

Selective Link Cost Alteration in Reservation-Based Multi-Hop Wireless Mesh Networks

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Abstract—Link state protocol-driven wireless mesh networks are known for their flexible and highly scalable structure, due to a high degree of individuality, in terms of routing table generation in each connected node. QoS-focused research allows these nodes now to make accurate next-hop decisions based on QoS-sensitive routing metrics. This development enables significantly improved QoS-performance on the network layer. To further adapt link cost calculation to QoS-demands posed by digital media services on higher layers, we propose the Selective Link Cost Alteration (SLCA) scheme, which includes resource reservation demands into the process of neighbor link evaluation, in a distributed fashion. SLCA's goal is to avoid that best effort packets competing with a protection-worthy QoS stream, therefore routing conditions are altered in order to keep the best available path free for QoS-related packets.

Keywords-Wireless Mesh Network; WirelessLAN; Multi-Hop; Multi-Path; Reservation-Based; Policy-Based; OLSR.

I. INTRODUCTION

Wireless Mesh Networks (WMN) based on IEEE 802.11 W-LAN links have long passed the border to offer simple connectivity between wireless nodes and gateways, since a lot of valuable research has been conducted on this field. Due to these improvements, mostly achieved by well supported mesh routing protocols, research on WMNs now merely concentrates on bringing efficient Quality-of-Service (QoS) approaches to WMNs. To create digital media-ready WMNs is the next important step in WMN research, to finally satisfy also consumer demands on modern wireless networks. Integrated QoS enables to handle high definition content and real time communication, without forcing real-time traffic to compete with best effort traffic on a shared medium. Besides classic approaches to encounter QoS problems, such as bandwidth shaping of disturbing traffic or packet prioritization in the MAC layer, WMNs offer a third highly effective feature: rerouting. In the best case, several routes are available to a destination. This allows to chose a different route for QoS streams in order to avoid bottlenecks or saturated links, or even bypass disturbing traffic to the

second-best path, in order to keep the best path “clean” for QoS-related packets. In practice, classic destinations are merely gateways to external host networks, such as the Internet. Intra-mesh client traffic is less common.

The most common approach to improve QoS support in mesh clouds or backbones is by implementing more sophisticated routing metrics. Often cross-layer architectures, which include channel usage and congestion information are used. Since the presented approach is based on, respectively extends the popular Optimized Link State Routing Protocol (OLSR) [1], one of the first QoS-favored routing metrics to consider would be the Expected Transmission Time (ETT). It's a combination of the standard Expected Transmission Count (ETX) metric [1] and the actual bandwidth of a link. Bandwidth, a crucial factor for QoS, is determined via a packet-pair technique [2] within ETT. But making a node aware of such complex link state parameters sometimes comes with a conceptual misbehavior of the load distribution: when more than one next hop is available towards a destination, the entire load (QoS- and potentially disturbing best-effort traffic) tranceived by one of the two end-to-end communication partners, will first be routed towards the best link until it gets saturated and available bandwidth decreases. With ETT then link cost increases due to the usage of the link, which results in a load shift to the next best next-hop. After a while the first link recovers, the load shifts again and the first link is used anew. This results in an oscillating load shift between two next-hops. Such issues make load distribution unpredictable in a larger network scale.

We propose a novel *Selective Link Cost Alteration (SLCA)* scheme with n metric alterations resulting in n routing table variations, which exploits the initially described rerouting ability by distributing reservation messages along the network to reserve concrete bandwidth resources between a source and a destination. Packets not belonging to a reservation are urged to take the next best path. SLCA also solves the described 'load oscillation issue right from

the start, since several paths are used simultaneously, if available.

This paper is structured as followed: Section 2 deals with other research work related to SLCA. Section 3 summarizes the system model. Both Section 4 and 5 then deal with the impact of SLCA. Section 4 depicts SLCA basic algorithm in a concrete example, whose measurement results are summarized in Section 5. Section 6 concludes the work; Section 7 outlines future SLCA improvements.

