On Optimal Route Construction in Wireless Mesh Networks

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***Abstract*—We provide a comparative analysis of various routing strategies that affect the end-to-end performance in wireless mesh networks. We first improve well-known link quality metrics and routing algorithms to better operate in wireless mesh environments. We then investigate the *route optimality* and its impact on the network performance by comparing the achieved end-to-end performance with the optimal offline routing. Various network topologies, number of concurrent flows, and interference types are considered in our evaluation and we reveal that a non-optimal route is easily established because of routing protocol's misbehavior, interflow interference, and their interplay, thus affecting the end-to-end performance.**

I. Introduction

Wireless mesh networks have received considerable interests thanks to their realm of possibilities such as instant deployability, self-configuring, last-mile broadband access provisioning, and low-cost backhaul services for large coverage. Providing reliable high throughput network connectivity to wireless clients is the most important property for wireless mesh networks.

Factors that have been studied to enhance the wireless backhaul capacity include (i) various algorithmic issues (e.g., routing, link rate adaptation), (ii) physical and geographic uncertainties (e.g., device specifics, network topology), and (iii) wireless medium characteristics (e.g., link quality metric, intra-/interflow interference, a-/symmetric link characteristics). Research on designing a link metric that represents time-varying wireless link quality for wireless mesh routing has been quite active [1], [2], whereas the effort to improve the efficiency of utilized routing algorithms has been relatively few. Most (if not all) simply adapt routing algorithms devised for MANET (Mobile Ad hoc Network) and do not provide any synthetic view of the employed routing protocol and link metric combination.

Recently, the IEEE 802.11s working group is working towards standardizing wireless mesh networking in the context of IEEE 802.11 [3]. A routing algorithm is developed, i.e., HWMP (Hybrid Wireless Mesh Protocol), which can enable a tree-based routing. The core operations, however, are nearly identical to AODV (Ad hoc On-demand Distance Vector) [4], and the draft itself does not include detailed analysis of the expected performances, which has not been investigated thoroughly in the literature.

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This paper investigates and analyzes various causes that affect *route optimality*. A route is the optimal route if it has the best end-to-end route metric in terms of the given link metric and the route selection criterion. To this aim, we build an offline routing scheme and compare its end-to-end metric and throughput performance with those based on dynamic routing. We consider state-of-the-art link quality metrics and routing protocols, and diverse environmental settings in terms of network topology, external interference, and number of concurrent flows. We provide a synthetic view of the performance dynamics of wireless mesh networks and the components that impact the performance, each of which cannot give the complete analysis for the network behavior by itself.

The rest of the paper starts with required modifications of the state-of-the-art link quality metrics and routing algorithms in Sections II and III. After describing considered network configurations in Section IV, we explore various impacts of network configurations on the end-to-end performance in Sections V and VI. We conclude this paper with Section VII.

II. Link Quality Metric Revisions

ETX (Expected Transmission Count) [1] is a mesh link metric that was designed to overcome the limitation of HOP (minimum hop count). The ETX of a link is the expected number of transmissions required to successfully send a packet over the link, including retransmissions. The derivation of ETX starts from measuring the forward and backward packet delivery ratios, (d_f, d_b), over the link. Assuming that each transmission is independent from previous transmissions, the expected transmission count is given by ETX $= \frac{1}{d_f \times d_b}$. ETX, however, fails to implicate the *multi-rate* feature on its formula; hence, ETX over a multi-rate link may misestimate the link quality.

ETT (Expected Transmission Time) [2] is a bandwidth-adjusted ETX; the time spent in transmitting the data packet is multiplied by ETX. ETT = ETX $\times \frac{\ell}{r}$, where ℓ denotes the nominal size of data packets and r is the raw link rate. While ETT employs the rate information to represent the wireless link quality more precisely than ETX, it is based on ETX, the original issues of ETX inherently exist with ETT.

