A Multi-Mode MAC Protocol with Relay Support

Arif Otyakmaz, Ismet Aktas, Marc Schinnenburg, Ralf Pabst

(ComNets, RWTH Aachen University, Faculty 6, Aachen, Germany)

{aoz|isi|msg|pab}@comnets.rwth-aachen.de

***Abstract*— Future mobile radio networks will have the requirement of very high data rates. Typical wireless data communication will not only occur in short range scenarios like hotspots in airports, city centres, exhibition halls, etc., but also in wide area environments, e.g. a moving car in a rural environment. Data services will require a ubiquitous mobile radio system and demand better quality of service, like high data rates and low delays. Two promising concepts for future mobile radio communication are, the deployment of relays and the ability to adapt to various deployment strategies by using different Radio Access Technologies, i.e. modes with a common technology basis.**

The former concept allows enlarging the cell coverage. Relays are not wired connected and consequently a cost-efficient alternative to base stations that work in a decode-and-forward principle. The latter concept provides modes that are tailored solutions for specific environments and thus allow the adaptation to various scenarios by selecting the most adequate one. The aim of this work is to merge the advantages taken from both concepts to one solution.

***Index Terms*— Multi-Mode Protocol, Relay, FDD, TDD, B3G, 4G, MAC, WINNER**

I. INTRODUCTION

IN next generation mobile radio systems typical wireless data communication will not only occur in short range scenarios like hotspots in airports, city centres, exhibition halls, etc., but also in wide area environments, e.g. a moving car in a rural environment. Furthermore these systems will demand quality of service, like high data rates and low delays. The EU FP6 project WINNER (Wireless World Initiative New Radio) [1] aims at defining radio interface technologies needed for a ubiquitous radio system concept and a single ubiquitous radio access system concept, scalable and adaptable to different short range and wide area scenarios [2]. Such a system requires an amount of solutions each tailored for specific environments and the ability to select a tailored solution. Therefore, re-configurability and Multi-Mode capability are key issues what users of Beyond 3rd Generation (B3G) or rather Fourth-Generation (4G) communication systems expect. Multi-Mode capability means the ability to adapt to multiple scenarios by using different modes, for example, Radio Access Technologies (RAT), of a common technology basis. Regarded candidates for such modes are the duplex procedures Time Division Duplex (TDD) and Frequency Division Duplex (FDD). One aim of this work is to allow the coexistence and cooperation between multiple modes.

A promising concept to satisfy the requirement of ubiquitous wireless communication can be realised by a network deployment using relays [3]. A network deployment with a relative high density of Base Stations (BS), also referred to as Access Points (AP), is economically not reasonable, because the costs for connecting BSs to the fixed core network would be enormous. Due to the fact that data rates of a User Terminal (UT) behave reciprocally to the distance to its BS and high data rates are intended, a possibility must be found to increase the range of a BS. An auspicious approach is the application of relay enhanced cells (RECs). With this approach the range of a BS is extended by already mentioned Relay Nodes (RN), also referred to as Fixed Relay Stations (FRS), which are not connected wired to the fixed network, but wireless via a BS. The ability to adapt to different environments can be provided by a Multi-Mode protocol [4]. Of course, this protocol must integrate the usage of RNs. A simulative performance evaluation has been made in order to prove the applicability of a Relay Capable Multi-Mode Medium Access Control (MAC) Protocol.

The remainder of this paper is organized as follows. In Section II the realisation of the Multi-Mode MAC protocol is presented. Section III describes simulation scenarios, parameters and contains appropriate results. At the end of this paper a conclusion and an insight to further work are given.

II. CONCEPTION

The general concept of a relay capable Multi-Mode MAC protocol and differences to approaches considering the exchange of the whole MAC protocol [5] are presented in [6]. Therefore in the following the proposed protocol, especially the frame structure is introduced in a detailed way.

