A Token-Based MAC For Long-Distance IEEE802.11 Point-To-Point Links

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***Abstract*—WiFi-based Long Distance (WiLD) networks have emerged as a promising alternative approach for Internet in rural areas. However, the MAC layer, which is based on the IEEE802.11 standard, comprises contiguous stations in a cell and is spatially restricted to a few hundred meters at most. In this work, we summarize efforts by different researchers to use IEEE802.11 over long-distances. In addition, we introduce WiLDToken, our solution to optimizing the throughput and fairness and reducing the delay on WiLD links. Compared to previous alternative MAC layers protocols for WiLD, our focus is on optimizing a single link in a multi-radio multi-channel mesh. We implement our protocol in the ns-3 network simulator and show that WiLDToken is superior to an adapted version of the Distributed Coordination Function (DCF) for different link distances. We find that the throughput on a single link is close to the physical data-rate without a major decrease over longer distances.**

***Index Terms*—WiLD, Long-Distance WiFi, IEEE802.11, Token, MAC, rural areas**

I. INTRODUCTION AND MOTIVATION

Internet connectivity is considered as a basic requirement for economic development. In densly populated areas in developed countries, Internet Service Providers (ISPs) offer very high bandwidth at very low cost because competition is strong and cable-based service provisioning is cheap when distances are small. In rural areas, however, distances are large, and digging a cable into the ground is extremely expensive in relation to the small number of potential customers at the end of the cable. This discrepancy leads to a digital divide, where urban areas enjoy a high-quality service at low cost while rural areas suffer from the reverse.

Wireless technologies provide an option for decreasing service provisioning cost. In particular, commercial off-the-shelf (COTS) hardware based on the IEEE802.11 (WLAN) family of standards can significantly reduce capital expenditure (CAPEX) for ISPs. Unfortunately, WLAN was not designed for long-distance links, so efforts have been made to optimize its implementation over long distances in conjunction with directional antennas, leading to the work on WiFi-based Long Distance (WiLD) networks.

A key advantage of COTS systems is that all the WLAN mass-market developments come for free for other deployment scenarios. In particular on the physical level, IEEE802.11 has experienced a tremendous technological development over the last five years, boosting raw data-rates close to the physical limits. The situation on the Media Access Control (MAC)-layer is different, here timings play a key role in system performance. Our initial work on optimizing WiFi-based Long Distance (WiLD) links was based on the standardized distributed media access and lead to significant performance improvements for distances beyond several kilometers [1]. This paper presents the idea of replacing that media access method by a token-based mechanism.

The paper is structured as follows. In Section II, related work in the context of MAC-layer for long-distance IEEE802.11 links is presented. In Section III, we provide motivation for our new approach by describing further optimization potential for these links. In Section IV, we formally introduce our token-based MAC protocol before providing our methodology in Section V. Section VI provides our results. This paper closes in Section VII with a short summary and possible future work.

II. RELATED WORK

The purpose of this section is to provide related work in the context of WiLD links, focusing on the MAC. This section is has two parts. In the first part, challenges and necessary adoptions for successfully operating the default IEEE802.11 MAC over long-distances are presented. The second part summarizes alternative MAC layer solutions dedicated to the use-case of WiLD links.

A. DCF and long-distance

The IEEE802.11 MAC layer utilizes a technique called DCF, which employs the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) concept with a binary exponential back-off algorithm. The DCF was specifically designed by the IEEE802.11 task group for contiguous stations in a cell and spatial restrictions of a few hundred meters at most. However, the topology of a WiLD network is usually based on point-to-point (P2P) links with single-hop distances ranging from a few hundred meters to several kilometers. Instead of numerous stations applying for time on the shared medium, only two participants get into contention with a non-negligible propagation delay.

