A resource management system for transmission capacity enhancement in wireless mesh networks

Sistema de gestión de recursos para mejorar la capacidad de transmisiones en redes malladas inalámbricas

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Resumen

With numerous active nodes in an 802.11-based wireless mesh network, operating on longer multi-hop routes, the total transmission capacity is limited and the overall network becomes unpredictable and less reliable. The presented work describes the next steps towards a more efficient resource management of a multi-radio node, in order to enhance the performance in this kind of networks. If non-overlapping channels are used for communication, the system enables an optimal usage of the available 802.11 spectrum. To manage bundles of multiple WLAN links between mesh neighbors, a modified node architecture and a novel middle-layer software module have been created. Hop-to-hop load balancing in a bundle is included in each node. In parallel, the inclusion of a distributed channel assignment protocol is foreseen. Packet scheduling is performed based on a set of pre-defined load balancing modes. The modes introduce awareness of current network conditions and cover a wide variety of requirements on mesh networks, from improved performance to robustness. Further inspiring technologies, like layer 2 forwarding and hop-to-hop priority queuing, have been tailored in the novel architecture. The achievement is a flexible platform that can be used for different purposes, ranging from a commercially oriented mesh backbone to spontaneously setting up wireless emergency networks. A set of simulator-driven measurements outlines the effectiveness of the multi-interface system.

Palabras clave: node architecture, resource management, transmission capacity, wireless mesh networks.

Abstract

La capacidad de transmisión en una red mallada inalámbrica basada en 802.11 es limitada, si hay numerosos nodos activos que operan en largas rutas de múltiples saltos. En este caso, la red global se vuelve impredecible y menos fiable. El trabajo presentado describe los próximos pasos hacia una gestión de recursos más eficaz de un nodo con múltiples radios, con la meta de mejorar el rendimiento en este tipo de redes. Si se utilizan los canales no solapados para la comunicación, el sistema permite un uso óptimo del espectro disponible en 802.11. Para gestionar los paquetes de múltiples enlaces WLAN (bundles) entre vecinos, se han creado una arquitectura modificada de un nodo y un novedoso módulo de capa media. El balanceo de carga de salto a salto dentro de un bundle se incluye en cada nodo. En paralelo, se prevé la inclusión de un protocolo distribuido de la asignación de canales. La distribución de paquetes se realiza basada en un set de modos de balanceo de carga predefinido. Estos modos introducen la consideración de las condiciones actuales de la red y cubren una amplia variedad de requisitos de las redes malladas; de un mejor rendimiento hasta robustez. Otras tecnologías inspiradoras, como el reenvío en la capa 2 y colas de prioridad entre múltiples saltos, se han adaptado a la nueva arquitectura. Se logró crear una plataforma flexible que se puede utilizar

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para diferentes propósitos, que van desde una red mallada orientada comercialmente, hasta la construcción espontánea de redes inalámbricas de emergencia. Para demostrar la efectividad del sistema multi-interfaz, se usó un conjunto de mediciones en un simulador.

INTRODUCCIÓN

The bandwidth demand in Internet Protocol (IP)-based telecommunication services is increasing constantly. This is due to the rising number of users and end-devices (especially wireless ones), cheaper hardware prices, and lower rates for using access and delivery networks. At the same time, increasingly more digital media content (voice, video, IP Television (IPTV), video game streaming, and others) is exchanged worldwide.

Often, last mile networks tend to become bottlenecks in the overall Internet communication structure because they have to fulfill direct user demands in terms of sufficient bandwidth levels and Quality-of-Service (QoS). This work focuses on last mile wireless networks, which can be direct user-to-user networks, wireless backbones (e. g., a public city-wide network) or both, in a hybrid form.

Wireless Mesh Network (WMN) technology is mostly used to create economic and flexible wireless backbones, which are often maintained by communities. Planners of wireless consumer- and industry- networks have seen the various advantages and diverse applications of WMNs and have slowly begun to adapt the technology to present market solutions. Still, broad market acceptance is still missing. One reason is the fact that WMNs are mostly based on nodes equipped with a single Wireless Local Area Network (WLAN) Interface (IF) [1]. A WLAN based WMN suffers from the same risks of negative channel conditions on the Physical (PHY) layer, like fading or distortion effects in a non-line-of-sight situation. Such effects ultimately turn the pure throughput of a WLAN IF into a highly conditional parameter. But in wireless multi-hop networks (e.g., WMNs), there are other significant factors which may drastically limit the transmission capacity.

WLAN does not allow full duplex communication [2]"container-title":"2011 IEEE 8th International Conference on Mobile Adhoc and Sensor Systems (MASS, which causes a rapid performance and capacity degradation on multi-hop routes [3], [4] Also, 802.11 Medium Access Control (MAC) is designed for shared channel communication [5] and is partly based on random back-off timers, making a consistent packet forwarding unreliable [6]. Shared parts of a route are prone to congestion and unfair traffic treatment [7]. Finally, routes separated on layer 3 might still interfere on the same layer 2 collision domain [7]. Apart from various interference types with WLAN, traffic in a WMN is often heterogeneous, because users create mostly vertical traffic [8]. This leads to congestion [9] near those mesh nodes which serve as traffic portals to external networks, or the Internet. Also, end-to-end routes pointing to an external gateway generally have to carry more traffic. Vertical traffic is not protected on those routes and has the same priority as intra-mesh traffic. These limitations cause that standard WMNs have a limited transmission capacity. This issue moves WMNs further away from what users would expect from a modern wireless delivery network /backbone: high downlink and uplink data rates, and high accessibility and reliability.

To enhance the transmission capacity in WMNs depicts the basic motivation for this work. A multi-interface node offers a suitable basis for this intention. The simultaneous usage of multiple orthogonal WLAN channels by a multi-interface node is a feasible method to achieve this goal [10]network endures from low capacity and throughput due to frequent back offs and packet collisions, hence single-radio multiple-channels (SR-MC.

