# Comparative Study of Routing Metrics for Multi-Radio Multi-Channel Wireless Networks

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*Abstract*— **The multi-radio multi-channel network architecture has been recognized as one of the promising approaches to improve the system throughput of IEEE 802.11-based multi-hop wireless networks. In this paper, we study the routing issues under this new network architecture and propose a new routing metric, called AETD (adjusted expected transfer delay). The key idea of AETD is to consider both delay and jitter of candidate routes when making the routing decision. It is designed to select a route on which hops operating on the same frequency channel are separated as far as possible. This way, interference and channel contention may be minimized along the selected route and the system throughput may be improved. Our in-depth simulation shows that the proposed AETD routing metric outperforms several other routing metrics significantly, including HOP (hop count), ETX (cumulative expected transmission count), CETT (cumulative expected transmission time), and WCETT (weighted cumulative expected transmission time).**

## I. INTRODUCTION

Despite the fact that multiple non-interfering frequency channels are available to IEEE 802.11 devices [1], most existing 802.11-based multi-hop wireless networks follow the single-radio single-channel paradigm, where each node is equipped with a single radio interface and all radio interfaces operate on the same frequency channel at any given time. Such system often suffers low channel utilization and poor system throughput for the following reasons. First, a node with a single radio interface can not transmit and receive at the same time, thus the capacity of relay nodes are at least halved. Second, the system relies on sub-optimal contention resolution algorithms to deal with the inevitable interference and channel contention among adjacent links.

Recently, the multi-radio multi-channel network architecture has been recognized as one of the promising approaches to improve the system throughput of 802.11-based multi-hop wireless networks. In comparison to the traditional single-radio single-channel network architecture, each node is now equipped with multiple radio interfaces and each radio interface may operate on one of multiple available non-interfering frequency channels. Moreover, the rate adaptation capability [2, 3] of an 802.11 device allows it to adjust its transmission rate dynamically to the varying link quality between itself and the receiving node.

The multi-radio multi-channel network architecture has presented many new research challenges such as optimal channel assignment, coordination among neighboring nodes, high-throughput routing, etc. In this paper, we focus on the routing problem in multi-radio multi-channel wireless networks.

The popular hop-count routing metric (HOP) does not perform well in multi-radio multi-channel wireless networks. The reason is that HOP does not consider any of the three fundamental factors when designing a routing metric for such networks: transmission rate, link quality, and channel diversity. The authors of [4] proposed a routing metric for single-radio single-channel wireless networks, called the cumulative expected transmission count (ETX), which takes into account the link quality factor. The WCETT (weighted cumulative expected transmission time) routing metric [5] was designed specifically for multi-radio multi-channel wireless networks. It calculates the ETT (expected transmission time) of each hop and makes the routing decision based on the cumulative ETT (CETT) and the channel diversity of each candidate route, which is characterized indirectly by the sum of ETTs of hops operating at the bottleneck frequency channel (BETT). The tradeoff between CETT and BETT is indicated by a weight $\beta$:

$$\mathrm{WCETT} = (1-\beta)\cdot \mathrm{CETT} + \beta \cdot \mathrm{BETT}. \qquad (1)$$

Unfortunately, such WCETT metric may not be adequate to reflect the actual channel-diversity level of a route. As we will show in Section II-C, under certain circumstances, two candidate routes with different channel-diversity patterns may have the same WCETT value.

Based on the above observations, in this paper, we propose a new routing metric, called AETD (adjusted expected transfer delay), for multi-radio multi-channel wireless networks. The work is inspired by the following observation. By selecting a route on which hops operating on the same frequency channel are separated as far as possible, the interference and channel contention may be minimized, hence improving the system throughput. The key idea of AETD is to make the routing decision based on the expected end-to-end transfer delay of a single packet as well as the expected delay jitter between consecutive packet transmissions, which serves as a good indicator of the channel-diversity level. As a result, AETD is able to identify the routes with better channel diversity and make the appropriate routing decision.

The authors of [6, 7] proposed an MCR (Multi-Channel Routing) scheme that includes an interface assignment strategy and a routing protocol to utilize all available channels effectively in multi-channel multi-interface wireless networks. The routing metric used in MCR accounts for channel diversity and

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The work reported in this paper was supported in part by NSF under Grant No. CNS 0520102 and the Information Infrastructure Institute (I-Cube) of Iowa State University.

