Aggregation-aware routing in wireless multi-hop networks with frame aggregation

Sascha Gübner and Christoph Lindemann
Department of Computer Science
University of Leipzig
Augustusplatz 10, 04109 Leipzig, Germany

{guebner, cl}@rvs.informatik.uni-leipzig.de

Abstract—**Recently, two trends in wireless communication are observable. First, traffic patterns tend to be unsaturated, due to an enormous increase of traffic types like mobile video and voice streaming. Second, new standards like IEEE 802.11n or IEEE 802.11ac allow huge physical data rates up to several Gbit/s. However, to utilize these data rates an efficient usage of the new frame aggregation feature is necessary. We formulate an analytical model that captures the impact of frame aggregation on routing and transform it into an integer linear program. Furthermore, we propose a heuristic approach that simplifies the computational complexity and show both through extensive simulations and real-world testbed experiments that an aggregation-aware routing scheme helps to efficiently aggregate several unsaturated flows and leads to decreased end-to-end delay and decreased contention in wireless multi-hop networks.**

Keywords-Wireless mesh networks and protocols; Cross layer design and optimization

I. INTRODUCTION

In the last years, there are two trends in wireless communication observable: First, there is a drift towards unsaturated traffic conditions. For example, mobile video is widely considered to become a killer application for wireless networks. According to a recent Cisco forecast [4], mobile video traffic will more than double every year till 2015 and has the highest growth rate of any application category measured within this forecast. Because cellular networks may not be able to keep up with the huge traffic, we suppose that multi-hop mesh networks may be an option to cope with the increased traffic demands arising from mobile video streaming, especially from High Definition (HD) video. Other high potential fields of application for video streaming over mesh networks include real-time video streaming for emergency coordination or wireless video surveillance systems, e.g. for public safety or on building sites.

The second trend observable, is the introduction of new and fast communication standards, like IEEE 802.11n [9] and IEEE 802.11ac [8]. For example, with IEEE 802.11n, high physical data rates up to 600 Mbit/s are achievable. However, these high data rates on the physical layer can only by harnessed at upper layers, if the medium access is efficient [17]. Therefore, IEEE 802.11n introduces frame aggregation on the MAC layer. With frame aggregation, multiple subframes can be transmitted in an aggregated frame, with the overhead for medium access and physical header transmission arising only once. With increasing data rate this overhead would otherwise quickly overcome the actual transmission duration. Note that frame aggregation will also be a key technology in the upcoming standard IEEE 802.11ac.

Although vital for an efficient usage of the provided physical data rate, frame aggregation has drawn very little attention in academia, especially frame aggregation in multi-hop networks. Thus, in this paper, we first want to point out, how important the interplay between routing and frame aggregation is, especially for unsaturated traffic conditions. Therefore, we give in the next section a simple example topology and shed light on the frame aggregation mechanism. Thereafter, we propose a framework to optimize routing decisions in general multi-hop networks with frame aggregation. Our contributions can be summarized as follows:

- We formulate a graph-based model that captures the interplay between frame aggregation and routing and transform it into an integer linear program
- We propose a heuristic approach that converts the integer linear program into an easier computable linear program
- We extend our model to a decentralized aggregation-aware routing scheme to efficiently aggregate unsaturated streams in wireless multi-hop networks
- We demonstrate the performance of our aggregation-aware routing approach and show that it reduces the average end-to-end delay and end-to-end loss

The remainder of this paper is organized as follows. In Section II we go into detail on frame aggregation. In Section III we introduce our analytical model and propose our heuristic approach in Section IV. In Section V we evaluate the impact of our routing scheme both through experiments and simulations. We discuss related work in Section VI and conclude in Section VII.

II. DETAILS ON FRAME AGGREGATION

With increasing data rates at the physical layer, the time needed for collision avoidance of IEEE 802.11 MAC and the physical layer convergence procedure exceeds the time needed for the transmission of an actual data frame. This overhead is on the one hand due to compatibility constraints and to provide interoperability between IEEE 802.11 devices operating at different data rates. On the other hand, this overhead arises due to physical constraints, like the time needed to switch from receiving data to sending an acknowledgement or the physical convergence procedure. Note that this also holds for the upcoming IEEE 802.11ac [8]

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standard. Due to this constant overhead, the efficiency of the IEEE 802.11 MAC hugely decreases for higher physical data rates [17].