METHODOLOGY

This article provides mesh networks operators with an overview of techniques to enhance capacity and QoS in multi-radio WMNs and further proposes a holistic system which combines these methods. First, common issues, such as interference and unfair treatment of vertical traffic in WMNs are identified, followed by possible counter-measures and -approaches. Information was gathered using high-quality scientific databases ("IEEE Xplore", among others). A systemic method was applied for the following overall design of the system and the relationships between its components.

Finally, a practical (experimental, empirical and heuristic) method was applied in form of simulations, to obtain the presented results.

RELATED WORK

A carefully designed resource allocation strategy, which matches node-specific availability of radios and at the same time the desired network behavior, is a crucial success factor [2]"container-title":"2011 IEEE 8th International Conference on Mobile Adhoc and Sensor Systems (MASS. This means introducing a distributed, or centralized Channel Assignment (CA), and a Load Balancing (LB) mechanism.

[11] provides a comprehensive review on existing load distribution models. They claim that skewness between asymmetric routes is a major issue in multipath load balancing. With hop-to-hop load balancing, skewness is of minor importance.

The first stage to exploit channel diversity is often an unmanaged, non-LB related solution. An often-used approach in a WMN backbone is to have two separate radios for edge nodes, at best using separate bands (2.4 GHz and 5 GHz). One serves local clients and the other radio is for sole backbone communication. Such examples are found in [12 and [13]. A next stage denotes the use of 2 or more radios in the backbone, to minimize intra-flow interference. In Fraunhofer's Wireless Back-Haul (WiBACK) architecture [2] two 802.11 radios are deployed, with a gap of at least 60Mhz between two 20Mhz channels. This avoids a throughput decrease at each hop. In [14], full-duplex communication is achieved with a dual-radio scheme.

A CA study [15] also deals with the question of how many Wireless Network Interface Cards (WNIC) are actually needed: It is often the case that WNICs are distributed evenly, which does not match the requirements of heterogeneous mesh traffic. It causes bottlenecks at Gateways (GW), which are in need of more resources, while other Mesh Routers (MR) do not fully utilize their radios. Wu et al. [15] intend to minimize the number of WNICs and recommend an absolute amount for different WMN sizes (both chain and grid setups are considered), based on a heuristic and an optimal approach.

Before network parameters are optimized, basic connectivity needs to be guaranteed. The CA approach in [16] focuses on this aspect. The centralized CA approach of Robitzsch et al. [17] facilitates an autonomously controlled entrance of a node in a WMN, considering adjacent- and inter-carrier interference. Most approaches do not distinguish between orthogonal or overlapping channels. Not so in [18]; here CA is optimized for partially overlapping channels.

Receiver-based Channel Assignment (RCA) schemes [19], [20] are straightforward, proactive, topology-considerate and easy to implement. Negotiation-based Channel Assignment (NCA) schemes perform CA on-demand and allow interference-free transmissions in most cases [19]. But their reactive nature makes them more suitable for MAC layer approaches, where the channel is negotiated per frame. For layer 3 packets, NCA would be too slow. Still, RCA and NCA are considered too decentralized approaches. There is no consideration of 2-hop neighbors and WNIC resources cannot be assigned in a parallel task; for example, based on the next-hop type.

Scheduling is the next logical step after CA. If sufficient resources (i.e., additional WNICs) are available between two adjacent nodes, bundling is able to improve the resource utilization beyond CA measures [21] Furthermore, channel bundling can be used to reduce signaling overhead [21]. Also, the allocation of channels to a single bundle reduces computational cost, since "all the channels in the same bundle are either available or busy simultaneously, a secondary user can sense each bundle of channels instead of each channel individually" [21].

[22] describes a Virtual Interface (VI) which sits upon multiple WLAN MACs and controls them. Within the VI, the IF with the best link quality is chosen for transmission, on a per-packet-basis. The group's approach fully segregates low performing interfaces in a bonded set of IFs, which wastes capacity in certain constellations. Basic channel assignment is not included, which causes additional configuration efforts for the user. A neighbor table is maintained, which holds information on the interface availability and link states in the neighborhood. To signal a node's associate IF addresses, a modification of the Address Resolution Protocol (ARP) is used.

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Hu confirms that establishing channel diversity (by having single channel links) is not enough; this diversity must be actively utilized, in order to improve capacity. In their work [23], a system model is described, which uses multi-radio for parallel transmission between nodes. Again, a VI with a virtual MAC address is used. In their simulator testbed, two kinds of Transmitter (TX)-oriented, scheduling algorithms are tested. Although entirely different in their behavior, both consider hop-to-hop scheduling. Hu defends this decision with the varying nature of the wireless medium, making multi-hop / flow coordinated scheduling too complex. The first algorithm creates redundant packet copies and schedules one per selected IF. Unfortunately, the receiver behavior is not specified in this case. This mode aims to improve loss-resilience, but has only a moderate impact on throughput, as expected.

The second algorithm applies "partition-based" scheduling, to improve throughput. A radio is randomly chosen, while its TX probability is directly based on the Expected Transmission Time (ETT) value. This design is straightforward; also, the metric is interchangeable. Both modes can increase throughput up to 10% with Transmission Control Protocol (TCP); the second algorithm enables 90% with User Datagram Protocol (UDP). The work is one of the first TX approaches for parallel transmissions. It does neither take traffic, nor roles of nodes into account. The authors recognize this and state that future solutions need to include full awareness of multi-hop conditions, to optimize scheduling.

A key concept depicts the abstraction of resources; for the sake of simplicity, compatibility and modularity. Adding a cross-layer design has high benefits [24]. The CARMEN architecture [25] introduces an abstraction layer, which hides particularities of different access technologies. An open virtual layer is also deployed in [26]. It accommodates different 802.11x IFs and makes them independent of layer 3. For each specific interface type, a new Logical Link Control (LLC) substitute module is introduced. The underlying algorithm uses one module or another, in dependence of flow requirements. A bundling within the virtual layer is not applied. Like many other Multi-Interface / Multi-Channel (MIMC) approaches, the group targets to optimize throughput and end-to-end delay as QoS parameters. A virtual layer/ interface is essential for MIMC WMNs which shall be compatible and open to different mesh protocols and metrics. It can also gather and

reorganize all types of reusable cross-layer input. A well-designed VI is further able to provide a usable platform to combine different measures to improve capacity and support heterogeneous traffic.

