Opportunistic Routing in Wireless Networks: Models, Algorithms, and Classifications

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Opportunistic Routing (OR) is a new promising paradigm that has been proposed for wireless networks. OR has gained a lot of attention from the research communities for its ability to increase the performance of wireless networks. It benefits from the broadcast characteristic of wireless mediums to improve network performance. The basic function of OR is its ability to overhear the transmitted packet and to coordinate among relaying nodes. In OR, a candidate set is a potential group of nodes that is selected as the next-hop forwarders. Hence, each node in OR can use different potential paths to send packets toward the destination. Any of the candidates of a node that have received the transmitted packet may forward it. The decision of choosing the next forwarder is made by coordination between candidates that have successfully received the transmitted packet. In OR, by using a dynamic relay node to forward the packet, the transmission reliability and network throughput can be increased. In this article, we explain the fundamental idea of OR and its important issues by providing some examples. We then categorize each of the important issues and explain them in detail. Furthermore, we illustrate different protocols from each category and compare their benefits and drawbacks. Finally, some potential directions for future research in OR is explained.

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1. INTRODUCTION

Over the course of the past few years, multihop Wireless Networks (MWNs) [Akyildiz and Wang 2005, 2009] have attracted much attention; they have become a very popular topic in the research communities. In MWNs, radio transmission of nodes is affected by the distance between nodes and environmental elements. Therefore, the quality of wireless links in terms of packet delivery probability is different for each link in a MWN. Unlike wired networks, in MWNs, the transmission of a packet to an identical next-hop node may be heard by many other neighboring nodes.

To cope with heterogeneous wireless links that offer differing quality, in conventional routing protocols used to reach each destination, each node must select a specific node

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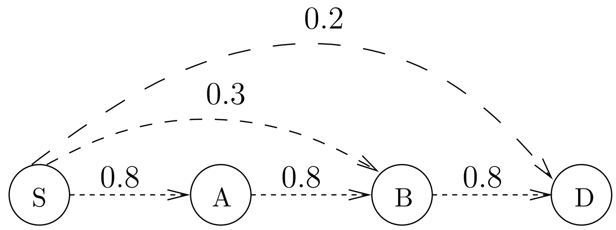

Fig. 1. An example of OR.

that provides the best performance. Therefore, to reach a destination, an identical path is constructed before the transmission starts. When a node receives a packet to forward, its preselected next-hop is used to forward the packet. When all next-hop nodes are selected, the path that all packets will travel on toward the destination will be the same. This type of protocol is usually called *unipath* routing. The idea of using a single path to deliver packets is borrowed from the Internet Protocol (IP forwarding). Unipath routing is not a suitable choice for wireless networks because transmission failure happens frequently. Furthermore, as mentioned earlier, in wireless networks, the transmission of signals from a node to an identical neighbor can be heard by many other nodes in their neighborhood. This fact is usually considered a negative effect in wireless network research. Therefore, the research community has put most of its effort into providing wireless links that are as perfect as wired ones. In other words, they ignore the usefulness of the broadcast characteristic of the wireless medium.

Opportunistic Routing (OR) became popular in the field of wireless networks because it could be used as an approach to increase the performance of MWNs. It considers the benefits of overhearing wireless signals. It is also referred to as diversity forwarding [Larsson 2001] or any-path routing [Dubois-Ferriéandre et al. 2007; Dubois-Ferriére et al. 2011]. In OR, a set of nodes is selected as potential forwarders. The nodes in the selected set will forward the packet according to some criteria after they receive the packet. This group of nodes in OR is usually called a Candidate Set (CS). This is different from traditional unipath routing, which selects one next-hop forwarder before starting the transmission [Boukerche 2008, 2004]. A priority is assigned to each candidate in the CS. Candidate priority shows the level of ability of a candidate to act as the next forwarder. The highest priority is given to the candidate that can reach the destination at the lowest cost. This cost could be understood in different terms: for example, distance to the destination in terms of the number of hops, power consumption, the Expected Number of Transmissions (ExNT), and the like.

By using OR, each packet is allowed to dynamically build the route toward the destination; this is done according to the condition of the wireless links at the moment when the packet is being transmitted. In OR, the nodes do not select an identical next-hop before the transmission starts. OR selects a set of nodes as potential candidates. The candidates that have received the transmitted packet coordinate among each other to decide which of them must forward the packet and which must discard it. This process is usually called *candidate coordination*. In other words, a sender broadcasts the data packet first, and one of its candidates that has received the packet will continue the forwarding process; therefore, the chance of delivering the packet to the destination is increased.

We show an example of OR in Figure 1. It presents the meaning of OR and shows the difference between traditional routing and OR protocols. We consider nodes S and D as the source and the destination, respectively. Furthermore, assume that packet transmission in each link follows a Bernoulli distribution, with the delivery probability

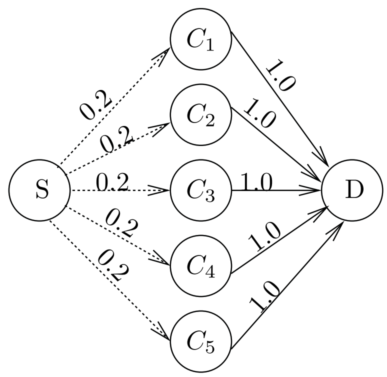

Fig. 2. An illustration of virtual link in OR.

specified over the links. If a traditional routing protocol is applied on this network, the best path from source S to destination D is S-A-B-D. When the source sends a packet, if node B correctly receives the sent packet from the source, it cannot forward the packet, and the packet has to be resent until it reaches the designated next-hop A. Therefore, as we can see, in this kind of routing scheme many retransmissions and wasted network resources may occur. Another situation that might occur is that the packet may be received by both nodes A and B. Because the distance of B to the destination is less than that of node A, the packet might be delivered to the destination with a smaller number of transmissions if node B forwards it. Because source S has not selected node B as its next-hop forwarder to destination D, node B is not allowed to forward the received packet. By contrast, OR can increase the progress of a packet toward the destination by taking advantage of these situations. An OR protocol can use $\{D, B, A\}$ as the CS of source S to reach the destination. Note that in Figure 1, considering the closeness of nodes to the destination, the priority of node B in the CS of the source is higher than that of A. As mentioned earlier, when the source sends a packet, if any node in the CS receives the packet successfully, it can forward this packet, and the source does not need to retransmit the packet. Furthermore, if nodes A and B receive the packet but not node D, since node B has a higher priority than A, it will then forward the packet while node A simply discards it. It is obvious that whenever there is the possibility of having an alternative forwarder, by applying OR, it is highly feasible to avoid retransmissions. Therefore, by using OR and by decreasing the number of transmissions, the throughput of a network is improved and network resources are saved.

Another benefit of OR is its ability to have backup links in the case of transmission failures in one of the wireless links. This is more useful when it combines weak links in a *virtual link*. The delivery probability of the virtual link is stronger than that of each link; hence, this reduces failure probability [Hsu et al. 2011]. As we can see in Figure 2, the links between the sender and its neighbors do not provide a high delivery probability while the neighbors have a perfect link to the destination. When the traditional routing protocol is used, only one node among the five intermediate nodes has to be selected as the next relay node. Note that there is no difference in the selection of each of them. Therefore, the traditional routing protocol requires five transmissions, on average, to deliver the packet from s to one of the intermediate nodes (next-hop). Note that one other transmission is needed from the next-hop to the destination (in total 6 transmissions). In comparison with OR, we can select all five intermediate nodes as the CS. The combined link has a delivery ratio equal to

$(1 - (1 - 20\%)^5) \approx 67\%$. As a result, when delivering a packet to any of the five candidates, the ExNT is only $1/0.67 = 1.48$, and, like the previous case, one additional transmission is necessary to deliver the packet from the selected candidate to the destination. Therefore, on average, it takes only 2.48 transmissions.

As we can see, the principal root of performance improvement provided through OR is the ability to take advantage of the benefits of the transmitted packet in the network. We explain the important key issues concerning the design of an OR protocol in the following section.

1.1. Important Issues in Opportunistic Routing

The performance of an OR protocol depends on different key issues. Usually there are three main issues concerning the design of an OR protocol: (1) OR metric, (2) candidate selection algorithm, and (3) candidate coordination method. To accurately select and prioritize the CSs, OR algorithms require a metric. Initially, proposals of OR algorithms were based on simple metrics inherited from traditional unicast routing; for example, hop count or Expected Transmission Count (ETX) [De Couto et al. 2005; Boukerche et al. 2011]. After selecting a proper metric, the wireless nodes use the *Candidate Selection Algorithm*. This is run to select and order a group of neighboring nodes, called *candidates*, and it is able to help in forwarding the packets to a given destination. To send a data packet using OR, a node usually includes its CS in the header of the data and broadcasts it. There should then be a mechanism, referred as *Candidate Coordination* that is used by the candidate to determine which of them has to forward the packet. The highest priority candidate must forward the received packet, and the other ones will drop it. Candidate Coordination mechanisms usually require signaling among the nodes. If the coordination between the candidates is done imperfectly, it may result in the sending of duplicate transmissions of packets by different candidates.

Most of the research in OR is related to the three main issues just described, but there are some other areas of OR that have been investigated as well. The application of OR in multicast protocols and the adoption of OR protocols for mobile scenarios are examples of other research directions in this topic. Performance evaluation of OR with analytical models is another research direction for the OR topic also investigated.

In this article, a comprehensive review of the important issues and different aspects of the state of the art of OR protocols is presented. Our greatest focus is on the three main issues in OR: routing metrics, candidate coordination, and candidate selection algorithms; these are explained in Sections 2, 3, and 4, respectively. Based on the classification of different issues, we then review the most important and most notable protocols proposed in the literature. We also review works proposed in other areas of OR that suggest the use of OR in multicast delivering packets (Section 5.4). Additionally, the most notable and important analytical models proposed in OR are presented in Section 6, and the use of OR in mobile scenarios (Section 5.5) is another topic that we investigate in this survey.

2. ROUTING METRICS IN OPPORTUNISTIC ROUTING

The main target of OR is to reduce the ExNT of a packet when delivering it to a given destination. If OR succeeds in reducing the number of transmissions, the end-to-end delay, the delay variations (jitter), and the energy consumption at each node [Darehshoorzadeh 2012] will be reduced. The performance of OR is highly affected by the CSs that each node in the network has selected. The priority is assigned to each candidate considering the candidate ability to operate as a next forwarder. Therefore, the selection of a good metric for the purpose of finding and ordering candidates has a large impact on network performance.

The use of metrics mainly depends on the network information provided at each node. In this sense, metrics can be classified as *Local* and *End-to-End*.

—Local metric: In this case, the selection and prioritization of candidates depend on the local information of neighbors (e.g., the geographic position of nodes) or the link properties of neighbors (e.g., the link delivery ratio of the links).
—End-to-End: The global information of the network topology is used to select and order the CSs. The main factors that form this metric are the characteristics of the wireless links and nodes. In other words, the calculated metric for each node is dependent on the cost of the remaining path from the neighbors of a node to its destination.

Obviously, using a metric that represents an end-to-end quality helps to produce an optimal CS since the nodes are aware of all the information concerning the whole network topology. If nodes select the optimal CS, the ExNT in the network will be minimized. On the other hand, the computation cost of the end-to-end metrics could lead to significant overhead.

Considering the parameter that a metric aims to characterize, the metrics in OR can be classified in the following three categories: hop-count, link delivery property, and geographic position. To determine if a node may suitably be considered as a candidate, the hop-counts on the path from the neighboring nodes to the destination are utilized in the hop-count metric. In the link delivery property metric, candidates are selected based on the success delivery probabilities of the links on the path from source to destination. Finally, the location information of nodes is used as the metric in the geographic position metric to find and order CSs. The following sections describe and classify the usual metrics that have been widely used in the literature.

2.1. Usual Metrics in Opportunistic Routing

An overview of the usual metrics proposed for OR according to the classifications that have been defined in Section 2 is described here. We use the following notations in this section:

—$p_{i,j}$: the link delivery probability between two nodes i and j.
—$C^{s,d} = \{c_1, c_2, \ldots, c_{ncand}\}$: the CS of node s used to reach destination d using OR.
—*ncand* shows the maximum number of candidates that each node can select.

Note that we have assumed that in $C^{s,d}$ the candidate c_1 has the highest priority while c_{ncand} has the least priority. That is, c_{ncand} will be chosen as the forwarder if none of the higher priority candidates ($c_i, i < ncand$) has received it.

