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Channel Aware Opportunistic Routing in Multi-Radio Multi-Channel Wireless Mesh Networks

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Abstract Opportunistic routing (OR) involves multiple candidate forwarders to relay packets by taking advantage of the broadcast nature and multi-user diversity of the wireless medium. Compared with traditional routing (TR), OR is more suitable for the unreliable wireless link, and can evidently improve the end to end throughput. At present, there are many achievements concerning OR in the single radio wireless network. However, the study of OR in multi-radio wireless network stays the beginning stage. To demonstrate the benefit of OR in multi-radio multi-channel network, we propose a new route metric — multi-channel expected anypath transmission time (MEATT), which exploits the channel diversity and resource of multiple candidate forwarders for OR. Based on the new metric, a distributed algorithm named Channel Aware Opportunistic Routing (CAOR) is proposed. The simulation results demonstrate that MEATT improves 1.14 and 1.53 times of the average throughput than existing expected anypath transmission time (EATT)and metric of interference and channel switching cost (MIC) respectively. The average delay of MEATT is 17% and 40% lower than those of EATT, MIC, respectively.

Keywords wireless mesh network, multi-radio, multi-channel, opportunistic routing

1 Introduction

Opportunistic routing (OR) has been recently proposed as a novel paradigm, which exploits the broadcast nature and multi-user diversity of the wireless channel to increase the reliability of wireless transmissions.

In OR, when a sender broadcasts its data, any node that hears the transmission may forward the data toward the destination. As long as there is one forwarder that is closer to the destination and receives the transmission, the data can move forward. In this way, opportunistic routing can effectively combine multiple weak wireless links into a strong link. And recent researches[1-5] have validated that compared with traditional routing (TR), OR can evidently promote the end to end throughput of multi-hop wireless network, especially wireless mesh networks (WMNs)[6].

Equipping each node with multiple radios is a promising approach for improving the capacity of WMNs. The availability of cheap, off-the-shelf commodity hardware also makes multi-radio solutions economically attractive. Current work[1-5] on OR focuses on single-radio and single-channel wireless networks, however OR in multi-radio multi-channel wireless networks is still an open problem.

Design OR routing metric in multi-radio multi-channel WMNs is very challenging. One way to design the metric is to directly use the single channel OR metric[7-9], such as expected transmission count (ETX)[10], expected anypath transmission (EAX)[11], expected anypath transmission time (EATT)[12]. However, these single channel OR metrics fail to find an optimal OR routing to exploit multi-radio resource in WMNs because these metrics ignore the channel diversity. The other way to design OR metric is based on current multi-channel routing metrics, such as weighted cumulative ETT (WCETT)[13], self-interference aware metric (SIM)[14], metric of interference and channel switching cost (MIC)[15]. However, these multi-channel routing metrics cannot exploit the resource of multiple candidate forwarders for OR. Therefore, both above solutions cannot select suitable route for OR in multi-radio multi-channel WMNs.

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To demonstrate the benefit of OR in multi-radio multi-channel WMNs, this paper proposes a novel routing metric — multi-channel expected anypath transmission time (MEATT), which concurrently considers the channel diversity and multiple candidate forwarders. Based on the metric, a distributed algorithm named Channel Aware Opportunistic Routing (CAOR) is presented. We have done extensive simulations. The simulation results demonstrate that MEATT/CAOR improves 1.14 and 1.53 times of the throughput than existing EATT and MIC respectively. The average delay of MEATT/CAOR is 17% and 40% lower than that of EATT and MIC respectively. The aggregative throughput with multi-flow of MEATT/CAOR is higher than that of EATT and MIC by 9.51% and 17.6% respectively.

The rest of this paper is organized as follows. Section 2 briefly reviews the concepts of OR and related work. We analyze the OR route selection in multi-radio multi-channel WMNs in Section 3. The system model is introduced in Section 4. Section 5 presents the proposed routing metric. The distributed routing algorithm is proposed in Section 6. Section 7 presents the simulation results. Conclusions are drawn in Section 8.

2 Concepts of OR and Related Work

2.1 Concepts of OR

Let us describe the concepts of OR via a simple example. There are five wireless nodes in a chain WMN as shown in Fig.1. The digit above the edge between two nodes represents the packet delivery ratio (PDR) of the transmission link, which is calculated by the probability of successfully transmitting a packet from the sender to the receiver. PDR is equal to the total number of sending packets divided by the number of correct receiving packets. Many factors impact PDR such as barrier, transmission rate, and distance. When the barrier and transmission rate are fixed, the longer the distance is, the lower the PDR is. In the example, there is a session from node 0 to node 4.

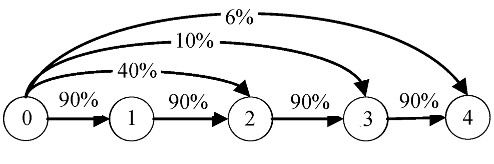


Fig.1. Concepts of OR.

Traditional routing could forward data through some sub-sequence of the chain, for example 0-4 or 0-1-2-3-4. A packet may be sent more than once due to packet loss or multi-hop. In the former case, if a packet is not accepted by node 4, nodes 1, 2 and 3 are able to overhear the packet due to the broadcast nature of wireless channel. Retransmission of the packet from node 1, 2, or 3 is better than from node 0. In the latter case, if a packet from node 0 to node 1 is correctly overheard by node 2, 3 or 4, it is wasteful of channel resource that node 1 forwards the packet to node 2.

OR exploits the diversity of multi-user and uses multiple candidate forwarders instead of pre-selected one next-hop. OR defers the selection of the next hop after the packet has been received by candidate forwarders. The "closest" node to the destination among the candidate forwarders which received the packet should forward this packet. OR can reduce the number of transmissions and improve throughput. In Fig.1, nodes 4, 3, 2 and 1 are the candidate forwarders of node 0. If a packet transmission from node 0 is not accepted by node 4, reaching only nodes 1 and 2, then node 2 which is the closest node to node 4 becomes the real forwarder and forwards the packet. If a packet from node 0 is received by nodes 4, 2, and 1, nodes 2 and 1 do not forward the packet since node 4 is the ultimate destination. OR involves multiple candidate forwarders into packet relaying by taking advantage of the broadcast nature and multi-user diversity of the wireless medium. Compared with traditional routing (TR), OR is more suitable for the unreliable wireless link. As the backbone of WMNs is composed of lots of static, non-power constrained and dense wireless routers, WMNs provide plenty of static and robust candidate forwarders for OR. Therefore, compared with other multi-hop wireless networks (wireless ad hoc network or wireless sensor network), OR in WMNs can achieve higher performance.

2.2 Related Work

Most of the route selection work in opportunistic routing focuses on single channel wireless network, including expected transmission count (ETX)[10], expected any-path transmission (EAX)[11], expected anypath transmission time (EATT)[12].

Expected transmission count (ETX)[10] is defined as the number of transmissions required to successfully deliver a packet over a wireless link. The ETX of a path is defined as the sum of ETX of each link along the path. However, ETX is a single-path metric and does not represent correctly the node's true distance when using opportunistic routing. To the best of our knowledge, Zhong *et al.*[11] are the first to propose the expected anypath number of transmissions (EAX) metric which calculates the expected transmission count through all possible paths rather than a single path from the source to destination. ETT considers the actual time incurred in using the channel. According to the extension of EAX, [12] proposes the expected anypath transmission time (EATT). Although these metrics consider the multi-path of opportunist routing, the influence of channel diversity is ignored.

