TIME-DRIVEN ACCESS AND FORWARDING IN IEEE 802.11 MESH NETWORKS

Mario Baldi and Riccardo Giacomelli

***Abstract*— Various solutions based on both prioritization and resource allocation have been proposed in the literature and standard bodies to support end-to-end Quality of Service (QoS) in wireless multihop scenarios. However, their performance is not satisfactory in terms of achievable overall network throughput and tradeoff between end-to-end delay and network utilization. This paper proposes Time-driven Access and Forwarding (TAF), a novel multilevel solution to guarantee deterministic end-to-end QoS for real-time traffic and improve overall network throughput and utilization in 802.11 mesh networks.**

I. INTRODUCTION

Quality of Service (QoS) support in wireless mesh networks is still an open problem, exacerbated by limited resource availability, usually being addressed at multiple protocol layers in a coordinated way. The large amount of resources typically available in wired networks enables a low complexity solution for satisfying the QoS requirements of current multimedia applications: as long as the percentage of traffic with QoS requirements is low with respect to the overall network capacity, e.g., around 20-30%, traffic differentiation mechanisms like Differentiated Services (DiffServ) coupled with some sort of priority queuing can provide QoS guarantees or, at least, “good enough” QoS, both on individual links (i.e., at the data link layer) and across multiple nodes (i.e., at the network layer). However, since wireless network capacity is roughly 10 to 100 times lower than wired network capacity, keeping the abovementioned ratio is costly, highly inefficient, and in some scenarios impossible. Consequently, differentiation mechanisms and simple static priority queuing are not suitable to guarantee the required QoS, and reservation mechanisms coupled with flow level traffic segregation are needed.

This paper presents *Time-driven Access and Forwarding* (TAF), a mutilevel solution involving the forwarding level and the Medium Access Control (MAC) level solution (Fig. 1). Exploiting time information shared between the two levels and common to all network nodes, TAF both supports end-to-end QoS across multiple wireless links and coordinates nodes access to the shared channels. The contribution of this work is the proposal and the evaluation of a reservation based combined access and forwarding solution. The shared time information (achieved through a synchronization solution that is outside the scope of this work) and the proposed reservation procedure are the link between the two levels: at the forwarding level they enable pipeline forwarding [1], a well known QoS packet scheduling mechanism, whereas at the MAC level they avoid collisions and grant a contention free medium access to each wireless link. The synergy between the two levels ensures deterministic, minimal delay and controlled jitter to real-time traffic across multiple wireless hops.

Moreover this solution obviously enables seamless integration with a wired backbone also deploying pipeline forwarding so that a deterministic service with the abovementioned features can be provided seamlessly across both the wireless and wired networks.

Section II describes TAF, proposes a reservation procedure, and analyzes its properties. Related work is discussed in Section III. Section IV describes preliminary simulations comparing TAF with some of the IEEE 802.11 medium access control standards with both real-time and best-effort traffic. The results show how TAF provides the required QoS to the former and higher throughput for the latter, while ensuring better medium utilization. Conclusions are drawn in Section V.

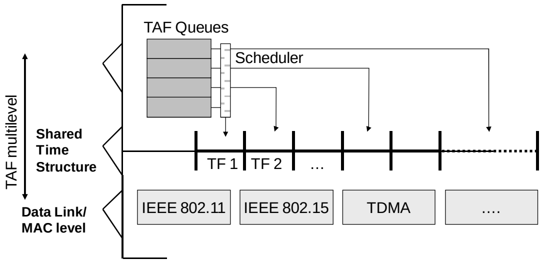

Fig 1. TAF scope.

II. KEY ELEMENTS AND OPERATING PRINCIPLES

TAF deals with packet forwarding and access to a shared channel as two faces of the same coin, as shown in Fig. 1. TAF solves both issues simultaneously utilizing (*i*) *shared time information* between the forwarding and the MAC level that is common to all network nodes and (*ii*) proper *resource reservation*.

A. Common Time Reference

All the network nodes are synchronized with a common time reference (CTR), while utilizing a basic time period called time frame (TF), as it is done in pipeline forwarding [1]. In a possible design UTC (Coordinated Universal Time), as obtained from a time-distribution system such as GPS (Global Positioning System), can be used to derive the TF duration; alternatively, a clock synchronization protocol can be utilized among the network nodes. TFs are grouped into time cycles (TCs) and time cycles are further grouped into super cycles, each super cycle lasting for one

UTC second. Both the forwarding level and the MAC level rely on TFs for their operation: reserving a TF ensures both timely forwarding (Subsection II.C) — i.e., avoiding long queuing delays — and access to the shared channel without collisions (Subsection II.B) — i.e., avoiding delays, loss, and bandwidth waste due to retransmissions.

