Routing Metrics for Minimizing End-to-End Delay in Multiradio Multichannel Wireless Networks

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Abstract—This paper studies how to select a path with the minimum expected end-to-end delay (EED) in a multiradio multichannel (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 *multiradio achievable bandwidth* (MRAB) for a path, taking the impact of inter-/intraflow 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, multiradio multichannel networks, end-to-end delay, achievable bandwidth

1 Introduction

Routing in the multihop 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) multihop wireless network cannot scale up with the network size, due to the cochannel interference [17]. The multiradio multichannel (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 (EED), 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.

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 1,100 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* proposed in this paper considers both the transmission delay and the queuing delay. Each node needs to not only monitor the transmission failure probability to estimate the transmission delay, but also count the number of packets waiting in the

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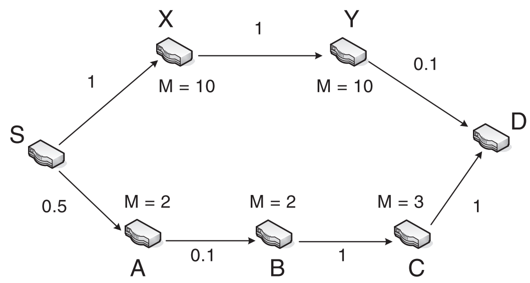


Fig. 1. The impact of queuing delay on path selection.

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 multihop wireless network is particularly impacted by the interference among different hops, which can be classified into interflow and intraflow interference [17]. We further propose a path metric called *multiradio achievable bandwidth* (MRAB) to accurately capture the impact of inter-/intraflow interference and space/channel diversity along a path. We consider a practical scenario that an end-to-end path may consist of both multiradio nodes and single-radio nodes. In particular, we develop a subpath-based iterative approach to model the complex interactions among interflow interference, intraflow 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 (CDC) 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 multiradio multichannel 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 nonadditive 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 intraflow interference. The MRAB metric is integrated with the EED metric to form the WEED metric for routing over the multiradio 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], and [13] define routing metrics for load balancing in the multihop 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 cannot describe the complex inter-/intraflow 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* and the associated path metric of *weighted cumulative ETT* (WCETT) are proposed in [7] for multichannel mesh networks to enhance the ETX by counting the heterogeneous channel rate and capturing intraflow interference, but the interflow interference is not considered. The metric of *interference and channel switching* (MIC) [8] incorporates both interflow and intraflow interference, whereas it only considers the number of interfering nodes as the total amount of the interflow interference. In [19], we propose a metric of *multihop effective bandwidth* (MHEB) to compute the achievable bandwidth when both inter- and intraflow interference are present. However, the MHEB metric uses only a simple weighted average to combine the inter- and intraflow 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, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2012.323, 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. 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

$$D_i = E[Y_i + T_i]. \tag{1}$$

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., becomes 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

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

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

$$D_i = (Q_i + 1)E[T_i], \tag{3}$$

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.

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

$$\text{EED} = \sum_{i=1}^{H} D_i. \tag{4}$$

Note that the EED given in (4) does not capture the effect of cochannel interference in the multihop wireless networks which is based on the assumption that all the packets can continuously go through the path hop-by-hop. However, in a multihop 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 intraflow transmissions or interflow 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 cochannel interference.

4 Achievable Bandwidth over a Multiradio Multichannel Path

In this section, we develop an algorithm to compute the achievable bandwidth along a multiradio multichannel path, termed as *multiradio achievable bandwidth*, by capturing the complex interplay between the interflow and intraflow interference. The end-to-end delay over a multiradio multichannel 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*. A byproduct of MRAB analysis is a *channel diversity coefficient* defined to quantify the resource consumption along a multiradio multichannel path. For convenience, we summarize the main notations in Table 1.

4.1 Multiradio Multichannel 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

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

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 predetermined 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 Multiradio Achievable Bandwidth

4.2.1 Interflow Interference

We first compute the *achievable bandwidth under the interflow interference* (ABITF) over link i, denoted as $B_{IT,i}$. Every node can monitor the received power to estimate the magnitude of the interflow 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, 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 interflow 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 Intraflow Interference

Along a path, the links close to and interfering with each other cannot transmit simultaneously, which is termed as intraflow 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 $r(\geq 1)$ hops. We

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.

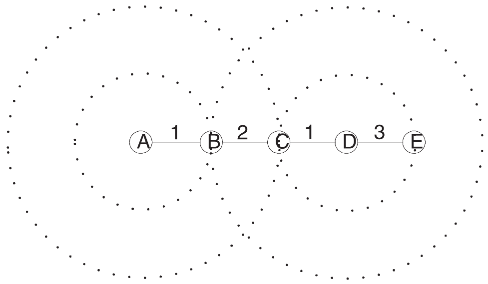


Fig. 2. Example of interference in a multiradio multichannel path.

define a new concept of *subpath*: along a path, a subpath 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 subpath. In general, given an interference range r, a subpath spans $r+2$ hops under the 802.11-based interference model and an H-hop path contains $H-r-1$ subpaths.