The malicious behavior of the DCF for long-distance links was initially analyzed by Leung et. al. in [2]. The authors found that the Short Interframe Space (SIFS) after a packet transmission is not suitable for long-distance links with an increased propagation delay. Detailed investigations have been conducted by Simo-Reigadas et. al. in [3] and [4]. The authors found several MAC-related timing parameters have to be adapted and propose further optimization of the DCF for long-distance links. Similar work has been conducted in [5]. We analyzed the operation of the IEEE802.11n MAC on long-distance links in detail in [1]. In general, longer link distances lead to increased transmission delays for an individual MAC packet. The sending stations therefore have to wait longer for the acknowledgement to arrive. In addition, the slot-time, which defines the carrier-sensing interval during the back-off needs to be increased (cf. Figure 1). Both parameters are specified in the standard [6]. The standard defines the so-called coverage class such that an increase of one equals 3 μs of additional air propagation time with a maximum value of $cc = 255 \;\widehat{=}\; 765\ \mu s \;\widehat{=}\; 229.3\ km$. In [1], we propose a model to calculate the throughput and delay for long-distance IEEE802.11n links and provide an optimized version of the back-off timings for the standard MAC protocol.

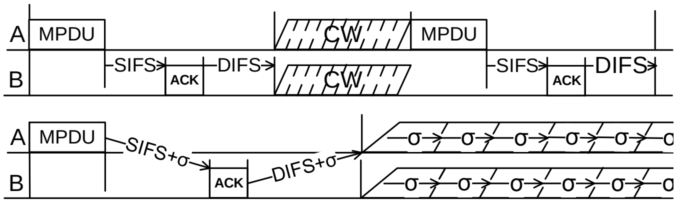

Fig. 1. Operation of the DCF. On top short distances, on the bottom increased timings on long-distance links.

B. Alternative MAC protocols

In the past, various MAC protocols have been proposed either to partially or fully replace the standard IEEE802.11 MAC layer or to operate on top of it. Each protocol has been designed and optimized for a specific environment and equipped with a tailored set of functions and properties.

Most of these protocols use a Time Division Multiple Access (TDMA) approach. Each station in the network is granted a specific amount of time to transmit data. The length of these time slots can either be fixed or variable, depending on the protocol's design constraints, e.g. to provide predictability (fixed) or to adapt to changing traffic demands (variable). To prevent collisions, time synchronization between the stations is crucial since each station has to be aware of the beginning and end of each time-slot. The time-slot synchronization can be tight or loose. Tight synchronization refers to the case that all nodes are synchronized to a global time source, loose synchronization instead uses a packet exchange (e.g. a token) for synchronization purposes. In [7], Hussain et al. provide an overview of TDMA-based approaches for long-distance IEEE802.11 links. The authors compared six different MAC layer techniques and rated them based on defined criteria. The most important approaches are shortly summarized in the following.

An alternative MAC layer protocol called 2P was first proposed in 2004/2005 by Raman et al. in [8]. The protocol is designed to use a single wireless channel over the whole backhaul network to provide more spectrum for wireless access technologies. For each link, one radio connected to a high gain directional antenna is used. Despite the high directionality of these antennas, side lobes still lead to interference. Due to these interferences, the main idea of 2P is to divide the transmission into two phases, which the authors call Synchronous Operation. For a single location, all radios are in either a transmitting or a receiving state. The network topology graph has to be bipartite[1] to find a fulfilling group assignment among the stations. A switch between the states is done when either a defined send limit or a timeout is reached. Marker tokens are sent from the transmitting to the receiving station to indicate the end of the transmission.

2P was identified as a good starting point when trying to develop an alternative MAC layer protocol, but several research groups have identified room for improvements. In 2007, Patra et.al presented WiLDNet [9] as a descendant of 2P, introducing mechanisms for better link utilization (packet aggregation) and robustness to packet loss. In 2008, a second improvement to 2P (and WiLDNet), JazzyMAC was presented by Nedevschi et. al. [10]. A major improvement over WiLDNet is the support of variable length time slots and overlapping transmissions to improve link utilization and moving away from the topology graph having to be bipartite. In [11], Salmeron et al. show a comparison between an adapted version of the DCF and WiLDNet.

In 2010, Ben et. al introduced JaldiMAC [12]. While 2P and its extensions are dedicated to a single-channel operation of P2P links, JaldiMAC has been proposed as a point-to-multipoint (P2MP) wireless subscriber line using directional antennas. JaldiMAC claims to achieve increased performance by combining dynamic transmission slots with a novel ply scheduling algorithm and Quality of Service (QoS) support.

