Opportunistic Routing for Wireless Ad Hoc and Sensor Networks: Present and Future Directions

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ABSTRACT

Opportunistic routing has recently attracted much attention as it is considered a promising direction for improving the performance of wireless ad hoc and sensor networks. With opportunistic routing, intermediate nodes collaborate on packet forwarding in a localized and consistent manner. Opportunistic routing greatly increases transmission reliability and network throughput by taking advantage of the broadcast nature of the wireless medium. In this article we first illustrate the basic idea behind opportunistic routing, and then categorize current research work based on different criteria. We illustrate how different protocols work, and discuss their merits and drawbacks. Finally, we point out potential issues and future directions in opportunistic routing for wireless ad hoc and sensor networks.

INTRODUCTION

Routing is crucial in wireless ad hoc as well as sensor networks. The tasks of routing include route selection and packet forwarding. Route selection is to select one or more routes connecting a pair of nodes. Packet forwarding makes a one-hop decision on which neighbor should be chosen for forwarding a packet along the selected routes. The highly dynamic and lossy nature of the wireless medium makes routing in wireless networks a challenging problem.

Traditional routing protocols for wireless networks perform best path routing that preselects one or more optimized fixed routes before transmissions start and uses a fixed neighbor to forward a packet in each hop. This strategy does not adapt well to the dynamic wireless environment where transmission failures occur frequently, which would trigger excessive link-level retransmissions, waste of network resources, or even system breakdown.

Recently, opportunistic routing (OR) has received a great deal of attention and research work. The key idea behind OR (also called opportunistic forwarding) is to overcome the drawback of unreliable wireless transmission by taking advantage of the broadcast nature of the wireless medium such that one transmission can be overheard by multiple neighbors. The forwarding task can continue as long as at least one neighbor along a route receives the packet. It has been shown that OR improves performance over that of traditional best path routing.

As an example, a directed graph in Fig. 1 represents a wireless network in which a link (x,y) has a delivery probability $P(x,y)$. The traditional routing achieves only 20 percent end-to-end delivery probability for any possible routing path from node s to node t. However, an OR approach called relay-based opportunistic forwarding could achieve a delivery probability of $(1 - (1 - 20 \text{ percent})^5) \approx 67$ percent if all five neighbors of s are selected as relay candidates. As another example, Fig. 2 illustrates how opportunistic forwarding can affect an entire routing path. For clarity, the delivery probabilities for some links are not shown in Fig. 2. It should be clear that each of links (s,B), (B,D), (D,t) has a 60 percent delivery probability, and (s,C), (C,t) each has a 40 percent delivery probability. A packet from source s may follow different paths to reach destination t. Traditional best path routing would always choose the most reliable link to forward a packet to the next hop, which results in the path $s \rightarrow A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow t$, which has an $(80 \text{ percent})^6 \approx 26.2$ percent end-to-end delivery probability with six hops. With OR, if we restrict OR to route data packets via paths with at most three hops, there are four paths meeting this requirement: $s \rightarrow C \rightarrow t$, $s \rightarrow C \rightarrow D \rightarrow t$, $s \rightarrow B \rightarrow C \rightarrow t$, and $s \rightarrow B \rightarrow D \rightarrow t$, which form an interleaved forwarding directed mesh connecting the s-t pair. The former two paths have a successful delivery probability of

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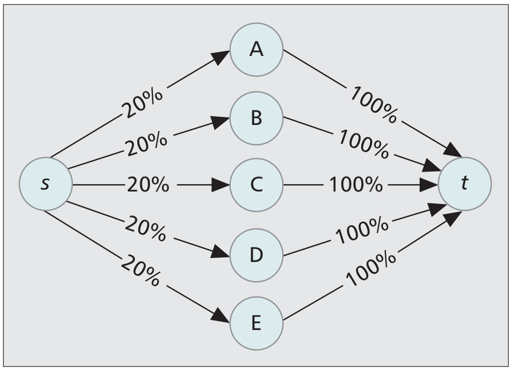

