Routing Metrics for Minimizing End-to-End Delay in Multi-Radio Multi-Channel Wireless Networks

Hongkun Li, Yu Cheng, Chi Zhou and Weihua Zhuang

Abstract—This paper studies how to select a path with the minimum expected end-to-end delay (EED) in a multi-radio multi-channel (MR-MC) wireless mesh network. While the existing studies mainly focus on the packet transmission delay due to medium access control (MAC), our new EED metric further takes into account the queuing delay at the MAC layer. In particular in the MR-MC context, we develop a generic iterative approach to compute the *multi-radio achievable bandwidth* (MRAB) for a path, taking the impact of inter-/intra-flow interference and space/channel diversity into consideration. The MRAB is then combined with the EED to form the metric *weighted end-to-end delay* (WEED). As a byproduct of MRAB, a channel diversity coefficient is defined to quantitatively represent the channel diversity for a given path. Moreover, we design and implement a distributed WEED-based routing protocol for MR-MC wireless networks by extending the well-known AODV protocol. Extensive simulation results are presented to demonstrate the performance of EED/WEED based routing, with comparison to some existing well-known routing metrics.

Index Terms—Routing, multi-radio multi-channel network, end-to-end delay, achievable bandwidth

1 INTRODUCTION

Routing in the multi-hop wireless mesh networks is a hot research area in recent years, with the objective to achieve as high throughput as possible over the network. The main methodology applied in most of the existing works is to select a path based on interference-aware or load-balancing routing metrics to reduce network-wide channel contentions. It has been revealed that the capacity of a single-radio single-channel (SR-SC) multi-hop wireless network cannot scale up with the network size, due to the co-channel interference [17]. The multi-radio multi-channel (MR-MC) technique has been shown as an efficient approach to increase the wireless network capacity [3], [4]. Design of efficient routing schemes for an MR-MC wireless mesh network is much more challenging, as compared to the SR-SC case.

The existing studies of routing in MR-MC networks [4], [12], [13], [15] mainly focus on throughput performance. Considering that many popular multimedia applications (e.g., voice over IP, IPTV, and online gaming) have a strict delay requirement, in this paper, we aim at designing a routing metric to minimize the end-to-end delay, including not only the transmission delay but also the queuing delay at the medium access control (MAC) layer. The transmission delay of the packet being served at the MAC layer is the major concern in the previous works [7], [8]; however, in many cases the queuing delay takes a significant portion of the total delay over a link. The delay through a node, which has many packets in the buffer but a short transmission time, can be larger than that through another node, which has less packets in the buffer but a much longer transmission time.

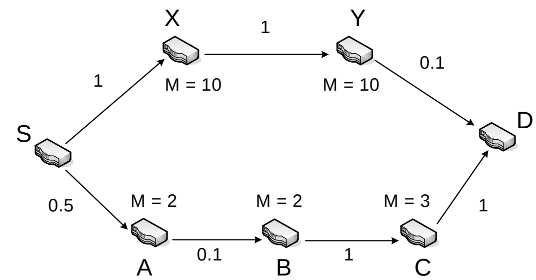


Fig. 1. The impact of queuing delay on path selection.

We here use an example inspired by the one in [1] to show the impact of queuing delay on routing, illustrated in Fig. 1. The number associated with each link is the probability for a successful transmission over the link, denoted as p_s, which means on average it takes $1/p_s$ attempts to successfully deliver a packet. The integer variable M denotes the number of packets in the MAC layer buffer waiting to be served. Suppose that the bandwidth of each link is 11 Mbps, and the packet length is 1100 bytes, resulting in a transmission time of 0.8 ms over a link. If the queuing delay is not considered, the expected transmission time (ETT) based routing [7] would prefer the path S-X-Y-D (9.6 ms) over the path S-A-B-C-D (11.2 ms). In fact, a new packet will arrive at the destination in a shorter period along the path S-A-B-C-D if the queuing delay is taken into account. In this case, the end-to-end delay over S-X-Y-D is 97.6 ms, but only 24 ms over S-A-B-C-D. Note that we ignore the overhead at the MAC layer when computing the transmission delay (e.g., the back-off time in 802.11), which is considered in our discussions later.

The routing metric of expected *end-to-end delay* (EED) proposed in this paper considers both the transmission delay and the queuing delay. Each node needs to not only monitor

This work was supported in part by NSF grant CNS-0832093 and CNS-1053777.
This work was presented in part at INFOCOM 2009 [16].
Hongkun Li, Yu Cheng and Chi Zhou are with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, USA (email: {hli55, cheng, zhou}@iit.edu).
Weihua Zhuang is with the Department of Electrical and Computer Engineering, University of Waterloo, Canada (email: wzhuang@uwaterloo.ca).

the transmission failure probability to estimate the transmission delay, but also count the number of packets waiting in the buffer to estimate the queuing delay. The EED metric also implies the concept of load-balancing. The path with a smaller EED normally consists of the links with fewer packets in the queues, and thus balances the traffic from those congested links. Moreover, counting the number of buffered packets is a convenient implementation; most of the existing load-balancing routing schemes require the traffic information, which is difficult to obtain as the priori in practice [12].

In addition to the transmission delay and queuing delay, the end-to-end delay over a multi-hop wireless network is particularly impacted by the interference among different hops, which can be classified into inter-flow and intra-flow interference [17]. We further propose a path metric called *multi-radio achievable bandwidth* (MRAB) to accurately capture the impact of inter/intra-flow interference and space/channel diversity along a path. We consider a practical scenario that an end-to-end path may consist of both multi-radio nodes and single-radio nodes. In particular, we develop a sub-path based iterative approach to model the complex interactions among inter-flow interference, intra-flow interference, and simultaneous transmission due to space and channel diversity. The MRAB is then integrated with the EED to form a metric called *weighted end-to-end delay* (WEED). As a byproduct of MRAB, a channel diversity coefficient is defined to quantitatively represent the channel diversity along a given path.

We then design and implement a WEED-based routing protocol for MR-MC wireless networks. There exist limited studies on designing a routing protocol for a multi-radio multi-channel network [8]. Efficient routing protocol design in the MR-MC context is challenging. A large space of possible channel and radio configurations over each hop incurs complex message exchange to find a proper path. In our previous work [16], we implemented EED based routing in the SR-SC networks by extending the dynamic source routing (DSR) protocol [29]. However, the DSR takes the source routing model, which can hardly be extended to WEED-based routing in MR-MC networks due to the following reasons: 1) the DSR resorts to overhearing path information to improve efficiency, which cannot guarantee the optimal performance in the MR-MC context. The WEED path metric interleaves all the link metrics along the path through iterative computations in a non-additive manner, by which an optimal end-to-end path does not necessarily ensure the optimality for each path segment due to various local interference situations. 2) Source routing tends to incur large bandwidth overhead by listing all the previous nodes in the packet header. Such overhead will be further exaggerated in the MR-MC context; not only the node address but also the radio sequence number and channel assignment information need to be carried in the packet to identify a transmitting/receiving entity. 3) To the best of our knowledge, how to develop an NS2 package for extending DSR to the MR-MC context is still an open issue.