II. RELATED WORK

Exploiting path diversity with parallel transmissions from a source to a destination is a widely discussed research topic. It has led to a fair amount of multi-path routing protocols in the past few years. One of the more recent ones, developed by Hu et al. [3], is named Multi-Gateway Multi-Path Routing Protocol (MGMP) and extends the Hybrid Wireless Mesh (single path) Protocol (HWMP), which was included in the IEEE 802.11s draft. Their research reveals that using multiple paths to a destination clearly improves QoS parameters such as throughput, delay and packet loss. Similar to standard OLSR and OLSR with SLCA extension, Ghahremanloo [4] compares the standard Ad-hoc On Demand Vector (AODV) protocol with its multi-path version Ad-Hoc On Demand Multi-Path Distance Vector (AOMDV). He comes to the conclusion that AOMDV outperforms single-path AODV in terms of total throughput and end-to-end packet delay. Path diversity was a strong motivation for the SLCA development, but rather in a way that the best path shall be blocked for a priority QoS stream so that alternative paths remain for other traffic. This led to the inclusion of distributed reservations. An initial motivation to investigate routing metric manipulation and link cost alteration was to merge the receiver-initiated Resource Reservation Protocol (RSVP) [5] with the layer 3 routing engine: instead of pure resource reservation through bandwidth reduction of non-reserved traffic along a single path, the impact of using rerouting capabilities for such traffic in every node is investigated here. Concerning RSVP QoS levels, SLCA applies *rate-sensitive* reservations. Köhnen et al. extended the RSVP concept in a broad manner with their QoSILAN approach [6]. QoSILAN aims on providing access technology/layer 2 independent and self-organized QoS resource reservations, in originally unmanaged heterogeneous single path LAN networks. QoSILAN is server-based and relies on collaborative bandwidth shaping of all hosts involved in a packet stream. A host generates an end-to-end reservation message and unicasts it to a control server (QoSILAN manager). This server proactively monitors the network topology and advises all involved hosts of this stream/path to lower the bandwidth of their ongoing processes, in order to keep free the to-be-reserved resource, on a per link basis. The QoSILAN system includes monitoring and classification for outgoing traffic, using a variation of the Statistical Protocol IDentification

(SPID) algorithm [7] and optionally deep packet inspection features. Such a capability describes a mandatory component for SLCA-ready OLSR-based wireless mesh networks, since actual bandwidth demands of services have to be identified by the originator node. Still, this feature is not included; SLCA furthermore offers a QoS framework for networks, which support QoS-traffic detection and classification. SLCA now extends the QoSILAN scheme, in a way that bandwidth used for non-reserved traffic does not have to be lowered by involved nodes, as it is necessary in single-path Ethernet or infrastructure networks, where mostly only one path is available. Furthermore SLCA reroutes those packets, if several paths are available. Also, a distributed solution is preferred to a central one, since it better suits the ad-hoc character of a mesh network. Routing topology consistency across the entire mesh network is a crucial deployment factor for SLCA. It relies on all mesh nodes to individually calculate and maintain the same topology, all with the same link cost values. A condition, which is favored by increasing the OLSR Topology Control (TC) message interval, or by using the OLSR fisheye algorithm [1]. Couto et al. deal with the problem of routing table inconsistency due to high OLSR signaling packet loss rates, which might have a severe impact in large-scale mesh networks. For instance, different views on the real topology might lead to routing loops. To further increase common routing table stability, they propose to include control packet loss rates in the development of new routing metrics. Furthermore, the level of inconsistency in routing tables may be increased by adding receive-acknowledgments for topology control updates to new routing protocols.

III. ROUTING TABLE MANAGEMENT

A. Concept

The proposed system follows a distributed policy-based, or more precisely said, a reservation-based routing approach, implemented in the mesh protocol. A reservation message basically contains the regarding source and destination sockets, the to-be-reserved bandwidth plus flow identification and may be initiated by any single service running on any node in the mesh cloud and is valid for an entire path. The residual bandwidth always remains available for other traffic. Every node individually increases selected link costs on the best path between the source and the destination (their addresses are included in a reservation r_n), according to the demanded bandwidth value. n is the reservation index. This virtually increases the overall cost of the to-be-reserved path. Routing decisions for packets, which match r_n will not be affected by this alteration and therefore will favor the best route/next hop. Routing decisions for all other packets will see the reserved route as virtually burdened. Thus, a rerouting of potentially disturbing traffic is facilitated, no matter if such traffic occurs or not; a contribution to the proactive character of OLSR. Each new reservation n takes up the routing table

valid during the previous reservation r_{n-1} and adds new routing entries for the affected source and destination nodes, according to the demanded resources in r_n .

