

A Survey on Multi-Channel Based, Digital Media-Driven 802.11 Wireless Mesh Networks

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Abstract—802.11 hardware has ultimately made its way into the electronic consumer market. But, especially in home networks, it clashes with high quality demands of rich multimedia streaming applications, that WirelessLAN can only partly cope with. This work describes basic features and fundamental flaws of 802.11, particularly with regard to multimedia streaming and Quality-of-Service (QoS) requirements. To overcome current problems of missing bandwidth resources in wireless home environments, the presented work points towards future multi-interface extensions of 802.11-based networks, in combination with decentralized Wireless Mesh Network (WMN) structures. The work provides an overview of all relevant 802.11 and WMN components with reference to important research works and indicates basic design aspects, crucial success factors and challenges of a future QoS-ready, multi-layer system that combines the advantages of decentralized wireless networks and of multi-channel MAC usage.

Keywords-802.11; Mesh; Multi-Interface; QoS

I. INTRODUCTION

All things considered global consumer industry has made great experiences with the IEEE family of WirelessLAN 802.11 standards. But, the increased usage of wireless connections by consumer end devices has made wireless networks, especially home networks, become more heterogeneous. At the same time, new media applications raised the requirements on wireless networks and users expect the same quality of experience (QoE) from web based service platforms (e.g., YouTube) as it is well known from broadcast TV signals for example. So what has been achieved for wireless *connectivity* has to be achieved for *Quality of Service (QoS)* on future wireless links. The 802.11 spectrum is not fully exploited in most setups, although for example IEEE 802.11a would provide up to 12 orthogonal channels for simultaneous usage. Multi-channel / multi-interface WLAN networks offer a viable solution for these problems and some key aspects of their exploitation will therefore be presented in this work.

Furthermore, this work deals with 802.11 multi-channel systems in combination with *Wireless Mesh Networks (WMN)*. Recent hardware development favors the shortfall of access points in home setups, since nodes with multimedia capabilities provide more CPU resources and are able to compute complex routing decisions and forward packets in mesh networks on their own. To decrease the dependency on wired backbones and to enable a more scalable collective network, with enhanced all-wireless coverage and connectivity over a larger area, a WMN is the most suitable approach [1]. This advantage is in particular valuable in residential buildings, where often a single AP is not sufficient to connect all clients over several floors. Home networks with the purpose to essentially transport real-time media and less data traffic (e.g., a file download) are a key motivation scenario of this work.

The rest of the work is structured as followed: Section II provides essential knowledge about underlying 802.11 PHY and LLC techniques. Relevant mesh routing strategies are highlighted in Section III. Section IV identifies general QoS requirements. Finally, Section V outlines challenges and chances of possible multi-channel solutions for WMNs. In Section VI representative 802.11 measurements are presented and Section VII concludes the presented aspects. References to related works are included throughout the article.

II. 802.11 - OVERVIEW AND RELEVANT COMPONENTS

The IEEE 802.11 standard covers the Medium Access Control (MAC) sublayer and the physical layer of the OSI reference model. But, an effective QoS-sensitive transmission chain requires the revision of QoS-related parameters (e.g., CPU power, buffer sizes, encryption, etc.) on almost every OSI layer. In this chain, 802.11 sub-protocols, especially in MAC layer, are at risk to become a bottleneck [2]. This section now covers the threat potential of known 802.11

issues in reference to QoS constraints, in order to efficiently apply mesh structures in home networks.

A. 802.11 Physical Layer Schemes

To conquer interference problems, 802.11 PHY layer natively provides frequency diversity: Depending on the region, 802.11b/g offers between 2 and 3, and 802.11a up to 12 non-overlapping channels. This generally favors the deployment of mesh nodes equipped with multiple wireless network interface cards (WNIC), but, current WLAN stations mostly deploy only a single interface, which can only communicate on one channel at a time. The first standardized attempt (in consumer hardware) to increase spectrum utilization within a single WNIC is described by 802.11n [2]. Besides MIMO antenna features, 802.11n allows to bond two 20 MHz channels and thus to increase the bandwidth on the PHY layer. Still, applying 802.11n physical bonding in 2.4 GHz band would consume up to two-thirds of the available spectrum and might hence increase interference levels. Those considerations about effective spectrum utilization may lead to a later addressed *dynamic bundling* approach, which envisions MAC coordinated channel bundling.

