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Routing in Multi-radio Multi-channel Multi-hop Wireless Mesh Networks with Bandwidth Guarantees

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Abstract—In this paper, we propose a new path metric for finding the maximum available bandwidth path in the multi-radio multi-channel wireless mesh networks. We formally prove that the path metric is isotonic, which is the necessary and sufficient condition for assuring the proper operation of the routing algorithm. Based on the metric, we develop a routing protocol which jointly considers the path selection and the channel assignment. The time complexity of our routing algorithm is polynomial. We conduct the simulation experiments to compare the proposed metric with the existing metrics for finding the maximum available bandwidth path.

I. INTRODUCTION

Recently, wireless mesh network (WMN) has attracted lots of attention due to the desirable features, such as low-cost network configuration and convenience way to access the Internet. In the study of multi-channel multi-radio wireless networks, there are three fundamental issues to be addressed: interface assignment, channel allocation, and data routing. The interface assignment determines over which frequency channel each NIC should operate. There are two kinds of assignment mechanisms: static or dynamic [1]. Following the existing works [2], [3], we assume a static interface assignment scheme in this paper. In this case, each NIC of each node is assigned to a specific channel in advance of the path computation process.

As we know, there are two kinds of wireless interferences: inter-flow interference and intra-flow interference [2]. The inter-flow interference affects the estimation of the available bandwidth of each link. The available bandwidth of a link is defined as the common unconsumed bandwidth resources of the transmitter and the receiver [4]. Lots of works study how to estimate the local available bandwidth of each node [4]–[6]. In this work, we assume that the available bandwidth of each link is known. Thus, we can give the network model in this work, as illustrated in Fig. 1. From Fig. 1, node s and u have two NIDs operating on the channel 1 and channel 2, respectively. s is in the transmission range of u, and we consider there are two logical links between s and u. One operates on channel 1 and another operates on channel 2. The tuple (10, 1) annotated on link (s, u) means that the available bandwidth of link (s, u) is 10 when it operates on channel 1.

There have been lots of works studying the problem of identifying the widest path (the path with the maximum available bandwidth) in wireless mesh networks. Some new path metrics have been proposed to reflect the bandwidth available on a link or a path. In [7], the expected transmission count (ETX) metric is proposed, which computes the average number of transmission attempts required to send successfully a packet over the link. It is the earliest link metric developed and many other metrics are extended from it, such as mETX, ENT [8], ETT [9], and MHEB [10]. The link metric ETT is used for designing the path metrics WCETT (weighted cumulative expected transmission time), iAware [11], and MIC [12]. Unfortunately, all the proposed metrics, except ETX and ETT, are not isotonic, which is an important property for designing a proper routing protocol [13]. The link metric CATT proposed in [14] extends ETX by considering the different transmission rates of different channels. This work does not consider the multiple transmission rates. In fact, [5] shows that it is not efficient to use the packet loss probability to reflect the available bandwidth of each link. The link metric LC in [15] considers both the number of interference links and the current unconsumed bandwidth resources of each link simultaneously, and the path metric Bottleneck Link Capacity (BLC) is defined as the minimum of LC metrics of each link on the path. This implies that BLC does not directly reflect the available bandwidth of a path. In summary, the new metrics mentioned above cannot truly reflect how much bandwidth is still available on a path.

In this work, we propose a new path metric which reflects the available path bandwidth in the multi-channel wireless mesh networks. We formally prove that our path metric is left-isotonic¹, so that the routing algorithm applying our metric must find the maximum available bandwidth path. Our metric can be easily incorporated in the existing routing protocols, such as DSDV, DSR, or AODV. We investigate the performance of our proposed metric by conducting the simulation experiments. In the following discussion, we first present the existing method of computing the available path bandwidth in Section II. In Section III, we present our new path metric with the isotonicity property. Finally, we give the simulation results in Section IV.