Frame aggregation, we mean throughout the paper A-MPDU aggregation, allows the transmission of multiple frames, called subframes in a sequence, with the overhead for medium access and physical header transmission arising only once. To demonstrate the impact of frame aggregation, we review the example topology in Fig. 1. In both topologies A and B there are 4 nodes with two flows. If assuming perfect channel conditions, the best routing for f_2 is quite obvious a direct transmission from 2 to 4. But does it make a difference how we route f_1? In the case of unsaturated traffic over links with frame aggregation, the answer is yes. Due to various mechanisms in the IEEE 802.11 MAC, the overhead time T_{OH} before and after a transmission can be calculate by:

$$T_{OH} = T_{DIFS} + T_{cw} + T_{PHY} + T_{SIFS} + T_{ACK} \tag{1}$$

The overhead arises before a data transmission (a DCF interframe space (T_{DIFS}), the decreasing congestion window (T_{cw}), and the transmission of the physical header (T_{PHY})) and afterwards (short interframe space (T_{SIFS}) and the transmission of an acknowledgement (T_{ACK})). Note that this overhead is even bigger if RTS/CTS is used and that this time is independent of the amount of data sent. If we further assume that 1 and 4, and 2 and 3, respectively, are within interference range, and if we assume an aggregate size of 1 subframe per frame, we can calculate the sum of all transmission durations by:

$$\begin{aligned} T_A &= 3 \cdot (T_{OH} + T_{frame}) \\ T_B &= (T_{OH} + 2 \cdot T_{frame}) + (T_{OH} + T_{frame}) \end{aligned} \tag{2}$$

So we have in the first case 3 transmissions with one subframe per aggregate each and in the second case one transmission with one subframe per aggregate (1→2) and one transmission with 2 subframes per aggregate (2→4). This relates to a theoretical improvement of 40% for the time needed to transmit at a physical data rate of 300 Mbit/s. Another advantage of topology B is the decreased contention, due to the reduction of contending transmitters; 2 nodes instead of 3. Measurement results of our indoor mesh testbed underlining the theoretical analysis are given in section V.

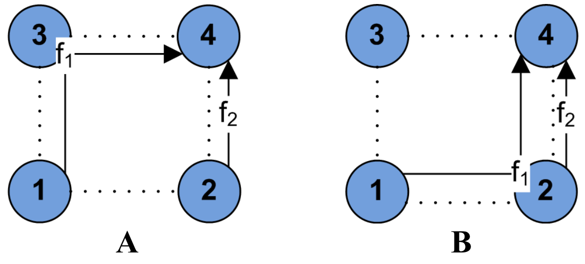

Figure 1. Sample topologies illustrating the impact of Frame Aggregation

III. ANALYTICAL MODEL

To investigate the influence of the frame aggregation mechanism on multi-hop communication in wireless networks, we formulate in this section our analytical model. The aim of this modeling approach is to minimize the overall transmission overhead, as a result of inefficient aggregation. As the metric to minimize, we use the time needed to route a batch of packets from all sources to their correspondent destinations. Note that this approach differs from other approaches, aiming to maximize throughput, as we consider transmission time minimization under unsaturated traffic conditions. We introduce our graph-based network model and transform it into a multiple commodity flow problem with fixed costs. We then examine the effects of interference and spatial reuse and adjust our model accordingly. Thereafter, we propose a decentralized practical framework for our model.

A. *Analytical Model*

We consider a single-radio, single-channel wireless multi-hop network with a topology described by a directed connectivity graph $G = (V, E)$. Here, V denotes the set of all nodes in the network and E the set of all links between the nodes. Furthermore, we assume that a bandwidth function B and a set of demands D is given. B represents the physical bit rates of the links in G. The demands D are described by pairs of source ($n_{S,k}$), destination ($n_{D,k}$) and mean aggregate size (d_k), for every stream k in the network. Furthermore, we define the number of concurrent streams K as $K = |D|$.

