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Interferer Link-Aware Routing in Wireless Mesh Networks

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***Abstract*— This paper presents a new metric for routing in wireless mesh networks (WMNs). The proposed metric does not only consider the quality of wireless links to choose a high throughput path between a pair of nodes, but it also includes the resulting interference introduced by using such links. The philosophy behind this metric is to choose a good path for an arriving connection, not necessarily the best in terms of throughput, but that alleviates the resulting interference in order to preserve good paths for the subsequent arriving connections. In doing so, we find that our metric significantly outperforms previously proposed routing metrics when multiple concurrent flows are considered in the network. The total network throughput is indeed increased.**

***Index Terms*— Wireless mesh networks, routing, interference aware path selection, performance evaluation.**

I. INTRODUCTION

An ambitious vision for future Internet networks would include “community wireless networks” [1] [2]. Wireless mesh networks (WMNs) provide indeed the necessary ingredient needed for building bandwidth efficient and flexible networks to support the increasing demand for mobile wireless access to the Internet. Typically, a WMN comprises static wireless mesh routers, also called access points (APs). Each AP serves multiple mobile users and connects them through multi-hop wireless routing to the wired network. The mesh nodes connected directly to the wired network (i.e., connecting the WMN to the wired network) are called gateways. They represent the traffic sinks and sources to the WMN.

One of the major concerns in such multi-hop networks is how to route packets efficiently through “good paths” in order to satisfy the QoS flows’ requirements. By “good paths”, we mean paths that are able to effectively transport data with reasonable delay, throughput and reliability. This problem is more challenging considering the context of WMNs, where the radio environment is unstable and hampered by interferences. The link conditions may change over time so that an active route is no more the best route.

Routing has been extensively studied in mobile ad-hoc networks (MANETs) [3], where protocol designs have focused mainly on copying with rapidly topology changes due to mobility. The main objective has been therefore to adapt quickly to topological changes, which occur occasionally in WMNs. Designed for ad-hoc networks, these protocols are not suitable for typical WMN applications for two main reasons: the static topologies of WMNs and the different communication patterns.

As opposed to ad-hoc networks, WMNs have a stable topology, which changes occasionally due to AP failures or when new APs are added to the system. As a second main distinguishing feature from ad-hoc networks, the communications in WMNs are performed chiefly between the gateways and their associated APs, and not directly between arbitrary pairs of mesh nodes. In this context, it has been shown in [4] – [6] that shortest path routing does not perform well in WMNs. In other words, a route that minimizes the hop count does not necessarily maximize the throughput of a flow since the shortest path routing picks routes that probably include poor (lossy or slow) links. A routing algorithm can then select better paths by explicitly taking into account the quality of wireless links.

In view of this, many metrics have been proposed in the literature to measure wireless links quality [4] – [8]. Each of these metrics represents a different notion of what constitutes a good link quality. Accordingly, the routing protocol attributes the current best route for an arriving connection. However, this procedure of path selection fails to take into account the impact of such choice on the subsequent connection arrivals. Indeed, an arriving flow may be attributed to the path allowing the best throughput based on the current network state. But, doing so does not necessarily maximize the total throughput in the long term as users join and leave the network. Hence, selecting the best current route for a connection in terms of bandwidth and loss rate may deteriorate severely the quality of the remaining available resources in the network due to the resulting interference. Consequently, new arriving connections will experience poor services. The seriousness of this issue is expected to increase with the increase of the number of concurrent flows served by the network.

To overcome these limitations, we propose in this paper a new routing metric, called Interferer Neighbors Count (*INX*), that captures the impact of routing decisions in terms of interference on the service of subsequent arriving connections. The philosophy behind our metric is to choose a good path, not necessarily the best in terms of throughput, but that alleviates the resulting interference in order to preserve good paths for the subsequent arriving connections. The *INX* metric tries therefore to provide more opportunity for subsequent arriving connections to be satisfied.

A simulation model has been developed to illustrate and evaluate the potential performance gains of *INX*, using *ETT* [5] and shortest path routing as baseline examples. A variety of system scenarios are considered, including different traffic patterns and varying number of simultaneous connections.

