On Routing in Multichannel Wireless Mesh Networks: Challenges and Solutions

Tehuang Liu and Wanjiun Liao, National Taiwan University

Abstract

Wireless mesh networks have emerged as a promising solution to providing cost-effective last-mile connectivity. Employing multiple channels is shown to be an effective approach to overcoming the problem of capacity degradation in multihop wireless networks. However, existing routing schemes that are designed for single-channel multihop wireless networks may lead to inefficient routing paths in multichannel WMNs. To fully exploit the capacity gain due to multiple channels, one must consider the availability of multiple channels and distribute traffic load among channels as well as among nodes in routing algorithms. In this article we focus on the routing problem in multichannel WMNs. We highlight the challenges in designing routing algorithms for multichannel WMNs and examine existing routing metrics that are designed for multichannel WMNs, along with a simulation-based performance study. We also address some open research issues related to routing in multichannel WMNs.

Wireless mesh networks (WMNs) are considered a promising solution to last mile broadband access thanks to their desirable features, such as low upfront cost, easy network maintenance, robustness, and reliable service coverage [1]. In WMNs each node plays the roles of both a host and a router, and packets are forwarded in a multihop fashion to and from the gateway to the Internet. The major challenge in WMNs is to conquer the degradation of capacity due to the interference problem. Recent research results [2, 3] show that employing multiple channels is an effective approach to increasing network capacity. This improvement comes from concurrent transmissions on nonoverlapping channels, which are available in IEEE 802.11 WLAN standards. The emerging IEEE 802.11s standard for WMNs further introduces the concept of a Common Channel Framework (CCF) [4], which defines the operation of single-radio devices in a multichannel environment. While employing multiple channels improves the network capacity, the multichannel environment introduces new research challenges, including routing, scheduling, and allocating wireless channels. In this article we focus on the routing problem in multichannel WMNs. This problem is to determine which nodes to include on the routing path and which channel to use on each link of the path.

Although there are many routing algorithms [5–7] proposed for single-channel multihop wireless networks, they may lead to inefficient routing paths in multichannel WMNs. To fully exploit the availability of multiple channels in WMNs, routing algorithms should account for the existence of channel diversity on a path in the network. Consider the 10-node multichannel WMN shown in Fig. 1, where each node is equipped with two radios (i.e., each node can transmit or receive data on two nonoverlapping channels simultaneously), and the label on each wireless link indicates the channel on which the link operates. We can easily identify three possible routes from node H to gateway node A in the network, including H-D-A (involving channel 2), H-D-E-A (involving channels 2 and 3), and H-G-C-A (involving channels 6, 5, and 1). It may be hard to tell which path is best for node H to node A since path H-D-A is the shortest, but paths H-D-E-A and H-G-C-A are more *channel-diverse*.

The routing problem in multichannel WMNs is exacerbated by the fact that the network topology is determined by the channel assignment [3, 8]. For example, in Fig. 1, even though nodes G and D are located within the transmission range of each other, they cannot communicate with each other directly without a radio tuned to a common channel. This implies that the routing paths between any two nodes in the network are also restricted by channel assignment. As a result, a well designed routing algorithm for multichannel WMNs may become useless with an improper channel assignment algorithm. Furthermore, in some types of multichannel WMNs [2, 4], nodes have to dynamically negotiate the channels used for communication. Thus, it is difficult for the multichannel routing algorithm to predict the end-to-end performance of a path in such a dynamic environment.

In this article we study the routing problem in multichannel WMNs from the perspective of layer 2 routing. We identify the challenges in designing routing algorithms for multichannel WMNs and survey existing routing metrics designed for multichannel WMNs along with a simulation-based performance study. We also address some open research issues on routing for multichannel WMNs and cover the state-of-the-art developments in the IEEE 802.11s standard.