We thus modify the ad hoc on-demand distance vector (AODV) protocol to implement the WEED based routing in MR-MC networks in a distributed manner. The message exchanges among network nodes are enhanced to carry necessary information of channel/radio assignment, so that each node can independently calculate the MRAB value for any path segment terminating at it. Such a property allows searching for an optimal WEED-based path for any given source-destination pair in a scalable manner. In addition, information exchange in the hop-by-hop routing can considerably reduce messaging overhead compared to the source routing model. We develop an NS2 package for the WEED-based routing according to the general guidance on how to extend AODV to MR-MC networks [31]. Extensive simulation results confirm that EED/WEED provides better performance, compared to some existing well-known routing metrics.

The reminder of this paper is organized as follows: Section 2 reviews more related works. Section 3 introduces the routing metric of EED. Section 4 presents an algorithm to compute the MRAB, which captures the interaction between the inter- and intra-flow interference. The MRAB metric is integrated with the EED metric to form the WEED metric for routing over the multi-radio mesh networks. The routing protocol is described in Section 5. Section 6 presents the simulation results. Section 7 gives concluding remarks.

2 Related work

The studies in [4], [12], [13] define routing metrics for load balancing in the multi-hop wireless network. The routing metrics there however require real-time traffic information. A routing algorithm is presented in [25] to minimize the delay and achieve the load balance. The metric of *expected transmission count* (ETX) is proposed in [15] to describe the channel contentions over a wireless link. The ETX works well in a homogeneous SR-SC environment, but can not describe the complex inter-/intra-flow interference over different channels in the MR-MC context. The ETOP metric enhances the ETX by incorporating the impact of link positions [1].

The link metric of *expected transmission time* (ETT) and the associated path metric of *weighted cumulative ETT* (WCETT) are proposed in [7] for multi-channel mesh networks to enhance the ETX by counting the heterogeneous channel rate and capturing intra-flow interference, but the inter-flow interference is not considered. The metric of *interference and channel switching* (MIC) [8] incorporates both inter-flow and intra-flow interference, whereas it only considers the number of interfering nodes as the total amount of the inter-flow interference. A routing metric is designed considering the inter-/intra-flow interference for flow routing and fair bandwidth allocation [8]. In [19], we propose a metric of *multi-hop effective bandwidth* (MHEB) to compute the achievable bandwidth when both inter- and intra-flow interference are present. However, the MHEB metric uses only a simple weighted average to combine the inter- and intra-flow interference. The MRAB proposed in this paper is based on the MHEB, but applies a more accurate approach to capture the complex interplay between the two types of interference. A recent work [35] proposes new retransmission schemes for route discovery in wireless ad hoc networks, which are shown with the capability of finding better paths compared to existing route discovery schemes used in DSR and AODV. It will be an interesting research topic to incorporate the proposed retransmission schemes with our routing protocol in the MR-MC wireless networks.

Due to the space limit, we will review more literature in the supplementary file associated with this paper on queue length based routing, channel assignment in MR-MC networks, and DSR and AODV based implementations.

3 End-to-End Delay Metric

The end-to-end delay over a path is the summation of delays experienced by all hops along the path. For convenience, we use EED to denote both the routing metric and the delay over an entire path; the meaning should be clear in the context. In order to compute the EED metric over a wireless channel, each node needs to monitor the number of packets waiting for the service in the buffer, as well as to measure the transmission failure probability. The *transmission failure probability* is the probability that a MAC-layer transmission fails due to either collisions or poor channel quality. While counting the number of packets in the queue is straightforward, how to measure the transmission failure probability over a link is discussed in Section 5. The average delay D_i for a packet over link i consists of the queuing delay Y_i and transmission delay T_i as

$$D_i = E\left[Y_i + T_i\right]. \quad (1)$$

The *transmission delay* can also be interpreted as the packet service time, which is defined as the period from the instant that a packet begins to be served by the MAC layer to the instant that it is either successfully transmitted or dropped after a predefined maximum number of retransmissions. The *queuing delay* is the time interval from the instant that a packet enters the queue to the instant that it is served (i.e., become the head of queue).

At MAC layer, the transmission delay consists of the time interval when channel is busy as well as the backoff time when channel is idle. In this sense, the transmission delay is good enough to capture the interference at the sender side. To measure a transmission delay, the node needs to monitor the MAC layer buffer, recording the time when a packet becomes the head of the queue and the time when the same packet is transmitted or dropped. Note that the transmission delay can also be termed as the service time of a packet. Let $T_{i,n}$ denote the nth service time samples measured over link i. The average transmission delay over link i can be estimated by the exponential weighted moving average scheme [32] as

$$E[T_i] = (1-\beta)E[T_i] + \beta T_{i,n} \quad 0 \leq \beta \leq 1. \quad (2)$$

If there are Q_i packets in the buffer when a new packet enters the queue of link i, the average delay over link i can be estimated as

$$D_i = (Q_i + 1)E[T_i] \quad (3)$$

which means that the total delay over a link equals queuing delay (i.e., the MAC service time of those packets queuing ahead of the new packet) plus the transmission delay (i.e., the MAC service time of the new packet itself). Note that the delay expression in (3) implies the memoryless property of the packet service time, as the head-of-line packet only needs to finish a residue packet service time when the new packet comes in. It is well-known that only an exponentially distributed service time has the memoryless property. It has been demonstrated in [28] that the MAC packet service time over 802.11 DCF can indeed be approximated by an exponential random variable.

TABLE 1
Summary of main notations.

Notations	Descriptions
R_i	Interference degree ratio (IDR) over link i
$B_{IT,i}$	Achievable bandwidth under the inter-flow interference (ABITF) over link i
$B_{IR}(ij)$	Achievable bandwidth under the intra-flow interference (ABIRF) over link i and j
$B_A(ij)$	Available bandwidth under interference (ABI) over link i and j
B_{Sub}	ABI of a sub-path
D_i	Overall delay over link i
Q_i	Queue length of link i
T_i	Packet service time over link i
γ	SINR threshold for a successful transmission
$P_v(u)$	Received signal power at node v from node u
N	Received background noise power

Consider an end-to-end path including H hops, the EED metric of the path is defined as

$$\text{EED} = \sum_{i=1}^{H} D_i. \quad (4)$$

Note that the EED given in (4) does not capture the effect of co-channel interference in the multi-hop wireless networks under the assumption that all the packets can continuously go through the path hop-by-hop. However, in a multi-hop wireless network, if two links over the same channel are located close to each other, while one link is in transmission, the MAC protocol will freeze the other link. Such channel freezing can be due to either intra-flow transmissions or inter-flow transmissions, which result in extra delays in addition to the basic EED given in (4). In the following section, we discuss how to extend the EED to take account of the co-channel interference.

4 Achievable Bandwidth over a Multi-Radio Multi-Channel Path

In this section, we develop an algorithm to compute the achievable bandwidth along a multi-radio multi-channel path, termed as *multi-radio achievable bandwidth* (MRAB), by capturing the complex interplay between the inter-flow and intra-flow interference. The end-to-end delay over a multi-radio multi-channel path can be described more accurately by incorporating the MRAB metric into the EED computation to form a new metric *weighted end-to-end delay* (WEED). A byproduct of MRAB analysis is a *channel diversity coefficient* (CDC) defined to quantify the resource consumption along a multi-radio multi-channel path. For convenience, we summarize the main notations in Table 1.