To overcome the addressed problems, we consider the multi-rate feature of IEEE 802.11 PHY along with ETX and ETT. We assume that d_f and d_b are estimated for a given link-rate set $\mathbb{R}$; d_{f,r_i} is the forward delivery ratio with the link rate r_i, where $r_i \in \mathbb{R}$, and d_{b,r_i} is for the backward direction. The best ETX over a wireless link should be the minimum out of all available ETX measures:

$$\mathrm{ETX}^* = \arg\min_{r_i \in \mathbb{R}} \mathrm{ETX}_i, \tag{1}$$

where $\mathrm{ETX}_i = \frac{1}{d_{f,r_i} \times d_{b,r_i}}$. Then, the estimation of ETT becomes accurate by employing the modified ETX:

$$\mathrm{ETT}^* = \arg\min_{r_i \in \mathbb{R}} \mathrm{ETX}_i \times \frac{\ell}{r_i}. \tag{2}$$

We consider a method for the link quality estimation as follows. As the calculation of d_f and d_b is based on the knowledge of PER (Packet Error Rate) that depends on ℓ and the employed modulation and coding scheme (r_i), the estimation of a link metric becomes simple, if we have a predetermined PER vs. SNR (Signal-to-Noise Ratio) information in advance. Such a table can be obtained either from the measurement, or from the vendor's datasheet. This setting makes the estimate of a given link metric consistent and prevents the metric value from unexpectedly fluctuating over time. The dynamics of the considered link metric value is not a desired property [1], [2], since it may lead to frequent, unnecessary route changes [5].

A route is set up by selecting the path that has the minimum sum metric among all available paths. The problem to find the best route with ETT is to find CETT* (Cumulative ETT*):

$$\mathrm{CETT}^* = \arg\min_{j \in \mathbb{P}} \mathrm{CETT}_j, \tag{3}$$

where $\mathbb{P}$ is the set of all feasible paths from the source to the destination.

III. Revisiting Routing Protocols

We revisit representative routing protocols, AODV [4] and OLSR [6], considering which properties should be carefully utilized and enhanced to operate in wireless mesh networks.

A. AODV (Ad hoc On-demand Distance Vector)

1) Use of Link Quality Metrics: The route discovery of AODV relies on the exchange of RREQ (Route Request) and RREP (Route Reply) packets between the source and the destination. As for AODV with HOP, the shortest-hop path is preferred and hence, there is no need to process and forward later received RREQs with the same sequence number as long as they have the same broadcast ID, coming from the same source.

With the new link quality metrics, the protocol needs modifications to find the optimal path. Duplicate RREQs that carry a better cumulative link metric value must be forwarded, so that all the possible routes are considered and the optimal path is selected.

2) Link Failure Detection: AODV utilizes an RERR (Route Error) packet to alert the link connectivity problem. The RFC specifies how to detect a link failure as follows: timeout expiration in `HELLO_INTERVAL` × `ALLOWED_HELLO_LOSS` [7].

As mesh routers are typically stationary, link failures due to mobility are rare. Instead, a link is disconnected and RERR is triggered when a transmission fails due to router malfunction, packet collisions, or wrong link rate selection.

If a false detection occurs, every node that receives the RERR removes the corresponding entry from its routing table and rebroadcasts it. Source nodes that use the broken link bootstrap the route establishment process by sending an RREQ. Consequently, network resources are wasted unnecessarily. In the case of TCP, we observed that a TCP timeout may occur due to such a false detection and TCP performance drastically decreases.

To mitigate the false detection problem, we revise the detection procedure algorithm as follows:

Algorithm 1: ***Revised Link Failure Detection***

1) A mesh node, $\mathcal{A}$ that is expecting the reception of the next hello from its neighbor, $\mathcal{B}$ sends a unicast HREQ (Hello Request) to $\mathcal{B}$, before the timeout expiration (e.g., at `HELLO_INTERVAL` × (`ALLOWED_HELLO_LOSS`− 1).
2) When the HREQ arrives at $\mathcal{B}$, it replies with a unicast HREP (Hello Reply).
3) If $\mathcal{A}$ does not receive the HREP, $\mathcal{A}$ generates an RERR as specified in [7]. Otherwise, $\mathcal{A}$ does not have to invoke the link failure detection and route rediscovery procedure.

3) Receiver-centric Metric Caching: When a route is being established, RREQs need to convey link metrics that will be used for the route decision at the destination. Hence, each node must include the link metric information to all its neighbors in the RREQ before forwarding, as it does not know which neighbor will be the next hop node of the route, except the node where the RREQ came from.