2.1.1. Local Opportunistic Routing Metrics. The local metrics are only dependent on the local information provided at each node. One of the simple metrics that considers the geographic position of nodes as the measurement of appropriate proximity is Distance Progress (DP) [Zorzi and Rao 2003]. The closeness of nodes to the destination in DP is considered as the measurement for the selecting and prioritizing of candidates. The definition of DP is as follows:

$$DP^{s,d}_{c_i} = Dist(s, d) - Dist(c_i, d), \tag{1}$$

where $Dist(i, j)$ is the Euclidean distance between nodes i and j. By using DP, a node can estimate the remaining distance needed to reach the destination d, when the packet is delivered to candidate c_i. Each node can send a *beacon* message to provide its position information. The performance of DP may change based on the way that it is measured and the way it broadcasts the geographic information. Note that in

Equation (1), the geographic position of the destination is needed so that it may be provided by a location-based service.

The use of DP is limited to a scenario where each node can select as many candidates as possible. In this scenario, the probability of reaching candidates is not important since the node has selected all the candidates that may help it reach the destination. However, if the node cannot select as many candidates as possible, the delivery ratio of wireless links plays an important role in selecting a set of appropriate candidates. In this case, DP is not a reliable choice because it may select only those candidates that are close to the destination, but the link between them and the node cannot offer an acceptable delivery ratio. Expected Distance Progress (EDP) [Darehshoorzadeh and Cerdà-Alabern 2012] is proposed as an extended version of DP that improves the performance of DP by addressing this concern.

—**Expected Distance Progress (EDP)** [Darehshoorzadeh and Cerdà-Alabern 2012] calculates the average distance advancement of the transmitted packet by using a CS.

The EDP of node s to deliver a packet to destination d is calculated by using Equation (2):

$$EDP(s, d, C^{s,d}) = \sum_{i=1}^{|C^{s,d}|} DP_{c_i}^{s,d} \times p_{s,c_i} \prod_{j=1}^{i-1}(1 - p_{s,c_j}). \tag{2}$$

Note that $DP_{c_i}^{s,d}$ in Equation (2) can be calculated using Equation (1).

EDP considers the node positions and the link delivery probability of reaching them as an OR metric. Recall that candidate c_i, which has received the packet, will transmit it, if the higher priority candidates (c_j, $1 \leq j \leq i-1$) have not received it. EDP considers this property of OR using $\prod_{j=1}^{i-1}(1 - p_{s,c_j})$ in Equation (2). EDP is classified in the local metric category, which considers the geographic position of nodes and the delivery property of links together.

Both metrics, EDP and DP, disregard the costs of delay related to coordination between candidates, which can highly affect the throughput of the network. Both metrics assume that the candidate with the highest priority that has received the packet is responsible for forwarding the packet and that the other candidates should discard the packet. Expected One-hop Throughput (EOT), which is a local metric, was proposed by Zeng et al. [2008].

—**Expected One-hop Throughput (EOT)** achieves a balance between the advantages of using DP and the costs related to the medium time delay.

The formula for EOT has many parameters and details, so we omit it here. EOT is a combination of DP, transmission quality, and the delay of a MAC medium as a result of candidate coordination. Therefore, it is a local metric that considers the link delivery ratio, the geographic position of nodes, and the candidate coordination process. Zeng et al. [2009] have extended their metric to adapt it with the multirate transmission.

2.1.2. End-to-End Opportunistic Routing Metrics. In contrast with local metrics, which only consider the local topology information, the end-to-end metrics are based on the whole topology information. *Hop-Count* metric [Yuan et al. 2005; Westphal 2006] is a simple metric developed from traditional routing protocols and reflecting the number of hops that build the route between two nodes. The nodes with a smaller number of hops to the destination are a better choice than those with a larger amount of hops. Each node needs to know the topology information and its hop-count to the destination. The hop-count metric does not consider the link delivery probability of reaching the candidates. Since this metric considers only the number of hops in its calculation to reach the destination, it may happen that a node has a smaller number of hops on its path toward the destination; subsequently, the link delivery probability to reach that node is very low. Therefore, the source may select some of its neighbors with smaller hop-counts, while the process of reaching them is very hard.

Another metric that is also borrowed from traditional routing protocols is the Expected Transmission Count (ETX) [De Couto et al. 2005].

—**Expected Transmission Count (ETX)** measures the number of times that a packet must be transmitted/retransmitted, on average, at a link or on route, to be received by the designated node.

The transmission of packets between nodes i and j is here assumed to be the Bernoulli trail, which has $p_{i,j}$ as the link delivery probability between two nodes i and j; therefore, the ETX of the corresponding link is:

$$ETX(i,j) = \frac{1}{p_{i,j}}. \tag{3}$$

It is easily derived from the definition that by adding up the ETX of each link on a path, the ETX of that path can be obtained. ETX is a simple metric to calculate and implement. Expected Transmission Time (ETT) [Draves et al. 2004] has been proposed as an extension of ETX to work in a multirate transmission scenario. The period of time that a packet needs to be transmitted across a link is defined by ETT. It multiplies ETX by the bandwidth of the corresponding link. Therefore, ETT can compute the time necessary to transmit the packet over the link. ETX and ETT are actually borrowed from the traditional routing protocols; they do not adapt well to OR because they only consider one link with the lowest cost. Authors [Dubois-Ferriere et al. 2007; Li et al. 2009a] have proved that ETX does not always find an acceptable CS. In Lu and Wu [2009], the authors showed that the performance of the network may degrade when the combination of OR with ETX is applied.

When a node is able to reach multiple neighbors, these multiple links can increase the probability of progressing toward the destination. Therefore, the cost of moving the packet forward depends not only on the link delivery probability but also on the number of links this can lead to. Li et al. [2009] proposed a new metric called Successful Transmission Rate (STR); it captures the expected successful transmission rate between a node and the destination. The authors formulated STR as follows:

$$STR(s,d,C^{s,d}) = \sum_{i=1}^{|C^{s,d}|} p_{s,c_i} \times STR(c_i,d,C^{c_i,d}) \prod_{j=1}^{i-1}(1-p_{s,c_j}). \tag{4}$$

STR considers that there is a possibility that multiple neighbors may receive the packet, and a priority is assigned to each of them. Note that STR does not capture the ExNT using OR.

Zhong et al. are the first researchers to propose Expected Any-path Transmission (EAX) [Zhong et al. 2006], which has been completely adopted for the process of OR.

—**Expected Any-path Transmission (EAX)** [Zhong et al. 2006] captures the ExNT while taking into account the multiple paths that can be used in OR.

Several mechanisms have been developed to estimate the EAX metric [Dubois-Ferriere et al. 2007; Li et al. 2009a; Cerdà-Alabern et al. 2010]. The following simple example illustrates the meaning of EAX. Consider the network topology shown in Figure 3.

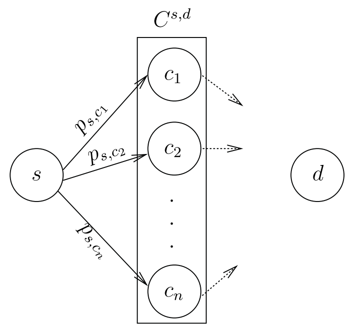

Fig. 3. Expected Any-path Transmission (EAX) calculation.

Let s and d be the source and destination nodes, respectively. Furthermore, assume that $C^{s,d}$ is the CS used to reach the destination d from node s. The probability that a packet transmitted by s can reach at least one of the candidates in $C^{s,d}$ is $1 - \prod_{i=1}^{|C^{s,d}|}(1 - p_{s,c_i})$. Therefore, the ExNT needed to deliver a packet from source s to at least one of its candidates in $C^{s,d}$ is given by:

$$S(C^{s,d}, s, d) = \frac{1}{1 - \prod_{i=1}^{|C^{s,d}|}(1 - p_{s,c_i})}. \tag{5}$$

After a node(s) in the CS of s receives the packet, the candidate with the highest priority is responsible for forwarding the packet. The ExNT used to reach the destination d from one of the nodes in $C^{s,d}$, which is responsible for forwarding the packet, is depicted through the following equation:

$$Z(C^{s,d}, s, d) = \frac{\sum_{i=1}^{|C^{s,d}|} EAX(C^{c_i,d}, c_i, d)\, p_{s,c_i} \prod_{j=1}^{i-1}(1 - p_{s,c_j})}{1 - \prod_{i=1}^{|C^{s,d}|}(1 - p_{s,c_i})}. \tag{6}$$

Note that in Equation (6), the product $\prod_{j=1}^{i-1}$ is equal to 1 for $i = 1$. Furthermore, node c_i acts as the next-hop forwarder if none of its previous candidates ($\{c_1, c_2, \ldots, c_{i-1}\}$) receives the packet successfully. Using the same assumptions as in Equation (3), the ExNT needed to reach destination d from s can be calculated; this is done by summing up the number of transmissions from the source to its CS ($S(C^{s,d}, s, d)$) and the number of transmissions from CS to the destination ($Z(C^{s,d}, s, d)$), given by the recursive formula:

$$EAX(C^{s,d}, s, d) = S(C^{s,d}, s, d) + Z(C^{s,d}, s, d). \tag{7}$$

Due to the recursive nature of EAX formula, the cost of calculating EAX in a large network with a great number of candidates is very high. But, on the other hand, the ExNT for the candidate selection algorithms that use EAX is better than those that use ETX [Darehshoorzadeh and Cerdà-Alabern 2010; Darehshoorzadeh et al. 2011]. We further discuss these two issues in Sections 5.

One of the pitfalls of all these mentioned metrics is that they consider all nodes to be awake and listening to the media at all times, which is not the case when a node is in sleep mode. The problem is more serious for a network where nodes may turn off their radio antenna due to energy constraint properties; for example, Wireless Sensor Networks (WSNs). Ghadimi et al. [2012] introduced a new metric that considers the energy efficiency of the network. An analytical model that captures the expected number of duty cycles was provided by the authors. Their formula is quite complex to be used on a protocol for the selecting of the CSs. Thus, an estimation of end-to-end

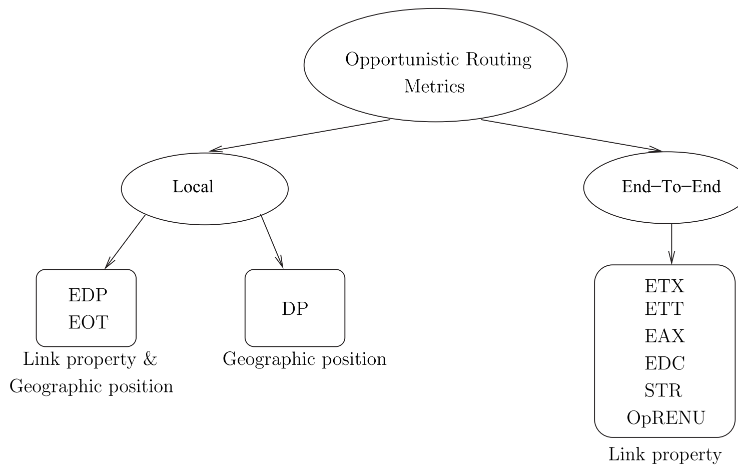

Fig. 4. Classification of OR metrics.

antenna duty cycle is calculated as Estimated Duty Cycle (EDC) wake-ps. It shows the energy consumption of the nodes that are on the path to forward the packets from sink to the destination.

All of the explained metrics are based on the delivery property between nodes or on the geographic position of them. Wu et al. [2008] defined a new metric based on a function of benefit and transmission cost. After successfully delivering a transmitted packet, the utility of the delivery is defined as the benefit after deducing the cost of transmission. The metric proposed based on this definition is called Opportunistic Residual Expected Network Utilities (OpRENU) and is formulated thus:

$$Opu_s^{C^{s,d}} = \sum_{i=1}^{|C^{s,d}|} \left(Opu_i^{C^{i,d}} \times p_{s,i} \prod_{j=1}^{i-1} (1 - p_{s,j}) \right) - COST, \tag{8}$$

where $Opu_i^{C^{s,d}}$ is the OpRENU of node i employed for the purpose of reaching destination d by using $C^{s,d,}$ and $COST$ is the transmission cost at node s. For a set of candidates, OpRENU reflects the utility of forwarding the packet toward the destination using this set of nodes. As we can see, OpRENU is a recursive formula that considers the benefit and cost of transmission under OR.