4.1 Multi-Radio Multi-Channel System

Consider a wireless mesh network, where each node is equipped with one or more radio interfaces. The radio interfaces assigned with different channels, either at the same node or at different nodes, can be active simultaneously. Thus, the network throughput can be significantly improved as compared with a single-radio system [4]. The radio interfaces working on different channels form distinct interference topologies. We assume that the channel assignment is given and fixed, according to the discussion in Section 2. All the nodes are stationary, and any node can be used as a router. We consider that the WMN operates over the IEEE 802.11 based MAC, and assume that the routing control information exchanges among neighboring nodes are error free.

We utilize the physical interference model presented in [14] to describe the interference among different hops. Such an interference model indicates that a transmission from node u to node v is successful if the signal to interference and noise ratio (SINR) at receiver v is not less than a pre-determined threshold γ, i.e.,

$$\frac{P_v(u)}{N + \sum_{k:k\neq v} P_v(k)} \geq \gamma \tag{5}$$

where N denotes the received background noise power, $P_v(u)$ the received signal power at node v from node u, and $P_v(k)$ the interference power from a different transmitting node k.

4.2 Multi-Radio Achievable Bandwidth

4.2.1 Inter-flow interference

We first compute the *achievable bandwidth under the inter-flow interference* (ABITF) over link i, denoted as $B_{IT,i}$. Every node can monitor the received power to estimate the magnitude of the inter-flow interference around its neighborhood. Based on the interference model (5), the SINR threshold implicitly denotes the maximum interference power that a node can tolerate to obtain a successful communication. We define the *interference degree ratio* (IDR), R_i, for link i between node u and v as

$$R_i = \frac{\sum_{k:k\neq v} P_v(k)}{P_v^I(u)}. \tag{6}$$

where $P_v^I(u) = \frac{P_v(u)}{\gamma} - N$ is the maximum tolerable interference power at node v to receive the signal from node u based on (5), and $\sum_{k:k\neq v} P_v(k)$ is the total power of undesired signals at node v. The ratio reflects the utilization of the channel assigned to link i. Note that if there is no interference, the IDR is 0, implying that the entire bandwidth of this channel is available for link i. On the contrary, an IDR of 1 indicates that the channel has been fully occupied by other links, and no residual bandwidth is available for link i until the ratio gets smaller than 1. Based on this definition, we evaluate the ABITF [1] at link i as

$$B_{IT,i} = \frac{(1-R_i)B_i}{\text{ETX}_i} \tag{7}$$

where B_i denotes the channel bandwidth of link i, and ETX_i [15] denotes the *expected number of transmission attempts* to achieve a successful transmission over link i. The product $(1-R_i) \cdot B_i$ indicates the available bandwidth for a transmission under the inter-flow interference. Equation (7) expresses the net bandwidth usage under the transmission failure probability p_i, considering a successful transmission needs ETX_i attempts on average.

It is noteworthy that the calculation in (6) and (7) take account of the interference on the receiver side (i.e., measuring the received power and estimating the SINR). The delay analysis introduced in Section 3 essentially captures the interference at the sender side.

The measurement of the interference degree ratio in (6) is according to the physical interference model. In 802.11 system, RSSI is the relative received signal strength in a wireless environment. Different vendors provide their own accuracy and mapping between RSSI value and actual received power. With RSSI, the packet SNR can then readily be computed using NIC noise measurements [33]. Furthermore, in MadWiFi [34], which is a configurable wireless card driver widely used, the reported RSSI for each packet is actually equivalent to the Signal-to-Noise Ratio (SNR). In addition, it is possible for a receiver to obtain the transmission power and the path loss from the desired transmitter through message exchange and channel monitoring, and thus calculate the signal power at the receiver [36], [37]. Based on the SINR measured by the wireless card, the receiver could then estimate the interference power received by deducting the signal and noise from the total receiving power. Estimating signal power is not a trivial issue though. In static wireless networks, the studies in [38] and [39] develop methods to measure the signal power at a receiver by scheduling the RSSI measurement at interference free time instances. In fact, how to accurately estimate the interference power is still an open research issue [40], [41]. Our routing protocol design provides an application which further demonstrates the importance of interference estimation.

4.2.2 Intra-flow interference

Along a path, the links close to and interfering with each other cannot transmit simultaneously, which is termed as intra-flow interference. We consider a 802.11-based interference model in which a successful transmission requires that both the transmitter node and the receiver node should be outside the interference range of other active transmitters and receivers. Assume that the transmission range of a node is *one hop*, while the interference range is r (≥ 1) hops. We define a new concept of *sub-path*: along a path, a sub-path starting from a given link consists of all the consecutive links that will interfere with each other if tuned to the same channel. An example is illustrated in Fig. 2. Suppose that there is only one channel. If r is 1, links AB, BC and CD interfere with each other under the 802.11-based interference model and therefore form a sub-path. In general, given an interference range r, a sub-path spans $r+2$ hops under the 802.11-based interference model and an H-hop path contains $H-r-1$ sub-paths.

Considering the impact of intra-flow interference, a sub-path is equivalent to a virtual link, as a new packet can enter a sub-path only after the previous one leaves. The achievable bandwidth over a sub-path can be iteratively obtained from the

1. Note that the term ABITF does not strictly represent the bandwidth, but is a metric reflecting the impact of interference power on the available bandwidth. The accurate computation of achievable bandwidth B incurs non-linear computation according to the Shannon formula.

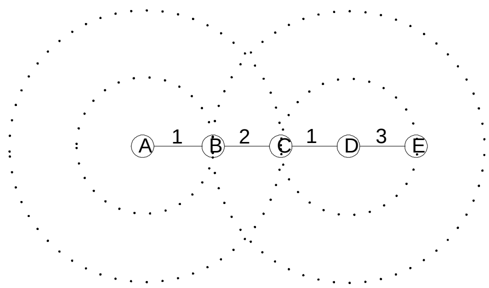


Fig. 2. Example of interference in a multi-radio multi-channel path.

achievable bandwidth over two interfering links. For example, consider two consecutive co-channel links i and j within a sub-path, and links i and j have bandwidth B_i and B_j, respectively. Let L be the packet size. Since the two links cannot be active simultaneously, the equivalent *achievable bandwidth under the intra-flow interference* (ABIRF) over links i and j, denoted as $B_{IR}(ij)$, satisfies

$$\frac{L}{B_{IR}(ij)} = \frac{L}{B_i} + \frac{L}{B_j}. \tag{8}$$

It can then be obtained that

$$B_{IR}(ij) = \frac{B_i B_j}{B_i + B_j}. \tag{9}$$

Extending the $B_{IR}(ij)$ result to the whole sub-path can be iteratively implemented: In each iteration, consider those links that have been processed as one virtual link whose bandwidth equals to the ABIRF value already obtained, and then apply the computation of (9) over the virtual link and the next-hop link. Note that the impact of inter-flow interference on link capacity can be conveniently integrated with the intra-flow interference to obtain an aggregate *available bandwidth under interference* (ABI) by using the ABITF computation (7) as the link capacity in the place of physical bandwidth B. Specifically, the ABI over links i and j, denoted as $B_A(ij)$, is given by

$$\begin{aligned} B_A(ij) &= \frac{B_{IT,i} B_{IT,j}}{B_{IT,i} + B_{IT,j}} \\ &= \frac{(1-R_i)(1-R_j)B_i B_j}{(1-R_i)B_i \mathrm{ETX}_j + (1-R_j)B_j \mathrm{ETX}_i}. \end{aligned} \tag{10}$$