Dhekne et al. proposed a "TDMA MAC for WiFi-based Rural Mesh Networks" in [13]. Compared to other approaches, this TDMA protocol relies on static time slots and a tight time synchronization. A central node assigns time slots to the participating stations.

In [14], Eznarriaga et al. present an approach called SoftToken, a token-based medium access protocol that works on top of the default CSMA/CA contention mechanism. The motivation for their approach is to enhance the IEEE802.11 QoS capabilities under heavy load situations. SoftToken is implemented as a master-slave architecture in which a central node coordinates channel access of the participating stations (slaves) using control messages called token requests.

As an alternative to TDMA different authors have presented Frequency Division Multiple Access (FDMA) based approaches for long-distance links. The main idea is to use two directional antennas on each side of the link and assign non-interfering channels enabling a full-duplex transmission. In [15], the design of this protocol is reduced to the problem of edge coloring on a directed graph.

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[1] A graph is bipartite if it is possible to divide all of its vertices into two disjoint subsets such that every edge in the graph connects a vertex in one subset to a vertex in the other subset.

III. MOTIVATION

In this Section, we provide the reader with our motivation for a new token-based MAC protocol for long-distance links. In general, we try to achieve the following goals compared to an adapted but optimized version of the DCF [16]:

- Increased throughput,
- Less delay and jitter,
- Better fairness and the ability to parameterize the up- and downlink ratio.

As described in Section II-A, with an increasing range of the link, DCF related timings need to be increased accordingly. Figure 1 shows the default operation of the DCF on short- and on long-distance links. Especially during the back-off, the increasing propagation delay σ leads to more idle time on the medium. As described in [1], the MAC layer aggregation mechanism of IEEE802.11 can significantly reduce the ratio between idle and transmission times since the size of the data packet is significantly increased. In addition, we described in [16] how the number of back-off slots can be reduced. However, a reduced number of back-off slots leads to a higher probability for collisions, which again reduces the throughput. Our goal is to further minimize the idle times and provide an aggregated link throughput close to the physical rate and nearly independent of the distance.

The same reasoning for an increased throughput can be transferred to a decreased delay. With the additional propagation delay added for each slot in the back-off, the packet delay also increases with the distance.

The last goal we want to address is fairness and the ability to set the up- and downlink ratio. In general, the DCF is based on a random process during the back-off. Due to different hardware and software implementations on both stations, it is possible for one station to receive more time on the medium. In addition to that, our use-case is back-hauling. A desired feature is to set fixed up- and downlink capacities to account for asynchronous traffic patterns.

IV. A TOKEN-BASED MAC

In this section, we describe our approach to a token-based MAC protocol. Our protocol follows the main ideas of 2P [8] and especially the extensions provided by JazzyMAC [10] but with some crucial differences described in the following.

Our protocol design focuses solely on the token exchange on a single long-distance link. We assume that this link is part of a Multi-Radio Multi-Channel Wireless Mesh Network (WMN) where non-interfering frequencies are assigned to each link. This can be achieved by an intelligent Channel Assignment (CA) protocol. The main idea can be summarized as follows: The station currently holding the token is able to transmit a specified amount of data. When transmitting is finished, or no data is present, the token is passed to the other station. The previously sending station switches to the receiving state. In this protocol, no back-off is needed since a station on a link is either in receiving state or holds the token. There are no collisions on the medium.

A. Protocol Design

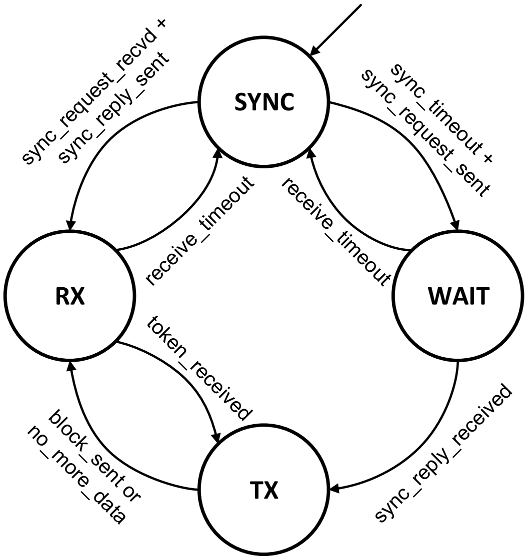

Fig. 2. WiLDToken: State machine.