¹In this paper, we assume each link is symmetric, then left-isotonic also implies right-isotonic. A metric is isotonic if it is both left-isotonic and right-isotonic [13].
II. AVAILABLE PATH BANDWIDTH

Following the work in [3], we define the transmission range of a node as one hop, while the interference range is \( r(r \geq 1) \) hops. We assume that the WMN operates over the IEEE 802.11 based MAC. Given two nodes \( u \) and \( v \), and the transmission range of each other, if there are NICs on \( u \) and \( v \) working on channel \( c \), there is a logical link \( e = (u, v; c) \) (corresponding to a physical link in a wired network). Denote \( C(e) \) to be the channel used in link \( e \), and so \( C(u, v; c) = c \). Given any two links \((u, v; e_1)\) and \((i, j; e_2)\), if \( e_1 = e_2 \), and \( i \) (or \( j \)) is in the interference range of \( u \) (or \( v \)), we say that link \((u, v)\) and \((i, j)\) interfere with each other. Note that it is possible that \( i \) (or \( j \)) is the same node as \( u \) (or \( v \)). Such interference model is adopted by the existing works in [2], [3], [16]–[18], and is called the Transmitter-Receiver Conflict Avoidance (TRCA) model [19]. For example, in Fig. 1, assume \( r = 1 \). Link \((s, u; 1)\) interferes with links \((u, a; 1)\) and \((a, c; 1)\), but not with link \((c, g; 1)\), since \( c \) or \( g \) is not in the interference range of \( s \) or \( u \). Links \((s, u; 2)\) and \((u, a; 1)\) do not interfere with each other since they work on different channels.

Lots of works, such as [3], [5], [20], [21], apply the clique-based method to compute the available bandwidth of a given path. Following the work in [3], [20], we do not consider a path \( p = \langle v_1, v_2, \ldots, v_h \rangle \), where node \( v_j \) is the neighbor of \( v_{j-1} \), where \( j = i + 1 \) or \( j < i - 1 \). That is, a node on a path is only a neighbor of its previous hop and the next hop, but not other nodes on the path. This is reasonable because if a node is a neighbor of a node that is two hops away on a path, it means the path can be shortened to reduce interference. Let \( B(e) \) be the available bandwidth (unconsumed bandwidth resources) of link \( e \). Given a path \( p = \langle v_1, v_2, \ldots, v_h \rangle \), denote \( WB(p) \) as the available bandwidth of path \( p \). As referred to [3], [5], [20], [21], we give the formula to compute \( WB(p) \) as follows. The formula works in both single channel and multiple channel situations.

\[
WB(p) = \min_{1 \leq j \leq h - r - 2} \left\{ p_j = \langle v_j, v_{j+1}, \ldots, v_{j+r+2} \rangle \right\}
\]

(1)

The formula implies that to find the bandwidth of a path, we can find the bandwidth of all the subpaths with \( r + 2 \) links, and take the minimum one as the path bandwidth. When \( r = 1 \), the subpath is of three links. We now describe how to find the bandwidth of a subpath. We assume that \( r = 1 \) for the ease of discussion and the result can be easily extended to any value of \( r \). Assume that \( p_j \) is composed by three links \( e_1, e_2, \) and \( e_3 \). Equations (2), (3), and (4) present how to compute \( B(p_j) \). Interested readers can refer to [3] for more detailed discussions.

1) If three links \( e_1, e_2, \) and \( e_3 \) use three different channels, we have

\[
WB(p_j) = \min\{B(e_1), B(e_2), B(e_3)\}
\]

(2)

2) If two links \( e_1 \) and \( e_2 \) use the same channel, while the other one \( e_3 \) uses a different channel, then

\[
WB(p_j) = \min\{\frac{B(e_1)B(e_2)}{B(e_1) + B(e_2)}, B(e_3)\}
\]

(3)

3) If all three links \( e_1, e_2, \) and \( e_3 \) use the same channel, we obtain

\[
\begin{align*}
& B_1 = \frac{B(e_1)B(e_2)}{B(e_1) + B(e_2)}B_3, \\
& WB(p_j) = \frac{B_1}{B_1 + B_3}
\end{align*}
\]