A. *Configurable and Flexible Frame Structure*

A frame usually consists of a specified number of attributes or rather phases that determine the chronological processing of the system. Present second-generation (2G) and third-generation (3G) mobile radio systems process the phases determined by the given frame in a static manner. When enabling the usage of different Modes, the frame structure must be adapted according to the requirements of each Mode. In the context of this work, a concept has been designed to

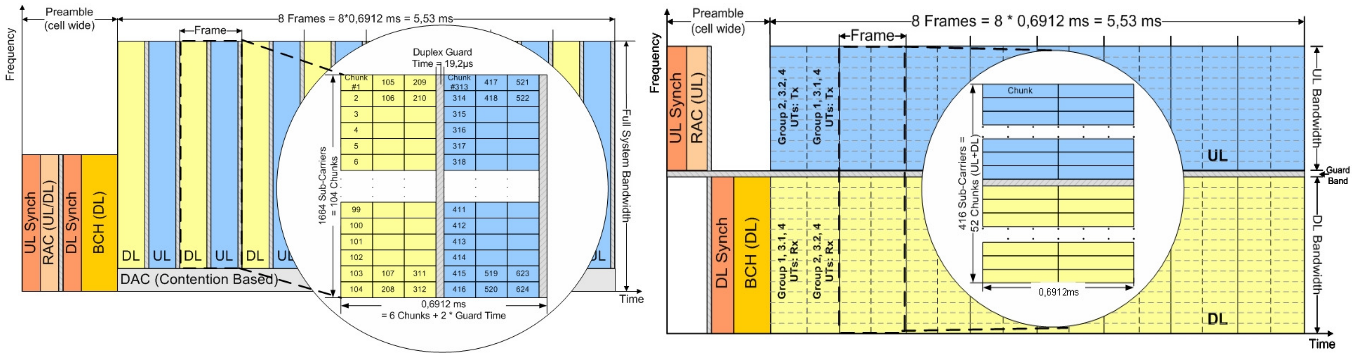
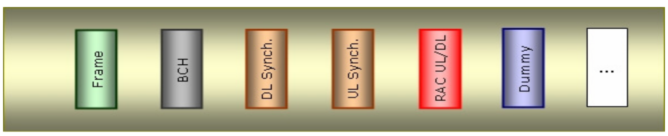


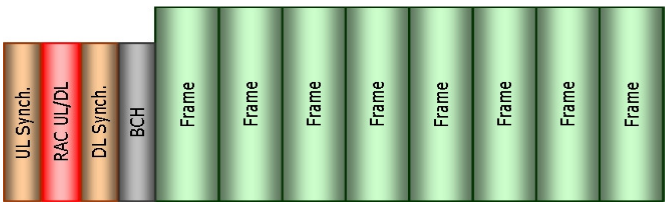
Fig. 1 WINNER TDD and FDD super-frames consisting of 8 frames and a preamble [7]

facilitate a configurable and flexible frame structure that allows the adaptation according to the requirements of each Mode. The idea is to define a list of events that determine the chronological sequence of phases within a frame. Fig. 1 exemplifies the so called WINNER super-frames. Note that this example is just for illustrative purposes, in order to point out that the introduced flexible frame structure can model any kind of MAC frames. In short both the WINNER TDD and FDD super-frames consist of a preamble phase with UL/DL synchronisation, a Random Access Channel (RAC) and a Broadcast Channel (BCH) for cell-wide information and 8 frames [7]. The functionality of the above mentioned events which model the different phases of a frame have to be provided in a toolbox in advance. Fig. 2a shows such a toolbox containing the necessary events to be able to construct e.g. the TDD super-frame structure (see Fig. 2b). In this way, i.e. by adding, removing, (re-)ordering of events any kind of frame structure of frame based MAC protocols can be modelled, since the frame structure is obtained by simple configuration. Consequently the relay support of a protocol can be realised by such flexibility, namely when the relay acts differently over time, in some frames as UT and in others as BS. Of course, this flexibility also allows the reconfiguration of the frame structure during runtime on condition that the protocol facilitates this feature by means of appropriate signalling.