The remainder of this paper is organized as follows. Section II presents an overview of the related works, followed by a description of the system model to be studied in section III. The *INX* routing metric is then introduced in section IV. Simulation results are provided in section V, where we evaluate

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the performance of our proposal, using two well known routing protocols as baseline examples. Finally, section VI contains our concluding remarks.

II. RELATED WORK

Management of wireless multi-hop networks has been an active research area in the last few years and numerous routing algorithms have been proposed. Comprehensive surveys on WMNs and routing in multi-hop wireless networks can be found in [7]. Several routing schemes have been proposed for WMNs. Here, we mention only those studies that are directly relevant to our work.

Hop-count, which is the most commonly used routing metric in existing routing protocols such as Ad Hoc On-Demand Distance Vector (AODV)and Destination Sequenced Distance Vector (DSDV) treats all links in the network to be alike and selects paths with the minimum number of hops. It has been demonstrated that the shortest path routing does not perform well in WMNs and does not necessarily maximize the throughput of a connection since it does not account for the quality of radio links, which can often result in paths with high loss ratio and poor performance [4] – [6].

To overcome these limitations, authors in [4] introduced the “expected transmission count” (*ETX*) metric that selects paths with minimum link loss rate between source-destination pairs. The *ETX* of a link indicates the number of transmission attempts needed to achieve a successful transmission over that link. The lower the *ETX* metric for a link, the better is the link. The path metric is the summation of *ETX* of each link in the path. However, as it will be shown in section IV, this metric does not cope well with the inter-path (or inter-connection) interference experienced by the wireless links, so that the network utilization can not be fully optimized. In addition, *ETX* reflects only the loss ratio of a link and does not account for the link bandwidth or data rate. It has been shown in [5] [8] that *ETX* does very well in homogeneous single-radio environments but it does not perform as well in environments with different data rates.

To reflect both the bandwidth and the loss rate of a link, the expected amount of time it would take to transmit successfully a packet is considered instead of *ETX*. This new metric is called the expected transmission time (*ETT*), which can be written as $ETX \times S/r$, where S is the packet size and r is the bit rate of the link. The extension of the *ETT* metric to the multi-radio environment is called “weighted cumulative expected transmission time” (*WCETT*) [5]. This metric explicitly accounts for the interference among the different hops of a connection using the same channel (i.e., inter-hop interference). Using this metric alleviates the throughput decrease due to inter-hop interference. However, this metric still does not consider the inter-connection interference between simultaneous connections.

In [9], routing and interface assignment algorithms for WMNs are proposed. The protocols allow efficient interface assignment and route computation using the load information. However to achieve this, the authors assume that the traffic load between all nodes is known, a priori.

So far, the above-mentioned routing schemes have focused mainly on providing link quality-aware routing metrics to select the best route for an arriving connection based on the current network state. This procedure of path selection fails to take into account the impact of such choice on the subsequent connection arrivals. As such, these routing policies does not necessarily maximize the network throughput as it will be shown later. One may select the best current route for a connection in terms of bandwidth and loss rate. But using this route may result in blocking or deteriorating the quality of the remaining available resources in the network. Consequently, a new arriving connection may be blocked since the require QoS can not be satisfied due to resources’ unavailability. In this regard, it may be unlikable to select automatically the best current route for a given connection request, in order to provide more opportunity to subsequent arriving connections to be satisfied. To achieve this, we propose a new routing metric that considers the inter-connection interference.

III. SYSTEM MODEL

We represent a WMN by a directed graph $G(V, E)$, called a connectivity graph. Each node $v \in V$ represents an Access Point (AP), which is characterized by a circular transmission range $R_t(v)$ and a carrier sensing range $R_h(v)$. During the transmission of a node v, all the nodes inside its carrier sensing range, denoted by $H(v)$, sense the channel to be busy and can not access the medium. Hereafter, we denote by $H^+(v) = H(v) \cup \{v\}$ and by $H^-(v)$ the set of nodes that node v can not hear, i.e., $H^-(v) = V \backslash H^+(v)$. A bidirectional wireless link exists between v and every neighbor $u \in N_e(v)$ and is represented by the directed edges (u, v) and $(v, u) \in E$. Note that $N_e(v)$ is the neighborhood of the node v, which corresponds to the nodes residing in its transmission range.