Every TF can be reserved for unicast transmission between two nodes or a broadcast transmission from a node to the nodes in its transmission range. A TF reservation is periodic, i.e., repeated each TC or super cycle, and valid for all nodes within the interfering area of the transmitter. TAF does not need a central coordination point to guarantee contention free access: reservation information is not centrally maintained, but spread across nodes in *allocation tables*. The allocation table maintained by every node is updated during the reservation procedure described in Subsection II.F and contains a row for each TF storing the type of traffic (pipelined or non-pipelined) for which the TF has been reserved, the node having the right to transmit during that TF, the node that is supposed to receive the transmission, other information required to properly handle TF reservations, and the amount of bits not yet reserved.

On the other hand, two non-interfering nodes can transmit simultaneously (with or without reservation), thus enabling spatial reuse. During unreserved TFs nodes try to gain control of the channel utilizing one of the standard IEEE 802.11 MACs.

B. MAC

TAF is not bound to any specific physical layer or data link layer protocol; the only requirement is that at the MAC level every transmission is aligned with the beginning of a TF and does not last beyond the end of the TF. This paper focuses on the deployment of TAF in IEEE 802.11-based mesh networks. Only minor modifications are required to the standard IEEE 802.11 mechanisms to enable TAF. Since a reserved TF and the Transmit Opportunity (TXOP) defined in the IEEE 802.11e standard are both defined as a window time during which a node has exclusive access to the channel, a node transmitting during a TF can use the timing, i.e., Inter Frame Spacing, specified for a TXOP: transmission can begin after a Short Inter-Frame Space (SIFS) time from the beginning of the TF and the Acknowledgement packet is transmitted by the receiver after an additional SIFS after the data packet reception[1]. This reduces the complexity and the cost of implementing TAF and of possibly adding it to existing IEEE 802.11e interfaces. Retransmissions follow TAF operational rules. For example, if a packet holding a reservation is lost, it is retransmitted during the next TF reserved to its flow, rather than deploying the IEEE 802.11 backoff procedure.

C. Forwarding

Availability of a time structure shared among all the network nodes enables the deployment of *pipeline forwarding*, possibly in its Time Driven Priority (TDP) [1] implementation, to provide deterministic end-to-end QoS to real-time traffic. During a resource reservation phase (Section II.F), each flow requiring a deterministic service is allocated one or more *p-TFs*, or *pipeline-forwarding-TFs* on each link along its path to ensure proper *pipeline forwarding* [1] of packets. This results in a periodic schedule, repeated every TC, for packets to be switched and forwarded by each node along the path. The basic pipeline forwarding operation is regulated by two simple rules: (*i*) all packets that must be forwarded in TF t by a node must be in its output port buffers at the end of TF $t-1$, and (*ii*) a packet p transmitted in TF t by node n must be transmitted in TF $t+\tau$ by node $n+1$, where τ is an integer constant called *forwarding delay*. The value of the forwarding delay is determined at *resource-reservation time* and must be large enough to satisfy rule (*i*) given the propagation delay on the links, the processing time and the switching delays within nodes.

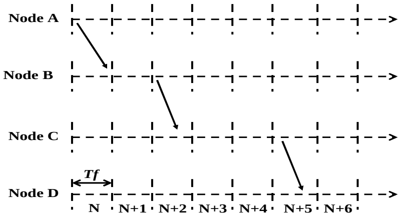

Fig 2. Pipeline Forwarding operating principle.

In pipeline forwarding, a *synchronous virtual pipe* (SVP) is a predefined schedule for forwarding a pre-allocated amount of bytes during one or more TFs along a path of subsequent nodes deploying TDP. Fig 2 exemplifies the journey of a packet from node A to node D. Packets traveling through the network on an SVP receive a deterministic service: no packet will be lost or delayed due to congestion and the time of exit from the SVP is uniquely determined by the reserved TF in which the SVP has been entered with an uncertainty of 1 TF. The end-to-end delay can be calculated as the number of nodes crossed times the forwarding delay τ introduced by each node.

Point-to-multipoint SVPs can be deployed to implement multicast and broadcast packet delivery with guaranteed quality.

Since, as explained in Section II.D, nodes perform statistical multiplexing of best-effort traffic, i.e., forward best-effort packets in unused p-TFs, SVPs are not at all like traditional Time Division Multiplexing (TDM) circuits: link capacity allocated and not used by pipelined traffic can be fully utilized by non-pipelined traffic. Moreover, any service discipline, e.g., service differentiation, can be applied to packets to be transmitted in unused TFs.

D. Non-pipelined Traffic

Packets that do not require deterministic service quality, either being best-effort traffic or belonging to a differentiated traffic class (e.g., according to the DiffServ or IEEE 801.1q approach) do not need to be handled with pipeline forwarding. They are transmitted in *hop-by-hop TFs*, or *h-TFs*, that are not

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[1] The SIFS cannot be eliminated since it is the minimum time required by a node to switch from transmission mode to reception mode and vice versa.

allocated for a specific packet or packet flow, but in general for transferring packets between two neighboring nodes. The h-TF reservation policy, that is not within the scope of this paper, can be based on an estimation of traffic matrices and possibly dynamically adapted to actual traffic conditions. As part of such policy, some TFs can be left free for nodes to use them to dynamically get access to the channel by means of one of the IEEE 802.11 Carrier Sense Multiple Access with Collision Avoidance CSMA/CA-based MAC standards. Also, a TF can be allocated to a subset of nodes allowed to contend for the communication medium, thus reducing the collision probability, which might be useful in a mesh network with high node density.