Challenges

With multiple channels, each radio interface on adjacent links can be assigned a different channel such that the interference among links can be eliminated and the network capacity can

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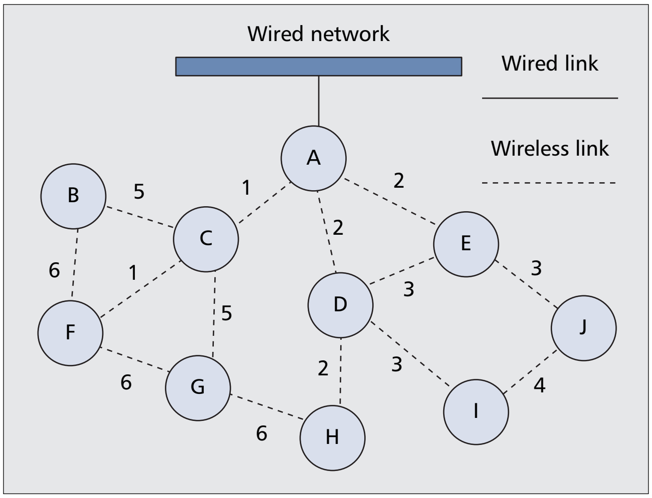


■ Figure 1. *A 10-node multichannel WMN where each node is equipped with two radios.*

be improved. In general, with proper design, leveraging multiple channels available today has several benefits, including increasing system throughput, decreasing end-to-end delay (due to less contention and interference), achieving better load balancing, and preventing the starvation problem in single-channel WMNs. In the following we highlight the challenges in designing routing algorithms and protocols for multichannel WMNs.

Need for a New Routing Metric

The routing metric is a criterion to judge the "goodness" of a path in routing algorithms. The most typical routing metric for multihop wireless networks is the hop count. This metric, however, cannot capture the quality of a path in wireless environments. The study in [5] reports that using a radio-aware routing metric that incorporates the link condition can result in much better performance than the minimum hop count approach. In [6] the authors show that a routing metric which accounts for multirate capability and interference can discover paths with much higher capacity than other routing metrics. In multichannel WMNs the channel diversity is another key factor since the end-to-end performance of a routing path is governed not only by which nodes this path comprises, but also by to which channels the links of this path are tuned. Incorporating channel diversity into the routing metric introduces two new issues:

- How to balance the trade-off between network throughput and per-node throughput
- How to quantify the channel diversity of a path

To expand on these two issues, we take Fig. 2 as an example, where the label on each link indicates the channel on which the link operates. We first consider paths P1 and P2 in the network. Obviously, if shorter paths are favored, P1 is selected; if the end-to-end throughput per flow is the priority, P2 is chosen. This is because the three links of P1, all of which operate on channel 1, may contend for the radio resource mutually, but the four links of P2 operating on different channels do not contend with each other. The path that presents higher channel diversity may not be the shortest one. As a result, channel-diverse paths may consume more radio resource in the network than the shortest paths, and thus may degrade the achievable system aggregate throughput. This constitutes the trade-off between maximizing network throughput and maximizing per-node throughput (or the trade-off between global goodness and selfishness [9]) in the network. Thus, it is desired to find a routing metric that strikes a balance between maximizing resource utilization and improving the end-to-end performance per flow for multichannel WMNs.

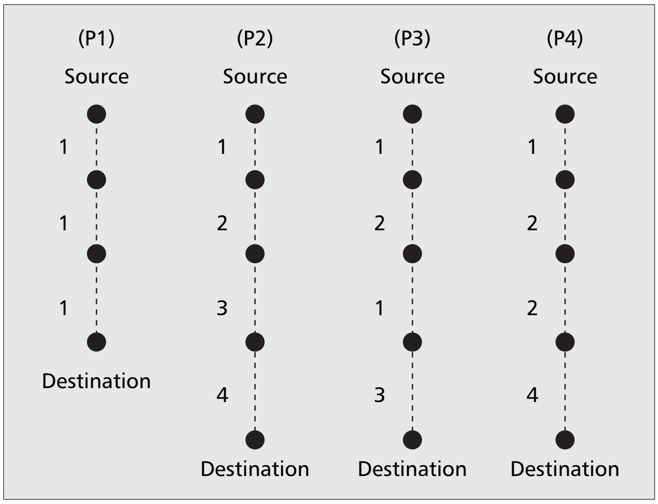
Paths P3 and P4 in Fig. 2 are an example with a similar level of channel diversity for two paths. However, the challenge here is how to quantify the channel diversity of a routing path, and sometimes it is hard to determine which path is preferable.