We model the problem as an integer linear program (ILP). We denote $a_{u,v,k}$ as the aggregate (mean number of subframes) of stream k traveling over the link $(u,v) \in E$ of the network. We denote s_{pkt} as the average packet size and $c_{u,v}$ as the maximum allowed aggregate size on link $(u,v) \in E$ of the network. This is 64 for IEEE 802.11n and IEEE 802.11ac, respectively, but may differ dependent on the used hardware. The ILP formulation is then given by:

$$\begin{aligned} &\min \sum_{(u,v)\in E} \Big[\sum_{k=1}^{K} \frac{a_{u,v,k} \cdot s_{pkt}}{B_{u,v}} + y_{u,v} \cdot T_{OH}\Big] \\ &\text{s.t.} \\ &1.\ a_{u,v,k} \geq 0, \quad \forall (u,v) \in E, 1 \leq k \leq K \\ &2.\ \sum_{(u,v)\in E} a_{u,v,k} - \sum_{(v,u)\in E} a_{v,u,k} = \begin{cases} d_k, u = n_{S,k} \\ -d_k, u = n_{D,k} \\ 0, \text{else} \end{cases} \\ &3.\ \sum_{k=1}^{K} a_{u,v,k} \leq y_{u,v} \cdot c_{u,v}, \quad \forall (u,v) \in E, y_{u,v} \in \{0,1\} \end{aligned} \tag{3}$$

The first constraint assures that all routed aggregates on each edge are non-negative. The second one is the aggregate conservation constraint, i.e. aggregates are only produced by streaming sources and are consumed only by their appropriate destinations. If a node is neither one of this, it only forwards the aggregates while the aggregate size for a certain stream remains constant. The last constraint assures that the maximum aggregate size on a link is not exceeded. The binary variables $y_{u,v}$ are 1 if an aggregate is transmitted over link (u,v). Note that due to the minimization of the objective function they usually are also 1 only iff really an aggregate is transmitted.

The aim of the objective function is to reduce the overall transmission time to reduce unnecessary transmission delays, lowering energy consumption and further reducing medium contention. We define the transmission time to be the sum of a fixed constant part (the transmission overhead due to physical convergence, MAC acknowledgement transmission etc.) and a variable part (time for the actual data transmission dependent on the bit rate on that link). Note that the constant overhead part only arises if the link is really used. Therefore we multiply it with the active-link-indicator $y_{u,v}$. Note further that our model can also be extended to take other metrics, like the expected transmission count (ETX) [5] into account, for example by multiplying it to the transmission time of each link.

B. Interference Modeling

The current problem formulation doesn't take the effects of half-duplex transmission, interference and spatial reuse of the wireless medium into account. We address these problems by extending our model using a conflict graph, like in [11]. An undirected conflict graph $G_C = \{N_C, E_C\}$ for a given network describes the relations between the links of the corresponding connectivity graph. The set of nodes N_C of the conflict graph corresponds to the set of links E in the connectivity graph. For simplicity, we assume here unweighted edges, representing a distance based model of interference. In this model, an edge in the conflict graph exists, if the two corresponding edges in the connectivity graph are within a certain interference range (R_I). To reflect the situation in IEEE 802.11, where both the transmitting and the receiving node of a link mustn't be in the interference range of another node, we define the edges in the conflict graph more precisely: $\{(u,v),(u',v')\} \in E_C$, iff $\|a,a'\| < R_I$, with $a \in \{u,v\}$, $a' \in \{u',v'\}$, and the Euclidean distance $\|\cdot\|$. We define the set $I_{u,v}$ of interfering links of a single link (u,v) by:

$$I_{u,v} = \{(u',v') \mid \{(u,v),(u',v')\} \in E_C\} \tag{4}$$

To better approximate the spatial reuse in wireless networks, we use the concept of independent sets in the conflict graph. An independent set in a graph is a set of nodes, where no two nodes of the set are adjacent. In the sense of a conflict graph, this means that all links in an independent set can transmit in parallel. We use this concept to only consider the transmission time for each active independent set. Then, the objective function can be seen as the total time needed to transport a batch of packets (an aggregate) from all sources to their appropriate destinations.