E. Routing and Scheduling

When an SVP is set up, resources, in the form of the capability of transmitting during specific TFs, are reserved for packets carried on the SVP. Existing routing protocols can be deployed to choose a path for the packets. Specifically, *Dynamic Source Routing* (DSR) proposed for wireless mesh networks is particularly suitable to being deployed with TDP because, being based on source routing, the ingress node to an SVP can make sure that packets follow the path along which the reservation has been made. In fact, the route chosen for an SVP should not change frequently as TF scheduling and reservation must be performed on a new route. This is in most practical cases not an issue as routes are stable when nodes are not moving and neighboring nodes have stable communication channels. Although a very interesting issue that deserves in-depth study, routing is outside the scope of this paper.

As previously proposed in the literature [1][2], scheduling and resource reservations can be performed distributedly using a data structure called *availability vector*. The *link availability vector* can be derived from the *allocation table* as the TFs that have not yet been reserved for transmission over a wireless channel. A *call availability vector* is used by the distributed scheduling algorithm processes to gather information on resource availability along the path chosen for an SVP, i.e., to summarize the content of the link availability vectors of all the wireless channels along the route. The set of TFs chosen by the scheduler, based on the information gathered in a call availability vector, is called a *schedule*. The reader is referred to [2] for a detailed explanation of a previously proposed distributed scheduling procedure that can be directly applied in this context.

F. Time Frame Reservation

Once a schedule has been selected for an SVP, resources have to be reserved in the corresponding TF(s) on each link on the path of the SVP. Performing such resource reservation in wireless mesh networks is not straightforward due to the shared nature and physical properties of the links. One of the contributions of this work is indeed a TF reservation procedure and the analysis of its properties. The constraints for the reservation of TFs for TAF stem from the characteristics of the wireless communication channel. The Friis model [8] provides a representation of signal propagation in wireless communication, which the following refers to (see Appendix A.1 for details):

- The transmission range Tx_k is a circle of radius R_{Tx} around a transmitter N_k within which nodes can receive the transmission correctly;
- The interference range I_j is a circle of radius R_I around a receiving node N_j, at distance $r_{k,j}$ from the transmitter N_k, within which an interfering node N_i can interfere with N_j.

In a wireless mesh network a node N_k has the potential to transmit to all its *one-hop neighbors* whose set is defined as

$$\alpha_k = \{N_l\}, \forall l : r_{k,l} \le R_{Tx}.$$

Transfer of a packet on a path $P_{1,n}$ from node N_1 to N_n, after is accomplished through $n-1$ transmissions from nodes N_k, $k = \{1,...,n-1\}$ to the respective nodes $N_j \in \alpha_k$ $j = \{2,...,n\}$ (the receiving node on the kth link of the path). In order to make sure that the $n-1$ transmissions are successful using TAF, one or more TFs must be reserved on every link to avoid interferences from other nodes[2], i.e., the allocation table must be updated accordingly by all nodes within the interference range I_j of each receiving node N_j. For this purpose, the following *TF reservation procedure* must be performed, where k and j are initiated to 1 and 2, respectively, and updated at each reservation cycle as described below:

1. N_k transmits[3] to N_j a *Reservation Request (RR)* that includes the identifiers (number within the TC) of the TF(s) to be reserved, a field Tx containing the address of N_k, and a *Sequence Number* SN_k — randomly generated by N_k at startup and incremented at each new reservation — to identify duplicated requests, i.e., received more than once through different paths across the network. To ensure the correct reception of the RR packet, if N_k does not receive a RR packet from at least one of its neighbors $N_l \in \alpha_k$ containing the reserving TFs within a timeout period of one TC, it retransmits the RR packet[4].
2. Every node $N_l \in \alpha_k, N_l \ne N_j$, i.e., receiving an RR packet whose MAC source address matches the Tx field and the MAC destination address is not its own, after making sure that the packet is not a duplicate, updates its allocation table and broadcasts the RR packet to its neighbors. This step ensures that the RR packet originated by N_k reaches all the nodes $N_p \in \alpha_l, \forall l : N_l \in \alpha_k$.
3. Every node $N_p \in \alpha_l, \forall l : N_l \in \alpha_k$, i.e., receiving a RR packet whose MAC source address does not match the Tx

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[2] Note that this is the case when the transmission is for both pipelined traffic (p-TF) and non-pipelined traffic (h-TF) if contention is to be avoided.

[3] Packets used in the reservation procedure are transmitted during non conflicting TFs dedicated to control traffic. Every node reserves a control TF per TC. The allocation of these TFs during the initial network setup has been well studied and is outside the scope of this paper.

[4] N_k might set a minimum number of received RR packets, based on the estimated cardinality of α_k, below which it retransmits its own.

field, after making sure the packet is not a duplicate, updates its allocation table accordingly without further retransmitting the RR packet.