(4)

Given a two-hop path \( p = \langle e_1, e_2 \rangle \), if \( C(e_1) \neq C(e_2) \), we have \( WB(p) = \min\{B(e_1), B(e_2)\} \); otherwise, we have \( WB(p) = \frac{B(e_1)B(e_2)}{B(e_1) + B(e_2)} \). For example, in Fig. 1, we compute the available bandwidth of path \( p = \langle s, u; 2 \rangle, (u, a; 1) \), \((a, c; 1) \), \((c, g; 1) \rangle \). By (3), we compute the available bandwidth of path \( \langle s, u; 2 \rangle, (u, a; 1) \rangle \) as 10. By (4), the available bandwidth of path \( \langle u, a; 1 \rangle, \langle a, c; 1 \rangle, \langle c, g; 1 \rangle \rangle \) is 8. We then compute \( WB(p) = \min\{10, 8\} = 8 \) by (1).

III. THE PROPOSED PATH METRIC

In many routing protocols, when a node identifies several paths to a destination, it keeps only the best one, and in distance-vector based protocols, it also advertises the information to its neighbors. When a node obtains a new path, it should determine whether the new path is better than the existing one. However, in WMN, if we want a neighbor to identify its own best path to a certain destination, keeping only the best path may not be enough. For instance, consider the network in Fig. 2(b). We can easily compute the available bandwidths of paths \( \langle b, c; 1 \rangle, \langle c, f; 2 \rangle \rangle \) and \( \langle b, d; 1 \rangle, (d, f; 2) \rangle \) to be 10 and 9, respectively. From \( b \)'s perspective, the widest path is \( \langle b, c; 1 \rangle, \langle c, f; 2 \rangle \rangle \). Let's consider \( a \). The bandwidth of paths \( \langle a, b; 2 \rangle, \langle b, c; 1 \rangle, \langle c, f; 2 \rangle \rangle \) and \( \langle a, b; 2 \rangle, \langle b, d; 1 \rangle, (d, f; 2) \rangle \rangle \) are 4 and \( \frac{9}{2} \), respectively. Therefore, from \( a \)'s perspective, \( \langle a, b; 2 \rangle, \langle b, d; 1 \rangle, (d, f; 2) \rangle \rangle \) is better. We can see that if \( b \) keeps only its own best path without letting \( a \) knows \( \langle b, d; 1 \rangle, (d, f; 2) \rangle \rangle, a \) cannot identify its own best path. We can see that in order to obtain the widest path from any node to a destination, each node only advertising its best path to the destination is not enough.

In fact, an isotonic routing metric capturing the path available bandwidth information is necessary and sufficient to assure that each node can obtain the widest path from itself to a destination. We first give the definition of isotonicity introduced in [13].

Definition 1: Left-isotonicity The quadruplet \( (S, \oplus, w, \geq) \) is left-isotonic if \( w(a) \geq w(b) \) implies \( w(a \oplus c) \geq w(b \oplus c) \), for all \( a, b, c \in S \), where \( S \) is a set of paths, \( \oplus \) is the path concatenation operation, \( w \) is a function which maps a path to a weight, and \( \geq \) is the order relation.

From Definition 1, we can see that in addition to design an appropriate function which maps a path to a weight, we also need to give the definition for the order relation \( \geq \).

In this section, we present a new path weight which captures the available path bandwidth information. We give the path comparison mechanism such that the better path has larger
available path bandwidth. We formally prove that our path weight is left-isotonic, which is the necessary and sufficient condition to assure that the hop-by-hop routing protocol can properly operate [13].

In the following definition, we give our proposed path weight, called Multi-channel Composite Available Bandwidth (MCAAB), and the corresponding order relation. Let $SB(p)$ be the available bandwidth of the first two-hop subpath of $p$, and $FB(p)$ be the available bandwidth of the first link on $p$. Given $p = <v_1, ..., v_k>$, we have $SB(p) = WB(v_1, v_2, v_3)$ and $FB(p) = B(v_1, v_2)$.