Figure 1. *An illustration of relay-based opportunistic forwarding.*

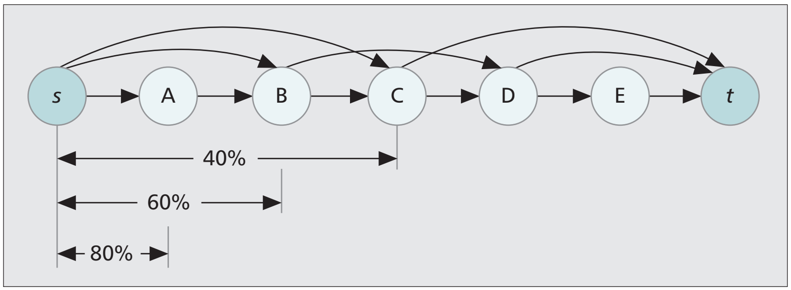

Figure 2. *An illustration of path-based opportunistic forwarding.*

$P_{sC} \times (1 - (1 - P_{Ct}) \times (1 - P_{CD} \times P_{Dt})) = 40$ percent × (1 – (1 – 40 percent) × (1 – 80 percent × 60 percent)) ≈ 27.5 percent. Similarly, the last two paths have a successful delivery probability of 60 percent × (1 – (1 – 60 percent × 60 percent) × (1 – 80 percent × 40 percent)) ≈ 33.9 percent. The overall successful delivery probability by the above four paths is therefore 1 – (1 – 27.5 percent) × (1 – 33.9 percent) ≈ 52.1 percent. In large wireless networks, the example in Fig. 1 illustrates the question of how each sender should select a good forwarder set to move a packet downstream, and the example in Fig. 2 illustrates the question of how to build an efficient forwarding mesh structure to improve the performance of OR in end-to-end packet delivery.

The key design issues in opportunistic routing include forwarder set selection and prioritization, and duplicate transmission avoidance/suppression. For instance, in our examples the forwarder sets for source s in Figs. 1 and 2 are $\{A, B, C, D, E\}$ and $\{B, C\}$, respectively. In Fig. 1 each forwarder candidate has the same priority, while in Fig. 2 node C has higher priority if faster end-to-end delivery is preferred. In this article we discuss in detail how each of the above issues is tackled using different strategies.

CLASSIFICATION OF OPPORTUNISTIC ROUTING PROTOCOLS

Fundamental issues in the design of OR protocols include forwarder set selection, prioritization, and duplicate forwarding avoidance/suppression. Resolving these issues needs to consider routing efficiency, protocol overhead, compatibility with existing medium access control (MAC) protocols, use of network state information, location information, and use of coding function. By taking these factors as well as different design strategies into consideration, we categorize the current major OR protocols as follows.

END-TO-END VS. HOP-BY-HOP FORWARDER SET SELECTION

By end-to-end forwarder set selection, the set of forwarders can be determined once and for all (forwarder-set-related information can be carried by data packets [1–3], kept at intermediate nodes [4], or determined on the fly on a per packet basis using certain criteria [5, 6]). End-to-end forwarder set selection may lead to duplicate transmissions since non-neighboring forwarders can make inconsistent decisions on packet forwarding. With hop-by-hop forwarder set selection, each packet holder (including the source) independently determines its own forwarder set along the path to the intended destination. A selected forwarder will again continue this process until the packet reaches its destination. Example protocols of this type can be found in [7–9]. In general, end-to-end strategy outperforms hop-by-hop strategy since the former can optimize the selection of a forwarder set with more network state information gathered. However, the hop-by-hop strategy is easy to implement and scales well. The size of the forwarder set is also a factor affecting the performance of an OR protocol. A larger size can increase the one-hop successful delivery probability, but may introduce some forwarder candidates with small progress toward the destination.