4. N_j, that receives from N_k an RR packet whose MAC destination matches its own and MAC source address matches the Tx field, after making sure that it is not a duplicate, updates its allocation table[5], and generates an RR containing the identifiers of the receiving TFs (i.e., the ones listed in the RR from N_k) and the forwarding TFs (i.e., the ones N_j wants to reserve to forward packets received from N_k).

Note that this begins a new reservation cycle that both reserves TFs on the ($k+1$)th link and confirms the reservation on the kth link of the path. Depending on their roles, nodes perfom actions listed above in cases 1 to 4 where k, j must be updated to $k = k+1$ and $j = j+1$. When N_j is the last node on the path (i.e., $j = n$) it behaves as in case 2.

A TF reservation procedure is effective — i.e., all the nodes that can cause interference with a transmission are aware of the resources having been reserved for that transmission — if the following two Theorems hold true:

Theorem 1 *For any TF m reserved for transmission from node* N_k *to node* N_j *utilizing a TF reservation procedure, reception by node* N_j *will not be disrupted by interference from any other well-behaved network node, i.e., correctly abiding to the reservation procedure and TF access rules.*

Theorem 2 *For very TF m flagged as not reserved in the allocation table of node* N_i*, a transmission by node* N_i *does not interfere with an existing reservation.*

These two theorems can be proven for the TF reservation procedure presented above (see Appendix A.2) on a wireless mesh network satisfying the following constraint:

Let

- G_{Tx} be an undirected weighted graph obtained connecting two nodes N_k and N_j $\forall k, j$ with an edge $e_{k,j}^{G_{Tx}}$ of weight 1 if and only if $r_{k,j} < R_{Tx}$ —G_{Tx} represents the graph of the nodes that can communicate with each other directly);
- G_I be an undirected graph obtained connecting two nodes N_i and N_j with an edge $e_{i,j}^{G_I}$ if and only if $r_{i,j} < R_I$ — G_I represents the graph of the nodes that can cause interference to a transmission between a node N_k and N_j in the worst case where $r_{k,j} = R_{Tx}$;

$\forall i, j : \exists e_{i,j}^{G_I}$, $\forall k : \exists e_{k,j}^{G_{Tx}}$ there must exist a path $P_{k,i}^{G_{Tx}}$ on the graph G_{Tx} between N_k and N_i such that the total weight $W_{P_{k,i}^{G_{Tx}}} \le 2$.

An example of network satisfying this constraint is a regular grid with fixed distance (R_{Tx}) between nodes. In general, it is not unlikely that dense wireless mesh networks deployed in practical cases satisfy this constraint. The set of the nodes informed of a new reservation by the presented TF reservation procedure is a superset of the nodes that can cause interference with the transmission for which the reservation was made. Consequently, the TF reservation procedure does not allow optimal space reuse of the wireless channel, i.e., there are cases in which nodes that would not interfere with each other are not able to transmit during the same TF. The problem can be mitigated through a power control MAC; however, this solution is beyond the scope of this work. Furthermore, the scheduling and reservation procedures presented in this paper support only reservation of a single p-TF or multiple consecutive p-TFs.

A TF reservation procedure that features the properties expressed by the above theorems on a wireless mesh network not necessarily satisfying the above constraint can be devised by substituting RRs with binary energy signals. Such a reservation procedure, that is not as simple as the one presented in this paper, will be the subject of future work.

III. RELATED WORKS

IEEE 802.11 Point Coordination Function (PCF) and IEEE 802.11e Hybrid Coordination controlled Channel Access (HCCA), although explicitly designed to provide a deterministic channel access, are not deployed in distributed wireless mesh networks as they require a central coordination point. IEEE 802.11 DCF and its variant EDCA specified within IEEE 802.11e are currently utilized as MAC solutions in wireless mesh networks, but they raise a number of issues.

The more recent IEEE 802.11s draft for a mesh network standard utilizes the IEEE 802.11e EDCA as a building block, adding support for congestion control and an optional Mesh Deterministic Access (MDA) to reduce the channel access time. However, such solution does not ensure deterministic end-to-end QoS.

Another issue stems from node density. In wireless mesh networks it is advisable to have short wireless links in order for them to likely be reliable, fast, and stable notwithstanding the dynamic nature of the wireless signal quality. Consequently, a high number of APs should be deployed in a dense fashion. However, in contention-based MACs, such as DCF and EDCA, the channel throughput decreases when the number of nodes sharing it increases, i.e., throughput lowers as node density increases. Our solution, utilizing shared time information in the network, eliminates the contention before the transmission thus avoiding waste of bandwidth. Finally, the hidden and exposed node problem, fairness, and TCP instability are still open issues with contention based MACs.