We represent the graph connectivity by a connectivity matrix. The connectivity matrix of $G(V, E)$ is a matrix with rows and columns labeled by the graph vertices V, with 1 or 0 in position (v, u) according to whether v and u are directly connected or not. Each node v is equipped with a 802.11 wireless card and transmits with a rate $r_{v,u}$ to its neighbor $u \in N_e(v)$. The available transmission bit rate $r_{v,u}$ is determined by the link condition. Typically, $r_{v,u}$ depends on the distance between nodes v and u and the resulting loss rate on that link.

In our system model, all the radios share the same channel. The RTS/CTS mechanism is disabled. It was shown in [10] that RTS/CTS increases the overhead without really improving the network performance. In view of this, the basic access mode (i.e., Data/ACK) is considered.

It is worth noting that once a node v accesses successfully to the shared medium, it blocks the transmission of all nodes inside its carrier sensing range (i.e., $H(v)$) during the transmission time of the data packet, denoted by T_{data}. The node v transmission may also prevent the nodes in $H(v)$ to receive correctly packets from their neighbors (i.e., according to the signal capture property). On the other hand, a successful transmission from v to u requires all the hidden nodes from v (i.e., $H^-(v) \cap H(u)$) to be silent during $T_{data} + SIFS$ (called also vulnerable period [11]), otherwise the receiving node u will not return an ACK frame to v. If this happens, node v considers the packet as unsuccessfully transmitted and schedules for a retransmission later. Consequently, a successful packet delivery from v to u needs or results in the silence of each wireless link (m, n) (i.e., $d(m, n) \leq R_t(m)$) verifying the following condition:

$$\begin{cases} d(v,m) \leq R_h(v) \text{ or } d(v,n) \leq R_h(v) \text{ or } d(m,u) \leq R_h(m) : \\ \text{during the transmission of the data packet from } v \text{ to } u, \\ d(u,m) \leq R_h(u) \text{ or } d(u,n) \leq R_h(u) \text{ or } d(m,v) \leq R_h(m) : \\ \text{during the transmission of the ACK frame from } u \text{ to } v, \end{cases} \qquad (1)$$

where $d(m,n)$ denotes the distance between nodes m and n. If the link (m,n) verifies the condition (1), it is referred to as interferer link to the link (v,u). We call $S(v,u)$ the set of interferer links of the link (v,u). We note that in (1), we have not considered the signal capture property.

Based on the interferer link definition, we associate to the connectivity graph G a conflict matrix C. The conflict matrix C of $G(V,E)$ is a matrix with rows and columns labeled by the vertices V, such that in position (v,u):

$$C_{vu} = \begin{cases} |S(v,u)| & \text{if nodes } v \text{ and } u \text{ are directly connected,} \\ 0 & \text{otherwise,} \end{cases}$$

where $|S(v,u)|$ represents the number of interferer links resulting from the use of the link (v,u). Note that $C_{vu} = 0$ means that v and u are not directly connected; otherwise the graph G is not connected.

The number of interferer links of a path is defined as the sum of the number of interferer links of each link in the path. We denote by I the interference matrix, which represents the number of interferer links of the paths connecting the mesh nodes. I_{vu} denotes the number of interferer links of the path used between pair of nodes (v,u). Evidently, the matrix I depends of the used routing policy (i.e., the adopted routing metric).

IV. THE INTERFERENCE-AWARE ROUTING METRIC: *INX*

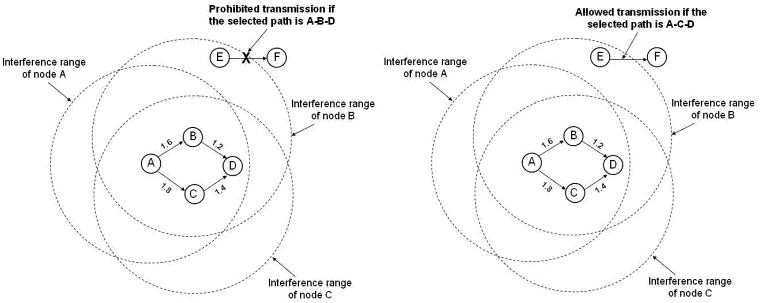
This section introduces our new routing metric, called Interferer Neighbors Count (*INX*), that takes into consideration the number of interferer links. To gauge the efficiency of our proposal, it will be first compared to the well-known *ETX* metric. Then using simulations, we compare it to the hop-count metric and *WCETT*, which can be viewed as an enhancement of *ETX*. Note that in our work, we deal with single-radio environments. Hence, *WCETT* and *ETT* turns out to be equivalent.

