A Contention-Aware Routing Metric for Multi-Rate Multi-Radio Mesh Networks

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***Abstract*—We present a new routing metric for multi-rate multi-radio mesh networks, which takes into account both contention for the shared wireless channel and rate diversity in multi-radio multi-channel mesh networks. A key property of the proposed Contention-Aware Transmission Time (CATT) metric is that it is isotonic, hence can be applied to link-state routing protocols. We have implemented the CATT metric in the OLSR routing protocol, and evaluate it in a test-bed with mesh nodes each equipped with four radio interfaces. Our experiments show that the proposed routing metric significantly outperforms other metrics that have appeared in the literature, in a number of scenarios that correspond to different mesh network topologies.**

Keywords: routing, wireless channel contention, multi-channel, multi-rate

I. Introduction

Wireless mesh networks have the potential to provide ubiquitous network access in urban and rural areas with low operation and management costs, to both fixed and mobile users. Multi-radio mesh networks, where mesh nodes have multiple radio interfaces operating in different channels, by exploiting channel diversity can achieve significantly higher capacity compared to single-radio mesh networks, hence can provide high-speed broadband access that competes with or even surpasses the speed of wired access technologies such as ADSL and cable.

Routing protocols in wireless mesh networks, in addition to supporting connectivity between mesh nodes, should also target to optimize the utilization of wireless links by selecting high throughput paths. Shortest path routing algorithms are not appropriate for wireless multi-radio mesh networks due to a number of reasons. First, they do not account for the quality of a wireless link, which can be important since packet losses due to wireless channel errors can be significant. Second, they do not consider the transmission rate of wireless links, which can influence the achievable throughput. Finally, they do not account for interference or location-dependent contention, which is significant in wireless mesh networks due to the shared access nature of the wireless channel and the attenuation of radio signals.

Prior work has proposed routing metrics to deal with the first [1], the second [2], [3], and all three issues [4], [5], [6] identified above. We present a brief overview of this work in Section II. A common observation for the interference-aware routing metrics proposed in prior work is that they capture inter-flow and intra-flow interference independently. Such an approach results in routing metrics that are either not isotonic, hence do not allow efficient and loop-free computation of routing paths [4], [6], or require a special mapping to become isotonic [5], which increases their complexity. Moreover, previous proposals heuristically introduce tuning parameters [4], [5], [6], which necessitate careful investigation of how these parameters influence overall performance, and how they should be appropriately tuned for different topologies or traffic patterns. Another direction investigated in previous work involves maximum throughput-based metrics [7], [8], which have the disadvantage that they cannot be used in link-state routing protocols, which combine Dijkstra's algorithm for path computation and hop-by-bop routing.

In this paper we investigate routing in multi-rate multi-radio mesh networks, and make the following contributions:

- We present a model for MAC layer wireless channel sharing that gives an upper bound for the achievable throughput, while capturing the influence of multi-rate operation. The model is extended to the case of weighted service differentiation and when nodes are allowed to hold the wireless channel for a time interval once they gain access to it, rather than transmit a single packet.
- Based on the above model, we present a new Contention-Aware Transmission Time (CATT) routing metric that captures both location-dependent contention and rate diversity in multi-radio mesh networks.
- Key properties of the proposed metric is that it captures intra-flow and inter-flow interference in a unifying manner, and is isotonic thus allowing efficient and loop-free computation of paths using link-state routing protocols.
- We present an implementation of the new routing metric in the OLSR (Optimized Link State Routing) protocol, and evaluate it in a multi-radio mesh network test-bed consisting of nodes with up to four radio interfaces each. For a number of scenarios that correspond to different

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mesh network topologies, experimental results show that the proposed routing metric can achieve significantly higher performance compared to other metrics.

The remainder of the paper is structured as follows: In Section II we present a brief overview of routing metrics that have been proposed in the literature. In Section III we first present a model for MAC layer wireless channel sharing that gives an upper bound for the maximum throughput, while capturing the influence of rate diversity, and then we present the proposed Contention-Aware Transmission Time (CATT) routing metric. In Section IV we present our implementation of the new routing metric in the OLSR protocol, and in Section V we evaluate the new metric in a number of topologies, comparing it with other routing metrics that have appeared in the literature. Finally, in Section VI we conclude the paper identifying ongoing and future research directions.

II. Prior work on routing metrics

Next we present a brief overview of routing metrics that appeared in the literature, identifying where they differ from the Contention-Aware Transmission Time (CATT) metric proposed in this paper.

Expected Transmission Count (ETX): The ETX metric measures the expected number of transmissions, which includes retransmissions, needed to send a packet across a link [1]. If p_l denotes the probability that a packet transmission over link l is not successful, then

$$ETX_l = \frac{1}{1-p_l}\,.$$

The packet loss probability p_l is estimated based on the packet loss probability in the forward p_l^f and reverse direction p_l^r using $p_l = 1-(1-p_l^f)(1-p_l^r)$. Route selection involves choosing the path with the smallest aggregate ETX value for all links in the path.

Experiments show that the ETX performs well for single-rate single-radio mesh networks, but its performance degrades in the case of multi-rate multi-radio mesh networks [4].

Expected Transmission Time (ETT) and Weighted Cumulative Expected Transmission Time (WCETT): The ETT metric is a "bandwidth adjusted" ETX [4]. Hence,

$$ETT_l = ETX_l \cdot \frac{L_l}{R_l}\,,$$

where L_l denotes the packet size and R_l the bandwidth (link transmission rate) of link l. Independently, [2], [3] propose the Medium Transmission Time metric, which considers the expected transmission time based solely on the link transmission rate, without accounting for retransmissions.