Load Distribution among Channels

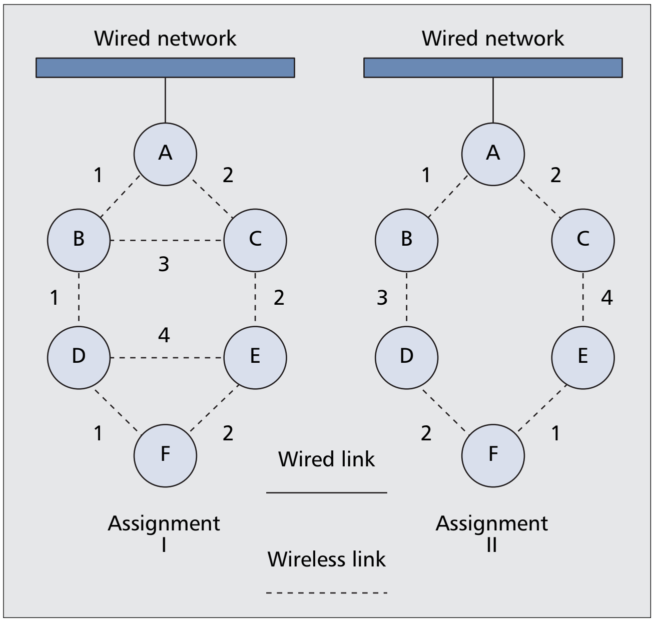
Utilizing multiple channels allows parallel transmissions on nonoverlapping channels. However, without accounting for the traffic load among channels (as well as among nodes), traffic may be skewed on certain channels, thus degrading network utilization. To avoid this problem, multichannel routing algorithms should compare different possible routes, which are composed of alternative nodes as well as alternative channels, between source and destination. However, gathering information about all possible routes to find an optimal path is computationally infeasible because an exponential number of such combinations may exist for any pair of nodes. As a result, suboptimal paths may be selected. Moreover, in multichannel WMNs, the path diversity between any pair of nodes is determined by the network topology, which is in turn controlled by the channel assignment algorithm (explained later) [3, 8]. Thus, if the channel assignment algorithm dose not account for traffic load, the effectiveness of load-balancing routing algorithms may be limited [3].

Dependence on Channel Assignment

Channel assignment is a companion issue for routing in multichannel WMNs [3, 8, 10]. The objective is to bind each radio interface to a channel such that the network capacity is maximized. Since two neighboring nodes can communicate with each other only if they are assigned a common channel, the channel assignment controls the network topology and consequently restricts the possible routes between any pair of nodes in the network. Therefore, a well designed routing algorithm for multichannel WMNs may become useless with an improper channel assignment algorithm. Figure 3 gives two channel assignment examples for the same network. Each node is equipped with two radios, and the label on each link indicates the channel on which the link operates. In this example assignment I generates more robust network connectivity, while assignment II provides nodes D, E, and F with better



■ Figure 2. *Example paths. P1 and P2 illustrate the trade-off between global goodness and selfishness. P3 and P4 are said to have a similar level of channel diversity.*



■ Figure 3. *Two different channel assignment examples for a four-channel WMN.*

routes (in terms of channel diversity and path length) to reach gateway node A. This example demonstrates that the effectiveness of multichannel routing algorithms depends on the employed channel assignment. It is due to this dependence that the multichannel routing and channel assignment problems are usually addressed jointly [3, 8, 10].

The routing problem is exacerbated if a dynamic[1] channel assignment strategy is adopted. In such a case, it is almost impossible for routing protocols to measure the channel diversity of a path since the channels used along the path are determined dynamically. Sometimes, even static channel assignments may need to be recomputed to achieve better load balancing [3] or interference avoidance [11]. With channel reassignment, some links and routes may not exist anymore, leading to broken routes and service disruption. As a result, route repair and flow redirection [11] are required.