After having introduced the configurable and flexible frame structure in the next but one section the construction and usage of different Modes is explained. But before a short description of the Functional Unit (FU) concept is given in the next section. Both concepts are an essential part of the introduced Multi-Mode MAC protocol.



a) Toolbox of events for frame construction



b) Building the TDD super-frame of WINNER by using predefined events

Fig. 2 Configurable frame structure

B. *Functional Units*

The FU concept [8] is a framework that is the basis for implementing a (re-)configurable protocol stack. The reason for introducing this concept is that it presents a platform to implement a relay capable Multi-Mode MAC protocol. The key point of the Functional Unit concept is to decompose a layer into small units, so that each of these units has a cohesive responsibility. That means each unit should preferably have an explicit functionality (atomic) without dependencies to other units (autonomous). The advantages taken by this approach are reducing of maintenance and development costs. Furthermore, the quality of the software is increased through the possibility of unit tests. But the interface of such units is complex since tight coupling of units must be avoided. Debus et al. called these units Functional Units and have proposed interfaces to avoid tight coupling.

C. *Construction and Usage of Modes*

In this section the framework of the Multi-Mode concept is outlined in detail. First of all, the idea to construct Modes by using FUs is described. Afterwards, in a next step the usage of the constructed Modes is presented. To underline the flexibility and applicability of this concept, it is applied on the WINNER TDD- and half-duplex FDD-Modes. Thereby, the WINNER-Modes are constructed and are classified in a whole framework. Moreover, when facilitating Multi-Mode capability, a way must be offered to allow the selection of available Modes based on a decision criterion. Since this would go beyond the scope of this paper, the Mode selection is not further considered.

A Mode can be regarded simplified as the aggregation of several FUs. Such an aggregation is in [8] referred to as Functional Unit Network (FUN). It is important to note that FUs must be offered in advance before using them to construct a Mode. The first step to construct a Mode is to define the connector sets of all FUs. The connector set determines the structure of the FUN or rather the Mode. The connections of FUs within a Mode are completely independent from other Modes and the rest of the FUN, which thereby facilitates different configurations for each FU within a Mode. Thus,

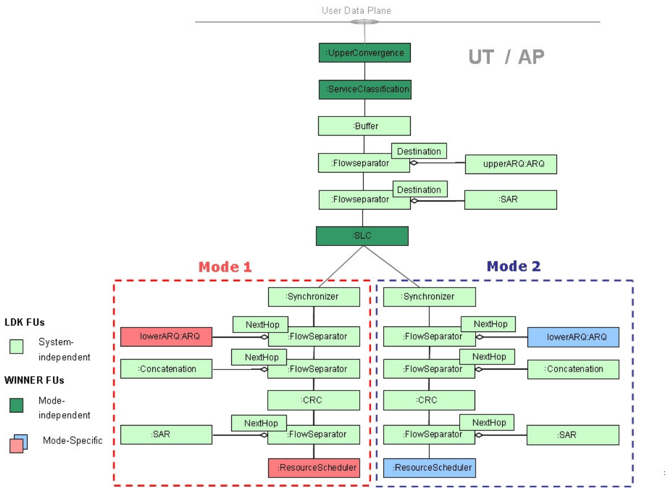


Fig. 3 Data Link Layer (DLL) with two different Modes composed of FUs

with changing some FUs or changing the behaviour of a FU by applying a different configuration, it is easy to achieve a different Mode, i.e. the used FUs can belong to the same FU classes but differ in their used strategies and accordingly this leads to different Modes. For example, a Mode X can comprise an ARQ-FU that uses the strategy Stop-and-Wait whereas a Mode Y uses the same ARQ-FU with the strategy Go-Back-N. Fig. 3 illustrates the preliminary user data plane of the Data Link Layer (DLL) of a WINNER UT/BS with two different Modes composed of FUs. The system-independent FUs like Segmentation and Reassembly (SAR) or Cyclic Redundancy Check (CRC) are highlighted in light green. FUs highlighted in dark green are the WINNER-specific but Mode-independent ones. The FUs that are depicted in red and blue are the Mode-specific FUs. The Mode-specific FUs not essentially differ in their functionality but possibly in their strategy or any parameter. The reason to make some differences is just to show that there is a possibility to use different FUs. In fact, for understanding the concept, it is not important to understand the offered functionality of each depicted FU but rather it should be simply assumed that every FU has some cohesive functionality, e.g. the usage of the above introduced flexible frame concept is applied in the ResourceScheduler-FU, in order to realise the already mentioned WINNER TDD- and half-duplex FDD Modes. The aim of the usage of different colours is to emphasise the generic and specific parts. Note that Modes need not differ much. It is possible that few FUs can differ and consequently that means that different Modes have a lot of (generic) parts in common.