Figure 4 summarizes all metrics discussed in this section. The parameter that each metric uses under each classification is shown in this figure. As we can see, most of the proposed metrics are in the end-to-end taxonomy, with link delivery property as the parameter of measurement. Generally speaking, using the metrics that reflect an end-to-end property (e.g., ETX, ETT, or EAX) requires the network information to be gathered by an underlying link-state routing protocol. The accuracy of these kinds of metrics depends on the way they estimate the quality of the links and on the way they broadcast the information. In Section 5, we review different OR protocols with the metrics that they use to find and order the CSs.

3. CANDIDATE COORDINATION METHODS

Coordination between candidates is a challenging issue in OR. It is the mechanism used by candidates to clarify whether to forward the received packet or discard it. To coordinate between candidates, nodes need to send control messages. Therefore, unsuccessful signaling may cause more than one candidate to forward the packet, and the network will suffer from unnecessary transmissions. An effective candidate

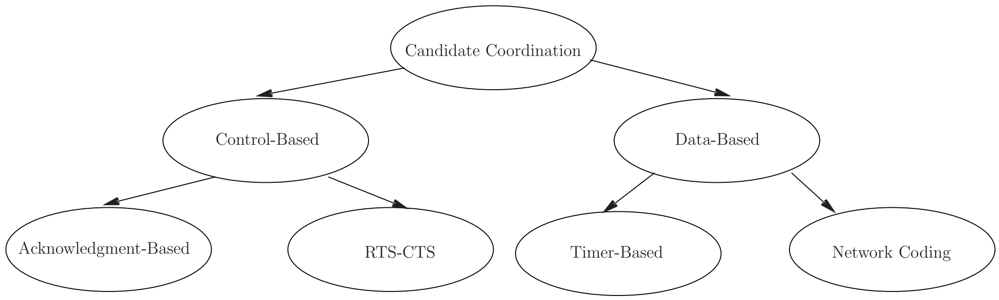

Fig. 5. Candidate coordination classifications.

coordination mechanism must avoid the transmission of more than one packet by selecting the best candidate to forward the packet.

Figure 5 lists the solutions for candidate coordination proposed in the literature. *Control-based* and *data-based* candidate coordination are two main categories. Each candidate in the control-based method uses a control packet to inform the other candidates whether it has received the packet or not. On the other hand, data-based approaches do not rely on any control packets. In the following sections, we explain each candidate coordination approach in more detail.

3.1. Control-Based Coordination

In the control-based approach, each node orders its CSs according to a metric. Upon receiving the packet by a candidate from a previous node, this approach sends out an explicit control packet: for example, acknowledgment (ACK) or Request-to-Send (RTS)-Clear-to-Send (CTS). This control packet is sent back to the sender according to the priority order mentioned in the CS. We explain in the following sections two of the most important approaches of control-based coordination: *Acknowledgment-based* and RTS-CTS coordination.

3.1.1. Acknowledgment-Based Coordination. The Acknowledgment-based (ACK-based) method is one of the first solutions proposed for candidate coordination. When candidates receive a packet, they return a short acknowledgment message (ACK). The ACKs are sent out in an up-down order, in which the candidate with the highest priority is the first and the lowest priority candidate is the last. This method was first proposed in Larsson [2001] as the coordination mechanism for the Selection Diversity Forwarding (SDF) protocol. Based on the ACKs received, the sender sends a *forwarding* control packet to the best candidate. The best candidate will forward the packet, and the other ones will discard it.

Extremely Opportunistic Routing (ExOR) [Biswas and Morris 2004] uses a similar approach provided by SDF. In ExOR, candidate coordination needs to modify the MAC layer of 802.11. Each candidate has a reserved slot of time to send back the ACK. The ACK implies that the corresponding candidate has successfully received the packet. Moreover, the ACK message for each candidate carries the IDs of the other higher priority candidates that have received the packet successfully. The candidates must listen to all slots in order to be able to make the decision to forward the packet. Therefore, in the case that the ACK of a higher priority candidate was not received correctly by some candidates, its ID may appear in the ACK of a lower priority candidate.

Figure 6 shows how ACK-based coordination works. Consider a network in Figure 6 with source S and destination D. Assume that the CS of S is $\{A, B, C\}$ (A has the highest priority and C has the lowest one). Suppose that all candidates receive data

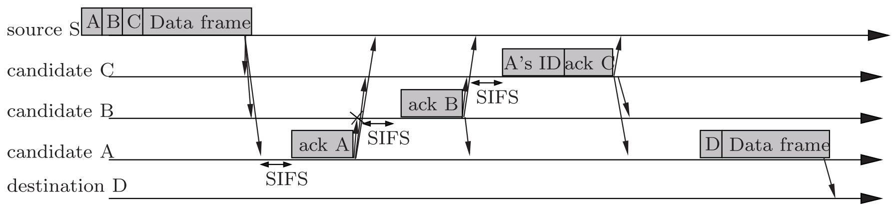

Fig. 6. Acknowledgment-based coordination using a modified 802.11 MAC.

sent from the source. All candidates transmit their acknowledgments in the decreasing order of candidate priority. That is, A sends its ACK in the first time slot, the second acknowledgment slot belongs to node B, and the third slot is dedicated to C. In this example, we have assumed that B cannot hear the ACK sent by A; however, node C hears the ACK of A. Furthermore, we assume that the ACK of C is heard by node B. If the ID of the successful recipient with the higher priority known to C (i.e., the ID of A) is not included in C's ACK, node B would then forward the packet. Due to the knowledge of B, it is the recipient with the highest priority. Note that when node C puts A's ID in its ACK, it indirectly notifies node B that another higher priority candidate (node A) has received the packet. After the three time slots, node A will forward the packet.

The ACK-based coordination strategy requires candidates to be close to each other so that the ACK transmission can be heard by the other candidates. If a candidate with a lower priority cannot hear any other higher priority ACKs, there will be a duplicate packet transmission. The other drawback of this method is the modification of current off-the-shelf 802.11 network cards so that they are able to send ACKs at different time slots.

In Yang et al. [2009a], the authors show that in the coordination mechanism based on ACK, the wireless channel will stay idle for a period of time if the candidate with the highest priority does not receive the packet. This period of time is longer than the Distributed Inter Frame Space (DIFS). Therefore, the ACK sequence for the lower priority candidates may collide with another transmission flow from other nodes that did not hear the data packet. As a result, when none of the candidates receives any ACK from higher priority candidates, they all will transmit the packet.

To address the issue regarding ACK-based coordination methods, the authors [Yang et al. 2009a] proposed an enhanced mechanism called Fast Slotted Acknowledgment (FSA). FSA provides a lower period of delay than other similar methods. In FSA, only one ACK is sent by the highest priority candidate that has received the packet. It sends the ACK after a delay period of Short Interframe Space (SIFS). The other candidate must monitor the channel for a period of $T_{Sensing}$. If they detect any ACK, they will prohibit the further sending of any ACK. Otherwise, they assume that the candidate with the highest priority did not receive the packet and, therefore, the second candidate is supposed to send the ACK when the next $T_{Sensing}$ starts. This process will continue until a candidate that has received the packet successfully returns an ACK.

The performance of FSA is dependent on the precision of the channel-sensing technique. It may occur that some candidates consider another interference in their channel as the ACK sent by a higher priority node. In this case, they will suppress the response to forward the packet [Yang et al. 2009a]. In addition, consider the case where a lower priority candidate fails to detect the ACK of another higher priority one. Thus, the lower priority candidate will send its ACK, which may collide with the other ACK and result in duplication.

3.1.2. RTS-CTS Coordination. Coordination based on control messages, which are sent before a data packet transmission starts, is proposed in Jain and Das [2008] and Zorzi

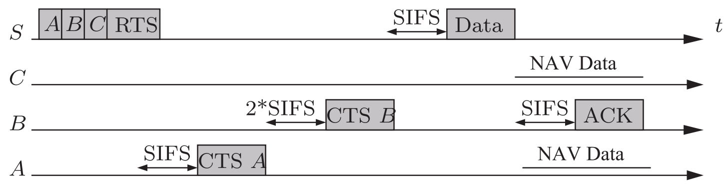

Fig. 7. RTS-CTS coordination approach.

and Rao [2003]. The sender puts the IDs of the candidates in the RTS packet, ordering them based on a metric and broadcasting it.

The transmission of CTS must be done based on the order of the candidates: the highest priority candidate sends the CTS after a period of time equal to SIFS, the second candidate in the list of priority sends the CTS after a period of 2×SIFS, and so on. The sender starts to send the data packet to the intended candidate when it receives the first CTS. The data transmission starts after a delay of SIFS. This makes the other candidates prohibit the sending of their CTS when they overhear the data transmission. They all put their channels on Network Allocation Vector (NAV). This approach provides only one winner and thus prevents a multiple transmission of a single packet.

Figure 7 explains the RTS-CTS mechanism through an example. Assume that the three available nodes (A, B, C) are chosen as the candidates. The priority of each candidates is assigned in decreasing order of their names: A is the candidate with the highest priority and C has the lowest. As shown in this figure, the first CTS sent by A fails to be delivered to the sender, although it received the CTS of B. Therefore, S will send the packet to B, and the rest of the candidates will set their channel to NAV. In this method, the candidate with the highest priority thatsends the CTS successfully will forward the packet.

Note that the candidate coordination in RTS-CTS is finished before sending out the data packet, and, when a node is specified as the next forwarder, the packet will be sent to it in the unicast mode. It may happen that, because of channel condition, a candidate that is selected as the next forwarder may not receive the data packet, and the source will then need to retransmit the packet. Like the ACK-based method, the current off-the-shelf 802.11 network cards have to be modified to enable the sending of multiple CTSs during the broadcast mode in different time slots.

3.2. Data-Based Candidate Coordination

The control-based approach has to perform some modifications on the current off-the-shelf 802.11 network cards. Furthermore, it needs some control packets that, in a large network, may lead to a poor scalability. On the other hand, data-based coordination does not rely on any extra control packets. It can be done through Timer-based or Network Coding (NC) approaches, which are explained in the following sections.

3.2.1. Timer-Based Candidate Coordination. In the Timer-based coordination mechanism, the coordination and data forwarding are joined together. In this method, the candidate must be ordered based on a metric, and, based on this order, a time slot is assigned to each candidate. When a data packet is sent, the candidates that have received the packet must forward the packet according to this order. In this mechanism, the ith candidate forwards the packet at the ith time slot. The candidate listens to the channel before its time slot arrives to determine if any other candidates have forwarded the packet.

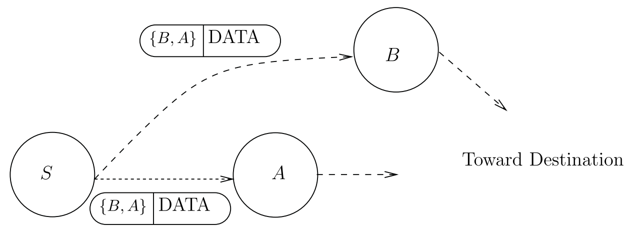

Fig. 8. Timer-based coordination.

In this method, the candidate with a lower priority forwards the packet in its assigned time slot only when it does not hear the candidate with a higher priority forwarding the packet. In the example of Figure 8, assume that $\{B, A\}$ is the CS of source S used to reach destination D (B has a higher priority than A). After receiving the packet sent by S, candidate B forwards the packet in the first time slot, while A will forward in the second slot. If A is in the radio range of B, and A overhears the data packet sent by B, A knows that a higher priority candidate than itself has received the packet and has forwarded it; thus, A simply discards the packet.

This approach has no extra control packet and is easy to implement. The overhead for the timer-based coordination is candidate waiting time. Usually, the link quality used to reach the highest priority candidate is low, and, most of the time, the packet will not be delivered to this candidate. Therefore, the candidates with a lower priority need to wait for a period of time before they have a chance to forward the packet. If only the lowest priority candidate receives the packet, it has to wait for a long period of time to confirm that it is the only one that has received the packet. Thus, this increases the waiting time, whichdegrades throughput. The other drawback of this method is duplicate transmission because there is no guarantee that all candidates can overhear forwarding from the selected candidate. Therefore, when a lower priority candidate does not hear the transmission of a higher priority candidate, it will forward the packet.

