LETTER

Boosting VoIP Capacity of Wireless Mesh Networks through Lazy Frame Aggregation*

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SUMMARY   A novel method of voice frame aggregation for wireless mesh networks is presented. In the method, the degree of aggregation is automatically regulated by the congestion level on the wireless link. On the IEEE 802.11-based mesh network, it is shown to yield approximately twice the call capacity, while incurring no additional delay for frame aggregation.
key words: *frame aggregation, mesh, VoIP, WLAN*

1. Introduction

With the emerging mesh networks [1], the prospect of VoIP traffic flowing on multi-hop wireless path is fast becoming a reality. Unfortunately, VoIP traffic has been shown to be highly inefficient even in single-hop wireless networks [2], which is only exacerbated in multi-hop networks due to routing message loss [3], beat-down problem, and spatial interference such as the exposed terminal problem. Let us consider the example multi-hop network in Fig. 1.

Suppose the voice traffic arrival rate at each end node is denoted by λ, so the voice traffic arrival rate to an intermediate node is $2v\lambda$, where v is the number of ongoing calls. With the G.729 codec [4] with 20 ms payload, $\lambda = 50$ pkts/s. The average transmission time of a RTP/UDP/IP-encapsulated G.729 voice frame on an uncongested 802.11b link is around 835 μs [2], making the service rate $\mu \approx 1,200$ pkts/s = 24λ. The total traffic sensed or relayed at the bottleneck node, node 2, dictates the throughput of the entire network. For $v = 3$, the node spends 6λ for transmission (for relaying), 6λ for reception (from node 1 and 3), 6λ overhearing node 1 and 3's transmission (to the end terminals), and at least 3λ for the sensing (but not receiving) the end terminals' transmissions. Then the total load on the node 2 is $21\lambda < \mu$, which is also the load on the most congested node for more elongated call paths. But as v increases to 4, the total load is $28\lambda > \mu$. Therefore, with the 4-hop constraint the maximum number of sustainable G.729 calls on 802.11b-based mesh network is merely 3. This poor performance is due mainly to the spatial interference, which wastes over 70% of the total capacity in Fig. 1.
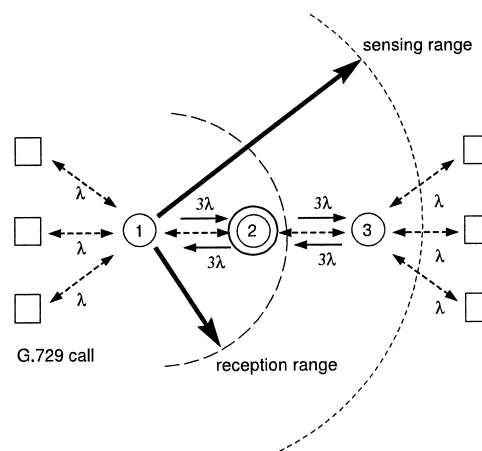
Fig. 1   Example topology with $v = 3$ voice sources and $h = 4$ hops.

2. Lazy Frame Aggregation (LFA)

Voice frame aggregation [2], [5]–[7] can reduce the absolute number of MAC frames on the wireless link and consequently alleviate the spatial interference illustrated in Fig. 1. The conventional aggregation methods can be classified as the "eager" type, where the aggregation is always performed with a fixed aggregation delay, hence irrespective of the congestion situation in the network. In our previous work [2], we showed that *lazy* frame aggregation (LFA) can outperform these eager methods in terms of the number of sustainable calls in the single-hop wireless environment. This letter evaluates the efficacy of the LFA method in the multi-hop wireless mesh network environments.