**Definition 2:** Given a path $p$, the MCAAB of $p$, denoted by $\vec{\omega}(p)$, is $(\omega_1(p), \omega_2(p), \omega_3(p), \omega_4(p), \omega_5(p))$ where $\omega_1(p) = \mathcal{C}(\mathcal{N}(p)), \omega_2(p) = \mathcal{C}(\mathcal{N}(p)), \omega_3(p) = WB(p), \omega_4(p) = SB(p)$, and $\omega_5(p) = FB(p)$.

$v_1(p_1) \succeq v_1(p_2)$ iff $\omega_1(p_1) = \omega_1(p_2), \omega_2(p_1) = \omega_2(p_2), \omega_3(p_1) = \omega_3(p_2), \omega_4(p_1) = \omega_4(p_2)$, and $\omega_5(p_1) \geq \omega_5(p_2)$.

For example, in Fig. 1, the weight of path $p = <s, a, b; 1>, (u, a; 1), (a, c; 1), (c, g; 1>)$ is $(2, 1, 8, 40, 10)$, where 2 and 1 denote the channel information of the first two links on the path, 8 denotes $WB(p)$, 40 denotes $SB(p)$, and 10 denotes $FB(p)$. Note that the MCAAB metric is still suitable for the single-channel wireless networks. Before showing that MCAAB is left-isotonic, we would like to introduce the following lemmas.

**Lemma 1:** Given two paths $p_1 = <e_1, e_2, ..., e_h>$ and $p_2 = <e'_1, e'_2, ..., e'_n>$ from node $v$ to node $d$, where $\mathcal{C}(e_1) = \mathcal{C}(e'_1)$ and $\mathcal{C}(e_2) = \mathcal{C}(e'_2)$, suppose that $\mathcal{C}(e_1) \neq \mathcal{C}(e_2)$. If $WB(p_1) \geq WB(p_2), TB(p_1) \geq TB(p_2)$, and $FB(p_1) \geq FB(p_2)$, then $WB(p_1) \geq WB(p_2)$ for any path $p$ that ends at $v$.

**Lemma 2:** Given two paths $p_1 = <e_1, e_2, ..., e_h>$ and $p_2 = <e'_1, e'_2, ..., e'_n>$ from node $v$ to node $d$, where $\mathcal{C}(e_1) = \mathcal{C}(e'_1)$ and $\mathcal{C}(e_2) = \mathcal{C}(e'_2)$, suppose that $\mathcal{C}(e_1) = \mathcal{C}(e_2)$. If $WB(p_1) \geq WB(p_2), SB(p_1) \geq SB(p_2)$, and $FB(p_1) \geq FB(p_2)$, then $WB(p_1) \geq WB(p_2)$ for any path $p$ that ends at $v$.

Due to space limitation, we skip the proofs for Lemmas 1 and 2 since they can be easily verified according to Equations (1)-(4). In fact, Lemma 1 and Lemma 2 gives the sufficient conditions to determine which path should be advertised in order that no widest path will be dropped by the intermediate node. On the other hand, in order to minimize the advertisement overhead, each node should try to reduce the number of the paths to be advertised. In the following, we also show that the conditions in Lemma 1 and Lemma 2 are also necessary. In other words, by using the proposed path selection mechanism, the advertisement overhead is minimized. [22] considers the single-channel network and show that the conditions in Lemma 1 are necessary. Since the single-channel network is a subset of the multi-channel network, we can say that the conditions in Lemma 1 are still necessary in the multi-channel network. To show that $WB(p_1) \geq WB(p_2) and FB(p_1) \geq FB(p_2) and SB(p_1) \geq SB(p_2)$ in Lemma 2 is also a necessary condition for $v$ to determine whether $p \oplus p_1$ is better than $p \oplus p_2$.

we use examples to illustrate that if either one of them does not hold, $WB(p \oplus p_1) \not\geq WB(p \oplus p_2)$ may not hold even the other two are satisfied.