A. *Motivating the* INX *routing through an example*

As stated before, although the performance improvement of *ETX*, *ETT* and *WCETT* metrics over the minimum hop-count metric, they do not cope well with the inter-path interference when there are multiple flows in the network. Indeed, a successful transmission over a link $l = (v,u)$ either needs the silence or prevent the transmission over the interferer links of l. Specifically, a first subset of source nodes in the WMN (i.e., $H(v)$) will be automatically *blocked* since the common channel is sensed as busy during the transmission of v. A second subset of receiving nodes will not be able to receive correctly from their neighbors (i.e., due to collisions) since they receive at the same time the in-progress transmission of v. Finally, a third subset of nodes (i.e., hidden nodes from v) have to remain silent to avoid collisions at u with the transmitted packet by v.

To allow the maximum simultaneous transmission within the WMN, and then improve the total network throughput, the blocked interferer links need to be minimized. However, the above routing metrics pay little attention to employ such information to build paths. To illustrate this, let us consider the six-node WMN of Fig. 1 where each wireless link is associated with its *ETX* metric.

Assume that two connections requests C_1 and C_2 arrive successively. The first arriving connection C_1 that needs to be served is from A to D. According to the *ETX*-based routing, this connection is carried through the path $\mathcal{P}_1 = [A,B,D]$ instead of $\mathcal{P}_2 = [A,C,D]$ since $\mathcal{P}_1$ achieves better *ETX* value (i.e., $2.8 < 3.2$). Meanwhile, the second connection request C_2 from E to F arrives. This connection will be blocked until the service of the current packet, since E is already busy due to the transmission of the intermediate node B on $\mathcal{P}_1$. In other words, (E,F) is an interferer link with regard to the link $(B,D) \in \mathcal{P}_1$. We can see that connections C_1 and C_2 interfere and the service of one of them results in the blockage of the second one. Hence, the total throughput is divided by a factor of two.



(a) (b)

Fig. 1. Understanding inter-path interference: (a) ETX-based selected path: A-B-D, (b) Alternative path: A-C-D

Alternatively, if C_1 was served through the path $\mathcal{P}_2$, the connection C_2 would be satisfied through the link (E,F) without any interference with C_1. Hence, both connections can be served simultaneously, in the sense that nodes D and F can receive packets at the same time from their respective sender nodes A and E.

This example shows the limitation of the *ETX* metric to learn enough about its environment in order to maximize the number of accepted connections. *ETX*, *ETT* or *WCETT* metrics may select the best path with the highest throughput for a given connection. But this choice does not necessarily ensure the highest total network throughput. Typically, the *ETT*-based routing enables to find the best current route for an arriving connection, however, it does not consider the impact of that choice on the resulting network state.

B. *The INX routing metric*

In this subsection, we propose to extend the *ETT* metric to take into account the interference experienced by the wireless links. The new metric is called Interferer Neighbors Count (*INX*). The *INX* of a link (v,u) is defined as the product of the *ETT* of the link (v,u) and the number of all the interferer links resulting from a transmission on that link (v,u) (i.e., the parameter C_{vu} of the conflict matrix C) weighted by their respective bit rates as follows:

$$INX(v,u) = ETT(v,u) \sum_{\text{link } (m,n) \in S(v,u)} r_{m,n} \tag{2}$$

Clearly, *INX* captures the quality of the wireless links by including the *ETT* metric. We also want to consider the impact of using this link on subsequent connection arrivals. Simply counting the number of interferer links will not ensure correctly this property, since we are distinguishing between good (high throughput) and bad (low throughput) interferer links. To reflect this, our metric includes the bit rate of each interferer link.