We call our proposed protocol WiLDToken. To describe the protocol, Figure 2 shows a state machine. Note that this state machine runs on both stations simultaneously and has no terminating state. In general, the state machine/protocol is divided into two different phases:

- Data exchange phase (RX and TX states),
- Synchronisation phase (SYNC and WAIT states).

During regular operation, a station is either in TX or RX state. In TX state, the node holds the token and is allowed to transmit data. Since we deploy block transmission, the TX node is allowed to transmit one block of data from its transmission queue. If the queue is empty, the node may keep the token for a minimum_holding_time. After this timeout or when the block is transmitted, the token is piggypacked to the block, and the station changes into RX mode, waiting for the Block ACK from the recipient.

The receiving node receives the block of data and the token (or just a token if no data was transmitted). The receiving node turns from RX to TX state. Since it is holding the token, it is immediately allowed to transmit the Block ACK for the received data, a block of data waiting in the transmit queue, and the token. The token moves back and forth between the two nodes, together with data, Block ACK and retransmitted packets if necessary. No time is wasted waiting for IFS other than SIFS. If both nodes have traffic to send, the medium is continuously used for data transmission.

The synchronisation phase is necessary for the initial token generation and to handle token loss. The Sync state is the initial state of the node and is entered whenever a rec_timeout indicates that the token was lost. In Sync state, the node (and typically both nodes) waits for a Sync packet to arrive or for an arbitrary timeout to fire. The node where the timeout elapses first generates a Sync Request by sending a Sync packet to the second node, and enters WAIT state. The second node should

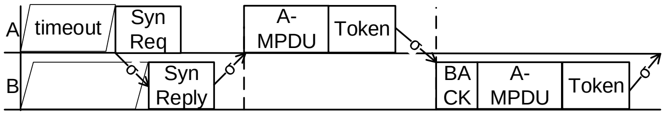

Fig. 3. Operation of the WiLDToken showing the random timeout at the beginning, the synchronization packets and the data packet exchange for the RX and TX states.

receive the Sync Request, generate a Sync Reply and enter RX state. The node in WAIT state receives the Sync Reply, enters TX mode and communication can start or continue as described before. This synchronization is expected to be a rare event in a typical network.

A complete packet exchange for the protocol is shown in Figure 3. The Figure shows, particularly, the idle times on the medium are significantly reduced compared to an optimized version of the DCF (cf. bottom of Figure 1). Instead of numerous times during the back-off, the propagation delay is only relevant after a transmission.

In the following, some timing-related parameters of this protocol are discussed in more detail.

1) Send limit: The send limit is an important factor in several ways. It directly influences the throughput and the delay of the protocol. In addition, it is limited by different restrictions in the IEEE802.11 standard. The most obvious limitation is a maximum continuous airtime for a station on the medium. Depending on the standard and region, this maximum airtime ranges from $4\ ms$ to $8\ ms$.

2) Sync and Receive Timeout: The sync timeout defines the time before a station starts to generate a Sync Request. There are two important considerations about this time_out. First, two stations should not generate a Sync Request at the same time. Second, the propagation delay should be included in this timeout so that the other station can the packet and reply to the request. Therefore we chose the default back-off mechanism of a long-distance DCF.

B. Token format

There are two different options for implementing the token and sync exchange: Using additional and dedicated packets or using header fields. One of the main implementation goals is to keep the additional overhead as low as possible. We therefore decided to implement the signaling in the IEEE802.11 header of an empty frame. In the frame control part of this header, we exploit two different fields. First, we are using the type field with a configuration of '11', which is currently not used. Afterwards, we exploit the subtype field to signal a sync request, sync reply or token.