Various reservation based schemes, have been proposed to overcome the above issues and support QoS in wireless mesh networks. A first possible approach to perform a bandwidth

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[5] The content of the Tx, and SN_k fields of each reservation being performed are stored in the allocation table entry corresponding to the TF(s) being reserved. If the value of the Tx, and SN_k fields of a received RR packet matches the ones already in the corresponding entry of the allocation table (the SN_k field value of the packet can also be smaller), the packet is a duplicate and discarded by the node.

reservation on a path is a MAC level periodic reservation of time slots at each hop on the path. Time slot reservations are periodic, i.e., a time slot reservation is repeated at a fixed interval time. According to this approach time slots are not organized in a fixed time structure since their beginning time depends on the time of arrival (as far as the reception is concerned) and of transmission (as far as forwarding is concerned) of packets with a reservation and do not have fixed length since their length depends on the packet size. This increases the complexity in the management of time slots especially when aiming at achieving high link utilization and short forwarding delay.

Multiple Access Collision Avoidance with Piggyback Reservation (*MACA/PR)* [3] and *Distributed end-to-end Allocation of time slots for REal-time traffic* (*DARE)* [4] are two examples of such an approach that differ slightly in the reservation procedure deployed to set-up a reservation. In MACA/PR every packet of a flow contains the information of the reservation and sets up the reservation for the following packets while traveling to the destination. According to DARE a control packet is transmitted end-to-end to set-up the reservation before the data transmission. Unlike TAF, both solutions rely specifically on IEEE 802.11 and cannot be directly deployed with other MAC protocols. The lack of a common time structure and coordination at reservation time among network nodes results in less efficient time slot scheduling in both MACA/PR and DARE when compared to TAF. In DARE the first available time slot after the packet reception is reserved for packet transmission on a link-by-link basis from source to destination, thus every node must try to make a *preliminary* [4] reservation with roll-back if the time slot was already occupied. Instead in TAF the availability of a common time reference enables the scheduling operation to be based on comprehensive time slot availability information previously collected along the whole path as part of the distributed reservation procedure Furthermore variable duration of time slots in both MACA/PR and DARE results in bandwidth fragmentation and a lower network utilization and throughput if compared to an approach with a fixed time structure like TAF, as highlighted by the authors of MACA/PR themselves [3].

Another possible reservation based approach is to deploy Time Division Multiple Access (TDMA). Differently from the previously presented reservation based schemes and similarly to TAF, TDMA time slots have fixed duration and are organized in a time cycle common to all the network nodes. Wireless mesh networks employ TDMA in a decentralized manner: rather than being assigned to subordinates nodes by a master node (centralized TDMA), time slots are assigned through a distributed reservation procedure. For example, *Evolutionary Time Division Multiple Access* (E-TDMA) [6] utilizes the *Five Phase Reservation Protocol* [7]: at the beginning of the time cycle, during a *contention phase*, nodes contend for the time slots of the time cycle. Like all other exiting TDMA-based solutions, E-TDMA provides deterministic channel access time, but by not implementing end-to-end scheduling it does not ensure end-to-end delay to be below a given bound.

In essence, existing TDMA-based solutions leverage on TDMA for medium access, but do not implement any specific forwarding functionality to achieve deterministic end-to-end QoS, which could be provided by a TDMA-based TAF implementation. Specifcally a TDMA time slot structure could be deployed without the need for a contention procedure for time slots, like in E-TDMA, since the TAF scheduler grants collision free time slot reservation and access. In addition, TAF also ensures the deterministic end-to-end QoS not achieved in E-TDMA.

IV. SIMULATION EXPERIMENTS

The performance of the proposed solution to carry both real-time and best-effort traffic over wireless multi-hop networks is assessed through simulation and compared to the case in which standard IEEE 802.11 protocols are being used.

A. *Simulation Environment*

Simulations have been carried out using the publicly available network simulator ns-2 (version 2.28), also including a module for IEEE 802.11e EDCA. A module implementing TAF has been developed in the context of this work. The allocation protocol has been emulated on line and a static reservation has been accordingly set-up on the path of each flow.

B. *Simulation scenario*

Two multi-hop scenarios have been simulated, both satisfying the constraints defined in Section II.F under which the presented reservation procedure features the properties expressed by the abovementioned Theorems. The first one is a linear chain of ten nodes and the second is a thirty node network in an area of 1500x1500 meters. This area corresponds to the size of a large campus or of a industrial plant, or of a rural area. In the first scenario the distance between subsequent nodes is about 120 meters, while in the second scenario nodes are uniformly distributed in the area at a distance of about 230 meters. The transmission range of the nodes is 250 meters. Consequently, a node has two to four nodes within its transmission range in the first scenario, and three to four in the second one. The Dijkstra algorithm is used to pre-calculate routes to all destinations to then statically fill out the routing tables of the nodes. IEEE 802.11g is utilized in all the simulations. The maximum fixed data rate is 54 Mbps (there is no Auto-fall-back) and the basic data rate is 5 Mbps. The free-space propagation model has been utilized. The TC duration is 20 ms with 100 TFs per TC.

