Routing in Multi-hop Wireless Mesh Networks with Bandwidth Guarantees

[Extended Abstract]
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ABSTRACT
This paper presents a distributed polynomial algorithm for finding the maximum bandwidth path in Wireless Mesh Networks (WMNs). Our proposed algorithm can be applied for designing the proactive hop-by-hop routing protocol with bandwidth guarantee. To the best of our knowledge, our work is the first distributed path calculation algorithm in WMNs.

Categories and Subject Descriptors
D.2.8 [Computer-Communication networks]: Network architecture and design—Wireless Communication

General Terms
Algorithm, Design, Performance

Keywords
Wireless Mesh Networks, QoS routing, Distributed algorithms

1. MOTIVATION
Wireless Mesh Network (WMN) is the edge network for extending the Internet coverage. However, due to the wireless interference, providing the bandwidth guarantee is a big challenge [5]. In [7], it has been shown that proactive hop-by-hop routing protocols are the most appropriate for mesh networks. Developing the distributed path calculation mechanism is a fundamental issue for designing the hop-by-hop routing protocol. In this paper, we present a distributed polynomial algorithm for finding the maximum bandwidth path in a WMN. Due to space limitation, we only describe the main results and we refer interested readers to [1] for further details.

2. PATH CALCULATION ALGORITHM
Generally speaking, there are two kinds of wireless interference: inter-flow interference and intra-flow interference [3]. The work in [3] adopts the technique of estimating the available bandwidth of each link to solve the inter-flow interference. There have been several works on how to estimate the available bandwidth of each link [5]. Accordingly, we assume that the available bandwidth of each link is known. We are going to discuss how to calculate the available bandwidth of a multi-hop path.

We adopt the Transmitter-Receiver Conflict Avoidance (TRCA) model [2] since it reflects the popular IEEE 802.11 technologies more closely. Under this model, the neighbors of the transmitter and the receiver cannot send or receive data in order to avoid collision. We assume that, given a path \( \langle v_1, v_2, \ldots, v_h \rangle \), only the on-path nodes \( v_{i-1} \) and \( v_{i+1} \) are the neighbors of \( v_i \), where \( 1 < i < h \). This assumption is reasonable since the path with the low hop-count is preferred in order to reduce the interference probability [4].

Given the whole path information, [3] presents the solution for computing the available bandwidth of a path when intra-flow interference is taken into account. For instance, in Fig. 1, the number on each link represents the available bandwidth. By applying the method in [3], which is based on the conflict graph model, the available bandwidth of path \( \langle a, b, c, f, g \rangle \) is \( \frac{12}{13} \). Interested readers can refer to [3] for detailed discussion. In the following, we are going to show how to compute the bandwidth of a path in a distributed manner.

2.1 Distributed path computation
Let \( WB(p) \) be the available bandwidth of path \( p \). We have the following lemma.
The proof of the lemma can be found in [1]. As illustrated in Fig. 2, Lemma 1 suggests that $v_1$ can compute $WB(p)$ without knowing the whole path information, as long as $v_2$ advertises $WB(p')$ and the available bandwidth of $(v_2, v_1)$, as well as $(v_3, v_1)$, to $v_1$. For example, in Fig. 1, $WB(<b, c, f, g>) = \frac{12}{17}$, $b$ advertises this information together with the bandwidth of links $(b, c)$ and $(c, f)$ to $a$. Then, $a$ can compute $WB(<a, b, c, d, e>)$ to be $\frac{18}{23}$ by using the method in [3]. By Lemma 1, it determines $WB(<a, b, c, f, g>)$ to be $\min(\frac{12}{17}, \frac{18}{23}) = \frac{12}{17}$.