There are preliminary progresses[7-8,16-18] on the multi-channel opportunistic routing, but [7-8,16-17] focus on channel assignment. [7] builds a model for OR and concurrent sets, and gains the theoretical upper bound of single flow throughput by linear programming. After determining the candidate forwarders, [7] tries to find the best method of channel assignment and scheduling to gain the optimal throughput. Wu *et al.* present a simple extension for MORE[3] (EMORE) to work in MRMC-WMNs in [8]. And a Workload-Aware Channel Assignment algorithm (WACA) for OR was designed which identifies the nodes with high workloads in a flow as bottlenecks, and tries to assign channels to these nodes with high priority. Our work of Low-Complex Channel Assignment for Opportunistic Routing (LcCAOR)[16] assumes the number of channel and radio are equal and Candidate Forwarder Set Channel Assignment (CFSCA)[17] assigns channel candidate forwarder set with regard to the one-to-more transmission mode. How to select OR in multi-radio multi-channel WMNs is out of the scope of these papers. The route in [7-8, 16-17] is pre-selected by the above single channel OR metrics. Only Multi-Channel Extremely Opportunistic Routing (McExOR)[18] solves the problem of selecting candidate forwarders under single-radio multi-channel environment, without handling the route selection in multi-radio WMNs.

There are some researches on traditional routing in multi-radio multi-channel networks, such as weighted cumulative ETT (WCETT)[13], self-interference aware metric (SIM)[14], metric of interference and channel switching cost (MIC)[15].

WCETT[13] was proposed to reduce the number of nodes on the path of a flow transmitted on the same channel. Specifically, let Xc be defined as the number of times channel c is used along a path. Then WCETT for a path is defined as the weighted sum of the cumulative expected transmission time and the maximal value of Xc among all channels. However, not all links using a same channel will interfere in a path. SIM[14] decreases the range of punishing using a same channel from the whole path to interference range. MIC[15] is designed to support load balanced routing and to consider intra-flow and inter-flow interference, in addition to being isotonic. MIC tries to overcome the limitations of WCETT by directly considering intra-flow and inter-flow interference. However they do not consider the multiple candidate forwarders of OR and cannot select suitable route for OR in multi-radio multi-channel WMNs.

In this paper, we propose a novel OR routing metric and a distributed opportunistic routing algorithm for multi-radio multi-channel OR.

3 Motivation Example

We use an example to show the difference of opportunistic routing selection in single radio and multi-radio multi-channel WMNs. In single radio WMNs, every node is equipped with one radio and works on a same channel. According to the routing metric EAX or EATT, OR route selection should select the candidate forwarders from all neighbors. The candidate forwarders constitute a forwarder set. Fig.2 is the route selection from s to d in single radio WMNs. The neighbors of s are nodes 1, 2, 3 and 4. According to routing metric, nodes 1 and 2 are chosen as the candidate forwarders of s and they constitute the forwarder set of s. The neighbors of node 1 are nodes 2, 3, 5 and s. Nodes 2 and 5 are chosen as the candidate forwarders of node 1 and they constitute the forwarder set of node 1. Similarly, node 2 chooses node 5 and d from its neighbors (nodes 1, 5, s and d) as its candidate forwarders. Node 5 chooses node d from its neighbors (nodes 1, 2 and d) as its candidate forwarders. Then OR from s to d includes following five available paths and the forwarder set is shown in Table 1:

$$s \to 1 \to 2 \to d,$$
$$s \to 1 \to 5 \to d,$$
$$s \to 1 \to 2 \to 5 \to d,$$
$$s \to 2 \to d,$$
$$s \to 2 \to 5 \to d.$$

Depending on which nodes successfully receive the packet at each hop, only one of the available paths is traversed.

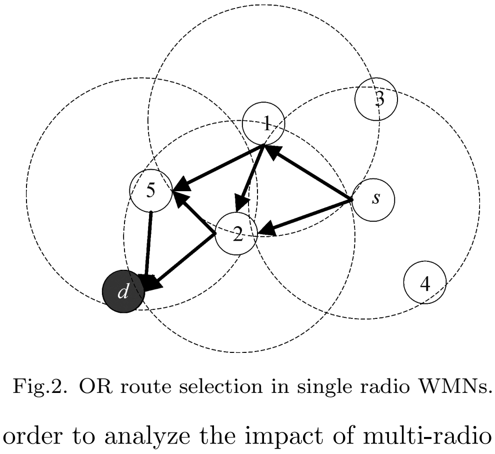


Fig.2. OR route selection in single radio WMNs.

In order to analyze the impact of multi-radio multi-channel, each node in Fig.2 is equipped with two radios working on two channels, and the new topology is

Table 1. OR Route Selection in Single Radio WMNs

Nodes	Forwarder Set
s	{1, 2}
1	{2, 5}
2	{5, d}
5	{d}

shown in Fig.3. In multi-radio multi-channel WMNs, the nodes with multiple radios work on multiple channels. Although each radio has mapped a working channel, a node has different neighbors when it works on different channels, which results in different data rates and channel quality. And the rate and channel quality are different. For example, when node s works on $ch1$, it has a neighbor set of nodes 1, 2, 3 and 4, while it has a neighbor set of nodes 1, 2, 3, 4 and 5 when it works on $ch2$. The more the neighbors are, the better the quality of link may be. Therefore, OR route selection should judge the next hop's working channel. If radio on $ch1$ is chosen, then nodes 1 and 2 are candidate forwarders of node s. If radio on $ch2$ is chosen, then nodes 1, 2 and 5 are candidate forwarders of node s. In Fig.3, the latter is chosen. Similarly, nodes 1, 2 and 5 also need to identify their working channels and further identify their forwarder sets. Node 1 chooses nodes 2 and 5 as its forward set with radio on $ch1$; node 2 chooses nodes 5 and d as the forward set with radio on $ch1$; node 5 chooses node d as the forward set with radio on $ch2$. Radios on different channels make different neighbors leading to different candidate forwarders, rates, and channel quality. Compared with OR in single radio, OR in multi-radio should first identify each next hop's working channel, based on which further decide the next hop's forwarder set.

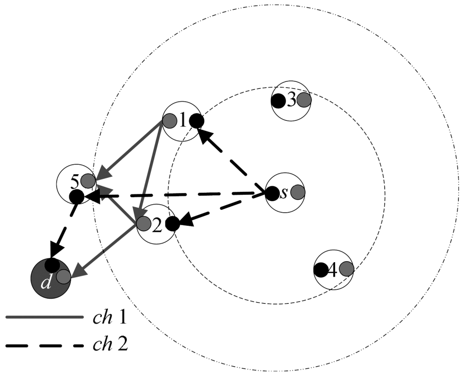


Fig.3. OR route selection in multi-radio multi-channel WMNs.

4 System Model

We consider a multi-radio multi-channel wireless mesh network with a set V of nodes as shown in Fig.4. It consists of a mesh gateway and several mesh routers. Each node u ($u \in V$) is equipped with one or more wireless interface cards, referred to as radios in this work. Each radio is mapped a working channel. Denote the number of radios in a node as R. Assume K orthogonal channels are available in the network without any inter-channel interference. For simplicity, we assume each node transmits at the same data rate B_k on channel k. We also assume half-duplex on each radio, that is, a radio cannot transmit and receive packets at the same time. It is usually true in practice. Let $p(u,v,k)$ be the packet delivery ratio (PDR) from node u to node v on channel k; that is, if a packet is transmitted from node u to node v on a common channel k, then with probability $p(u,v,k)$ the packet can be decoded at v. Two nodes, u and v, can communicate with each other if they operate on a same channel and the $p(u,v,k)$ between them is larger than a threshold P_0 ($P_0 \ll 1$).