If the route with the best conditions (when considered in a load-free state) between a source and a destination is now already loaded with other traffic before r_n is distributed, rerouting this non-reserved traffic to alternative routes is facilitated, instead of forcing the QoS-traffic of r_n to take less loaded paths. If the overall path capacity, partially used by a running stream of an active r_n suddenly decreases due to changing link conditions, it is probable that best effort traffic using the same route is shifted to other routes, before the *entire* load (including r_n traffic) would eventually be rerouted. Such load shifting aspects fundamentally differ from those of existing mesh routing concepts.

It is important to notice that SLCA does not describe a full multi-path system, since packets of a single reservation will never be scheduled over multiple paths simultaneously. It is possible and intended though, that best effort traffic to a common destination might take a different route. Due to stream differentiation, load balancing and packet reordering between multiple paths, as common issues in multi-path systems, are of no importance here, since a single flow always takes a single path. SLCA combines concrete and strict resource reservation methods, described in protocols like RSVP or MPLS, with the dynamical mesh routing character, represented by individual next-hop decisions made by every node. The design reflects a “soft” reservation method, since the reservation is not strictly forced and traffic is rerouted only if applicable. As an example, it wouldn’t make sense to reroute disturbing traffic over a route with 4 hops, if the destination is only 1 hop away. On the contrary, SLCA offers strong advantages if several routes are available, which have more or less similar routing conditions. SLCA especially improves the QoS level if the bandwidth of a reserved stream is not constant during transmission, but the maximum peak bandwidth shall still be available constantly. Details on the SLCA algorithm are described in Section IV.

B. Requirements

There are certain general requirements for the used mesh network. At first, r_n has to be known to every node. Therefore, network-wide OLSR topology control messages are chosen for distribution. Every node, respectively its services, must be able to determine bandwidth demand for a stream included in r_n . The ability to predict QoS demands of a service or application, define all necessary parameters required for a valid reservation and generate and trigger a concrete reservation message is therefore considered as given by an external entity, module or program. Our modified OLSR daemon has to run on every node, otherwise topology inconsistency is likely to occur and routing may become unstable, due to differing link cost calculation bases. If SLCA is not active on all nodes in the network, the overall

routing behavior might become unpredictable. SLCA also requires every node to have the same view on the topology, since nodes must be able to frequently calculate the best path between the source and the destination of r_n . SLCA is only effective on multi-hop routes, for example evoked through long inter-node distances or obstacles. If the source and the destination of r_n plus potential disturbers roam all within the same coverage area on a shared medium, the impact of reservation is low.

C. OLSR extensions

Here we briefly mention required additions to OLSR’s core functionalities. OLSR does not naturally generate routing tables with multiple entries for the same target. This ability was therefore added to its routing engine. The routing core is now also able to process the IP source address of a passing packet. This aspect, combined with the ability to poll the port number from the packet’s transport header, is mandatory to finally determine the source and destination sockets of a packet. Finally, a new Wireshark dissector was written to interpret modified TC signaling messages (Wireshark OLSR message type 202).

D. Routing Metric

The SLCA scheme is compatible with any routing metric supported by OLSR, as long as its link cost calculation scheme includes bandwidth as one link quality parameter. Examples for such metrics are WCETT [9], MIC [9] or ETT [2]. For our testbed, we extended ETT (see Eq. 1) in 2 steps:

- 1) By replacing the bandwidth B in the original ETT Equation with the *residual bandwidth* B_{residual} (see Eq. 2). This extension is already more effective than the regular ETT, as it includes the capacity of a link and therefore offers a more accurate picture of the link condition [10]. In our implementation, the necessary maximum link capacity is obtained by a simple statistical bandwidth analysis of the link: the peak bandwidth is measured and stored over a variable time window. After this period, peak bandwidth is supposed to be the highest achievable bandwidth B_{max} of the link. Each time a higher peak is reached, previous B_{max} is replaced with the fresh value.
- 2) By subtracting the reserved bandwidth from the residual bandwidth (see Eq. 3).

$$ETT_{\text{original}} = ETX * \frac{S}{B} \quad (1)$$

$$ETT_{\text{residual}} = ETX * \frac{S}{(B_{\text{max}} - B)} = ETX * \frac{S}{(B_{\text{residual}})} \quad (2)$$

$$ETT_{\text{SLCA}} = ETX * \frac{S}{(B_{\text{residual}} - B_{\text{reserved}})} \quad (3)$$

where S is the packet size in Bytes, ETX is the Expected Transmission Count metric and B is the actual bandwidth value obtained by link probing.