Due to physical limitations, PHY layer does not always match the requirement that “using n interfaces equals n -fold performance” [3] and so only offers a limited modularity for WNIC combinations. Per node performance is also limited by hardware capacities [4] and upper layer buffers; a less relevant effect for consumer hardware. Disadvantageous alignment of wireless cards and distances and angles between antennas might also jeopardize performance [5]. In reality negative radio effects like ACI might also occur on low SIR levels, despite the general assumption that two non-overlapping channels with physical proximity are supposed to be interference free [6]. Apart from that, capacity gain is always superior to all single-interface setups.

B. 802.11 MAC Layer Schemes

Besides physical interference, also the chance of a high amount of nodes sharing the same coverage area is responsible for the inherent unreliability of wireless systems. The more nodes are active, the higher is the packet congestion: Although 802.11 PHY layer is designed for multi-channel purposes, the medium access control (MAC) scheme implies a single channel shared by all stations, using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). CSMA/CA was originally designed for solely best effort transmission, not considering distinction and prioritization of different packet classes. The lack of QoS support in 802.11 led to the first standard amendment 802.11e [7], that takes different traffic priorities into account. In 802.11e, standard 802.11 Distributed Control Function (DCF, with its strong best effort character) is replaced with the Hybrid Coordination Function (HCF), which increases the transmit probability for QoS-sensitive packets. 802.11e performance

strongly depends on packet inspection methods in the MAC layer in order to detect protection-worthy traffic, or on the corresponding QoS signaling in IP headers, performed by upper layers (e.g., DiffServ). This denoted dependency underlines the advances of a cross-layer QoS system [8].

Because of their poor scalability, random access protocols such as CSMA/CA are not an efficient solution for WMNs. Standard 802.11 MAC is not designed for multi-hop communication, which creates elementary problems in intermediate nodes, which forward packets between source and destination. These packets have to be replicated multiple times through multiple nodes, but still belong to the same end-to-end flow. The 802.11 standard does not consider this and forces every to-be-sent packet to compete for the medium anew, although it would be sensible to coordinate common time slots for coherent forwarding packets on all involved intermediate nodes on the multi-hop route. In affect, the available throughput for each node is not only limited by the raw channel capacity, but also by the forwarding loads imposed by other nodes, since only one node can access the medium at a time. This results in an inefficient store-wait-and-forward process along the route. To reduce overhead time wasted for channel access negotiation, Bononi et. al. [8] described a basic and a fast-forward negotiation mode. The former mode equals standard DCF procedure, the latter mode extends RTS / CTS messages by a flow identifier and by a variable reservation period for each forwarded stream, facilitating multi-hop transmissions. These schemes can be further optimized by including a distributed multi-interface usage, for example when a set of interfaces A is responsible for the actual data transmission, while another set B coordinates the synchronized medium access along the route. Such enhanced functionality, when packet forwarding indicated by the network layer is supported by link layer, further argues for a cross-layer approach to decrease delay. IEEE standard committee recognized these needs and has formed the *Robust Audio/Video Streaming Task Group*, who defined general QoS requirements on WLAN in the 802.11aa standard amendment [9]. 802.11aa mainly depicts enhanced signaling between APs/stations and robust multi-cast, but also relies on packet inspection methods. A general overview of related 802.11 amendments is given in [10].

III. WIRELESS MESH NETWORKS AND ROUTING PROTOCOLS

Especially in WMNs deployed in the private sector (e.g., home network) users frequently access external Internet resources and thus routes to the gateway node are more often penetrated than any other node-to-node connection, which provokes bottlenecks near the Internet gateway. If routing measures cannot compensate such limitations, alternative solutions have to be found in the underlying 802.11 access technology (see Section V).