In multi-radio multi-channel WMNs, each radio has mapped a working channel. When a node forward packets, it should decide the next-hop forwarder set and the working radio. In Fig.3, there is an OR from s to d. We show how to describe OR route result in multi-radio multi-channel WMNs through the example in Fig.3. s and d are connected through a mesh composed of the union of multiple paths, which is defined as a multi-channel anypath. We use solid and black dashed lines to represent the working channel $ch1$ and $ch2$. The forwarder set of s is nodes 1, 2 and 5, the working radio is on channel $ch2$, denoted by a two-array (forwarder set, radio) $(\{1,2,5\}, ch2)$. Similar to Table 1, Table 2 shows OR route selection result which are the forwarder set and working radio on the multi-channel anypath for s-d flow. Therefore, OR in multi-radio multi-channel WMNs from s to d includes six available multi-channel paths:

$$s \xrightarrow{ch2} 1 \xrightarrow{ch1} 2 \xrightarrow{ch1} d,$$

$$s \xrightarrow{ch2} 1 \xrightarrow{ch1} 5 \xrightarrow{ch2} d,$$

$$s \xrightarrow{ch2} 1 \xrightarrow{ch1} 2 \xrightarrow{ch1} 5 \xrightarrow{ch2} d,$$

$$s \xrightarrow{ch2} 2 \xrightarrow{ch1} d,$$

$$s \xrightarrow{ch2} 2 \xrightarrow{ch1} 5 \xrightarrow{ch2} d,$$

$$s \xrightarrow{ch2} 5 \xrightarrow{ch2} d.$$

Table 2. OR Route Selection in Multi-Radio Multi-Channel WMNs

Nodes	(Forwarder Set, Radio)
s	({1, 2, 5}, $ch2$)
1	({2, 5}, $ch1$)
2	({5, d}, $ch1$)
5	({d}, $ch2$)

Then OR works as follows. Several nodes successfully receive the packet at each hop. There is more than one multi-channel path available from the source to the destination. But for one packet only one of the available multi-channel paths is traversed. We show a path possibly taken by the packet, which is $s \xrightarrow{ch2} 1 \xrightarrow{ch1} 2 \xrightarrow{ch1} d$. Succeeding packets may take completely different paths with other radios along its way, for example $s \xrightarrow{ch2} 5 \xrightarrow{ch2} d$.

Given a static wireless mesh network of router nodes with multiple radio interfaces and the static channel assignment of all nodes, this paper want to effectively find an OR path which can exploit the multi-radio resource and multi-user diversity to improve the performance of networks.

Hence, to identify the best OR route, we design a new metric to select the best forwarder set of each hop and along the path select each node's working radio to forward packets. There are two tasks to find opportunistic routing in multi-radio multi-channel WMNs:

- a new metric which selects the best forwarder set among all neighbor sets and selects the working radio of each node along the OR paths;
- a routing algorithm based on the new metric to obtain the candidate forwarder set and working radio used to reach the candidate forwarder set at the same time.

5 Metric Design

As aforementioned, one major task is what metric should be used to quantify the performance of OR in multi-radio multi-channel WMNs. Consider the simple example shown in Fig.4.

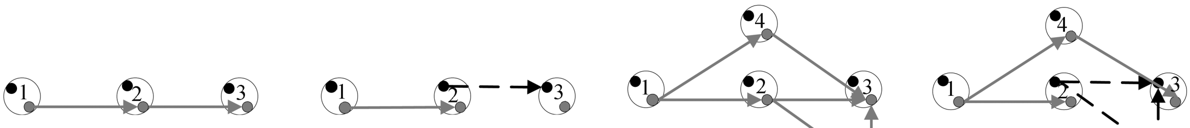
In Fig.4, every node has an 802.11a radio and an 802.11b/g radio. Assume there is one traffic flow from nodes 1 to 3. In Figs.4(a) and 4(b), every node has only one candidate forwarder. In Fig.4(a), both links (1, 2) and (2, 3) are assigned to channel 802.11a (which is referred as pattern 1), while in Fig.4(b), link (1, 2) is assigned to channel 802.11a and link (2, 3) is assigned to channel 802.11b/g on a different interface (pattern 2). Obviously, pattern 2 is much more desirable than pattern 1 as pattern 2 makes use of both channels and may give a higher aggregated throughput.

In Figs.4(c) and 4(d), every node has not only one candidate forwarder. In Fig.4(c), links (1, 2), (1, 4), (2, 5), (4, 3), (5, 3) and (2, 3) are assigned to channel 802.11a (which is referred as pattern 3), while in Fig.4(d), links (1, 2), (1, 4) and (4, 3) are assigned to channel 802.11a and links (2, 3), (2, 5) and (5, 3) are assigned to channel 802.11b/g on a different interface (pattern 4). Obviously, pattern 4 is much more desirable than pattern 3 as pattern 4 makes use of both channels, and pattern 2 as pattern 4 makes use of candidate forwarders, and may give a higher aggregated throughput. The question is how can we quantify that pattern 4 is indeed better than pattern 3 and pattern 2.

In this section, we will propose a novel routing metric, called multi-channel expected anypath transmission time (MEATT), which considers channel diversity on different radios and multiple candidate forwarders. The basic idea is that we firstly propose multi-channel expected transmission time (METT) according to the concurrent transmissions on different radios with orthogonal channel for Figs.4(a) and 4(b). Then in order to support multiple candidate forwarders for Figs.4(b) and 4(d), we design multi-channel expected anypath transmission time based on METT.

Firstly, the metric must identify different channels on different radios. Expected transmission time is an important metric on WMNs, therefore our metric focuses on end-to-end expected transmission time. If two consecutive links that share the same node use a same channel, due to the half-duplex on radio co-channel interference the consecutive links cannot concurrently transmit. Therefore the end-to-end expected transmission time is the sum of the ETT values of the two individual links. If the two consecutive links use orthogonal channels on different radios, the consecutive links can concurrently transmit. Therefore the end-to-end expected transmission time is lower than that with the same channel. As shown in Figs.4(a) and 4(b), the metric with different channels should be lower than that with same channel. In order to make a difference between these two situations, the METT metric of a path from s to d is defined as follows:

$$METT(s,c,d) = \min_k (ETT(s,c,k) + \alpha \times METT(c,d)),$$



(a) (b) (c) (d)

Fig.4. Topology for MEATT illustration. (a) Pattern 1. (b) Pattern 2. (c) Pattern 3. (d) Pattern 4.

$$\alpha = \begin{cases} \beta_1, & \text{if } k \neq CH(c), \\ \beta_2, & \text{if } k = CH(c), \end{cases} \quad 0 \leqslant \beta_1 < \beta_2, \qquad (1)$$

where s and d are the source and destination respectively, and c is the next hop of s. $CH(c)$ is the channel used for the next hop at node c. To consider channel diversity we introduce a tunable parameter α into the metric. If the channel k used by s is not the same as $CH(c)$, α is set to β_1. If the channel k used by s is the same as $CH(c)$, α is set to β_2. In order to avoid consecutive hops in a path operating on identical channels, we give it a higher cost, by setting $\beta_1 < \beta_2$. s selects the radio mapped channel k which minimizes METT to forward packets.

Secondly, as shown in Figs.4(c) and 4(d) in order to support multiple candidate forwarders, we get MEATT by taking account of all the cost of all candidate forwarders. The MEATT from a source s to a destination d is defined as:

$$MEATT(s,d) = \min_k MEATT(s,d,k) =$$

$$\min_k \frac{L/B_k + \sum\limits_{c_i \in J} \alpha_i MEATT(c_i,d) p_{c_i,k} \prod\limits_{j=1}^{i-1} (1 - p_{c_j,k})}{1 - \prod\limits_{c_i \in J} (1 - p_{c_i,k})},$$

$$\alpha_i = \begin{cases} \beta_1, & \text{if } k \neq CH(c_i), \\ \beta_2, & \text{if } k = CH(c_i), \end{cases} \quad 0 \leqslant \beta_1 < \beta_2, \qquad (2)$$

where s and d are the source and destination respectively, L is the packet size, B_k is the channel bit rate on channel k, J is the candidate forwarder set, c_i is the candidate forwarder with priority i of s in J, $p_{c_i,k}$ is the PDR between s and c_i on channel k, α_i is a tunable parameter to consider channel diversity on different radios similarly to α in METT.