3.2.2. Network Coding Candidate Coordination. If Network Coding (NC) [Ahlswede et al. 2000] is applied to OR, it is able to avoid duplicate transmissions by coding the packet, without any need to coordinate the method between candidates. Here, the nodes can combine multiple packets in a single packet and transmit them all in a single transmission. In this method, the flow of packets is split into batches that contain many original packets without coding (native). The source then broadcasts packets that are a linear combination of native packets. The candidates forward the received coded packets that are linearly combined. The original packets can be decoded at the destination whenever the destination receives enough linearly independent coded packets. To better clarify the advantage of combining NC with OR, consider the example of Figure 9. Assume that source S transmits two packets a and b using $\{C_1, C_2\}$ as the CS. Assume that C_2 receives both packets but C_1 receives only one of them (see Figure 9). Node C_1 transmits first because it is closer than C_2 to the destination. In the NC, node C_2 can create a new packet with content $a \oplus b$ and forward it. When D receives transmitted packets from C_1 and C_2, it can decode and restore the original packets.

However, using NC in OR may cause a lot of candidates to send coded packets, which results in redundant transmissions. That is, there are some packets that are not duplicates, but they do not provide new information. On one hand, the destination needs to receive enough coded packets to be able to decode the original packets from them, but, on the other hand, transmitting several unnecessary packets degrades the performance of the network [Bruno and Nurchis 2010]. Moreover, the delay caused by

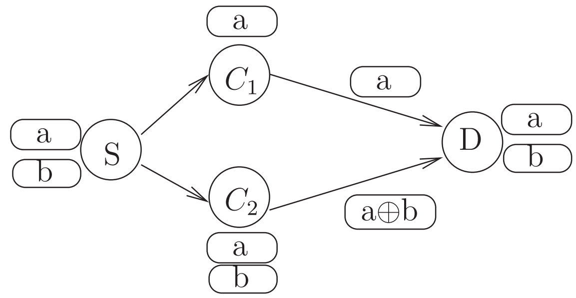

Fig. 9. NC coordination approach [Liu et al. 2009].

the coding and decoding process will increase the end-to-end delay of the transmitted packets.

4. CANDIDATE SELECTION ALGORITHMS IN OPPORTUNISTIC ROUTING

Another important component of OR is candidate selection. The candidate selection algorithm is a mechanism that helps a node select and sort a group of neighboring nodes as candidates. The candidates then serve as forwarders to help the source send the packet toward the destination. *Candidate Selection* is the name assigned by researchers to this type of algorithm. The selecting of different candidates has a great effect on the performance of a network. If the candidates coordinate perfectly with each other, then selecting more candidates decreases the number of transmissions in the network. Note that the number of candidates that each node is allowed to choose should be limited because having a greater number of candidates results in having more overhead attributed to the candidate coordination process in the network.

A node needs to have some information about the network in order to be able to select some of its neighboring nodes as candidates. Candidate selection algorithms, based on the amount of information needed to select the candidates, are categorized into two main categories: topology-based and local-based (geographic-based).

—Topology-based selection: The CSs are selected based on the topological information of the network.
—Local/Geographic-based selection: Limited information is used in each node to independently determine the CSs based on the local information.

The selection of CSs in the topology-based approach is dependent on global topology information; therefore, a node is required to maintain some network state information. Usually, the taxonomy of candidate selection algorithms is relatively close to the metric classification they use. Most of the topology-based and local-based candidate selection algorithms use end-to-end and local (geographic) metrics, respectively (see Section 2). As we mentioned in Section 2, the use of an end-to-end metric in comparison with local metrics for the selection and prioritization of CSs results in a better network performance. Usually, the topology-based mechanisms provide better performance than do local-based ones; this is because the topology-based strategies are able to select better CSs, using more information about the network obtained by applying the end-to-end metrics. On the other hand, a node in a topology-based approach usually has to delay its candidate selection process until its neighbors find their CSs. Furthermore, they usually use metrics with a recursive formula. Therefore, the execution time of a topology-based algorithm is longer than that of a local-based one. However, the local-based (geographic-based) strategies requiring less control packets are easier to implement and scale better than do topology-based algorithms.

Considering the main aim of OR, which is the reduction of the number of packet transmissions in the network, the candidate selection algorithms can be classified into two classes: optimum and nonoptimum. The optimum algorithms find the CSs that minimize the most important metric in OR (ExNT). Nonoptimum algorithms, conversely, usually use a heuristic algorithm to find the CSs. Note that EAX is a metric that captures the ExNT from a node to a given destination using OR. Therefore, an optimum algorithm has to use EAX as the metric for choosing and prioritizing the CSs. Since the optimum candidate selection algorithms use EAX and target finding the best CSs, their computational costs are much higher than nonoptimum ones. Darehshoorzadeh et al. [Darehshoorzadeh and Cerdà-Alabern 2010; Darehshoorzadeh et al. 2011] investigated the performance and execution time of different algorithms for candidate selection. They showed that some heuristic algorithms have a performance similar to the optimum ones although their execution times are much shorter than optimum algorithms. In Section 5, we review some notable candidate selection algorithms from both topology and local-based (geographic-based) algorithm categories.

The first candidate selection algorithms were proposed to apply OR in a unicast scenario. Like the traditional routing protocols, OR can be applied for delivering packets to multiple destinations by taking the benefits from the broadcast characteristic of the wireless medium. From this point of view, there are two different kinds of OR protocols: unicast OR and multicast OR protocols. Compared to the unicast OR, there are few works that have been proposed to adapt OR to multicast scenarios. In the presence of more than one destination, the processes of selecting and coordinating between candidates become more complicated. In Section 5.4, we discuss the differences between OR applied in multicast and unicast protocols and review the state-of-the-art of multicast OR protocols.

5. OVERVIEW OF OPPORTUNISTIC ROUTING PROTOCOLS

In this section, we review the most notable OR protocols proposed in the literature. Based on the classification introduced for candidate selection in Section 4, we examined four different types of protocols: topology-based, geographic-based, network coding, and multicast OR. To show the differences among the most notable and referenced protocols, we use a simple example in Section 5.1.

5.1. Topology-Based Opportunistic Routing Protocols

Recall that candidate selection algorithms based on topology information find CSs according to global network topology information. Furthermore, from the point of minimizing a metric in the network, the OR protocols are nonoptimum or optimum (see Section 4). To be more precise, we have distinguished each topology-based OR protocol as being either a nonoptimum and an optimum protocol.

5.1.1. Nonoptimum Opportunistic Routing Protocols. Larsson [2001] presented SDF, which is based on combining the forwarding and MAC layer protocols. In SDF, the sender includes the CS in the header of the data packet and broadcasts it. The nodes, which are included in the CS, reply to the sender in order of priority with an ACK packet. The sender selects one of them according to the current link conditions to forward the packet. The requirements of the upper layer protocols affect the decision to select the next-hop forwarder. For example, the next-hop forwarder can be a node that can be reached by less ExNT. After the sender selects the next forwarder, it sends a *forwarding* control packet. The node whose ID is mentioned in the *forwarding* packet is selected as the next forwarder, and the other candidates drop the packet. SDF simply suggests an easy way to provide a CS through a classical SPF algorithm, such as the distributed Bellman Ford algorithm. Authors have shown that SDF performs better than traditional protocols in terms of forwarding progress of packets. SDF uses a four-way handshake method to forward the packet. Obviously, the waiting time experienced before sending the *forwarding* packet can increase the end-to-end delays.

Biswas and Morris proposed ExOR [Biswas and Morris 2004]. In ExOR, candidates are selected based on the ETX metric. The Shortest Path First (SPF) with ETX as the weight of links is run in ExOR to find the CSs. Every node *s* with the exception of the destination node runs SPF from itself to the destination. If the ETX of the first node in the found path is less than the ETX of node *s* to the destination, it is then selected as the candidate. The algorithm continues by removing the link between node *s* and the selected candidate. It will continue until no new candidate can be added to the CS. At the end, to sort the candidates in the CS, the ETX of a candidate to the destination is considered as a metric. Whenever the source decides to send a packet, it puts the list of candidates into the packet and broadcasts it. Any of the candidates receiving the packet successfully returns an ACK message to inform the source and other candidates. Indeed, ExOR uses the ACK-based approach for candidate coordination. The highest priority candidate that has received the packet will forward it while others discard it.

In Biswas and Morris [2005] another version of ExOR is developed. Here, ExOR uses the batch transmission of 10–100 packets to solve issues regarding the ACK-based coordination method. Packets are collected to be transferred in a batch. Each batch starts only after the end of the current batch. In this new implementation of ExOR, which is the same as the old version, priority is assigned to candidates based on the ETX. To avoid duplicate transmissions, a map is included in a batch. This map shows that, for each packet, the candidate with the highest priority has received the packet successfully. While the packet is progressing to the destination, the receiving node uses the information of the batch map included in the packet to update its local map. The node may then forward the packet only if the packet has not been forwarded by a node with a higher priority. Based on this, it is obvious that the coordination method is based on the timer-based technique (see Section 3.2.1). The protocol is evaluated by using an outdoor 802.11b-based network on Roofnet [Roofnet 2002]. This implementation of ExOR transmits 90% of packets using the batch and OR mechanisms, and the remainder of the packets are sent using the traditional unicast routing mechanism.

In both versions of ExOR, if a candidate with lower priority cannot hear any of the other higher priority candidate ACK messages or forwarded packets, there will then be a duplicate packet transmission in the network. The other drawback of the first version of ExOR is its method of modifying the current off-the-shelf 802.11 network cards so that it sends ACKs in different time slots.

Simple Opportunistic Adaptive Routing (SOAR) [Rozner et al. 2009] has been proposed after ExOR. SOAR selects the candidates located close to or along the shortest path; therefore, they are able to overhear each other. This technique reduces duplicate transmissions while benefiting from path diversity. Because the selected candidates are close to the node on the shortest path toward the destination, the candidates with a reasonable link delivery probability can hear each other, thus coordination can be simplified. SOAR finds the SPF from the source to the destination based on ETX, then the nodes close to the shortest path may be selected to be in CS. Moreover, SOAR makes sure that the ETX of the links between all pairs of candidates are within a threshold. This is essential to making sure that all candidates are able to hear each other. SOAR uses the timer-based approach for candidate coordination. The destination returns an ACK to the source whenever it receives a group of packets; this is done to announce to the source the amount of packets it has received. Authors compared SOAR with ExOR in Ns-2 [Issariyakul and Hossain 2008] simulator and an 18-node wireless mesh test bed. Their results showed that their proposal outperforms ExOR and traditional routing protocols in a wide range of scenarios.

Both ExOR and SOAR use ETX for the candidate selection algorithm. As we mentioned in Section 2.1.2, ETX does not adapt well to OR; this is because ETX only considers one link that has the lowest cost for the purpose of reaching the destination, whereas EAX is completely adapted to the function of OR. The first protocol that used EAX as the metric for candidate selection was Opportunistic Any-Path Forwarding (OAPF) [Zhong et al. 2006; Zhong and Nelakuditi 2007]. It adds the candidates one by one to the CS. First, the algorithm determines an initial CS for the source based on the ETX of each neighbor needed to reach the destination. A node with a smaller ETX to the destination than the source node is included in the initial CS.

Using OAPF, all candidates selected in the initial CS are required to select their candidates first. The source node then uses the initial CS to select those candidates that provide the best EAX from the source to the destination. The best candidate is added to the actual CS of the source, and it is removed for the initial set. The next best candidate is selected from the initial set of the source. The above-mentioned algorithm is repeated until there are no more candidates for selection. The final CS is ordered according to the EAX of each candidate to the destination. OAPF use the timer-based approach for the coordination process.

The performance of OAPF at the link-layer is measured and analyzed in MIT Roofnet [RoofNet 2002]. It is shown that to reduce the number of transmissions effectively, the number of candidates must be limited and moderate. Consequently, only those nodes that would significantly reduce the cost of a packet will be included in the CS. The performance of OAPF is better than ExOR, although its complexity and the time needed to find the CS are more than that of ExOR.

Finding candidates in OR requires sending control packets. Authors in Ajmal et al. [2013] addressed the computational overhead of OR by designing the Coordinated Opportunistic Routing Protocol for WMNs (CORP), which does not rely on a preselected CS. The destination broadcasts a packet to find the possible paths toward the destination. Each node that receives the packet calculates the measurement of its link cost to the node from which it has received the packet, then updates the cost of reaching the destination and rebroadcasts the packet. Note that the link cost in Ajmal et al. [2013] is in terms of ETX. In this way, the source will find paths toward the destination with different hops and cost. By a simple formula, the source divides the network topology into different regions. The source broadcasts its data packet. Each node that has received the packet sent from the source calculates the region in which it is located according to the region that the packet arrived from. If the receiving node is located in a region that makes the received packet progress toward the destination, then it will be responsible for forwarding the packet; otherwise, it will drop the packet. The advantage of this approach is that each node does not need to find the CS before sending or forwarding the packet. But, on the other hand, it may happen that more than one node receives the packet in a region and will thus forward the packet. The same problem for candidate coordination will happen if the candidates cannot hear each other.