### 2.2 Path Selection

We now know how to compute the available bandwidth of a path advertised by a neighbor. In the traditional hop-by-hop protocol, after computing the bandwidth of the paths advertised by the neighbors, a node advertises the “best” one among them. However, this may not facilitate a neighbor to identify its own best path. For example, in Fig. 1, $WB(<b, c, f, g>) = \frac{12}{17}$ and $WB(<a, b, c, f, g>) = \frac{12}{17}$, while $WB(<b, d, e, g>) = WB(<a, b, d, e, g>) = 1$. From $b$’s perspective, the best path is $<b, c, f, g>$. Unfortunately, if $b$ only advertises this path to $a$, $a$ cannot identify its own best path, which is $<a, b, d, e, g>$. A trivial way for assuring all the maximum bandwidth paths can be found is to advertise all the possible paths to a destination. This is definitely too expensive. To reduce the overhead, we should not advertise those paths that would not be a subpath of any maximum bandwidth path. Therefore, we study the necessary and sufficient condition for a node to determine whether a path would be a subpath of any maximum bandwidth path. Given a path $p=<v_1, v_2, ..., v_n>$, denote $FB(p)$ as the available bandwidth of the link $(v_1, v_2)$, and $TB(p)$ as the available bandwidth of the subpath $<v_1, v_2, v_3>$. $TB(p)$ is computed based on the method in [3]. Let $p_1$ be a path from $v$ to $v_1$, $p_1 \oplus p$ denotes the concatenated path with $p_1$ and $p$. Lemma 2 gives the sufficient condition to determine a path that is not worthwhile to be advertised.

**Lemma 2.** Suppose that $p_1$ and $p_2$ are two paths from $v$ to $d$. If $WB(p_1) \geq WB(p_2)$, $TB(p_1) \geq TB(p_2)$, and $FB(p_1) \geq FB(p_2)$, then $WB(p_1 \oplus p_2) \geq WB(p_1 \oplus p_2)$ for any path that ends at $v$.

Lemma 2 shows that, given paths $p_1$ and $p_2$ from a source to a destination, if $WB(p_1) \geq WB(p_2)$, $TB(p_1) \geq TB(p_2)$, and $FB(p_1) \geq FB(p_2)$, $p_2$ must not be a subpath of any maximum bandwidth path in network. Thus, $p_2$ is not worthwhile to be advertised. As a matter of fact, we found that these conditions for determining whether a path is worthwhile to be advertised are also necessary.

### 2.3 Isotonic path weight

Studies in hop-by-hop routing show that not every routing metric facilitating an optimal path can be found [6]. The isotonicity property of the path weight is the necessary and sufficient condition for a routing protocol satisfying the optimality requirement [6]. Interested readers can refer to [6] for the detailed explanation about optimality. The definition of isotonicity defined in [6] is as follows:

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

Based on Lemma 2, we can develop an isotonic path weight, called composite bandwidth, which captures the available bandwidth of a path.

**Definition 2.** Given a path $p$, the composite bandwidth of $p$, denoted by $\omega(p)$, is $(\omega_1(p), \omega_2(p), \omega_3(p))$ where $\omega_1(p) = WB(p)$, $\omega_2(p) = TB(p)$, and $\omega_3(p) = FB(p)$. $\omega(p) \succ \omega(p_2)$ iff $\omega_1(p_1) \geq \omega_1(p_2)$, $\omega_2(p_1) \geq \omega_2(p_2)$, and $\omega_3(p_1) \geq \omega_3(p_2)$.

Composite bandwidth is left-isotonic and the proof can be found in [1]. That is, given two paths $p_1$ and $p_2$ from $s$ to $d$ and any path $p$ that ends at $s$, if $\omega(p_1) \succ \omega(p_2)$, it holds that $\omega(p \oplus p_1) \succ \omega(p \oplus p_2)$. In this case, we say that $p_1$ is better than $p_2$.

### 3. CONCLUSION

In this paper, a distributed polynomial algorithm for computing the maximum bandwidth path has been proposed. We also introduce a new path weight, composite bandwidth, which captures the available bandwidth information. In the future, we are going to consider the issues for developing the proactive hop-by-hop routing protocol by applying the proposed path weight, such as constructing the distance table and the routing table, and how to design the hop-by-hop packet forwarding mechanism in order to satisfy the consistency requirement [6]. Moreover, we would like to further demonstrate the performance of our QoS routing protocol with the IEEE 802.11 MAC protocol under a widely used simulator, such as NS2.

### 4. REFERENCES