Both scenarios are two access networks with some nodes acting as portals for Internet access: the tenth node of the chain in the first scenario and the two nodes in the upper corners of the simulation area in the second scenario. Most of the traffic, both real-time and the best-effort traffic, is directed towards the portal nodes; in the second scenario there is some background internal traffic in the network. The traffic sources are the first node of the chain in the first scenario and six nodes in the lower part of the simulating area in the second scenario. Real-time traffic sources transmit Constant Bit Rate (CBR) traffic flows (User Datagram Protocol-UDP packets) with transmission data rates multiples of 200 kbps, while best-effort flows are File Transfer Protocol (FTP) connections (Transmission Control Protocol-TCP packets). While best-effort traffic is transmitted during h-TFs allocated hop-by-hop, real-time flows are pipeline forwarded using TDP with a TF allocation from source to destination.

C. Results

Throughput and packet delay obtained with TAF, IEEE 802.11 DCF, and IEEE 802.11e EDCA are compared. In the simulation of the traffic sources transmit in the network a total amount of input real-time data traffic of 2.6 Mbps (near TAF maximum load for this scenario), whereas the total amount of best-effort traffic is 600 Kbps. The traffic is totally directed to the last node of the chain emulating an Internet access. The results in Fig 3 show that TAF can guarantee very low delays both for real-time transmissions (2 ms) (utilizing end-to-end reservation), and for best-effort transmission (2.8 ms) (utilizing hop-by-hop reservation), while IEEE 802.11 DCF and IEEE 802.11e protocols show very high packet delays (bigger than 400 ms). Furthermore TAF shows a constant goodput of 2.6 Mbps (100% of the input traffic) while IEEE 802.11 DCF and IEEE 802.11e EDCA shows respectively a goodput of 1.4 Mbps and of 1.8 Mbps (54% and 69% of input traffic). For best-effort traffic IEEE 802.11 DCF and IEEE 802.11e EDCA protocols show a goodput almost equal to zero meaning that best-effort traffic suffers of starvation, while TAF shows a stable goodput. The starvation of best-effort traffic is partially caused by the prioritization mechanism of IEEE 802.11e protocol and by the congestion control of TCP protocol. In the second simulation of the thirty nodes network the total amount of input real-time traffic is 3.2 Mbps (near the TAF maximum load for this scenario) whereas the total amount of best-effort traffic is 600 Kbps. The traffic is directed towards two nodes in the upper corner of the simulation region acting as Internet portals. shows goodput and packet delay for real-time traffic in the network (best-effort traffic goodput is not illustrated since it is meaningless, equal to zero). TAF achieves constant goodput of 3.2 Mbps (100% of input traffic) for real-time traffic while both IEEE 802.11 DCF and IEEE 802.11e shows a lower goodput. Packet delay is very low (less than 3 ms) while IEEE 802.11 protocols even show packet delays of seconds.