5.1.2. Optimum Opportunistic Routing Protocols. Optimum OR protocols find those CSs that minimize the ExNT in the network. In Dubois-Ferriéandre et al. [2007, 2011], an optimum candidate selection algorithm referred to as Least-Cost Opportunistic Routing (LCOR) was proposed. EAX is used in LCOR [Dubois-Ferriere et al. 2007] to find the CSs. The finding process is completed over iterations, and all possible CSs are checked during each iteration, which can use a large amount of computational time in a dense network.

Minimum Transmission Selection (MTS) [Li et al. 2009a] is another optimum candidate selection protocol. Like LCOR, EAX is used in MTS to find the CSs. MTS first chooses the node with the least EAX to reach the destination. Then the algorithm moves backward to the source from the selected node. MTS uses the following rule to build the CS: if a node i provides a smaller amount of ExNT compared to its neighbor j, then including node i and its candidate sets in the CS of node j will improve the ExNT to the destination from node j [Darehshoorzadeh and Cerdà-Alabern 2010]. Based on this fact, the algorithm finds the node with the smallest value of EAX, which is called *MinNode*. MTS then adds *MinNode* and its CS to the CS of the neighbors of the *MinNode*. It uses the timer-based approach for candidate coordination among the nodes that have successfully received the packet. Darehshoorzadeh et al. [2011] showed that MTS has a shorter execution time compared to LCOR, whereas the ExNT in both algorithms is the same.

Jie Wu et al. [Wu et al. 2008] proposed a utility-based OR protocol for balancing tradeoff between the cost of transmitting a packet and transmission reliability. The objective is to maximize utility; this is defined as a function of transmission cost and benefit. They used OpRENU, defined in Section 2.1.2, as the metric for optimization. They proved that if the protocol is able to maximize the OpRENU, then it is not necessary for the selection algorithm to choose the candidates only from those neighbors close to the destination. The authors proposed two algorithms to find a CS based on OpRENU: an optimum and heuristic candidate selection algorithm.

Existing works on OR in WMN only focus on delivering the packets from a node to a particular destination in a WMN. A recent work, *Plasma* [Laufer et al. 2012], addressed the problem of gateway any-casting via OR. In Plasma, selecting the path and gateway for each packet is made on the fly by nodes as the packet is forwarded in the network. Each packet in Plasma can be delivered to any of the gateways. Furthermore, it uses the idea of OR to reach one of the gateways. The authors proposed an optimal distributed routing algorithm from a source to any gateway in the WMN.

As a preliminary measure, most of the presented protocols and algorithms of candidate selection are evaluated against the traditional routing protocol. The only study that compares the performance of different candidate selection algorithms was conducted by Darehshoorzadeh et al. [Darehshoorzadeh and Cerdà-Alabern 2010; Darehshoorzadeh et al. 2011]. The authors assumed that, for all algorithms, candidate coordination works perfectly. They performed a comparison among a variety of algorithms ranging from simple ones like ExOR, algorithms with moderate computational complexity such as OAPF, and highly complex algorithms that find the optimal set of candidates, such as LCOR and MTS. The main metrics evaluated by the authors were the ExNT and the variance from the mean number of transmissions. Moreover, the authors provided the processing time of each algorithm needed to build the CSs. Their first important observation is that when an unlimited number of candidate is used in each node, all candidate selection algorithms perform almost the same.

Under the condition of a limited maximum length for the CSs, the performance analysis shows that ExOR results in a larger number of transmissions compared to the other algorithms, whereas OAPF can perform as well as the optimal algorithms. From another observational point of view, ExOR performs faster than the other algorithms since it is proposedly based on ETX, whereas algorithms that use EAX to build the CSs run more slowly. Note that although MTS and LCOR have high computational time in dense networks, MTS runs much faster than LCOR. However, OAPF outperforms optimum algorithms in terms of execution time.

We implemented and compared the performance of different OR protocols using NS-2 [Issariyakul and Hossain 2008] in Darehshoorzadeh and Boukerche [2014]. The

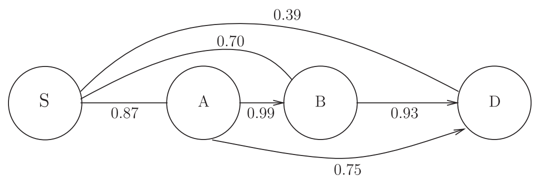

Fig. 10. Example of candidate selection algorithms.

Table I. ETX of Each Node to *D* in Figure 10

Node	ETX(Node, *D*)
S	2.48
A	1.33
B	1.07
D	0

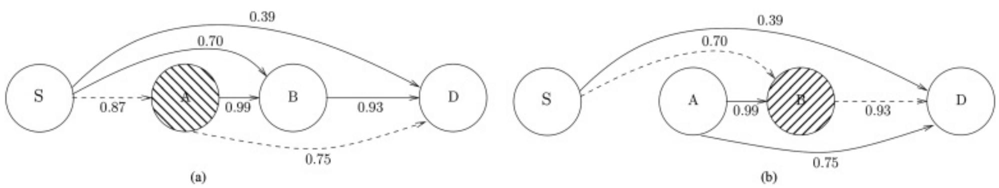

Fig. 11. Example of candidate selection algorithms using ExOR.

performance of OR protocols was measured in different terms: packet delivery ratio, expected number of transmissions, hop-count, and end-to-end delay. The simulation results show that having two candidates and two or three retransmissions, in the case that none of the candidates receives the packet, causes a high packet delivery ratio. We found that the end-to-end delay of ExOR is less than the other protocols under study, but there are more transmissions from ExOR in the network.

5.1.3. An Example of a Candidate Selection Algorithm. We finish the topology-based OR protocol section by applying three candidate selection algorithms from different ranges to a simple example shown in Figure 10. The candidate selection algorithms are ExOR [Biswas and Morris 2004], OAPF [Zhong et al. 2006], and an optimum algorithm called MTS [Li et al. 2009a]. As we can see, the selected algorithms range from nonoptimum (ExOR) to optimum (MTS). We use this example to show the way different candidate selection algorithms work. Regarding candidate coordination in each protocol, we explain the different approaches used in Section 3.

Assume that node S is the source and D is the destination. The delivery probability of each link is indicated over the corresponding link (see Figure 10), while the maximum number of candidates for each node is set to 2. The ETX of each node to destination D, using unipath routing as shown in Table I. We just explain the way the source uses to find its CS. In the case of other nodes, the algorithm works the same as it does for the source node.

Assume that node S in Figure 10 wants to find its CS using ExOR. Figure 11 shows the ExOR algorithm applied on this example. According to ExOR, node S finds the SPF to D, which is S-A-D (dashed path in Figure 11(a)) with ETX = 2.48 (see Table I). Therefore, node A will be one of the candidates for S (shaded node in Figure 11(a)). Edge S-A is then removed from the topology, and SPF is run again. The new shortest path from S to D becomes S-B-D (Figure 11(b)) with ETX = 2.50, and B is selected as

Table II. CS of A and B in Figure 10 using OAPF

Node	Candidates Set	EAX
A	$\{D, B\}$	1.26
B	$\{D\}$	1.07

Table III. OAPF Operation

Iteration	Selection		
1	$EAX(\{A\}, S, D) = 2.41$,	$EAX(\{B\}, S, D) = 2.50$,	$EAX(\{D\}, S, D) = 2.56$
2	$EAX(\{B, A\}, S, D) = 2.16$,	$EAX(\{D, A\}, S, D) = 1.81$	

another candidate. Finally, to sort the CS, the ETX of each selected candidate to the destination D is used. The final CS of node S is $C^{S,D} = \{B, A\}$ with the ExNT equal to 2.16.

Now assume that node S in Figure 10 wants to find its CS using OAPF. First, it creates its initial CS $\hat{C}^{S,D}$. Because the ETX of all source neighbors (A, B, and D) to D is less than its ETX (see Table I), the initial CS of S is the $\hat{C}^{S,D} = \{A, B, D\}$. Recall how in OAPF nodes in the initial CS have to find their CS before S. In Table II, we summarized the CS and related the ExNT for nodes B and A using OAPF.

Table III shows the process of selecting candidates for the source S using OAPF. The notation $EAX(c_1, c_2, \ldots, c_{ncand}, S, D)$ in Table III refers to the ExNT required to deliver a packet to D from source S using $\{c_1, c_2, \ldots, c_{ncand}\}$ as the CS. In the first iteration, the source selects A as its candidate because A is the candidate that reduces for most the EAX from S to D. The CS of S in the first iteration is $C^{S,D} = \{A\}$. Node A is then removed from the initial set. In the second iteration, the source looks for the second candidate from the remaining potential candidates in $\hat{C}^{S,D} = \{B, D\}$. As we can see in Table III, the next candidate that most greatly reduces the ExNT from S to D is D. The EAX of each selected candidate to the destination is then used to order the CS. Therefore, the final CS for the source using OAPF is $C^{S,D} = \{D, A\}$ with EAX equal to 1.81.

To find the CS for a node in ExOR and OAPF, it is not necessary to find the CSs of all nodes in the network. If the CSs of nodes on the opportunistic path from a source node to the destination are found, then the source node is able to find its CS. While in MTS, for the purpose of finding the CS of the source node, all nodes in the network must find their CS.

MTS starts by inserting all nodes except the destination into the initial set. Furthermore, it initializes the transmission cost of each node in the initial set to reach the destination. The initial cost of nodes S, A, and B to transmit to the destination D is $\frac{1}{0.39}$, $\frac{1}{0.75}$, and $\frac{1}{0.93}$, respectively. This parameter for destination D is equal to 0. If a node has a link to the destination, it adds the destination to its CS (see Figure 12(a)). The box above each node in Figure 12 shows the CS and EAX related to the corresponding node. In the next iteration, MTS searches for the node that has the minimum EAX to the destination. As we can see in Figure 12(a), the EAX of B to reach the destination is the minimum one (1.33); it is then removed from the initial set; node B and all its candidates ($C^{B,D} = \{D\}$) are added to the CSs of all B's neighbors; that is, nodes S and A (see Figure 12(b)). The unshaded nodes in Figure 12 are the nodes in the initial set. Note that, in each iteration, the EAX of each node is updated according to the new CS. In the third iteration, the node with the minimum EAX is A, with an ExNT equal to 1.26. It is removed from the initial set, and node A and its CS are added to the CSs of all A's neighbors; those are still in the initial set (i.e., node S). Now, each of the nodes in Figure 10 has a set of candidates to reach D (see Figure 12(c)). Note that until this step is accomplished, MTS finds the CSs without any restriction on the number of

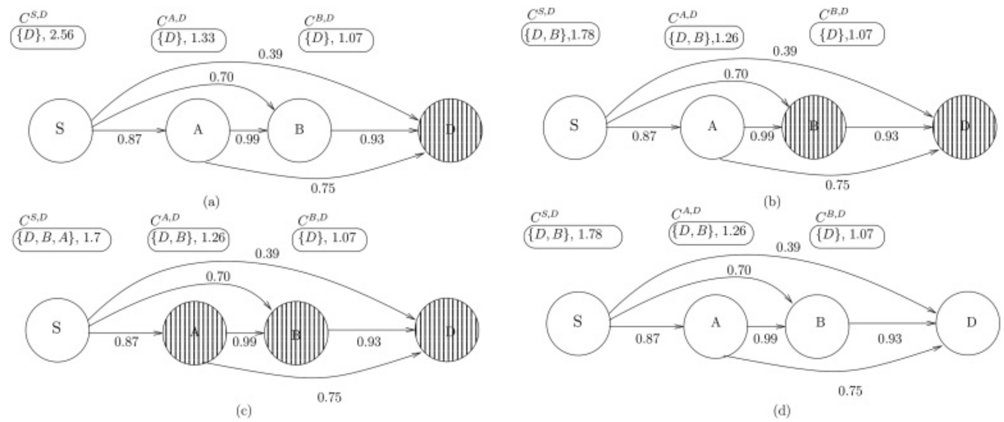

Fig. 12. Example of candidate selection algorithms using MTS.