We further want to find maximal independent sets, which are sets that can't be enlarged any further. This means that adding any further node to the set would result in a violation of the definition of an independent set, i.e. at least two nodes in the set share an edge. Note that finding all maximal independent sets is NP-complete, therefore we propose Algorithm 1 as a greedy heuristic. It creates the set S of independent sets assuring that that each link of the connectivity graph is at least in one independent set. Note that there are not necessarily $|N^C|$ independent sets in the conflict graph, but Algorithm 1 assures that each node is at least once in a subset of S. Note further, that Algorithm 1 can be changed to also reflect the physical interference model. We add these independent sets to our ILP and modify the objective function by:

$$\min \sum_{I \in S} [\lambda_I \cdot \max\{T_{u,v} \mid (u,v) \in I\}], \quad \lambda_I \in \{0,1\}$$

$$T_{u,v} = \sum_{k=1}^{K} \frac{a_{u,v,k} \cdot s_{pkt}}{B_{u,v}} + y_{u,v} \cdot T_{OH} \tag{5}$$

Here, λ_I are binary variables indicating if independent set I is active. The transmission time for this independent set is set to the maximum transmission time of its links. To determine if an independent set is active, we further have to add the following constraint to our ILP:

$$y_{u,v} \leq \sum_{I \in S \wedge (u,v) \in I} \lambda_I \tag{6}$$

This inequality assures that a link in the connectivity graph can only be active, if it is in at least one active independent set. The value of the objective function is directly related to the time needed, for all aggregates to be shipped from their respective sources to their destinations. Note that we only approximate the optimal solution by adding only a subset of all possible sets (for example at most $|N^C|$ in Algorithm 1) as we would have to add potentially exponential many independent sets for a given graph to find the optimal solution. Therefore, we do not exactly model the end-to-end delay of all streams.

<u>Algorithm 1</u>

```
S = ∅
for u ∈ N_C
    I = {u}
    for v ∈ N_C \ {u}
        violation_found = false
        for v' ∈ I
            if {v,v'} ∈ E_C then violation_found = true
        end for
        if violation_found = false then
            I = I ∪ {v}
        end if
    end for
    S = S ∪ {I}
end for
return S
```

Figure 2. Algorithm to find maximal independent sets

C. Decentralized solution

We integrate our approach into OLSR, a well-known proactive routing protocol. The advantage of OLSR is that the current topology is known by every node, allowing us to derive the connectivity graph directly out of OLSR's topology representation. To deduce the interference graph, we exploit the 2-hop neighborhood information, maintained by OLSR. We assume that two links interfere with each other, whenever the sender of one link and the receiver of the other are in each others 2-hop neighborhood. To derive the other needed information, we implemented a cross-layer component gathering information about the mean aggregate size at each node and to find source-destination pairs. To this goal, the component reports on MAC-layer the mean aggregate size of packets originated from this node and their appropriate destination. So we know for each stream its source, destination and the resulting approximate mean aggregate size. This information is posted to the routing layer, i.e. the OLSR agent on that node. The agent propagates the destination and aggregate size pairs to its neighboring nodes by piggybacking them on the extended OLSR HELLO-messages. To allow a sufficient look at the topology, the information about a stream source-destination pair is also distributed in the topology control messages of OLSR. However, to avoid an excessive computational overhead, only the sources of a stream calculate the best routing choice for their streams. If the route for a stream changed from the previous run, it is propagated through a special OLSR unicast packet. The packet contains the whole route and is directed to the streaming destination. Each node on the derived route extracts its next hop, updates its routing table for this stream and resends the packet to its next hop.