This approach drastically increases the size of RREQ messages, which contributes the overhead of the route setup. In our scheme, instead of making an RREQ sender include link metrics toward all neighboring nodes, the metric of a link is appended in the RREQ by the receiver of the link (i.e., the node that just received the RREQ). Let $\mathcal{A}$ and $\mathcal{B}$ be adjacent neighbors. According to the typical hello-based quality estimation [1], [2], $\mathcal{B}$ measures the link quality in terms of the metric of interest, say $LQ_{\overline{\mathcal{AB}}}$. Instead of transferring $LQ_{\overline{\mathcal{AB}}}$ to $\mathcal{A}$, $\mathcal{B}$ keeps and uses it for the future RREQ forwarding. As a result, $\mathcal{A}$ does not have to include metric value of all neighboring links in an RREQ.

B. OLSR (Optimized Link State Routing)

1) Routing Entry Calculation: In OLSR, each node maintains the neighbor and topology tables for routing that are obtained by receiving and processing hello and TC (Topology Control) messages, respectively. The shortest path calculation described in OLSR [8] optimally works with HOP; starting from 1-hop neighbors, routing entries are calculated in an increasing order of HOP. To use non-binary link quality metrics, we modified the routing entry calculation adopting the optimal method, Dijkstra's algorithm.

2) MPR Selection: The concept of MPR (Multi-Point Relay) is one of the core in OLSR that contributes to the optimization of the routing process. In order to reduce the overhead in disseminating link quality information, each node

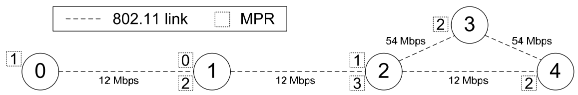


Fig. 1. An illustrative example of the MPR selection problem.

selectively chooses MPRs. An MPR node is responsible for forwarding link information between itself and its MPR selectors, i.e., the ones who select the node as their MPR.

As the amount of disseminated information directly hinges on the number of MPRs selected by each OLSR node, the MPR selection rule is the critical part of OLSR design. The selection criterion is as follows: $\mathbb{M}^* = \arg\min_{\mathbb{M}\subset\mathbb{N}_1} |\mathbb{M}|$, such that $\mathbb{M}$ covers $^\forall n$ for $n \in \mathbb{N}_2$, where $|\cdot|$ is the operator that counts the number of elements in a given set, $\mathbb{M}$ is the set of MPRs chosen by the MPR selector $\mathcal{A}$, and $\mathbb{N}_i$ is the set of $\mathcal{A}$'s i-hop nodes.

With respect to non-binary link metrics, the MPR concept itself might throttle the optimization of OLSR route establishment, even if it reduces the overhead. Fig. 1 illustrates this problematic effect of MPR. The network is composed of five mesh nodes and the average employed link rates are described in the unit of Mbps. Small square boxes near each mesh node are the selected MPRs that cover all two-hop neighbors of the reference node. Because N_4 chooses N_2 as its MPR the link quality information between two nodes, $LQ_{\overline{24}}$ is propagated over the network conveyed into hellos and TCs generated by N_2. The link information between N_3 and N_4, i.e., $LQ_{\overline{34}}$ never reaches N_0 because of the MPR selection by N_4. Hence, N_0 has no way of knowing $LQ_{\overline{34}}$, irrespective of its feasibility. Details about such an MPR selection issue will be discussed in later sections.

IV. Framework for Comparative Evaluations

To comparatively evaluate the effect of various combinations of link metrics and routing protocols on the performance of wireless mesh networks, we modified the ns-2 simulator. AODV and OLSR are modified to support ETX and ETT as addressed previously. In order to observe the optimal route setup and its end-to-end performance, we build and employ an offline route calculation called MANUAL that provides the optimal route in terms of a given link metric. Single-channel/-radio environments is considered during all evaluations.

IEEE 802.11 module is enhanced to support 802.11a PHY. For the link rate selection, we use an RTS (Request-To-Send)/CTS-based SNR-triggered link rate adaptation scheme [9]. The use of RTS/CTS makes the analysis of routing performance clear as over/underestimated link rates are suppressed. Hidden nodes can easily exist in multi-hop wireless networks. Therefore, we force mesh nodes to transmit all control frames at the lowest transmission rate to minimize the hidden node effect on multi-hop communications.

We assume that a mesh access point forwards traffic from or to client devices, thus working as a source or a destination node of such traffic. We use a log-distance path-loss model with the path-loss exponent of four in AWGN (Additive White Gaussian Noise) channel to simulate the indoor mesh environment. We use LLC/IP/TCP as the upper layer protocol suite. Long-lived TCP flows are used and the MAC payload size is fixed at 1024 bytes. Each mesh node calculates the considered link metrics between its neighbors and itself based on distances and the given path-loss model, which is a ground reflection (two-ray) model [10].