D. *Variety of Possible Scenarios*

Fig. 4a - 4f show some examples from the variety of feasible scenarios enabled by the Multi-Mode concept. In Fig. 4a the classical Multi-Hop scenario is depicted. In this case just one Mode is used. In Fig. 4b the envisaged Heterogeneous Relay Node (HERN) scenario of WINNER is shown. In this case the RN is able to use two Modes, one for a RN-UT link and one for a BS-RN link. It is also possible that the BS is able to use

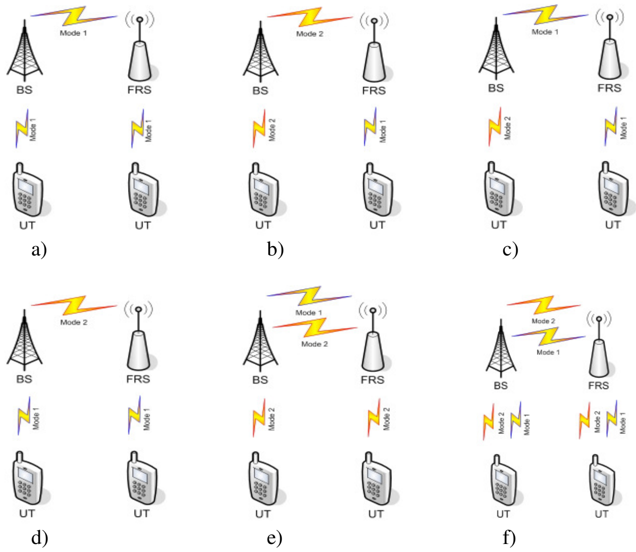


Fig. 4 Variety of possible scnearios

multiple Modes and in turn the RN is simple like depicted in Fig. 4c. The BS uses two Modes and the RN just one. Remark, in each scenario it is assumed that the UT is able to use all Modes since it has to be served. In Fig. 4d the BS and RN respectively are flexible to use multiple Modes. So far, only one Mode is used to a certain time but Fig. 4e shows that the BS and the RN use two Modes simultaneously. This is possible if the Modes do not use the same spectrum and if a strategy is chosen that passes the compound to both Modes. The most complex scenario is depicted in Fig. 4f where all station types are able to use all Modes in parallel. Remark the fact that using some Modes in parallel increases the hardware complexity and interference, but this is not concerned here because this section just introduces feasible scenarios with the described concept.

III. SIMULATION SCENARIOS AND RESULTS

A. *Scenarios and Parameters*

The simulations are conducted for the deployment scenario which is illustrated in Fig. 5. It is given by a single BS,