For illustration, let revisit the example of Fig. 1. Assume that all the wireless links have the same bit rate 1 Mbit/s. $C_{AB} = |S(A,B)| = |\{BA, AC, CA, CD, DC, BD, DB, EF\}| = 8$, hence $INX(A,B) = 1.6 \times 8 = 12.8$. On the other hand $INX(A,C) = 1.8 \times 7 = 12.6$.

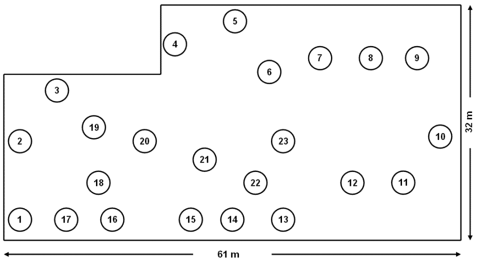


Fig. 2. 23-node wireless mesh network

The path metric $INX(\mathcal{P})$ for a given path $\mathcal{P}$ is the normalized summation of the INX of each link in the path and can be written as follows:

$$INX(\mathcal{P}) = \frac{1}{N_l} \times \sum_{link\ l \in \mathcal{P}} INX(l) \qquad (3)$$

where N_l is the total number of directional links in the WMN.

Note that our proposed metric can be easily implemented and combined with any existing routing metric (e.g., *ETX*, *WCETT*). Moreover, if two or more paths experience the same value of *INX*, the one with the minimum number of hops will be selected. Revisiting again the example of Fig. 1, we have $INX(\mathcal{P}_1) = \frac{1}{10} \times (1.6 \times 8 + 1.2 \times 9) = 2.36 > INX(\mathcal{P}_2) = \frac{1}{10} \times (1.8 \times 7 + 1.4 \times 7) = 2.24$. As such, the path $\mathcal{P}_2$ will be used to carry the connection C_1 instead of $\mathcal{P}_1$ as dictated by the basic *ETX*-based routing. In doing so, the arriving connection C_2 will start its service without waiting for the end of the service of C_1.

V. PERFORMANCE EVALUATION

In this section, we describe the results of our experiments. To achieve this, a simulation model has been developed using ns-2 [12]. The section is organized as follows. First, we present results for the network given that at any time only one connection (flow) is active. Studying this basic case enables us to explore the impact of inter-hop interference on the network throughput. Then, we investigate the case of multiple simultaneous connections, which is more likely the case in real networks. We present results that compare our proposed routing metric *INX* to *ETT* and shortest path routing under various communication patterns. We show the potential performance improvement gained by using *INX*, which deals better with inter-connection interference increasing thus the total network throughput compared to the underlying schemes. The results reported in this section are obtained using the 23-node WMN of Fig. 2 [5] [8] with AODV as routing protocol. Note that the carrier sensing range R_h of each node is taken equal to twice the transmission range R_t.

A. Basic Performance

Before we discuss the performance of our metric with multiple simultaneous connections, it is essential to establish a baseline with only one active connection at any time.

In our simulations and as in [13], we carried out a 3-minute TCP connection between each pair of nodes. During each TCP connection, the sender node transmits as much packets as it could. In our simulations, each source node transmits 512-byte data packets at a rate of 11Mbps. It has been demonstrated in [8] that 1-minute TCP connections were of sufficient length to overcome start up effects. Hence, between consecutive TCP connections, we set a 1-minute idle period in which the adopted routing metric is calculated and serves to establish the route for the next arriving connection.