The core idea of the LFA in the multi-hop wireless environment is that at each wireless router, we pack the voice frames from the same call that concurrently reside in the LLC queue at the time of aggregation into the same MAC frame, without waiting for any more voice frames to arrive. The philosophy here is that we save bandwidth through frame aggregation exactly by as much as there is bandwidth shortage (i.e., congestion) [2]. By simply packing as many voice frames together as induced by the given load condition on the 802.11 WLAN, the LFA algorithm always finds the optimal degree of aggregation, and does not incur any unwarranted delay cost. This is in sharp contrast to the existing frame aggregation methods [5]–[7] that operate with a fixed frame aggregation delay budget. Queuing-theoretically, the LFA can be closely approximated by M/M/1//M, which is
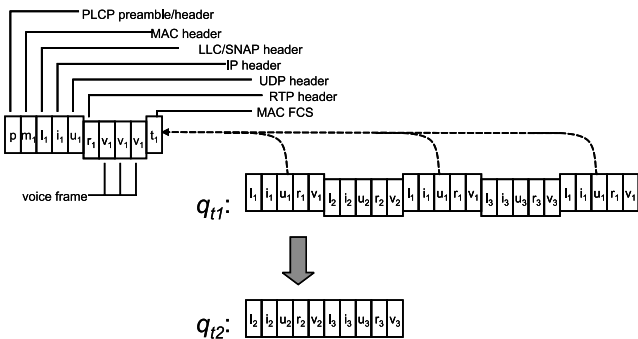
Fig. 2   LFA operation example.

known to be strongly self-regulating in face of congestion [2].

Figure 2 depicts the operation of the LFA scheme. At time t_1, the queue has 5 LLC/SNAP encapsulated voice frames (q_{t_1}). When the first voice frame is removed from the queue for MAC transmission attempt, the voice frames from the same call ("1") are coalesced into the same MAC frame. As a consequence, a MAC frame carries out three voice frames from the queue, while the voice frames from other calls ("2" and "3") are left in the queue for later transmissions (q_{t_2}).

3.   Experiments

Now, we evaluate how effective the LFA is to help boost the call capacity for the multi-hop wireless networks through simulation. For simulation, we use `ns-2` [8]. We assume that VoIP traffic is constant bit-rate (CBR) traffic with a 20 ms interval, as in the G.729 codec (i.e., the voice activity factor α is 1). The default values defined in the 802.11b standard are used for the MAC parameters [9]. Other parameters used in the evaluation are summarized in Table 1. As to the simulation topology, we assume the linear topology as shown in Fig. 1. Each experiment simulates 300 seconds of the system dynamics, of which the first 30 seconds are discarded as perturbation. For each case, 3 simulation instances are run with different seeds.

In Fig. 3, we can estimate the number of supportable calls versus the number of hops that the calls travel before it breaches the delay requirement. We regard the delay as the primary QoS metric since in the 802.11 WLAN environment, the frame loss on wireless channel is mostly translated to delay by retransmissions up to 4 or 7 times. Here we assume that each wireless router queue has 50 slots, which roughly maps to 50 ms of queuing under the maximum 802.11b speed of 11 Mbps. It is about 20% of the rule-of-thumb guideline for Internet router configuration [10], but we use a smaller value since the VoIP traffic must go over multiple wireless links in the mesh network, and there could be other delay component in the wired section of the call and at the end terminals. For this, the ITU-T G.108 specifies that for Internet telephony one-way mouth-to-ear delay be smaller than 250 ms for G.729 [11].

Table 1   Parameters used in the performance evaluation.

Parameter	Values
Network Architecture	Infrastructure Basic Service Set (BSS)
Simulation time	300 seconds
Transmission Rate	11 Mbps
PLCP Header	192 μs (Long Preamble)
Voice Codec	G.729
Framing Interval	20 ms
RTS-CTS	Disabled

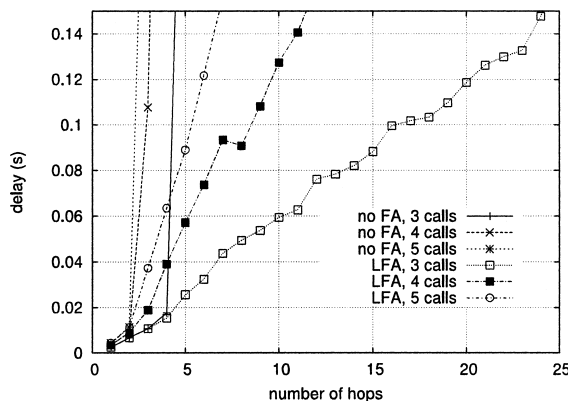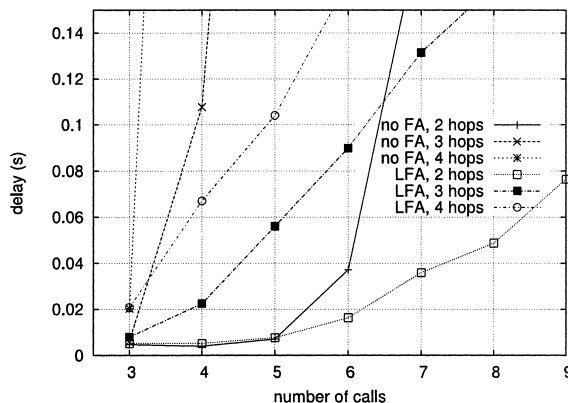**Fig. 3**   Wireless delay vs. number of hops.