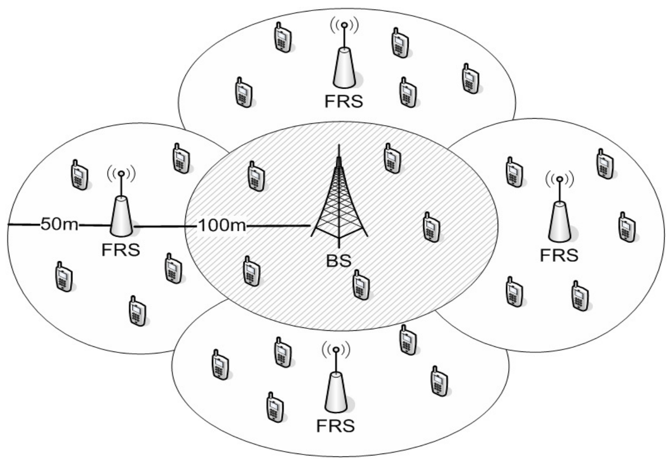


Fig. 5 Relay enhanced cell, two-hop

Parameter	TDD100	TDD20	FDD40	FDD20
Multiplexing Scheme	TDMA/ OFDMA	TDMA/ OFDMA	TDMA/ OFDMA	TDMA/ OFDMA
Signal bandwidth	81.25 MHz	20.31 MHz	32.5 MHz	81.25 MHz
Chunk duration	108.8 µs	108.8 µs	345.6 µs	345.6 µs
Symbols per chunk	80	80	96	96
Data carriers	1664	416	832	416
Subbands	104	26	2 x 52	2 x 26
OFDMA symbol duration	21.76 µs	21.76 µs	28.8 µs	28.8 µs
Frame length	691.2 µs	691.2 µs	691.2 µs	691.2 µs
Super-frame Length (SFL)	5.6 ms	5.6 ms	5.6 ms	5.6 ms

Tab. 1 Mode parameters (except TDD20 coming from [7])

supported by a tier of 4 RNs located at a distance of 100m. The sub-cells served by the BS and the RNs have a radius of 50m and comprise 5 UTs. The resulting overall radius of the REC is 150m, which represents a gain in range of 50% and a gain in coverage area of 125%. The resource allocation in the relay enhanced cell is assumed to be coordinated by the BS in such a way that the full set of resources, in this case OFDMA subbands, is available at all nodes, but a certain resource may only be used by one station (BS/RN/UT) at the same time. Therefore, no intra-REC interference occurs. RNs act in turn as BS to its UTs in one frame and as UT to the BS in the next.

At first, each of the envisaged Modes TDD20, TDD100, FDD20 and FDD40 is evaluated for a cell with each station (BS/UT/RN) operating in Single-Mode. Afterwards the same evaluation is done for several combinations of Multi-Mode stations. The parameters of the different Modes are listed in Tab. 1. In the scope of this paper the parameters do not have to be discussed in detail. It is only important to know that a chunk is a resource unit, in order to be able to determine the maximum theoretical throughput of each Mode analytically, so that it is later possible to compare these results with the simulative ones.

B. Analytical Results

In order to calculate the maximum throughput of a Mode per super-frame first the chunk capacity $ChunkCapacity_{Mode}$ has to be determined according to (1).

$$ChunkCapacity_{Mode} = SymbolsPerChunk_{Mode} \cdot BitsPerSymbol \quad (1)$$

Due to the used modulation and coding scheme *QAM16 ½* the number of bits per symbol is 2. For the maximum achievable throughput per Mode additionally the number of chunks per Mode is needed. It can be obtained by (2).

$$\#Chunks_{Mode} = CT_{Mode} \cdot CF_{Mode} \cdot F_{Mode} \quad (2)$$

Mode	Chunk Capacity	CT	CF	#Chunks	Max Throughput
TDD20	160 Bit	6	26	1248	35.7 MBit/s
TDD100	160 Bit	6	104	4992	128.3 MBit/s
FDD20	192 Bit	2	26	416	14.2 MBit/s
FDD40	192 Bit	2	52	832	28.5 MBit/s

Tab. 2 Analytical results for different Modes

Hereby CTMode is the number of usable chunks in time, CFMode the number of usable chunks in the frequency dimension, and FMode the number of frames within a super-frame, namely 8. Having obtained the mentioned values the maximum achievable throughput per Mode can be calculated according to (3).

$$MaxThroughput_{Mode} = \frac{\#Chunks_{Mode} \cdot ChunkCapacity_{Mode}}{SFL} \quad (3)$$

Tab. 2 shows the according values for the different Modes. Note that the FDD Modes are half-duplex ones, so that the number of usable chunks in the frequency dimension are 26 and 52 respectively instead of 52 and 104.