Table IV. CSs and EAX of Each Node in Figure 10 Using Different Algorithms

Node	ExOR	OAPF	MTS
S	{B, A}, 2.16	{D, A}, 1.81	{D, B}, 1.78
A	{D, B}, 1.26	{D, B}, 1.26	{D, B}, 1.26
B	{D}, 1.07	{D}, 1.07	{D}, 1.07

candidates. Performing an exhaustive search while constraining the maximum number of candidates for selection in each node to 2 results in the optimum CSs, with a length at most that equals 2; this is shown in Figure 12(d).

We summarize the CSs and EAX of each node in Figure 10 by using different algorithms under study in Table IV. The first item in each cell is the CS for the corresponding node, and the second item is the EAX of the corresponding node using the said set. As we can see in Table IV, the algorithms that use EAX to select CSs have a better ExNT than ExOR, which uses ETX for the selection of candidates.

5.2. Geographic-Based Opportunistic Routing

Most of the OR protocols proposed in the literature use global topology and link quality information to find CSs that transmit to the destination. In practice, the geographic position of nodes can also benefit from OR. However, this is not an optimal solution due to the lack of global knowledge of the network. Boukerche and Rogers [2001] proposed GPS Zone Routing Protocol (GZPR) as an approach to send the routing query message only to those nodes that are farther away from the query source. Therefore, GZPR reduces the amount of query message dissemination in the network.

Contention-Based Forwarding (CBF) [Füßler et al. 2003] is a geographic-based OR mechanism. When a source has data to send, it includes its position information and the position of the destination in the packet and broadcasts it. In CBF, the neighbors of a source decide if they should forward the packet or not. Upon receiving a data packet from a node, CBF schedules a timer to determine when to forward the packet. Actually, CBF uses a timer-based method for the coordination process. That is, the timeout value is determined based on the DP metric; the node that is closer to the destination is given a shorter waiting time. The node forwards the packet if its timer is expired and if, during the waiting time, it does not hear any other transmission of the same packet. Note that in CBF the candidates are not determined by the source, and all neighbors that have received the packet and are closer than the source to the destination can be used as the CSs. Disadvantages of the timer-based approach exist in CBF. Some candidates may not hear the other transmissions, and they may decide to forward the packet. Holger et al. used the Two-Ray Ground propagation for CBF simulation results. However, this propagation model is not very realistic; it may happen that with a more realistic propagation model a lot of nodes will not hear the other transmissions, and some duplicated packets may be sent through the network. Furthermore, since CBF is allowed to select candidates without any limitation on their number, the waiting time for low-priority candidates will increase if candidates with a higher priority fail to receive the packet.

Geographic Opportunistic Routing (GOR) [Zeng et al. 2007a, 2007b] is another geographic OR protocol. The authors claim that assigning high priority to nodes close to the destination does not guarantee the best performance. Therefore, they employ EOT, which helps GOR by estimating the bit-meter progress per second. A candidate selection algorithm based on EOT is proposed by the authors. The algorithm includes a new node in the CS without changing the priorities among the already selected candidates; thus, the EOT of the new CS increases. In terms of coordination, GOR uses the ACK-based method.

Position-based Opportunistic Routing (POR) [Yang et al. 2009b] was proposed by Shengbo et al. in 2009. Each node in POR selects its CS based on the distance between its neighbors and the destination (DP metric in Equation (1)). It uses the distance of candidates from the destination to order them. The source inserts the CS into the packet header and it sends the packet. The ID of the best candidate is used to fill the next-hop field in the packet. Upon reception of the packet, the nodes check their position in the CS and use the timer-based approach to coordinate and forward the packet. POR relies only on the information of neighbors. The overhead of POR comes from updating the information of neighbors by sending out beacon packets. Note that in POR the packets are sent in unicast form. To benefit from the broadcast characteristic of the wireless medium, some modifications of the MAC layer need to be done. When a node receives a packet that has an ID that does not belong to the next-hop field of the packet, the packet has to be delivered to the upper layer for further processing by POR. In their experiments, the authors have used five as the number of candidates that each node can select and have compared POR with the Ad Hoc On-Demand Distance Vector (AODV) [Perkins et al. 2003] and Greedy Perimeter Stateless Routing (GPSR) [Karp and Kung 2000]. Their simulation results show that POR outperforms both these traditional geographic routing protocols.

POR forms the CSs by choosing the nodes close to the destination; however, as we have discussed earlier in Section 2.1.1, under the condition of a limited and small number of candidates (for example, two), it is important to consider the link delivery probability between sender and candidate. Distance Progress Opportunistic Routing (DPOR) [Darehshoorzadeh and Cerdà-Alabern 2012] is an algorithm that copes with this issue by considering the delivery probability of the wireless links. Wireless nodes that use DPOR aim to use those nodes as candidates that are not only close to the destination, but also have a good link quality to the sender in terms of delivery probability. EDP is the metric that has been used in DPOR to select the CSs. In detail, the source node selects a group of neighbors that are closer to the destination than itself. Then, by considering the EDP of reaching the destination using the selected neighbors, the best node is picked to be the candidate. The selected candidate will be added to the CS and removed from the set of neighbors. The process is repeated over the remaining neighbors until the source cannot find any appropriate neighbor to add into the CS. The evaluation study of DPOR showed that it outperforms POR and ExOR in terms of EAX. Moreover, the performance of DPOR is slightly higher than that of the optimum algorithm (i.e., MTS). Note that DPOR is a candidate selection algorithm; therefore, to send packets in the network, it needs to use one of the candidate coordination methods.

5.3. Network Coding Opportunistic Routing Protocols

Network Coding (NC) is also capable of improving the throughput of the wireless network by considering the benefit from the broadcast behavior of wireless media. However, NC is not effective in an environment where the packet loss ratio is high because nodes cannot receive enough coded packets to be able to decode the data packet. On the other hand, in OR, a packet can go through different paths and has a higher chance of progressing toward the destination. Therefore, by taking advantage of applying OR jointly with NC, the performance of the network can be improved in environments with a high packet loss ratio.

One of the most referenced OR protocols, called MAC-independent Opportunistic Routing & Encoding (MORE), uses NC and was proposed in Chachulski et al. [2007]. MORE uses the ETX metric to build CS and does not need any changes to be applied to the MAC layer. The main idea of MORE is to divide the flow into batches that contain some amounts of packets. A source makes a linear combination of packets from the same batch. The CS will be added to the header of the coded packet, and MORE broadcasts it in the network. After receiving a packet, the node looks for its ID in the CS. If it can find its ID in the CS, then it must forward the packet. Before forwarding the packet, the node has to check the independence of the packets from those it has received before. If the recently received packet is linearly independent from earlier packets, then the node creates a new linear combination of packets before forwarding. This is due to the fact that a linear combination of coded packets represents a linear combination of original packets [Chachulski et al. 2007]. The destination only returns the ACK message when the amount of received packets is enough to decode the original batch. As a result, the source stops sending packets when it receives the ACK. MORE has been evaluated via simulations, and its performance is compared with ExOR. The results show a significant improvement in network throughput by using MORE. Moreover, unlike ExOR, MORE does not depend on the global coordination method. However, MORE is not able to cope with an increasing number of flows because it does not have any mechanism to control the rate. When the destination receives enough packets to decode, it sends an explicit ACK to the source. The source node stops coding the packets when it receives the ACK packet. This waiting time degrades the performance of a network as the size of the network grows.

Unlike MORE, which keeps broadcasting one batch at a time, Coding Opportunistic Routing (CodeOR) [Lin et al. 2008] broadcasts more than one batch simultaneously; it therefore improves the network performance by utilizing the network resources efficiently. CodeOR also provides a new hop-by-hop ACK, in addition to supporting the end-to-end ACK. Each intermediate node sends an ACK to the upstream node to inform it whenever it has received adequate packets to be able to continue its current coding. Therefore, the upstream node is able to move forward and transmit the next batch. Authors show that CodeOR is able to improve the throughput of the network by a factor of two, on average, as compared to MORE [Chachulski et al. 2007].

MORE uses ETX for the selection of CSs. As we mentioned in Section 2.1, ETX is not a good metric for choosing the CSs in OR. Li et al. [2009] proposed the Fair Opportunistic Routing Linear Coding (FORLC) protocol. The STR metric is used in FORLC to select the CSs. The source includes the neighbors in the CS and, by adding them to the CS, the STR metric increases. When the source has data to send, like MORE, it breaks the file into batches. A random linear combination of packets in the same batch is created and broadcast by the source. The other process of handling the received packet is the same as that in MORE. Simulation results show that the FORLC protocol increases throughput by 30% more than the MORE protocol.

As an efficient NC mechanism, COPE [Katti et al. 2006, 2008] also benefits from the broadcast feature of the wireless media in MWNs. A node broadcasts the packets in its small neighborhood on the path to the destination. It also takes advantage of the opportunistic sensing channel to gather information about neighbors and encoded packets. The node keeps the overheard coded packets for a limited period of time [Katti et al. 2006]. Since all neighbors listen to the media, the rebroadcasting of a packet can be used to inform neighbors about those packets that a node received. Before transmitting a packet, the node may perform XOR over packets it has intended to send along with the packets it has overheard from its neighbors. Note that the node performs XOR over the overheard packet if it ensures that its neighbors are able to decode the packet. This decision is made based on the overheard packets from the neighbor's transmission.

Coding-aware Opportunistic Routing mechanism & Encoding (CORE) [Yan et al. 2008, 2010] is an OR protocol that exploits the NC mechanism to improve the throughput of MWNs by utilizing an inner-flow coding technique. As an OR protocol, the next-hop forwarder is selected dynamically through a consideration of the coding gain that it may achieve. By considering the NC technique, CORE is able to send multiple packets at a time via a single transmission. The source sends packets that can be encoded with other packets. The candidates then coordinate among themselves to choose one node as the next forwarder. The decision is made to consider the coding possibility at each node. The packets are forwarded in this manner until they reach the destination. CORE uses timer-based coordination to collaborate between candidates. Note that CORE uses DP to select its CSs.

NC (XC) Opportunistic Routing (XCOR) [Koutsonikolas et al. 2008] is another protocol that combines the reliability of OR with the efficiency of interflow NC. The candidate selection of XCOR builds the CS by following the SPF from source to destination using ETX as a metric. The candidate coordination method is timer-based, and the candidate that has the best access to the destination (ETX) will forward the packet while the rest of the candidates follow the timer according to their priority. Nodes also inform their neighbors about the received packets by broadcasting a report message. At each node, XCOR uses a heuristic algorithm to find the flow with the highest utility. The utility of the flow is computed by considering the utility of the combinations of packets for different flows. Simply put, the flow with the higher load will get the better utility.

However, the combination of OR and NC may cause a lot of candidates to forward coded packets, which results in redundant transmissions. There must be a compromise between forwarding sufficient amounts of coded packets to ensure that the destination is able to decode the original packets and avoiding unnecessary transmissions so that the network resources are used efficiently [Bruno and Nurchis 2010; Darehshoorzadeh 2012]. As a result, to develop a coding-aware OR protocol, many factors such as network topology, traffic profile, and the methods for reducing the network overhead must be considered [Liu et al. 2009].

5.4. Multicast Opportunistic Routing

Most of the studies in OR do not use this routing for multicast protocols, and most of these studies are devoted to the candidate selection algorithms: methods of coordination in unicast OR. OR can be applied to instances where packets are delivered to multiple destinations by using the benefits of the broadcast behavior of the wireless medium.

It is not straightforward to develop a multicast protocol using OR because a source targets more than one destination. Therefore, the first issue is to find a way to share the potential forwarders for multiple paths. Unlike the unicast OR protocols, which aim to select only one candidate to forward the packet, multicast OR protocols are expected to select multiple candidates to forward packets to all destinations. Moreover, it is necessary to modify the candidate coordination mechanism to allow more than one candidate to engage in forwarding the packets. From another point of view, a candidate in a multicast OR may forward the packet to reach multiple destinations, whereas in a unicast OR a candidate always targets one destination. In Section 5.3, we explained the MORE [Chachulski et al. 2007] protocol, which provides both unicast and multicast operational modes.