MEATT is constructed by two parts. One is the cost from s to candidate forwarder set J. The other is the cost from candidate forwarder set J to d. In the first part, $(L/B_k)/(1 - \prod\limits_{c_i \in J}(1 - p_{c_i,k}))$ is the cost of s successfully sending packets to candidate forwarder set J on channel k, that is, at least one candidate forwarder successfully receives the packet. In the second part, $MEATT(c_i,d)$ is the MEATT value from node c_i to d. $\frac{p_{c_i,k} \prod_{j=1}^{i-1}(1-p_{c_j,k})}{1-\prod_{c_i \in J}(1-p_{c_i,k})}$ is the probability of c_i to forward packet for s on channel k. Node c_i will be the relaying node only when it receives the packet and none of the nodes whose priority is higher than node c_i receives it. The mathematical expectation of all MEATT of c_i is the cost from candidate forwarder set J to d. For a given candidate forwarder set J, s can select the radio mapped channel k from all channels which minimize MEATT to forward packets. Actually by easily extending our metric, we can use more radio resources. We extend our metric to use N radios as following when there are R radios ($N \leqslant R$). We still select the minimum $MEATT(k)$ as the final MEATT. However we choose the N radios and channels which have the top N minimum $MEATT(k)$ value for forwarding. The divide of data transmitted in N radios can be on average or in priority order where the radio with smaller $MEATT(k)$ takes more data.

The candidate forwarders set J is decided in the following algorithm, and at the same time the working radio is decided.

6 Distributed Channel Aware Opportunistic Routing Algorithm

In this section, we firstly design a channel aware opportunistic routing algorithm (CAOR) based on the new metric and propose a distributed protocol. Then an example is given to show how CAOR works. Finally we analyze the computational overhead of CAOR.

6.1 CAOR Algorithm

Based on the MEATT metric, we design a channel aware opportunistic routing algorithm (CAOR) to select route similar to Dijkstra algorithm. The pseudocode of the CAOR algorithm is shown in Algorithm 1.

Given a graph $G(V,E)$, the algorithm calculates the shortest multi-channel anypaths from all nodes to a destination d. In the algorithm, we refer to $MEATT(i,d)$ simply by $MEATT_i$ for convenience. For each node $i \in V$, we keep a different metric estimate $MEATT_i^{(k)}$ for every channel $k \in K$.

The estimate $MEATT_i^{(k)}$ is an upper-bound on the metric of the shortest multi-channel anypath from i to d using channel k. In addition, we also keep its corresponding candidate forwarder set $F_i^{(k)}$, which stores the set of candidate forwarders used for i to reach d using channel k. We use $MEATT_i$ and F_i without the indicated channels to store the minimum metric estimate among all channels and its corresponding candidate forwarder set, respectively. We also keep a channel T_i for every node, which stores the channel used to reach d. Finally, we keep two data structures, namely S and Q. Set S stores the set of nodes for which we already have a shortest multi-channel anypath defined. We store each node $i \in V - S$ for which we still do not have a shortest multi-channel anypath in a priority queue Q keyed by their $MEATT_i$ values.

The key idea of the CAOR algorithm is that each node $i \in V$ has an independent metric estimate

```
Algorithm 1. CAOR Algorithm (Channel Aware Opportunistic Routing $(G, d)$)
1: for each node $i$ in $V$ do
2:     $MEATT_i \leftarrow \infty$
3:     $F_i \leftarrow \varnothing$
4:     $T_i \leftarrow$NIL
5:     for each channel $k$ in $K$ do
6:         $MEATT_i^{(k)} \leftarrow \infty$
7:         $F_i^{(k)} \leftarrow \varnothing$
8:     end for
9: end for
10: $MEATT_d \leftarrow 0$
11: $S \leftarrow \varnothing$
12: $Q \leftarrow V$
13: while $Q \neq \varnothing$ do
14:     $j \leftarrow EXTRACT\text{-}MIN(Q)$
15:     $S \leftarrow S \cup \{j\}$
16:     for each incoming edge $(i, j)$ in $E$ do
17:         for each channel $k$ in $K$ do
18:             $J \leftarrow F_i^{(k)} \cup \{j\}$
19:             if $MEATT_i^{(k)} > MEATT_j$ then
20:                 $MEATT_i^{(k)} \leftarrow \dfrac{L/B_k + \sum\limits_{c_i \in J} \alpha_i MEATT_{c_i} p_{c_i,k} \prod_{j=1}^{i-1}(1 - p_{c_j,k})}{1 - \prod_{c_i \in J}(1 - p_{c_i,k})}$
21:                 if $MEATT_i^{(k)} > MEATT_i^{'(k)}$ then
22:                     $MEATT_i^{(k)} \leftarrow MEATT_i^{'(k)}$
23:                     $F_i^{(k)} \leftarrow J$
24:                     if $MEATT_i > MEATT_i^{(k)}$ then
25:                         $MEATT_i \leftarrow MEATT_i^{(k)}$
26:                         $F_i \leftarrow F_i^{(k)}$
27:                         $T_i \leftarrow k$
28:                     end if
29:                 end if
30:             end if
31:         end for
32:     end for
33: end while
```

Fig.5. Algorithm 1.

$MEATT_i^{(k)}$ for each channel $k \in K$ and we keep the minimum of these estimates as the node metric $MEATT_i$. At each round of the while loop, the node with the minimum distance from Q is settled. Let this node be j. For each incoming edge $(i, j) \in E$ on channel k, we check if the metric $MEATT_i^{(k)}$ is larger than the metric $MEATT_j$ of the node just settled. If that is the case, we calculate the node temporary metric $MEATT_i^{'(k)}$ by temporarily adding j to the candidate forwarder set of node i. If $MEATT_i^{(k)}$ is larger than the temporary metric $MEATT_i^{'(k)}$, then node j is added to the candidate forwarder set $F_i^{(k)}$ of that specific channel and metric $MEATT_i^{(k)}$ is updated accordingly. If the new metric $MEATT_i^{(k)}$ is shorter than the node metric $MEATT_i$, we update the node metric $MEATT_i$ as well as the candidate forwarder set F_i and channel T_i to reflect the new minimum. After node i is settled, the candidate forwarder set F_i and channel T_i are obtained.

Inspired by the distributed Bellman-Ford protocol, we present the following distributed synchronous proactive protocol based on our CAOR algorithm. Each node maintains a routing table entry for each destination <destination, MEATT weights, candidate forwarder set, channel>. The time line is divided into a sequence of time intervals of a constant length, each of which is used for one iteration in lines 14~32 of CAOR. In each time interval, each node runs CAOR to update its anypath to each destination. If the entries in the routing table change, this node sends path vector tuples <destination, MEATT weights, channel> to all its immediate neighbors with all channels. This is called path vector updating. In the next iteration, its immediate neighbors can use these new path vectors to update their routing tables.

Since our synchronous proactive protocol requires a rough time synchronization, we also propose an asynchronous proactive table-driven protocol. Every node periodically sends path vector tuples <destination, MEATT weights, channel> to all its immediate neighbors with all channels. The updating operation frequency depends on the size and the dynamic of the network. Whenever the entries in the routing table change, this node also triggers the path vector updating. Once a node receives the path vector updates, it uses CAOR to update the anypath to the destination. If this computation leads to a routing table change, it triggers a path vector updating.

Now we discuss the stopping criteria for the iterations in our synchronous proactive protocol. Obviously, for a dynamic network this protocol should periodically update the path vector. However, for a static network, we know we can terminate the algorithm after $|V|$ times iterations.

Theorem 1. *The distributed synchronous proactive protocol is convergent after $|V|$ times iterations.*

Proof. The process of distributed synchronous proactive protocol is as following. In each iteration, each node obtains the distance (PDR in our protocol) between it and its neighbors and exchanges the route table with its neighbors. Then each node updates its route metric MEATT according to the neighbors route metrics. For a static network, there are $|V|$ nodes. Because the longest path of the shortest path is $|V| - 1$ hops, after $|V|$ times of iterations the distributed synchronous proactive protocol is convergent. ☐

6.2 Example

As shown in Fig.6, we consider a wireless mesh network with five nodes, in which every node has 2 radio interfaces. The solid lines represent links with 802.11a. The black dashed lines represent links with 802.11b/g. The expected transmission time (ETT) is labeled on each link. Fig.7 shows the execution of CAOR algorithm using the MEATT metric. We see in Fig.7(a) the graph right after the initialization. Figs.7(b)∼7(e) show each iteration of the algorithm. At each step, the value besides node i presents the metric $MEATT_i$ from that node to the destination d and the arrows in boldface present the shortest multi-channel anypath to d. Nodes with boldface circles are the settled nodes in S. The graph in Fig.7(f) shows the result of the CAOR algorithm right after settling the last node. The candidate forwarder set and radio from s to d are showed in Table 3. Fig.8 shows the result of MEATT.