METRICS FOR PRIORITIZATION

After a forwarder set has been selected, we need to assign priorities for these forwarders. Selecting a good metric has a large impact on network performance. Forwarder candidates can be prioritized based on expected transmission count (ETX) [1, 2], hop count [6, 7], geo-distance [8, 9], coding chances [3], and so on. Utilization of hop count or ETX needs an underlying routing protocol (either reactive or proactive) to gather such information. Geo-distance requires the availability of location information of nodes. A coding approach can be used to minimize the number of transmissions. How these metrics are integrated into protocol design can greatly affect the routing performance. Moreover, the accuracy of a metric depends on the proper measurement of link quality and timely dissemination of such information.

DISTRIBUTIVE COORDINATION FOR PRIORITIZATION

In some mechanisms [1, 2, 4] the decision on priorities is made by distributive coordination among forwarder candidates that, upon receiving a data packet, compete with each other to select the best one to continue the forwarding task while the rest resign. This deferred choice gives each transmission several opportunities to make progress. However, it can introduce certain extra packet delivery latency. Some other mechanisms [7, 8] may use explicit control packet(s) exchanged immediately before or after a data transmission for the distributive coordination. For example, the request-to-send/clear-to-send (RTS/CTS) scheme can be used to select the best among potential forwarders that respond in a priority order [8]. Upon receiving the first CTS, the sender immediately starts to transmit data to that node. This strategy can avoid duplicate transmissions. Another strategy is to enable forwarder candidates that, upon receiving a data packet, send back a short acknowledgment (ACK) in a predetermined order. The first node returning an ACK wins and the others resign. This strategy requires that forwarder candidates be neighbors of each other such that the transmission of an ACK can be overheard by all of them. Among existing work, there are also some mechanisms [2, 4–6] that require no coordination among forwarder candidates. In these mechanisms data packets are broadcast to the air, which can largely ease the design of the MAC protocol at the penalty of increased duplicate transmissions seen at destination nodes.

DETERMINISTIC VS. PROBABILISTIC FORWARDER SELECTION

Whether a forwarder candidate receiving a packet will be a true forwarder can be decided in either a deterministic or probabilistic manner. Example protocols of the former type can be found in [3, 4, 8]. The Opportunistic Routing in Dynamic Ad Hoc (OPRAH) networks protocol [4] requires each node in the prebuilt forwarding mesh structure to definitely serve as a forwarder. Here, a forwarding mesh structure is a collection of nodes that form partially overlapped multiple paths connecting a source-destination pair. Alternately, in [3, 8] the forwarder candidate with the highest priority is selected as the next forwarder. In contrast, by probabilistic forwarder selection [5, 6], upon receipt of a data packet, a forwarder candidate will independently decide a probability with which it chooses itself as a forwarder. Probabilistic selection requires no coordination among forwarder candidates and is more resilient to highly lossy and uncertain wireless environments. However, duplicate transmissions can be significantly too many if the size of the forwarding set and forwarding probability are not properly chosen.

LOCATION-BASED VS. TOPOLOGY-BASED SELECTION

By location-based selection [8, 9], the forwarders and their priorities are determined with little or no global topology-based network state information. In contrast, topology-based selections [1–3] require network state information (either local or global) to enable efficient opportunistic routing. With more information, a sophisticated but efficient metric can be used to help forwarder set selection and prioritization. In general, topology-based selection has better routing performance while location-based selection has better scalability for large-scale wireless networks.

CODING VS. NON-CODING

Integration of OR with an appropriate coding strategy can greatly improve the routing performance. For example, forward error correction (FEC) can reduce the packet loss ratio of links, which consequently affects forwarder set selection and prioritization. Hybrid Automatic Repeat Request (ARQ) [9] can increase the transmission range and link layer transmission reliability. Integration of network coding and OR can reduce the total amount of transmissions by guiding packets to next hops with more coding chances [3]. In general, design of efficient coding-aware OR protocols needs to consider topology, traffic pattern, and reduction of extra overhead.