4.2.3 Multi-radio achievable bandwidth

The multi-radio multi-channel connection makes the capacity analysis of a sub-path more complicated. When two links work on different channels through different radio interfaces, they can send/receive packets simultaneously without interference. It is possible that the two end-hops of a sub-path are co-channel links, while other hops in the middle may work on different channels. The iterative procedure discussed above to compute the ABI for a co-channel sub-path can also be extended to the multi-channel sub-path. The achievable bandwidth over two consecutive links i and j is $\min(B_i, B_j)$, if they are assigned with different channels (according to Subsection 4.1, we assume the channel assignment scheme will choose different radios to enable simultaneous transmissions over different channels). Specifically, the iterative steps to compute the *ABI for a sub-path* (ABSUB), denoted as B_{Sub}, are as follows:

Step 1 : For the first link l of the sub-path, set B_{Sub} equal to $B_{IT,l}$ associated with the channel on which the link works.

Step 2 : Go to the next link in this sub-path, say link i, and check whether the channel assigned to link i is used by any of previous links in this sub-path. If yes, go to step 4; otherwise go to step 3.

Step 3 : Set

$$B_{Sub} = \min(B_{Sub}, B_{IT,i}) \tag{11}$$

and go to step 5.

Step 4 : Set

$$B_{Sub} = \frac{B_{Sub} B_{IT,i}}{B_{Sub} + B_{IT,i}} \tag{12}$$

and go to step 5.

Step 5 : If this is the last link of the sub-path, terminate the iteration; otherwise, go to step 2.

For any H-hop path including multiple sub-paths, let $B_{Sub,j}$ denote the achievable bandwidth over the jth sub-path. The multi-radio achievable bandwidth can be computed by

$$\mathrm{MRAB} = \min_j (B_{Sub,j}) \tag{13}$$

for $j = 1, 2, ..., H - r - 1$. If $H - r - 1 \leq 0$, we set $j = 1$, which means the path is short so that there is only one sub-path along the whole path. The computation in (13) exploits the bottleneck concept, but is applied at the sub-path level instead of the link level.

4.3 WEED Metric

In order to evaluate the delay performance over a multi-radio multi-channel path, the MRAB metric is integrated with the EED metric to form a *weighted end-to-end delay* (WEED) metric, given by

$$\mathrm{WEED} = \alpha \sum_{i=1}^{H} D_i + (1-\alpha)\frac{N_P L}{\mathrm{MRAB}} \tag{14}$$

where $0 \leq \alpha \leq 1$ is tunable weight factor, and N_P denotes the total number of packets in the buffers along the path. Recall that L is the packet size. The WEED is a versatile metric, which comprehensively describes the impact on delay due to the factors including network topology, link quality, MAC collisions, interference, and channel/space diversity. The first term of WEED incorporates the transmission and queueing delay considering link quality, MAC collision, and hop count. The second term describes the impact due to intra-/inter-flow interference in the MR-MC context.

The weighted average scheme in WEED is a heuristic operation. Although the two terms of WEED represent delay effect in a complementary manner, they are not in a simple additive relationship. The weighted average based on the tunable parameter α offers the flexibility to adjust the routing metric according to the context. We discuss the impact and selection of α using simulation results in Section 6. Another perspective to interpret the WEED metric is that it contains not only the end-to-end delay information regarding a single packet transmission, but also the transmission delay for a block of packets due to the bottleneck bandwidth MRAB. Therefore, selecting a shortest path based on the WEED metric tends to minimize both the short-term and the long-term delay.

Remark 1: It is indicated in [5] that monotonicity is one of necessary properties of a routing metric for the consistent and loop-free routing implementation. For example, the well-known WCETT metric [7] is monotonic. It can be proved that WEED is also monotonic metric by showing that the two terms in (14) are both non-decreasing with an increasing number of hops. Due to the limited space, we omit the details here, which can be found in the conference version [16].

4.4 Channel Diversity Coefficient

A challenging issue being widely studied in the area of multi-channel wireless networks is how to quantify the channel diversity for a given path. Channel diversity is a kind of performance gain compared to a single channel scenario, produced by assigning different channels to different links within a path so that they can be active simultaneously. The fact of achieving the channel diversity gain is that multiple-channel assignment breaks the whole collision domain in the single channel context to multiple separate ones, each over a unique channel. Each separate domain then has a smaller number of entities contending for the channel, thus a smaller collision probability. The more channels are used along a path, the less number of links share the same channel. Intuitively, an ideal quantity describing the channel diversity should capture various aspects, including the number of hops, the number of channels, and the interference relationship among the links. Our approach has demonstrated that the MRAB metric indeed takes all these factors into account. Therefore, we define a *channel diversity coefficient* (CDC) based on the MRAB as

$$\text{CDC} = \frac{\text{MRAB}}{B_s} \tag{15}$$

where B_s denotes the achievable bandwidth of a path, according to the algorithm in Section 4.2.3, if all links of the path work on the same channel, named as the *single-channel path capacity*. For convenience of comparison, we choose the minimum ABITF value among all links in a path as the link capacity when computing single-channel path capacity B_s. Thus, the CDC is always larger than or equal to 1, and the higher CDC the better the channel diversity. The readers can refer to [16] for an example on the WEED and CDC calculation and how the CDC can indicate the channel diversity effect.

4.5 Implementation Issues

4.5.1 Update interval

It is obvious that both EED and WEED heavily depend on the queue length information, so they can be viewed as a load sensitive metric. Similar to other load sensitive metrics, the re-routing process is necessary by updating the traffic status (backlog information in this paper) and re-calculating the route to avoid congestion in the network. The route update interval is a critical factor, balancing the tradeoff between performance and the overhead. On one hand, over-frequent updates exceeding the timescale of network status changes incur unnecessary overhead. On the other hand, an inappropriate large update interval will prevent the route from timely tracing the network status, and the network may experience degraded performance in terms of delay or packet loss due to untimely backlog updates. We investigate the impact of update time intervals through simulation in Section 6.

It is noteworthy that routing oscillation is a cost inherent to the load balancing in routing. The traffic engineering technique can not completely remove the routing oscillation but can mitigate the impact of routing oscillation. With Multi-Protocol Label Switching (MPLS) technique, the path for a traffic flow will be fixed by the virtual circuit technique, so all packets of this traffic flow will flow the same path and arrive at the destination in order. The load balancing will be implemented as assigning paths (virtual circuits) to traffic flows based on the EED routing metric.