V. The Effect of Route Optimality

We first investigate the impact of route optimality on the route construction when background traffic exists. We consider a grid topology as shown in Fig. 2(a) that is composed of 48 nodes and one gateway, with the link distance of 15 meters. The interfering background traffic is generated from N_{44} (INT. SRC) to N_{20} (INT. DST), while one of 48 nodes is selected as a source and activates a long-lived TCP flow towards the gateway. 1000-byte CBR flow with 5 Mbps generation rate starts to generate interference for 3 seconds when the TCP flow is initiated.

Figs. 2(b), 2(c), and 3 show the comparison of throughput performance of different routing strategies, metric discrepancies, and hop counts. Results are sorted by mesh node indexes (x-axis) that match up to those in Fig. 2(a).

A. Non-optimal sum metric yields throughput degradation

In most cases, we observe that non-optimal route setup presented as metric discrepancies in Figs. 2(b) and 2(c) results degraded throughput performance.

In the case of OLSR, not only the non-optimal setup, but another aspect also contributes to the throughput degradation. With ETT in Fig. 2(c), about 70.8% of samples do not build the optimal route, thus generating less throughput than that of MANUAL. Three cases that build non-optimal paths, i.e., N_0, N_6, and N_{20}, show similar performance to MANUAL. Through our investigation, the reason is revealed as the problematic MPR selection addressed in Section III-B2. The reason why those source nodes result in good throughput is as follows. Even though the source node has non-optimal route information, an intermediate node can find the optimal route. It happens the intermediate node successfully receives hellos or TCs, while the source does not. That is, nodes that are composed of a path may have unequal knowledge of link metric.

It is interesting to see that all optimal sum metric routes with OLSR+ETT do not show similar throughput as MANUAL. N_{26}, N_{39}, N_{45}, and N_{46} show the identical sum metric, and yet use a different path when sending TCP packets. As a source node can find multiple feasible paths, it is possible to have more than one path that present the identical and optimal sum metric. Therefore, such four cases are exceptional, yet possible scenarios, showing the optimal sum metric, but non-optimal throughput. There are other two noticeable cases such as N_{36} and N_{47}, where the dominant cause that yields throughput degradation is not the non-optimal route setup, but the TCP timeout. Due to interference, TCP timeout occurs, leading to degraded throughput. Other than those exceptions, the cases that have the identical sum metric show throughput

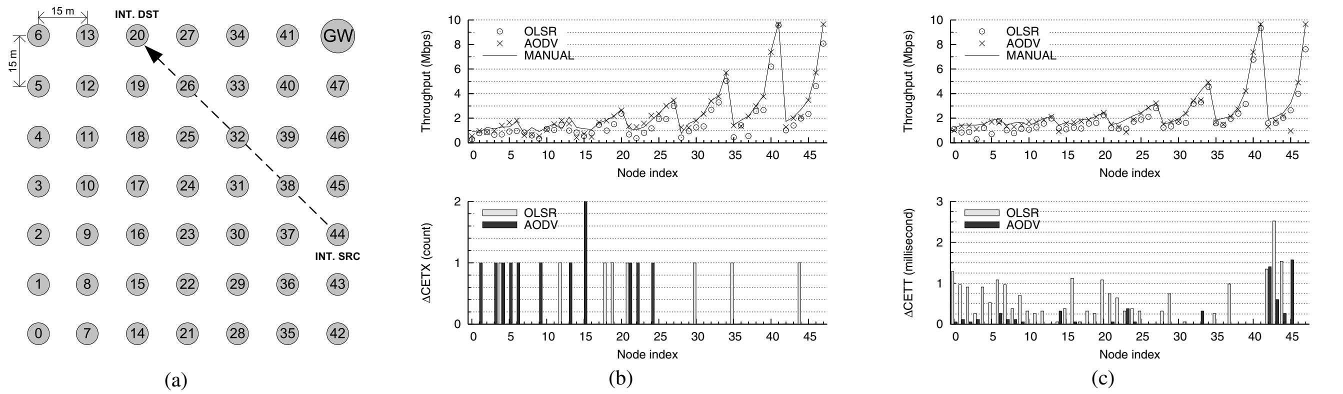


Fig. 2. Performance comparison of MANUAL, AODV, and OLSR with ETX and ETT metrics: (a) a 7×7 square-grid topology network, where N_{44} generates a interfering signal that is destined to N_{20}; (b) performance comparison with ETX; and (c) performance comparison with ETT.

performances as good as those of MANUAL (with 10% error margin). The case of OLSR with ETX will be discussed in detail later.