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SURVEY ON OPPORTUNISTIC ROUTING PROTOCOLS

In this section we introduce some major OR protocols. We explain how each of them works, and discuss their merits and drawbacks.

EXTREME OPPORTUNISTIC ROUTING

Extreme Opportunistic Routing (ExOR) [1] is a state-of-the-art OR protocol for wireless multihop networks and has been implemented on the RoofNet testbed at Massachusetts Institute of Technology (MIT). ExOR integrates routing and MAC protocols. It improves routing performance by utilizing long-range but lossy links. ExOR is designed for batch forwarding. The source node includes a forwarder list in each packet, prioritized by ETX distance to the destination: the shorter the distance, the higher the priority. Only those nodes that are closer to the destination than the source are included in the forwarder set. Each packet has a BITMAP option, which marks those packets that have been received by the sending node or nodes with higher priorities. All packets are broadcast. A forwarder transmits a packet only if no forwarder with higher priority has explicitly acknowledged receipt of it, as indicated in the BITMAP position for this packet.

ExOR has good routing performance. However, it also has the following drawbacks. First, it reduces spatial reuse because it enforces global coordination among forwarders. Second, forwarders connected with low-quality links or no links can make inconsistent decisions on packet forwarding because a forwarder may not hear the acknowledgment from other forwarders with higher priorities, which causes duplicate transmissions.

OPPORTUNISTIC ANY-PATH FORWARDING

In ExOR, the condition for a node to be selected into a forwarder set is simply that its ETX value to the destination is shorter than that of the source. This simple condition may cause data packets to take low-quality routes. To overcome this problem, Opportunistic Any-Path Forwarding (OAPF) [10] introduces an expected any-path count (EAX) metric such that it recursively calculates the near-optimal forwarder set at each potential forwarder to reach the destination. The

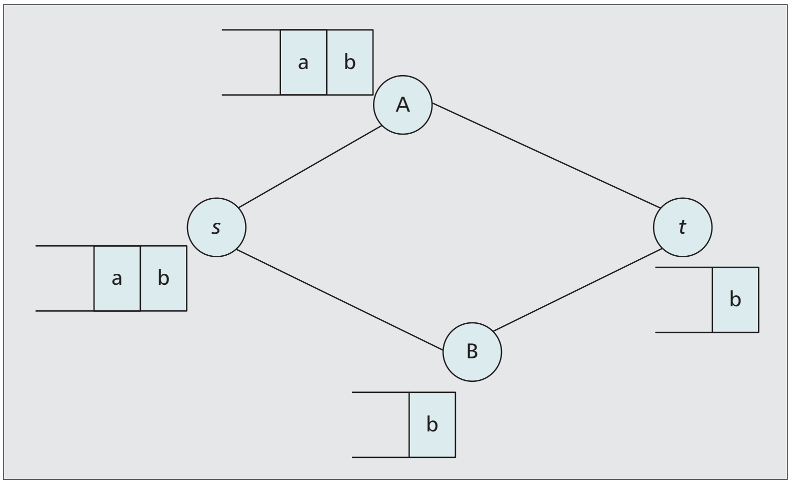

Figure 3. *An illustration of potential duplicate transmissions in ExOR.*

extra cost paid is the high computational overhead and more network state information gathered.

MAC-INDEPENDENT OPPORTUNISTIC ROUTING AND ENCODING PROTOCOL

MAC-Independent Opportunistic Routing and Encoding Protocol (MORE) [2] integrates OR and intra-flow network coding and is targeted for enhancing ExOR. Figure 3 illustrates how ExOR can cause duplicate transmissions. In this example, after source s sends out packets a, b, Node B receives b, and node A receives a and b. Node B transmits first because it is closer to t than A. Node A has the following three choices: forwarding a, b, or both a and b. There is 2/3 probability of duplicate transmissions. In MORE node A can forward a coded packet $a \oplus b$. Then destination t performs an XOR operation on the two received packets: $a \oplus b \oplus b = a$. Thus, no duplicate transmission occurs at t.