4.5.2 Impact of queue length

Besides the update interval, the queue length information itself affects the estimation of queuing delay for the EED and WEED metrics as well. The instantaneous queue length changes rapidly. If we directly use it to estimate the queuing delay, frequent rerouting might be incurred. To prevent this problem, we maintain a weighted average queue length at each node, denoted as $\bar{Q}$, and use this weighted average value as the backlog information instead of instantaneous sample value for the EED computation. Specifically, each node samples the instantaneous queue length according to a schedule, and let Q_n denote the nth sample. The average queue length $\bar{Q}$ by incorporating the instantaneous queue length Q_n, according to the exponential weighted moving average scheme [32], is

$$\bar{Q} = (1-\beta) \cdot \bar{Q} + \beta \cdot Q_n. \tag{16}$$

5 ROUTING PROTOCOL DESIGN

We design a routing protocol to implement the EED and WEED metrics in a multi-radio multi-channel network. Different from our previous work [16], we choose the *hop-by-hop routing* instead of *source routing*. The hop-by-hop routing has the advantages in reducing overhead, facilitating accurate delay estimation, and enabling distributed implementation in an MR-MC network, referring to the discussion in Section 1. Specifically, we extend the basic AODV protocol to implement the WEED based routing protocol in an MR-MC network. Each radio acts as an independent entity in the routing process. Each radio exchanges information with its neighbors, estimates the transmission failure probability of a link, and manages the routing table by calculating the WEED metric of the segment from source to itself. Assume that the channel assignment is given and time invariant. Due to the page limit, we present all the implementation details in the supplementary file associated with this paper. There, we first summarize the basic AODV operation, and then present the details of extending the basic

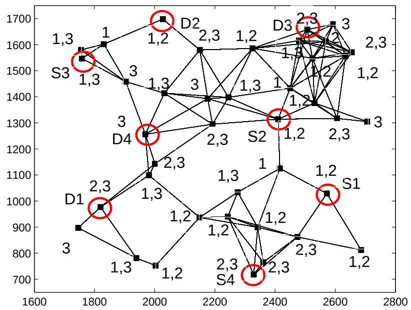
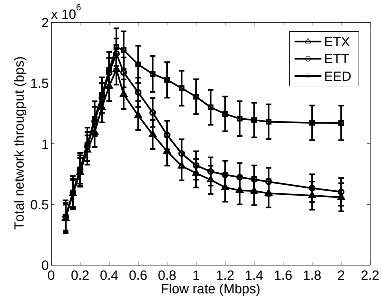
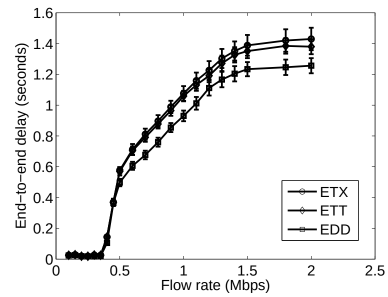


Fig. 3. The random topology.



(a) Total network throughput



(b) Average end-to-end delay

Fig. 4. The routing performance versus flow rate.

AODV to achieve a WEED-based routing protocol for MR-MC networks. In addition, we discuss the overhead introduced in protocol implementation.

6 Performance Evaluation

In this section, we evaluate the performance of the new routing protocol, which is based on the EED and WEED metrics, in both SR-SC and MR-MC contexts. We consider a random topology as shown in Fig. 3, where 40 nodes are randomly placed in a $1000m \times 1000m$ area with necessary adjustment to maintain the connectivity.[2] We use the popular tool NS2 [24] to conduct our simulations. The transmission power of each node is set to give a transmission range of 250m and the carrier sensing threshold is set to give an interference range of 550m. We run 4 multi-hop flows over the network. The source and destination nodes for flow i $(i = 1, 2, 3, 4)$ are denoted as S_i and D_i respectively. Over each channel, the 802.11 DCF MAC protocol is simulated with the RTS/CTS mechanism disabled. Each channel has the capacity of 11 Mbps and the packet size is 1000 bytes.[3] The HELLO message is broadcast every 5 seconds to estimate the link quality. The parameter α is set 0.5 if not mentioned. In the simulation, we mainly use the UDP traffic to observe the optimal operation point [18] since an 802.11 based network by nature has an optimal operation point which implies the capacity region given network and traffic dynamic. It is difficult to accurately compute the optimal operation point. Simulation is a good way to observe the optimal operation point. We also investigate the performance with TCP traffic.

With a specified flow rate r, we generate random traffic arrivals using uniformly distributed packet inter-arrival times with the mean value of $1/r$. In each experiment, we repeat the simulation 100 times to obtain the average performance and the 95% confidence interval. We conduct a comprehensive simulation study to investigate the performance of new routing protocol. Due to the page limit, studies of the impact of α, impact of β and channel diversity result are presented in the supplementary file associated with this paper.

Currently, there is no existing package in NS2 to implement the routing protocol in the multi-radio multi-channel environment. The only reference known to us is [31], based on which we extend the NS2 package for a multi-radio multi-channel network. Specifically, we add several functionalities to the network simulation architecture developed in [31] for radio-based operations including message exchanging, routing metric calculation, and routing table management. Moreover, we implement the physical interference model in the channel class in NS2 by assuming that the transmission power is the same at all nodes.

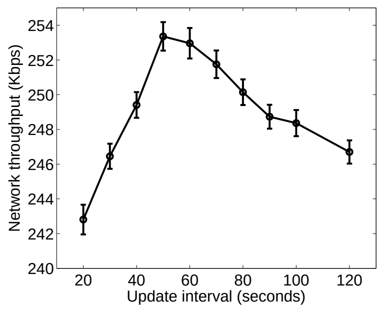
6.1 EED-based Routing in SR-SC Context

The EED metric by itself can be used as an efficient routing metric in the SR-SC context, since it effectively captures not only the queuing delay but also the transmission delay at the MAC layer. We present the average performance along with confidence interval of EED in comparison with the well-known metrics ETT and ETX.

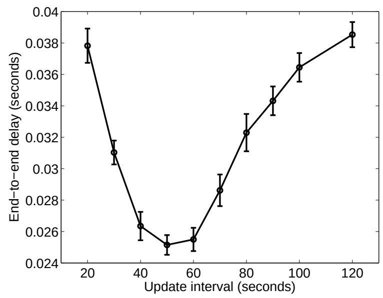
The throughput performance is shown in Fig. 4. The buffer size at each node is 50 packets, and the route update interval is set as 20 seconds. Both EED and ETT outperform the ETX metric in terms of throughput and delay, since ETT and EDD take account of the link bandwidth and transmission failure probability when computing the path, while ETX only addresses the latter. Specifically, the queuing delay is negligible under light traffic, therefore EED and ETT are almost equivalent since they both exploit the transmission failure probability and bandwidth for each link at the MAC layer. While ETX addresses only the transmission failure probability, it is not as accurate as EED and ETT in path selection. Once

2. In the conference version of this work [16], we also consider a grid topology. Performance evaluations for the grid topology is not included in this paper due to the page limit. All the insights revealed from the random topology apply to the grid topology too.