A key limitation of the ETX metric, which also applies to the other loss-dependent routing metrics defined next, is that the loss probability is different for different transmission rates. For this reason, there are proposals to use probe packets at different transmission rates [9].

The sum of the ETT metric for all link belonging to a path considers the rate diversity of different links, but does not capture the interference or channel diversity. For this reason, [4] proposes the Weighted Cumulative ETT (WCETT) metric for path p defined as

$$WCETT_p = (1-\beta)\cdot\sum_{l\in p} ETT_l + \beta\cdot\max_{1\le j\le k} X_j\,,$$

where ETT_l is the ETT metric for link l, $\beta\in[0,1]$ is a tunable parameter, and X_j is defined as

$$X_j = \sum_{\text{hop } l\in p \text{ is on channel } j} ETT_l \quad 1\le j\le k\,,$$

with k being the total number of channels. Hence, the second factor of the WCETT path metric is the aggregate ETT for the most congested channel, which is the channel with the highest aggregate ETT, summed for all links using the same channel. Note that this factor captures the intra-flow interference, since the computation of X_j considers only links belonging to the path for which the WCETT metric is computed.

An important property of routing metrics is whether they are isotonic [10], [5], since isotonicity determines if efficient algorithms such as Dijkstra or Bellman-Ford can be used to find minimum cost paths, and whether hop-by-hop routing protocols yield loop-free paths. If W_a denotes the cost (weight) of path a, and $a\oplus b$ denotes the concatenation of two paths a and b, then W_a is isotonic [10] if $W_a\le W_b$ implies that both $W_{a\oplus c}\le W_{b\oplus c}$ and $W_{c\oplus a}\le W_{c\oplus b}$, for all paths a,b,c. An important disadvantage of the WCETT metric is that it is not isotonic [5], hence the Dijkstra and Bellman-Ford algorithms cannot be used to efficiently compute minimum cost paths, which typically suggests that such non-isotonic metrics can only be used with source routing protocols. For this reason, [4] applies the routing metric to a source routing proactive protocol LQSR (Link Quality Source Routing).

Metric of Interference and Channel Switching (MIC) and Interference Aware Resource Usage (IRU): Whereas the WCETT metric captures only intra-flow interference, the MIC metric captures both intra-flow and inter-flow interference [5]. To achieve this, it consists of two components (metrics): Interference-aware Resource Usage (IRU) and Channel Switching Cost (CSC). The IRU metric for link l is defined as

$$IRU_l = ETT_l \cdot N_l\,,$$

where N_l denotes the number of neighbors with which the transmission on link l interferes. Hence, the IRU component captures the aggregated channel time that link l transmissions consume on neighboring nodes.

The second component of MIC, Channel Switching Cost (CSC), captures the intra-flow interference for node i and is defined as:

$$CSC = \begin{cases} w_1 & \text{if } Channel(Prev(i)) \neq Channel(i) \\ w_2 & \text{if } Channel(Prev(i)) = Channel(i) \end{cases}$$

where $0\le w_1 < w_2$, $Prev(i)$ is the channel used in the previous hop of node i, and $Channel(i)$ is the channel node i uses to transmit to the next hop. Note that the above definition of CSC captures the intra-flow interference only between two consecutive nodes in a path.

The MIC metric for path p is defined as

$$MIC_p = \alpha \cdot \sum_{l \in p} IRU_l + \sum_{\text{node } i \in p} CSC_i \,,$$

where factor a is defined as $a = 1/[N \cdot \min ETT]$, with N being the number of nodes in the network. [5] indicates that IRU essentially represents the inter-flow interference that the flow may impose to the network. However, the set of nodes N_l that may be interfered with by the transmission on link l can include nodes of the same path (to which link l belongs) that are upstream or downstream of link l. Hence, IRU does indeed capture some form of intra-flow interference as well.

If applied directly, MIC is not isotonic. For this reason, [5] proposes a mapping of the real network to a virtual network that decomposes MIC into isotonic weight assignments. The need for such a mapping makes it more complicated to implement MIC in a link-state routing protocol. Moreover, the above definition of the CSC component considers intra-flow interference only between two consecutive nodes. The complexity of the virtual network mapping increases significantly if the CSC component is extended to capture intra-flow interference between more than two consecutive nodes.

Interference Aware Routing Metric (iAware): The iAware metric uses the same path metric formula as WCETT, but replaces ETT with the iAware metric defined as

$$iAware_l = \frac{ETT_l}{IR_l} \,,$$

where the Interference Ratio for link l between nodes i and j is defined as

$$IR_l = \frac{Noise_i}{Noise_i + \sum_{k \in InterferenceSet(i) - \{j\}} \theta(k) P_i(k)} \,,$$

where $Noise_i$ is the background noise at node i, $InterferenceSet(i)$ is the set of nodes that can interfere with node i, $P_i(k)$ is the signal strength of a packet from node k at node i, and $\theta(k)$ is the normalized rate at which node k generates traffic averaged over a period of time. Note that $0 < IR_l \leq 1$, and that a higher interference results in a smaller value of IR_l.

The iAware metric captures interference in terms of the level of the power that a node receives from all other nodes. However, it does not capture interference at the MAC layer: if two nodes interfere at the MAC layer, then they cannot both transmit at the same time, and the degree of interference depends on their transmission rates. On the other hand, if they do not interfere at the MAC layer (i.e., the nodes are too far apart for one to affect the other's carrier sense operation), then one node's transmission will reach the other node as interference, which will affect its transmission rate; hence, such interference can be taken into account by considering a multi-rate model, as the one presented in the next section.