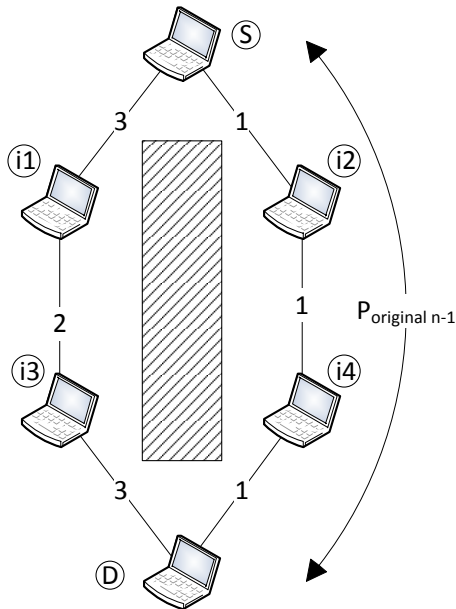


Figure 1. Test setup, no present reservations

Note, that the common advantages of a link cost routing protocol still apply. If the actual link quality changes, whether or not a reservation is active or traffic is present, it will have a proper effect on proactive routing decisions. While using OLSR here, SLCA may be applied to any other link state protocol, as long as routing tables are created in a proactive fashion.

IV. VALIDATION OF CONCEPT

Here, the general steps to put a new, network-wide distributed reservation to practice, are explained through a simplified example. Observing only 6 nodes allows to follow the changing routing table entries in detail. Note that this scenario was also used for performance evaluation in Section V. The distance between nodes is 80m, to favor a multi-hop scenario. A solid obstacle, placed in the middle, also serves to shape the desired topology. For the sake of simplicity, $n = 1$ here. Figure 1 shows the topology present in the network layer; The source (S) will distribute a reservation of 5 Mbit/s for bidirectional traffic with the destination node (D). In this concrete setup, the maximum available bandwidth per link is set to 7 Mbit/s. The corresponding dimensionless link cost values are shown in Figure 2, with the resulting routing table for S. The following steps are performed:

- 1) S is about to start a media stream to D and generates a reservation message m_n , which specifies: $\text{socket}_{\text{source}}$, $\text{socket}_{\text{destination}}$, demanded bandwidth [bits/s] by the stream/application/service, flow ID, transport protocol information (TCP/UDP) and DSCP/DiffServ class priority (yet unused)

Bw _{residual} [Mbit/s]	Cost
7	1
6	2
5	3
4	4
3	5
2	6
1	7

S	Dst	NH	Cost
1	1	3	
2	2	1	
3	1	5	
4	2	2	
D	2	3	

To-be-protected path / next hop

Figure 2. Initial routing table for S with raw link cost map

- 2) m is included in OLSR TC messages and flooded using the OLSR Multi-Point-Relay (MPR) mechanism
- 3) S and the intermediate nodes 1-4 individually determine the best route available from S to D. The best path naturally is $P_{\text{original-n-1}}$ due to the lowest overall cost of 3, which shall be protected.
- 4) All nodes change and extend their original routing tables ($n-1$) by recalculating $i1_n - i4_n$ and by adding additional entries for D_n and S_n , as shown in Figure 3. Note, that intermediate nodes have two entries for S and D, in case they forward packets (mis)matching the reservation criteria. S and D also have routing entries for each other, for packets between them, which do not belong to any reserved stream between the two-end-to-end points (e.g., best effort traffic).
- 5) All nodes adapt the new costs for every single link of $P_{\text{original-n-1}}$: the bandwidth component within the routing metric and it's output is manipulated according to the reserved bandwidth. Link costs on the reserved route are virtually increased accordingly. The updated costs are used by all nodes to recalculate paths to all destinations. A new topology is created as described by Figure 4. Despite virtual worsening, all paths are still load free. $P_{\text{alternative-n}}$ shall now be preferred by disturbing traffic.
- 6) Packets, which match *all* reservation's criteria are allowed to use unaltered routing entries D_{n-1} and S_{n-1} , all other packets are routed according to S_n , 1_n , 2_n , 3_n , 4_n and D_n . In this way S, D and all forwarding nodes between them use the best route for the reserved stream, while all other traffic is urged to not use the virtually more expensive route between S and D, if possible. This leads to less congestion on $P_{\text{original-n-1}}$, which increases QoS level on this path.
- 7) The media stream is running on reserved route. Even if the load situation in the network changes dynamically, selective alteration is always applied to changing link costs.
- 8) Reservation is either actively relinquished by S when the media stream ends, or becomes invalid automatically, due to a validity time counter t added to OLSR (*soft state* - S has to refresh its reservation constantly)