3. In the conference version [16], the channel capacity and packet size are set as 1 Mbps and 512 bytes, respectively. In this paper, we consider the higher-rate situation to better demonstrate the impact of queueing delay and the throughput performance, when the network is close to saturation.



(a) Total network throughput



(b) Average end-to-end delay

Fig. 5. The impact of EED update interval on routing performance.

the network becomes congested (i.e., with heavy traffic larger than 0.6 Mbps), the queuing delay takes a larger portion of end-to-end delay. In this case, EED is preferred to ETT and ETX since it takes queuing delay into account during the path selection phase.

Another interesting observation is that the network throughput under all the three routing metrics first increases linearly with the flow rate when the network is lightly loaded, but then starts degrading when the flow rate increases exceeding a certain level. Correspondingly, the delay is almost 0 before input rate exceeds 0.4 Mbps, and then it starts increasing rapidly. Such phenomenon reflects that the network becomes congested with the per-flow rate larger than 0.4 Mbps and the queuing delay has more impact on the performance in a congested network. This can also explain why the throughput arrives at the peak value around 0.4 Mbps for all three metrics.

6.2 The Impact of Route Update Interval

We next examine the impact of the route update interval on the routing performance in a single channel context. The basic idea of rerouting is to redistribute traffic within the network according to traffic dynamics. Traffic dynamics can be observed at different time scales. At the packet level (time scale of sub-second), a specific random process can be used to model the packet arrival process. At the bursty chunk level (time scale of second), traffic can be generated according to alternate on/off periods, for example, in a voice or video traffic flow [23]. At the traffic flow level (time scale of tens of seconds), the flow or call arrivals and departures obviously change the traffic load. The existing traffic engineering studies for both wire-line and wireless networks [22], [23] have suggested a route update interval at the time scale corresponding to call level dynamics.

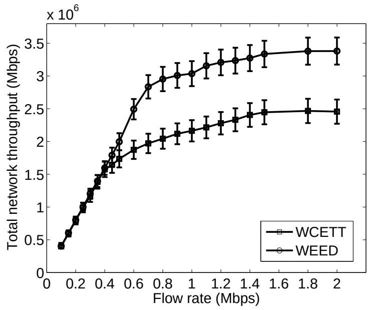
To demonstrate the impact of route update interval, we particularly set up bursty traffic flows with exponential on/off periods, where the average on and off durations are 1 second and 1.5 seconds, respectively, and traffic rate in each on period is 0.4 Mbps. At the flow level, S1 and S2 maintain active during the simulation, while S3 and S4 periodically join and leave the network. Both S3 and S4 use an exponential inter-arrival time with the average of 100 seconds and an exponential flow duration time with the average of 100 seconds. The buffer size at each node is limited to 200 packets. Each source node incurs rerouting based on the route update interval.

Fig. 5 shows the network throughput and the end-to-end delay versus different update intervals. Both inappropriately small and large intervals result in low throughput and large delay. On one hand, an inappropriately small update interval induces over-frequent link metric updates and results in a large messaging overhead. On the other hand, an inappropriately large update interval does not respond to a congested link in a timely manner and results in a longer waiting time in the buffer or even unnecessary packet loss due to the limited buffer size. From Fig. 5, we can observe that route update interval for the optimal performance does show at the time scale of tens of seconds, corresponding to call level dynamics as suggested by existing traffic engineering works [22], [23]. In the following experiments, we always set route update interval at 50 seconds.

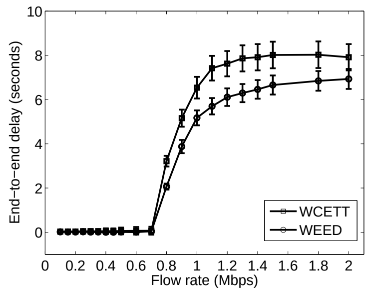
6.3 Routing Performance in MR-MC Context

We also run simulations in the MR-MC context to compare the routing performance under the WEED metric to that under the WCETT metric. The channel assignment scheme is given in Fig. 3. There are 3 available channels and each node is equipped with either 1 or 2 radios. The numbers associated with each node indicate the channels assigned to the node. The physical bandwidth per-channel is set to 11 Mbps for all channels. The tunable parameter α in (14) is set to 0.5, so EED and MRAB have the same importance in the path selection.

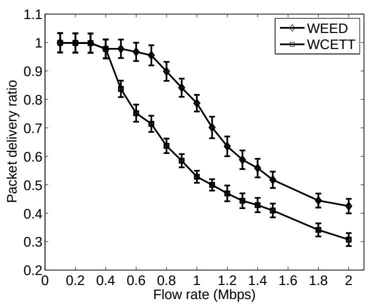
We get two important observations from Fig. 6: 1) The WEED outperforms the WCETT in terms of throughput and delay as expected under a congested network (i.e., per-flow rate larger than 0.6 Mbps). The WEED can redirect the traffic to lightly loaded paths according to the queuing delay, thus relieve the congestion. Fig. 6(c) shows that the packet delivery ratio under WEED is considerably better than that under WCETT when the network is intermediately loaded or heavily loaded. Further, the increment of throughput slows down when the per-flow rate keeps increasing, especially when the rate is larger than 0.8 Mbps. The reason is that, even with a higher input rate, the packet loss frequently takes place at nodes due to the limited buffer size, which prevents throughput from increasing. This fact also implies that the network is approaching its maximum achievable throughput; 2) We achieve better throughput performance with multiple radios and channels than that in the SR-SC scenario, comparing Fig. 6(a) to Fig. 4(a). However, the throughput is not three times of that in the SR-SC context, though there are 3 available channels. There are two main reasons. One is that the channel assignment is static, thus a node cannot dynamically switch



(a) Total network throughput



(b) Average end-to-end delay



(c) Packet delivery ratio

Fig. 6. The routing performance versus flow rate.

to other channels for better throughput. The other is that some nodes have only one radio interface, which restricts the full utilization of all 3 channels. Note that the network arrives at the peak throughput around 0.4 Mbps for the input rate in a single channel scenario, but keeps increasing even at the input rate higher than 1.4 Mbps in the multi-channel context. This further demonstrates that an MR-MC network can accommodate a much larger amount of network traffic than its SR-SC counterpart. It is noteworthy that the delay is supposed to keep increasing with the increment of input rate; however, the curves in Fig. 6(b) become flat, because we only count those packets which successfully arrive at the destination when computing the end-to-end delay. The packets dropped at intermediate nodes are not taken into account for delay calculation, and therefore the delay tends to keep steady even if more packets are dropped at intermediate nodes due to a large input rate. We also present the network throughput performance in Fig. 7 with 6 channels and 3 radios to show that the WEED metric continues to give the good gain compared to WCETT with more available channels and radios.

Comparing Fig. 6(b) to Fig. 4(b), we can see that delay performance degrades in the MR-MC context, which are due to the two factors. One is that the short path between source and destination node may be cut off due to the channel assignment, and a longer path will be used. The other is that it takes a longer time in the MR-MC context to search for a better path in each route discovery operation. Specifically, during the route discovery phase, a source node may send out multiple RREQs through different radios, and each RREQ may traverse a couple of paths since any intermediate node broadcasts the RREQ through all its radios.