V. METHODOLOGY

To evaluate our WiLDToken, we decided to use a simulation. We use and extend the well-known ns-3 network-simulator in version 3.24 [17]. The WiFi implementation in ns-3 is roughly divided into three different submodules[2]: the PHY layer model (carrier sensing, sending and receiving), the MAC low model (queuing, ACK, retransmission) and the MAC high model (association, beaconing). In addition, the DCF is implemented in the so called DcfManager. This manager retrieves information from the carrier-sensing model and grants access to the medium for the MAC low models. We replaced the DCF manager by our WiLDToken state machine and used most of the other models as they were. For the upper MAC models we chose the IEEE802.11 ad-hoc mode, which is sufficient for P2P links.

In ns-3, we simulate P2P links from 100 m to 50 km and IEEE802.11n radios operating in the Unlicensed National Information Infrastructure (U-NII) band. Since ns-3 does not support the combination of directional antennas and WiFi, we use omni-antennas with an artificial gain of 23 dBm. In combination with 30 dBm output power of the cards, this leads to an EIRP of 53 dBm which is the maximum defined by the Federal Communications Commission (FCC) for U-NII point-to-point links. Currently ns-3 is not capable of MIMO simulations. We are therefore limited to SISO with a maximum Modulation and Coding Scheme (MCS) of 7. In addition, we chose a 20 MHz bandwidth, leading to a physical data-rate of 72.2 Mbps. We use IP/UDP as network layer and transport layer protocol respectively.

VI. MEASUREMENTS AND RESULTS

This section presents the results we obtained with our simulations in ns-3. It contains two parts. First, we show a short validation of our model for long-distance IEEE802.11 links [1]. Afterwards, we evaluate the performance of WiLDToken compared to an adapted and optimized version of the DCF.

A. Mathematical Model and ns-3 Simulations

Our first experiment intends to validate the correlation between our proposed mathematical model [1] and a simulation of such links in ns-3. The mathematical model has been validated with real hardware and links in [1]. This step is important since we want to ensure that ns-3 simulates WiLD links correctly before we compare the result with our newly proposed token protocol. Therefore we set all distance dependent timings of the DCF to the values presented in [1]. Due to space limitation, we skipped additional details in this paper but have made the ns-3 source code available to the community on our website[3]. We saturate the link with bi-directional traffic originating from both stations.

An example of the results of this validation process is shown in Figure 4. This figure visualizes the throughput estimated by the mathematical model and the ns-3 simulation for different fixed A-MPDU sizes (aggregation factor). We chose this example to emphasize the influence of the idle times during the back-off on long-distance links. In addition, the adapted slot time ($9\mu s + \sigma$) has been added. The results show the typical throughput decrease on longer distances for the DCF. Figure 4 reveals that we adapted ns-3 successfully to simulate long-distance IEEE802.11 links on the MAC layer in accordance with our model presented in [1].

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[2] https://www.nsnam.org/docs/release/3.24/models/html/wifi-design.html

[3] www.mc-lab.de

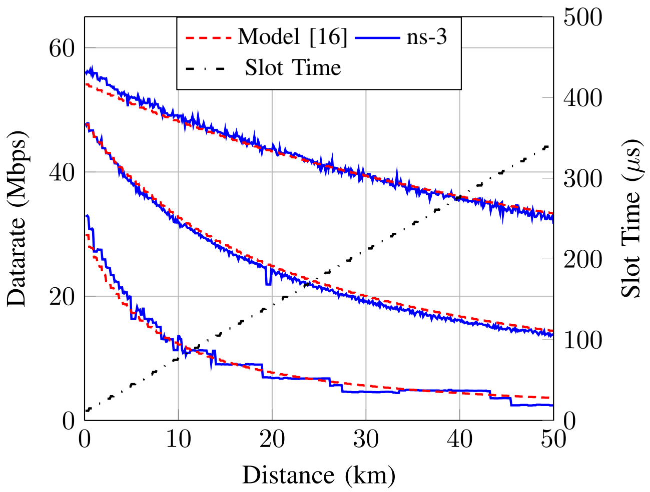

Fig. 4. Comparison between mathematical model [16] and ns-3 simulation for an adapted and optimized version of the DCF on long-distance links. Three different values of maximum A-MPDU aggregation: 1023 Byte, 8191 Byte, 65.535 Byte, bounded by 4 ms medium occupancy. MCS7, 20 MHz, Short GI.