Fig. 4   Wireless delay vs. number of calls.

We notice in Fig. 3 that with the same number of VoIP calls contending for the wireless bandwidth, the LFA significantly extends the span of the QoS-satisfying VoIP calls. For instance, the maximum number of reachable hops subject to a peak delay requirement $\hat{d}_w = 150$ ms with 5 calls is 6 with the LFA, but 2 without the LFA. For 3 and 4 calls the improvement becomes larger, i.e., 24 vs. 4 and 11 vs. 3, respectively. With $\hat{d}_w = 100$ ms, it is 16 vs. 4, 8 vs. 2, and 5 vs. 2 hops, for 3, 4, and 5 calls respectively.

Figure 4 illuminates the LFA performance from the capacity angle. Here we estimate the number of supportable calls when the wireless span of the calls are fixed at 2, 3, or 4. Again, the LFA is more effective whether or not the maximum tolerable wireless delay is less than $\hat{d}_w = 150$ ms. We observe from the figure that the capacity under LFA is nearly doubled for each case. Specifically, it increases from
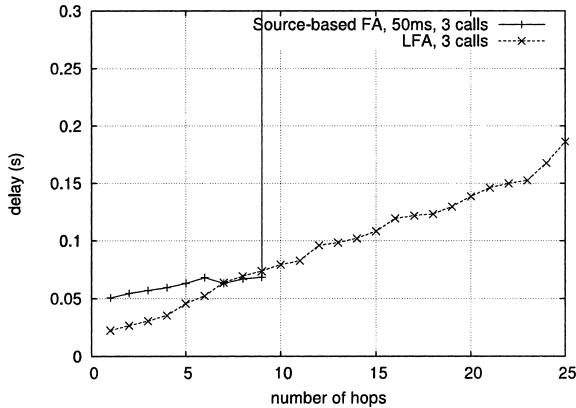
Fig. 5 Wireless delay for VoIP of LFA vs. source-based aggregation.

3 to 5, 4 to 7, and 6 to 10+ for 4, 3, and 2 hops, respectively.

These experiments show that the LFA can visibly increase the call capacity or the call path length in the multihop wireless networks. Compared to the LFA, the traditional fixed-delay frame aggregation performed at the voice source [5]–[7], exhibit rigid queuing behavior hence relatively poor performance. Without the adaptive capacity, the traditional source-based method fails to achieve optimality in most parameter ranges. Figure 5 shows the *capacity-bounded* nature of the source-based frame aggregation. With 3 calls, the delay becomes unbounded after 9 hops. With smaller number of hops on the other hand, the constant delay used at the source is excessive, and it leads to larger delay than in the LFA that always finds the optimal level of aggregation. In contrast, the LFA is self-regulating in face of congestion, and the delay gradually increases. So the call capacity or the call path length of LFA is *delay-bounded*. There is no delay explosion point, and the call capacity and the path length can always be increased given more lenient delay bound.

4. Conclusion

We present a novel voice frame aggregation called the LFA,

to be performed at the wireless routers in wireless mesh networks. Despite its simplicity, it has many desirable properties. It significantly improves the call capacity or the call path length. It does not incur additional delay during aggregation. It makes the system delay-bounded instead of capacity-bounded, so the call capacity or the path length can be always increased if the delay requirement is relaxed. Finally, the LFA does not require any modification for existing 802.11 protocol. The local LLC queuing implementation at the wireless routers is sufficient to induce the VoIP call capacity improvement as demonstrated in this letter.

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