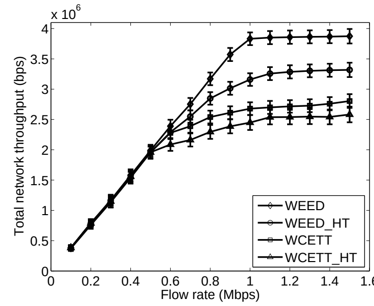


Fig. 7. Network throughput with 3 radios and 6 channels.

We also investigate the performance of the proposed routing protocol with heterogenous ranges, which is shown in Fig. 7, denoted as WCETT_HT and WEED_HT. We randomly change the transmission power of each radio in NS2, and maintain the same threshold. Therefore, different radios have different communication and interference ranges. It can be seen that there is about 15% throughput loss for WEED with heterogenous ranges. The reason for such performance loss is that homogeneous interference range is assumed in calculating the achievable bandwidth, which may overestimate the actual available bandwidth with the heterogenous ranges. On the contrast, WCETT performance decreases by less than 10 %. In other words, WCETT is more robust to the heterogeneous case. This is because WCETT assumes all links within a path interfere with each other, which means WCETT selects the path based on a conservative interference estimation.

We further investigate the performance with TCP traffic, where the random topology and channel assignment scheme in Fig. 3 is used. Fig. 8 shows the result. WCETT and WEED have much better throughput than ETT and EDD, because ETT and EDD do not account for the multi-channel interference. Since TCP applies both the congestion control and flow control, the input rate of each flow is automatically controlled within the capacity region. The receiver window does not increase until the acknowledgement for current packet is successfully received. Unlike the UDP, TCP traffic leads to a lower throughput, but can guarantee a high delivery ratio. This is the reason that WCETT and WEED achieve a very similar throughput under TCP.

7 Conclusion

In this paper, we aim at designing link/path metrics that can lead to path selection with the minimum end-to-end delay and a high network throughput in the multi-radio multi-channel wireless network. The key contributions are in three aspects:

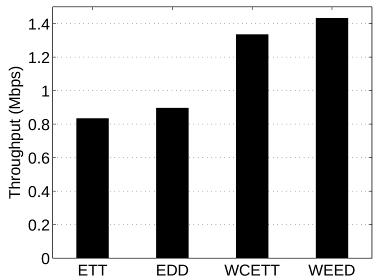


Fig. 8. Throughput with TCP traffic.

1) Both the queuing delay and transmission delay at the MAC layer are incorporated into the EED link metric computation; 2) A generic iterative approach is developed to compute the achievable bandwidth over a multi-radio multi-channel path, which captures the complex interaction among hop count, channel assignment, and inter/intra flow interference to form the WEED path metric; 3) A practical routing protocol is designed based on AODV to implement the EED/WEED metric. Each node can independently make the routing decision, thus reducing the communication overhead and improving the efficiency. We demonstrate the efficiency of the EED/WEED based routing via extensive NS2 simulation results.

REFERENCES

[1] G. Jakllari, S. Eidenbenz, N. Hengartner, S. V. Krishnamurthy, and M.Faloutsos, "Link positions matter: a noncommutative routing metric for wireless mesh network," in *Proc. IEEE INFOCOM*, 2008, pp.744–752.

[2] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in *Proc. ACM MobiCom*, Aug. 2005, pp. 73–87.

[3] H. Li, Y. Cheng, C. Zhou, and P. Wan, "Multi-dimensional conflict graph based computing for optimal capacity in MR-MC wireless networks," in *Proc. IEEE ICDCS*, Genoa, Italy, June 21-25, 2010.

[4] A. Raniwala and T.-C. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *Proc. IEEE INFOCOM*, 2005, pp. 2223–2234.

[5] Y. Yang and J. Wang, "Design guidelines for routing metrics in multihop wireless networks," in *Proc. IEEE INFOCOM*, 2008, pp.1615 - 1623.

[6] Charles Perkins, "Ad-hoc on-demand distance vector routing," in *MILCOM Panel on Ad Hoc Networks*, 1997, pp. 1–37.

[7] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. ACM MOBICOM*, 2004, pp. 114–128.

[8] Y. Yang, J. Wang, and R. Kravets, "Designing routing metrics for mesh networks," in *Proc. IEEE WiMesh*, 2005, pp. 25–33.

[9] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," *IEEE Trans. Automat. Contr.*, vol. 4, no. 12, pp. 1936-1948, Dec. 1992.

[10] M. J. Neely, "Optimal backpressure routing for wireless networks with multi-receiver diversity," in *Proc. Conf. Information Sciences and Systems (CISS)*, 2006, pp. 18-25.

[11] L. Ying, S. Shakkottai, and A. Reddy, "On combining shortest-path and back-pressure routing over multihop wireless networks," in *Proc. IEEE INFOCOM*, 2009, pp. 1674-1682.

[12] J. So and N. H. Vaidya, "Load-balancing routing in multichannel hybrid wireless networks with single network interface," *IEEE Trans. Veh. Technol.*, vol. 56, no. 1, pp. 342–348, Jan. 2007.

[13] T. Liu and W. Liao, "Capacity-aware routing in multi-channel multi-rate wireless mesh networks," in *Proc. IEEE ICC*, 2006, pp. 1971–1976.

[14] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Proc. ACM MOBICOM*, 2003, pp. 66–80.

[15] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," in *Proc. ACM MOBICOM*, 2003, pp. 134–142.

[16] H. Li, Y, Cheng, C. Zhou, and W. Zhuang "Minimizing end-to-end delay: a novel routing metric for multi-radio wireless mesh networks," in *Proc. IEEE INFOCOM*, 2009, pp.46–54.

[17] H. Zhai, J. Wang, and Y. Fang, "Distributed packet scheduling for multihop flows in ad hoc networks," in *Proc. IEEE WCNC*, 2004, pp. 1081–1086.

[18] H. Zhai, X. Chen and Y. Fang, "How well can the IEEE 802.11 wireless LAN support quality of service?," *IEEE Trans. on Wireless Communication*, vol. 4, no. 6, pp. 3084–3094, Nov 2005.

[19] H. Li, Y. Cheng, and C. Zhou, "Multi-hop effective bandwidth based routing in multi-radio wireless mesh networks," in *Proc. IEEE Globecom*, 2008, pp 1-5.

[20] M. Alicherry, R. Bhatia, and L. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in *Proc. ACM MobiCom*, 2005, pp. 58–72.

[21] G. Bianchi "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Select. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[22] A. Balachandran, G. M. Voelker, P. Bahl, and P. V. Rangan, "Characterizing user behavior and network performance in a public wireless LAN," in *Proc. ACM SIGMETRICS*, 2002, pp. 58–72.

[23] Y. Cheng and W. Zhuang, "Dynamic inter-SLA resource sharing in path-oriented differentiated services networks", *IEEE/ACM Trans. Networking*, vol. 14, no. 3, pp. 657-670, Jun 2006.

[24] NS2 simulator: http://www.isi.edu/nsnam/ns/.

[25] J. Gao and L. Zhang , "Load-balanced short-path routing in wireless networks," *IEEE Trans. Parallel and Distributed Systems*, vol. 17, no. 4, pp. 377–388, Mar 2006.