Considering the impact of intraflow interference, a subpath is equivalent to a virtual link, as a new packet can enter a subpath only after the previous one leaves. The achievable bandwidth over a subpath can be iteratively obtained from the achievable bandwidth over two interfering links. For example, consider two consecutive cochannel links i and j within a subpath, 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 subpath 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 interflow interference on link capacity can be conveniently integrated with the intraflow 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 Multiradio Achievable Bandwidth

The multiradio multichannel connection makes the capacity analysis of a subpath 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 subpath are cochannel links, while other hops in the middle may work on different channels. The iterative procedure discussed above to compute the ABI for a cochannel subpath can also be extended to the multichannel subpath. 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 Section 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 subpath* (ABSUB), denoted as B_{Sub}, are as follows:

- Step 1: For the first link l of the subpath, 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 subpath, say link i, and check whether the channel assigned to link i is used by any of previous links in this subpath. 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 subpath, terminate the iteration; otherwise, go to step 2.

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

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

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

4.3 WEED Metric

To evaluate the delay performance over a multiradio multichannel path, the MRAB metric is integrated with the EED metric to form a *weighted end-to-end delay* 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 queuing delay considering link quality, MAC collision, and hop count. The second term describes the impact due to intra-/interflow 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 nondecreasing 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 multichannel 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* based on the MRAB as

$$\mathrm{CDC} = \frac{\mathrm{MRAB}}{B_s}, \tag{15}$$

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 rerouting process is necessary by updating the traffic status (backlog information in this paper) and recalculating 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, overfrequent 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 also mitigate the impact of routing oscillation. With multiprotocol 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 multiradio multichannel network. Different from our previous work [16], we choose the *hop-by-hop routing* instead of *source routing*. The hop-by-hop

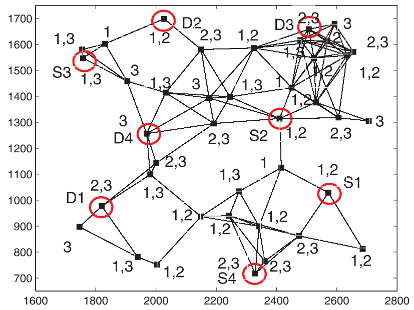


Fig. 3. The random topology.

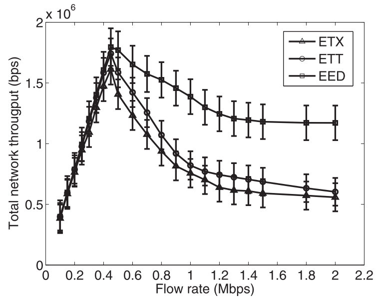
routing has the advantages in reducing overhead, facilitating accurate delay estimation, and enabling distributed implementation in an MR-MC network, referring to the discussion in Section 1. Specifically, we extend the basic AODV protocol to implement the WEED-based routing protocol in an MR-MC network. 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 online supplementary file associated with this paper. There, we first summarize the basic AODV operation, and then present the details of extending the basic 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

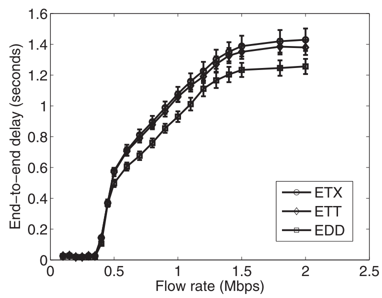
In this section, we evaluate the performance of the new routing protocol, which is based on the EED and WEED metrics, in both SR-SC and MR-MC contexts. We consider a random topology as shown in Fig. 3, where 40 nodes are randomly placed in a $1{,}000\ \mathrm{m} \times 1{,}000\ \mathrm{m}$ area with 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 250 m and the carrier sensing threshold is set to give an interference range of 550 m. We run four multihop 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 1,000 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 interarrival 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 percent confidence interval. We conduct a comprehensive simulation study to investigate the performance of our new routing protocol. Due to the page limit, studies of the impact of α, the impact of β and the channel diversity results are presented in the online supplementary file associated with this paper.

Currently, there is no existing package in NS2 to implement the routing protocol in the multiradio multichannel environment. The only reference known to us is [31], based on which we extend the NS2 package for a multiradio multichannel 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.



(a) Total network throughput



(b) Average end-to-end delay

Fig. 4. The routing performance versus flow rate.