Cross-Layer Design of Routing and MAC

In this article we consider layer 2 routing based on medium access control (MAC) layer addresses in WMNs for two reasons. First, IEEE 802.11-based WMNs have been viewed as a cost-effective approach to last mile access. An IEEE 802.11 WMN is composed of mesh stations and mesh access points (APs). Since APs are layer 2 (link layer) devices, it is infeasible to add layer 3 (network layer) routing functionality to an AP. Second, integrating the routing functionality into layer 2 is considered a more efficient approach to executing cross-layer design. This is because the physical layer affects MAC and routing by its transmission rate and bit error rate, and many radio-aware routing metrics [5–7, 9] require such information from the physical layer.

Multichannel MACs can be categorized into multichannel single-radio (MCSR) [2, 4] and multichannel multiradio (MCMR) [9]. With MCSR MAC, each node has only one radio and needs to switch channels on the radio frequently to communicate with different nodes. As a result, the network topology and interference among nodes vary with time. The impact of such channel switching on routing is twofold. First, it causes difficulty in performing basic functionalities such as path discovery, selection, and maintenance for routing protocols due to the lack of a radio being tuned to a common channel permanently. Second, it complicates the support of some advanced features such as load balancing and quality of service (QoS) support, since these features require additional mechanisms to coordinate the routing protocol and MAC scheme such that the channels used along the path can be well managed. For MCMR MAC, a mesh node is equipped with multiple radios, each of which is associated with its own MAC and physical layer. Therefore, the routing functionality should be implemented at a common sublayer that coordinates the transmissions on different radios.

Routing Metrics

The routing metric is the key component of the multichannel routing algorithm and significantly influences network performance. In this section we survey two existing multichannel routing metrics, weighted cumulative expected transmission time (WCETT) [9] and normalized bottleneck link capacity (NBLC) [12], both of which are designed for multichannel multiradio multirate[2] WMNs.

WCETT

WCETT [9] is extended from a radio-aware routing metric, expected transmission count (ETX) [7], which is designed for single-channel multihop wireless networks. The ETX metric measures the expected value of total packet transmissions (including retransmissions) required to successfully send a unicast packet over a link. The ETX-based routing algorithm is then to select the path whose sum of ETX values of all hops on the path is minimized. The ETX metric considers both the link loss rate and total consumed resource on the path. The study in [5] reports that the ETX metric achieves better performance than the hop count, per-hop round-trip time, and per-hop packet pair delay metrics in the network only consisting of stationary nodes. However, since the ETX metric is designed for single-channel systems, it does not account for channel diversity in multichannel WMNs.

WCETT is extended from ETX for multichannel wireless environments. The calculation of the WCETT metric can be divided into two parts: the estimation of the end-to-end delay of the path and the determination of the channel diversity of the path. To reflect the actual quality of a link, a “bandwidth-adjusted ETX,” called expected transmission time (ETT), is introduced. Specifically, ETT represents the expected total air time spent in transmitting a packet successfully on a link. Therefore, ETT is obtained by multiplying the ETX value of a link by the transmission time of one packet. The calculation of WCETT then requires the sum of ETTs (SETT) for all links of the path, which corresponds to an estimation of the end-to-end delay experienced by the packet. To quantify the channel diversity, it needs to determine the bottleneck group ETT (BGETT). The group ETT (GETT) of a path for channel c is defined as the sum of ETTs for the path’s links which operate on channel c. The BGETT is then referred to as the largest GETT of the path. The rationale is that the total path throughput is dominated by the *bottleneck channel* (i.e., the

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[1] *With static channel assignment strategies, each radio is assigned to a channel either permanently or for a relatively long interval compared to the channel switching delay. Dynamic channel assignment strategies allow a radio to perform channel switching frequently or on a per packet basis [10].*