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interface-switching cost. It differs from our proposed AETD routing metric in the following aspects: (1) ETT is not considered in the MCR routing metric; and (2) MCR is based on the hop-distance-based channel interference model and, hence, may suffer from the zigzag-route issue that we will discuss in Section II-A.

There are several recent work [8, 9] that perform theoretical analysis on joint optimization of channel assignment and routing in multi-radio multi-channel wireless networks, which is different from the issues we address in this work.

The rest of this paper is organized as follows. Section II describes the details of our proposed AETD routing metric. Section III presents and evaluates the simulation results and, finally, the paper concludes with Section IV.

## II. AETD: THE PROPOSED ROUTING METRIC

When a sequence of packets are transmitted from a source node to a destination node, the achieved throughput is determined by the following features of the selected route:

- ETD: the expected end-to-end transfer delay of a single packet;
- EDJ: the lower bound of the expected delay jitter between consecutive packet transmissions.[1]

Apparently, an ideal route shall have a small ETD as well as a small EDJ.

ETD is affected by the following: (1) the hop count of the route; and (2) the bandwidth and link quality of each hop along the route that determine the per-hop transmission rate and transmission time. A shorter route (measured in hops) does not necessarily yield a smaller end-to-end transfer delay. It is likely that a smaller hop count implies a longer average hop distance and, consequently, lower transmission rates and larger overall transfer delay. On the other hand, a route with a larger hop count but shorter average hop distance may instead yield a smaller end-to-end transfer delay.

EDJ is affected by the following: (1) the channel diversity of the route; and (2) the bandwidth and link quality of each hop along the route that determine the per-hop transmission rate and transmission time. A more channel-diverse route experiences less interference as packet transmissions on different channels do not interfere with each other. In the extreme case when the route is perfectly channel-diverse, i.e., when packet transmissions on any two hops along the route do not interfere with each other — either because they are far apart from each other or because they operate on different frequency channels, packet transmissions on each hop may proceed successfully at the same time without encountering any channel contention and the consequent contention resolution procedure. Hence, a very short delay jitter between consecutive packet transmissions is expected under such scenario, which equals the maximum single-hop transmission time along the route.

### A. Calculations of ETD and EDJ

Let $\mathcal{N}_r = \{0, 1, \cdots, k\}$ denote the node sequence along route $r$ of $k$ hops from the source node 0 to the destination node $k$. Let $\mathcal{H}_r = \{h_1, h_2, \cdots, h_k\}$ denote the corresponding hop sequence along route $r$, and let $h_i$ represent the hop between nodes $(i-1)$ and $i$. For each hop $h_i$, let $C_{h_i}$ denote the frequency channel nodes $(i-1)$ and $i$ use to communicate with each other, and let $\text{ETT}_{h_i}$ denote the expected packet transmission time over hop $h_i$.

Then, $\text{ETD}_r$, the expected end-to-end transfer delay of a single packet over route $r$ is simply

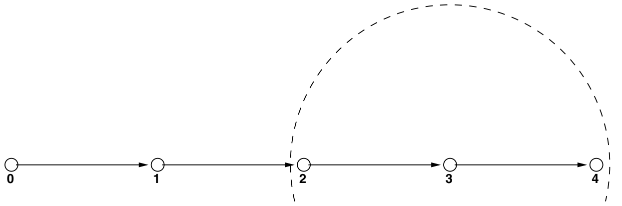
$$\text{ETD}_r = \sum_{h_i \in \mathcal{H}_r} \text{ETT}_{h_i}. \quad (2)$$

The calculation of $\text{EDJ}_r$, the lower bound of the expected delay jitter over route $r$, varies with the interference model. There are two types of interference models: *physical-distance-based interference model* and *hop-distance-based interference model*. The physical-distance-based interference model reflects the actual interference phenomenon in the network, while the hop-distance-based interference model makes the following assumptions to simplify the modeling of the interference:

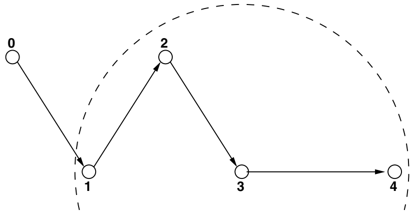
- Packet transmissions may only interfere with each other if they operate on the same frequency channel and are within the interference distance;
- The interference distance is measured in hops and is calculated as:

$$\text{interference distance} = \left\lceil \frac{\text{interference range}}{\text{average hop distance}} \right\rceil. \quad (3)$$

Unfortunately, these assumptions may not hold under certain circumstances. Next, we explain this problem by comparing two routes shown in Fig. 1.