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

2. In the conference version of this work [16], we also consider a grid topology. Performance evaluations for the grid topology are 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.

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 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.

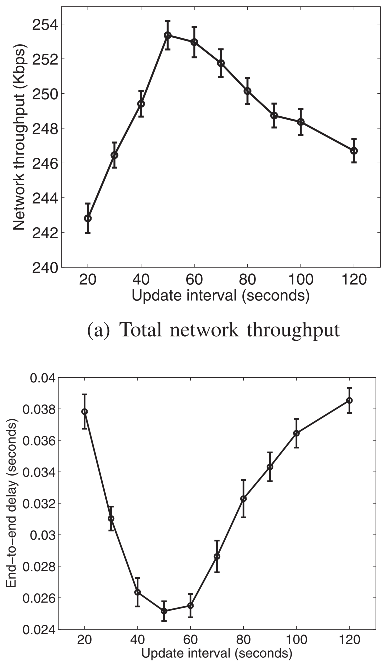
Another interesting observation is that the network throughput under all the three routing metrics first increases linearly with the flow rate when the network is lightly loaded, but then starts degrading when the flow rate increases exceeding a certain level. Correspondingly, the delay is almost 0 before 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 subsecond), 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 interarrival 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 overfrequent link metric updates



(a) Total network throughput

(b) Average end-to-end delay

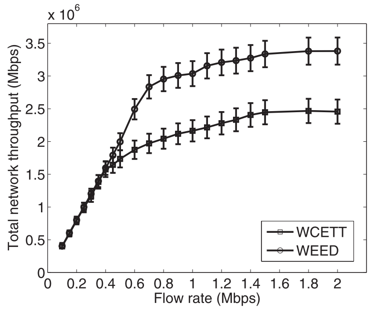
Fig. 5. The impact of EED update interval on routing performance.

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.

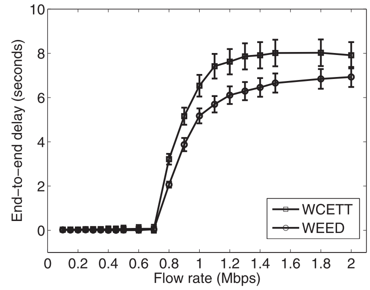
6.3 Routing Performance in MR-MC Context

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 three 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.

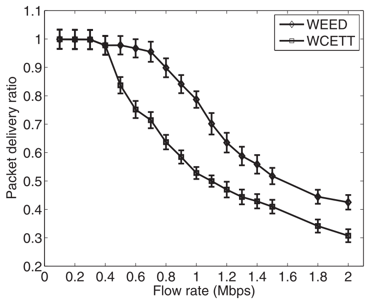
We get two important observations from Fig. 6: 1) The WEED outperforms the WCETT in terms of throughput and delay as expected under a congested network (i.e., per-flow rate larger than 0.6 Mbps). The WEED can redirect the traffic to lightly loaded paths according to the queuing delay, thus relieve the congestion. Fig. 6c 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



(a) Total network throughput



(b) Average end-to-end delay



(c) Packet delivery ratio

Fig. 6. The routing performance versus flow rate.

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. 6a with Fig. 4a. However, the throughput is not three times of that in the SR-SC context, though there are three available channels. There are two main reasons. One is that the channel assignment is static, thus a node cannot dynamically switch to other channels for better throughput. The other is that some nodes have only one radio interface, which restricts the full utilization of all three 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 multichannel 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. 6b become flat, because we only count those packets which successfully arrive at the destination when

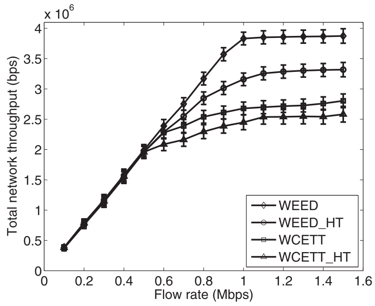


Fig. 7. Network throughput with three radios and six channels.

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 six channels and three radios to show that the WEED metric continues to give the good gain compared to WCETT with more available channels and radios.

Comparing Fig. 6b with Fig. 4b, 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.

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 percent 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 percent. 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 multichannel 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

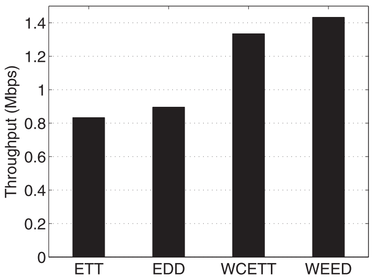


Fig. 8. Throughput with TCP traffic.

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 multiradio multichannel wireless network. The key contributions are in three aspects: 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 multiradio multichannel path, which captures the complex interaction among hop count, channel assignment, and inter/intraflow 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.

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