Like WCETT, the iAware metric is also not isotonic, and hence it cannot be applied to link-state routing protocols. Finally, note that the inclusion of the normalized rate parameter $\theta(k)$, makes the iAware metric load-dependent. However, as we discuss in Section III-C2, care must be taken to avoid routing instability and loops.

Throughput-based routing metrics: The work of [7], using a modelling framework similar to the one presented in this paper, proposes a routing metric where the cost of a path is the smallest (bottleneck) capacity of all links in the path; the path with the largest bottleneck capacity is selected for routing. A routing metric with the same target is proposed in [8], which uses a model of the 802.11 MAC to identify maximum throughput paths based on the channel busy time. However, the metric that assigns to each path the smallest (bottleneck) capacity of all links in the path does not satisfy strict isotonicity, defined as follows [10]: If W_a denotes the cost (weight) of path a, and $a \oplus b$ denotes the concatenation of two paths a and b, then W_a is strictly isotonic [10] if $W_a < W_b$ implies that both $W_{a\oplus c} < W_{b\oplus c}$ and $W_{c\oplus a} < W_{c\oplus b}$, for all paths a, b, c. As a simple example, consider two paths a, b with bottleneck capacity $W_a = 7, W_b = 10$, hence we have $W_a < W_b$. If we prefix both paths with a path c of capacity $W_c = 5$, then the bottleneck capacity is $W_{c\oplus a} = W_{c\oplus b} = 5$, hence the bottleneck capacity metric is not strictly isotonic. Lack of strict isotonicity means that the metric cannot be used with Dijkstra's algorithm and hop-by-hop routing to route packets along optimal paths [10], [11]. Hence, it is necessary to use either source routing (e.g., [8] proposes to use the metric in a source routing protocol LQSR [4]), or the Bellman-Ford algorithm (as proposed by [7]). However, there are disadvantages to both source routing and hop-by-hop routing based on the Bellman-Ford algorithm, such as distance-vector routing, which makes them less appropriate for wireless mesh networks compared to hop-by-hop routing based on Dijkstra's algorithm, such as link-state routing [12].

III. CATT: A Contention-Aware Transmission Time Metric

We first discuss a MAC layer throughput model for shared wireless channel access, starting from a discussion of IEEE 802.11's MAC. Although we start our discussion with the 802.11 MAC, the resulting throughput model is more general, since it provides an upper bound for the MAC layer throughput in a wireless network containing nodes with different transmission rates. Moreover, we present extensions to the basic model for the case of weighted service differentiation and when nodes are allowed to hold the channel for a specific time interval once they gain access to it, e.g., as with 802.11e's transmission opportunity (TXOP). Then, based on the above throughput model we present the proposed Contention-Aware Transmission Time (CATT) metric, identifying key differences with the routing metrics discussed in the previous section. Finally, we discuss extensions of the basic CATT metric to include loss and load-dependence.

A. Throughput model for shared wireless channel access

IEEE 802.11's DCF mechanism can be modelled as a stochastic process with three types of intervals: a successful transmission interval T^{suc}, a collision interval T^{col}, and an idle interval T^{idl}. The duration of these time intervals depends on the physical layer encoding, and whether the RTS/CTS mechanism is used [13].

Let τ be the rate at which a node attempts to transmit a packet in one slot, and N be the total number of nodes contending for the wireless channel. Under saturation conditions where nodes always have a packet to transmit, and when nodes have the same transmission rate, the throughput achieved by a single node can be approximated by [13]

$$x_i = \frac{\tau(1-\tau)^{N-1}L_i}{N\tau(1-\tau)^{N-1}T^{suc} + P^{col}T^{col} + P^{idl}T^{idl}}$$

where L_i is the packet length for node i. The probability of a collision P^{col} and of an idle interval P^{idl} are given by

$$P^{col} = 1 - (1-\tau)^N - N\tau(1-\tau)^{N-1}, \quad P^{idl} = (1-\tau)^N .$$

If nodes have different transmission rates, then the successful transmission interval T_i^{suc} for node i with rate R_i is

$$T_i^{suc} = \frac{L_i}{R_i} + O ,$$

where O is the physical and MAC layer overhead (which includes the IFS overhead and the MAC layer acknowledgement transmission time) involved in the transmission of a packet.

In 802.11 with RTS/CTS, the data transmission rate does not affect the collision interval, since a collision involves RTS packets that are sent at the basic rate. Hence, for 802.11 with RTS/CTS, the average throughput x_i for node i is given by [14], [15]

$$x_i = \frac{\tau(1-\tau)^{N-1}L_i}{\tau(1-\tau)^{N-1}\sum_{j=1}^{N}(\frac{L_j}{R_j} + O) + P^{col}T^{col} + P^{idl}T^{idl}} . \tag{1}$$

If the basic CSMA/CA mechanism is used, then the collision interval will also depend on the transmission rate. If the number of contending nodes is small or if the minimum contention window is appropriately adjusted [16], then the collision probability is small, hence its influence in the denominator of (1) is smaller than the other factors.