(a) a straight-line route



(b) a zigzag route

Fig. 1. Problem with the hop-distance-based interference model

The interference range of packet transmissions from nodes 3 to 4 is shown as the dashed circles in Fig. 1. Then, according to the hop-distance-based interference model, the interference distance is 2 hops. Clearly, the 2-hop interference distance holds

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[1] EDJ is obtained by assuming perfect contention resolution among contending stations. We choose not to include the contention resolution time in EDJ as this would depend on the implementation details of the underlying MAC layer protocol.

*This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.*

in Fig. 1(a) with a straight-line route while in Fig. 1(b), due to the zigzag nature of the route, packet transmissions from nodes 0 to 1 are interfered by packet transmissions from nodes 3 to 4 although they are 3 hops apart.

In general, it is not trivial to incorporate the physical-distance-based interference model into the routing metric, since it requires complicated message exchanges between neighboring nodes and more traffic flow information maintained at each node. In this paper, our calculation of $\text{EDJ}_r$ is based on the hop-distance-based interference model and, as we will discuss in Section II-B, when we incorporate $\text{EDJ}_r$ into our proposed routing metric, special considerations are made to counter the above-described problem associated with the hop-distance-based interference model. The calculation details of $\text{EDJ}_r$ are as follows.

First, we define $\text{EDJ}_{r(i)}$ as the expected delay jitter from node $i$ to the destination node $k$ ($k > i$) along route $r$, which may be calculated recursively as follows:

$$\text{EDJ}_{r(i)} = \begin{cases} \text{ETT}_{h_k} & \text{if } i = k-1, \\ \text{ETT}_{h_{i+1}} + \text{EDJ}_{r(i+1)} & \\ \qquad \text{if } \exists\, i+1 < j \leqslant \min\{i+m+1,\ k\} & \\ \qquad \text{such that } C_{h_{i+1}} = C_{h_j}, & \\ \max\left\{\text{ETT}_{h_{i+1}},\ \text{EDJ}_{r(i+1)}\right\} & \text{else,} \end{cases} \tag{4}$$

where $m$ is the interference distance (measured in hops) in the hop-distance-based interference model. The "+" operation in Eq. (4) accounts for the fact that, when some packet transmissions from node $(i+1)$ to the destination interfere with the packet transmission over hop $h_{i+1}$, both transmissions may not succeed at the same time. On the other hand, the "max" operation in Eq. (4) corresponds to the perfect pipelining between packet transmissions over hop $h_{i+1}$ and from node $(i+1)$ to the destination when they do not interfere with each other. Then, $\text{EDJ}_r$ is simply a special case of $\text{EDJ}_{r(i)}$ when $i$ = 0:

$$\text{EDJ}_r = \text{EDJ}_{r(0)}. \tag{5}$$

Note that, given two routes with the same ETD, the one with better channel diversity or with a better channel-diversity pattern shall have a smaller EDJ.

### B. AETD: The Proposed Routing Metric

Based on the above analysis, we propose a new routing metric, called AETD (adjusted expected transfer delay), that combines ETD and EDJ:

$$\text{AETD} = (1-\alpha) \times \text{ETD} + \alpha \times \text{EDJ} \tag{6}$$

where $\alpha$ is a tunable parameter between 0 and 1.

The $\alpha$ value in ATED shall be kept small. This is because, with a small $\alpha$ value, only the routes with fairly small end-to-end transfer delay may be selected, meaning that the selected route is less zigzag. Consequently, the problem associated with the hop-distance-based interference model may be alleviated. In Section III-B.2, we will show the effects of $\alpha$ on the throughput performance using simulation results.

### C. An Example

We use a simple example to illustrate different route selections with different routing metrics, including HOP, ETX, WCETT, and AETD. Fig. 2 shows the network topology and each communication link in the network is characterized by its operating frequency channel ($C$), the expected transmission count (etx), and the expected transmission time (ETT) over the link. Assume that the interference distance is two hops, meaning that, if packet transmissions are within two hops from each other, they interfere and can not succeed at the same time.

