Flexibility of Routing Framework Architecture in IEEE 802.11s Mesh Networks

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Abstract

The fundamental challenges in wireless multi-hop networks design are the problems of routing and hidden stations. Defining mesh networking, IEEE 802.11s amendment addresses both issues. It includes a routing protocol and novel deterministic channel access method, called MCCA, complementing random access traditional in IEEE 802.11 networks. The routing framework architecture allows extending or even replacing the default routing protocol for specific niche application, but it is not flexible enough to take advantage of using both traditional random access and novel deterministic access, as we show in this paper. Proposed flexibility enhancements are illustrated to bring benefits for the network performance.

Keywords

IEEE 802.11s; HWMP; MCCA; QoS; MAF; path selection metric; Airtime Link Metric; load balancing, FLAVIA

I. Introduction

In spite of IEEE 802.11 technology [1] has been initially designed as just indoor cable replacement for Local Area Networking, nowadays it is widely used in many niches, including wireless multi-hop self-coordinated networks (mesh networks or MANETs).

It is obvious that in these networks *routing*, providing packets delivery between stations even if they are out of transmission range of each other, is a critical issue. It is less obvious, but widely shown in literature, that *channel access* is also a critical issue, as a multi-hop network is something more complicated than several single-hop networks, and so called hidden stations affect badly the network performance when traditional for IEEE 802.11 random channel access is used, e.g. see [2].

Mesh concept has a lot of applications which often impose heterogeneous (or even opposite) requirements, so it is difficult to develop a way general technology. IEEE 802.11s amendment draft [3] is a modular framework providing minimal co-existence for mesh devices of various vendors and the functionality of such critical parts as routing protocol may be extended or replaced for specific applications. Also, the framework includes an access method, called MCCA, complementing random access method, EDCA, with a reservation technique. Ironically, because of independent development of IEEE 802.11s framework modules, as well as general intention to simplify protocol design and make driver development easier, the path selection and packet forwarding are just general whatever channel access method is used. Though it is possible to replace the default routing protocol, more flexibility is needed to take advantage of using two access methods. For example, the usage of two routing metrics

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for two channel access methods may be very efficient as the operation principles of EDCA and MCCA are very different.

In this paper, we discuss possible ways to extend the flexibility of routing protocol architecture in IEEE 802.11s so that, keeping routing independent from channel access, adapt the architecture and open it for innovative solutions based on cooperation with the access method, which may be efficient in some applications.

The work on flexibility analysis presented in this paper is the part of FLexible Architecture for Virtualizable wireless future Internet Access (FLAVIA) project [4]. FLAVIA changes the role of the wireless network interfaces, from closed architectures implementing standardized and constrained service access points, to programmable wireless-processors (with standardized instruction sets) for composing specific access operations [5]. In particular, with FLAVIA flexible architecture, it would be possible to implement the solutions proposed in this paper.

The rest of the paper is organized as follows. In Section II, we analyze IEEE 802.11s routing and channel access methods, briefly overview related literature and discuss some architectural routing limitations in IEEE 802.11s. Flexibility improvements proposed in this paper are presented and evaluated in Sections III and IV. Finally, the concluding remarks are given in Section V.

II. Channel Access and Routing Analysis in IEEE 802.11s

A. *Mesh Deterministic Channel Access*

Traditionally, IEEE 802.11 networks are based on random channel access which distinctive feature is the collisions. In single-hop ad hoc networks, when all stations are in the transmission range of each other, collisions only occur if stations start their transmissions exactly at the same moment. In multi-hop networks, due to the hidden stations effect transmissions may intersect even if they are started at different moments of time, so the collision probability is higher than in single-hop networks.

To decrease the collision probability and meet QoS requirements, IEEE 802.11s defines deterministic channel access method called MCF Coordinated Channel Access (MCCA). With MCCA, two stations may agree the set of time intervals called MCCAOP reservation. During reserved intervals, one of the stations, called *MCCAOP owner*, obtains prioritized channel access when transmitting packets to the other station, called *MCCAOP responder*. Meanwhile, other MCCA-capable stations which are neighbors of the MCCAOP owner and responder defer their transmissions. To inform neighbor stations about its reservations, a station periodically broadcasts the advertisement reporting MCCAOPs reservations of two following types.