From (1), an upper bound on the transmission throughput for both the basic CSMA/CA and the RTS/CTS mechanism is given by

$$x_i = \frac{L_i}{\sum_{j=1}^{N}(\frac{L_j}{R_j} + O)} , \tag{2}$$

which if we disregard the packet transmission overhead reduces to

$$x_i = \frac{L_i}{\sum_{j=1}^{N}\frac{L_j}{R_j}} . \tag{3}$$

Note that the last equation gives the throughput, which is the same for all stations, independent of their transmission rate. Hence, the equation captures a key property of 802.11 wireless networks: a station with a low transmission rate affects not only its own throughput, but the throughput of all stations in the same network. This property also holds for a polling system, where a polled station is allowed to transmit one packet in each polling round, each with a different transmission rate. Also, in an ideal polling system equation (2) becomes exact, since there are no collisions or idle intervals.

More generally, (3) can be used to approximate the throughput of any shared channel access mechanism with multi-rate transmitters, which transmit a single packet when they gain access to the wireless channel. Indeed, a similar approximation has been used for optimally associating wireless clients to access points [17], [18], [19].

1) Weighted service differentiation: Expression (3) can be extended to account for multiple weighted services classes, where the throughput achieved by a flow belonging to a class is proportional to the weight of the class. An example is 802.11e's EDCA (Enhanced Distributed Channel Access) standard, which supports different minimum contention window values. It is known that to achieve in EDCA an average throughput proportional to some weight, the minimum contention window should be inversely proportional to this weight [20], [21]. Also, a node's attempt probability when the degree of contention is not high, is approximately inversely proportional to the minimum contention window. Hence, if w_i is the weight for node i, (3) obtains the following form in the case of weighted service differentiation

$$x_i' = \frac{w_i L_i}{\sum_{j=1}^{N}\frac{w_j L_j}{R_j}} . \tag{4}$$

2) Access based on channel holding time: Now we extend (3) to the case where a node is allowed to transmit for some time interval (channel holding time), once it gains access to the wireless channel. An example is the transmission opportunity (TXOP) parameter of 802.11e's EDCA mechanism. Hence, if node i is allowed to hold the channel for a time interval h_i, an upper bound to his average throughput is given by

$$x_i'' = \frac{h_i \cdot R_i}{\sum_{j=1}^{N} h_j} . \tag{5}$$

B. CATT: A Contention-Aware Transmission Time metric

An estimate of the time to transmit a packet across link l is L_l/x_l, where x_l is the average throughput for link l given by (3). Based on this, we propose the following Contention-Aware Transmission Time metric (CATT) for a link l

$$CATT_l = \sum_{j \in N_l} \frac{L_j}{R_j} , \tag{6}$$

where N_l is the set of links whose transmission can interfere with the transmission on link l. Note that N_l includes link l.

It is easy to see that the CATT metric is strictly isotonic, since the aggregate path cost is the sum of the costs for all links in the path, and link costs are non-negative. Hence, the metric can be implemented in link-state routing protocols that use Dijkstra's algorithm to find minimum cost paths and hop-by-hop routing. In Section IV we present our implementation of the CATT metric in the OLSR protocol. Also, note that the proposed metric does not include any tuning parameters.

The CATT metric for a link l captures the influence that transmissions from other flows (inter-flow interference) and transmissions of the same flow on links other than l (intra-flow interference) have on the time for transmitting a packet over link l; hence, CATT uniformly captures both inter-flow and intra-flow interference, and performs path selection in a selfish manner by selecting the path that minimizes an estimate of the total packet transmission time. On the other hand, the MIC metric independently captures intra-flow and inter-flow interference, and its IRU component captures the cost (impact) that a new flow imposes to other (existing) flows. Hence, route selection based on IRU altruistically selects a path that minimizes the cost (impact) that the new flow will impose on other flows. Finally, note that iAware accounts for interference in terms of the resulting signal-to-noise ratio, without accounting for rate diversity, which has a significant impact on the throughput as indicated by the model of Section III-A.

An alternative to the model-based approach followed in this section for capturing contention, is to use measurements to estimate the channel access time; however, such an approach requires careful selection of the measurement interval and procedures to smooth link-layer fluctuations [22].

1) CATT metric for weighted service differentiation: Following the same approach as above, an estimate of the time to transmit a packet across link l is L_l/x_l, where x_l is now given by (4). Hence, the CATT metric in the case of weighted service differentiation is given by

$$\mathit{CATT}'_l = \frac{1}{w_l} \sum_{j \in N_l} \frac{w_j L_j}{R_j} \,,$$

where w_l is the weight at the transmitting node of link l.

2) CATT metric for access based on channel holding time: As above, based on (5) the CATT metric is given by

$$\mathit{CATT}''_l = \frac{1}{h_l \cdot R_l} \sum_{j \in N_l} h_j \,,$$

where h_l and R_l is the channel holding time and the transmission rate, respectively, at the transmitting node of link l.

C. Extensions

Next we present two extensions to the basic CATT metric, given by (6), to include loss and load-dependence.