To extend regular wireless mesh networks to multi-interface, QoS-ready WMNs, distance vector protocols like AODV are suitable in principle [12], because they already share a lot of neighbor information (included in signaling messages) locally, which could be extended with channel allocation information of the involved interfaces. On the other hand distance vector (DV) protocols are less scalable and produce high amounts of overhead, since comprehensive routing information is exchanged. In addition, DV protocols do not converge fast enough, due to the unsynchronized and unacknowledged way that distance vector information is exchanged. A fast convergence might be a critical factor for a home network, since users expect multimedia devices to be quickly integrated into the network. Link state protocols like OLSR [11] offer contrary and thus positive characteristics: Low network overhead (since exchanged information only contains single link characteristics), good scalability and fast convergence.

Research works show that cross-layer routing metrics may heavily increase performance in mesh routing [12]. Including medium-specific characteristics like e.g., the actual throughput, packet delay or packet delivery ratio values, directly obtained from driver API, allows a precise evaluation of the link quality, but, at the expense of compatibility (the system then always depends on a special operating system or WLAN driver). For a better multimedia performance in home networks, standard metrics should be replaced with *residual bandwidth capacity* and *round-trip-time*, which plays to the requirements of a video/audio stream. For a best effort traffic transmission high speed and low delay are not necessarily mandatory to carry out its duty, but rather a *high packet delivery rate*.

To enhance this multi-layer metric concept, in a next step routing metrics should adapt to changing network conditions [13]. Given the assumption that traffic is spread heterogeneously, the cumulative equation that describes the used routing metric in total could beneficially combine several sub-metrics and weight them with a factor that depends on dynamic zones in the mesh network. In zones with low QoS-related traffic activity and low packet collision/contention probability, it is better to traverse packets as fast as possible through this area, rather than observing the general bandwidth utilization in this zone for example. In this case *packet delay* and *hop count* dominate (represented by a higher weight factor). In zones with high network loads, that might threaten QoS performance on busy links, it is sensible to consider *the residual bandwidth capacity* instead. To realize a proactive indication whether a part of a route is about to carry real-time traffic or not, a source node could broadcast network-wide QoS-reservation messages for a planned end-to-end route, before starting the actual stream. Köhnen et al. [14] already implemented such functionalities in Ethernet networks. The reservations are included in the cumulative metric equation as weight factors.

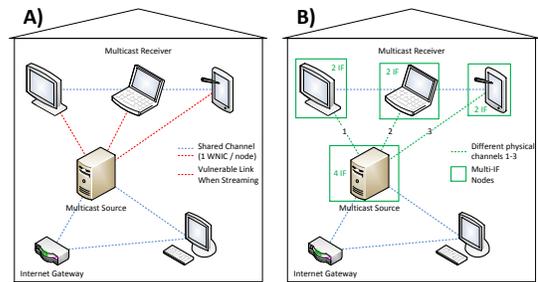


Figure 1. Single-Interface / Multi-Interface Home Topology

IV. TRANSPORT LAYER AND BEYOND

Introducing QoS in a home mesh reveals structural issues of standard WLAN setups: Advanced scenarios might require multicasting of local video/audio sources, which is contrary to common point-to-point data communication and may further provoke bottlenecks (see red links in Figure 1, A)). To implement QoS, the correct identification and classification of real-time packets is mandatory, but also hard to accomplish, due to the convergence of Media over IP traffic (e.g., YouTube, Hulu or Telekom Entertain), best effort traffic (e.g., HTTP protocol) and linear DVB broadcasts. Traffic can be identified in several ways and the identification process should never slow down the actual packet processing of the node. Most of the current setups require a deep packet inspection with a thorough payload analysis [14] to determine the real nature of a packet's content, which is generally not a problem with common home consumer devices. After a successful identification, transport protocols like the Resource Reservation Protocol (RSVP) can reserve bandwidth for certain flows. RSVP requires that every client supports the protocol and is therefore mainly applied in homogeneous cable backbones and less in wireless mesh networks. Besides bandwidth reservation and packet prioritization (e.g., 802.11e) the consideration of a multi-interface environment marks a third viable alternative to protect traffic. The benefits are regarded in the following sections.