- Own reservations: MCCAOPs for which the station is the owner or responder. During these MCCAOPs, the neighbors of the station are forbidden to initiate their transmissions.
- Interfering reservations: MCCAOPs, for which the station is neither owner nor responder, but at least one neighbor of the station is the owner or responder. Neighbors of the station are forbidden to set up with the station new MCCAOP reservations intersecting its Interfering reservation.

MCCA is designed to be used for bulky or periodic traffic, e.g. voice traffic. For aperiodic or spontaneous traffic, traditional EDCA is used, as setting-up an MCCAOP takes time and channel resources. To regulate the amount of MCCA and EDCA traffic in the network, IEEE 802.11s defines MCCA Access Fraction Limit (MAF Limit) which is the maximum percentage of time which may be occupied by MCCAOP reservations. A station calculates its current MAF value based on tracked MCCAOPs reservations. A station rejects requests for new MCCAOP reservation set up if its own MAF value or the value of MAF on any neighbor stations exceeds MAF Limit.

B. Routing Framework

IEEE 802.11s routing framework contains

- forwarding framework, and
- path selection framework which includes
  - path selection protocol,
  - path selection metric.

Packets are forwarded based on information which at least consists of:

- the destination address which identifies the forwarding information,
- the next-hop address,
- the precursor list,
- and the lifetime of this information.

It means that for all packets destined for a station, the same path is used regardless of the used channel access method or packet access category.

Forwarding information is generated by the path selection protocol. IEEE 802.11s defines a default path selection protocol called Hybrid Wireless Mesh Protocol (HWMP) based on well-known MANET routing protocol AODV [6]. Unlike AODV, HWMP is designed to use MAC-layer information and path selection metric.

Here we provide a simplified description of reactive part of HWMP. For the details, please refer to the original specification [3].

When the source station (called *path originator*) needs to send a packet to a destination station (*path target*), it broadcasts a Path REQuest frame (PREQ). Upon reception of this frame, a station drops it if it received another PREQ from the same path originator with the same sequence number and this other PREQ offered better path metric value. Otherwise, it processes the received PREQ as follows:

- the station creates or updates the forwarding information to the path originator;
- if the station is not the path target, it increases the metric value in received PREQ by the metric value towards the previous mesh station transmitting this PREQ and broadcasts the updated PREQ;
- if the station is the path target, it replies with a Path REPly frame (PREP) which is forwarded to the path originator using information on each station on the path.

If a station receives several PREP frames with the same ID, but sent through different paths, it saves the information about the path with the best metric value.

HWMP assumes that all paths are symmetric, so the best path from the path target to the path originator is used for packet transmission in both directions.

When a path is broken, e.g. due to stations mobility, the station which detects the routing errors generates a Path ERRor frame (PERR) to all station in the corresponding precursor list, indicating the path target address. Upon reception of a PERR, a station invalidates incorrect forwarding information and generates another PERR to its own precursor list. Thus, in the end, all stations using the broken path invalidate incorrect forwarding information.

IEEE 802.11s defines Airtime Link Metric as a default path selection metric. The physical meaning of Airtime Link Metric is as follows: its value equals the time interval duration when the channel is busy with transmitting the standard packet over the link. The metric value, c_a, of a link is calculated as follows:

$$c_a = \left(O + \frac{B_t}{r}\right) \frac{1}{1 - e_f}, \tag{1}$$

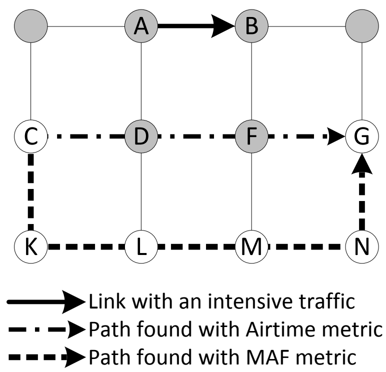

Figure 1. Two Flows scenario

where O and B_t are constants representing channel access overhead and standard packet size respectively, r is the data rate, and e_f is the transmission error probability. The path metric is calculated as the sum of the values of corresponding link metrics.