IV. DYNAMIC SLOPE SCALING HEURISTIK

We propose to use a heuristic approach to solve the integer linear program. Note that the fixed charge network flow problem is in general NP-hard and even its approximation within a factor is NP-hard. We therefore extended a technique known as dynamic slope scaling [13] to be used with multiple flows in our model. Dynamic slope scaling relaxes the binary constraints of our problem formulation and iteratively computes approximations to the solution of the original problem. Starting with the original problem formulation in (3) we relax the binary constraint of the $y_{u,v}$, denoting active links. We then compute a solution of the now linear program and adapt the flow-dependent costs of each arc. Thus, in each iteration the variable costs, $s_{pkt}/B_{u,v}$ in our case, are recomputed to match the costs with the fixed overhead costs. In each iteration, the fixed costs of the used link are added proportionally to the variable costs. We have the following update rule for the variable costs of an arc, denoted as $\upsilon_{u,v}$:

$$\upsilon_{u,v}^{i+1} = \upsilon_{u,v}^{0} + \frac{T_{OH}}{\sum_{k=1}^{K} a_{u,v,k}^{i}} \tag{7}$$

Here, υ^{i+1} and a^{i} denote the value of the variable costs and the aggregate size at the *i+1*-th and *i*-th iteration of the algorithm. Note that υ^{0} is set to the initial variable costs $s_{pkt}/B_{u,v}$ for each link. If in the next generation the same amount of flow is routed over that arc again, the real costs are perfectly matched. The heuristic stops, when no further changes occur in the variable costs.

For our interference modeling approach with independent sets, we relax the λ_I's, to take both the interference constraints given by the independent sets and the overhead constraints into account. We adapt the objective function to:

$$\min[\alpha \cdot \sum_{I \in S} (\lambda_I \cdot T_{MAX}) + (1-\alpha) \cdot \sum_{(u,v) \in E_C} (\upsilon_{u,v}^{i} \cdot \sum_{k=1}^{K} a_{u,v,k})], \alpha \in [0,1] \tag{8}$$

The first term reflects a weighted version of (5), where we replaced the real value $T_{u,v}$ with T_{MAX}, a fixed, worst-case value of the duration of a transmission. We set it to the transmission duration of a fully aggregated frame. The second part is the heuristic version of our initial objective function Note that $\upsilon_{u,v}^{i}$ are the costs as defined in (7). We set the weighting factor α to 0.5 in all our simulations.

To examine the convergence behavior, we use the linear programming solver package *GLPK* on a working PC with an Intel Core2 Duo 3GHz CPU. We created 10 different problems of the given number of nodes and calculated the time and iteration count needed for the heuristic to stop. We observe a fast convergence in time and iteration count of the procedure. The results are depicted in Fig. 3 and Fig. 4.

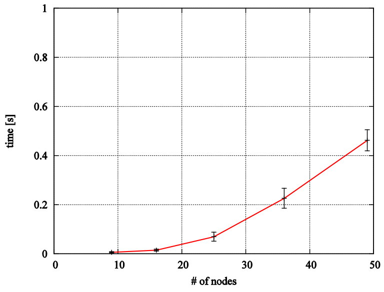

Figure 3. Convergence of the proposed heuristic (computational time vs. number of nodes)

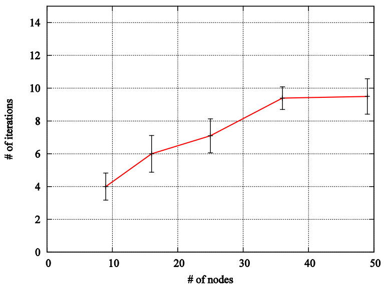

Figure 4. Convergence of the proposed heuristic (number of iterations vs. number of nodes)

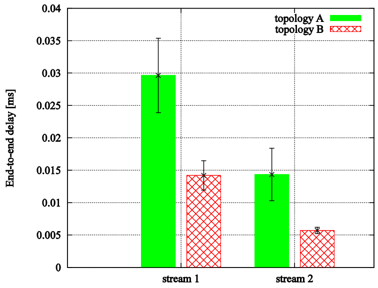

Figure 5. Comparison of the end-to-end delay between both routing schemes in Fig. 1.