V. CHALLENGES OF MULTI-INTERFACE ENVIRONMENTS

This section attends to initial problems of multi-interface / multi-channel (MIMC) networks. In most multi-interface solutions a single virtual MAC interface (which is presented as such to upper layers) combines and manages PHY interfaces. This architecture provides a good trade-off between portability and channel diversity exploitation, since the original 802.11 standard needs no further modifications and future PHY modulation schemes such as 802.11ac [10] can be easily adopted.

Xu et al. [13] examined differences between the aim to *exploit channel diversity* in MIMCs, which implies assigning as much different channels as possible to different neighbor-to-neighbor links, and sole *channel bonding*, which means

aggregating bandwidth capacities of the involved interfaces between two neighboring nodes. The group states that under high traffic load conditions, with a high degree of packet collisions that deteriorate the throughput and delay performances, relying on channel diversity greatly reduces collisions and may improve both throughput and delay since traffic can be equally distributed on more channels. Channel bonding only slightly decreases packet delays in high-traffic conditions. On the other hand, when traffic is low, the bonding of two interfaces achieves low delay values on a link and therefore favors QoS streams. Bonding has a better leverage effect when applied to concrete links that form parts of routes carrying QoS-packets between two nodes. MIMC is rather suitable to balance and absorb high packet quantities (both best effort and real-time) in the mesh network. The two concepts are regarded and shall be combined in the following subsections.

A. Channel Distribution in MIMC Environments

Channel distribution for multi-interface nodes must aim to at least equally distribute available channels in a hop-by-hop fashion, in order to decrease per channel congestion and mutual interference levels. Also, in this way the network topology might be actually shaped through (physical) route separations by frequencies; for example to separate three different streaming/multicast single hop links, as depicted in the in-house scenario B in Figure 1. First of all channel distribution has to be applied in a way that a *logical connectivity* (appearance in the routing table, despite of the used channel) between a node and every neighbor within its coverage range is guaranteed. If nodes transmit on different channels without further knowledge of the channels their neighbors are reachable on, they become invisible to each other. In the literature this problem is referred to as *deafness*, which further leads to common hidden terminal issues on multiple hops [15]. Therefore a dedicated *control channel* (CC) is needed [16]. The scope of the CC ranges from sole transmission of signaling packets generated by MAC (RTS, CTS, ACK) and network layer (e.g., OLSR HELLO and *Topology Control* overhead traffic) to hybrid solutions where overhead traffic is mixed with best effort traffic. CC must be always accessible by all stations and must carry information about a node's general access to a set of channels and which of them are currently assigned to / used by its interfaces. To somehow consider the limited coverage area, for the sake of simplicity a node distributes this information only to its 1-hop and 2-hop neighborhood, to not provoke excessive overhead by network-wide flooding of its channel signaling information. The information itself can be distributed through an arbitrary message type or, more economically, embedded in existing signaling messages.

Another deciding design attribute of a multi-channel / multi-interface network is the question whether channel allocation is performed pro- or reactively. Bononi et. al. [8]

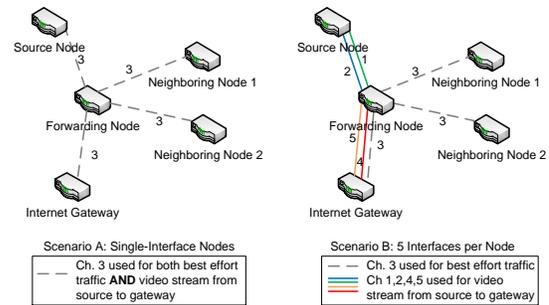


Figure 2. Separate Resources for Gateway Routes and QoS Traffic

deal with the question if channel assignment should follow after the actual route finding mechanism, or vice versa. Wu et. al. [16] implement channel allocation in a *reactive* manner by combining RTS/CTS management with the identification and distribution of unused channels within the 1-hop neighborhood, all based on a common CC. A proactive solution on the other hand might be more suitable, since a basic connectivity between nodes has to be established anyway. (Re-) Assigning channels in reaction to a transmit request by upper layers only consumes additional channel (re-)allocation time; a critical factor for delay-sensitive real-time traffic. Additionally, interference is prevented a priori when channels (orthogonal to each other) are assigned proactively, before upcoming flows.

