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Introduction

This chapter presents the case for opportunistic routing and related work. We will first introduce the background of multihop wireless networks (mesh networks, sensor networks, mobile ad hoc networks, vehicular ad hoc networks, etc.). We then point out the routing challenges in multihop wireless networks. Secondly, we discuss general wireless multihop routing, including traditional routing (AODV, DSR, etc.), geographic routing, context-based routing and opportunistic routing. We will discuss the motivation of these routing techniques, how they evolved, and their advantages and disadvantages. We will then discuss related opportunistic and collaborative techniques, including cooperative communication, opportunistic scheduling, network coding, multiple AP collaboration, etc. This will help to put opportunistic routing in perspective. We will also introduce related issues about opportunistic routing, including capacity studies of multihop wireless networks, multirate routing, energy-efficient routing, and link-quality measurement, etc.

1.1 Multihop wireless networks

A multihop wireless network (MWN) is a network of nodes (e.g. computers) connected by wireless communication links. The links are usually implemented with digital packet radios. Due to the limited transmission range of the radio, many pairs of nodes in MWNs may not be able to communicate directly; hence they may need other intermediate nodes to forward packets for them. Multihop wireless networks have broad military and civilian applications in many critical situations. They have received increasing attention in the past decade due to their broad applications and easy deployment at low cost without relying on existing infrastructure (Akyildiz and Kasimoglu 2004; Akyildiz *et al*. 2002, 2005; Cerpa *et al*. 2001; Chong and

Multihop Wireless Networks: Opportunistic Routing, First Edition.
Kai Zeng, Wenjing Lou and Ming Li.

Kumar 2003; Estrin *et al*. 2002; Lorincz *et al*. 2004). Different names are used to refer to them in different scenarios.

Mobile ad hoc networks (MANETs) Generally speaking, a mobile ad hoc network (MANET) is a self-configuring network of mobile devices connected by wireless links. Each device in a MANET is free to move independently in any direction. So the node-to-node connection and network topology will change frequently. The primary challenge in MANETs is continuously to maintain the routing information at each node required to properly route traffic. The applications of MANETs include search-and-rescue operations. Such scenarios are characterized by a lack of installed communications infrastructure because all the equipment might already be destroyed or the region could be too remote. MANETs can also provide communications between autonomous vehicles, aircraft and ground troops in the battlefield where a fixed communication infrastructure is always unavailable and infeasible.

Wireless sensor networks (WSNs) Wireless sensor networks (WSNs) (Akyildiz *et al*. 2002) are another variant of MWNs. They are normally used to monitor various physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. A large-scale WSN typically consists of hundreds or thousands of small and cheap sensor nodes with wireless communication capabilities. These sensor nodes may form local clusters, and reactively or periodically report the sensing results to one or multiple base stations via multihop routing. The sensors are usually powered by batteries with limited capacity. Energy efficiency is therefore the primary concern and key challenge in WSNs. The sensors are typically static but some more powerful sensor nodes may have mobile capability (Hu and Evans 2004).

Wireless-mesh networks (WMNs) Wireless-mesh networks (WMN) (Akyildiz and Wang 2005) are another type of MWNs, and are usually used to provide the last mile wireless broadband Internet access for the civilian users. They can also support enterprise networking, healthcare and medical systems, and security surveillance systems. They consist of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of WMNs. The integration of WMNs with other networks such as the Internet, cellular networks, IEEE 802.11 WLAN, IEEE 802.15, IEEE 802.16, and sensor networks can be accomplished through the gateway and bridging functions in the mesh routers. Mesh clients can be either stationary or mobile, and can form a client mesh (multihop) network among themselves and with mesh routers. Network capacity in WMNs is an important issue. The capacity of WMNs is affected by many factors such as network topology, node density, traffic patterns, number of radios/channels used for each node, transmission power level, carrier sensing threshold, node mobility, and environment (indoor/outdoor), etc. A clear understanding of the relationship between network capacity and the above factors provides a guideline for protocol development, architecture design, deployment and operation of the network.

Vehicular ad hoc networks (VANETs) In VANETs, every vehicle communicates with other vehicles (V2V) and with roadside infrastructures (V2I) by means of wireless communication equipment. The most important usage of these networks is to inform other vehicles in emergency situations such as car accidents, urgent braking or traffic jams. In such cases, a vehicle can inform other vehicles by broadcasting safety messages before facing the event. VANETs are a cornerstone of the envisioned Intelligent Transportation Systems (ITS). They will contribute to safer and more efficient roads in the future by providing timely information to drivers and concerned authorities. VANETs are similar to MANETs, but the key difference lies in that in VANETs, vehicles move in an organized fashion rather than randomly. The vehicles are restricted in their range of motion and their mobility can be predicted in the short term, because their movement should obey certain traffic rules.

Compared with traditional single-hop wireless networks, such as cellular networks and local area networks, MWNs have several advantages: 1. coverage extension and connectivity improvement; 2. reducing energy consumption; transmission over multiple short-range wireless links might require less transmission energy than that required over long-range single-hop links; 3. cost efficiency: they avoid wide deployment of cables and can be deployed in a cost efficient way; 4. robustness: in MWNs, multiple paths might exist between a pair of communication nodes, which can be used to increase robustness of the network.

1.2 Routing challenges in MWNs

The purpose of routing is generally to find a path or multiple paths from the source to the destination, maintain or update path(s) when the topology or link quality changes, and forward packets along the path(s). Routing protocol design in MWNs faces a great challenge mainly due to the following facts.

First, the wireless link is unreliable. The properties and quality of a wireless link may vary with the transmission power, transmission rate, distance and path loss between two nodes. Furthermore, channel fading (such as multipath fading and shadowing) results in fluctuations in the received signal strength and therefore intermittent link behavior. The difficulty in managing or controlling the link quality and reliability in wireless networks makes it very hard to find and maintain a good and stable path from the source to the destination.

Second, the wireless medium is broadcast in nature. Transmission on one link may interfere with the transmissions on the neighboring links. This broadcast medium contention brings fundamental constraints on the routing performance, such as throughput and delay. There is inevitable intra-path and inter-path contention due to the broadcast nature of the wireless medium. It is very challenging to achieve optimal routing performance even when there is a single flow, due to the complicate interdependence between the medium contention, route selection, and medium access control. When there are multiple flows (different source-destination pairs) in the network, optimizing overall routing performance becomes extremely hard.

Third, mobility is an inherent property and phenomenon in wireless networks. The node's mobility makes network topology change frequently, thus complicating the task of finding and maintaining a good path between the source and destination. Mobility also affects the link quality, which introduces further challenges in maintaining a timely good path.