1) Loss-dependence: The packet transmission time over link l is given by (6). If the probability of an unsuccessful transmission on link l is p_l, then the average number of attempts required to transmit a packet is $\mathit{ETX}_l = \frac{1}{1-p_l}$. Hence, a loss-dependent version of the CATT metric can be defined as

$$CATT_l^{LD} = \mathit{ETX}_l \cdot \sum_{j \in N_l} \frac{L_j}{R_j} \,. \tag{7}$$

2) Load-dependence: To understand how load-dependence should be added to the CATT metric, consider the following: the ratio L_j/R_j in (6) represents the duration of a transmission on link j. Moreover, (6) implicitly assumes that all links always have a packet to transmit (saturation conditions). If this is not the case, then the contribution of a link j to the channel access time will be less than L_j/R_j, and proportional to j's packet transmission attempt rate τ_j. Also observe that in saturation conditions the attempt rate for all nodes is $1/\sum_{k \in N_j} \frac{L_k}{R_k}$, where N_j is the set of links that can interfere with the transmission on link j. Hence, to add load-dependence to the CATT metric, the worst-case contribution of a link j to the channel access time, L_j/R_j, should be multiplied by the ratio of the actual packet transmission attempt rate over the packet attempt rate in saturation conditions:

$$\frac{\tau_j}{\frac{1}{\sum_{k \in N_j} \frac{L_k}{R_k}}} = \left(\sum_{k \in N_j} \frac{L_k}{R_k} \right) \cdot \tau_j \,.$$

Based on the above, the CATT metric incorporating both loss-dependence and load-dependence can be written as

$$CATT_l^{L2D} = \mathit{ETX}_l \cdot \sum_{j \in N_l} \left(\left(\sum_{k \in N_j} \frac{L_k}{R_k} \right) \cdot \tau_j \cdot \frac{L_j}{R_j} \right) \,.$$

In saturation conditions, the last equation reduces to (7).

It is known that load-dependence can result in routing loops and instability [23], and for this reason has not been deployed in large fixed networks. However, the manner in which contention is taken into account in the CATT metric (but also in the IRU metric) is a worst-case approach, since we assume that all neighboring nodes within the range of a link always interfere with the transmission over the link. However, this is true only if these neighboring nodes transmit packets. Hence, load-dependence in routing metrics for wireless mesh networks, in addition to achieving load-balancing (as in wired networks), also helps to accurately capture wireless channel contention [6], [24]. Additionally, it is interesting to note that route instability can be observed in static wireless mesh networks when the ETT link metric is used [9], [25], which depends directly on the loss probability, but does not depend directly on the traffic load. Such route instability is also present in the experiments that we present in Section V-B.

The $CATT_l^{L2D}$ metric is a linear (increasing) function of the load-dependent variable τ_j, a property that helps keep the system stable [26]. Two other approaches that add dampening to increase route stability are the following [26]: a) average the link costs over some time interval, and broadcast the average rather than the instantaneous costs, and b) include a minimum update threshold, i.e. broadcast new link costs only if they are larger than the previously broadcasted costs by the minimum update threshold. Indeed, [25], which as mentioned above contains empirical evidence of route instability when the ETT metric is used, proposes techniques to improve stability that are similar to the two aforementioned dampening procedures.

IV. Implementation in OLSR

A key advantage of the Contention-Aware Transmission Time (CATT) metric is that it is strictly isotonic, hence can be implemented in link-state routing protocols with hop-by-hop forwarding. We have implemented the metric in the OLSR (Optimized Link State Routing) protocol [27], and specifically in the OLSR daemon version 0.4.10. The remainder of this paper focuses on the basic metric given by (6), and for simplicity assumes that all transmissions involve packets with the same size.

Routing tables in OLSR are updated based on three types of control messages: Hello messages, TC (Topology Control) messages, and MID (Multiple Interface Declaration) messages. Hello messages are generated per interface, and transmitted to all neighbors; these messages are used for neighbor discovery and MultiPoint Relay (MPR) selection. TC messages carry link-state information which is used for route selection. Finally, MID messages are transmitted by nodes with more than one interface. Route calculation is performed using Dijkstra's algorithm. OLSR daemon's default interval for transmitting Hello and TC messages is 2 and 5 seconds, respectively.

Our implementation of the CATT metric utilizes fields in Hello and TC messages, hence does not require additional control messages. Each node initially obtains the transmission rate of its interfaces; this information is available through MadWifi's Wireless Extensions API. Subsequently, each node broadcasts the transmission rate of its interfaces to all one-hop neighbors using the *willingness* field of Hello messages. Hence, all neighbors have the necessary information to compute the CATT metric for their interfaces using (6), where we assume that the packet size on all links is the same. Next, each node broadcasts the CATT metric to other nodes using the *link quality* field of TC messages.

V. Evaluation

In this section we evaluate our implementation of the proposed CATT metric in the OLSR protocol, for a number of scenarios that correspond to different mesh network topologies. The experiments focus on the basic version of the CATT metric, given by (6), in order to quantify the improvements that can be achieved with a metric that captures contention in multi-rate multi-radio mesh networks more accurately than the loss-dependent metrics ETX, ETT, and IRU.[1]

A. Test-bed description

Our test-bed consists of six multi-radio mesh nodes, each with four wireless interfaces, and a number of laptops with one wireless interface. A mesh node, Figure 1, consists of a mini-ITX motherboard (VIA EPIA Nehemiah M10000G) with a 1 GHz VIA processor and 512 MB memory (DDR400 at 200 MHz). Each node contains four mini-PCI wireless interfaces (WLM54AG, atheros-based High Power 802.11a/b/g mini-PCI cards) placed on a MikroTik Router BOARD 14 four slot mini-PCI to PCI adapter. Each wireless interface is connected to a Triband APXtender 5 GHz, 2.2 dBi indoor antenna. Finally, each mesh node contains a 10/100 Ethernet interface and a 80 GB 2.5" hard disk.