[2] *The multirate feature is supported when the physical layer can perform dynamic modulation and coding to accommodate different channel conditions. Many modern wireless devices, such as those implementing the IEEE 802.11a/b/g and HiperLAN2 standards, provide multirate capabilities.*

	Hop count	WCETT	NBLC
Target system	Single channel, single radio	Multichannel, multiradio, multirate	Multichannel, multiradio, multirate
Radio-aware	No	Yes	Yes
Load balancing	No	Some	Yes
Factors	Path length	Path length, packet loss rates, data rates on links, channel diversity	Path length, packet loss rates on links, data rates on links, channel diversity, load on links, intraflow contention

■ Table 1. *Comparison of the hop count, WCETT, and NBLC metrics.*

busiest channel on the path). Thus, while low SETT implies short paths, low BGETT implies channel-diverse and high-bandwidth paths. However, the calculation of BGETT is somehow pessimistic, because if two links on a path are tuned to the same channel (no matter if these two links are far away from or adjacent to each other), they are assumed to be mutually interfered.

The WCETT metric is defined as the weighted average of the sum of SETT and BGETT,

$$WCETT \equiv (1 - \beta) \cdot SETT + \beta \cdot BGETT.$$

Accordingly, the routing algorithm is to select the path whose WCETT is the lowest. The WCETT metric strikes a balance between channel diversity and path length (or between throughput and delay) by changing the weighting factor β.

NBLC

NBLC [12] is a routing metric designed for multichannel multiradio multirate WMNs. The NBLC metric is an estimate of the residual bandwidth of the path, taking into account the radio link quality (in terms of data rate and packet loss rate), interference among links, path length, and traffic load on links. The main idea of the NBLC metric is to increase the system throughput by evenly distributing traffic load among channels and among nodes. To achieve the goal of load balancing, nodes have to know the current traffic load on each channel. Thus, each node has to periodically measure the percentage of busy air time perceived on each radio (tuned to a certain channel) and then obtain the percentage of free-to-use (residual) air time on each radio. Each node then periodically broadcasts this information to its *k*-hop neighbors via multihop forwarding on a dedicated control channel, where the *k*-hop neighborhood is an approximation of the interference neighborhood. At this point, each node knows the residual channel capacity (in terms of air time percentage) observed by itself and reported by its interfering neighbors. For a certain channel to which a node's radio is tuned, the actual residual channel capacity this node can further utilize on this radio is approximated by the lowest residual channel capacity reported by its interfering neighbors or observed by itself. The rationale behind this approximation is that since a node can interfere with any node within its interference range, the maximal free-to-use channel air time depends on the interfering neighbor whose perceived channel status is the busiest. Based on this calculation, each node can determine the percentage of free-to-use channel air time on each outgoing link (called the residual link capacity, RLC). To further determine the residual capacity of a path instead of a link, intra-flow contention is considered. Intra-flow contention occurs when nodes along a multihop routing path contend for medium access. Thus, for a link on a path, the actual air time consumed for the transmission of one packet along the path includes not only the air time spent in forwarding the packet on the link, but also the air time spent in keeping away from interference with the transmissions on some links operating on the same channel on the same path. This amount of consumed air time, called cumulative expected busy time (CEBT), for a certain link on a path is obtained by aggregating the ETT values for the path's links that operate on the same channel and interfere with this link. For a path *p* of length *L*, the NBLC metric is defined by