C. Simulative Results

The simulation results presented in this section have been obtained with the help of the modular simulation environment WNS (Wireless Network Simulator) [9], developed at ComNets [10]. The tool allows carrying out performance evaluations by means of event driven stochastic simulations. In order to show the applicability of a relay capable Multi-Mode MAC protocol, in a first simulation run all stations were conducted in Single-Mode. The simulations correspond to Fig. 4a. As resource handling aspects have not been in the scope of this work, the resource handler was a quite simple FIFO scheduler. Hence, to prevent evaluation of DL/UL-divergence effects, in the following only the DL-only throughput results are reviewed. In Fig. 6 the DL throughput curves for all Modes are plotted. The throughput saturation points are 6 MBit/s (FDD20), 12 MBit/s (FDD40), 13MBit/s (TDD20), and 55

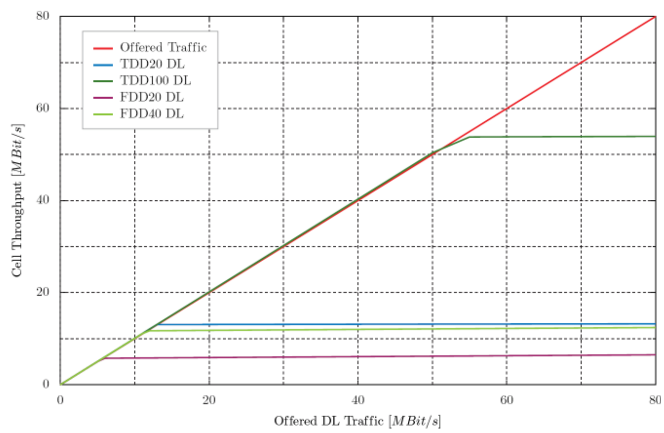


Fig. 6 DL cell throughput for Single-Mode scenario

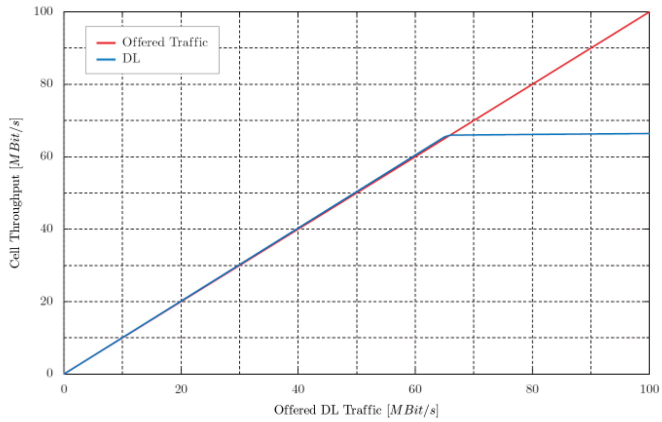


Fig. 7 DL cell throughput for Multi-Mode scenario with all stations having Modes TDD100 and FDD40

MBit/s (TDD100). All values are lower than the analytically calculated ones (Compare Tab2.). The differences can be traced back to signalling overhead of the protocol. Since the resources within a super-frame are equally distributed between DL and UL, the reference point for the simulative results apparently is half of the analytical value. The throughput saturation for FDD40 is lower than for TDD20 because FDD40 is operating half-duplex and half of the super-frame resources are not used, because the used resource scheduler can only handle one of the foreseen two half-duplex UT groups.

Fig. 7 shows the DL cell throughput for the case that all stations operate in two Modes in parallel, namely TDD100 and FDD40. The saturation point in this Multi-Mode scenario should be the sum of the Single-Mode saturation points. The throughput saturation point of TDD100 was about 55 MBit/s, the one of FDD40 was about 12 MBit/s. As it can be seen in Fig. 6 the maximum throughput is about 67 MBit/s, so that the expectations are fulfilled.

In the last scenario the BS offers two Modes, namely TDD100 and FDD40. All local UTs can use these two Modes when communicating with the BS. The two Modes can be considered as short range (TDD100) and wide area (FDD40) Modes [6]. Since the essential reason for using relays are reducing the deployment costs, in this scenario the RNs are quite simple and only have one Mode, namely TDD100. Fig. 8 shows the according cell throughput. It is observable that the maximum throughput is about 5 MBit/s higher than in the Single-Mode scenario which is obviously caused by the additional Mode between local UTs and the BS.