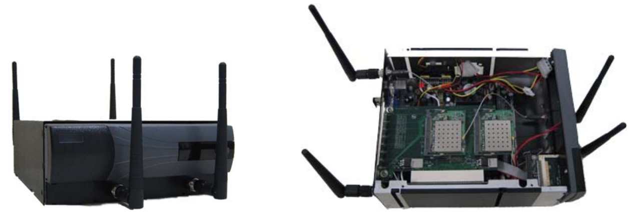


Fig. 1. Four-radio mesh node

Mesh nodes run Ubuntu 7.04 (Feisty Fawn), with Linux kernel 2.6.20-16-generic. The wireless device driver is MadWiFi version 0.9.3.1, and the driver configuration is performed using the Wireless Extensions API.

B. Experiments

The experiments reported in this section include scenarios with both single- and multi-radio nodes, and different transmission rates. Although simple, the scenarios correspond to topologies that will appear in actual mesh networks, in both indoor and outdoor city-wide deployments. For example, both asymmetric links [1], [28] and point-to-multipoint links [29], [30] are common in city-wide and long-distance 802.11 links. Moreover, simple topologies help us understand how the multi-rate nature of wireless networks affects contention, hence the overall performance. Such an understanding can help interpret results from more complex topologies.

The experiments were performed in a 60 square meter laboratory with cubicle walls. In each scenario, there are a number of existing flows with 1498 byte UDP traffic, generated using iperf version 2.0.2. The results show the average throughput when a new flow transmits UDP packets using iperf, and the end-to-end packet delay when a new flow transmits 84 byte packets using ping. We also present latency results for TCP traffic, which is generated by an http client that uses the `wget` utility to consecutively request 500 KByte files from an Apache http server; the interval between consecutive file transfers is exponentially distributed with a 40 second average. Due to space limitations, we present http latency results only for the asymmetric link scenario.

The values reported in the graphs are the average of 5 runs, each run having a duration of 200 seconds. The graphs also show the 95% confidence interval. Finally, all interfaces operate in IEEE 802.11a, with the RTS/CTS mechanism turned off. As noted previously, Hello messages are transmitted every 2 seconds. In addition to neighbor discovery, these messages are also used for estimating the loss probability in the ETX, ETT, and IRU metrics[2]. In our experiments, estimation of the loss probability is performed in 30 second intervals.

1) Single-radio scenario A: Figure 2 shows our initial single-radio scenario. All wireless interfaces are set to ad

[1]We consider the IRU metric rather than the MIC metric, since the latter requires a special mapping to become isotonic.

[2]The ETX metric was already implemented in the OLSR daemon; we additionally implemented the ETT and IRU metrics.

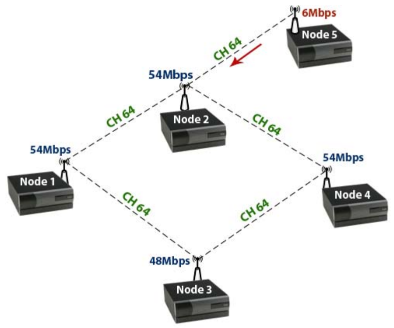
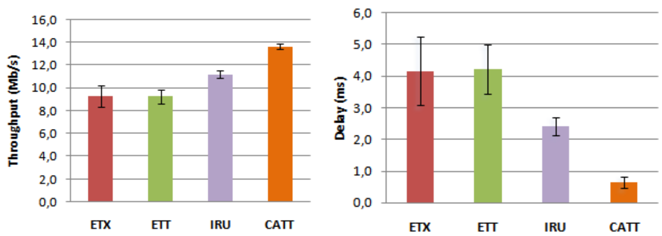


Fig. 2. Single-radio scenario A. There is one flow from node 5 to node 2. The new flow is from node 1 to node 4.



(a) UDP throughput

(b) End-to-end packet delay

Fig. 3. Performance for single-radio scenario A (Figure 2).

hoc mode and the same channel, and their transmit power is reduced so that each node can communicate only with its one-hop neighbors. In this scenario, observe that node 5 has a lower transmission rate (6 Mbps) compared to the other nodes. A new flow appears from node 1 to node 4, for which there are two alternative paths: 1-2-4 and 1-3-4.

Figure 3(a) shows that with the CATT metric, the new flow achieves throughput which is 22% higher than IRU, 48% higher than ETT, and 47% higher than ETX. For all three loss-dependent metrics IRU, ETT, and ETX, the route for the new flow fluctuates between the two available paths: 1-2-4 and 1-3-4. This route flapping stresses the importance of dampening procedures, such as those discussed in Section III-C and [9], [25]. On the other hand, CATT selects the highest throughput path, which is 1-3-4, and this route does not change. ETT tends to select path 1-2-4, because the transmission rate of node 2 (54 Mbps) is higher than node 3 (48 Mbps); hence, dampening procedures that reduce route flapping would not improve the performance of ETT. IRU achieves higher throughput than ETX and ETT, because it selects the higher throughput path 1-3-4 more times, but achieves lower throughput compared to CATT because the route fluctuates between the two alternative routes, due to fluctuations of the packet loss probability; although dampening procedures would improve IRU's performance in this scenario, it would not improve its performance in other scenarios, such as scenario B that we present latter.

Figure 3(b) shows that CATT achieves lower delay compared to the other metrics: 73% lower compared to IRU, 85% lower compared to ETT, and 84% lower compared to ETX.