Fourth, wireless-embedded devices, such as sensors and handheld devices, are typically battery powered. The lifetime of the battery imposes a limitation on the operation hours and connectivity of the network. Energy efficiency has been a critical concern in energy-constrained networks (e.g. wireless sensor networks). Finding paths that consume minimum energy to deliver the packets from the source to the destination is an important approach to save energy in wireless sensor networks, since the radio communication has been identified as the major source of energy consumption in such networks. However, finding minimum energy consumption path(s) is neither easy nor enough. It is hard mainly because of the unreliability of the wireless link, and it is not enough because we also have to achieve other performance goals, such as satisfying a delay constraint due to specific applications (e.g. surveillance). Choosing and maintaining path(s) that strike a good balance between energy consumption and performance is challenging, especially with the presence of unreliable wireless links.

A large body of research on routing protocols in MWNs has been motivated by the above challenges. Next, we will introduce the major routing protocols in the literature, and motivate the opportunistic routing.

1.3 Routing techniques in MWNs

The routing protocols in MWNs can be classified into different categories using different criteria. For example, they can be classified into link-state routing (e.g. OLSR – Jacquet *et al*. 2001) and distance-vector routing (e.g. AODV – Perkins and Royer 2001). They can also be categorized as proactive (e.g. DSDV – Perkins and Bhagwat 1994) and reactive (on-demand) (e.g. DSR – Johnson *et al*. 2001 – and TORA – Park and Corson 1997) routing. For a better understanding of the difference between opportunistic routing and other state-of-the-art routing protocols in MWNs, we would like to classify the routing protocols as traditional and opportunistic routing.

1.3.1 Traditional routing

Traditional routing protocols (Johnson *et al*. 2001; Perkins and Bhagwat 2001; Perkins and Royer 2001) for multihop wireless networks have followed the concept of routing in wired networks by abstracting the wireless links as wired links, and finding the shortest, least cost, or highest throughput path(s) between a source and destination. Most routing protocols rely on the consistent and stable behavior of individual links, so the intermittent behavior of wireless links can result in poor performance such as low packet delivery ratio and high control overhead. On the other hand, this abstraction ignores the unique broadcast nature and spacial diversity of the wireless medium. We introduce several well known traditional routing protocols in MWNs as follows.

AODV The Ad hoc On Demand Distance Vector (AODV) routing protocol (Perkins and Royer 2001) is designed for routing in MANETs. It is called, on demand, because it builds routes between the source and destination nodes only when source nodes request it. It maintains and updates the route as long as it is needed by the source node. AODV uses sequence numbers to ensure the freshness of routes. It is loop-free, self-starting, and scales to large numbers of mobile nodes.

AODV establishes routes using a route request and route reply discovery cycle. When a source node requires a route to a destination for which it does not already have a route, it broadcasts a route request (RREQ) message throughout the network. The RREQ message contains the source node's IP address, current sequence number, a broadcast ID, and the most recent sequence number for the destination of which the source node is aware. Intermediate nodes that receive the RREQ update their information for the source node and set up backwards pointers to the source node in their routing tables. A node receiving the RREQ will unicast a route reply (RREP) message back to the source if it is either the destination or if it knows a route to the destination with corresponding sequence number no smaller than that contained in the RREQ. Otherwise, it rebroadcasts the RREQ. Nodes keep track of the RREQ's source IP address and broadcast ID, and discard the RREQ that they have received recently and do not forward it.

As the RREP message is relayed back to the source node along the reversing path, nodes on the path set up forward pointers to the destination. Once the source node receives the RREP, it may begin to forward data packets to the destination along the path. If the source later receives a RREP containing a greater sequence number or contains the same sequence number with a smaller hop count, it may update its routing information for that destination and begin using the new route. In this sense, AODV tries to find the shortest path with fewest hops.

The route is active and maintained as long as there are data packets routed through it. Once the source node stops sending the data packets, the links on the path will time out and eventually be deleted from the intermediate nodes' routing tables. If a link break occurs while the route is active, the upstream node of the break link propagates a route error (RERR) message to the source node to inform it of this broken link. After receiving the RERR, if the source node still desires a route, it will initiate a route discovery again.

The advantage of AODV lies in that due to its on-demand (reactive) nature, it can handle highly dynamic topology change in MANETs. However, it possesses several disadvantages. First, AODV lacks support for high throughput routing metrics. It is designed to support the shortest hop-count metric, thus favoring long and low-bandwidth links over short and high-bandwidth links. Second, it may incur long route discovery latency. AODV does not discover a route until a flow is initiated. This route-discovery latency can be high in large-scale networks. Third, it may introduce broadcast storm problems in bandwidth-limited MWNs. Each network node participates in the route discovery process by rebroadcasting RREQ messages, which leads to redundant rebroadcasts, contention and packet collision.

DSR Dynamic Source Routing (DSR) (Johnson *et al*. 2001) is another well known on-demand routing protocol. It is similar to the AODV in that it forms a route on demand when a source node requests it. However, it uses source routing instead of relying on the routing table at each intermediate node.

In the route-discovery phase, like AODV, DSR uses RREQ and RREP messages. When the source node needs to send data packets to a destination and it does not know a route to it, it initiates a route discovery by broadcasting a RREQ message. The RREQ identifies the initiator (source) and target (destination) of the route discovery and contains a unique request ID. It also contains a record listing the address of each intermediate node through which this particular copy of RREQ has been forwarded. The route record is initialized to an empty list by the initiator.

When a node receives a RREQ, it checks if it is itself the target of this RREQ. If this is the case, the node returns a RREP, which contains the accumulated route record from the RREQ to the initiator. If it is not the case and it is the first time the node receives the RREQ, it appends its own address to the route record in the RREQ message and rebroadcast the RREQ. The node will drop the RREQ message if it is a duplicated one or when the node finds that its own address has already been in the route record.

When the source node receives a RREP message, it catches the route carried in the message and sends subsequent data packets to the destination along this route.

Dynamic source routing shares the same advantage as AODV: it is reactive, thus eliminating the need to flood the network periodically to update the routing table in a dynamic network. It actually does not maintain a routing table at each node but it maintains the whole path information to a destination at the source node. It is beaconless and hence does not require periodic Hello packet (beacon) transmissions, which saves bandwidth.

The disadvantage of DSR is that the route-maintenance mechanism does not repair a broken link locally. It may introduce a long connection setup delay due to its on-demand nature. Even though DSR performs well in static and low-mobility environments, the performance degrades rapidly with increasing mobility. Furthermore, a considerable routing overhead is involved due to the source-routing mechanism. This routing overhead is directly proportional to the path length. DSR also tends to find the shortest hop count path, which contains long and unreliable wireless links.