The *dynamic adaption* to actual traffic loads and QoS-demands in a node, instead of simply assuring a uniform distribution of channels, make assignment mechanisms even more effective. To classify next-hop links and thus the majority of traffic they are bearing, we distinguish between best effort links (low priority), links that carry traffic towards or coming from Internet gateways and links that carry QoS traffic (both high priority). Identification of the type of traffic may be provided by upper layers (deep packet inspection methods). Gateway nodes are identified through the routing table. As mentioned before, gateway routes generally carry the majority of traffic in WMNs and should receive more resources to prevent bottlenecks in the mesh region near the actual gateway node. The distributable channel resources depend on the amount of available interfaces per node. In a first step, QoS- and gateway routes are favored with separate interfaces, while best effort links may communicate on a shared channel, applying CSMA/CA. Figure 2 depicts a related scenario. In this case the channel distribution is calculated and seen from the forwarding nodes's point of view, which deploys 5 WNICs. A video stream that takes a gateway route receives 4 different orthogonal channels. This significantly increases bandwidth, lowers delay and prevents negative interference effects for this stream. Based on this example, *resources in MIMC environments* are either represented by separate channels for each neighbor, or in the advanced case, by *multiple* separate channels for each

neighbor, which lead to the application of *channel bundles*.

B. Channel Bundling in MIMC Environments

Bundles may be dynamically generated respectively degraded, depending on the variable amount of 1-hop neighbors (assuming that links suddenly break down or come up). In the particular case of fig. 2, each link of the QoS route aggregates capacities of two interfaces. Bundles are formed reactively (for example directly after the identification of a concrete QoS-stream), when extra capacity is needed and if the involved nodes can provide sufficient interface resources. Channel Bundling requires *load balancing*. To double bandwidth capacity, both channels can be loaded simultaneously with packets. Another concept sets the focus on stability: One channel might act as a fall-back option in case the main channel (that carries all packets) fails, or if the packet error rate on the main channel exceeds a threshold. Alternatively, redundancy (multiple transmission of the same packet) might increase stability as well. On the arrival side *packet reordering* has to be performed, depending on the chosen load balancing scheme. *Packet reordering* is a critical performance factor as well since wireless links are less predictable and packets may not always arrive in the correct order, due to different delay values of the interfaces.

In current research works, channel bundling options are still poorly considered, mostly because it is supposed that nodes may use all interfaces to serve different neighbors first. Therefore additional WNICs for bundling are rarely available. Still, channel bundling is the future concept to increase network capacity in 802.11. Tradeoffs between MIMC and bundling have to be defined here to enable efficient hybrid scenarios like in Figure 2, where all low-priority links can be served on a shared channel.

Channel bundling decreases packet delay times and for this reason it is especially interesting for supporting media streams. Since the overall transmission bandwidth of a link that contains bundled interfaces is enlarged, the transmission rate increases, which decreases packet transmission time, assuming a constant packet size.

VI. MEASUREMENTS

The presented measurements were simulated with Network Simulator NS-2, in combination with OLSR as proactive link state routing protocol. They reflect the promising performance gain of multi-interface (IF) over single-IF 802.11 mesh networks. Comparative throughput (respectively TCP/FTP goodput), packet delay and packet drop rate observations are considered to evaluate the performance of each scenario.