V. EVALUATION

A. Example toplogy

We evaluated the difference between the routing schemes depicted in Fig. 1 by conducting two experiments using 4 nodes of our indoor mesh testbed (the interested reader is referred to [7] for more details). We used static routing according to the topologies depicted in Fig. 1. We employ the traffic generator *iperf* [10] to create unsaturated constant bit rate traffic over UDP with a streaming rate of 20 Mbit/s over 30 seconds. We logged the traffic using *tcpdump* on all time-synchronized source and destination nodes. We repeated each experiment 10 times and calculated the average end-to-end delay and the average end-to-end loss. We observe in Fig. 5 that the end-to-end delay is greatly affected by the different routing schemes. It halves for both streams in the optimized topology B. We believe that this is, on the one hand, because of the increased aggregation and thus lower overheads. On the other hand, the medium contention is decreased, as only 2 instead of 3 nodes have to send data. We observe a similar picture in Table I, where we depicted the end-to-end loss for both topologies. We note that the end-to-end loss drops around 35% for both streams f_1 and f_2. This is again evidence that due to the optimized routing the medium contention decreases.

B. Simulation Environment

We evaluate our aggregation-aware routing scheme (AAR) through simulations in the network simulator NS-2 (version 2.34). We implemented the IEEE 802.11n frame aggregation scheme as an extension of the normal IEEE 802.11 MAC layer according to the IEEE 802.11n specification. We disable the RTS/CTS handshake and consider a channel bandwidth of 300 Mbit/s. We use constant bit rate traffic and set the payload size of data packets to 1,460 bytes. We compare our proposed decentralized approach to the routing protocol OLSR with ETX (expected transmission count) metric used. To integrate our approach into NS-2, we extend the UM-OLSR package as described in Section III E to have a fully decentralized solution. Each source uses our heuristic solver whenever an update event occurs. We start each measurement after a setup time and simulate 10 seconds of traffic to derive the considered performance metrics.

TABLE I. COMPARISON OF THE END-TO-END LOSS BETWEEN BOTH ROUTING SCHEMES IN THE EXAMPLE TOPOLOGY IN FIG. 1

	End-to-end loss for topology A	***End-to-end loss for topology B***
Stream 1	1.5714 %	0.9958 %
Stream 2	0.0362 %	0.0235 %

We divide the traces into batches with 1000 packets each to derive the 95% confidence intervals.

C. Grid topology

We use a mesh-typical grid-topology for our evaluation, setting the neighboring node distance allowing direct communication only to adjacent neighbors. We vary the grid size from 4 to 7, resulting in 16 to 49 nodes, respectively, and set the number of concurrent streams to match the used grid size minus 1. We use a streaming rate of 20 Mbit/s for all streams and repeat each configuration 10 times with randomly varying source-destination pairs. We compare the average end-to-end delay and the end-to-end loss for each stream between OLSR and AAR. We calculate the per stream reduction and derive the geometric mean for all streams in each repetition. We observe in Fig. 6 that for each grid size aggregation-aware routing reduces end-to-end delay and end-to-end loss, leading to up to 40% fewer losses. However, we notice that this effect flattens for larger grid sizes, possibly due to fewer aggregation possibilities. In the next experiment, we take a deeper look at the per stream gain in the end-to-end delay and end-to-end loss. We consider a random 4x4 grid topology where we set the wireless parameters to match the IEEE 802.11ac draft, with a data rate of 1.73 Gbit/s. We have 3 short streams (2, 3, and 4) and one long stream (1). Our routing approach aims to combine the short streams with the long stream. Both the end-to-end delay, depicted in Fig. 7, and the end-to-end loss, depicted in Fig. 8, decrease for nearly all streams, especially for the long one. The cooperative routing reduces the number of needed transmissions and of contending nodes, reducing the delay, as time costly MAC retransmissions occur less often, and, end-to-end loss, as also collisions occur less often (over 50% fewer compared to OLSR). We observe that nearly all streams profit from this approach, only stream 4 gaining only little benefits, as it lies in a heavy contented area.

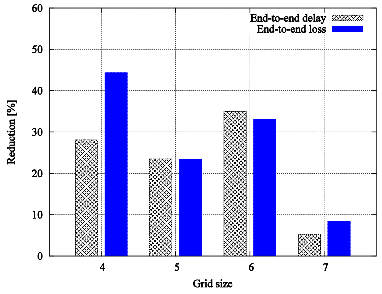

Figure 6. Average reduction of end-to-end delay and end-to-end loss vs. grid size for AAR compared to OLSR.