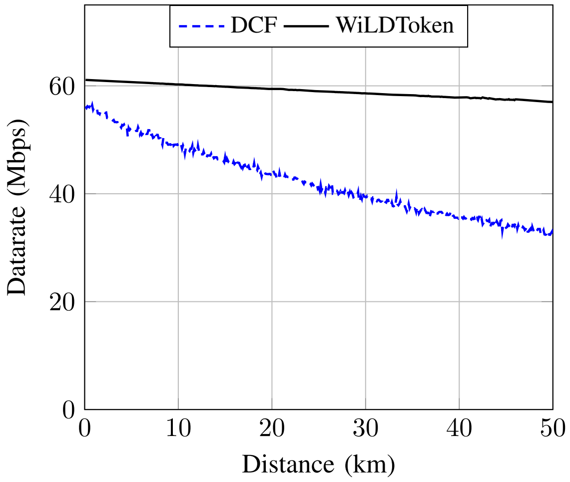

Fig. 5. Comparison between ns-3 long-distance DCF simulation and ns-3 WiLDToken simulation. Send limit 4 ms, MCS7, 20 MHz, Short GI.

B. WiLDToken

In this section, we simulate the capabilities of our token protocol and compare it to an optimized version of the DCF. The following experiments aim to validate our defined goals of an increased throughput, lower delay and jitter and better fairness.

1) Performance gain compared to the DCF: The most important goal of our development is to provide additional throughput compared to an adapted version of the DCF, especially on very long-distance links. We therefore conducted the same test used for Figure 4 with a WiLD token with a send limit of 4 ms, which is the corresponding value for the maximum A-MPDU size using the DCF. The results are shown in Figure 5.

The average throughput of WiLDToken decreases linearly (as expected) with increasing distance, loosing about 1 Mbps per 10 kilometers. The performance loss of the DCF is instead more significant due to the propagation delay in the backoff scheme. Thus, the performance gain using WiLDToken increases with the distance, leading to a gain of about 50% at 50 km. As described earlier, we are bounded to MCS7 in our simulation environment. We expect that with MIMO or even IEEE802.11ac, the performance gain would be even more significant.

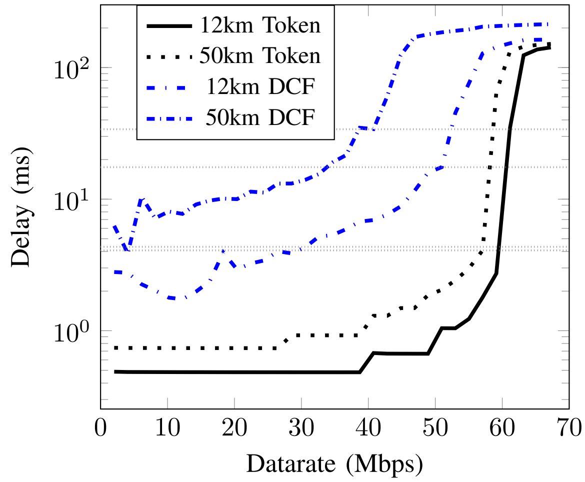

Fig. 6. Comparison between DCF ns-3 simulation and WiLDToken. Send limit 4 ms, A-MPDU factor 3, MCS7, 20 MHz, Short GI.

2) Delay compared to the DCF: Besides throughput, delay is an important parameter for QoS in WiLD networks. With increasing distance, propagation delay is a non-negligible factor that leads to an increased overall transmission delay especially for the adapted DCF. In Figure 6 we compare the delay of the DCF with WilDToken. In this experiment, we increased the UDP traffic incrementally. We use two fixed distances (12 km and 50 km) and a maximum send limit of 4 ms.