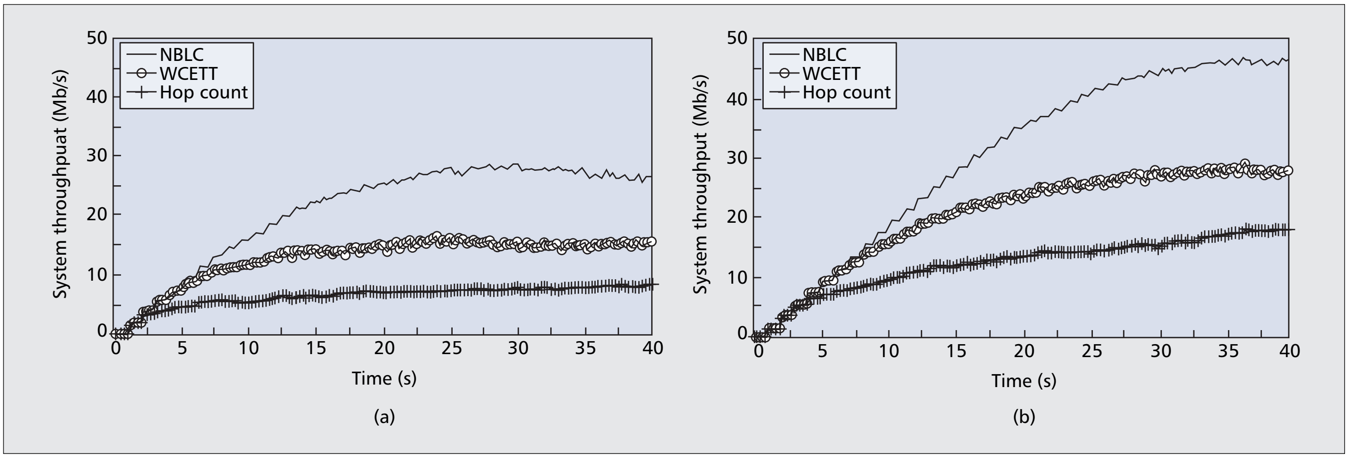
$$NBLC_p \equiv \min_{\text{link } i \in p} \left(\frac{RLC_i}{CEBT_{i,p}} \right) \cdot \gamma^L,$$

where γ is a tunable parameter implicitly indicating the probability of a packet being dropped by an intermediate node. Briefly speaking, the NBLC metric represents the residual capacity of the bottleneck link on a path normalized to the path length. A larger NBLC value indicates a shorter, less loaded, more channel-diverse path with a favorable link quality. Accordingly, the routing algorithm is to choose the path whose NBLC is the largest.

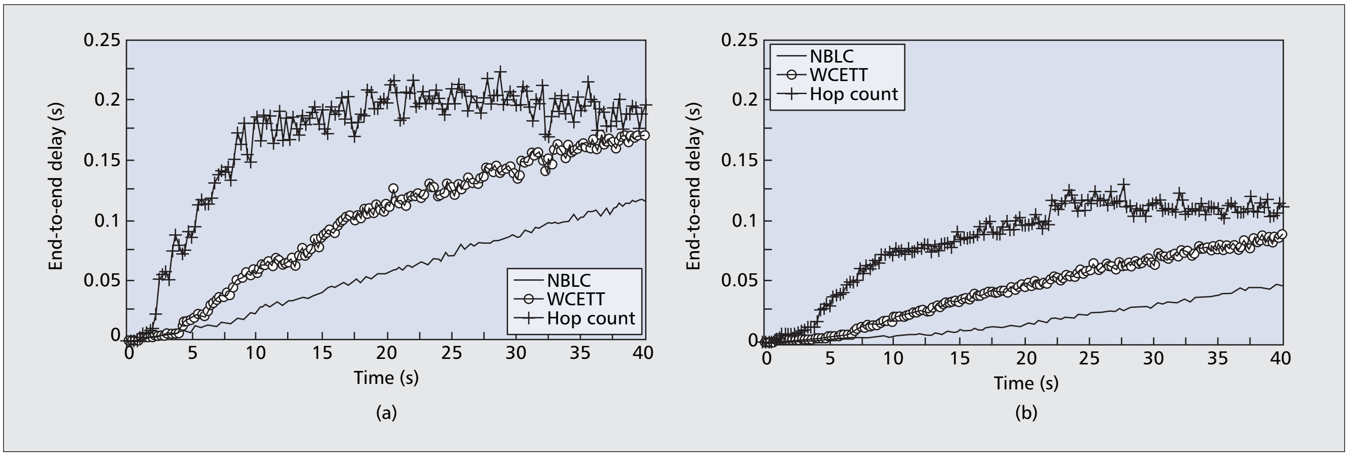
Table 1 summarizes the differences among the three metrics of hop count, WCETT, and NBLC with respect to the target system for which each metric is designed, the supportive features, and the factors each metric takes into account.