OLSR Optimized Link State Routing (OLSR) (Jacquet *et al*. 2001) is a proactive link-state routing protocol, which uses Hello and Topology Control (TC) messages to discover and then disseminate link state information throughout the MWNs. Each node maintains the global topology information of the network, and computes the next hop for all the other nodes in the network using shortest hop forwarding paths.

The OLSR protocol discovers two-hop neighbor information for each node through one-hop Hello packet broadcasts. In order to minimize the topology information flooding overhead, OLSR performs a distributed election of a set of multipoint relays (MPRs). Each node selects its MPR set among its one-hop neighbors such that the set covers all the nodes that are two hops away. These MPR nodes generate and forward topology control (TC) messages that contain the MPR selectors.

The TC messages are generated periodically. The neighbors that are not in the MPR set read and process the TC message but do not rebroadcast the message. The information diffused in the network by the TC messages helps each node to build its topology table and the routing table is calculated based on this. This functioning of MPRs makes OLSR different from other link state routing protocols in several ways. Only a subset of the network nodes generates link-state information and not all the links of a node are advertised – only those that represent MPR selections.

The advantage of OLSR over reactive routing protocols (such as AODV and DRS) is that it does not introduce route-discovery delay for a flow because the route is computed in a proactive way. This favors situations where route requests for new destinations are very frequent. The OLSR protocol is adapted to the network, which is dense and where communication is assumed to occur frequently between a large number of nodes.

The drawback of OLSR is that it maintains the routing table for all the destinations at each node, which may not be necessary. When the number of the nodes increases, the overhead from the control messages also increases. By only using MPRs to flood topology information, OLSR removes some of the redundancy of the flooding process, which may be a problem in networks with weak wireless links.

1.3.2 Opportunistic routing

In a wireless network, when a packet is unicast to a specific next-hop node of the sender at the network layer, all the neighboring nodes in the effective communication range of the sender may be able to overhear the packet at the physical layer. It is possible that some of the neighbors may have received the packet correctly while the designated next-hop node did not. Based on this observation, a new routing paradigm, known as **opportunistic routing** (OR) (Ai *et al*. 2006; Biswas and Morris 2005; Bletsas *et al*. 2006; Fussler *et al*. 2003; Larsson 2001; Shah *et al*. 2004; Zhao and Valenti 2005; Zorzi and Rao 2003a,b) has recently been proposed. Opportunistic routing integrates the network and MAC layers. Instead of deterministically picking one node to forward a packet to, the network layer selects a set of candidate nodes to forward a packet to and at the MAC layer one node is selected dynamically as the actual forwarder based on the instantaneous wireless channel condition and node availability at the time of transmission. Opportunistic routing takes advantages of the spacial diversity and broadcast nature of wireless communications and is an efficient mechanism to combat the time-varying links. It improves the network throughput (Fussler *et al*. 2003; Biswas and Morris 2005; Zeng *et al*. 2008; 2007a,c) and energy efficiency (Zorzi and Rao 2003a; Zeng *et al*. 2007b) compared to traditional routing.

Some variants of opportunistic routing, such as ExOR (Biswas and Morris 2005) and opportunistic any-path forwarding (Zhong *et al*. 2006; Dubois-Ferriere *et al*. 2007; Zhong and Nelakuditi 2007), rely on the path-cost information or global knowledge of the network to select candidates and prioritize them. Another variant of OR is geographic opportunistic routing (GOR) (Fussler *et al*. 2003; Zorzi and Rao 2003a; Shah *et al*. 2004) which uses the location information of nodes to define the candidate set and relay priority. In GeRaF (Zorzi and Rao 2003a), the next-hop neighbors of the current forwarding node are divided into sets of priority regions with nodes closer to the destination having higher relay priorities. Like GeRaF, in (Shah *et al*. 2004), the network layer specifies a set of nodes by defining a forwarding region in space that consists of the candidate nodes. The data-link layer selects the first node available from that set to be the next hop node. (Fussler *et al*. 2003) discussed three suppression strategies of contention-based forwarding to avoid packet duplication in mobile ad hoc networks. We will discuss state-of-the-art opportunistic routing protocols in Chapter 6.

The performance of OR depends on several key issues. The first **key issue** is the selection of forwarding candidates. Although the most effective way seems to be to involve all the neighbors with smaller cost to the destination, the overhead is expected to grow with the increase of the number of forwarding candidates. In dense networks, this overhead might potentially be even higher than cost incurred due to repeated transmissions (Shah *et al*. 2005). The prioritization of the candidates is the second **key issue** that affects the performance. In general, we want to forward the packet along the "shortest" path. The lower priority forwarding candidates are essentially the backup to the node that is on the "shortest" path. However, due to the opportunistic nature of OR, the "distance" from a certain node to its multihop away destination will no longer be the same as that obtained by traditional shortest path routing. The path cost also depends on the spacial diversity opportunities along the path. How to quantify and incorporate the spacial diversity opportunities in OR has not been well understood. The third **key issue** is candidate coordination in the MAC layer, which ensures the multiple receivers of a packet to agree upon a next-hop forwarder in a distributed fashion (Choudhury and Vaidya 2004; Larsson 2001; Souryal and Moayeri 2005; Zhao and Valenti 2005; Zhong *et al*. 2005; Zorzi and Rao 2003a,b).

Although opportunistic routing has shown its effectiveness in achieving better energy efficiency (Zorzi and Rao 2003a,b) and higher throughput (Biswas and Morris 2005) than traditional routing, many important issues in OR remain unanswered or not well understood. First, none of the existing works provides a thorough understanding of how well the opportunistic routing can perform and how the selection of the forwarding candidate set will affect the routing efficiency. Questions, such as "a. how many and which neighbor nodes should be involved in the local forwarding?" and "b. What are the selection criteria and how do they affect the relay priority among the forwarding candidates?" remain unanswered. Second, there is a lack of theoretical analysis on the throughput bounds achievable by OR. Third, one of the current trends in wireless communication is to enable devices to operate using multiple transmission rates. For example, many existing wireless networking standards such as IEEE 802.11a/b/g include this multirate capability. The inherent rate–distance tradeoff of multirate transmissions has shown its impact on the throughput performance of traditional routing (Awerbuch *et al*. 2006; Zhai and Fang 2006a,b). Generally, low-rate communication covers a long transmission range, whereas high-rate communication must occur at short range. It is intuitive to expect that this rate–distance tradeoff will also affect the throughput of OR. Because different transmission ranges also imply different neighboring node sets, this results in different spacial diversity opportunities. The rate–distance–diversity tradeoffs in

OR are not well studied. Furthermore, existing OR coordination schemes have some inherent inefficiencies such as high time delay and potential duplicate forwarding. An improperly designed coordination scheme will aggravate these problems and even overwhelm the potential gain provided by OR. It is necessary to design more efficient candidate coordination schemes. Finally, most state-of-the-art OR protocols (Biswas and Morris 2005; Zeng *et al*. 2007c) rely on link quality (packet reception ratio) information to select and prioritize forwarding candidates. It is important to measure the link quality accurately in order to make OR operate optimally. However, the existing link quality measurement mechanisms are subject to malicious attacks. Thus they may not be able to provide accurate link quality information for OR and other link state-based traditional routing.