PROPOSAL FOR A RESOURCE-MANAGEMENT SYSTEM

In mesh backbones, limited capacity and traffic unfairness have a negative influence on transmissions which flow to and from gateways. This work's focus lies on the enhancement of transmission capacity in mesh networks and on the optimization of these vertical flows. A node cannot guarantee that a packet eventually follows its calculated route towards the destination, therefore the necessity to enhance the performance of every single next hop link was identified. This can be achieved with the deployment of MIMC nodes. The enabling resource management system shall be described in this Section.

The proposal incorporates the combined use of various radios. This has been realized by assembling standard schemes and components in a custom manner and by analyzing the resulting approach in detail. Involved standard technologies include mesh routing, QoS and traffic engineering (parts of them adopted from the Multi-Protocol Label Switching (MPLS)), routing topology analysis, priority queuing and load balancing.

Overview of the compound architecture

The novel proposal of a node architecture for transmission resource management is shown in Figure 1 and contains existing components in a wireless mesh node (illustrated in grey), as well as novel ones (those related to resource management are illustrated in blue, and those related to packet processing in orange). Novel components are nested in a middle layer (2.5) solution with multi-layer input. In the following, the details of each component that integrate the architecture are described.

Layer 3 Information

The host system must provide the Routing Table (RT), Local IP/MAC Address Information, as well as access to each radio (this implies sending, receiving and switching its channel). The system design requires a proactive link state mesh routing protocol. Optimized Link State Routing (OLSR) [27]

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is the recommended protocol for this purpose and provides link cost values, as well as the 1-hop topology in the architecture in Figure 1. Especially the identification of nodes with access to the Internet (gateways) and connectivity information on the 1-hop Neighborhood is required from the topology. This identification is handled by the component Topology Parser. The main IP address of the smallest index j of the totality of all local radios $\sum r_j$ represents the node ID in the system. The ETT metric [28] is recommended to be used with OLSR, since it introduces bandwidth-related link quality awareness. ETT's proactive link state probing is performed for all radios.
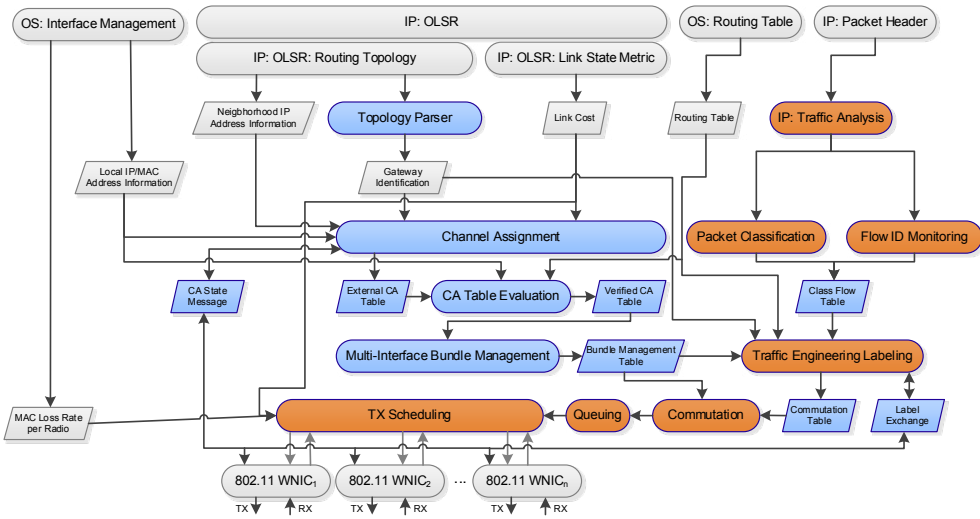

Figure 1. Mesh node architecture

Traffic Analysis

This component analyzes packets which enter the WMN via the host and thus pass the middle-layer module for the first time. It extracts basic DiffServ [29] information to consider QoS-demands. Five Differentiated Services Code Point (DSCP) encodings are mapped to a class code c_k. A single flow is determined through, Source (SRC) / Destination (DST) IP address and port, and whether TCP or UDP is used. When a new packet from upper layers passes for the first time, this information is stored in the Class Flow Table.

Channel Assignment

CA negotiates channels with neighbors via custom CA State Messages. CA is considered an external and exchangeable component in the system depicted in Figure 1, with a static format output. The expected table output of the CA protocol, the External CA Table, is exemplarily depicted in Chart 1 and taken as a recommendation to assign radios and channels to neighbors.

Chart 1: Expected channel assignment table.

Neighbor IP	Neighbor MAC	Channel
IP_1	MAC_1 of neighbor 1	1 ... z
IP_1	MAC_2 of neighbor 1	1 ... z
IP_1	MAC_n of neighbor 1	1 ... z
...	...	...
IP_m	$MAC_{1...n}$ of neighbor m	1 ... z

Any CA protocol can be chosen; still these are the most essential requirements it has to fulfill:

- Radios can operate on exclusive channels or on shared channels

- Obtaining and maintaining 1-hop connectivity has the highest priority in a CA algorithm

- Proactive (for network startup) and reactive (channel state-adaptive) assignment

- An idle radio must be distributed anew (proactively)

- CA has to determine how many radios are used per neighbor

- If a gateway is present in the 1- or 2-hop neighborhood, this next hop to the GW (or leading to it) is privileged; it receives more radios and high-quality channels

- If no GW is present, channels/radios are equally distributed among neighbors

- CA protocol can handle neighbors with a deviant amount of radios and set of used channels

- Possibility to configure a designated Control Channel (CC) [30]

Channel Assignment Table Evaluation

It is not sufficient to accept the unverified External CA Table as simply given. The novel CA Table Evaluation component offers an intermediary trust check between the output of any CA protocol and the system, before radios are actually utilized. For that, such a component shall make the following general decisions per channel:

- Is it an initially proposed channel a valid resource?