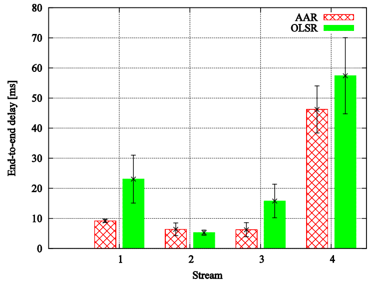

Figure 7. End-to-end delay per stream in an example topology for our approach and OLSR/ETX.

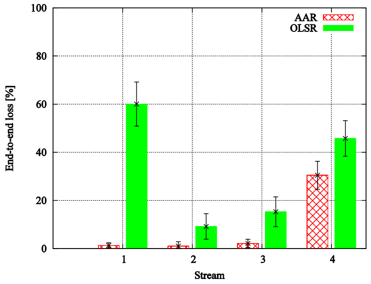

Figure 8. End-to-end loss per stream in an example topology for our approach and OLSR/ETX.

VI. RELATED WORK

In [16], the authors proposed the expected end-to-end delay metric. They herein considered both the transmission and the queuing delay and evaluated different DSR-based routing protocols in simulation studies. Ancillotti et al. [1] proposed a load-aware route selection algorithm, designed to identify network bottlenecks and to allocate network paths to ensure a more balanced utilization of the network. Opposed to [1] and [16], we focus on frame aggregation as an important factor for routing decisions, which these works didn't took into account.

Karlsson et al. [12] considered an aggregation-aware forwarding scheme in multi-path networks. They show through simulations that an aggregation-aware forwarding strategy leads to increased throughput and decreased delay. Opposed to [12] we consider global single-path routing optimization in this paper, instead of local forwarding strategies in multi-path networks. In [18], Sheshadri et al. conducted a large measurement study concerning the performance of standard routing protocols in wireless multi-hop networks with IEEE 802.11n. Opposed to [18], we developed a new aggregation-aware routing approach overcoming the drawbacks of previous routing protocols. In [15], Lee et al. showed through simulations that using multiple receiver frame aggregation with pseudo-broadcast can significantly increase the number of supported VoIP streams in a multi-hop network. In [3], Cai et al. presented an analytical model for studying the impact of frame aggregation and bidirectional transmission on voice and video performance for different aggregation schemes. Li et al. [17] proposed an analytical model assuming saturated traffic. They derived the effective throughput and optimal frame and fragment sizes for single-hop WLAN communication. In own previous work [6], we developed an analytical model for characterizing the effective throughput for a multi-hop chain topology in IEEE 802.11n wireless mesh networks. Opposed to [3], [6], [15], and [17], we consider a global routing optimization in multi-hop networks to naturally increase the aggregation on each node without actually changing the MAC standard.

Kim et al. [14] proposed a modification of the IEEE 802.11 MAC to allow aggregation of unicast and broadcast frames. They evaluated it using a wireless node prototype. In our own preceding work [7], we conducted various experiments in our wireless testbed, focusing on the impact of frame aggregation on streaming performance in terms of delay and packet loss. Bhanage et al. [2] proposed a backlogged queue aggregation approach that adaptively changes the aggregate size and both considers delay penalties and packet error rates. Furthermore, they tested their algorithm in a real-world WLAN setup. Opposed to [2], [7], and [14] we consider a global routing optimization in multi-hop networks to minimize delay and contention instead of changing local aggregation mechanisms.

VII. CONCLUSION

We showed in this paper through testbed experiments and simulations that under unsaturated traffic conditions aggregation-aware routing impacts end-to-end delay and contention among several streams. We formulated an analytical model capturing the impact of frame aggregation on routing decisions and derived a decentralized routing solution. We proposed a heuristic approach that transforms the complex integer linear program into a linear program. We showed through simulations that our aggregation-aware routing scheme reduces both end-to-end delay and end-to-end loss in multi-hop networks. For future work, we plan to implement and evaluate our decentralized solution in our real-world testbed. We further want to combine our global routing optimization approach with a local node-based aggregation optimization scheme to further improve its performance.

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