C. Related works

Though hundreds of papers consider various channel access methods or routing solutions, not so many literature can be found on HWMP and MCCA performance, to say nothing about routing based on MCCA and EDCA access methods. In [7], a distributed end-to-end reservation protocol for IEEE 802.11-based mesh networks is proposed. The paper proves that, in contrast to DCF and EDCA, the proposed protocol provides low and non-varying delay and constant throughput for each reserved flow. Well-known AODV [6] routing protocol is used with hop-count metric which is an inefficient solution in wireless networks, as further shown, e.g. in [8], [9].

In [10], the performance of MCCA, which in earlier IEEE 802.11s drafts was called Mesh Deterministic Access (MDA), is studied. The paper compares the network throughput in various scenarios when packets are transmitted using EDCA or MCCA. The obtained results prove the concept of MCCA and show that it allows to increase the network capacity in multi-hop networks significantly. However, the routes are considered to be fixed, and the influence of a path selection protocol on the amount of traffic transmitting via MCCA is left out of the scope of the paper.

What is widely missing in these papers is the analysis of routing efficiency when more than one channel access method is used. Our paper does study this issue.

D. Limitations of Existing Architecture

Routing and channel access co-operation may significantly improve network performance. A widely used approach of providing such a co-operation, while keeping modular architecture, is by using a path selection metric dependent on the channel conditions.

IEEE 802.11s defines two channel access methods, so that a station may choose the method individually for each flow or even packet. At the same time, the only path selection metric is defined, called Airtime link metric. This metric is designed for traditional random channel access (EDCA) and its value only depends on the data rate and transmission error probability, but not on the ratio of channel resources already reserved.

In some cases, it is impossible to set up an MCCAOP reservation over a selected path because the MAF Limit is reached at least on one of the link composing the path. Let us consider the topology shown in Fig. 1. Stations connected with the lines are neighbors and direct packets exchange between them is possible. Other pairs of stations do not sense transmission of each other. There is an intensive flow between nodes A and B. Because of this flow, the MAF value at all stations marked grey is close to MAF Limit. Station C needs to transmit multimedia traffic to G meeting QoS requirements.

With Airtime Link Metric which does not take into account the amount of reserved channel resources, HWMP selects the shortest path $C \to D \to F \to G$. But stations D and F have no free time intervals to set up new MCCA reservations because MAF Limit is exceeded.

The only possible way allowed in IEEE 802.11s in such a case is using EDCA. As mentioned in Section I, due to the hidden stations effect it does not guarantee meeting QoS requirements which may be preferable in some applications, e.g. when transmitting multimedia traffic. *The first contribution of this paper is the design of a simple MCCA-oriented path selection metric.*

The transmission cost over a path depends on the channel access method. The path which is cheap for MCCA may be very expensive for EDCA and vice versa. So, using a single metric for both methods may diminish the advantages of using two access methods. In [8], the idea of using multiple metrics is discussed. This approach may be extended for the case of multiple access methods. Unfortunately, the the routing framework in IEEE 802.11s allows using the only metric. *The second contribution of this paper is the developed method of using multiple metrics in IEEE 802.11s networks.*

Another problem is that, in base configuration, IEEE 802.11s routing framework does not allow using different paths to a destination even if different metrics are available which select paths depending on the access method. In other words, whatever the metric, the same path is used when transmitting with any access method. Moreover, when many flows use the same path, some of the flows may be forced to use EDCA instead of MCCA because of the lack of channel resources: MAF Limit may be reached. *The third contribution of this paper is the extension of forwarding algorithm in such a way that paths for different access methods may be different.*

An important thing in routing protocol design is the stability of paths. It takes time to set up all single-hop MCCAOP reservations along a selected path and to advertise the reservations. Moreover, according to the specification, a station must not use a newly set up MCCAOP reservation before the beginning of the first DTIM interval following the successful completion of the MCCAOP setup procedure. At the same time, HWMP routing protocol allows forwarding information to be updated at any time, with any frequency.