B. AODV sometimes shows higher throughput than MANUAL

AODV performs better than MANUAL in eight cases as shown in Fig. 2(b). Such an interesting behavior of AODV happens in the cases of N_4, N_5, N_{12}, N_{21}, N_{22}, N_{23}, N_{24}, and N_{28}, where AODV+ETX does not provide the optimal route due to the losses of control packets. This means that the established optimal route in terms of ETX cannot always result in the highest throughput performance.

C. TCP timeout may result in severe performance degradation in the case of OLSR with ETX

Table I shows the percentage of average throughput degradation of OLSR and AODV compared with MANUAL. Unlike the case of AODV, OLSR shows large throughput degradation, especially with ETX. Metric difference shows that OLSR generates non-optimal routes in eight cases, when working with ETX. We take into account the impact of TCP timeout with OLSR cases. OLSR shows approximately 44.4% increase of TCP timeout with ETX, compared with ETT.

As illustrated in Fig. 3, ETX-based routing that selects the minimum CETX route, prefers the shortest-hop path, which in turn makes the length of each hop relatively long. Thus, a low link rate is likely to be used, which requires a long transmission time. If a hidden situation, where node $\mathcal{C}$ receives nothing, while nodes $\mathcal{A}$ and $\mathcal{B}$ exchange RTS and CTS, exists, an ETX-based path is more susceptible to the hidden interference (e.g., from $\mathcal{C}$) than a path based on ETT due to the relatively long packet transmission time. We observe that in OLSR, in 29 out of 48 cases, there are larger number of collisions, due to the hidden interference, when operating with ETX than ETT, although we expect ETT to generate more collisions as it uses longer hop paths.

TABLE I
THROUGHPUT DECREMENT OF OLSR AND AODV.

metric	AODV	OLSR
ETX	5.3%	31.4%
ETT	9.0%	23.4%

The reason why AODV is less affected by the interfering flow than OLSR is the exposed time duration of routing control packets to interference. While the average required time for an RREQ/RREP exchange is 1 second in grid scenarios, OLSR's control packets such as hellos and TCs are affected during the entire interference duration, i.e., 3 seconds. Consequently, AODV shows less degraded performance due to interference than OLSR.

D. Impact of link metric design on end-to-end performance

Fig. 3 shows throughput performance and corresponding hop counts, when a selected source node operates MANUAL routing. The collected data are sorted with respect to the hop count of ETT-based routes. The hop count graph indicates that ETX prefers the shortest-hop path, while ETT gives the higher priority to the faster link. ETX shows high throughput (if not all) when the destination is reachable within two hops from the source. In other cases, ETT shows better performance (on average 11.9% throughput gain over ETX).

VI. INTERPLAY OF ROUTE OPTIMALITY AND INTERFLOW INTERFERENCE

We now investigate the interplay of route optimality and interflow interference when multiple concurrent flows exist. The same grid topology is considered as shown in Fig. 2(a) except the interference flow. k (= 2, 4, and 8) concurrent TCP flows are generated by randomly selected non-duplicate sources out of 48 mesh nodes. We repeated the experiment using 30 different random seeds.

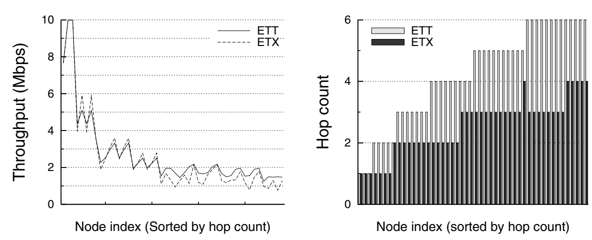
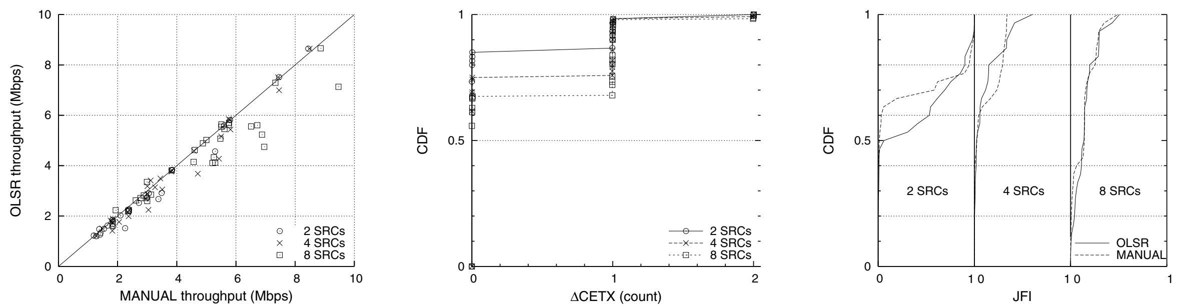