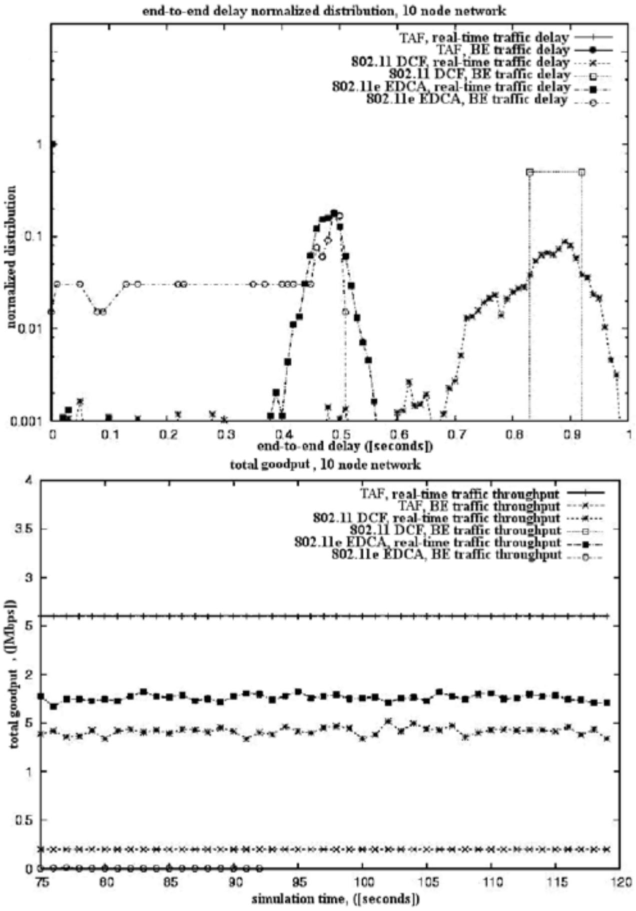

Fig 3. End-to-end delay distribution and goodput in a ten node network

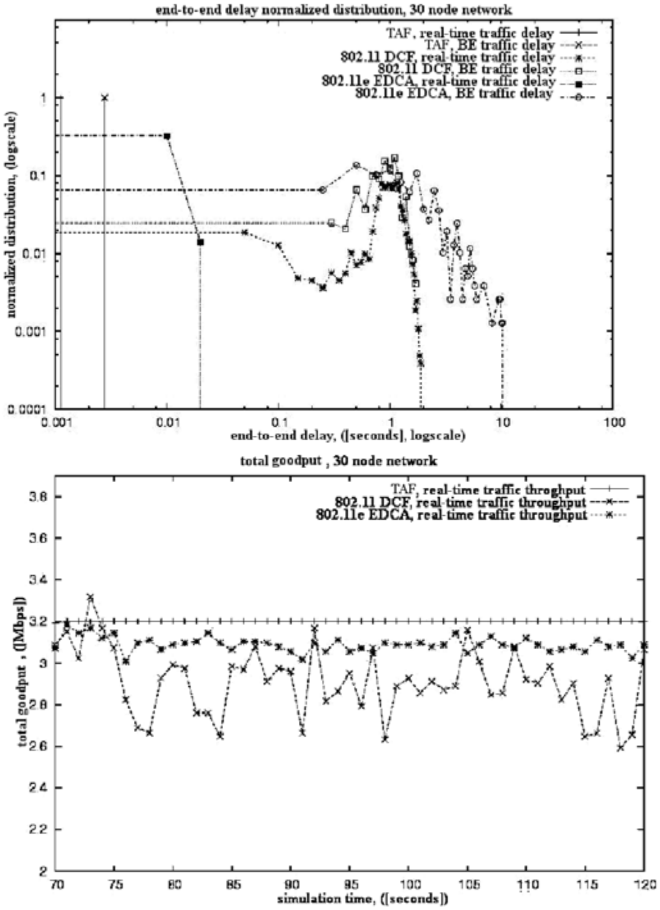

Fig 4. End-to-end delay distribution and goodput in a thirty node network

V. CONCLUSIONS AND FUTURE WORK

This paper presents the Time-driven Access and Forwarding (TAF) a multilevel solution that utilizing a common shared time structure among the nodes, the well-known pipeline forwarding and a resource reservation protocol can guarantee deterministic quality of service in terms of end-to-end delay and jitter, while improving overall throughput on wireless mesh networks. Furthermore the paper proves the properties of the proposed reservation protocol and provides some preliminary simulation results showing the performance achieved by the presented solution. Future work will include a feasibility study of the presented approach in scenarios with node mobility, an analytical model of the network performance in terms of achievable throughput, and a reservation procedure for general topology networks. Channel allocation maximizing the spatial reuse of the wireless channel and bandwidth utilization is another promising deployment scenario for the TAF-based solution for quality of service on wireless mesh network that will be the subject of further studies.

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APPENDIX A

A.1 Physical channel model

The Friis propagation model [8] describes a physical communication channel as follows**:**

$$P_{Rx} = P_{Tx} G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{r_{Tx,Rx}{}^{\delta}}\right)$$

where P_{Rx} is the signal power at the receiver, P_{Tx} is the transmission power of the transmitter, G_{Tx} and G_{Rx} are the antenna gains, λ is the transmission wavelength, $r_{Tx,Rx}$ is the distance between the transmitter and the receiver, and δ is the attenuation coefficient ranging from 2 to 5 depending on the transmission medium. Considering a transmission from node N_k to node N_j, an interfering node N_i, and assuming the noise negligible, the *Signal and Interference Noise Ratio* (*SINR*) at N_j is

$$SINR_{k,j}^{i} = \frac{P_{Tx} G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{r_{k,j}{}^{\delta}}\right)}{P_{Tx} G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{r_{i,j}{}^{\delta}}\right)} = \frac{r_{i,j}{}^{\delta}}{r_{k,j}{}^{\delta}}$$

The receiver is able to decode the transmission if SINR is greater than a reception threshold R_{Th}, thus N_j can receive the transmission correctly if $r_{k,j} \le r_{i,j} \Big/ \sqrt[\delta]{R_{Th}}$ (1). In this paper it is considered $\sqrt[\delta]{R_{Th}} = 2$, which is a reasonable value for IEEE 802.11 networks.

A node can sense a transmission if $SINR > Cs_{Th}$ where Cs_{Th} is the carrier sense threshold. The receiver is able to sense but not to decode the transmission if $Cs_{Th} \le SINR < R_{Th}$. It is reasonable to assume R_{Th} and Cs_{Th} to be fixed for the whole network.

The *transmission range* Tx_i is a circle of radius

$$R_{Tx} = \sqrt[\delta]{P_{Tx} G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{R_{Th}}\right)}$$

around a transmitter N_i within which nodes can receive the transmission correctly. The *carrier sense range* Cs_i around a receiver N_i is defined as the circle of radius

$$R_{Cs} = \sqrt[\delta]{P_{Tx} G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{Cs_{Th}}\right)}$$

within which the receiver can sense the transmission. The *interference range* I_i around a receiving node N_j, given the distance $r_{k,j}$ from the transmitter N_k to the receiver N_j, is a circle of radius

$$R_I = r_{k,j} \sqrt[\delta]{R_{Th}}$$

within which an interfering node N_i can interfere with N_j.