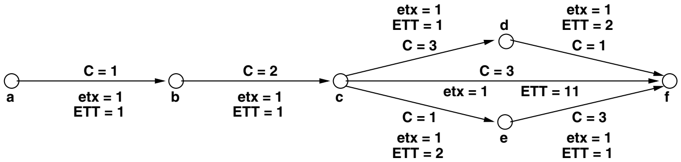

Fig. 2. An example network topology

Table I lists three possible routes from nodes a to f: [a-b-c-f], [a-b-c-d-f], and [a-b-c-e-f], and compares their respective routing metric values under different routing schemes. Both HOP and ETX select the shortest route [a-b-c-f] but with the largest end-to-end transfer delay of 13.

It is interesting to see that WCETT is unable to distinguish between routes [a-b-c-d-f] and [a-b-c-e-f], regardless of the $\beta$ value, although these two routes show different channel-diversity patterns. Note that route [a-b-c-d-f] has the perfect channel-diversity pattern: two hops operating on the same frequency channel of $C$ = 1 are placed at the opposite ends of the route. Hence, packet transmissions along this route don't interfere with each other and the perfect pipelining of packet transmissions may be achieved. On the other hand, along the route [a-b-c-e-f], packet transmissions from nodes a to b and from nodes c to e interfere with each other since they operate on the same frequency channel and are within the interference distance.

In comparison, our proposed AETD routing metric considers explicitly the channel-diversity pattern of a given route and, hence, is able to select the more channel-diverse route if available. As shown in the example, AETD recognizes the better channel diversity-pattern of route [a-b-c-d-f] and makes the right route selection.

## III. PERFORMANCE EVALUATION

In this section, we evaluate the effectiveness of the proposed AETD routing metric using the QualNet simulator [10].

### A. Simulation Setup

The simulated network is a square flat area with wireless nodes uniform-randomly deployed inside the network. All nodes are static. The source and destination nodes sit at the lower-left and upper-right corners of the network.

Each simulated node is equipped with two IEEE 802.11b [11] radio interfaces. The operation of the radio interfaces conform to the following rules:

- A link-quality-based rate adaptation scheme is employed at each radio interface so that it may operate at one of the four

TABLE I
ROUTE SELECTIONS WITH DIFFERENT ROUTING METRICS

| available routes | routing metrics | | | |
|---|---|---|---|---|
| | HOP | ETX | WCETT | AETD |
| [a-b-c-f] | 3 | 3 | $(1-\beta)\cdot 13+\beta\cdot 11$ | $(1-\alpha)\cdot 13+\alpha\cdot 11$ |
| [a-b-c-d-f] | 4 | 4 | $(1-\beta)\cdot 5+\beta\cdot 3$ | $(1-\alpha)\cdot 5+\alpha\cdot 2$ |
| [a-b-c-e-f] | 4 | 4 | $(1-\beta)\cdot 5+\beta\cdot 3$ | $(1-\alpha)\cdot 5+\alpha\cdot 3$ |
| route selection | [a-b-c-f] | [a-b-c-f] | [a-b-c-d-f] or [a-b-c-e-f] | [a-b-c-d-f] |

- available 802.11b transmission rates: 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps; the corresponding maximum transmission ranges for different rates are 249 m, 161 m, 146 m, and 103 m, respectively;
- Each pair of radio interfaces on neighboring nodes may communicate with each other via one of multiple available non-interfering frequency channels, and the channel assignment is random.

We evaluate and compare the throughput performance of the following routing metrics: (1) hop count (HOP); (2) cumulative expected transmission count (ETX); (3) cumulative expected transmission time (CETT); (4) weighted cumulative expected transmission time (WCETT) with $\beta$ = 0.2, 0.4, 0.6, 0.8, and 1.0, respectively; and (5) the proposed AETD routing metric with $\alpha$ = 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, and 1.0, respectively. Note that CETT is equivalent to WCETT with $\beta$ = 0.0 and AETD with $\alpha$ = 0.0.

We conduct the simulation with various node densities, network sizes, numbers of available channels, and node deployment patterns. In each simulation run, the source node sends 1000 UDP packets to the destination node. The source data rate is set high enough to saturate the network and, in order to have a fair comparison of the testing schemes, the queue size of each wireless node inside the network is set to infinite to avoid packet dropping caused by queue overflow. The packet size is 1024 octets.

