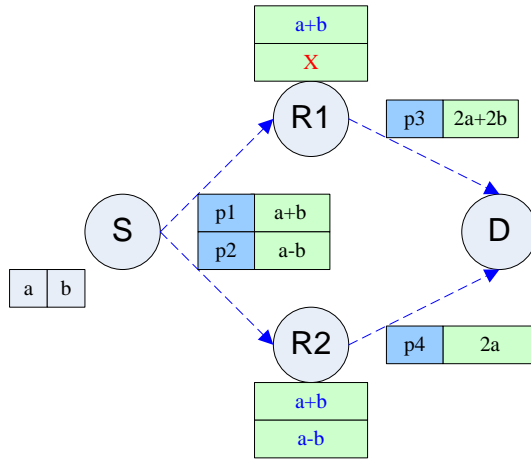


Figure 6. Network coding coordination method

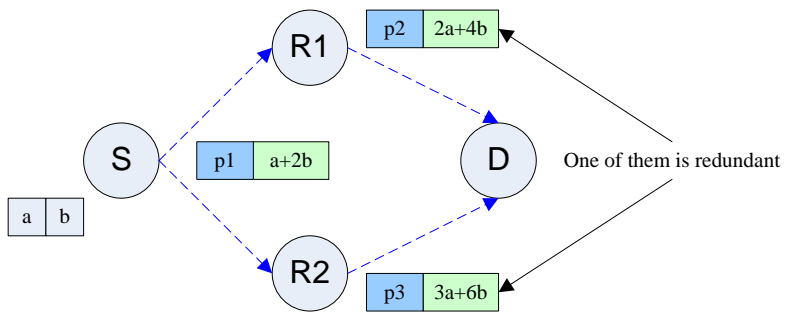


Figure 7. Redundant packets – scenario 1

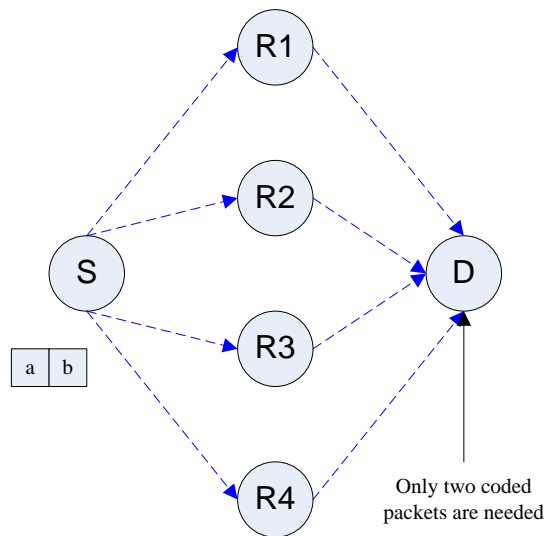


Figure 8. Redundant packets – scenario 2

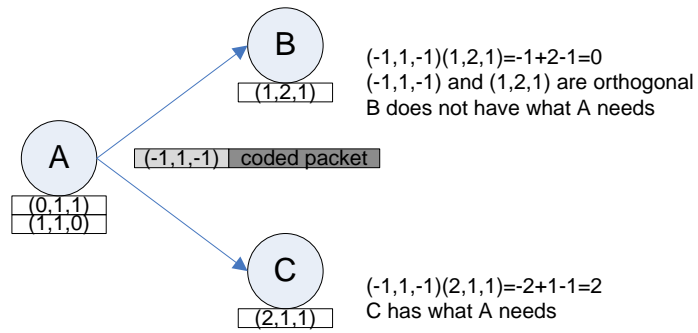


Figure 9. NSB coded feedback

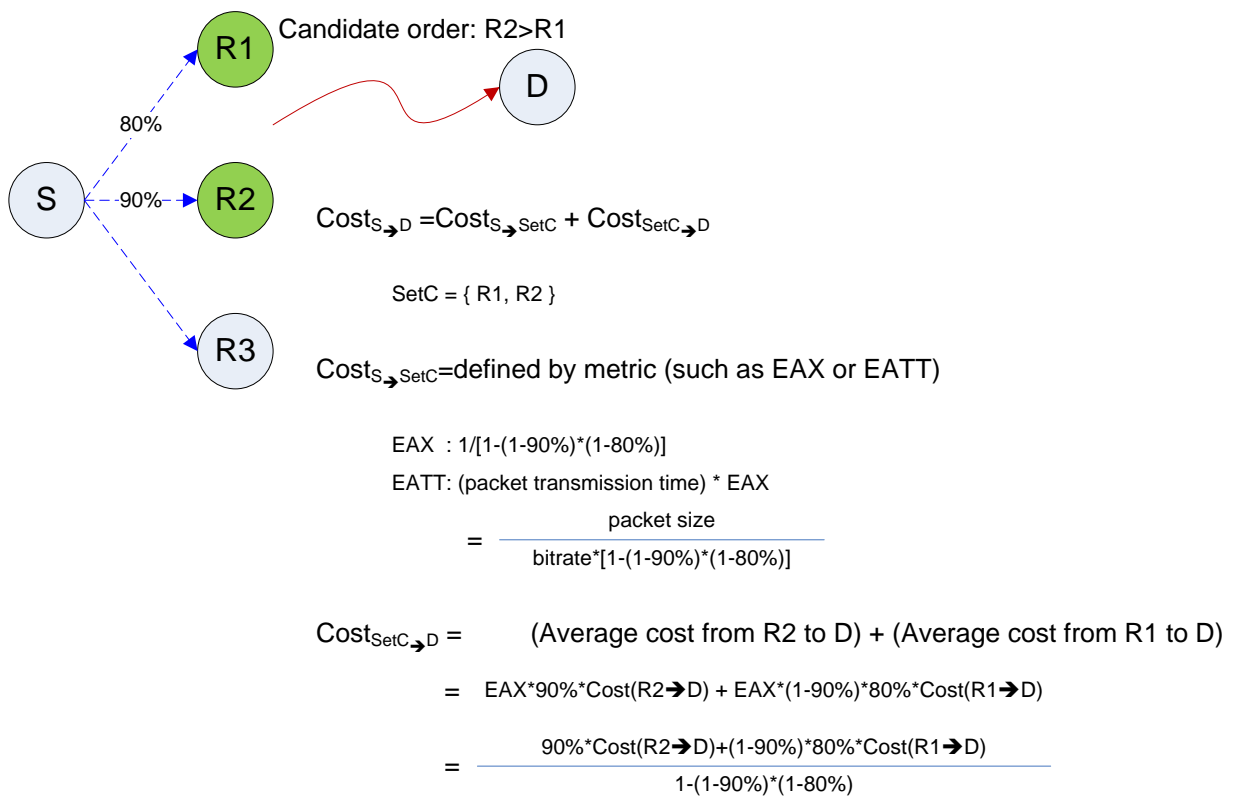


Figure 10. Calculating the cost of OR for candidate order  $R2 > R1$

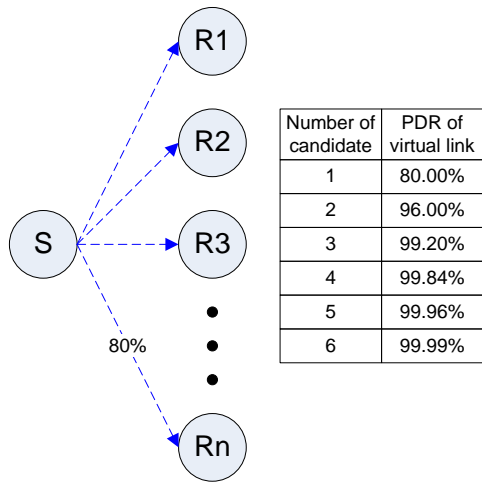


Figure 11. Virtual link strength

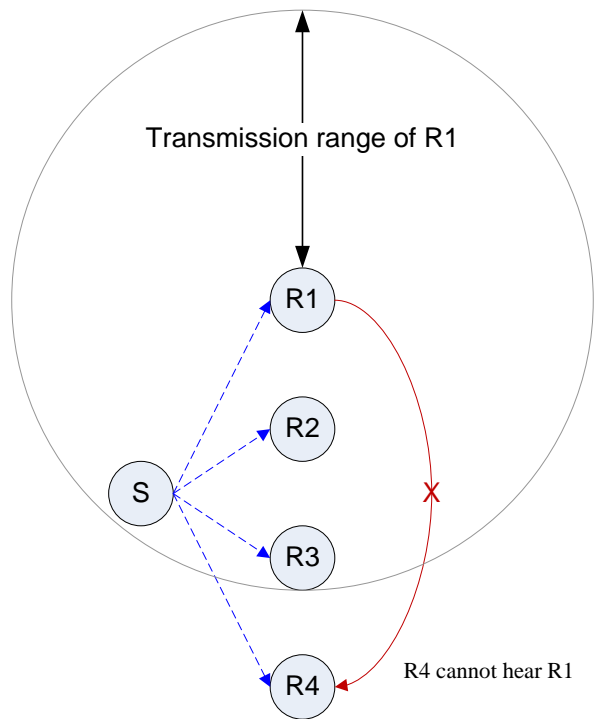


Figure 12. Candidate connectivity



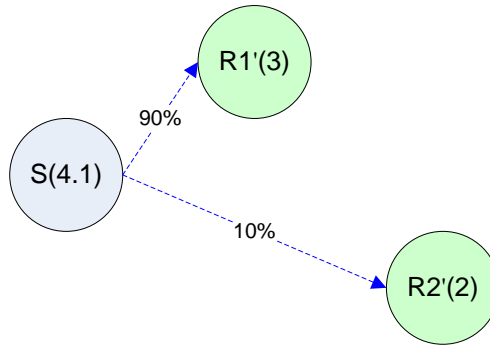


Figure 13. Impact of candidate order

	R1'	R2'
PDR	90%	10%
advancement	1.1	2.1
time	3+1	3+2

	R2'	R1'
PDR	10%	90%