- Can it be justified to switch a channel which is already overtaken in the current CA table?

- Can it be justified to shift a radio resource to another neighbor?

In the optimal case, decisions are based on whether the supposed neighbor is actually reachable via the tested channel, the channel's current load, the current overall load of its bundle and the next-hop type.

The CA Table Evaluation currently fulfills the basic requirement of testing the connectivity of a channel. The outcome of the component is that only those channels are overtaken, on which the neighbor has responded. The result of the CA Table Evaluation is the Verified CA Table.

Traffic Engineering Labeling

Based on the Traffic Engineering Labeling (TEL) component in Fig. 1, the system grants higher priorities to GW flows and flows with QoS-demands over horizontal traffic. TEL introduces a custom header (shown in Figure 2), which comprises the Next-Hop Field (NHF) and the Queue Selector Field (QSF).
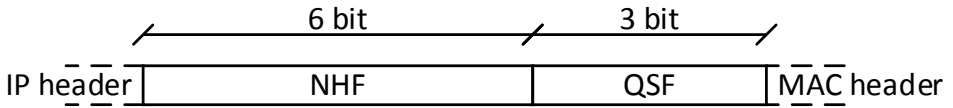
Figure 2. Custom header

If the carrying flow is passing on a GW route, the packet receives the first label (NHF) for fast layer 2 forwarding (label swap on a per-hop basis) by the TEL engine, plus a second label (QSF) to put it in the highest priority queue in each node (label content remains the same here). To determine the affiliation to a GW flow, the packet's IP Destination (DST) must coincide with a mesh-external IP address. The content in the NHF decides whether a packet receives a standard layer 3, or a swift, MPLS-like layer 2.5 forwarding. But contrary to MPLS, a fixed Label Switched Path (LSP) cannot be regarded in the system, as the concept of a predefined path of routers is not conformable with the philosophy of ad-hoc routing ("hop to hop" principle). If a packet does not flow through, or enter via a GW, but still bears a DiffServ classification, its DSCP value is mapped to an equivalent custom label (i.e., QSF), which allows the packet to be queued with a higher priority than others. QSF determines the priority queue a packet will be queued in, on a hop-top-hop basis. A packet keeps the header until it reaches its intra-mesh destination or leaves the mesh cloud at the egress mesh node. Both of its fields will be discussed in the following.

The NHF facilitates forwarding of vertical (or gateway) flows, which enter and/or leave via a gateway. A requirement of the system is that both ends of a GW flow are able to detect themselves as such. With OLSR, gateway nodes typically broadcast Host and Network Association (HNA) [27] messages. Those entries are listed separately as 0.0.0.0 in the routing table, linked to the actual main IP of the node. The following rules apply for setting the NHF:

- Non-GW ingress MRs label packets with an NHF value $v \neq 0x0$, but only if their IP DST matches a mesh-external destination

- If the DST IP indicates a horizontal flow, NHF is set to 0x0

- Ingress GWs will set $v \neq 0x0$, no matter of the destination IP of the packet

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A Mesh Forwarding Information Base (M-FIB) in Chart 2 lists visible mesh-internal GW flow endpoints.

Chart 2: Mesh Forwarding Information Base table.

in-label	in-bundle	IP DST of	out-label	out-bundle
label	b_1	IP_0	label	b_1
…	…	…	…	…
label	b_m	IP_{l-1}	label	b_m

Where b is a bundle, h is its index, m is the current number of registered neighbors, IP DST refers to an IP(v4) destination address of a GW flow endpoint in the mesh, s is the GW flow endpoint, o is its index and l is the number of GW flow endpoints in the WMN seen from this node.

Next-hop specification per DST is directly transported from the layer 3 RT to the M-FIB. For the actual commutation operation, the reduced commutation table named Mesh Label Forwarding Instance Base (M-LFIB) is produced (equal to an M-FIB table without the IP DST column) and handed to Label-based Multi-Hop Packet Commutation (LMHPC). To enable label swapping, the following rules were defined:

- In-labels are the out-labels of all 1-hop neighbors and are exchanged via a lightweight label distribution protocol:

    - For each out-bundle, an individual Mesh Label Distribution Message (M-LDM) is created, which is depicted in Figure 3. With these messages, the used labels are communicated to 1-hop neighbors. The entry counter in the M-LDM specifies the amount of DSTs listed in a single message.

    - A node announces out-labels for both its locally created upload paths and for those paths which it has received from previous hops via M-LDMs.

- Locally determined in-label/-bundle values for GW DST entries are set to 0x0.

- There is a unique bundle-index per 1-hop neighbor.

- The out-label is unique within an out-bundle (respectively is unique for each next hop) and contains a random value between 1 and .
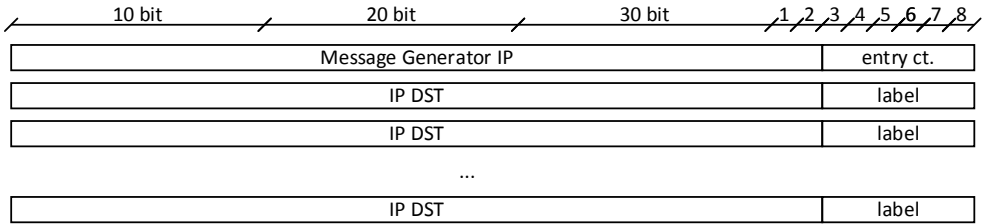
10 bit	20 bit	30 bit	1 2 3 4 5 6 7 8
Message Generator IP			entry ct.
IP DST			label
IP DST			label
...			
IP DST			label

Figure 3. M-LDM header

The mapping of the internally defined DiffServ class code to a set of seven queues is depicted in Chart 3.