III. More Flexible Routing Architecture

A. MAF Path Selection Metric

With MCCA, the transmission cost over a link (i, j) depends on the current value of MAF, or, strictly speaking, the percentage of used channel resources in the neighborhood, which is $\frac{m_i}{M}$, where m_i is the maximum of MAF values in the neighborhood of station i and M is MAF Limit.

The method for a station to obtain the MAF values of its neighbors is an open issue. The simplest way is to obtain them directly from neighbors' MCCA Advertisement information elements. This approach results in taking into account interfering reservations, while the station may use these intervals to transmit packets to other stations. Due to this limitation we implement another approach. To calculates MAF value of its neighbor k, station i takes into account k's own reservations and those k's interference reservations which intersect with at least one of own reservation of i's neighbor.

The transmission cost depends on duration d of each transmission attempt which, in turn, depends on the transmission rate and is calculated similar to Airtime Link Metric:

$$d = O_{mcca} + \frac{B_{mcca}}{r_{mcca}}, \tag{2}$$

with little differences: O_{mcca} and B_{mcca} constants take other values and r_{mcca} is the rate that is used for MCCA transmission.

Even when MCCA is used, a packet transmission may be unsuccessful, e.g. due to weak signal, and requires a retry. So the total transmission cost depends on the number n_{at} of attempts which are needed to transmit a packet with the required success probability.

By combining all components, we finally obtain that link (i, j) metric value c_m is calculated as follows:

$$c_m = 1 + \left(\frac{m_i}{M}\right)^{\gamma} \left(O_{mcca} + \frac{B_{mcca}}{r_{mcca}}\right) n_{at}, \quad (3)$$

where γ is a customizable metric parameter.

The metric value of a path is the sum of metric values of the links the path consists of.

This metric is designed for MCCA and should not be used with EDCA. For EDCA, Airtime Link Metric may be used.

B. Several Metrics Usage

To use multiple metrics simultaneously in IEEE 802.11s networks, we modify Mesh Configuration element format and make some modifications of the routing framework.

Mesh Configuration element is sent in beacon frames periodically and contains the values of main configurable parameters of the mesh network. To provide multiple metrics option, it contains not the only Path Selection Metric ID, but a Vector of Path Selection Metric IDs. For example, Airtime Metric Id and MAF Metric Id.

We do not need critical changes in HWMP. In modified HWMP, field $Metric$ in both PREQ and PREP is used as a container for values of all metrics configured in the network. We also change rules of comparing metric values and storing obtained forwarding information.

Received a PREQ (or PREP) the station updates forwarding information independently for each metric. For each metric value which is better than value offered with previously received PREP, the station creates or updates corresponding forwarding information. That is why we add additional field *Type of Metric*

When a station forwards a packet, the forwarding information is selected by packet's destination address and type of metric which depends on required channel access method.

C. Load Balancing

To make HWMP to use different paths to the same targets for different flows, we identify paths not only by the target address, but by the triplet:

- source address s;
- destination address d;
- traffic id t which value is an integer in the range of [0,255] generated by the source.

When a station has no valid forwarding information for triplet $\langle s, d, t\rangle$, it generates a PREQ, even if it has information for the same d, but other t and s. To provide such functionality, one has to include corresponding fields into HWMP frames.

If the number of flows is large, generating a path request for each flow may result in heavy overhead. To make routing framework flexible we define special constants ANY_TID and ANY_SOURCE. When the station decides not to use load balancing feature, it uses these constants when generating PREQs. Forwarding information with such source address and traffic id may be used to deliver any packets to the destination unless the packet belongs to the flow for which the station has special forwarding information.