The WiLDToken delay remains nearly constant until a certain link utilization is reached. In contrast, the DCF delay increases steadily with increasing utilization. The absolute delay values of both protocols differ significantly. If the two links are not saturated, the token delay stays well below 1 ms even for a 50 km link. In contrast, the adapted DCF suffers from the multiple propagation times added during the backoff and inevitable collisions. Even for non-saturated links, the average delay is above 5 ms for a 50 km link.

When the medium is fully saturated, the delay increase becomes disproportionately steeper, which is common to both WiLDToken and the DCF due to additional queuing of packets and the usage of a non-blocking UDP traffic. The point of saturation for each plot is marked in the figure by the different aid lines. Overall the WiLDToken protocol decreases the link delay significantly, for 12 km links approximately by a factor of 4, for 50 km links by a factor of 10. Again, the decrease in delay is expected to be more significant for MIMO and IEEE802.11ac.

3) Fairness compared to the DCF: Besides the throughput maximization and the delay minimization, an additional benefit of our protocol is the increased fairness at both stations. If the send limit is set equally on both nodes and since the

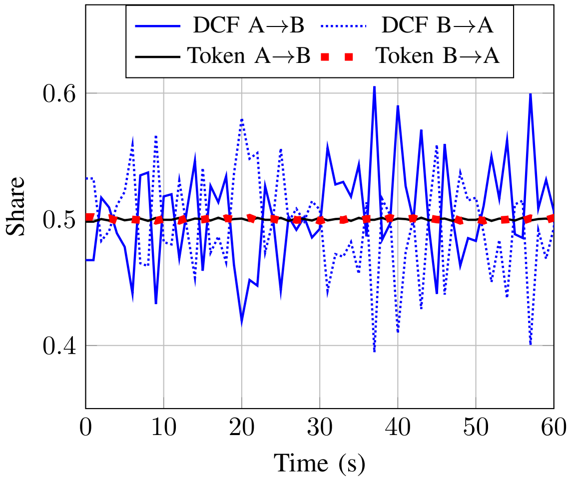

Fig. 7. Fairness: Comparison between ns-3 DCF simulation and ns-3 WiLDToken simulation. Send limit 4 ms, MCS7, 20 MHz, Short GI.

data transmission phase does not contain any randomness, fairness between the two nodes can be assumed. We conducted the following experiment: With the link fully saturated in both directions, we tracked the throughput every second for an overall duration of 60 seconds. The results are shown in Figure 7.

When using the DCF, the shares of the overall medium occupation for each directed data flow may vary significantly due to the random exponential back-off procotol. This difference may cause severe variations in jitter and delay, which can be harmful for Voice-over-IP (VoIP) or other realtime applications. With WiLDToken, the shares of each data flow remain constant unless otherwise adjusted. We are able to provide assured fairness between the data flows including roughly constant delay and jitter, according to our needs. In addition, our protocol, allows unfairness to be forced by specifying the sent-limit on each side of a link independently. The ability to set a specific up- and downlink ratio is a useful tool for traffic engineering on WiLD links.

VII. CONCLUSION

In this work we have presented our approach of a token-based MAC for long-distance links in MR-MC WMN. We formally introduced the protocol and provided details about our initial experiments using the ns-3 network simulator. The results show that WiLDToken is superior to an adapted version of the DCF, especially on long-distance links, in terms of throughput, delay and fairness.

A. Future Work

There are several possible future work items to address for WilDToken. While simulations are good for initial testing, a real-world implementation could lead to additional insights or required adaptations. QoS and traffic class differentiation is an important issues for modern Wireless Internet Service Provider (WISP). At the moment, our protocol does not provide functionalities to prioritize certain traffic classes.

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REFERENCES

[1] M. Rademacher, “Performance estimation and optimization of the IEEE802.11 MAC layer for long distance point-to-point links,” Hochschule Bonn-Rhein-Sieg, Grantham-Allee 20, 53757 Sankt Augustin, Tech. Rep., 2015.