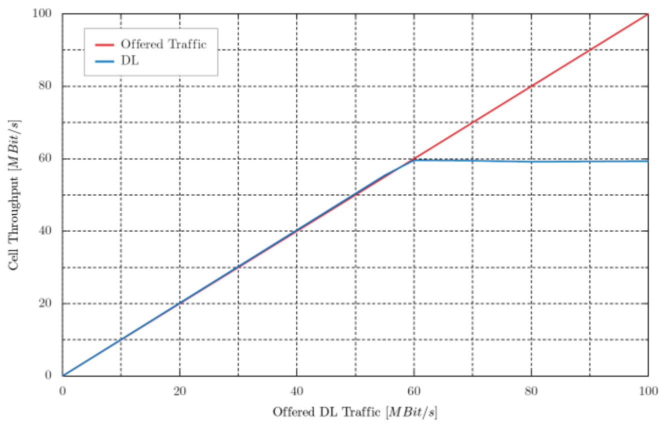


Fig. 8 DL cell throughput for Multi-Mode scenario flexible BS and UTs and simple RNs

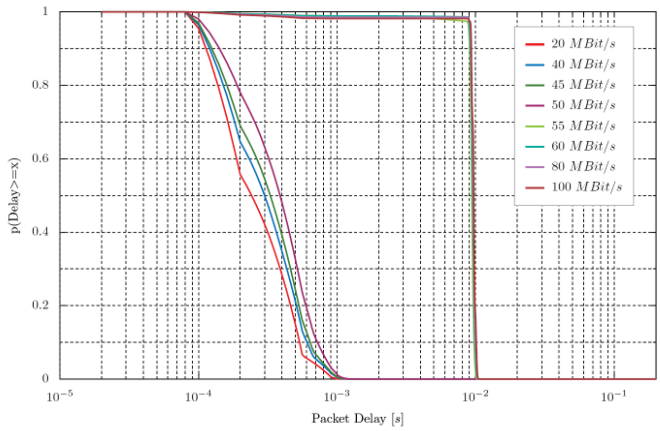


Fig. 9 TDD100 delay in single-hop scenario

Finally in order to illustrate the additional delay caused by the second hop in case the UT communicates with the BS via a relay, Fig. 9 and 10 show the delay values for the Mode TDD100 for the single-hop and the two-hop scenario respectively. Apparently the mean delay in the two-hop case is higher than in the single-hop case, but it is observable that the minimum delay in both cases is the same, namely 108.8 µs. This is the length of the smallest resource unit which can be scheduled, the chunk. Packets which can immediately be scheduled having a local UT as destination, i.e. are not transmitted via the RN exactly cause this delay.

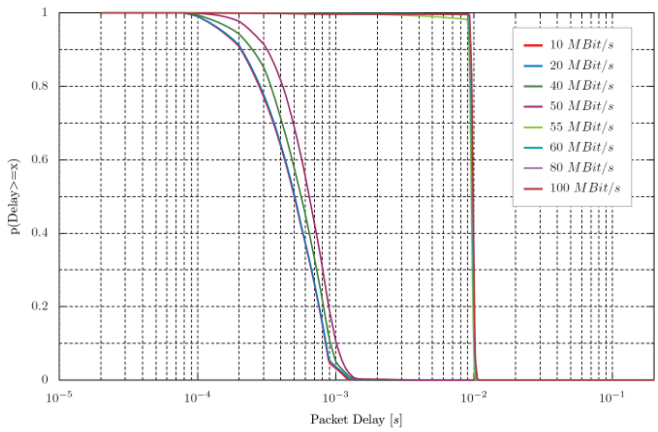


Fig. 10 TDD100 delay in two-hop scenario

IV. CONCLUSION AND FUTURE WORK

In this paper it has been shown that a Multi-Mode MAC protocol in relay based mobile radio networks is feasible. A concept for the Multi-Mode capability has been presented, implemented and validated by means of simulation. The protocol has been designed in such a way that several Modes can be achieved by parameterisation. This adaptability is proven by the parameterisation of half-duplex FDD- and TDD-

Modes. Furthermore, it has also been shown that Modes are able to coexist.

In the future the introduced protocol shall be extended by algorithms for the detection and selection of different Modes. After detecting multiple Modes it shall be possible to select the best suitable Mode based on a certain strategy. Of course, when changing a Mode the context transfer from one Mode to another independent of whether changing the BS/RN or not shall be possible.

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