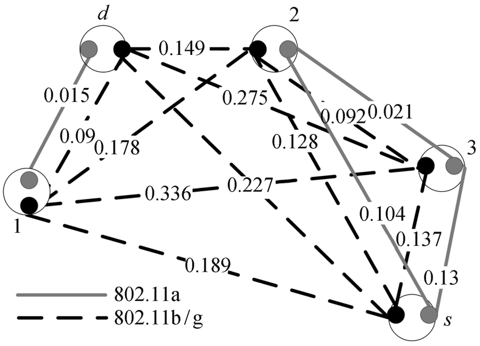


Fig.6. A five-node multi-radio multi-channel WMN.

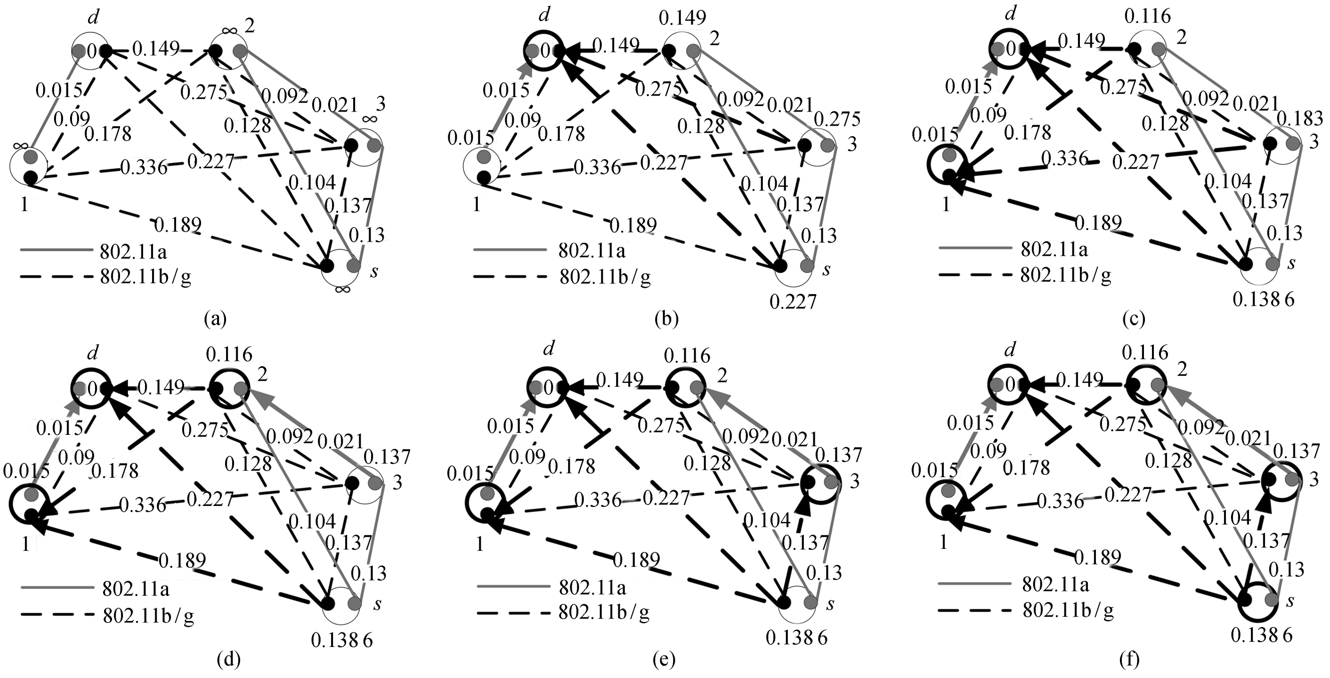


Fig.7. CAOR algorithm from every node to d. The weight of each link is the ETT. (a) The situation just after the initialization. (b)∼(e) The situations after each successive iteration of the algorithm. (f) The situation after the last node is settled.

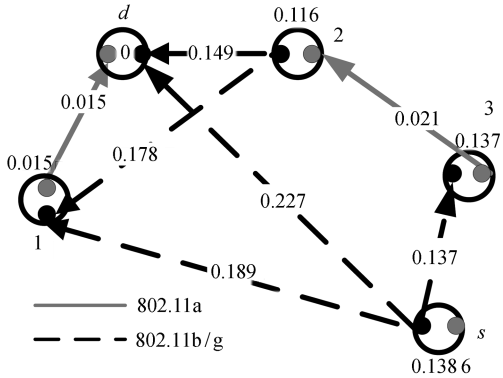


Fig.8. Route result of MEATT.

Table 3. Forwarder Set and Radio Result of MEATT Metric

Nodes	(Forwarder Set, Radio)
s	$(\{1, 3, d\}, b)$
1	$(\{d\}, a)$
2	$(\{d, 1\}, b)$
3	$(\{2\}, a)$

There are two other ways to select OR route. One way is directly use the single channel OR metric, such as EATT. Fig.9 and Table 4 are the results of EATT metric with the same topology. EATT does not consider the channel diversity, and treats all the links with different channels as the same. The candidate forwarders of s are nodes 1, 2 and d. The end-to-end throughput from s to d with EATT metric is 10.7 Mbps.

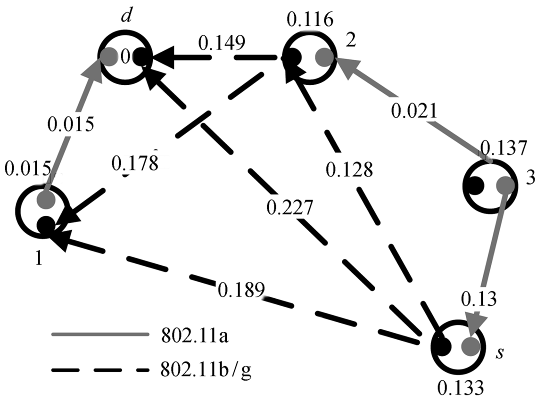


Fig.9. Route result of EATT.

Table 4. Forwarder Set and Radio Result of EATT Metric

Nodes	(Forwarder Set, Radio)
s	$(\{1, 2, d\}, b)$
1	$(\{d\}, a)$
2	$(\{d, 18\}, b)$

The other way to design the metric is based on current multi-channel routing metrics, such as MIC[15]. Fig.10 and Table 5 are the results of MIC metric with the same topology. MIC does not consider the forwarding opportunity of nodes 3 and 1 together. The candidate forwarders of s are only nodes 1 and d. The end-to-end throughput from s to d with MIC metric is only 9.68 Mbps.

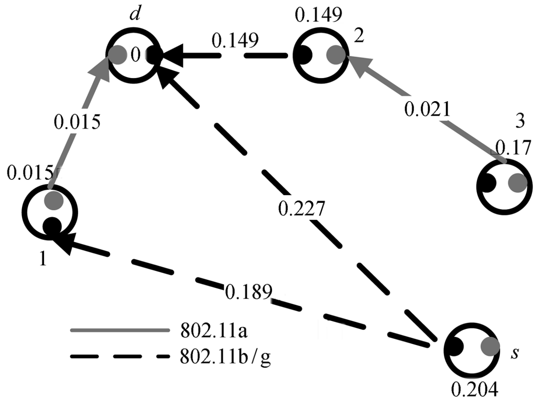


Fig.10. Route result of MIC.

Table 5. Forwarder Set and Radio Result of MIC Metric

Nodes	(Forwarder Set, Radio)
s	$(\{1, d\}, b)$
1	$(\{d\}, a)$

Compared with Fig. 9 and Fig.10 which are the results of EATT and MIC metric respectively, MEATT uses more suitable candidate forwarders. With MEATT the candidate forwarders of s are nodes 1, 3 and d with channel 802.11b/g. The end-to-end throughput from s to d with MEATT is up to 17.09Mbps. Throughput of MEATT/CAOR is higher than that of EATT and MIC by 59.7% and 76.9% respectively. MEATT/CAOR makes full use of the multi-radio multi-channel and opportunistic routing.