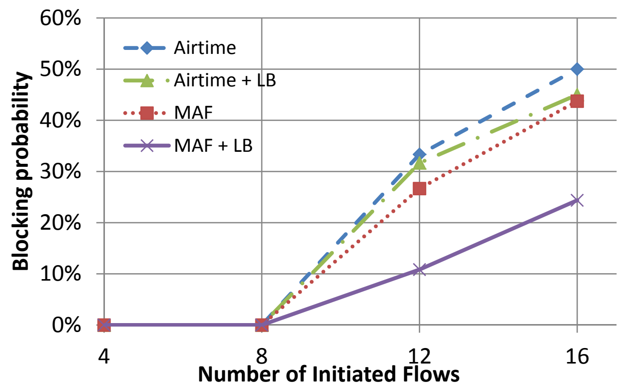

Figure 2. Blocking probability vs. No of initiated flows when traffic goes from a grid corder to the opposite one

The choice to use the load balancing feature or not depends on scenario and is beyond the scope of this paper.

Proposed adaptive load balancing mechanism protects the active forwarding information from being updated until it becomes invalid because new PREQ with the same triplet $\langle s, d, t \rangle$ is generated only when the path is broken.

IV. Performance Evaluation

To illustrate the efficiency of proposed methods we provide simulation results obtained with NS-3 [11] simulation tool which IEEE 802.11s module was developed and contributed to NS-3 project by IITP RAS. We set default values for all parameters of 802.11a+s stations transmitting at a power level of 16 dBm in 5 GHz band, see [1] and [3].

The lifetime of forwarding information generated by HWMP is 50 s. If no PREP is received, the originator repeats the corresponding PREQ not earlier than after 100 ms. MAF Limit equals 40%. The plots below are obtained with the value of γ defined in (3) set to 2.

To obtain statistically meaningful results, we run 50 repetitions for each selected combination of parameters.

A. Grid: from a corner to the opposite one

Let us consider a network of grid topology. The network is loaded with voice traffic generated by G.729 [12] codec. Packets of 20 bytes audio payload are generated with inter-arrival time of 20 ms. The source and destination nodes are two nodes in the opposite corners or the grid. The flows are initiated from a grid corner to the opposite grid corner, and in the reverse direction, one by one. If the network has not enough channel resources for the next flow, i.e. MCCA reservations cannot be set up through the chosen path, the flow is called blocked. Let us define *the blocking probability* as the ratio of the number of blocked flows to the total number of initiated flows.

Fig. 2 shows the blocking probability vs. the number of initiated flows for 7x7 grid, when either Airtime Link Metric or MAF Metric is used with load balancing feature enabled or disabled. Naturally, when the number of initiated flow is small all the flows are set up whatever the path is chosen. In contrast, when the number of initiated flows increases, the blocking probability becomes depend on the metric and load balancing option. It appears that MAF metric proposed in Section III provides significantly lower blocking probability than the Airtime Link metric when the load balancing feature is enabled.

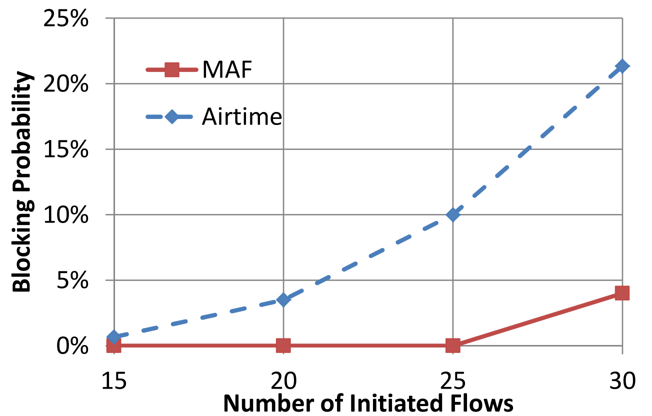

Figure 3. Blocking probability vs. No of initiated flows in a grid with random flows

B. *Grid: random flows*

This scenario differs from the previous one in the only part of source-destination pairs choice. In this scenario, source-destination pairs are chosen randomly among all nodes on the grid.