Case I: $FB(p_1) \geq FB(p_2)$ and $SB(p_1) \geq SB(p_2)$ but $WB(p_1) \not\geq WB(p_2)$, as illustrated in Fig. 2(a), where $p_1 = <(b, c; 1), (c, f; 2), (f, g; 1)>$ and $p_2 = <(b, d; 1), (d, e; 2), (e, g; 1)>$. We have $WB(p_1) = \frac{10}{9}$ and $WB(p_2) = 4.5$. Let $p = <(a, b; 2)>$. We thus have $WB(p \oplus p_1) \not\geq WB(p \oplus p_2)$.

Case II: $WB(p_1) \geq WB(p_2)$ and $FB(p_1) \geq FB(p_2)$ but $SB(p_1) \not\geq SB(p_2)$, as illustrated in Fig. 2(b), where $p_1 = <(b, c; 1), (c, f; 2)>$ and $p_2 = <(b, d; 1), (d, e; 2)>$. Let $p = <(a, b; 2)>$. It turns out that $WB(p \oplus p_1) \not\geq WB(p \oplus p_2)$.

Case III: $WB(p_1) \geq WB(p_2)$ and $SB(p_1) \geq SB(p_2)$ but $FB(p_1) \not\geq FB(p_2)$, as illustrated in Fig. 2(c), where $p_1 = <(c, f; 2), (c, b; 1)>$ and $p_2 = <(f, d; 2), (d, e; 1)>$. Let $p = <(a, b; 2)> and we have $WB(p \oplus p_1) \not\geq WB(p \oplus p_2)$.

**Theorem 1:** The Multi-channel Composite Available Bandwidth (MCAAB) is left-isotonic.

**Proof:** Let $p_1$ and $p_2$ be two paths from node $v$ to destination $d$, such that $\vec{\omega}(p_1) \geq \vec{\omega}(p_2)$. Let $p_3 = <e_1, e_2, ..., e_h>$ from node $s$ to $v$. Denote $p = p_3 \oplus p_1$ and $p' = p_3 \oplus p_2$. We are going to show that $\vec{\omega}(p) \geq \vec{\omega}(p')$.

Firstly, since $p$ and $p'$ share the same first link from $s$, we have $\omega_1(p) = \omega_1(p')$.

If $h \geq 2$, $p$ and $p'$ also share the same second link from $s$. We thus have $\omega_2(p) = \omega_2(p')$. If $p$ just contains one link $e_1, \omega_2(p) = \omega_1(p_1)$ and $\omega_2(p') = \omega_1(p_2)$. Since $\omega_1(p_1) = \omega_1(p_2)$, we have $\omega_2(p) = \omega_2(p')$.

We first consider the case that $\omega_1(p_1) = \omega_2(p_1)$. Since $FB(p_1) \geq FB(p_2)$ and $SB(p_1) \geq SB(p_2)$, we have $TB(p_1) \geq TB(p_2)$ based on the discussion in Section II. By Lemma 1, we have $\omega_3(p) \geq \omega_3(p')$. If $\omega_1(p_1) \neq \omega_2(p_1)$, by Lemma 2, we have $\omega_5(p) \geq \omega_5(p')$.

As both $p$ and $p'$ share the same first link, we have $\omega_5(p) = \omega_5(p')$.

In order to prove that $\omega_4(p) \geq \omega_4(p')$, we need to consider two cases. In the first case that $h > 1$, both $p$ and $p'$ share the same second link, we thus have $\omega_4(p) = \omega_4(p')$. In the second case that $h = 1$, we have $\omega_4(p) = \omega_5(p_1)$ and $\omega_4(p') = \omega_5(p_2)$. Since $\omega_5(p_1) \geq \omega_5(p_2)$, we have $\omega_4(p) \geq \omega_4(p')$.

Therefore, we have $\vec{\omega}(p_3 \oplus p_1) \geq \vec{\omega}(p_3 \oplus p_2)$. 