6.3 Computational Overhead

The running time of the CAOR algorithm depends on the implementation of Q. The initialization in lines 1∼9 takes $O(VK)$ time. Assuming that we have a Fibonacci heap, the EXTRACT-MIN operations in line 14 takes a total of $O(V \log V)$ aggregated time. We assume that the distance calculation of $MEATT_i'^{(k)}$ in line 20 is optimized to take a constant time, similarly to [12]. As a result, the for loop in lines 16∼32 takes $O(EK)$ aggregated time. The total running time is therefore $O(V \log V + (E + V)K)$, which is $O(V \log V + EK)$ if all nodes are able to reach the destination. Compared with the Dijkstra algorithm, the CAOR algorithm allows nodes to take advantage of their multiple channels at the cost of just a small increase in the running time.

7 Simulation

In this section, in order to evaluate the performance of our routing metric and algorithm MEATT/CAOR, we implement three kinds of OR route selection schemes.

In the first routing scheme, each node calculates its outgoing link's cost on each channel according to packet delivery ratio, packet length, and channel bit rate. According to our proposed OR routing metric MEATT in (2), our proposed CAOR algorithm is applied to find the route of each node to the destination with minimum MEATT. We set β_1, β_2 to 1 and 2 respectively. In the Subsection 7.5, we discuss the effect of β_1's and β_2's values.

In the second routing scheme, we use existing EATT[12] metric and apply CAOR algorithm to find the route with minimum EATT cost. Because EATT is originally designed for single radio network, to fairly compare, we extend EATT to support multi-radio and multi-channel which can be calculated as follows. The node calculates the EATT value on every channel and chooses the smallest one as its final EATT.

$$EATT(s,d) = \min_{k} \frac{L/B_k + \sum\limits_{c_i \in J} EATT(c_i, d) p_{c_i,k} \prod\limits_{j=1}^{i-1} (1 - p_{c_j,k})}{1 - \prod\limits_{c_i \in J} (1 - p_{c_i,k})}, \tag{3}$$

where the parameters are same in MEATT. Extended EATT is similar to MEATT, but it treats all channels as the same.

In the third routing scheme, we use existing MIC metric and apply CAOR algorithm to find the route with minimum MIC cost. The node calculates the MIC value on every channel and chooses the smallest one as its final MIC. MIC supports load-balanced routing and consider intra-flow and inter-flow interference, in addition to being isotonic. The MIC metric from s to d is calculated as follows:

$$\begin{aligned} &MIC(s,d) = \alpha IRU(s,c,CH(s)) + CSCc + MIC(c,d),\\ &IRU(s,c,CH(s)) = ETT(s,c,CH(s)) \times \\ &\qquad\qquad |N(s,c,CH(s))|,\\ &CSCc = \begin{cases} w1, & \text{if } CH(s) \neq CH(c),\\ w2, & \text{if } CH(s) = CH(c), \end{cases} \quad 0 \leqslant w1 < w2, \end{aligned} \tag{4}$$

where s and d are the source and destination respectively, node c is the next hop of s. α is a tunable parameter that allows to vary the weight given to the two components of MIC which are Interference-Aware Resource Usage (IRU) and Channel Switching Cost (CSC). IRU considers inter-flow interference and CSC represents the level of intraflow interference. $N(s,c,CH(s))$ is the total set of neighbor nodes which would be interfered by the link (s,c) operating on channel $CH(s)$. $CH(c)$ is the channel used for the next hop at node c. We set $w1$, $w2$ to 0 and 0.1 respectively.

7.1 Methodology

In our simulations, unless otherwise specified, the default number of nodes in the network is 25, and every node is equipped with two radios. One radio works on 802.11a and the other works on 802.11b/g. There are two orthogonal channels. The mesh gateway node is in the middle of the terrain area.

The shadowing model is used in which frame losses are proportional to the distance between wireless nodes. Note that this model assumes that losses between the source and different forwarders are independent. Therefore, intra-path and inter-path collisions occur in a random manner. We list the parameters used to obtain results in Table 6.

Table 6. Parameters Used to Obtain Results

Parameters	Values
Transmission power *Pt*	0.281 838 15 W
TX antenna gain *Gt*	1.0
RX antenna gain *Gr*	1.0
Frequency *freq*	2.4GHz/5GHz
System loss *sysLoss*	1.0
Path loss model	Shadowing model
Path loss exponent	2.0
Shadowing deviation	4.0
Distances *dist*0	1.0
Receive threshold *rxThresh*	2.445 47e−08
Channel bit rate	11 M/54 M
Packet length	1 000 bytes

Two metrics are used to evaluate the performance. One is throughput which is the aggregative throughput of all flows. The other is delay which is the aggregative delays of all flows. In order to evaluate the performance of OR in multi-radio multi-channel WMNs, we propose a multi-radio multi-channel OR programming model by extending a kind of model-driven optimization OR named Dice[19] which can obtain higher throughput than MORE[3] by rate allocation. Given the OR route, it models the coding, MAC, routing, flow conservation and bandwidth constraints to obtain maximum throughput keeping the fairness. Because our multi-radio multi-channel OR model is a convex model, we use LINGO API to solve it and get the each flow's throughput. According to the throughput and data size of flow, we can get the delay of flow. In our model, the MAC layer protocol and traffic load on links are considered. For the MAC layer protocol, it requires that in each time slot, the receive antenna of any node u allows the broadcast transmission from at most one transmitter within its range (including itself). For traffic load on links, it satisfies the flow conservation constraint. In each run, we examine three kinds of OR route selection schemes sequentially with the same source-destination pairs.

Various factors affect the performance. We perform three set of simulations to analyze the effect of node density, flow distribution, and the number of radios. As follows, we show the simulation results respectively.

7.2 Effect of Node Density

In our first set of simulations, we change the density of nodes and evaluate the end-to-end throughput and delay from the random node to the gateway node. We fix the terrain area at 400 m × 400 m and randomly distribute 16, 25, 36, 49, 64 and 81 nodes into it. For each density, all nodes as sources of simulation are performed, with four random topologies and node distributions.

Figs.11 and 12 present the average throughput and delay respectively, achieved by EATT, MIC and MEATT affected by the number of nodes in the terrain area. Fig.11 shows that the average throughput is low with poor network connectivity, i.e., when the number of nodes is small (16 or 25). MEATT always achieves the highest throughput in the evaluated cases. The gain of average throughput and delay between EATT, MIC and MEATT are denoted as EATT/MEATT and MIC/MEATT respectively which equal the value of MEATT divided by the value of EATT and MIC respectively. Fig.13 and Fig.14 present the gain with different node densities. The average gain of EATT/MEATT and MIC/MEATT are 1.14 and 1.53 times in throughput and 17% and 40% in delay respectively.

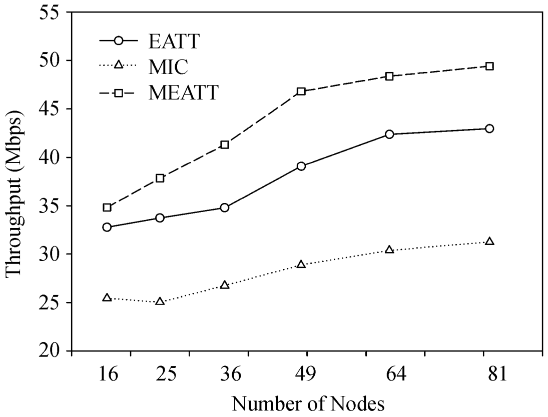


Fig.11. Average throughput with different node densities.