2) Single-radio scenario B: The scenario is similar to the previous single-radio scenario A, but with additional interfer-

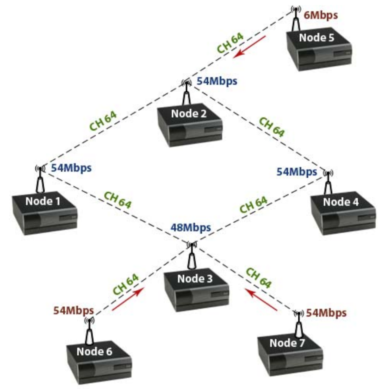
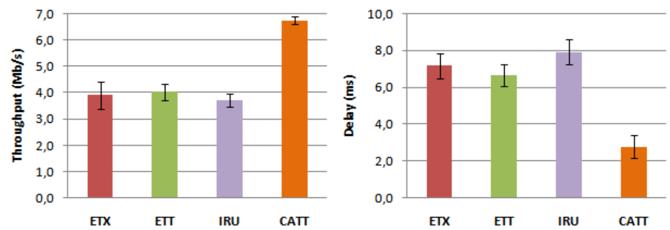


Fig. 4. Single-radio scenario B. There are three existing flows: from node 5 to 2, and from nodes 6 and 7 to node 3. The new flow is from node 1 to 4.



(a) UDP throughput

(b) End-to-end packet delay

Fig. 5. Performance for single-radio scenario B (Figure 4).

ing nodes, Figure 4. As in the previous scenario all wireless interfaces are set to ad hoc mode, and are tuned to the same channel. Each node can communicate only with its one-hop neighbors. A new flow appears from node 1 to node 4, for which there are two alternative paths: 1-2-4 and 1-3-4.

Figure 5(a) shows that the average throughput achieved by the new flow using CATT is 81% higher than IRU, 67% higher than ETT, and 73% higher than ETX. CATT selects the highest throughput path, which is 1-3-4; this is due primarily to the low rate of node 5, which interferes with node 2 and results in path 1-2-4 having lower throughput than path 1-3-4. On the other hand, IRU selects path 1-2-4 because node 3 has more interfering neighbors than node 2. ETT and ETX perform slightly better than IRU, because they select path 1-3-4 more often, since they do not consider the number of interfering nodes as IRU. Nevertheless, with both ETT and ETX the selected route alternates between the two available paths, due to fluctuations of the packet loss probability, and hence they both achieve lower throughput compared to CATT, which does not exhibit route fluctuations.

Figure 5(b) shows that CATT also achieves significantly lower average end-to-end packet delay for the new flow: 65% lower than IRU, 58% lower than ETT, and 61% lower than ETX. The average delay for IRU is a little worst than with ETT and ETX, for the same reasons identified above.

3) Mixed single- and multi-radio scenario: Figure 6 shows a mixed single- and multi-radio scenario. The results presented below are for a new flow from node 1 to node 4.

Figure 7(a) shows that with the CATT metric, the new flow achieves 76% higher average throughput than IRU, 79%

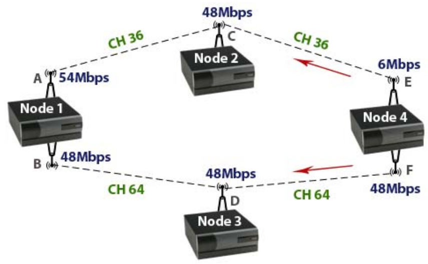
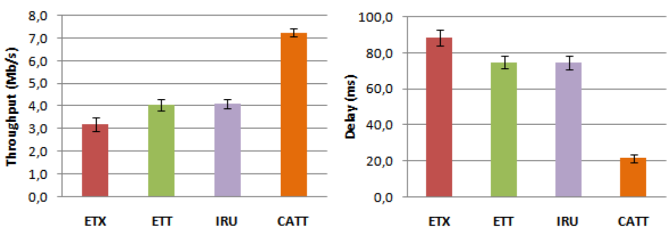


Fig. 6. Mixed single- and multi-radio scenario. There exist two flows: from node 4 to 2 and from node 4 to 3. The new flow is from node 1 to 4.



(a) UDP throughput (b) End-to-end packet delay

Fig. 7. Performance for mixed single- and multi-radio scenario (Figure 6).

higher than ETT, and 126% higher than ETX. Figure 7(b) shows that the CATT metric achieves significantly higher performance also in terms of the end-to-end packet delay: with the CATT metric, the new flow achieves average delay 71% lower compared to ETT and IRU, and 76% lower compared to ETX. CATT achieves significantly higher performance than the other routing metrics because it captures the influence of the very low transmission rate (6 Mbps) of interface E on node 4, which leads it to select path 1-3-4 for the new flow. The other routing metrics do not capture such contention, and select the lower throughput path 1-2-4 most of the time.

4) Asymmetric link scenario: The scenario in Figure 8 contains an asymmetric link between node 2 and node 4. The

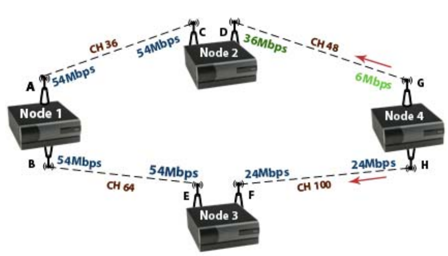
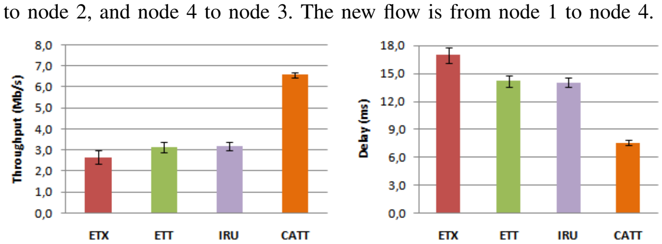
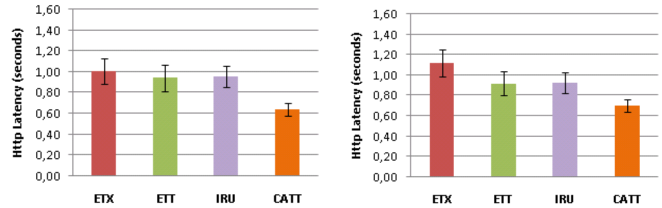


Fig. 8. Asymmetric link scenario. There are two existing flows: from node 4 to node 2, and node 4 to node 3. The new flow is from node 1 to node 4.