TABLE I
RESULTS FOR THE P2P TRAFFIC WHEN ONLY ONE CONNECTION IS ACTIVE

Hops	Number of pairs			Throughput (Kbps)			Packet Loss Rate (%)		
	INX	ETT	HOP	INX	ETT	HOP	INX	ETT	HOP
1	111	111	114	2125	2125	2060	0.348	0.338	0.393
2	119	119	124	1037	1041	845	0.534	0.548	0.944
3	125	120	130	663	672	477	1.037	0.934	1.819
4	69	72	72	477	491	283	1.624	1.477	4.854
5	51	48	50	372	395	218	3.196	2.077	11.839
6	31	36	16	365	376	238	2.345	2.29	9.373
Total network throughput				5039	5100	4121			

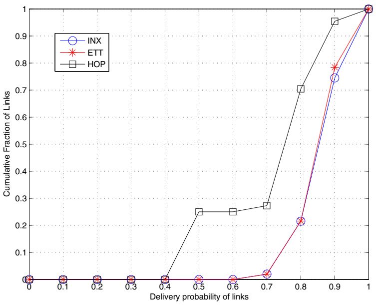


Fig. 3. CDF of delivery probabilities of used links when only one connection is active at any time

We consider two types of communication patterns. In the first pattern, called P2P traffic, TCP connections are performed between each pair of mesh nodes, so a total of $X \times (X-1)$ connections were carried out. In the second pattern, only communications with the gateway (i.e., node 1 in Fig. 2) are allowed. Due to space limitation, we only present hereafter the results regarding the P2P traffic.

Table I shows the average network throughput and average packet loss rate when one active communication exists at any time. The values are arranged according to the hop-count. First, we notice that *ETT* provides slightly better results than our proposed *INX* metric. The rationale behind this can be explained as follows. Both *INX* and *ETT* take into account the bandwidth and the packet loss rate of the wireless links. As a distinguishing feature from *ETT*, *INX* takes also into account the impact of a selected path on the subsequent arriving flows. In other words, *INX* may select a poorer path than *ETT* to preserve good paths for subsequent connections. This is clearly shown in Fig. 3, which compares the Cumulative Distributed Function (CDF) of delivery probabilities for the links used by *INX*, *ETT* and hop count. The median delivery probability is 0.85 for both *INX* and *ETT*, meaning that these metrics often use links with loss rate of 15% or more. Whereas, in the hop count metric, the median delivery probability is 0.75, which means that this metric often uses links with loss rates of 25% or more. *INX* may favor the use of lower quality links to reduce the resulting interference with eventual new arriving connections. However, since there is only one active connection in the network at any time, one would expect no improvement of *INX* over *ETT*. Instead, we would expect that *ETT* outperforms *INX*, since *ETT* selects always the best available path as opposed to *INX*. This is indeed confirmed by results in Table I where *ETT* provides slight improvement (around 1.2%) in average throughput than *INX*.

B. Simultaneous Connections

In the previous section, only a single TCP connection was active at any time. This is unlikely to be the case in real

TABLE II

AVERAGE TCP THROUGHPUT AND PACKET LOSS RATE BETWEEN THE GATEWAY AND EACH NODE IN THE NETWORK WHEN M SIMULTANEOUS ACTIVE CONNECTIONS ARE PRESENT AT ANY TIME

Hops	Number of pairs			Throughput (Kbps)			Packet Loss Rate (%)		
	INX	ETT	HOP	INX	ETT	HOP	INX	ETT	HOP
$M = 2$									
1	5	8	8	1741	1320.37	1113.75	0.34	1.98	1.99
2	8	7	7	804.62	715.28	293.43	2.99	1.53	4.86
3	3	5	6	455.67	244	118.2	6.69	7.02	7.72
4	5	2	1	154	131	93.25	1.5	2.66	24.74
5	1	-	-	230	-	-	4.3	-	-
Total network throughput				3385.29	2410.65	1618.63			
$M = 4$									
1	5	5	8	799	739.5	505.25	0.88	1.36	17.6
2	4	6	7	350	324	268.67	8.15	7.46	34.46
3	5	5	6	221.4	112	94.8	7.67	13	54.4
4	2	3	1	166	56.5	3	25.34	42.81	88.98
5	2	3	-	111.5	54.34	-	28.64	31.83	-
6	2	-	-	122	-	-	26.36	-	-
7	1	-	-	115	-	-	36.11	-	-
8	1	-	-	114	-	-	33.8	-	-
Total network throughput				1998.9	1286.34	871.72			
$M = 8$									
1	4	5	8	254.5	248	207	28.31	31.46	37.52
2	4	5	7	60.5	52	42	21.39	23.41	55.71
3	5	5	6	89.67	113	6.34	26.58	13.68	78.88
4	3	2	1	58	37	0	41.74	45.8	99.83
5	2	3	-	59.5	124	-	47.83	26.95	-
6	2	2	-	56.5	79.5	-	47.75	31.53	-
7	1	-	-	56	-	-	45.6	-	-
8	1	-	-	56	-	-	45.1	-	-
Total network throughput				690.67	653.5	255.34			