Reliable Opportunistic Multicast Protocol (ROMP) [Wenzhong et al. 2010] creates a Steiner tree based on ETX and sends data packets through links using OR. The cost of reaching multiple destinations is calculated by averaging the EAX of each candidate to reach that subgroup of destinations. The protocol limits the candidates to be near the default multicast tree. The idea of NC is used in ROMP to send data packets. Like the second version of ExOR, some batches of packets are created by the source. A random linear combination of the packets in a batch is created and broadcast by the source. Upon receiving a packet, the node looks for its ID in the CS. If its ID is included in the CS, the linear in-dependency of the packet from other packets already received from this batch is checked. The candidate then creates a random linear combination of packets that it has heard from the same batch and broadcasts it. The destination decodes the received packets when it receives enough innovative packets. ROMP constructs the tree based on ETX, which is a metric for unicast protocols. Furthermore, ROMP just considers the average ExNT of each node that uses the unicast OR to reach some destinations as a metric for candidate selection and prioritization. In other words, ROMP does not consider the fact that the packet is going toward more than one destination. Furthermore, in a mobile scenario, the reconstruction of the tree is very costly.

Tan et al. proposed MSTOR [Le and Liu 2010], an overlay multicast tree, to adapt OR to delivering packets to multicast destinations in wireless networks. The packets are sent along the Steiner tree at the overlay level. In MSTOR, a unicast OR protocol is used to send the packets through the links in the overlay tree. To create the Steiner tree, MSTOR first calculates the optimum CS using algorithm proposed in [Laufer et al. 2009] between each pair of nodes in the network. When the source has a data packet to send, it assigns the CS the task of reaching its children nodes. It uses an ACK-based method for candidate coordination. MSTOR is different from MORE in the sense of making the multicast tree. The multicast tree is built at the upper level to estimate the good-put of receiving transmissions using an opportunistic technique at the bottom line level of the MWN [Le and Liu 2010]. MSTOR does not utilize the overhearing capability of relay nodes from the independent OR paths. Furthermore, computing the optimum CS for each pair of nodes in the network, especially in a mobile scenario, is very costly and time consuming.

Multicast Opportunistic Routing Protocol (MORP) [Darehshoorzadeh and Cerdà-Alabern 2011] is another multicast routing protocol based on OR which employs a set of candidates to deliver a packet to multiple destinations. In each transmission, MORP creates a multicast tree considering the candidates that receive the packet. In order to reach the destination, MORP creates a CS. It selects some of the candidates that have received the packet to continue forwarding the packet toward the destinations. In MORP, each selected candidate will send the packet to a group of destinations.

Multicast Candidate Set (MCS) is a candidate set used to reach all destinations. The union of all CSs to reach all destinations is used to create the MCS. Upon receiving the sent broadcast packet from the sender, candidates send back an ACK. According to the received ACK, if the source cannot reach all the destinations, it will retransmit the data packet. The source can select some candidates to forward the packet to, and the destination that each candidate must forward to is also selected by the source. For each destination, the source selects the candidate with the highest priority that sends back the ACK. The source then broadcasts a notification packet with IDs of selected candidates to inform them to forward the packet. Furthermore, it includes the addresses of the destinations that each candidate has to forward to. Candidate coordination in

MORP uses a three-way handshake. Therefore, it is a perfect coordination without any duplicate transmission.

The method of selecting forwarders in MORP is not very efficient. The source only considers the best candidates that have sent out ACKs. It may happen that there are some candidates who commonly qualify to reach different destinations, but the source only considers the best ones. Therefore, many candidates may be chosen to forward the packet. Darehshoorzadeh et al. extended their work [Darehshoorzadeh and Cerdà-Alabern 2013] to reduce the number of forwarders in a more efficient way by merging candidates that have received the packet, but these are not necessarily the best ones. By using the new approach, the number of forwarders selected by the source is reduced. As a consequence, the number of transmissions in the network is reduced. Recall that, due to the three-way handshaking in each node, the end-to-end delay of MORP increases.

5.5. Opportunistic Routing Protocols in Mobile Scenarios

The first idea of OR was proposed for static networks. In a static network, finding the CSs is relatively easy. But in a dynamic environment, finding the candidates becomes problematic. Using the end-to-end metrics based on global topology information is very costly in high- activity mobile scenarios. Therefore, local metrics, like the geographic position of nodes, can be a good solution in mobile scenarios.

Mobile ad hoc networks receive less attention from the research community in OR. OPportunistic Routing in dynamic Ad Hoc networks (OPRAH) [Westphal 2006] is one of the few OR protocols that considers mobility and is applied to ad hoc networks. OPRAH is an on-demand protocol that depends on AODV to build the route to the destination. The nodes with a smaller distance to the destination compared to the source-destination distance attempt to act as forwarders. To increase path diversity, OPRAH builds a group of paths between a source and the destination pair during a request-reply route establishment process. Therefore, the source is able to initiate more than one path to the destination when it receives the route replys. Those nodes that are selected as forwarders transmit the packets upon receiving. Although OPRAH copes with dynamic networks, it is unable to benefit from transmissions that reach the nodes rather than the forwarders that have been selected beforehand.

TOpology-assisted Geo-Opportunistic routing (TO-GO) [Kevin C. Lee and Gerla 2009] is a geographic OR protocol proposed for Vehicular Ad Hoc Networks (VANETs). Most of the geographic-based protocols consider nodes located between the source and destination as the CS [Füßler et al. 2003; Zorzi and Rao 2003]. TO-GO focuses on a more effective CS selection method between the sender and the target node. The target node in TO-GO is the farthest node on the current road segment. To find the CS, TO-GO takes the road topology information into account. The protocol consists of three steps. First, the sender determines the target node, which is either the farthest away node or a node located at a junction. Note that a junction node can forward packets in any direction. In the second phase, the sender finds a set of candidates that can hear the target node and other candidate transmissions. Finally, after transmitting the data packet, each candidate uses timer-based coordination to decide to forward the packet or not.

6. ANALYTICAL MODELS OF OPPORTUNISTIC ROUTING

Like other research areas, some papers investigate the performance of OR using analytical models. Shah et al. [2005] tried to answer the question concerning when the use of OR makes sense in comparison to geographic routing protocols. To represent OR and geographic routing, they used the basic idea of geographic OR and traditional geographic routing. The metrics they measured in their simulation are power consumption, end-to-end delay, and good-put. From the results obtained via simulation, the authors conclude that the performance of OR is better than geographic routing when the wireless medium does not provide good performance and the density of the nodes is higher in the network [Shah et al. 2005].

One of the few works to use a shadowing propagation model in OR was proposed by Luk et al. [2008]. The authors considered a network of nodes with uniform distribution. Their model does not rely on specified candidate selection algorithm; it only estimates the expected progress distance of the transmitted packets. The proposed model showed that in the log-normal shadowing channel with Rayleigh fading, OR improves the average transmission advancement per packet by the factor of 3 compared to traditional routing.

Most researchers assume that the delivery properties of links are independent from each other. However, in Zubow et al. [2008], the authors claimed that the packet loss resulting from the shadow fading that occurs when candidates are close to each other is not independent for each node. Their claim is supported by an experiment in an indoor test bed. Their experiments show that it is not possible to dismiss the correlations between the losses if the distance between nodes is smaller than 2 m. However, if candidates with correlations are chosen, the opportunistic gain is significantly reduced.

One of the ways to improve the progress of a transmission in wireless networks is to use a directional antenna. The directional antenna can concentrate the beam energy in a particular direction. The use of OR in conjunction with a directional antenna was investigated by Luk et al. [Chun-Pong Luk and Yue 2009]. The results show that the expected progress made by sending packets with a directional antenna depends on node densities, radio propagation environments, and antenna settings [Chun-Pong Luk and Yue 2009]. Furthermore, they showed that the directional antenna works better in dense networks. Some settings of the antenna are provided by the authors [Chun-Pong Luk and Yue 2009] to achieve optimal beam-width in sparse networks in order to have good performance when OR is used.

To estimate the gain of using OR to improve the performance of the network, a Markov model was proposed [Cerdà-Alabern et al. 2010; Darehshoorzadeh et al. 2011]. The nodes are considered as states of the Markov model, and the transitions between states represent the progress of the packets between nodes in the networks. Cerdà-Alabern et al. [2010] showed that their model is applicable for several scenarios analyzing the performance of OR. They analyzed the performance of OR considering different scenarios and a different number of candidates in each node. The authors suggested that a small number of candidates (two for example) is feasible and can improve the performance of the network significantly. In the meantime, Li and Zhang [2010] used a similar formulation to calculate the cost of transmitting a packet using OR. Their way of solving their model has fundamental differences to other models proposed [Cerdà-Alabern et al. 2010; Darehshoorzadeh et al. 2011]. Unlike the model presented in Cerdà-Alabern et al. [2010] and Darehshoorzadeh et al. [2011], which conducted a discrete phase distribution, the proposed model in Li and Zhang [2010] is solved using spectral graph theory.

Much research aims at finding optimal CSs. The authors in Cerdà-Alabern et al. [2010, 2013] computed the best position in which to place the candidates. In their approach, packet progress toward the destination is maximized. The authors found that the addition of a new candidate to the CS does not affect the optimum position of the previously added candidates in the set. This finding is important in the sense that locating the candidates near the optimal places in a static network enables the network to benefit most from OR. In Cacciapuoti et al. [2010], the authors claimed that the size of CSs effects routing performance. Therefore, they proposed two algorithms to find the optimal CS in the case of constrained and unconstrained numbers of candidates. The runtime complexity of the proposed algorithm is exponential to the number of nodes.

We investigated the effect of the number of candidates on the performance of OR by proposing Distance-based MAximum number of Candidate Estimation (D-MACE) [Darehshoorzadeh et al. 2013]. We showed that choosing the same number of candidates from among those nodes that are close to the destination as nodes that are far from it does not improve the performance of OR protocols very much in terms of the expected number of transmissions. We proposed D-MACE, which reduces the number of candidates in each node according to the distance between the node and destination. The analytical results show that D-MACE reduces the number of selected candidates effectively in the network, which improves network performance compared to the case with the same number of candidat es in all nodes.

7. DISCUSSION

In this survey, we reviewed important key issues and research directions in OR protocols that benefit from the broadcast characteristics of the wireless medium. To do that, we presented the meaning of OR and different solutions, emphasizing the most important issues in this topic in addition to its relative strengths and weaknesses. We summarize all the examined protocols in Table V.

Using this table, we want to further clarify the main features of different types of approaches in OR. Furthermore, using Table V, comparisons among the various schemes in OR are made easier. The first column specifies the protocol name. The other columns in Table V are consecrated to the most representative features of OR approaches. Therefore, by looking at Table V, we can see the basic differences and common aspects of different approaches. The meaning of each column is explained in the following text.

Protocol: This field specifies the name of the protocol coined by the authors. We have used NA if no name was given to the protocol or analytical model. The corresponding reference is also provided here.

Topic: This field indicates the main topic investigated by the authors. We use *Cand. Sel.*, for candidate selection; *Coor* for candidate coordination; *A*, for analytical models of OR; and NC, to refer to Network Coding that uses OR. Some other areas, like the application of OR in multicast protocols (Multicast OR in Table V) or the use of OR in mobile scenarios, are mentioned in the context of VANETs or ad hoc networks in Table V.

Metric: This field specifies the metric used by the candidate selection algorithm of the protocol to find and order candidates (see Section 2). Some of the works, such as SDF, do not consider any special kind of metric, and we have used *NA* in their case in Table V. As we can see, most protocols used ETX or EAX, the two most important end-to-end metrics, to find and order candidates. Recall that in the end-to-end metrics, the global topology information of the network is needed, and this could lead to an optimum solution; on the other hand, local metrics, such as DP, require less information and lead to nonoptimum solutions with shorter computational costs.

Candidate Selection: This field specifies the type of candidate selection used in each protocol; it is based on the information used by this protocol to select candidates. We used the term *Topology* when the algorithm is related to the topological graph of the network and *Geographic* when the algorithm uses the local information of nodes to find the CSs. As we can see in Table V, the way to select candidates (*Topology* or *Geographic*) is closely related to the metric that each protocol uses.