Chart 3: Queue mapping via a custom header.

Queue	QSF value	Internal traffic class	DiffServ [29] equivalent
q_1	0x1	Gateway traffic	None
q_2	0x2	c_1	EF
q_3	0x3	c_2	AF4
q_4	0x4	c_3	AF3
q_5	0x5	c_4	AF2
q_6	0x6	c_5	AF1
q_7	0x0	Best effort traffic	Default PHB

Again, the priority of GW traffic excels any other internal traffic class specification.

Multi-Hop Radio Resource Management

Multi-Hop Radio Resource Management (MHRRM) describes the group of functionalities offered by the components Commutation, Queuing and TX Scheduling. MHRRM is a distributor of encapsulated packets. Vertical/outer-mesh traffic is favored in the forwarding process. MHRRM also manages bundles and has direct control over aggregated capacities. Figure 4 visualizes the processing of NHF and QSF (both in binary notation) in

the forwarding plane via three representative packets, which enter a node (see left side of the Figure).
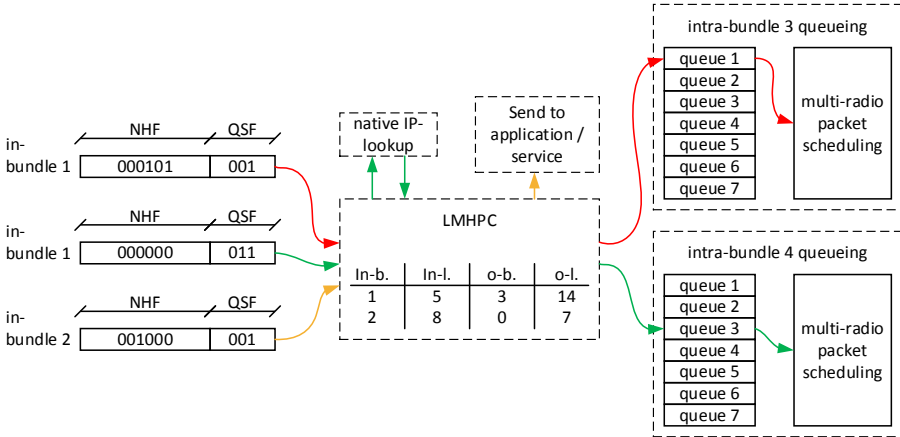

Figure 4. Example of flexible label treatment

The first encapsulated packet belongs to a GW flow and is forwarded. The second packet is forwarded between two non-GW mesh nodes. The third packet eventually arrives at the end of a GW connection.

To visualize the concept, a single virtual interface, which is provided to layer 3, is depicted in Figure 5.

The virtual interface structure enables a flexible way to visualize and manage traffic distribution to next hops. Different neighbors receive separate bundle indices, where m is the amount of registered 1-hop neighbors. Value 0x0 is never used as an index because it is reserved for a) when GW packets are created b) enter via the same node or c) when GW packets have arrived at their destination / gateway. A Radio Unit refers to a physical WLAN radio resource. This single resource can be a radio which is tuned to an exclusive channel (used with only a single neighbor), or to a channel which is shared with different neighbors. Thus, a physical radio can be assigned to multiple bundles at the same time. An internal Bundle Management Table (BMT) is maintained within MHRRM, in which bundles are defined. The table is primarily based on the Verified CA Table, since all local and neighbor- IP and MAC addresses (plus the deployed channels for each link) are provided with it. Additionally, the BMT stores statistics for load balancing.
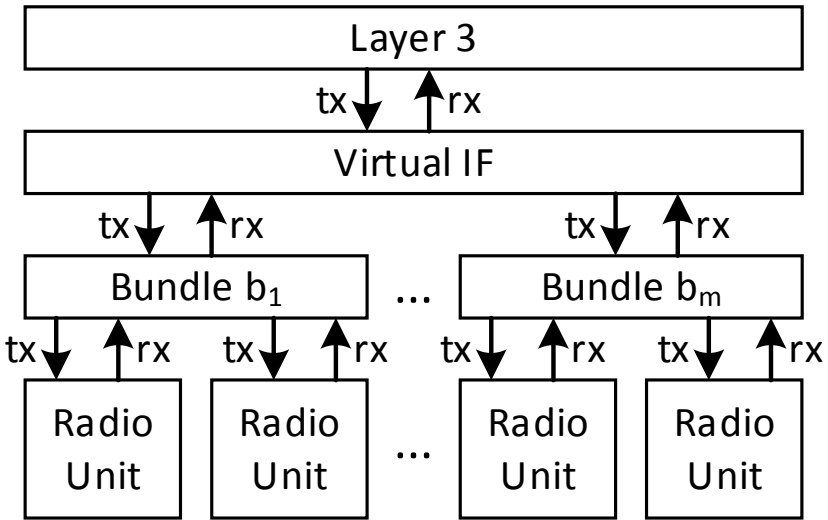
Figure 5. Virtual interface and bundle definition

The Label-based Multi-Hop Packet Commutation represents the operative treatment of packets, in terms of commutation. An incoming packet in an intermediate mesh node can be fast-forwarded, without the time- and hardware- consuming IP lookup. The next hop is still determined by OLSR, but routing information is now provided below layer 3. The main task of LMHPC is to swap in-labels to out-labels (based on the M-LFIB table) of packets of vertical flows and to commute these packets accordingly. The NHF allows LMHPC a faster mapping to an interface bundle. In the best case, a packet is forwarded with complete transparency to the IP layer between the ingress and the egress MR. The lookup process in the LHMPC core is reduced to compare short labels with a fixed length, based on a table which is much simpler than a full RT. If the commutation table lookup for a layer 2 packet results in an out-bundle with a value $v = 0x0$ and an out-label value , then the packet is forwarded to higher layers and its label is removed by TEL. If not, packet treatment after commutation involves two consecutive decisions: When a packet shall leave its queue and which radio shall be used for sending.