![Fig. 2. Examples of multi-channel network topologies.](attachment:image.png)
Given two paths $p_1$ and $p_2$, if $\omega(p_1) \succeq \omega(p_2)$, we call $p_1$ dominates $p_2$. If we cannot find a path dominating $p_1$, we call $p_1$ a non-dominated path. In order to ensure that the widest path from each node to a destination can be found, each node must advertise all the non-dominated paths. When $s$ receives a path $p$ from its neighbor $u$ to a destination $d$, $s$ will obtain $C$ new paths from itself to $d$ which is one-hop extended from $p$, where $C$ is the number of the logical links between $s$ and $u$. Node $s$ will compute the MCAB metric of all the new paths. Let $p'$ be the path concatenated with the link $(s, u, \eta)$ and $p$, and $p_1$ be $<(s, u, \eta), \eta, \eta, \eta>$. The MCAB metric of $p'$ is computed as $\omega_1(p') = \eta, \omega_2(p') = \omega_1(p), \omega_3(p') = \min\{B(p_1), \omega_3(p)\}, \omega_4(p') = \omega_5(p)$, and $\omega_5(p') = B(s, u; \eta)$.

We would like to use the network topology in Fig. 1 as an example to illustrate the process of our path calculation. Assume that each node computes the widest path from itself to destination $d$. When a path $p$ is one-hop, let $\omega_2(p) = \omega_1(p)$ and $\omega_5(p) = \omega_2(p)$. In the first step, $b$ and $c$ find one-hop path $<b, d; 2>$ with the MCAB metric $(2, 2, 20, 20, 20)$ and path $<c, g; 1>$ with the MCAB metric $(1, 1, 20, 20, 20)$, respectively, and they advertise the new paths to their neighbors. In the second step, based on the received path information, node $a$ obtains two new paths $<(a, b; 1), (b, g; 2)>$ and $<(a, c; 1), (c, g; 1)>$ with the MCAB metrics $(1, 2, 10, 20, 10)$ and $(1, 1, 10, 20, 20)$, respectively. Similarly, in the third step, node $d$ obtains two new paths $<(u, a; 1), (a, b; 1), (b, g; 2)>$ and $<(u, a; 1), (a, c; 1), (c, g; 1)>$ with the MCAB metrics $(1, 1, 8, 10, 40)$ and $(1, 1, 8, 20, 40)$, respectively. Since $(1, 1, 8, 20, 40) \succ (1, 1, 8, 10, 40)$, node $u$ just advertises path $<(u, a; 1), (a, c; 1), (c, g; 1)>$. In the fourth step, since there are two available channels on link $(s, u)$, node $s$ obtains two paths $<(s, u; 1), (u, a; 1), (a, c; 1), (c, g; 1)>$ and $<(s, u; 2), (u, a; 1), (a, c; 1), (c, g; 1)>$ with the MCAB metrics $(1, 1, 40, 40, 10)$ and $(2, 1, 8, 40, 10)$, respectively. We can see that the path $<(s, u; 2), (u, a; 1), (a, c; 1), (c, g; 1)>$ is the widest path from $s$ to $d$.

Since each node advertises all the non-dominated paths from itself to a destination, the advertisement overhead depends on the maximum number of the non-dominated paths. Assume that there are maximally $C$ logical links between any two nodes. We mentioned earlier that $C^2$ different sets such that all the paths in a set have the same $\omega_1$ and $\omega_2$ metrics. We now analyze the maximum number of non-dominated paths in each set. We can easily prove that if two different paths $p_1$ and $p_2$ share the same first two links, and also $WB(p_1) > WB(p_2)$, it holds that $\omega(p_1) \succeq \omega(p_2)$. This means that there are maximally $A^2$ non-dominated paths from a node to a destination in a set, where $A$ is the maximum number of neighbors of each node. Therefore, the number of non-dominated paths from a node to a destination is upper bounded by $C^2A^2$. We can see that the number of non-dominated paths is polynomial with the network size and topology. This also implies the time complexity of our routing algorithm is polynomial.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our algorithm via simulation and compare our proposed metric with the existing metrics for finding the maximum available bandwidth paths. We compare our proposed metric (MCAB) with BLC in [15] since both metrics are based on the local available link bandwidth estimation, and also BLC is shown to outperform the ETX based metric. We also compare our metric with the hop count metric since it is used widely by the existing routing protocol in wireless networks.