Performance Comparison

We conduct simulations with ns-2 simulator to compare the performance of the three metrics of hop count, WCETT, and NBLC. In this simulation we divide a 1170 m × 1170 m area into 9 × 9 squares, and place one node in the center of each square. Each node has a radio propagation range of 225 m and a radio interference range of 450 m. There are 12 nonoverlapping channels available in the system. Each node is equipped with four IEEE 802.11a network interface cards (NICs) and one control NIC. To decouple the effect of the channel assignment algorithm, all data NICs are randomly assigned different channels and the control NIC is tuned to a dedicated control channel. The data rate between any two neighboring nodes is randomly chosen from the set {6, 9, 12, 18, 24, 36, 48, and 54 Mb/s}, which are supported by IEEE 802.11a. The error rate of data packets between any two neighboring nodes is randomly chosen from the set {0.1 percent, 0.5 percent, 1 percent, 5 percent, and 10 percent}. These three metrics (hop count, WCETT, and NBLC) are incorporated into the on-demand routing protocol introduced in [12] for path selection. The route discovery is briefly described as follows. When a route is required for a source and destination pair, the source floods the ROUTE REQUEST (RREQ) packet on the control channel. The RREQ packet carries the required information for calculating the routing metric. An intermediate node, on receiving an RREQ packet, checks if its identification appears in the discovered partial path. If this is the case, it discards this packet. Otherwise, it determines



■ Figure 4. *System throughput: a) ad hoc scenario; b) backhaul scenario.*



■ Figure 5. *End-to-end packet delay: a) ad hoc scenario; b) backhaul scenario.*

the channel that is also used by the previous node (i.e., the node that forwards the RREQ packet) and leads to the best resulting partial path judged by the used routing metric (with random selection for tie breaking). Then the node updates the fields in the RREQ packet and rebroadcasts this RREQ packet on the control channel if this partial path is better than any it has ever seen. After the destination receives the first RREQ packet, it waits for an appropriate additional amount of time to learn all possible routes (i.e., for more RREQ packets). After timeout, the destination selects the route that is the best according to the routing metric and then unicasts a ROUTE REPLY (RREP) packet back to the source. Each intermediate node receiving an RREP packet knows the radios (and thus the channels) used to communicate with the previous and next hop nodes. It then establishes the forward and reverse paths accordingly. The source node starts transmission as soon as it receives the first RREP packet in reply. If the source node receives multiple RREP packets replied by different gateways in the mesh network, it will update the routing table and switch to a better path.

We consider two scenarios. The first is the ad hoc scenario, in which we randomly generate one constant bit rate (CBR) flow between two randomly selected nodes every second. In the second scenario we consider a wireless backhaul network, in which we designate the nodes in the central squares of the first and last rows as the gateways to the wired network. We generate one CBR flow destined to the wired network at a randomly selected non-gateway node every second. The sending rate of each CBR flow is set to 2 Mb/s. Each figure is averaged from 20 runs.

Figure 4 shows the system throughput (i.e., the aggregate throughput of flows in the system) in the ad hoc and wireless backhaul scenarios. As can be seen, the NBLC metric outperforms the WCETT and hop count metrics in both cases, and the WCETT metric outperforms the hop count metric. This is because NBLC accounts for the traffic load within a link's interference range and uses the residual capacity of a path to judge its goodness. Figure 5 shows the end-to-end packet delay in the ad hoc and wireless backhaul modes. As noted before, since the NBLC metric favors less congested routes, it has shorter queuing delays for packets at intermediate nodes than the other two metrics.

Open Research Issues

While the routing problem for multichannel WMNs has been addressed in several papers [3, 8–10, 12], many research issues related to routing in multichannel WMNs still remain unresolved.