This book carries out a comprehensive study on the capacity, energy efficiency, throughput, and security issues in OR and the associated multirate, candidate selection, prioritization, and coordination problems. Our goal is to understand fully the principles, the tradeoffs, the gains of the node collaboration and its associated cost to provide insightful analysis and guidance for the design of more efficient routing protocols.

1.4 Related work

1.4.1 Opportunistic techniques

Cooperative communication While opportunistic routing aims to harvest the diversity gain at the packet level, cooperative communication studies the diversity gain at the signal level. The idea of user cooperation diversity is usually attributed to Sendonaris, Erkip, and Aazhang in Sendonaris *et al*. (1998) but can also be traced back to the relay channel model first introduced in Meulen (1971). The relay channel generalizes the notion of a simple point-to-point channel with a single source and destination to include a relay whose sole purpose is to help transfer information from the source to the destination.

Cover and Gamal (1979) and Cover and Thomas (1991) are credited with developing most of the information theory results on relay channels. They analyzed the capacity of the relay channel under the assumption that all nodes operate in the same band. Under this assumption, the system can be decomposed into a broadcast channel from the viewpoint of the source and a multiple access channel from the viewpoint of the destination. The idea of user cooperation diversity first attracted the attention of the information theory after the paper by communit Sendonaris *et al*. (1998) was presented at the 1998 International Symposium on Information Theory. Many of the ideas and results that appeared in the literature shortly after Sendonaris *et al*. (1998) can be traced to Cover and Gamal (1979).

Sendonaris, Erkip, and Aazhang followed up on Sendonaris *et al*. (1998) with a more detailed information theory study of two-source transmission cooperation in a mobile uplink scenario in (Sendonaris *et al*. 2003a,b). This work was important in that it also exposed several practical implementation issues in cooperative transmission systems and attracted the interest of the communications and signal-processing communities. Also noteworthy are the contributions of Laneman and

Wornell (2002); Laneman (2002); and Laneman *et al*. (2004) for studying the performance of several practical cooperative transmission protocols in fading environments. Yet another important set of contributions came in the form of novel information theory results and new insights into information theory coding in Kramer *et al*. (2005). New information theory results and results on power control were also presented in Host-Madsen and Zhang (2005); Wang *et al*. (2005a). A variety of contributions to relaying including new bounds, cut-set theorems, power control strategies, LDPC relay code designs and some of the earliest results on half-duplex relaying were proposed in Khojastepour (2004). Researchers realized that relaying can mimic multiple-antenna systems even when the communicating entities were incapable of supporting multiple antennas. Prominent literature on the use of space-time codes with relays includes Laneman and Wornell (2002); Mitran *et al*. (2005); Nabar *et al*. (2004). Other interesting contributions are Boyer *et al*. (2004); Hasna and Alouini (2003); Liang and Veeravalli (2005); Toumpis and Goldsmith (2003).

The research in cooperative communication mainly focuses on the theoretical capacity under strict assumptions about user synchronization at the signal level. It is difficult to implement the proposed cooperative communication schemes in the real system. Opportunistic routing realizes the gains of cooperative diversity at the packet level, so it can be implemented in the standard radio hardware such as IEEE 802.11 devices.

Opportunistic scheduling Opportunistic scheduling aims to improve network utilization by taking advantage of the wireless channel fading across users and time. Knopp and Humblet (1995) showed that by scheduling transmission to the network user experiencing the best channel condition at the moment in cellular networks, significant system level gains can be realized. Thus fading essentially gives an opportunity for the network to ride on the peak channel condition at all times. However, opportunistic scheduling has its own costs and limitations (Liu *et al*. n.d.). In all the opportunistic scheduling schemes, signaling costs are unavoidable, because scheduling decisions inherently depend on channel conditions (and/or queuing status). Users need to estimate their channel conditions constantly and report to the base station. Hence, the actual scheduling gain should take into account the signaling costs. Furthermore, the timescale of channel fading plays an important role in opportunistic scheduling. The fluctuation of channels should be slow enough for user to estimate it and exploit it. On the other hand, the fluctuation should be fast enough, so that users do not experience extreme long delays.

In short, opportunistic routing is different from opportunistic scheduling in the following aspects. First, they target different problems. Opportunistic routing tries to improve packet forwarding reliability in multihop wireless networks by taking advantage of the spacial (user) diversity and the broadcast nature of the wireless medium whereas opportunistic scheduling aims to improve the system resource utilization by exploiting the channel fluctuations due to fading. Second, they are used in different networks. Opportunistic routing is used in multihop wireless networks whereas opportunistic scheduling is mainly used in single-hop cellular networks. Third, they are implemented at different layers. Opportunistic routing is a cross-layer design that is implemented at the network and MAC layers. In Chapter 7, we will see by integrating network coding, the opportunistic routing can be just implemented at network layer. While opportunistic scheduling is usually implemented at MAC layer with physical layer channel-state information.

AP collaborations Protocols like MRD (Miu *et al*. 2005), SOFT (Woo *et al*. 2007) and Link-Alike (Jakubczak *et al*. 2009) all exploit different aspects of the same concept: multiple receiver diversity in WLANs. Consider, for example, a sender that has poor connectivity to multiple nearby APs. A transmitted packet is unlikely to reach any specified AP; any bit in the packet is likely to be received by at least one AP. All the above protocols exploit this receiver diversity by allowing APs to combine received bits or packets over the wired network and hence can increase uplink reliability without any retransmissions.

However, none of these schemes can similarly address a lossy downlink without expending medium time on retransmissions. SourceSync (Rahul *et al*. 2010) complements all these protocols by harnessing sender diversity to increase downlink reliability without any retransmissions, analogous to existing receiver diversity mechanisms on the uplink. Specifically, instead of requiring that a client receive packets from only one AP at a time, in SourceSync, multiple neighboring APs can transmit simultaneously to the client, and increase throughput.