S	Dst	NH	Cost
1 _n	1	3	
2 _n	2	6	
3 _n	1	5	
4 _n	2	12	
D _{n-1}	2	3	
D _n	1	8	

1	Dst	NH	Cost
S _{n-1}	S	3	
S _n	S	3	
2 _n	S	9	
3 _n	3	2	
4 _n	3	11	
D _{n-1}	3	5	
D _n	3	5	

2	Dst	NH	Cost
S _{n-1}	S	1	
S _n	S	6	
1 _n	S	9	
3 _n	S	11	
4 _n	4	6	
D _{n-1}	4	2	
D _n	4	12	

3	Dst	NH	Cost
S _{n-1}	1	5	
S _n	1	5	
1 _n	1	2	
2 _n	1	11	
4 _n	D	9	
D _{n-1}	D	3	
D _n	D	3	

4	Dst	NH	Cost
S _{n-1}	2	2	
S _n	2	12	
1 _n	D	11	
2 _n	2	6	
3 _n	D	9	
D _{n-1}	D	1	
D _n	D	6	

D	Dst	NH	Cost
S _{n-1}	4	3	
S _n	3	8	
1 _n	3	5	
2 _n	4	12	
3 _n	3	3	
4 _n	4	6	

n = 1
 (n - 1)... previous/original table
 to-be-protected
 improvement through re-routing

Figure 3. Simulation Results: Routing Table Development

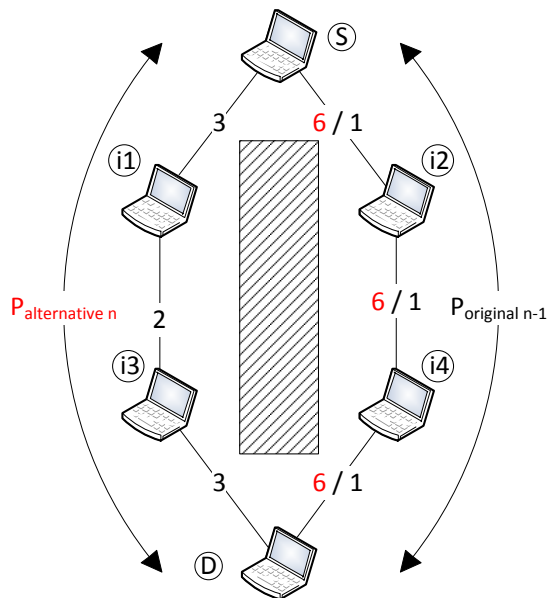


Figure 4. Altered topology with 1 active reservation

Figure 3 reveals that 5 of 6 routing tables show improvements, marked in red, in a way that the next hop decision was altered in favor of the relief of $P_{original-n-1}$.

V. MEASUREMENTS

The QoS performance in terms of bandwidth for the measurement setup depicted in Figure 1 is evaluated. As