(a) UDP throughput (b) End-to-end packet delay

Fig. 9. Performance for asymmetric link scenario (Figure 8).



(a) One http client (b) 10 http clients

Fig. 10. Http latency for asymmetric link scenario (Figure 8).

results presented below are for a new flow from node 1 to 4, for which there are two alternative paths: 1-2-4 and 1-3-4.

Figure 9(a) shows that the average throughput achieved by the new flow using CATT is 106% higher than IRU, 110% higher than ETT, and 147% higher than ETX. This is because IRU, ETT, and ETX mostly select path 1-2-4, since the transmission rate (36 Mbps) of interface D on node 2 is higher than the rate (24 Mbps) of interface F on node 3. On the other hand, CATT captures the interference due to the low-rate (6 Mbps) of interface G on node 4, and selects the higher throughput path 1-3-4. Figure 9(b) shows that the end-to-end packet delay for the new flow with CATT is 46% lower than IRU, 47% lower than ETT, and 55% lower than ETX.

Next we consider the http latency for transmitting, using TCP, finite size (500 KByte) files from an http server to a client, which requests the files using the `wget` utility. In this experiment existing flows contain UDP traffic with a sending rate that is half the transmitting node's rate. Figure 10 shows that the CATT metrics achieves http latency which is lower than IRU, ETT, and ETX by 33%, 32%, and 37% in the case of one client, and 21%, 21%, and 35% in the case of 10 clients.

5) Point-to-multipoint scenario: Figure 11 shows a point-to-multipoint scenario, where the same interface (interface A in node 1) is in the range of two nodes, nodes 2 and 5, where the latter has a low transmission rate (6 Mbps). The results presented below are for a new flow from node 1 to node 4.

Figure 12(a) shows that with CATT the new flow achieves an average throughput which is 16% higher than IRU, 58% higher than ETT, and 54% higher than ETX. The reason is that CATT captures the influence of node 5's low rate. On the other hand, due to route fluctuations, IRU achieves a lower throughput compared to CATT. Figure 12(a) shows that the

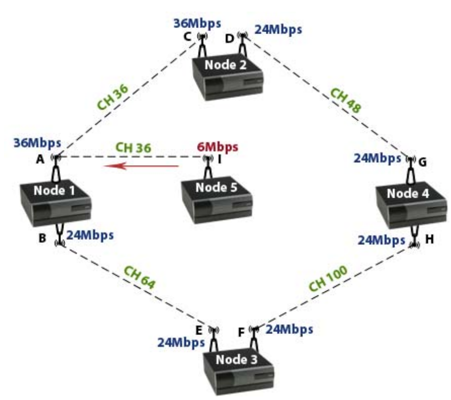
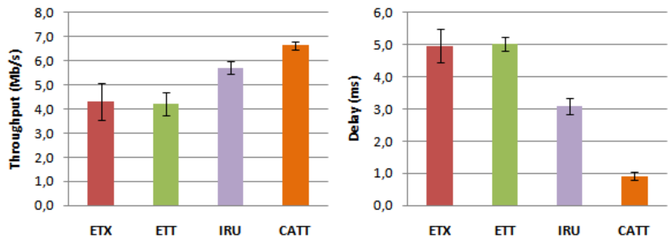


Fig. 11. Point-to-multipoint scenario. There is one existing flow from node 5 to node 1. The new flow is from node 1 to node 4.



(a) UDP throughput (b) End-to-end packet delay

Fig. 12. Performance for point-to-multipoint scenario (Figure 11).

end-to-end packet delay for the new flow with CATT is 70% lower than IRU, and 82% lower than ETT and ETX.

VI. Conclusions

We have presented a new contention-aware routing metric (CATT) for multi-rate multi-radio mesh networks. Key properties of the routing metric is that it captures both location-dependent contention and rate diversity, while being strictly isotonic, which allows it to be implemented in link-state routing protocols that use Dijkstra's algorithm with hop-by-hop routing. The proposed metric has been implemented in OLSR, and experiments have shown that it has significantly higher performance compared to other routing metrics, in a number of scenarios that will appear in actual mesh network deployments, and include asymmetric links and point-to-multipoint links containing nodes with different transmission rates. The key reason for CATT's higher performance is that it captures both the number of interfering links and the level of their interference, which depends on their transmission rate.

Ongoing work is investigating the performance of the CATT metric for a larger number of nodes and in metropolitan scale tests. For the former, we are currently extending our laboratory test-bed to more than 20 nodes, which will include 14 four-radio mesh nodes similar to the ones used in the experiments reported in this paper. For the metropolitan tests, we will utilize the metropolitan wireless mesh network we have deployed in the city of Heraklion[3] [30]. The performance evaluation, in addition to throughput, packet delay, and latency, will include fairness investigations. Future work will also investigate the loss and load-dependent extensions of the proposed metric, and the cases of MAC layer weighted service differentiation and wireless access based on channel holding time.

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