In this category of research, the main focus is on how to improve the last-hop uplink or downlink transmission reliability, while routing is not a major concern. In opportunistic routing, the forwarding candidate selection and prioritization are not only dependent on the local one-hop instant link quality but also affected by the cost/distance from the candidates to the destination. Therefore, in comparison with AP collaborations, opportunistic routing faces more challenges.

1.4.2 Network coding

Candidate coordination is a challenging problem introduced by opportunistic routing. If the forwarding candidates are not well coordinated, multiple nodes may hear a packet and forward the same packet unnecessarily, which in turn degrades the network throughput. Fortunately, network coding can effectively alleviate this problem. Next we introduce the basic concepts of network coding, and then explain why it can be used to improve the routing performance in MWNs.

Network coding disposes of the traditional end-to-end packet forwarding paradigm, and enables intermediate nodes to mix the received packets and has the potential to increase network throughput. Intuitively, by combining received packets, a coded packet sent by an intermediate node could benefit multiple receivers simultaneously, thus improving the bandwidth efficiency. In the seminal paper by Ahlswede *et al*. (2000) it was shown that, for a butterfly network topology, the multicast capacity can be achieved by performing network coding at the routers. Later, Li *et al*. (2003) showed that linear codes are enough to achieve the maximum multicast capacity bounds under the same network topology, while Ho *et al*. (2006) extended their results to random linear codes. For unicast traffic, Li and Li (2004) showed that network coding results in higher throughput than pure forwarding for specific unicast topologies. The above results are for general networks; in the following, we give a brief review of how network coding can be applied to multicast/broadcast/unicast sessions with emphasis on multihop wireless networks and its advantages and limitations in both theory and practice.

From the theoretical viewpoint, Lun *et al*. (2008) proved that random linear network coding can be used to construct a capacity-approaching scheme for multicast over lossy wireless networks. Adjih *et al*. (2007) showed that by using a simple broadcast rate selection strategy, network coding can ensure that every transmission has a high probability of being useful. Fragouli *et al*. (2008) studied network coding-based efficient broadcast from both theoretical and practical points of view. They showed that network coding is able to increase the bandwidth/energy efficiency by a constant factor in fixed networks. They also proposed a probabilistic forwarding-based algorithm for random networks, which shows a significant reduction in the total transmission count compared with probabilistic flooding.

To bridge the gap between theory and practice, Chachulski *et al*. (2007) proposed MORE, which is the first practical network coding-based opportunistic routing protocol that achieves high throughput for both unicast and multicast sessions. The main motivation of MORE is to solve the candidate coordination challenge of opportunistic routing (Biswas and Morris 2005). Its idea is to combine opportunistic routing with network coding. By randomly mixing packets before forwarding them, MORE ensures that the routers hearing the same transmission do not forward the same packet. In this way, MORE eliminates the need of complicated coordination mechanism between multiple forwarders in pure opportunistic routing. However, MORE is inefficient when applied to multicast or broadcast, since almost every node in the network may become a forwarding node, which can cause heavy congestion (Koutsonikolas *et al*. 2009). Moreover, in mobile MWNs, traditional tree-based multicast schemes fall short in that they incur large overhead in maintenance of the tree structure as the topology changes very fast.

Recently, a special type of network coding, symbol-level network coding (SLNC) (Katti *et al*. 2008) is proposed. Taking a step further beyond the usual packet-level network coding (PLNC) method which processes information in the unit of packets, SLNC enables a node to combine information in the smaller granularity of “symbol”, which may consist of several physical layer symbols. The immediate advantages brought by SLNC are enhanced error and interference tolerance, whereas the benefits of network coding are automatically inherited. In addition, SLNC also possesses the potential to enhance spacial reuse by encouraging concurrent transmissions, and it has been shown to be able to significantly improve the throughput of unicast in wireless mesh networks compared with PLNC (Katti *et al*. 2008). However, how and how much SLNC can improve the bandwidth efficiency in mobile WMNs is still not well understood.

In this book (Chapter 7), we exploit network coding and opportunistic listening in designing high-performance broadcast protocols in mobile MWNs, especially vehicular ad hoc network (VANET). In order to resolve the challenges posed by lossy links and fast-changing topology, SLNC is combined with a novel push-based broadcast method where the relay nodes (forwarders) are selected in a dynamic, opportunistic, and fully distributed manner, in contrast with the traditional tree-based multicast method in fixed MWNs. The coordination among relay nodes can be greatly simplified through the use of network coding. The gains of using SLNC and the opportunistic relay selection method are characterized, which again demonstrates the importance of being opportunistic (in the mobile setting).

1.4.3 Opportunistic forwarding in opportunistic networks

Opportunistic networks are an important class of Delay/Disruption Tolerant Networks (DTNs) in which contacts (time-windows when data can be exchanged) appear opportunistically without any prior information (Wang *et al*. 2005b). In opportunistic networks, source and destination nodes might never be fully connected at the same time. That is, there is no guarantee on the existence of a complete path between two nodes wishing to communicate. Examples of such networks are sparse mobile ad hoc networks, such as ZebraNet (Juang *et al*. 2002). Packet forwarding or routing in such networks is the most compelling issue. Nodes are not always connected to each other, so the forwarding algorithms in such networks follow a store-carry-forward paradigm. Typical algorithms differ based on their decisions as to who forwards the data, at what time the data is forwarded, and to whom the data is sent.

In general, the packet forwarding algorithms can be classified into three categories: flooding, simple replication, and history based.

In flooding algorithms, each node forwards any nonduplicated messages to any other node that it encounters. A representative protocol in this category is the epidemic routing protocol (Vahdat and Becker 2000), where messages diffuse in the network similarly to diseases or viruses, i.e., by means of pair wise contacts between individuals/nodes. The dissemination process is bounded because each message when generated is assigned a hop-count limit giving the maximum number of hops that the message is allowed to traverse before reaching the destination. The flooding algorithm delivers messages with the minimum delay but consumes a lot of bandwidth and node storage.

For simple replication algorithms, identical copies of the message are sent over the first k contacts. Only the source of the message sends multiple copies. The relay nodes are allowed to send only to the destination; they cannot forward it to another relay. This leads to small overhead as the message flooding is controlled to take place only near the source. This class of forwarding algorithms is also known as the two-hop relay algorithm (Chaintreau *et al*. 2005; Grossglauser and Tse 2002b). There is a natural tradeoff between overhead and data-delivery latency. A higher k leads to more storage/transmissions but has lower delays.