networks. In this section, we consider multiple simultaneous connections. We compare the network throughput provided by the different routing metric: *INX*, *ETT* and shortest path routing. In this section, we consider the communication patterns, where only TCP connections between the mesh nodes and the gateway are allowed. This traffic pattern is more likely the case of real networks, where WMNs provide essentially Internet access to the users rather than communications between mesh nodes. In view of this, most of the users talk only to the Internet gateway using the path with the best metric.

In this scenario, we assume that the TCP connections arrive consecutively every minute until the arrival of the M^{th} flow. The M simultaneous connections finish service one minute after the arrival of the M^{th} flow. A 1-minute quiet period precedes the arrival of the next M flows, which arrives again consecutively each minute, and so on and so forth. Note that in this case, an arriving connection may arrive while the network is free. Specifically, an arriving connection finds with equal probability the network already serving m connections, with $m = 0, ..., M$. The results reported hereafter are the measures obtained from the network when M simultaneous connections are in service ($M = 2, 4, 6$ and 8).

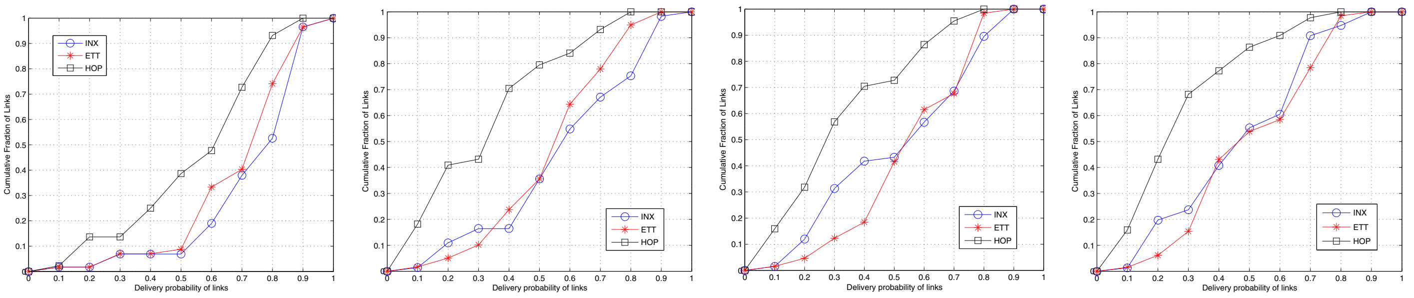
Table II shows the average network throughput and average packet loss rate regarding the aforementioned scenario. According to these results, we can draw three main observations.

First, shortest path routing provides the poorest results. As demonstrated in prior research [4] [5], the shortest path routing does not perform well in WMNs since this metric simply selects the shortest available path regardless the quality of links in that path. The performance of shortest path routing gets significantly worse as the number of simultaneous connections increases. This is because the simultaneous connections often share common links or use links with high interference due to shortest path routing. As such, the concurrent transmissions of the different connections collide and cause packet loss (see Fig. 5). In addition to the inter-hop interference, the inter-connection interference degrades considerably the network throughput, as shown in Table II.

Second, with *ETT*, the network throughput increases significantly compared to the shortest path routing. This is consistent with the results in [5].