Next, the QSF part of the custom header contains synthesized QoS- and topology- information. The queue subsystem interprets packet classes in QSF and manipulates the sending order of multiple flows. Again, GW and

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DiffServ-coded packets experience a faster removal from the queue, in case that multiple streams to the same next hop are polled. Separate queues per bundle allow to rearrange the original, chronological packet sending order of incoming flows, to a class-corresponding order. Queuing further enhances multi-radio scheduling: A priority queue can be combined with link-state sensitive Packet Scheduling (PS), by offering the best radios to the most important packets. A single set of queues is characterized by these main parameters:

- Fixed, tunable amount of queues (the amount of queues is the same in all bundles)

- Tunable queue length (in packets)

- Tail drop principle [31] within each queue

- Packet First In – First Out (PFIFO) principle [32] within each queue

- Dequeuing policy based on Weighted Fair Queuing (WFQ) [33], [34]

- Fixed, manually chosen weight w per queue

After a packet has been taken out of a queue, it is finally scheduled to be sent via one of the available radios in a bundle connected to the corresponding next-hop. Load balancing is not an issue related to mesh routing, to queuing or to layer 2 forwarding, and can therefore be detached from these processes, because packets are scheduled on a single-hop basis. A configurable set of load balancing modes is offered to a mesh operator. These modes are explained in the following.

With the Weighted Fair Scheduling (WFS) mode, radios with the best quality shall bear the majority of packets. WFS calculates a sending probability per link based on its cost, to determine the link's usage frequency. WFS mode is thus tailored to link state mesh routing. WFS also permits a fair treatment of interfaces with underperforming links, to prevent starvation of such. WFS mode is based on ETT, as it is the more accurate QoS-related metric. Applied to system parameters, the sending probability is calculated with equation (1):

$$g_j = \frac{v_j}{\sum_{i=1}^{n} b_h v_i} \qquad (1)$$

Where g is the send probability of a radio r with the index j, v is the link state/metric value of a radio r and n_{b_h} is the number of radios in a bundle .

The Round-Robin (RR) packet scheduling mode simply foresees that for n radios in a bundle b, each radio r will transmit n^{-1} of incoming packets.

The third mode describes an extended version of the simple Round-Robin mode: From a given set of n radios in a bundle b, a fixed number of Fallback (FB) radios B, $0 \leq B < n$ is reserved, where n is the amount of radios attached to the node. Fallback radios are used in case one or more of the currently used radios might fail. When B=0, standard RR is applied. When B = n – 1, single-interface transmission is applied on this link, while n - 1 radios remain silent. B is specified by the user. A fallback threshold rate $R = \frac{F_j}{d_j}$ per radio is maintained in the Bundle-Management Table. R triggers the replacement of an active radio. F is the frame loss rate between layer 1 and 2.

EVALUATION

The positive effect of selected system features on transmissions in MIMC mesh networks shall be outlined in this Section. The OMNeT++[1] simulator is used for evaluation. Channel assignment is statically configured in the simulations. No specific CA protocol is deployed. Also, Traffic Analysis is substituted by a manual setup of packet generators, which set determined class codes.

Scenarios

Nodes have multiple 802.11g radios. Nodes aligned in a grid or in a chain formation have a fixed distance of 140m between each other. Blue circles in the following figures indicate the minimum reception range.

At first a grid setup in Figure 6 with 37 nodes is analyzed. Each node has 1, 2, 4 and 6 radios, depending on the configuration. Round-Robin scheduling mode is used network-wide. Each radio is tuned to a separate orthogonal channel. All nodes thus have access to the same set of channels. Node 36 in the center of the map represents a gateway. Multiple instances of a File

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[1] OMNeT++ Network Simulation Library and Framework, http://omnetpp.org

Transfer Protocol (FTP) application start an upload to the GW. One after another, the following nodes become active: node 14, 9, 26, 0, 5, 35 and 30.

Next, the impact of different packet scheduling modes on the scenario in Figure 7 is tested. Here a UDP stream from node 0 to 4 with a TX bandwidth of 5 Mbit/s (datagram sizes are set to 500 and 1500 bytes) is locally congested by two streams from node 5 to 6, and 7 to 8 (both streams are transmitted with a bandwidth of 3 Mbit/s and a datagram size of 1024 bytes). Congestion is caused on the single channels 0 (node 5 to 6) and 1 (node 7 to 8). The nodes on the chain from 0 to 4 have 3 radios at their disposition, tuned to channels 0, 1 and 2 (free channel). All channels are chosen orthogonal in the simulation environment. All three scheduling modes are applied to test their impact on network performance.

The impact of different queue weighting schemes on parallel flows in a WMN is tested with the scenario in Figure 8. All nodes deploy 2 radios on channels 0 and 1, using the RR scheduling mode. Streams 1, 2 and 3 run from their prospective senders to destinations 1, 2 and 3 respectively. UDP is used in this scenario. Datagram sizes for the three streams vary between 250B, 500B, 1000B and 1500B. Streams 1 and 3 have a TX bandwidth of 1 Mbit/s, while stream 2 has a bandwidth of 2 Mbit/s. It is forced that all streams share parts of the chain constellation between nodes 0 and 4-6. Queues per neighbor are enabled in all nodes. An uneven weight distribution scheme (1) grants a 70% queue removal probability to packets of the flow to destination 2. The remaining share of 30% is granted evenly to streams to destinations 1 and 3 and for broadcast traffic. The second weighting scheme (2) includes an even removal probability for all traffic. The queue size is set to 20 packets for each of the seven queues.