MORE works as follows. When the source is ready to send, it keeps creating coded packets via random linear combination of the K native packets in the current batch. The source keeps sending such coded packets out until the whole batch is acknowledged by the destination, at which time the source proceeds to the next batch. In MORE, data packets are always coded and carry a list of forwarders and a code vector recording how the native packets are combined. Upon receiving such a coded packet, a node in the forwarder list first checks for the innovativeness of the packet (i.e., if it is linearly independent of the packets previously received). A forwarder only stores innovative packets. Furthermore, each forwarder keeps a TX counter, which is calculated by a distributed algorithm based on the concept of ETX. When a forwarder receives an innovative packet from an upstream node, it increments the counter by its TX credit ($0 < \text{TX} < 1$), and when the MAC allows the node to transmit, the node checks whether the counter is positive. If yes, the node creates a coded packet, broadcasts it, then decrements the counter by one. If the counter is zero or negative, the node does not transmit. Once the destination receives K innovative packets, it can decode the whole batch. It then sends an ACK back to the source to allow it to move to the next batch.

Different from ExOR, MORE uses the concept of *innovative packets* to judge whether a received packet brings new information instead of using *duplicate packets* as in ExOR. Moreover, it uses a TX counter at each forwarder to further reduce the amount of transmissions. Simulation results showed that MORE can greatly reduce the total number of transmissions compared to ExOR.

INTEGRATION OF AOMDV AND ANYCAST

Jain and Das developed an anycast MAC protocol to perform channel-state-based next hop selection among multiple next hop candidates [7]. The designed protocol is an extension of the IEEE 802.11 MAC layer. A sender first multicasts an RTS to the multiple next hop candidates, which contains the addresses of all the receivers. CTS transmissions are staggered in time in order of the priorities of the receivers, which can be based on hop count or queue length at the receivers. Upon receipt of a CTS, the sender transmits DATA to the sender of the CTS after a short interframe space (SIFS) interval, which notifies the remaining receivers to stop sending their CTSs. In [7], this anycast MAC protocol is further integrated with a multipath extension to the Ad Hoc On Demand Vector (AODV) routing protocol, referred to as AOMDV. Experimental and simulation results show that the integrated protocol can improve network performance in time-varying radio environments.

OPRAH

OPRAH [4] builds a braid multipath set between source and destination via on-demand routing to support opportunistic forwarding. For this purpose, OPRAH allows intermediate nodes to record more subpaths back to the source and also those subpaths downstream to the destination via received Route Requests and Route Replies. OPRAH can increase end-to-end forwarding reliability. In OPRAH the destination may receive duplicate data packets because a built route set may contain spatially disjoint paths or partially disjoint paths from an intermediate node down to the destination.

RESILIENT AND OPPORTUNISTIC ROUTING SOLUTION FOR MESH NETWORKS

To increase the forwarding resilience and reliability in highly lossy multirate wireless networks, a resilient and opportunistic routing solution for mesh networks (ROMER) [5] builds a forwarding mesh on the fly and on a per packet basis. In ROMER each packet carries an option indicating how far it is allowed to deviate away from the shortest path from source s to destination t, denoted *ExtraCost* (*ExtraCost* ≥ 0). Let $distance\_so\_far_i$ represent the distance a packet has gone thus far from its source to the current node i, and $shortest\_distance(x,y)$ the shortest distance from node x to node y. The precondition under which an intermediate node i overhearing a transmission is allowed to further transmit the packet is as follows: $distance\_so\_far_i + shortest\_distance(i,t) \leq shortest\_distance(s,t) + ExtraCost$, which (approximately) creates an ellipse-style mesh structure, centered on the long-term shortest path from source to destination. The mesh provides enough flexibility of rich and interleaved paths to accommodate the short-term radio channel dynamics and transient outages. In [5], to suppress duplicate copies, the forwarding probabilities at intermediate nodes not-on-shortest-path are adjusted based on their downstream links' instantaneous throughput. Moreover, the integration of AOMDV and anycast, OPRAH, and ROMER can support node mobility due to the high resilience of their created forwarding structures.