A history-based algorithm estimates the probability of delivery using the historical data forwarding record. Each node keeps track of the probability that a given node will deliver its messages. k highest ranked relays (based on delivery probability) are selected as forwarding nodes (Juang *et al*. 2002).

We should differentiate between the opportunistic forwarding in opportunistic networks and the opportunistic routing we study in this book. The former considers the node encounter probability as the opportunity, and store, carry, and forward the packet in a not completely connected network. It still abstracts each wireless link as a wired link, and does not consider exploiting spacial diversity to improve per-hop transmission reliability. The latter considers the broadcast nature of wireless medium as an opportunity and exploits the spacial node diversity in each transmission to improve the per-hop transmission reliability.

1.4.4 Geographic routing

Owing to its scalability, statelessness, and low maintenance overhead, geographical routing is considered as an efficient paradigm for data forwarding in multi-hop wireless ad hoc and sensor networks. Early work (Finn 1987; Karp and Kung 2000; Kuhn *et al*. 2003) on geographic routing exploited the concept of maximum advancement towards the destination to route packets in a greedy manner. However, recent empirical measurements (Couto *et al*. 2003; Zhao and Govindan 2003) have proved that the unit disk connectivity model, on which these solutions are based, often fails in real settings. More recent works on geographic routing are focused on lossy channel situations. Seada *et al*. (2004) articulated the distance–hop energy tradeoff for geographic routing. They concluded that packet advancement times packet reception ratio, the EPA, is an optimal metric for making localized geographic routing decisions in lossy wireless networks with ARQ (Automatic Repeat reQuest) mechanisms, and is also a good metric for Non-ARQ scenarios. Zorzi and Armaroli (2003) also independently proposed the same link metric. Lee *et al*. (2005) presented a more general framework called normalized advance (NADV) to normalize various types of link cost such as transmission times, delay and power consumption. Unfortunately, NADV only applies to geographic routing which involves a single forwarding candidate and cannot be directly used for geographic opportunistic routing.

1.4.5 Multirate routing

Multirate wireless networks have started attracting research attention recently. Draves *et al*. (2004) proposed using the weighted cumulative expected transmission time (WCETT) as a routing metric. Awerbuch *et al*. (2006) adopted the medium time metric (MTM). Zhai and Fang (2006b) studied the impact of multirate on carrier sensing range and spacial reuse ratio and demonstrated that the bandwidth distance product and the end-to-end transmission delay (the same as the medium time) are better routing metrics than the hop count. Zhai and Fang (2006a) also proposed the metric of interference clique transmission time to achieve a high path throughput. However, these metrics or protocols were proposed for routing on a fixed path following the concept of the traditional routing. In this book, we propose a framework to compute the end-to-end throughput bound of OR for different OR schemes in multiradio, multichannel and multirate networks.

The throughput bound derived in this book is the upper bound of the achievable throughput of the proposed and investigated OR schemes. We also study the impact of the protocol overhead and multirate capability on the performance of GOR under contention-based medium access protocols.

1.4.6 Energy-aware routing

Energy-aware routing has received significant attention over the past few years (Chang and Tassiulas 2000; Kar *et al*. 2003; Li *et al*. 2001; Singh *et al*. 1998). Singh *et al*. (1998) proposed five energy aware metrics such as *maximizing time to partition* and *minimizing maximum node cost*. These are important metrics for energy efficient routing. However, it is difficult to directly implement them in a local algorithm when even the global version of the same problem is NP-complete. Chang and Tassiulas (2000) proposed a class of flow-augmentation algorithms and a flow-redirection algorithm, which balances the energy consumption rates among the nodes in proportion to the energy reserves. The limitation of this approach is that it requires prior knowledge of the information generation rates at the origin nodes. Li *et al*. (2001) proposed an "online" power-aware routing and a zone-based routing, which maximizes the network lifetime without knowing the message generation rate. Following Li *et al*. (2001), another "online" routing algorithm was proposed in Kar *et al*. (2003), which aims to maximize the total number of successfully delivered messages. In this book, we study the energy efficiency of OR to tradeoff the routing performance and energy efficiency in terms of maximizing the bit advancement per unit energy consumption.

1.4.7 Capacity of MWNs

Theoretical work on the capacity of MWNs mainly focuses on two aspects. One is the asymptotic bounds of the network capacity (Grossglauser and Tse 2002a; Gupta and Kumar 2000). These works study the capacity trend with regard to the size of a wireless network under specific assumptions or scenarios. The other aspect of work on wireless network capacity is the computation of the exact performance bounds for a given network. Jain *et al*. (2003) proposed a framework to calculate the throughput bounds of traditional routing between a pair of nodes by adding wireless interference constraints into the maximum flow formulations. Zhai and Fang (2006a) studied the path capacity of traditional routing in a multirate scenario. Our work falls into this direction. However, distinct from the previous works, we propose a method to compute the end-to-end throughput bounds of opportunistic routing, which is different from the traditional routing in that we construct the transmitter (associated with multiple forwarding candidates) based conflict graph instead of a link conflict graph to capture the local broadcast nature of OR. Our framework can be used as a tool to calculate the end-to-end throughput bound of different OR variants, and is an important theoretical foundation for the performance study of OR. There has been recent work (Alicherry *et al*. 2005; Kodialam and Nandagopal 2005; Zhang *et al*. 2005) on capacity bound computation in multiradio multichannel networks. However, they are all based on the assumption that traditional routing is used at the network layer, where one transmitter can only deliver traffic to one receiver.

1.4.8 Link-quality measurement

The existing LQM mechanisms proposed in the literature (Couto *et al*. 2003; Kim and Shin 2006; Sang *et al*. 2007) can be generally classified into three types: active, passive and cooperative (Kim and Shin 2006). For broadcast-based active probing (Couto *et al*. 2003), each node periodically broadcasts Hello/probing packets and its neighbors record the number of received packets to calculate the packet reception ratios (PRRs) from the node to themselves. In passive probing (Kim and Shin 2006), the real traffic generated in the network is used as probing packets without introducing extra overheads. For cooperative probing (Kim and Shin 2006), a node overhears the transmissions of its neighbor to estimate the link quality from the neighbor to itself. However, for any of the existing LQM mechanisms, the inherent common fact is that a node's knowledge about the forward PRR from itself to its neighbor is informed by the neighbor. Since MWNs are generally deployed in an ad hoc style or in untrusted environments, nodes may be compromised and act maliciously. This receiver-dependent measurement opens up a door for malicious attackers to report a false measurement result and disturb the routing decision for all the PRR-based protocols.