[2] K. K. Leung, B. Mcnair, L. J. Cimini, and J. H. Winters, “Outdoor IEEE 802 . 11 Cellular Networks : MAC Protocol Design and Performance,” *Design*, pp. 595–599, 2002.

[3] J. Simo, A. Martinez, C. Figuera, and J. Seoane, “Distance Limits in IEEE 802.11 for Rural Networks in Developing Countries,” in *Proceedings of the Conference on Wireless Rural and Emergency Communications (Wrecom 2007)*, Rome, Italy, 2007, p. 5.

[4] J. Simo Reigadas, A. Martinez-Fernandez, J. Ramos-Lopez, and J. Seoane-Pascual, “Modeling and Optimizing IEEE 802.11 DCF for Long-Distance Links,” *IEEE Transactions on Mobile Computing*, vol. 9, no. 6, pp. 881–896, jun 2010.

[5] E. Lopez-Aguilera, J. Casademont, and J. Cotrina, “Propagation delay influence in IEEE 802.11 outdoor networks,” *Wireless Networks*, vol. 16, no. 4, pp. 1123–1142, may 2010.

[6] IEEE, “IEEE Standard for Information technology-Telecommunications and information exchange between systems Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, vol. 2012, no. March, pp. 1–2793, feb 2012.

[7] I. Hussain, N. Sarma, and D. K. Saikia, “TDMA MAC Protocols for WiFi-based Long Distance Networks: A Survey,” *International Journal of Computer Applications*, vol. 94, no. 19, pp. 1–8, 2014.

[8] B. Raman and K. Chebrolu, “Design and evaluation of a new MAC protocol for long-distance 802.11 mesh networks,” in *Proceedings of the 11th annual international conference on Mobile computing and networking - MobiCom ’05*, ACM. New York, New York, USA: ACM Press, 2005, p. 156.

[9] R. K. Patra, S. Nedevschi, S. Surana, A. Sheth, L. Subramanian, and E. A. Brewer, “WiLDNet: Design and Implementation of High Performance WiFi Based Long Distance Networks.” in *NSDI*, vol. 1, no. 1, 2007, p. 1.

[10] S. Nedevschi, R. K. Patra, S. Surana, S. Ratnasamy, L. Subramanian, and E. Brewer, “An adaptive, high performance mac for long-distance multihop wireless networks,” in *Proceedings of the 14th ACM international conference on Mobile computing and networking*. ACM, 2008, pp. 259–270.

[11] R. P. S Salmerón-Ntutumu J Simó-Reigadas, S. Salmerón-Ntutumu, J. Simó-Reigadas, and R. Patra, “Comparison of MAC Protocols for 802.11-Based Long Distance Networks,” in *Proceedings of the 1st Workshop Wireless For Development*, no. February, aug 2008.

[12] Y. Ben-David, M. Vallentin, S. Fowler, and E. Brewer, “JaldiMAC,” in *Proceedings of the 4th ACM Workshop on Networked Systems for Developing Regions - NSDR ’10*, ACM. New York, New York, USA: ACM Press, 2010, pp. 1–6.

[13] A. Dhekne, N. Uchat, and B. Raman, “Implementation and evaluation of a tdma mac for wifi-based rural mesh networks,” *NSDR’09*, 2009.

[14] L. Eznarriaga, C. Senguly, N. Bayer, J. I. Moreno, P. Lozano, and M. Simón, “Experiences with SoftToken: a token-based coordination layer for WLANs,” *International Journal of Communication Systems*, 2013.

[15] P. Dutta, S. Jaiswal, D. Panigrahi, and R. Rastogi, “A new channel assignment mechanism for rural wireless mesh networks,” in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*. IEEE, 2008.

[16] M. Rademacher and M. Kessel, “An Empirical Evaluation of the Received Signal Strength Indicator for fixed outdoor 802.11 links,” *VDE ITG-Fachbericht Mobilkommunikation*, vol. 20, pp. 62–66, 2015.

[17] T. R. Riley, George F and Henderson, “The ns3 Network Simulator,” in *Modeling and Tools for Network Simulation*, K. Wehrle, M. Güne, and J. Gross, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010.