Optimum: This fields states whether the proposed protocol finds the optimum CSs that minimize an OR metric or whether the protocol uses a heuristic solution leading to a non-optimum candidate selection algorithm. Although the general aim of OR is to minimize the number of packet transmissions in the network, some proposed protocols target the minimizing of other metrics in OR (e.g., OpRENU [Wu et al. 2008]). Recall

Table V. Summary of Opportunistic Routing Protocol Presented in This Survey

Protocol	Topic	Metric	Cand. Sel	Opt	Cand. Coor	Unicast/ Multicast
SDF [Larsson 2001]	Cand. Coor.	NA	Topology	×	4-way	Unicast
ExOR Ver-1 [Biswas and Morris 2004]	Cand. Sel. & Coor.	ETX	Topology	×	ACK	Unicast
ExOR Ver-2 [Biswas and Morris 2005]	Cand. Sel. & Coor.	ETX	Topology	×	Timer	Unicast
SOAR [Rozner et al. 2009]	Cand. Sel.	ETX	Topology	×	Timer	Unicast
OAPF [Zhong et al. 2006]	EAX metric& Cand. Sel.	EAX	Topology	×	Timer	Unicast
Plasma [Laufer et al. 2012]	Gateway any-casting OR	EAX	Topology	✓	Timer	Unicast
LCOR Ver-2 [Dubois-Ferriére et al. 2011b]	Cand. Sel.	EAX	Topology	✓	Timer	Unicast
MTS [Li et al. 2009a]	Cand. Sel.	EAX	Topology	✓	Timer	Unicast
OpRENU [Wu et al. 2008]	OpRENU & Cand. Sel.	OpRENU	Topology	✓	Timer	Unicast
CBF [Füßler et al. 2003]	Cand. Coor.	DP	Geographic	×	Timer	Unicast
GOR [Zeng et al. 2007b]	EOT metric & Cand. Sel.	EOT	Geographic	×	Timer	Unicast
POR [Yang et al. 2009b]	Cand. Sel.	DP	Geographic	×	Timer	Unicast
DPOR [Darehshoorzadeh and Cerdà-Alabern 2012]	EDP Metric& Cand. Sel.	EDP	Geographic	×	NA	Unicast
MORE [Chachulski et al. 2007]	NC, OR	ETX	Topology	×	NC	Unicast& Multicast
CodeOR [Lin et al. 2008]	NC, OR	ETX	Topology	×	NC	Unicast
FORLC [Li et al. 2009]	STR metric& NC	STR	Topology	×	NC	Unicast
COPE [Katti et al. 2008]	NC, OR	ETX	Topology	×	NC	Unicast
CORE [Yan et al. 2010]	NC, OR	DP	Geographic	×	Timer& NC	Unicast
XCOR [Koutsonikolas et al. 2008]	NC, OR	ETX	Topology	×	Timer	Unicast
ROMP [Wenzhong et al. 2010]	Multicast OR	ETX & EAX	Topology	×	NC	Multicast
MSTOR [Le and Liu 2010]	Multicast OR	EAX	Topology	×	ACK	Multicast
MORP [Darehshoorzadeh and Cerdà-Alabern 2013]	Multicast OR	ETX	Topology	×	3-way	Multicast
OPRAH [Westphal 2006]	Ad-hoc OR	Hop-count	Topology	×	NA	Unicast
TO-GO [Kevin C. Lee and Gerla 2009]	VANET OR	DP	Geographic	×	Timer	Unicast
NA [Shah et al. 2005]	A	Geo	Geographic	×	RTS-CTS	Unicast
NA [Zubow et al. 2008]	A	PER & Geo	Geographic	×	ACK	Unicast
NA [Luk et al. 2008]	A	DP	Geographic	×	NA	Unicast
NA [Lu and Wu 2009]	A	ETX,EAX OpRENU	Topology	×	NA	Unicast
NA [Chun-Pong Luk and Yue 2009]	A	Geo	Geographic	×	NA	Unicast
NA [Darehshoorzadeh et al. 2011]	A/Cand. Sel.	ETX/EAX	Topology	×	NA	Unicast
NA [Cerdà-Alabern et al. 2013]	A	Geo	NA	✓	NA	Unicast
NA [Cacciapuoti et al. 2010]	A	EAX	Topology	✓	Timer	Unicast

that optimality is achieved at the cost of providing the network topology information in each node. Furthermore, as we mentioned in Section 5.1.2, the computational cost of optimum protocols is much higher than nonoptimum ones.

Candidate Coordination: The coordination method used in each protocol is shown in this field. The table shows *NA* in those instances where a perfect coordination is assumed without relying on any specific type of coordination. We use *Timer* when the protocol uses the *Timer-based* approach, *ACK* when it uses the ACK-based approach, and *NC* when the coordination is done using Network Coding. Furthermore, some protocols, such as SDF and MORP, used four-way and three-way handshakes for coordination, shown by the terms *3-way* and *4-way* in Table V.

Coordination needs signaling, and imperfect coordination leads to duplicate transmissions in the network. Recall that in ACK or RTS-CTS approaches some control packets are used, whereas in the timer-based approach candidates used the data packets for coordination. NC is another method of coordination that does not rely on any kind of control packets. The duplication packet might happen in the ACK- and timer-based approaches, whereas in the RTS-CTS and NC, it does not happen.

Unicast/Multicast: This field indicates if the proposed algorithm or protocol sends a packet from a source to a destination using OR (unicast) or if the packet is broadcast to multiple destinations using OR (multicast). However, the first OR protocols were proposed to deliver a packet to a destination. The benefit of using OR in a multicast scenario where a packet is addressed to multiple destinations reveals that OR can be applied in multicast protocols. As we can see in Table V, a few works have tried to adapt OR to multicast protocols. Most of the proposed multicast protocols create a tree from the source that aims to reach the destinations and to forward packets over links using OR.

8. FUTURE RESEARCH DIRECTIONS FOR OPPORTUNISTIC ROUTING

OR exploits the broadcast characteristics of the wireless medium to improve the performance of the network using multiple relay nodes as next-hop forwarders. Although there is no doubt concerning the benefits of using OR to take advantage of the broadcast nature of wireless networks, there are many challenges which deserve more attention if we are to achieve better performance in OR protocols. In this section, we discuss some additional future research directions that can be investigated in OR.

8.1. Candidate Selection Algorithm

The main issues that arise in the design of an OR mechanism include the strategy of selecting candidates, efficient coordination between candidates, and the OR metric. The candidate selection algorithm is responsible for choosing the candidates and assigning priority to them. The efficiency of the algorithm is mainly related to the candidates it selects and to the computational time it takes to fulfill the tasks. The open issue is how to provide an effective algorithm with reasonable computational time that relies only on local topology information.

8.2. Candidate Coordination

Candidate coordination is another important issue in the design of OR protocols, one that receives less attention than candidate selection in the literature. Inefficient coordination between candidates increases duplicate transmissions and affects network performance by imposing useless flows on the network. To have complete candidate coordination, the OR protocol must use reliable signaling. Moreover, the contemporary technology of the radio antenna must be considered to develop a practical and affordable coordination mechanism. The coordination protocol can be either developed in the link layer or the network layer. Obviously, link-layer implementation can be made more solid by providing enhanced signaling; however, it forces some changes in the MAC layer of the IEEE 802.11 standard. Therefore, more investigation is needed to design a practical and efficient candidate coordination mechanism.

8.3. Opportunistic Routing Metric

The choice of routing metric has significant impact on the performance of an OR protocol. Our study shows that most of the proposed OR protocols use either ETX or EAX as a metric. An interesting research direction is to investigate the uncertainty of the delivery probability for wireless links in various network situations and its effect on the performance of OR protocol. Proposing a routing metric based on various considerations, such as minimizing delay, power management, and using multiple channels to avoid wireless interference, is another direction of research for OR issues and challenges in WSNs. A mobility-aware OR metric is also required to deal with the mobile scenario. Considering a metric that balances the energy of each node in the entire network while it adapts to the mobility model as proposed in Efstathiou et al. [2011] could be another solution to apply to OR on WSNs.

In OR, if there are more than one source in the network, a node may be selected as a candidate of different sources in order to forward the packet. In addition to the metric discussed in Section 2, the Quality of Service (QoS) of each node and its queue size can be considered as additional parameters to select a node as a candidate. To avoid congestion in OR, some methods like those proposed in Boukerche and Das [2003] and Boukerche et al. [2001] can be applied to allow the overloaded nodes to periodically divert traffic to other candidates by tuning local parameters without introducing much extra overhead.

8.4. Opportunistic Routing in Mobile Scenarios

Our literature review shows that OR is mostly developed for WMNs in which nodes are not mobile or have limited mobility. To be applicable to mobile networks such as ad hoc, WSNs [Boukerche et al. 2011; Boukerche 2008] and VANETs, the OR protocols must begin to find solutions to deal with mobility. The main issue regarding the mobility of nodes is the changing topology, which eventually affects the CSs; hence, as we have noted earlier, an efficient and fast algorithm for selecting candidates is required. It is essential to apply OR in a mobile scenario using a new metric like the one proposed in Boukerche et al. [2012], the direction-aware mobility-level metric, which considers the speed and direction of neighboring nodes in the direction of the destination. Selecting nodes that have reasonable speed in the progress to the destination could be a solution for selecting the CS. Accordingly, more research may focus on geographic routing while dealing with OR in VANETs. Geographic routing protocols possess the quality of being stateless, which means that they do not spread the state information of the wireless links to keep track of constructed paths. This property is feasible in the sense that exchanging packets and maintaining routes is costly and inefficient in multihop and highly mobile vehicular networks.

8.5. Multicast and Broadcast Delivery in Opportunistic Routing

Multicast delivery is a valuable application of wireless networks. The use of OR helps improve the performance of multicast delivery. We have provided a review of OR-based multicast delivery in Section 5.4. As we mentioned, very few multicast protocols based on OR have been proposed. The existence of more than one destination is the main challenge for selecting the CSs and for providing effective coordination between candidates. The limited number of proposals for multicast-enabled OR are inspired by the idea of building a multicast tree to reach all destinations from the source and to distribute the packets over the tree by means of OR. This is similar to making the shortest path toward all destinations and relying on OR to deliver the packets. More importantly, we did not find any analytical work that provides a model to explore the gains of using OR to perform multicast delivery.

Therefore, further work on adapting OR to multicast protocols is needed. Li et al. [2009b] proposed a way to disseminate warning messages using OR in VANETs. They employed the idea of OR to minimize the one-hop delay. Furthermore, they designed a coordination mechanism between candidates so that packet collisions are reduced effectively. Applying the OR approach to the broadcasting of a packet to all nodes in the network can be another interesting research direction.

8.6. Multipath Opportunistic Routing

In addition to OR, which can provide a highly reliable delivery of packets to the destination by selecting a set of candidates, multipath routing is another solution that increases the probability of reaching the destination. Traditional multipath routing protocols pre-define multiple paths from source to destination and send the packets through different paths. In addition to higher reliability, using a multipath approach provides load balancing over the network. Combining OR techniques with multipath routing to achieve high reliability could be another direction for research. Sumet Prabhavat and Kato [2012] present a literature review of various load-balancing models over multipath routing techniques. Applying the presented solutions in the earlier mentioned research on OR could provide a potential solution to developing an OR load-balancing protocol in wireless networks.

8.7. Multichannel Multiradio Opportunistic Routing

Most of the existing OR protocols are only applicable to single radio wireless networks that use only one channel at a time. However, by increasing the number of wireless devices using the shared media, multiradio multichannel networks gain increasing attention. Therefore, applying OR to boost the performance of multiradio networks is an interesting research area. The main issue in this area is that the candidate selection strategy depends on the channel assignment solution. Therefore, nodes need to employ different CSs for different wireless channels. A recent work [He et al. 2013] proposed applying the idea of multichannel in OR. In Candidate Forwarder Set based Channel Assignment (CFSCA), the source node finds the CSs to reach the destination. The interference between the selected candidates is then calculated, and a channel is assigned to each of them. The channel assignment aims to minimize interference between candidates, with the constraints of the channel number of CSs and the number of radio interfaces.

8.8. Security in Opportunistic Routing

A last but no less important issue is the securing of OR protocols in MWNs. Since the candidate selection algorithms utilize the information related to link quality for decision making, an attacker can mislead these algorithms easily by reporting false information about link quality. A potential attack to the coordination algorithm may happen when the highest priority candidate has not yet received the packet and while a malicious attacker uses its time slot to send an ACK to the sender. This malicious ACK makes the other candidate avoid returning the ACK, and, as a result, none of the nodes will forward the packet. Therefore, it is very difficult to develop secure OR protocols that have realistically robust and safe transmission.

9. CONCLUSION

OR has been proposed as an approach to exploiting the broadcast nature of WMNs by selecting multiple nodes as candidates forward packets. Multiple potential paths can be used in OR to deliver packets to the destination. By having multiple forwarding candidates, the successful rate of each transmission can be improved.

In this survey, we presented the OR paradigm by explaining its main features and key challenges. We classified different research areas in OR into the following items: routing metrics, candidate coordination, candidate selection, network coding, geographic routing based on OR, multicast OR protocols, and analytical models in OR. In each category, we reviewed the most important and representative proposals in the literature. Furthermore, we addressed some future research directions that need to be investigated more in this area.

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