advancement	2.1	1.1
time	3+1	3+2

$$EOT(R1' > R2') = \frac{1.1 \cdot 90\% + 2.1 \cdot (1-90\%) \cdot 10\%}{4 \cdot 90\% + 5 \cdot (1-90\%) \cdot 10\%} = 0.27$$

$$EOT(R2' > R1') = \frac{2.1 \cdot 10\% + 1.1 \cdot (1-10\%) \cdot 90\%}{4 \cdot 10\% + 5 \cdot (1-10\%) \cdot 90\%} = 0.24$$

Figure 14. EOT computation

Table 1. Comparison between OR and other related schemes

	Number of relay candidates	Type of relay selection	Timing of relay selection	Type of data transmission	Utilize overheard packets
Traditional routing	Single	Fixed	Before each data transmission session	unicast	No
Selection diversity	Multiple	Dynamic	Before each data transmission	unicast	No
Opportunistic routing	Multiple	Dynamic	After each data transmission	broadcast	Yes

Table 2. Spatial correlation in OR

	R1'	R2'	R3'
Probe-1	O	O	X
Probe-2	X	X	X
Probe-3	O	O	X
Probe-4	X	O	X
Probe-5	X	X	O
PDR	40%	60%	20%

R1' and R2' failed but R3' succeeded

Independent:  $(1-0.4) \cdot (1-0.6) \cdot 0.2 = 4.8\%$

Correlated:  $0.4 \cdot 0.5 = 20\%$

Table 3. Comparison of selected OR protocols

	Coordination Method	Candidate set			Batch transmission
		Metric	Filtering	Generated by	
CBF	Local timer	Geographic distance	n/a	Relay	No
GOR	Local timer	Geographic distance with coordination overhead	n/a	Relay	No
ExOR	Global timer	ETX	n/a	Source	Yes
SOAR	Local timer	ETX	Connectivity, Virtual link	Source and Relay	No
Economy	Token	ETX	Connectivity	Relay	No
MORE	Network coding (NC)	ETX	Pruning	Source	Yes
CCACK	NC with NSB-ACK	ETX	Pruning	Source	Yes