Fig. 3 shows the blocking probability vs. the number of initiated flows when either Airtime Link Metric or MAF Metric is used. Curves with load balancing feature enabled (not shown) coincide with the curves when it is disabled, as load balancing happens automatically with random source-destination choice.

The simulation results illustrate the advantage of MAF Metric over Airtime Link Metric. Let us define the network capacity as the maximum number of flows which can be initiated with the blocking probability lower than some predefined threshold. Say the threshold is 4%, then the usage of MAF metric increases the network capacity in this scenario by 50%.

V. Conclusion

The adequate level of flexibility, and thus complexity, of a technology is defined at the stage of its development based on the spectrum of envisioned applications. Vice-versa, when a technology is mature, its flexibility allows adapting the technology for new market niches. It is widely believed that the mesh concept may be applied in a variety of areas. So it is difficult to develop a way general technology and IEEE 802.11s amendment includes modules which are optional, independent from one another, and implied by design to be very different in various implementations.

In this paper, we propose improvements for routing framework architecture in IEEE 802.11s mesh networks. In contrast to monolithic cross-layer solutions known from the literature, the proposed approaches keep the architecture modular. Proposed modifications do not impose additional restrictions for mesh device developers, but bring new opportunities by making routing framework more flexible. We believe the modifications open the architecture for innovative solutions, e.g. those based on cooperation with the access method as illustrate in this paper.

Acknowledgment

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References

[1] *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2007.

[2] A. Lyakhov, I. Pustogarov, and A. Gudilov, "IEEE 802.11 direct links: Interference classification and modeling," in *Selected Lectures on Multiple Access and Queueing Systems. Revised Selected Papers from International Workshop on Multiple Access Communications (MACOM-2008)*, Saint-Petersburg, Russia, 16–17th June, 2008, pp. 15–24.

[3] *IEEE P802.11s/D10.0. Draft STANDARD for Information Technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment: Mesh Networking [Electronic resource]*, 2011.

[4] *FLexible Architecture for Virtualizable future wireless Internet Access (FLAVIA)*. [Online]. Available: http://www.ict-flavia.eu/

[5] P. Gallo, F. Gringoli, and I. Tinnirello, "On the flexibility of the ieee 802.11 technology: Challenges and directions," in *Future Network and MobileSummit*, 2011.

[6] "Ad hoc on-demand distance vector routing protocol," IETF MANET Working Group, INTERNET-DRAFT, February 2003. [Online]. Available: http://www.ietf.org/internet-drafts/draft-ietf-manet-aodv-13.txt

[7] E. Carlson, C. Prehofer, C. Bettstetter, H. Karl, and A. Wolisz, "A distributed end-to-end reservation protocol for ieee 802.11-based wireless mesh networks," *IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Multi-Hop Wireless Mesh Networks*, vol. 24, pp. 2018– 2027, November 2006.

[8] E. Khorov and A. Safonov, "Multiple metrics in manet with end-to-end qos support for unicast and multicast traffic," in *Proceedings of the Third international conference on Multiple access communications*, ser. MACOM'10. Berlin, Heidelberg: Springer-Verlag, 2010, pp. 251–262. [Online]. Available: http://portal.acm.org/citation.cfm?id=1881623.1881654

[9] A. P. Subramanian, M. M. Buddhikot, and S. Miller, "Interference aware routing in multi-radio wireless mesh networks," in *WiMesh*, 2006. [Online]. Available: http://www.wings.cs.sunysb.edu/ anandps/pub/anand-wimesh06.pdf

[10] G. Hiertz, S. Max, T. Junge, D. Denteneert, and L. Berlemann, "IEEE 802.11s – Mesh Deterministic Access," in *Proceedings of Wireless Conference 2008*, 2008, pp. 1–8.

[11] *The ns-3 network simulator*. [Online]. Available: http://www.nsnam.org/

[12] ITU-T, "Recommendation G.729 Coding of speech at 8 kbit/s using conjugate-structure algebraic-code-excited linear prediction (CS-ACELP)," Tech. Rep., January 2007.