DIRECTED TRANSMISSION ROUTING PROTOCOL

Directed Transmission Routing Protocol (DTRP) [6] works in a way similar to ROMER for creating a forwarding mesh and also on a per packet basis but adjusts the forwarding probability at potential forwarders in a different way. In DTRP, rules include:

- Nodes sitting on the shortest path from the source to the sink forward each packet with probability of one.
- Nodes not sitting on the shortest path forward a received packet with a probability determined by the minimum extra cost (i.e., extra distance).

The more the extra cost, the smaller the probability. In this way a high probability of end-to-end data delivery can be achieved. The advantages of ROMER and DTRP are their simplicity and high reliability in data delivery. Both DTRP and ROMER can provide redundant data copies on the forwarding mesh structure, which is suitable for highly lossy wireless environments.

GEOGRAPHIC RANDOM FORWARDING

Geographic Random Forwarding (GeRaF) [8] is a geographical forwarding protocol. It selects a forwarder set and prioritizes them using location information. In GeRaF each packet carries the locations of the sender and destination. Only those neighboring nodes closer to the destination than the sender can be forwarder candidates. Moreover, these eligible candidates rank themselves based on their geo-distances to the destination. In this way the forwarder set and prioritization can easily be implemented via an RTS-CTS dialog at the MAC layer, which also ensures that a single forwarder can be chosen. GeRaF adopts hop-by-hop forwarder set selection. It is targeted for relatively dense networks. GeRaF is simple to implement. However, the cost for acquiring location information may be too high to implement, at least in the near future.

HYBRID ARQ-BASED INTERCLUSTER GEOGRAPHIC RELAYING

Hybrid ARQ-Based Intercluster Geographic Relaying (HARBINGER) [9] is a combination of GeRaF with hybrid automatic repeat request (ARQ). In GeRaF, when nodes work with random sleep scheduling for battery saving, each transmission may need multiple handshakings at the MAC layer before a packet relay is made; thus, GeRaF degrades for sparser networks. The key difference between GeRaF and HARBINGER is as follows. When there is no forwarder within the range of a sender, with GeRaF, everything must start over again such that the sender will make a new transmission attempt. In contrast, in HARBINGER, hybrid ARQ is used for a receiver to combine the information accumulated over multiple transmissions from the same sender. Specifically, when a node decides to receive packets, it keeps each packet it receives from the same sender so that old information can be combined with fresh information gained after each new ARQ transmission. Eventually, this receiving node will be able to decode the packet. Accordingly, the more transmissions made by a sender, the more extended the communication range that can be achieved. HARBINGER provides a better energy-latency trade-off than GeRaF, in particular when node density is low.

CODING-AWARE OPPORTUNISTIC ROUTING MECHANISM

Coding-Aware Opportunistic Routing Mechanism (CORE) [3] is an integration of localized interflow network coding and opportunistic routing. Existing localized network coding mechanisms only adopt best path routing and passively wait for the appearance of coding chances on the path. This leads to inefficient use of network resources. By integrating localized network coding and opportunistic forwarding, CORE enables a packet holder to forward a packet to the next hop that leads to the most coding changes among its forwarder set. Such recursive hop-by-hop operations can greatly improve the end-to-end coding gain in packet delivery with little extra protocol overhead. Table 1 summarizes all the above discussed protocols based on the criteria listed in the previous section.