In our simulation, we assume that the available bandwidth resources of each node estimated by the bandwidth estimation tool is accurate. We do not consider the overhead introduced by MAC protocol. Following the work in [3], we set the interference range to be 1 hop. We wrote C++ simulator which simulates the wireless interference.

We consider static wireless mesh networks with 50 nodes uniformly deployed in a $1500m \times 1500m$ region. Each node has a fixed transmission range of 250m. The available bandwidth resources of the nodes are randomly and independently generated, reflecting there are some flows in the network. After identifying the widest path by using an algorithm, we deploy a flow on this path with a data rate to be the available bandwidth of this path computed by (1). We then test the actual throughput of this path. By comparing the throughputs of the different widest paths computed by the different algorithms, we can select the best algorithm, which finds the widest path with the largest throughput. We do not consider the node pair which is 1 hop away. Given any two node pair, let $r_m$, $r_b$, and $r_i$ be the throughputs of the widest paths found by MCAB metric, hop count metric, and BLC metric, respectively. There may be several paths with the same number of hops. In this case, we select the path with largest available bandwidth based on (1). Define $\frac{r_m}{r_i}$ and $\frac{r_b}{r_i}$ as the improvement ratios produced by MCAB and BLC metrics, respectively. Thus, a better algorithm should have a larger improvement ratio.

We conduct our simulations in two different traffic models. In the first scenario, the available bandwidth of the nodes follows the uniform distribution $U[150, 400]$kbps, while the bandwidth follows $U[50, 500]$kbps in the second scenario. Figs. 3 and 4 illustrate the simulation results under Scenario 1 and 2, respectively. Figs. 3(a) and 4(a) illustrate the improvement ratios produced by MCAB and BLC with the
function of the distance of node pairs, while Figs. 3(b) and 4(b) illustrate the average hop counts of the widest paths found by MCAB and BLC. Generally speaking, the improvement ratio of MCAB is larger than that of BLC, and also larger than 1. Therefore, MCAB outperforms BLC metric and the hop count metric. In the first scenario, the average improvement ratio of MCAB is between 1 and 1.2, as illustrated in Fig. 3(a), while that is larger than 1.4 under the second scenario, as illustrated in Fig. 4(a). Since the variance of the available bandwidth of each node under the second scenario is larger than that under the first scenario, the probability that the minimum hop path uses the links with very small bandwidth under Scenario 2 is larger than that under Scenario 1. Unfortunately, the hop count metric does not consider the available bandwidth of each link. On the other hand, MCAB tries to find a longer path which has the links with larger available bandwidth, as illustrated in Figs. 3(b) and 4(b). Therefore, MCAB is better than the hop count metric. Moreover, MCAB is better than BLC since the improvement ratio of MCAB is larger than that of BLC, as illustrated in Figs. 3(a) and 4(a). We mentioned earlier that BLC cannot directly reflect the available bandwidth of a path, and the path selection is based on BLC metric. Hence, the path with larger bandwidth may be dropped due to the smaller BLC metric. We also observe that the improvement ratio of BLC is less than 1 under some situations. We mentioned earlier that the path selection in the hop count metric is based on the available bandwidth of the identified paths computed by (1). It is possible that the hop count selects the better path than BLC due to the same reason that BLC cannot directly reflect the available bandwidth of a path.

V. CONCLUSION

In this paper, we studied the problem of identifying the maximum available bandwidth path, which is a fundamental issue for providing the Quality-of-Service in the multi-channel wireless mesh networks. We proposed a new path metric, called the Multi-channel Composite Available Bandwidth (MCAB). We formally showed that the routing algorithm by applying the proposed metric must find the maximum available bandwidth path from each node to a destination.

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