Results

Figure 9 shows the throughput results of the grid setup from Figure 6. Throughput and hence network capacity levels rise gradually, with an increasing number of radios. Still, the sole usage of RR PS cannot solve intra-route fairness issues, since all channels are loaded evenly, not adaptively. Still, if the hop count to GWs can be kept short (1-3 hops) in a WMN, RR becomes an attractive and yet simplistic scheme to improve throughput proportional to the amount of equipped radios. Figure 10 reveals that the

WFS scheduling enables the highest throughput levels in the scenario in Figure 7. This is given due to the advantage that if ETT-based delay probing results drop on a link in a bundle, adaptive LB with WFS assigns less load on it. WFS allows multi-hop streams to exchange more packets in total, although their route might be selectively congested.
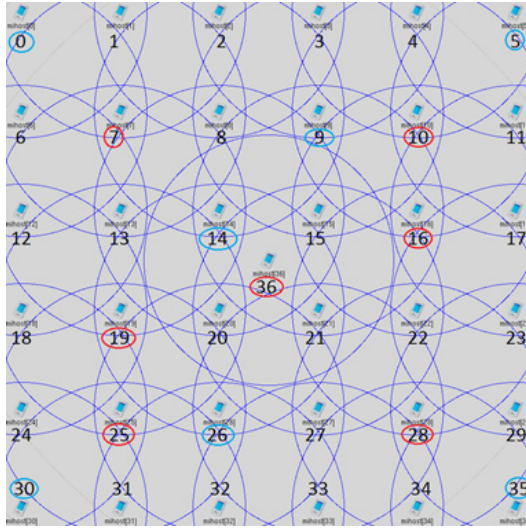

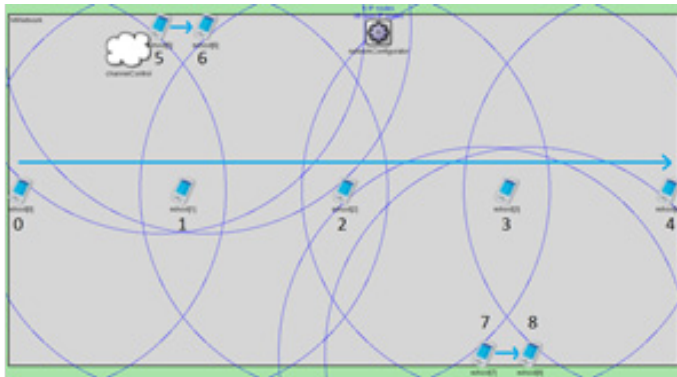**Figure 6**. Grid setup with 1 GW.

Figure 7. Chain setup with local interference

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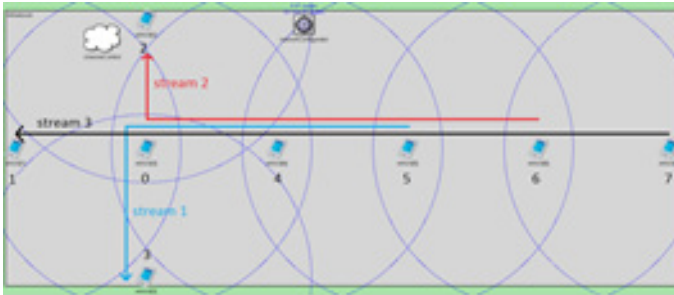ISSN: 0122-3461 (*impreso*)
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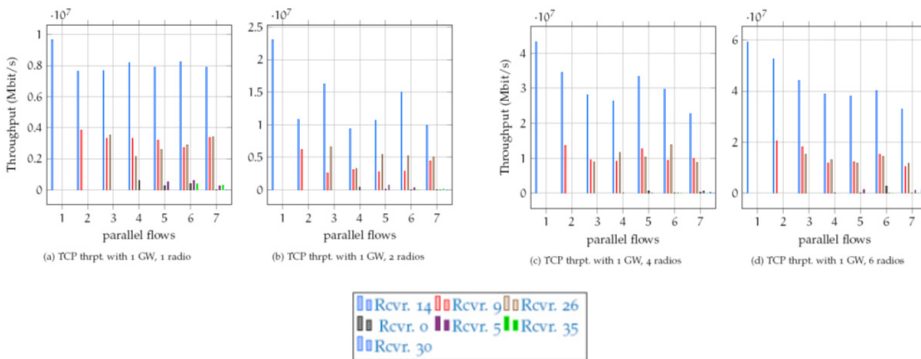**Figure 8**. Setup with shared route fragments

Figure 9. Throughput results of multiple flows.

Thus, WFS scheduling mode is recommended to facilitate the coexistence of different cross flows. Also, weighted-fair-based scheduling is useful when a rerouting option is considered too cost-expensive by OLSR. Capacities on the reputed bad next-hop link can still be optimized with WFS. The same principle of load shifting is found in the Extended RR mode, but in a more radical fashion, since a complete channel switch is forced. One step before the actual scheduling process, queues enable measures to improve performance of disadvantaged flows from the scenario depicted in Figure 8: The end-to-end delay represents a crucial QoS parameter and can be selectively decreased by applying per-hop queues. Fig. 11 demonstrates these improvements. Delay levels of flow to DST 2 were reduced with a queue-weighting scheme in its favor. This resolves unfairness due to intra-route interference and varying hop counts.

Queuing is independent from bundling and has the potential to even favor streams on single-channel paths; given a configured prioritization scheme.
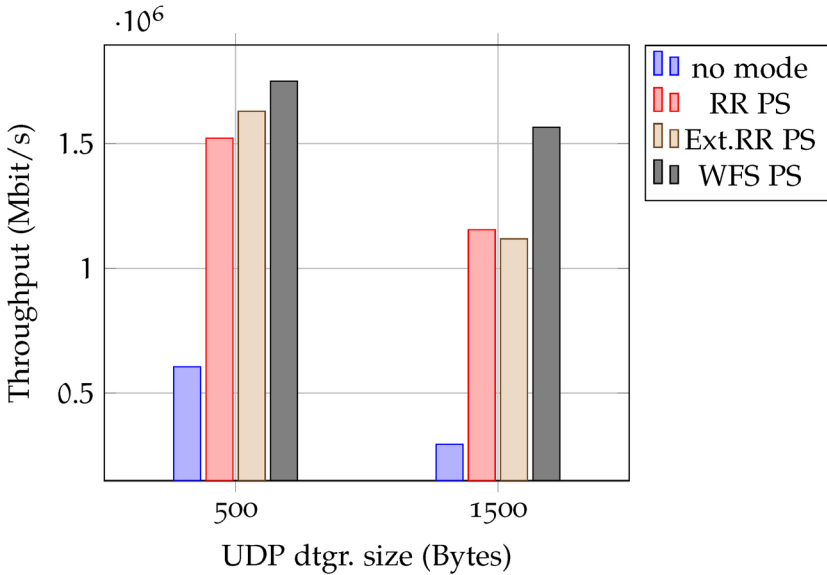