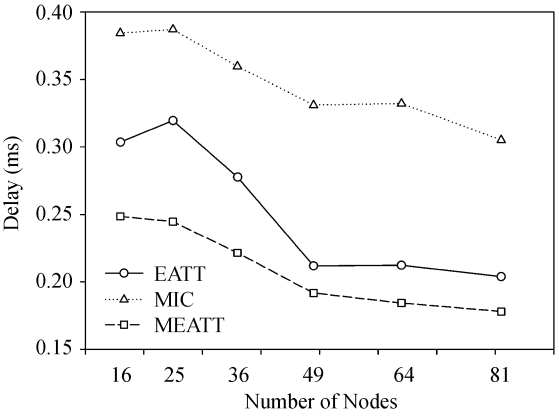


Fig.12. Average delay with different node densities.

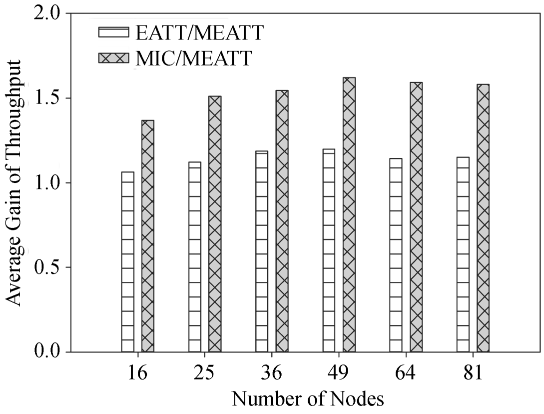


Fig.13. Gain of average throughput with different node densities.

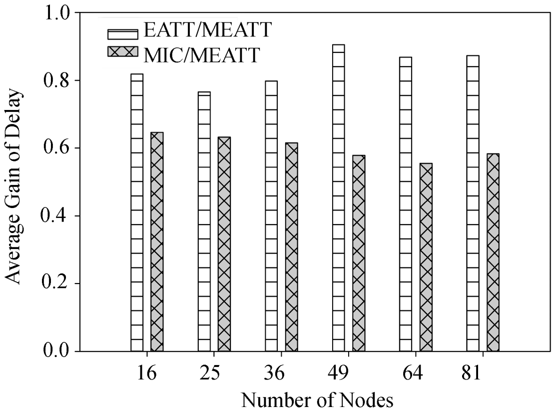


Fig.14. Gain of average delay with different node densities.

7.3 Effect of Flow Distribution

In our second set of simulations, we randomly distribute 25 wireless nodes in a terrain area of 400 m × 400 m and generate different flow distributions. It is to demonstrate that MEATT/CAOR improves the throughput and delay for different source-destination pairs in a randomly generated wireless network. We use four random topologies for our second set of evaluations. According to the flow distribution, we have two kinds of simulations: single flow scenario and multi-flow scenario. In multi-flow scenario, there are two kinds of case: gateway (multi-source single-destination) scenario and multi-source multi-destination scenario.

In the single flow scenario, there is only one flow at any time. We choose all nodes as the source sequentially and the mesh gateway as the destination. The results show that MEATT significantly improves the throughput and delay compared with other metrics. Fig.15 and Fig.16 show the cumulative function of throughput and delay respectively by using different routing metrics in single flow scenario. For the median case, MEATT achieves 18.9% and 95.7% higher throughput than EATT and MIC respectively and 9.9% and 47.3% lower delay than EATT and MIC respectively.

At the same time, we can get that the average throughput is 29.22 Mbps, 20.36 Mbps, 34.74 Mbps for EATT, MIC and MEATT respectively. MEATT obtains 18.87% and 70.62% more improvement than EATT and MIC respectively. And the average delay for EATT, MIC, and MEATT is 0.051 ms, 0.10 ms, and

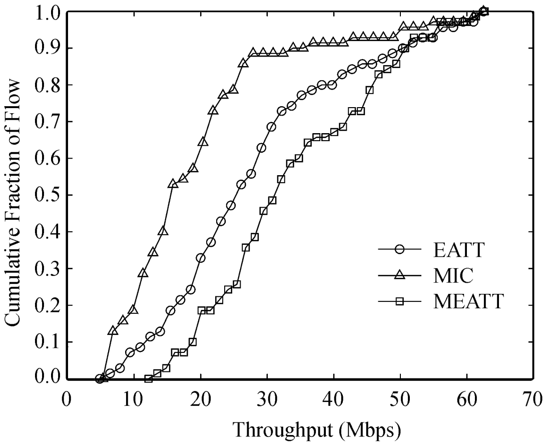


Fig.15. CDF function of throughput.

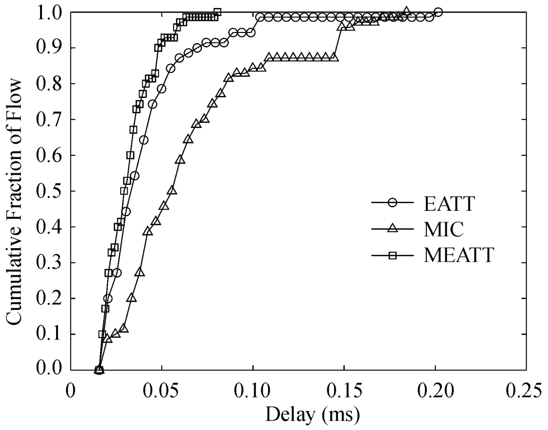


Fig.16. CDF function of delay.

0.043 ms respectively, and the result shows that MEATT decreases delay by 19.3% and 58.3% compared with EATT and MIC respectively.

In the gateway scenario, there are several flows with different sources but the same destination which is the mesh gateway. The number of concurrent flows increases from 1, 6, 12, 18 to 24. When it goes up to 24, all nodes are chosen as the sources. In each number except 24, we run the evaluation 20 times. In each run, we randomly choose sources and transmit packets by three OR routing metrics in turn, and then calculate their average aggregate throughput and delay. Fig.17 and Fig.18 show the average aggregate throughput and delay with different numbers of flows respectively. As the number of concurrent flows increases to 18 and 24, MIC is better than EATT because it considers the channel diversity and makes the best of channel resource. As the number of concurrent flows increases, the gain of MEATT decreases. The reason is that almost all nodes transmit packets and the channel resource is distributed in different flows. There is less space to improve the exploit of channel resources and candidate forwarders. The average throughput of MEATT enhances by 9.51% and 17.6%, and the average delay of MEATT decreases by 16.6% and 31.3%, compared with EATT and MIC respectively.

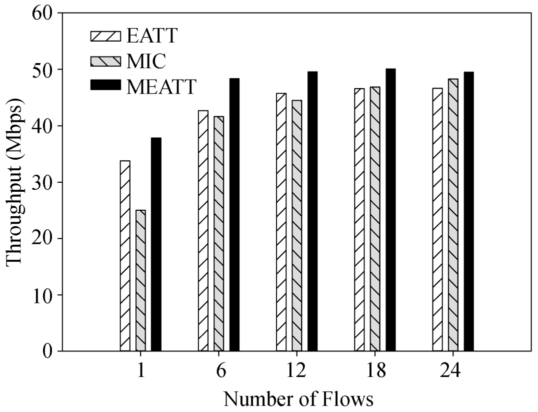


Fig.17. Average throughput of multi-flow in gateway scenario.

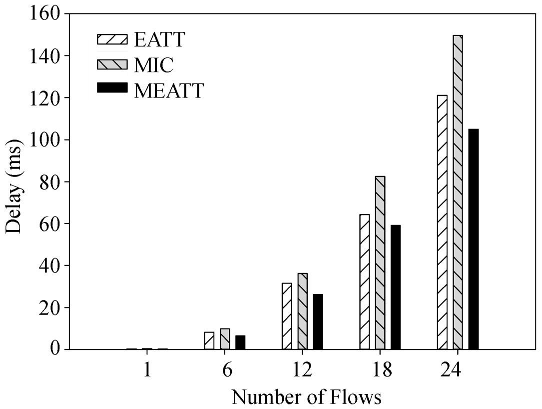


Fig.18. Average delay of multi-flow in gateway scenario.