Before addressing a home WMN, our first setup shall represent a large scale WMN and depicts a 150m x 150m area where 50 nodes were placed at random positions (cf. Figure 3). 4 extra nodes (yellow marked in fig. 3) are placed at fixed positions at the corners of the square

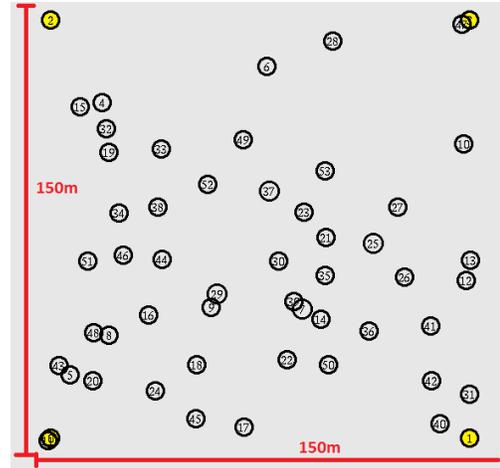


Figure 3. WMN with random node positions

area. Yellow node 1 initiates a TCP stream to node 2 in each of the 200 simulation runs, as well as node 0 to node 3. The two streams take different routes in each run due to their random character. A single-IF scenario, where all 54 nodes communicate on a shared 802.11a channel (54Mbits/s raw bitrate), is opposed to a multi-IF setup, where each of the 50 randomly positioned node contains two .11a interfaces. First interface is either tuned to channel 36 or 40, second IF to channel 44 or 48. Channels are selected randomly in each run. In this second scenario the 4 extra nodes apply 4 interfaces each to access all 4 used channels and to ensure a physical connection to all possible neighbors. Results are shown in Figure 4. Multi-IF setup clearly outperforms single-IF because limited single-channel resources are spatially disseminated on other frequencies, optimizing channel utilization. The “total” column of each graph refers to the overall value across the entire mesh.

Second measurement maps a typical indoor scenario in a 10m x 10m home (see Figure 5) where the left node on the top floor maintains a UDP stream for 200 seconds, which is interfered by a FTP stream after 100s. Again OLSR is used, but any other mesh protocol may be applied instead. Compared are both situations; undisturbed UDP/TCP stream and both UDP and TCP stream at the same time. Again, a single-IF setup (802.11a) is compared to a multi-IF environment (cp. legend in fig. 5). Results in Figures 6, 7 and 8 reveal that using a separate orthogonal channel for each link dramatically increases performance and makes the home network more suitable for QoS streams.

VII. CONCLUSIONS AND FUTURE WORKS

This work focuses on 802.11-based wireless mesh networks, used to transport real-time streams. As shown by the so far discussed flaws of 802.11, the development of network solutions that provide abundant streaming capacities for future rich multimedia formats is critical for the ongoing