Figure 10. Throughput results of packet scheduling modes

CONCLUSIONS

Standard WMNs suffer from multi-hop and interference limitations and from the instance that vertical traffic cannot be properly protected, without suitable measures. Several single solutions to manage or exploit multi-radio nodes exist in research. Additionally, standard and specialized QoS solutions can be applied. If applied isolated, each method may offer a punctual benefit, but cannot ultimately solve the true issues of limited mesh capacity and unprotected vertical traffic at the same time. Thus, available mesh technologies need to be analyzed and innovatively arranged. The result of this process, a unique and holistic combination of these methods, is described in this work.
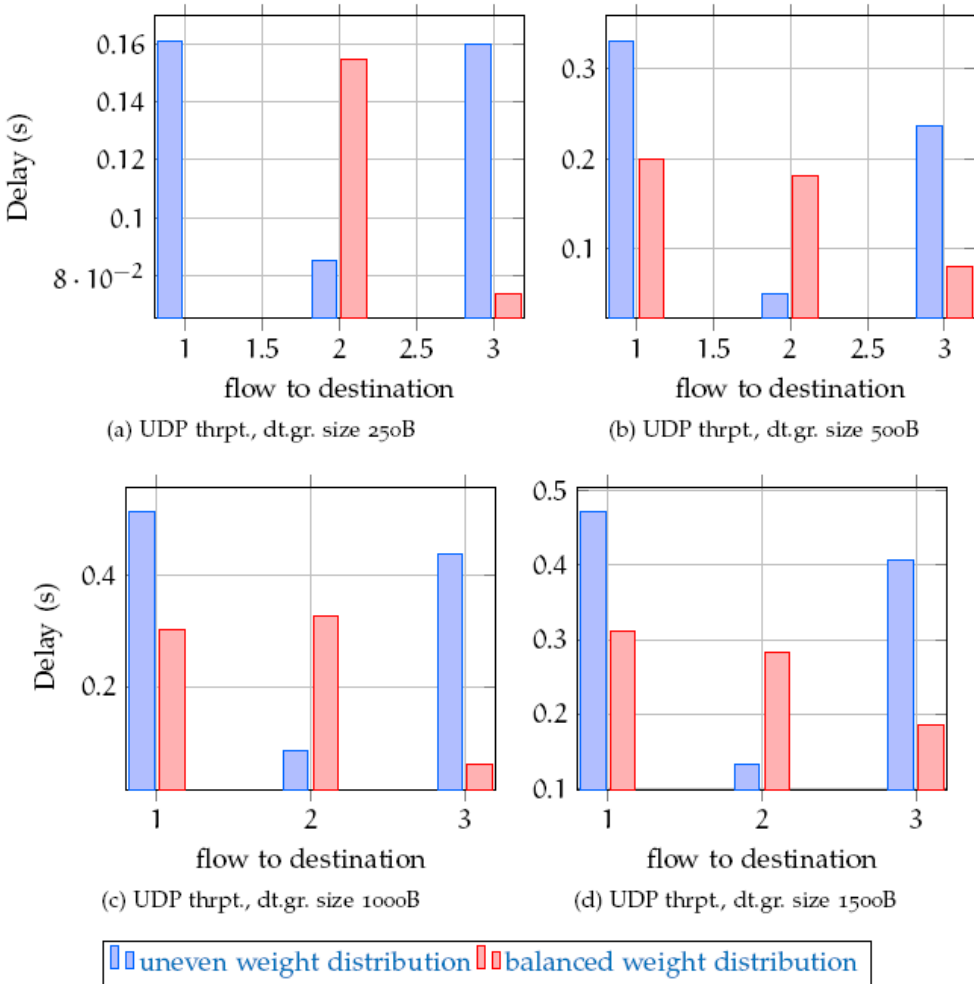
Figure 11. Delay results of priority and balanced queue scheme

The presented novel architecture for MIMC nodes is built around a custom middle-layer module, which processes cross-layer information. It enhances the transmission performance in WMNs and enables to bundle the capacity of WLAN radios. Improvements are achieved in comparison with single-radio mesh networks, or unmanaged multi-radio mesh networks. Furthermore, more general network parameters are improved, such as the overall capacity, or reliability of a wireless mesh backbone. The mesh operator can control the desired network characteristics by choosing the corresponding

packet scheduling mode. Forwarding is moved to sub-IP layer for selected packets. A novel traffic labeling chain enables to optimize bi-directional vertical traffic, on a hop-to-hop basis. Queues further protect GW flows against horizontal traffic. The use of labels in a custom header solves the problem that vertical and horizontal traffic are mixed and equally treated in a standard WMN, although vertical flows have a higher priority. The novel queue structure additionally allows to consider DiffServ.

Selected scenarios have shown that when multiple radios are used, the capacity is significantly increased. The link state-sensitive WFS mode is tailored for proactive, link-state mesh routing, and it conquers interference on congested channels. Tunable queue parameters provide a toolset to facilitate QoS policies, which lead to selective end-to-end delay improvement on multi-hop paths.

Future work will focus on the conceptual prioritization of one or more vertical flows within the same bundle, and to combine the single-path solution with multi-path mesh approaches. Also, future measurements shall regard the impact of channel switches during run-time, as well as the impact of layer 2 forwarding. The latter aspect will require implementing the system in a real-life network environment, since layer 2 forwarding in the simulator does not alter the packet processing.

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