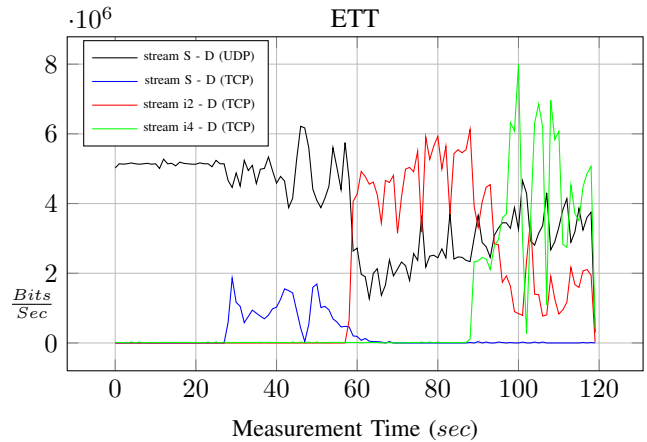


Figure 5. Results: BW comparison of 4 streams with regular ETT metric

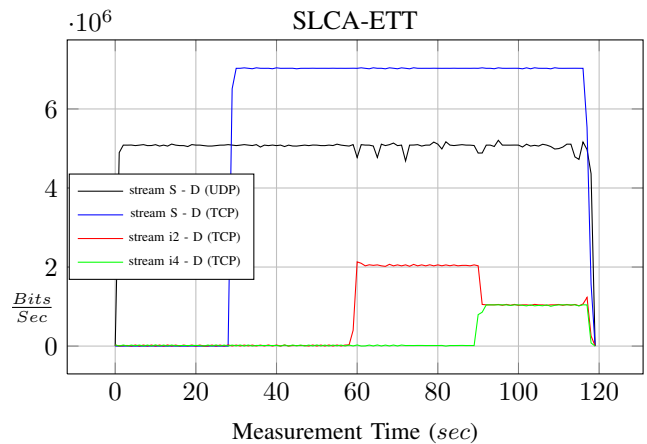


Figure 6. Results: BW comparison of 4 streams with SLCA-ETT metric

a multi-hop simulator, Omnet++ [11] with INETMANET framework [12] is deployed. The IEEE 802.11g mode is used on all links. The overall measurement time is 120 seconds. At first, node S initiates a 5 Mbit/s UDP stream to node D. After 30s, a TCP stream is initiated by S on the same path. The intermediate nodes 2 and 4 start a TCP stream to D after 60, respectively 90 seconds. At first, the regular ETT metric is used; results are shown in Figure 5. Secondly, SLCA is applied. Therefore, S broadcasts a reservation for its UDP stream at 5 Mbits/s, according to Section IV. Now, the next-hops in each node are chosen on a per packet-basis, depending on the to-be-routed packet (whether it matches criteria described in r_1 or not). The results in Figure 6 reveal that the reserved UDP stream suffers from less disturbances by best-effort TCP traffic and offers a more stable performance, in contrast to the unmanaged OLSR scenario in Fig. 5. Also, the two streams initiated by S (TCP and UDP) are separated on both available routes, which exploits the present path diversity.

VI. CONCLUSIONS

The Selective Link Cost Alteration is an experimental resource reservation scheme for WMNs, which facilitates rerouting of potentially disturbing traffic on reservation-protected multi-hop routes. SLCA provides a flexible framework for QoS-related media services in mesh networks. Its concept is adaptable to other QoS metrics as well, since the to-be-altered routing parameter, and its *actual* and *required* value, might be replaced by the packet delay, packet error rate or any other QoS parameter instead. A combination of several parameters is also feasible, in order to enable more precise QoS definitions.

VII. OPEN ISSUES AND OUTLOOK

As a typical problematic condition for both, centralized and distributed reservation systems, its resources are always finite. More than the available resources can't be assigned or managed. Now, research investigates into balancing a certain threshold, in a way that reservations are denied, or not even triggered, if single link capacities are physically limited. Similar to RSVP, a reservation cannot be guaranteed. Contrary to RSVP, the initiator of a reservation is not informed about its feasibility by intermediate nodes. It is intended to solve this issue by adding an unicast signaling message, to confirm a reservation to its originator. Although, such confirmations are not included yet, research has shown that alternating the link costs by considering QoS needs clearly works in favor of intended reservations.

Future performance evaluations of SLCA will also deal with a realistic maximum number of reservations per node. Although the routing table management is scalable and theoretically does not limit the amount of active r_n , too many additional routing entries for each new reservation might result in an unmanageable routing table, or fully occupied computation hardware. n is therefore always finite, which concludes in a threshold for n_{\max} . This threshold defines the state, from where new r_n (apart from pending ones) will have a contrary effect on QoS performance and is yet to be determined by further investigations. Using SLCA in larger mesh clouds without scaling n_{\max} might therefore cause unpredictable network performance problems.

Also SLCA allows for some general, conceptual amplifications. A prioritization of active reservations is desired. In the latest version, the earlier a reservation is registered by OLSR, the more unspoiled bandwidth resources it has available for link cost recalculation; all following reservations then only manage residual resources. This behavior might be replaced by a fairness scheme, which prioritizes reservations based on certain characteristics, even if they have arrived later than reservations for less relevant packet flows. Reservation usage feedback remains also subject to refinement: if a reservation is successfully applied on a multi-hop route, it should be used by the following related traffic as well. Future SLCA versions must register if reserved packets

are actually passing; an action, which requires further cross-layer elements, like statistical packet analysis, in a node. If not, expected packets, which haven't arrived or have arrived only in unsatisfying quantities, have to be announced and the reservation might be canceled ahead of schedule.

As our work is closely related to multi-interface, multi-channel mesh networks [13], it is intended to include channel diversity as another resource in SLCA, to further improve capacity utilization in wireless mesh networks.

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