Third, our *INX* metric improves considerably the network throughput compared to *ETT*. Indeed, the progressive increase of the number of simultaneous connections allows *INX* to attribute routes for arriving connections progressively while preserving good paths for the subsequent flows. In other words, the *INX* routing policy manages better the attribution of routes one by one than with *ETT*, where it affects the best current route for the arriving connection without caring about the subsequent flows. Compared to *ETT*, *INX* metric profits better from the parallelism in the network. It may attribute a slightly lower quality path than that selected by *ETT* for an arriving connection in order to keep useful resources for the subsequent connections. This is clearly shown in Fig. 4, which compares the CDF of delivery probabilities for the links used by the underlying routing metrics and when M simultaneous connections are active at any time in the WMN ($M = 2, 4, 6$ and 8). For example, when $M = 2$, the median delivery probability is 0.8 for *INX*, 0.72 for *ETT*, and 0.6 for hop count. This means that *INX*, *ETT* and hop count often use links with loss rates of 20% or more, 28% or more, and 40% or more, respectively. We can see that the second arriving connection find better routes than that when using *ETT*, as opposed to the Fig. 3. It is worth noting that when M is high, *INX* uses more high loss rate links than *ETT*. This increases the packet loss rate compared to *ETT*, as shown in Fig. 5.

Fig. 6 shows the effect of the number M of simultaneous active connections on the total network throughput for the different routing metrics. We can see that the network throughput decreases with the increase of M due to the contention between active connections. In addition, we notice that the performance



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

Fig. 4. CDF of delivery probabilities of used links when M simultaneous active connections are present at any time: (a) $M = 2$, (b) $M = 4$, (c) $M = 6$, (d) $M = 8$

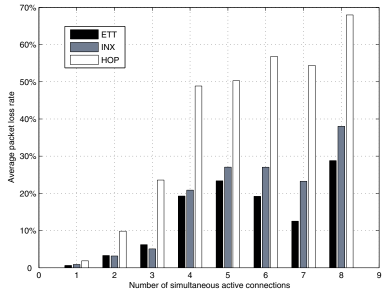


Fig. 5. Average packet loss rate per connection

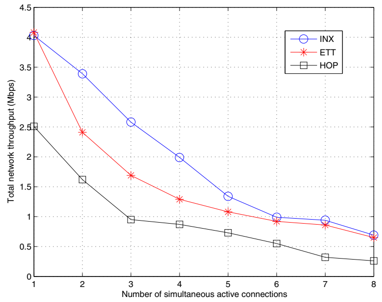


Fig. 6. Impact of the number of simultaneous active connections on the total network throughput

of *INX* becomes closer to *ETT* for high values of M (in our case, when M exceeds 6). This is simply because the network becomes congested and suffers therefore from severe collisions.

Finally, Fig. 7 plots the throughput between the pair of nodes 1 and 18 when several connections enter the network. In this case, the improvement achieved by *INX* in average throughput can attain 22% and 56% compared to *ETT* when $M = 2$ and $M = 4$, respectively.

VI. CONCLUSION

This work has focused on studying the benefits to the WMN throughput that can be gained by anticipating the impact of routing decisions, in terms of interference, on the service of subsequent arriving connections. We have shown that attributing always the best available route for an arriving connection in terms of bandwidth and loss rate may deteriorate the quality of the remaining available resources in the network due to the resulting interference. Consequently, new arriving connections will experience poor services and thus the total network throughput is affected.

To improve the network throughput, we have proposed in this paper our *INX* metric that captures, in addition to the quality of wireless links, the resulting interference introduced by using such links. It has been shown that this metric outperforms existing routing metrics when multiple concurrent flows are considered in the network; however, it does not perform well when a single connection is considered to be active at any time, which is unlikely to be the case in real networks.

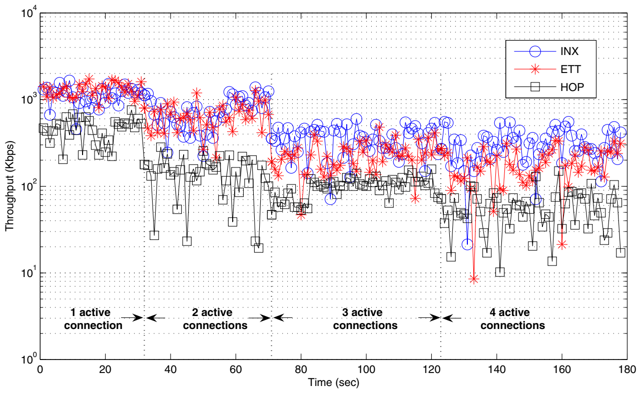


Fig. 7. Throughput of the connection between the pair of nodes 1 and 18

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