[26] F. Ren, T. He, S. Das, and C. Lin, "Traffic-aware dynamic routing to alleviate congestion in wireless sensor networks," *IEEE Trans. Parallel and Distributed Systems*, vol. 22, no. 9, pp. 1585–1599, Sep 2011.

[27] D. Koutsonikolas, Y. C. Hu and K. Papagiannaki, "How To Evaluate Exotic Wireless Routing Protocols?," in *ACM HotNets*, pp. 50–65, 2008.

[28] A. Abdrabou and W. Zhuang, "Service time approximation in IEEE 802.11 single-hop ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 1, pp. 305-313, Jan. 2008.

[29] D. B. Johnson, D. A. Maltz, and Y. Hu, "The dynamic source routing protocol for mobile Ad Hoc Networks (DSR)," in *IETF, INTERNET-DRAFT*, April 2003.

[30] K. Choi, W. Jeon and D. Jeong, "Efficient load-aware routing scheme for wireless mesh networks ," *IEEE Trans. Mobile Computing*, vol. 9, no. 9, pp. 1293–1307, Sep 2010.

[31] R. A. Calvo and J. P. Campo, "Adding multiple interface support in NS-2," http://personales.unican.es/aguerocr/, 2007.

[32] J. M. Lucas and M. S. Saccucci, "Exponentially weighted moving average control schemes: properties and enhance- ments," *Technometrics*, vol. 32, no. 1, pp. 1-12, Feb. 1990.

[33] D. Halperin, W. Hu, A. Shethy, and D. Wetherall, "Predictable 802.11 Packet Delivery from Wireless Channel Measurements," in *Proc. ACM SIGCOMM*, pp. 159–170, Oct. 2010

[34] K. LaCurts and H. Balakrishnan, "Measurement and analysis of real-world 802.11 mesh networks," in *ACM IMC*, pp. 123-136, Sep. 2010.

[35] X. Jin, T. Kunz and I. Stojmenovic, "Multi-retransmission route discovery schemes for ad hoc wireless networks with a realistic physical layer," in *Proc. IEEE International Conference on Advanced Information Networking and Applications*, pp. 558-565, March. 2012.

[36] S.I. Park, H.M. Kim, and W. Oh, "Reception power estimation using transmitter identification signal for single frequency network," *IEEE Trans. Broadcast.*, vol. 55, no. 3, pp. 652–655, Sep 2009.

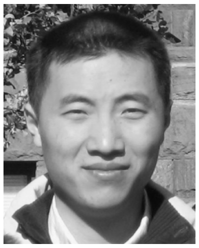
[37] M. Kohvakka, J. Suhonen, M. Hannikainen, and T.D. Hamalainen, "Transmission power based path loss metering for wireless sensor networks," in *Proc. IEEE PIRMC*, Sep. 2006.

[38] D. Son, B. Krishnamachari, and J. Heidemann, "Experimental analysis of concurrent packet transmissions in low-power wireless networks," in *Proc. ACM SenSys*, pp. 237-250, Sep. 2005.

[39] V. Sevani and B. Raman, "SIR based interference modeling for wireless mesh networks: A detailed measurement study," in *Proc. Fourth International Conference on Communication Systems and Networks*, 2012.

[40] S. Liu, G. Xing, H. Zhang, J. Wang, J. Huang, M. Sha, and L. Huang, "Passive interference measurement in wireless sensor networks," in *Proc. IEEE ICNP*, pp. 52-61, Sep. 2010.

[41] N. Baccour, A. Koubaa, L. Mottola, M.A. Zuniga, H. Youssef, C.A. Boano, and M. Alves, "Radio link quality estimation in wireless sensor networks: A survey," *ACM Trans. Sensor Network*, vol. 8, no. 4, pp. 652–655, Sep 2010.



Hongkun Li received the B.S. degree in information engineering from Zhejiang University, Hangzhou, China, in 2004 and the M.S. degree in electrical engineering from the Beijing University of Post and Telecommunications, Beijing, China, in 2007. He is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago. His research interests include capacity analysis for multi-radio multi-channel wireless networks and routing protocol design and analysis for wireless networks.

Yu Cheng received the B.E. and M.E. degrees in Electrical Engineering from Tsinghua University, Beijing, China, in 1995 and 1998, respectively, and the Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Waterloo, Ontario, Canada, in 2003. From September 2004 to July 2006, he was a postdoctoral research fellow in the Department of Electrical and Computer Engineering, University of Toronto, Ontario, Canada. Since August 2006, he has been with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, Illinois, USA, as an Assistant Professor. His research interests include next-generation Internet architectures and management, wireless network performance analysis, network security, and wireless/wireline interworking. He received a Postdoctoral Fellowship Award from the Natural Sciences and Engineering Research Council of Canada (NSERC) in 2004, and a Best Paper Award from the conferences QShine 2007 and ICC 2011. He received the National Science Foundation (NSF) CAREER award in 2011. He served as a Co-Chair for the Wireless Networking Symposium of IEEE ICC 2009, a Co-Chair for the Communications QoS, Reliability, and Modeling Symposium of IEEE GLOBECOM 2011, and a Technical Program Committee (TPC) Co-Chair for WASA 2011. He is an Associated Editor for IEEE Transactions on Vehicular Technology.

Chi Zhou received the B.S. degrees in both automation and business administration from Tsinghua University, Beijing, China, in 1997, and the M.S. and Ph.D. degrees in electrical and computer engineering from Northwestern University, Evanston, IL, in 2000 and 2002, respectively. From 2002 to 2006, she served as an Assistant Professor in the ECE Department, Florida International University. Since August 2006, she has been with the ECE Department, Illinois Institute of Technology, as an Assistant Professor. Her research focuses on wireless communications and mobile networks in general, especially in power control/resource allocation for various wireless networks, integration of heterogeneous networks, and reliable communications over OFDM or MIMO systems.

Weihua Zhuang has been with the Department of Electrical and Computer Engineering, University of Waterloo, Canada, since 1993, where she is a Professor and a Tier I Canada Research Chair in Wireless Communication Networks. Her current research focuses on resource allocation and QoS provisioning in wireless networks. She is a co-recipient of the Best Paper Awards from the IEEE Multimedia Communications Technical Committee in 2011, IEEE Vehicular Technology Conference (VTC) Fall 2010, IEEE Wireless Communications and Networking Conference (WCNC) 2007 and 2010, IEEE International Conference on Communications (ICC) 2007, and the International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QShine) 2007 and 2008. She received the Outstanding Performance Award 4 times since 2005 from the University of Waterloo, and the Premier's Research Excellence Award in 2001 from the Ontario Government. Dr. Zhuang is the Editor-in-Chief of IEEE Transactions on Vehicular Technology, and the Technical Program Symposia Chair of the IEEE GLOBECOM 2011. She is a Fellow of the IEEE, a Fellow of the Canadian Academy of Engineering (CAE), a Fellow of the Engineering Institute of Canada (EIC), and an elected member in the Board of Governors of the IEEE Vehicular Technology Society. She was an IEEE Communications Society Distinguished Lecturer (2008-2011).