QoS Routing

QoS routing in MCMR-based WMNs has been addressed in [8] with a heuristic flow allocation algorithm. Nevertheless, provisioning deterministic QoS routing still remains an open issue. QoS routing in MCSR-based WMNs is even more challenging, since a time-variant combination of channels on a path may causes difficulty in exploiting multichannel routing metrics. Moreover, MCSR-based QoS routing algorithms should cooperate with the MAC schemes (e.g., multichannel MAC [MMAC] [2] or CCF in 802.11s [4]) to better coordinate or reserve the channel on each link along the path such that the end-to-end QoS requirements can be satisfied.

Multipath Routing

Multipath routing can be used to improve the effective end-to-end bandwidth, balance traffic load among paths, and provide fault tolerance for data delivery. Typically, multipath routing is to discover multiple link-disjoint or node-disjoint paths for a source and destination pair. The multichannel system introduces a new dimension (i.e., channel-disjoint paths) into the routing problem. The challenge with using channel-disjoint paths is that while enjoying the advantage of less interference, it is not guaranteed to be node-disjoint. Thus, in addition to complexity, the routing protocol needs to take into account the degradation of reliability due to node failures.

Multicast Routing

Multicast is a bandwidth-conserving technology that reduces traffic by simultaneously delivering a single stream of packets to a group of recipients. Many multicast routing protocols have been proposed for single-radio multihop wireless networks. A typical approach to supporting multicast in such an environment is to construct a multicast tree and let each parent node be responsible for multicasting data to its child nodes. This approach works under the assumption that a parent node and its child nodes share a common channel. However, in multichannel WMNs this assumption may not hold. In addition, if the channel assignment is dynamic, extra overhead due to frequent tree reconstruction or retransmissions of multicast packets must be addressed. One possible solution is to employ a common control channel or hybrid channel assignment strategy to coordinate the channels used by the parent and child nodes. This still needs more research efforts.

Conclusions

In this article we focus on the routing problem in multichannel WMNs. We identify several design challenges and survey existing routing metrics designed for multichannel multiradio multirate WMNs (i.e., WCETT and NBLC). Both the WCETT and NBLC metrics take channel diversity into account, but NBLC further considers the traffic load on links when judging the goodness of a path. From the simulation results, we show that WCETT and NBLC both outperform the hop count metric in terms of network throughput and end-to-end delay, and that NBLC produces higher throughput and lower end-to-end delay than WCETT thanks to its load balancing consideration. Finally, we address some open research issues on routing in multichannel WMNs and their possible solutions.

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Biographies

TEHUANG LIU (tehuangliu@ntu.edu.tw) received a B.S. degree in electrical engineering from National Taiwan University, Taipaei, in 2003 and is currently a Ph.D. candidate in the Department of Electrical Engineering, National Taiwan University. His research interests include routing protocols, channel assignment mechanisms, and performance modeling in wireless mesh networks.

WANJIUN LIAO [SM] (wjliao@ntu.edu.tw) received her Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, in 1997. She joined the Department of Electrical Engineering, National Taiwan University, as an assistant professor in 1997. Since August 2005 she has been a full professor. Her research interests include wireless networks, multimedia networks, and broadband access networks. She is currently an Associate Editor of *IEEE Transactions on Wireless Communications* and *IEEE Transactions on Multimedia*. She served as Technical Program Committee (TPC) chair/co-chair of many international conferences, including Tutorial Co-Chair of IEEE INFOCOM '04, Technical Program Vice Chair of IEEE GLOBECOM '05 Symposium on Autonomous Networks, and Technical Program Co-Chair of IEEE GLOBECOM 2007 General Symposium. She has received many research awards. Papers she co-authored with her students received the Best Student Paper Award at the First IEEE International Conferences on Multimedia and Expo (ICME) in 2000, and the Best Paper Award at the First IEEE International Conferences on Communications, Circuits and Systems (ICCCAS) in 2002. She was the recipient of the K. T. Li Young Researcher Award of ACM in 2003, and the recipient of a Distinguished Research Award from National Science Council in Taiwan in 2006.