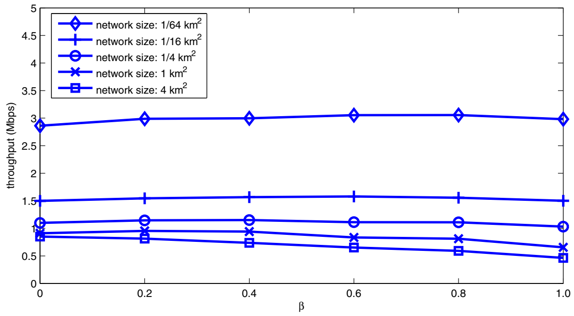

Fig. 3. Comparison of WCETT with various $\beta$

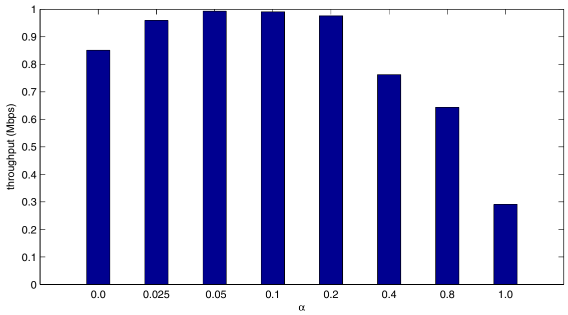

Fig. 4. Comparison of AETD with various $\alpha$

### *B. Simulation Results: Random Deployment w/o Obstacles*

In the first part of the simulation, we compare the testing schemes when there are no obstacles inside the network. Each point in the figures is averaged over 100 simulation runs.

*1) Effects of $\beta$ in WCETT:* We first evaluate the effects of the $\beta$ parameter in WCETT and show the results in Fig. 3. The node density is fixed at 200 nodes/km$^2$ and the number of available channels is three. The network size varies from (125 m × 125 m) to (2 km × 2 km), which correspond to the average path length of 2.6, 4.8, 10.3, 20.5, and 40 hops, respectively.

As shown in the figure, when the network size is small, WCETT shows throughput improvement over CETT. However, when the network size increases and the average path length becomes large, the throughput performance of WCETT (with a non-zero $\beta$ value) is comparable or even worse than that of CETT, which is consistent with the observations in [5]. In the following simulation runs, we fix the $\beta$ value to 0.2.

*2) Effects of $\alpha$ in AETD:* We also study the effects of the $\alpha$ parameter in the proposed AETD routing metric. The node density is fixed at 200 nodes/km$^2$ and the network size is fixed to be (2 km × 2 km). The number of available channels is three. Simulation results are plotted in Fig. 4.

In general, AETD metrics with smaller $\alpha$ values yield higher throughput than CETT, and the highest throughput is achieved when $\alpha$ = 0.05. On the other hand, the AETD throughput starts decreasing when $\alpha \geqslant 0.1$ and reaches the lowest point when $\alpha$ = 1.0. This is because, with a larger $\alpha$ value, AETD is more concerned about the channel diversity along the route and, as a result, a zigzag route may be selected. This observation supports our earlier statement that choosing a small $\alpha$ value is critical to counter the inherent problem associated with the hop-distance-based interference model by avoiding zigzag routes.

We have also noticed similar trends with various node densities, network sizes, and numbers of available channels. The only difference is that, with different network configuration, the highest AETD throughput may be achieved with different small $\alpha$ values. Overall, $\alpha$ = 0.05 seems to be a good choice and hence will be used in all following AETD simulation runs.

*3) Effects of Node Density:* In this set of simulation runs, we vary the node density in the network from 50 nodes/km$^2$ to 200 nodes/km$^2$. The network size is (2 km × 2 km) and the number of available channels is three. Simulation results are plotted in Fig. 5.