CONCLUSION AND FUTURE DIRECTIONS

In this article we have presented a survey on OR protocols for wireless ad hoc and sensor networks. Existing work shows that OR can largely improve the performance of wireless networks. Among the surveyed protocols, it is seen that integrating OR with network coding is an effective strategy for improved performance. Furthermore, localized coordination and location information can ease the implementation of an OR protocol. However, research topics in OR are far from exhausted. Next, we list some potential issues in this area.

Existing work shows that OR can largely improve the performance of wireless networks. Among the surveyed protocols, it is seen that integrating OR with network coding is an effective strategy for improved performance.

NEW METRICS FOR OR

As stated earlier, the choice of metric has great impact on the performance of an OR protocol and also its complexity. Existing work has mainly focused on using ETX, hop count, coding chances, and related facets as primary metrics. In [11] Cui *et al*. introduced power consumption as a primary metric in optimizing the design of

Protocols/ properties	Forwarder set selection	Metrics for prioritization	Forwarder candidates coordination	Deterministic or probabilistic forwarder selection	Location or topology-based	Coding or not
ExOR [1]	End-to-end	ETX	ACK-based	Deterministic	Topology-based	×
OAPF [10]	Hop-by-hop	EAX	ACK-based	Deterministic	Topology-based	×
MORE [2]	End-to-end	ETX	N/A	Deterministic	Topology-based	√
AOMDV+Any-cast [7]	Hop-by-hop	Hop count	RTS-CTS	Deterministic	Topology-based	×
OPRAH [4]	End-to-end	Hop count	N/A	Deterministic	Topology-based	×
ROMER [5]	End-to-end	Hop count	N/A	Probabilistic	Topology-based	×
DTRP [6]	End-to-end	Hop count	N/A	Probabilistic	Topology-based	×
GeRaF [8]	Hop-by-hop	Geo-distance	RTS-CTS	Deterministic	Location-based	×
HARBINGER [9]	Hop-by-hop	Geo-distance	ACK-based	Deterministic	Location-based	√
CORE [3]	Hop-by-hop	Code chances	Data-based	Deterministic	Topology-based	√

Table 1. *Classification of opportunistic routing protocols.*

an energy-efficient coding-aware OR protocol for wireless networks. Wu *et al*. [12] proposed a utility-based OR protocol, which uses the utility of each packet as a routing metric. In [12] the successful delivery of a packet brings benefit, and the utility of a packet equals its benefit value minus the transmission cost to reach the packet destination.

JOINT SCHEDULING AND OPPORTUNISTIC ROUTING

Transmission scheduling is to determine which node should transmit and also which packet should be transmitted at an instant. The decision should consider the instant radio conditions at different receivers. In contrast, route selection can affect how packets are routed through a network. Cui *et al*. [11] formulated the issue of joint opportunistic routing and scheduling when network coding is used as an optimization technique.

CROSS-LAYER OR

Besides transmission scheduling and route selection, there are still some other factors such as modulation techniques, packet size, transmission rates, and transmission ranges that can largely affect the quality of wireless links and then, in turn, affect the selection of forwarder set and prioritization. Therefore, designing cross-layer OR protocols is an effective strategy to achieve a desirable trade-off among different measurements.

OPPORTUNISTIC MULTICAST ROUTING

Multicast is an important communications paradigm in wireless networks. The availability of multiple destinations in a multicast tree can make the selection of forwarder candidates, distributed coordination among them, and related prioritization complicated. Thus far, little work has been done in this topic.

OR IN MULTICHANNEL MULTIRADIO NETWORKS

This involves the choice of an appropriate channel and/or radio between a sender and potential receivers. In this sense, a sender may have different forwarder candidates on different channels/radios, and their prioritization can be different as well. OR in multichannel multiradio networks can potentially improve network performance and deserves in-depth investigation.

In summary, opportunistic routing is a promising direction to improve the performance of wireless networks. Much work still needs to be done in this area to achieve high performance and low complexity for dynamic wireless networks.

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BIOGRAPHIES

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