1.5 Book contribution

The main contributions of this book are as follows:

- Chapter 2
  - We generalize the definition of EPA for an arbitrary number of forwarding candidates that follow a specific priority rule to relay the packet in OR.
  - Through theoretical analysis we prove that the maximum EPA can only be achieved by giving higher relay priorities to the forwarding candidates closer to the destination. This proof convinces us that given a forwarding candidate set, the relay priority among the candidates is only relevant to the advancement achieved by the candidate to the destination, but irrelevant to the packet delivery ratio between the transmitter and the forwarding candidate. The analysis result is the upper bound of the EPA that any GOR can achieve.
  - We find that given a set of M nodes that are available as next-hop neighbors, the candidate set achieving the maximum EPA with r ($r \leq M - 1$) nodes is contained in at least one candidate set achieving the maximum EPA with $r + 1$ nodes.
  - We prove that the maximum EPA of selecting $r(r \leq M)$ nodes is a strictly increasing and concave function of r. This property indicates that although

involving more forwarding candidates in GOR will increase the maximum EPA, the extra EPA gained by doing so becomes less significant.

- Chapter 3
  - We investigate the energy efficiency of GOR and propose two localized candidate selection algorithms with $\mathbf{O}(M^3)$ and $\mathbf{O}(M^2)$ running time in the worst case respectively and $\Omega(M)$ in the best case, where M is the number of available next-hop neighbors of the transmitter. The algorithms efficiently determine the optimal forwarding candidate set with respect to the EPA per unit of energy consumption.
  - We propose an energy-efficient geographic opportunistic routing (EGOR) framework applying the node selection algorithms to achieve the energy efficiency. Simulation results show that EGOR achieves better energy efficiency than geographic routing and blind opportunistic protocols in all the cases while maintaining very good routing performance. Our simulation results also show that the number of forwarding candidates necessary to achieve the maximum energy efficiency is mainly affected by the reception to transmission energy ratio but not by the node density under a uniform node distribution. Only a very small number of forwarding candidates (around 2) is needed on average. This is true even when the energy consumption of reception is far less than that of transmission.
- Chapter 4
  - We propose a new method of constructing transmission conflict graphs, and present a methodology for computing the end-to-end throughput bounds (capacity) of OR. We formulate the maximum end-to-end throughput problem of OR as a maximum-flow linear programming problem subject to the transmission conflict constraints and effective forwarding rate on each link. To the best of our knowledge, this is the first theoretical work on capacity problem of OR for multihop and multirate wireless networks.
  - We propose two metrics for OR under multirate scenario: one is *expected medium time* (EMT) and the other is *expected advancement rate* (EAR). Based on these metrics we propose two distributed and local rate and candidate selection schemes: least medium time OR (LMTOR) and multirate GOR (MGOR), respectively.
  - We show that OR has great potential to improve the end-to-end throughput under different settings, and our proposed multirate OR schemes achieve higher throughput bound than any single-rate GOR.
  - We make some observations about OR: 1. the end-to-end capacity gained decreases when the number of forwarding candidates is increased. When the number of forwarding candidates is larger than three, the throughput almost remains unchanged. 2. there exists a node-density threshold, higher than which 24 mbps GOR performs better than 12 mbps GOR, and lower

than which, vice versa. The threshold is about 5.5 and 10.9 neighbors per node on 12 mbps for line and square topologies, respectively.

- Chapter 5
  - We propose a unified framework to compute the capacity of opportunistic routing between two end nodes in single/multi-radio/channel multihop wireless networks by allowing dynamic forwarding strategies.
  - We discuss the radio/channel and interference constraints when constructing concurrent transmission sets, and study the capacity region of an opportunistic module.
  - We propose an LP approach and a heuristic algorithm to obtain an opportunistic forwarding and scheduling strategy that satisfies a traffic demand vector.
  - Leveraging our analytical model, we find that OR can achieve comparable or even better performance than TR by using fewer radio resources.
- Chapter 6
  - We propose a new scheme “fast slotted acknowledgment” for candidate coordination in OR, which adopts single ACK to confirm successful reception and suppress other candidates’ attempts to forward the data packet with the help of a channel-sensing technique.
  - Simulation shows that FSA can decrease the average end-to-end delay by up to 50% when the traffic is relatively light and can improve the throughput by up to 20% under heavy traffic load where other coordination schemes are already unable to delivery all the data packets.
  - The simulation results also validate that FSA can achieve performance similar to ideal coordination where relay priority can be ensured and duplicate packet forwarding is avoided.
- Chapter 7
  - We investigate the integration of network coding with opportunistic routing for easing the coordination in OR, and review MORE, a state-of-the-art MAC-layer independent OR protocol based on network coding.
  - We formulate the problem of mobile content distribution in a vehicular ad hoc network (VANET) and propose two mobile content broadcast schemes by leveraging symbol level network coding (SLNC) and combining it with opportunistic listening at the same time.
  - We propose two push-based broadcast protocols to exploit the benefits of SLNC fully, in which the content sources simply “pushes” information

  into the VANET actively, while a dynamic subset of temporary relay nodes from all the vehicles is determined in a fully distributed and localized way.

  - We observe that, in addition to the advantage brought by network coding in simplifying the transmission scheduling in MORE, by using symbol-level network coding, another benefit is gained for the broadcast. That is, due to the higher error and interference tolerance from symbol-level diversity, the hidden terminal problem can be alleviated, which yields the possibility of using much simpler coordination mechanism in medium access, i.e., carrier sensing. In contrast, the traditional packet-level network coding does not achieve best performance under the same coordination method due to the interference from hidden terminals.
  - Simulation shows that the proposed broadcast schemes achieve significant gains compared with state-of-the-art content distribution schemes in VANETs, where one important part of it comes from the use of SLNC and the other is attributed to the new push-based protocol design.

- Chapter 8
  - We investigate the impact of transmission rate and forwarding strategies (candidate selection, prioritization and coordination) on throughput of OR under a contention-based medium-access scenario.
  - We propose a local metric, *Opportunistic Effective One-hop Throughput* (OEOT), to characterize the tradeoff between the packet advancement and one-hop packet forwarding time under different data rates.
  - We propose a rate-adaptation and candidate-selection algorithm to approach the local optimum of this metric.
  - We propose a multirate link quality measurement mechanism.
  - We show that MGOR incorporating our algorithm achieves better throughput and delay performance than the corresponding opportunistic routing and geographic routing operating at any single rate, which indicates that OEOT is a good local metric to achieve high end-to-end throughput and low delay for MGOR.
- Chapter 9
  - We discuss possible attacks on opportunistic routing protocols and propose countermeasures.
  - We analyze the security vulnerabilities in the existing LQM mechanisms and propose an efficient broadcast-based secure LQM (SLQM) mechanism, which prevents the malicious receiver from reporting a higher PRR than the actual one.