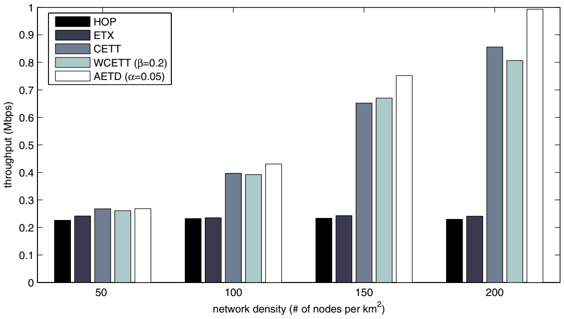

Fig. 5. Throughput comparison with various node densities

It is interesting to see that the throughput of HOP does not change with the node density. This is simply because the HOP metric always selects the route with minimum number of hops even when the nodes are densely-deployed in the network. We have a similiar observation on ETX but with different rationale behind. Since each node has the rate-adaptation capability, it can always lower its transmission rate, whenever necessary, to communicate with a far-away neighboring node in a sparse network, while maintaining a similar transmission count. For this reason, the node density in the network has minimum impact on the route selection by ETX.

As expected, AETD has the best throughput performance with each simulated node density and the performance improvement of AETD over CETT and WCETT becomes more significant as the node density increases. This is because, with more nodes deployed in the network, there are more routes available between the source and the destination nodes. Hence, it is more likely for AETD to find a route (1) with similar end-to-end transfer delay as that of the route selected by CETT or WCETT, and (2) with much better channel diversity. As shown in the figure, AETD outperforms CETT by 15.4% and 16.7%, and outperforms WCETT by 12.3% and 22.1%, when the node density increases to 150 and 200 nodes/km$^2$, respectively.

*4) Effects of Network Size:* Fig. 6 shows the simulation results with various network sizes: (125 m × 125 m), (250 m × 250 m), (500 m × 500 m), (1 km × 1 km), and (2 km × 2 km). The node density is fixed at 200 nodes/km$^2$ and the number of available channels is three.

In general, as the network size increases, the throughput decreases for all testing schemes. This is because the increasing distance between the source and destination nodes requires more packet relays in the network and creates potentially more interferences and channel contentions along the route. Note, however, that the throughput performance of AETD is least affected by the increasing network size, because the AETD metric favors the routes with good channel diversity, which may ameliorate the channel contention problem caused by the increased route length.

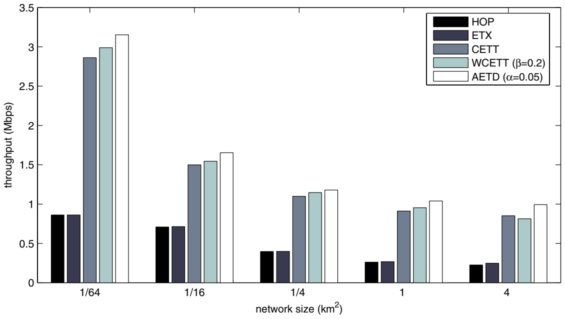

Fig. 6. Throughput comparison with various network sizes

*5) Effects of Number of Available Channels:* Fig. 7 shows the simulation results with various numbers of available channels. The network size is (2 km × 2 km) with the node density of 200 nodes/km$^2$.

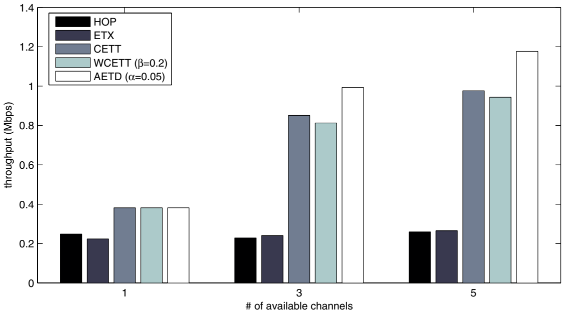

Fig. 7. Throughput comparison with various numbers of available channels

We have two observations. First, since neither HOP nor ETX considers channel diversity when making the routing decisions, both of them show marginal, if any, performance improvement when more communication channels are available for assignment in the network.

Second, when all the radio interfaces operate on the same frequency channel, i.e., when the number of available channels is one, AETD, CETT, and WCETT are equivalent. As the number of available channels increases, AETD, CETT, and WCETT all show significant performance improvement but due to different reasons. Recall that the communication channels between neighboring nodes are randomly assigned in our simulation. Therefore, with more channels assigned randomly in the network, the route selected by CETT may have better channel diversity. In other words, CETT benefits implicitly from the increasing number of available channels. WCETT takes into consideration the channel diversity in its routing metric, however, indirectly through its BETT component. In comparison, channel diversity is considered explicitly in the AETD metric, which allows AETD to take full advantage of the increasing number of available channels and achieve more performance improvement. As shown in the figure, the throughput improvement for AETD is 18.5% in comparison to 14.7% for CETT and 16.0% for WCETT when the number of available channels increases from three to five.