The one-hop neighbor set of a node N_k is defined as

$$\alpha_k = \{N_l\}, \forall l : r_{k,l} \le R_{Tx}.$$

And the set of nodes $\{N_m\}$ that cannot decode the transmission from the node N_k correctly suffering interference from N_k in the worst case scenario (in which N_m is receiving a transmission from the node N_k with $r_{k,m} = R_{Tx}$ and $R_I = R_{Tx} \sqrt[\delta]{R_{Th}}$) is defined as

$$\beta_k = \{N_m\}, \forall m : R_{Tx} < r_{k,m} \le R_I.$$

$\delta_k = \alpha_k \cup \beta_k$ is the set of all the nodes that can suffer interference from the node N_k.

A.2 Proof of Reservation Procedure Properties

Theorem 1 *For any TF m reserved for transmission from node* N_k *to node* N_j *utilizing the TF reservation procedure, reception by node* N_j *will not be disrupted by interference* *from any other well-behaved network node.*

Proof 1. The set of nodes informed of the new transmission from N_k to N_j, i.e., that will not transmit during TF *m*, is $\rho_t = \alpha_k \cup \alpha_j \cup \alpha_l \cup \alpha_b$. Every node in the network set

$$\rho_{t'} = \left\{ N_f \cup N_g \right\}, \begin{cases} \forall f : r_{k,f} \leq R_{Tx} \sqrt[\delta]{R_{Th}} \\ \forall g : r_{j,g} \leq R_{Tx} \sqrt[\delta]{R_{Th}} \end{cases} \quad (2)$$

corresponds in the graph G_I to a vertex of the edge $e_{k,f}^{G_I}$ or of the edge $e_{j,g}^{G_I}$, thus by definition of G_I there must exist a path $P_{k,f}^{G_{Tx}}$ and a path $P_{j,g}^{G_{Tx}}$ of weight $W \leq 2$ in the graph G_{Tx}. This means that the nodes $N_{f'}$ and $N_{g'}$ that are ending vertexes of paths $P_{k,f'}^{G_{Tx}}$ and $P_{j,g'}^{G_{Tx}}$ with weight $W = 1$ are in the transmission range of N_k or of N_j and thus they belong to $\alpha_k \cup \alpha_j$ by the definition of α_k and α_j. The nodes $N_{f''}$ and $N_{g''}$ that are vertex of paths $P_{k,f''}^{G_{Tx}} = \left\{ e_{k,l}^{G_{Tx}}, e_{l,f''}^{G_{Tx}} \right\}$ and $P_{j,g''}^{G_{Tx}} = \left\{ e_{j,l}^{G_{Tx}}, e_{l,g''}^{G_{Tx}} \right\}$ with weight $W = 2$, where N_l is in the transmission range of α_k or α_j (thus $N_l \in \left\{ \alpha_k \cup \alpha_j \right\}$ by definition of α_k and α_j), are in transmission range of N_l thus $N_{f''}, N_{g''} \in \left\{ \alpha_l \cup \alpha_b \right\}$ by definition of α_l and α_b, consequently $\rho_{t'} \subseteq \rho_t$.

Every node N_j is able to decode the transmission if $SINR_{k,j}^{i}$ is greater than R_{Th} thus to prove the theorem 1, (1) must be valid $\forall i : N_i$ is transmitting during the TF *m*. Considering a transmitting node N_i, and the worst case for the validity of (1): $r_{i,j} > \max(r_{k,j} \cdot \sqrt[\delta]{R_{th}})$, substituting $\max\left(r_{k,j}\right) = R_{Tx}$ otherwise N_k and N_j could not communicate with each other, and $\sqrt[\delta]{R_{Th}} = 2$, $r_{i,j} > 2R_{Tx}$ for (1) to hold; for every node $N_t \in \rho_t$ informed of the transmission from N_k to N_j and that will not interfere with it, $r_{t,j} \leq R_{Tx} \sqrt[\delta]{R_{Th}}$, since a transmitting node $N_i \notin \rho_t$, $r_{i,j} > 2R_{Tx}$.

□

Theorem 2 *For very TF m flagged as not reserved in the allocation table of node* N_i*, a transmission by node* N_i *does not interfere with an existing reservation.*

Proof 2. If node N_i has the TF *m* flagged as not reserved, while N_k has reserved the TF for transmission to N_j, then $N_i \notin \rho_t$ (from Proof 1) for any receiving node N_j. Hence,

$$r_{i,j} > 2R_{Tx} \quad (3)$$

for any receiving node N_j. According to (1), N_i can transmit during TF *m* without interfering with a transmission from N_k to N_j if

$$r_{k,j} \leq \frac{r_{i,j}}{\sqrt[\delta]{R_{th}}} \quad (4).$$

Considering the worst case for (4), $r_{k,j} \leq \min\left(r_{i,j} \big/ \sqrt[\delta]{R_{th}} \right)$, substituting $\min\left(r_{i,j}\right)$ from (3), with $\sqrt[\delta]{R_{Th}} = 2$, then must be $r_{k,j} \leq R_{Tx}$ that is always true otherwise N_k and N_j could not communicate with each other.

□