Fig. 3. Comparison of ETX and ETT along with MANUAL.



(a) Scatter plot of 90 random scenarios varying the number of source nodes.

(b) Cumulative fraction of metric difference measured by each source node.

(c) Comparison of cumulative fractions of fairness index for a given number of sources.

Fig. 4. Performance comparison of MANUAL and OLSR with ETX when multiple concurrent flows in a 7×7 square-grid topology.

We here consider the routing strategy of OLSR with ETX to observe the impact of both route optimality and interflow interference on throughput performance, and their interaction by comparing the measured metric difference and JFI (Jain's Fairness Index). We use a normalized JFI (nJFI) to make the lowest value zero for any k. That is, $\mathrm{nJFI} = (\mathrm{JFI} - \frac{1}{k}) \times \frac{k}{k-1}$. Fig. 4 shows the results based on the simulation setup as addressed above.

Fig. 4(a) shows the measured end-to-end throughput of MANUAL (x-axis) and OLSR (y-axis). The average aggregate throughput values of MANUAL over 30 random seeds are 2.96, 3.77, and 4.97 Mbps, for $k = 2$, 4, and 8 (depicted as k SRCs in the graphs), respectively. Meanwhile, the portion of paths that return the optimal sum metric value becomes smaller as the number of k increases as shown in Fig. 4(b).

When multiple concurrent flows exist, there should be unfair throughput sharing since neither TCP nor the 802.11 MAC provides fair resource allocation. Hence, a few sources may dominate network resources. The authors of [11] show that an extreme unfair throughput sharing typically yields high aggregate throughput at the sacrifice of fairness. We present JFI for different k as shown in Fig. 4(c), where the x-axis is JFI and the y-axis is the cumulative fraction of fairness index. In $k = 2$, the route optimality of OLSR shows at least 85%. The fact that MANUAL shows worse JFI in Fig. 4(c) explains that its aggregate throughput is higher than that of OLSR.

Except $k = 2$, MANUAL and OLSR show similar JFI performances. This result indicates that the unfairness itself cannot explain relatively good performance as shown in Fig. 4(a) because both MANUAL and OLSR show similar JFI when $k = 4$ and 8. Meanwhile, the metric difference becomes worse as k increases as shown in Fig. 4(b). This is also explained by the fact that the gain of MANUAL over OLSR increases from 6.8 % to 8.9 %, when k increases from 4 to 8.

We observe that OLSR outperforms MANUAL in seven cases out of 90. Among them, four cases are due to extremely unfair bandwidth sharing. For other three cases where JFI is quite fair, OLSR finds non-optimal routes, yet those routes yield better throughput due to unequal knowledge of link metric among nodes. It is an analogous observation that we have in the previous section that ETX may fail to find the best throughput path, even though the sum metric shows the optimal.

In summary, we observe that the route optimality can be an indicator to predict the end-to-end throughput performance, when multiple flows exist. However, an extremely unfair bandwidth share makes such an analysis less meaningful as one or a few nodes devour the entire network bandwidth, irrespective of established optimal routes.

VII. Conclusion

This paper analyzes the performance of wireless mesh networks with respect to the route optimality for a given link quality metric. We first suggested the improvements of mesh link metrics that better represent the multi-rate wireless link quality. Several important modifications to the routing algorithms, to operate better in wireless mesh networks, are considered. We presented a reference routing model that is capable of searching for the optimal route in terms of a given link metric. Comparative study in various mesh environments analyzed the impact of route optimality, selected link metrics and routing algorithms, on the multi-hop mesh network performance and fairness. Finally, this work hints that performance optimizations might be possible, yet need to carefully consider the various interactions among network components.

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