### C. Simulation Results: Random Deployment with Obstacles

In the second part of the simulation, we compare the testing schemes when there are some obstacles inside the network. Fig. 8 shows an example topology of such network: the blank areas correspond to obstacles where nodes are uniform-randomly deployed around them. We simulate 30 different scenarios and the results are plotted in Fig. 9.

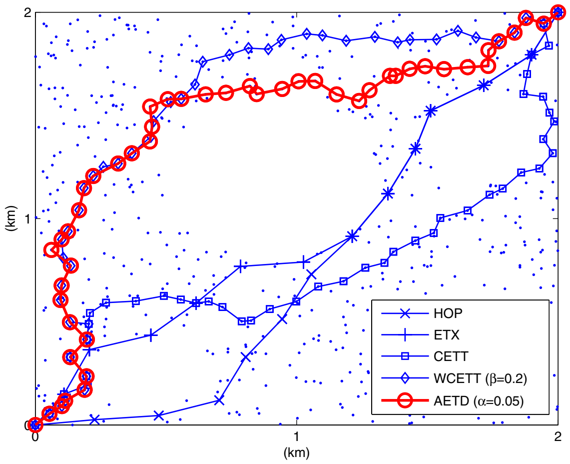

Fig. 8. An example network topology with obstacles

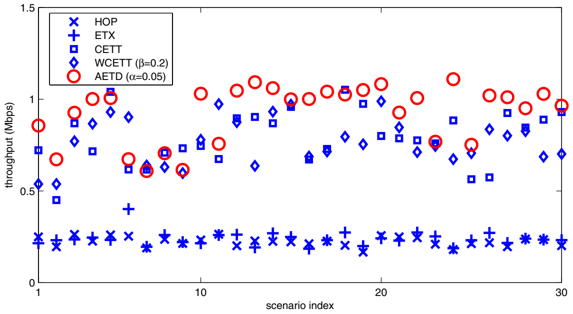

Fig. 9. Throughput comparison in networks with obstacles (30 scenarios)

As shown in Fig. 8, all routes are forced to detour around the obstacles. The routes selected by AETD, CETT, and WCETT are longer (measured in hops) than those selected by HOP and ETX, but with much better jitter and/or delay performances. Therefore, as shown in Fig. 9, AETD, CETT, and WCETT all achieve significantly higher throughput than HOP and ETX in each simulated network topology.

Another observation is that, because of better channel diversity in the AETD routes, AETD yields a higher throughput than CETT and WCETT in most of the simulated scenarios (shown in Fig. 9).

### D. Summary

Based on the observations from the simulation results, we summarize the effectiveness of AETD as follows:

- AETD considers explicitly the channel diversity when making the routing decision. For this reason, it achieves significantly higher throughput than HOP and ETX while outperforming CETT and WCETT in most simulated scenarios;
- It is critical to choose a small $\alpha$ value in AETD;
- AETD is most suitable for routing in wireless networks with high node densities and/or large numbers of available channels;
- With a well-planned channel assignment, AETD may achieve even higher throughput enhancement over other routing metrics.

## IV. CONCLUSION AND FUTURE WORK

In this paper, we investigate the routing issues in multi-radio multi-channel wireless networks. A new AETD (adjusted expected transfer delay) routing metric is proposed to take into account the expected end-to-end transfer delay of a single packet as well as the expected delay jitter between consecutive packet transmissions. Both analysis and simulation results suggest that the expected delay jitter is a good indicator of the actual channel-diversity level of a given route.

We compare the throughput performance of AETD via simulation against four well-known routing metrics: HOP (hop count), ETX (cumulative expected transmission count), CETT (cumulative expected transmission time), and WCETT (weighted cumulative expected transmission time). Simulation runs are conducted under various node densities, network sizes, numbers of available channels, and node deployment patterns, and results show that AETD consistently outperforms other routing metrics.

Future work include extension of the AETD routing metric to incorporate the physical-distance-based interference model and the inter-flow interference in the multi-flow scenarios, and design of a simple and effective channel assignment scheme to work with AETD.

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