In the multi-source multi-destination scenario, there are several flows with different sources and different destinations. The number of concurrent flows also increases from 1, 3, 6, 9 to 12. When it goes up to 12, all nodes are chosen as source-destination pairs except one node. Fig.19 and Fig.20 show the average aggregate throughput and delay with different numbers of flows respectively. The average throughput of MEATT enhances by 12.42% and 41.60%, and the average delay of MEATT decreases by 20.09% and 46.25%, compared with EATT and MIC respectively. In the gateway scenario, all traffic aggregates to the gateway node and the performance bottleneck is on the gateway node. In the multi-source multi-destination scenario, the traffic is distributed on the whole network. Therefore the gain of throughput and delay in the multi-source multi-destination scenario is higher than that in the gateway scenario.

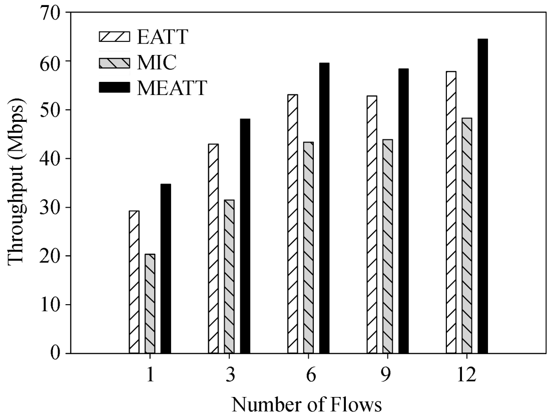


Fig.19. Average throughput of multi-flow in multi-source multi-destination scenario.

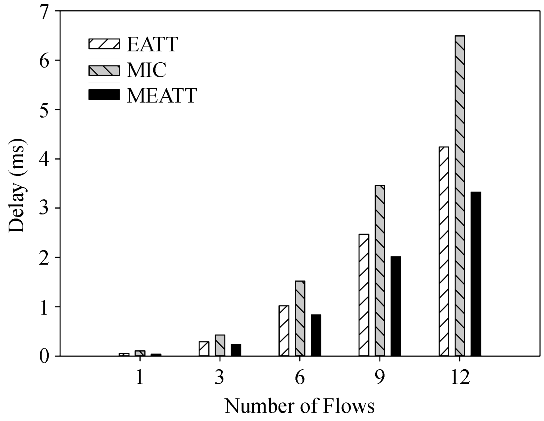


Fig.20. Average delay of multi-flow in multi-source multi-destination scenario.

7.4 Effect of the Number of Radios

In our third set of simulations, we vary the number of radios R from 1 to 6 in the network. There are six flows with different sources and different destinations. In Fig.21, the aggregate throughputs achieved by EATT, MIC and MEATT all increase as the number of radios increases. In Fig.22, the aggregative delays achieved by EAX, MIC and MEATT all decrease as the number of radios increases. The simulation result indicates that MEATT can achieve better performance than EAX and MIC with any number of radios. Compared with EATT and MIC, our MEATT can make use of radios more efficiently.

7.5 Effect of α's Value

MEATT is related with parameter α which is decided by β_1, β_2. To consider channel diversity we introduce a tunable parameter α into the metric. If consecutive hops in a path operate on different channels, α is set to β_1; otherwise α is set to β_2. In order to avoid consecutive hops in a path operating on identical channels, we give it a higher cost, by setting $\beta_1 < \beta_2$. We use different values of $\beta1, \beta2$ to test the performance of MEATT. We set β_1 to 1 and vary β_2 from 1 to 4. Fig.23 and Fig.24 show the throughput and delay achieved by MEATT with different β_1, β_2 respectively, for comparison, as well as the performances of EATT and MIC.

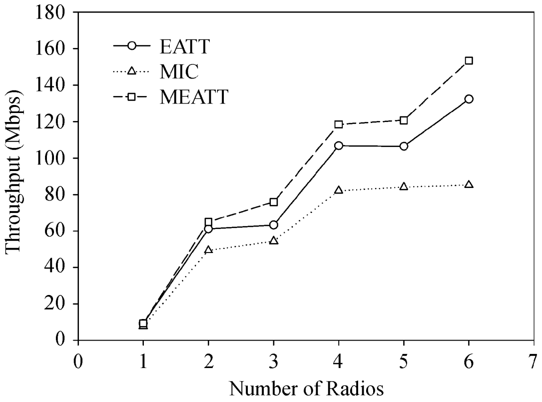


Fig.21. Throughput of number of radios.

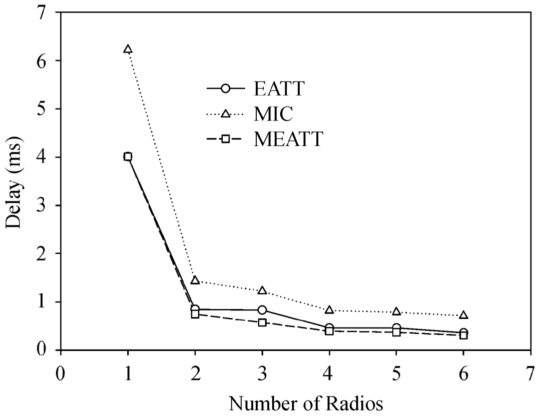


Fig.22. Delay of number of radios.

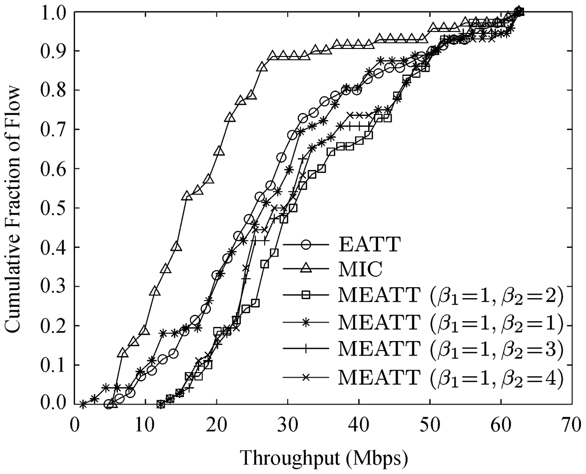


Fig.23. Throughput achieved by MEATT with different β_1, β_2.

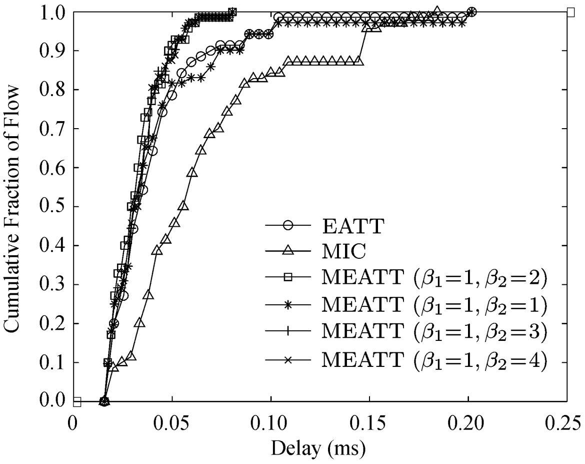


Fig.24. Delay achieved by MEATT with different β_1, β_2.

The performance of MEATT with $\beta_1 = 1, \beta_2 = 1$ is almost the same as EATT, and in the others cases MEATT outperforms EATT and MIC especially when $\beta_1 = 1, \beta_2 = 2$. When the value of β_2 exceeds 3, the routes selected by MEATT are the same and the throughputs of MEATT remain the same. Therefore only if β_2 is larger than β_1, MEATT can achieve better performance than EATT and MIC.

8 Conclusions

In this paper, we studied the opportunistic routing problem in multi-channel multi-radio wireless mesh networks. We proposed a new routing metric multi-channel expected anypath transmission time (MEATT), which considers the radio, channel resources and multiple candidate forwarders, and a distributed algorithm named Channel Aware Opportunistic Routing (CAOR) to find opportunistic routes. Simulation results show that MEATT achieves higher throughput and lower delay than existing routing metrics. Our future study will focus on designing efficient joint channel assignment and opportunistic routing algorithms/protocols.

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