  - We analyze the security strength, the cost and applicability of the proposed mechanism.

- Chapter 10
  - We study opportunistic broadcasting in vehicular networks, where we apply the concept of opportunistic routing to the design of a broadcast protocol.
  - In particular, we propose a multi hop *opportunistic broadcast* scheme, a fully distributed protocol that simultaneously achieves high reliability and fast message propagation while incurring low transmission overheads.
  - We propose a distributed *opportunistic broadcast coordination* mechanism to let the recipients of a single broadcast determine the "best" relay nodes in a localized manner. The proposed transmission coordination mechanism exploits the idea of opportunistic forwarding to enhance the reception reliability and reduce the hop delay in each single transmission.
  - Simulation results show that the proposed scheme achieves better performance than the state-of-the-art solutions and we characterize the tradeoff between broadcast reception reliability, end-to-end delay and transmission overhead.

1.6 System model and assumptions

We consider a multi hop wireless network with N nodes arbitrarily located on a plane. Each node n_i $(1 \le i \le N)$ can transmit a packet at J different rates $R^1, R^2, \ldots, R^J$. We say there is a **usable** directed link l_{ij} from node n_i to n_j, when the **packet reception ratio** (PRR), denoted as p_{ij}, from n_i to n_j is larger than a non-negligible positive threshold p_{td}. The PRR we consider is an average value of the link quality in a long timescale (e.g. in tens of seconds). There exist several link-quality measurement mechanisms (Couto *et al*. 2003; Kim and Shin 2006) to obtain the PRR on each link. We assume that there is no power control scheme and the PRR on each link for each rate is given. We define the **effective transmission range** L_m at rate R^m $(1 \le m \le J)$ as the sender-receiver distance at which the PRR equals p_{td}.

The basic module of opportunistic routing is illustrated in Figure 1.1. Assume node n_i is forwarding a packet to a remote sink/destination n_d. We denote the set of nodes within the effective transmission range of node n_i as the **neighboring node set** $\mathcal{C}_i$ (e.g., all the five nodes around n_i in Figure 1.1). Note that, for different transmission rates, the corresponding effective transmission ranges are different, then we have different neighboring node sets of node n_i, and the PRR on the same link l_{ij} may be different at different rates. We define the set $\mathcal{F}_i := \langle n_{i_1}, \ldots, n_{i_r} \rangle$ (e.g., $\langle n_{i_1}, n_{i_2}, n_{i_3} \rangle$ in Figure 1.1) as **forwarding candidate set**, which is a subset of $\mathcal{C}_i$ and includes r nodes selected to be involved in the local opportunistic forwarding based on a particular selection strategy. $\mathcal{F}_i$ is an ordered set, where the order of the elements corresponds to their priority in relaying a received packet.

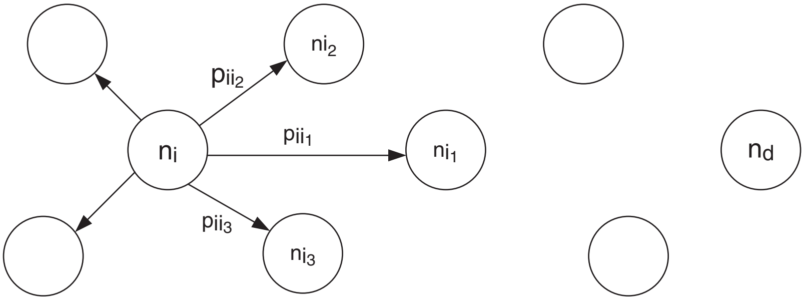

Figure 1.1 Node n_i is forwarding a packet to a remote destination n_d with a forwarding candidate set $\mathcal{F}_i = \langle n_{i_1}, n_{i_2}, n_{i_3} \rangle$ at some transmission rate. Reproduced by permission of © 2008 IEEE.

For GOR, we assume each node is aware of the location information[1] of itself, its one-hop neighbors and the destination. Given a transmitter n_i, one of its forwarding candidates n_{i_q}, and the destination n_d, we define the **packet advancement** d_{i_q} in Equation (1.1), which is the Euclidean distance between the transmitter and destination subtracting the Euclidean distance between the candidate n_{i_q} and the destination. This definition represents the advancement in distance made toward the destination when n_{i_q} forwards the packet sent by n_i.

$$d_{ii_q} = dist(n_i, n_d) - dist(n_{i_q}, n_d) \tag{1.1}$$

For GOR, because we are only interested in the neighbors that give positive advancement to the destination, we denote the set of those neighbors as $\mathcal{C}_i$, the **available next-hop node set**.

Opportunistic routing works by the sender node n_s forwarding the packet to the nodes in its forwarding candidate set $\mathcal{F}_s$. One of the candidate nodes continues the forwarding based on their relay priorities–if the first node in the set has received the packet successfully it forwards the packet towards the destination while all other nodes suppress duplicate forwarding. Otherwise, the second node in the set is arranged to forward the packet if it has received the packet correctly. Otherwise the third node, the fourth node, and so forth. A forwarding candidate will forward the message only when all the nodes with higher priorities fail to do so. When no forwarding candidate has successfully received the packet, the sender will retransmit the packet if retransmission is enabled. The sender will drop the packet when the number of retransmissions exceeds the limit. The forwarding reiterates until the packet is delivered to the destination. Several MAC protocols have been proposed in Biswas and Morris (2005); Fussler *et al.* (2003); Zorzi and Rao (2003a); Zubow *et al.* (2007) to coordinate the forwarding candidates and ensure the relay priority among them. In this book, for all the analysis, we assume the relay priority can

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[1] The node location information can be obtained by prior configuration, by the Global Positioning System (GPS) receiver, or through some sensor self-configuring localization mechanisms as in Bulusu *et al.* (2000); Savvides *et al.* (2001).

be perfectly realized. So there is no duplicate packet forwarding due to imperfect candidate coordination. We will show in Chapter 6 that it is a realistic assumption when our proposed candidate coordination scheme is used.

For capacity analysis in Chapters 4 and 5, we assume that packet transmissions at the individual nodes can be finely controlled and carefully scheduled by an omniscient and omnipotent central entity. So here we do not concern ourselves with issues such as MAC contention or coordination overhead that may be unavoidable in a distributed network. This is a very commonly used assumption for such theoretical studies (Jain *et al*. 2003; Zhai and Fang 2006a).

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