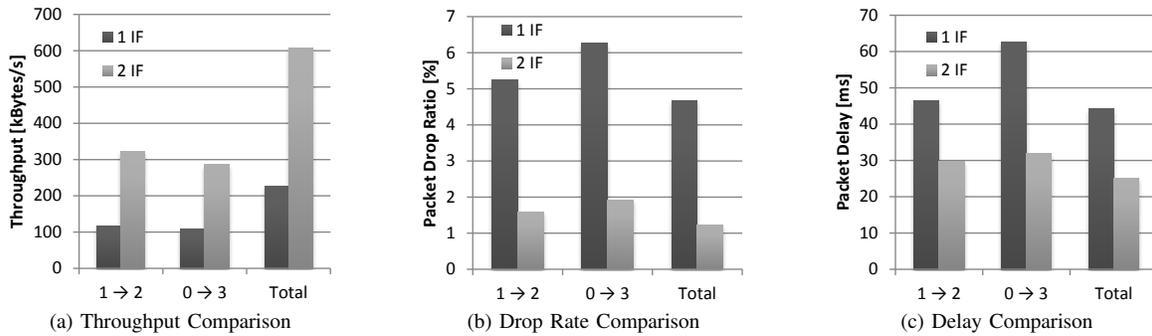


Figure 4. Single-IF vs. Multi-IF - Performance Comparison

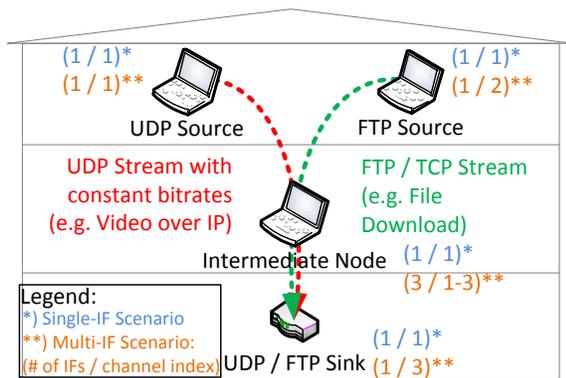


Figure 5. Home Mesh Scenario

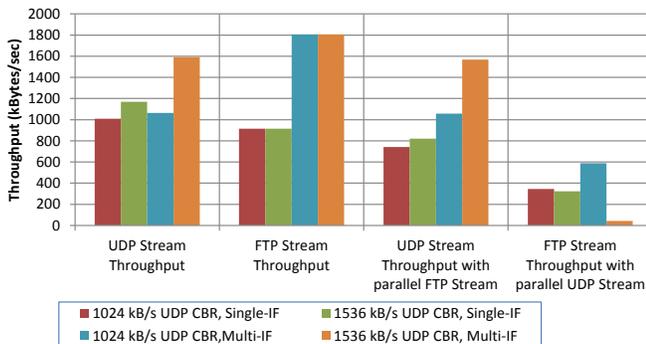


Figure 6. Throughput Results

adaption process of 802.11. Especially home networks based on standard single channel 802.11 links may not be able to provide sufficient bandwidth resources and high quality links to satisfy the constantly growing quality-of-service demands. This work provides a base for future multi-layer approaches. Multi-Layer Architecture allows routing metrics to get a more adequate view on the actual link states. Moreover, results of packet inspection methods can be used to facilitate traffic distribution over physically separated routes in the MAC layer, to decrease the general packet congestion per channel. A novel MAC layer instance to control the channel

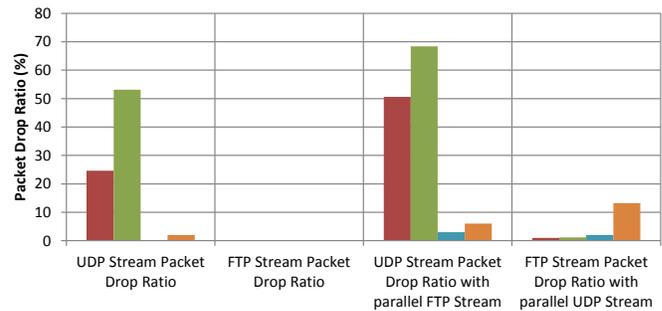


Figure 7. Packet Drop Ratio Results

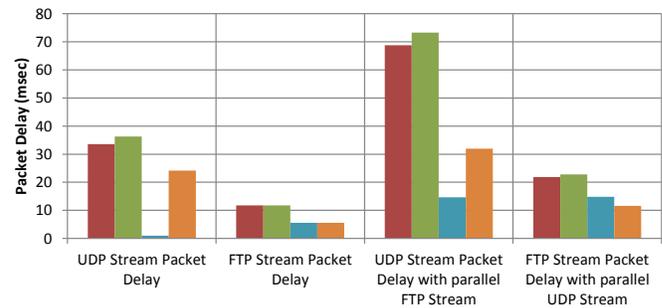


Figure 8. Packet Delay Results

assignment and channel bundling of connected interfaces forms part of the multi-layer strategy. To optimize the mixture of MIMC and bundling approaches is an important task for the future.

Now we are on the boarder to second and third generation mesh networks that offer quality features beyond simple connectivity of all nodes. 802.11s [18] is clear evidence that mesh structures are finally accepted in a broad range of wireless applications. To help the IEEE 802.11 standard to evolve with future requirements, its network structures have to become more dynamic and able to fully exploit the channel diversity offered by the PHY layer. Enhanced spectral efficiency and adaptive multi-channel utilization are the keywords for a significantly increased network capacity.

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