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A Multi-Mode MAC Protocol Integrating FDD and TDD for Next Generation Multi-Hop Mobile Radio Networks

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Abstract: There are two basic duplexing schemes for present and future mobile radio networks, frequency-division duplexing and time-division duplexing. In general each of these methods has its benefits and drawbacks. However, both schemes are more or less appropriate under consideration of the communication environment. In future mobile radio systems typical wireless data communication will not only occur in metropolitan area 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. A promising concept for future mobile radio communication is the ability to adapt to various deployment strategies by using different radio access technologies, so called modes. The concept provides modes that are tailored solutions for specific environments and thus allow the adaptation to various scenarios by selecting the most adequate one.

Another promising concept for next generation systems is the deployment of relays. They allow 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 aim of this work is to introduce a protocol which supports both described concepts.

Keywords: Multi-Mode Protocol, Relay, Multi-Hop, FDD, TDD, B3G, 4G, MAC, WINNER

1. 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) and its successor WINNER II [1] aim 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 future 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). Already existent mobile radio systems like UMTS [3, 4] and WiMAX [5] support both duplex schemes. However, in UMTS de facto only UTRA-FDD is in use and in WiMAX only TDD. Besides, there is no facility in either of the systems to provide a dynamic detection, not to mention switching between the schemes. The network operates either with the one or the other duplex scheme. A detailed discussion about the pros and cons of FDD or TDD in 4G mobile radio networks can be found in [6]. However, what can be definitely concluded from this discussion is that integrating both schemes in one system would be of a great benefit.

A promising concept to satisfy the requirement of ubiquitous wireless communication can be realised by a network deployment using relays, which extend the coverage area of a Base Station (BS) in a cost efficient way [7].

The aim of this work is to show what functionalities have to be provided in a relay capable Medium Access Control (MAC) protocol, in order to allow the coexistence and cooperation between multiple modes.

The remainder of this paper is organised as follows. In Section II the concept 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.

2. Conception

The general concept of a relay capable Multi-Mode MAC protocol and differences to approaches considering the exchange of the whole MAC protocol [8] are presented in [9]. In this section the structure of the Multi-Mode MAC protocol and the necessary functionalities to realise such a protocol are introduced.

2.1 Structure of the Involved Layers

The abstract structure of the implemented Multi-Mode MAC protocol is depicted in Fig. 1. It consists of the lower two layers of the ISI/OSI reference model, namely the Physical (PHY) Layer and the Data Link Layer (DLL) which is divided into the sub-layers Radio Link Control (RLC) and MAC. The MAC as well as the PHY layer contains two modes. These are the before mentioned duplex schemes TDD and FDD. They are modelled by considering the chronological build-up of the according frame phases for the two duplex schemes. The exact underlying frame structures are the WINNER frame structures. Fig. 2a and 2b show the so called super-frame structure of the WINNER TDD- and FDD-modes. It contains a preamble phase consisting of a Broadcast Control Channel (BCH) for sending cell-wide necessary information in broadcast, a Random Access Channel (RACH) for the initial access and eight frames each consisting of alternating DL and UL sub-frames in TDD. In the next section it will be explained for what purpose the BCH and RACH will be used. The FDD super-frame accordingly contains also eight frames, but the DL and UL frames are parallel in time in different frequency bands. All cells are fully synchronised in time. Each mode has its own resource scheduler, RACH and BCH phase, since it is assumed that TDD and FDD work in totally different frequency bands.

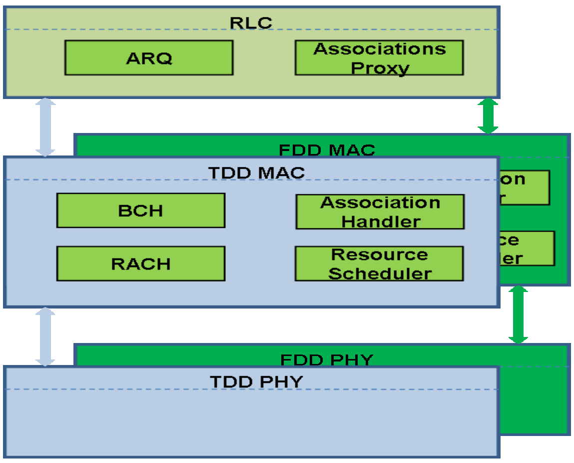


Fig. 1 Structure of the involved ISO/OSI layers

Furthermore, each mode has its own so called association handler, in order to be able to be connected via different modes independently. The association procedure will be outlined in more detail in the next section. Finally the RLC sub-layer consists of an End-to-End Automatic Repeat Request (ARQ), i.e. from the BS to the User Terminal (UT). So, a possible Relay Node (RN) is not involved in the ARQ meaning that there is no RLC sub-layer in a RN. The purpose of the associations proxy in the RLC is to have an instance which has an overview about all available modes, so that it is possible to decide which of the available modes to choose.

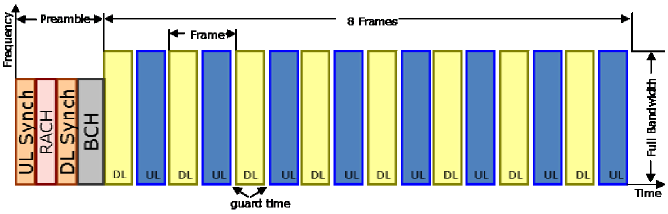


Fig. 2a WINNER TDD super-frame structure

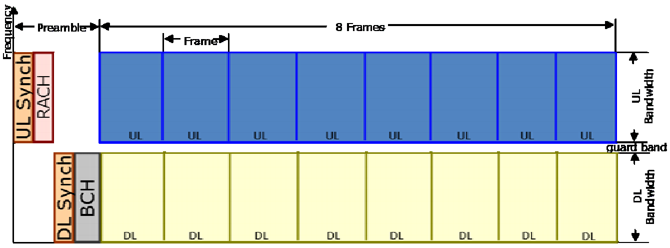


Fig. 2b WINNER FDD super-frame structure

2.2 *Association Procedure*

In principal the association procedure works as follows. During the preamble phase of the super-frame the UT tries to detect the cell information sent by each Radio Access Point (RAP) in the BCH. A RAP is the serving BS of a UT and can consequently be a BS or a RN. It is assumed that the BCH of neighbouring RAPs is sent on different subcarriers, so that it is possible to detect several RAPs at the same time. The UT collects the information about all detected BCHs above a certain threshold and evaluates them periodically concerning their signal quality. After that it starts an association process with the one which has the highest signal quality. The signalling for the association procedure during an exemplary inter-cell handover from a RN to another RN is depicted in Fig. 3. At the beginning the UT is associated to the source RN. After detecting the BCH of the target RN with a higher signal quality than the one of the source RN, the UT decides to make a handover to the newly detected RAP. Therefore the UT sends a disassociation_req to the source RN which is forwarded to the BS and afterwards to the GW. Thus the GW knows that packets in the DL coming from the backbone, e.g. the internet are not to be sent to the source BS any more. The BS confirms the disassociation by sending a disassociation_ack to the source RN which forwards it to the UT. The disassociation signalling is sent together with the user data meaning that there are no exclusive resources allocated for it. Of course, in a further state in can be thought of granting exclusive resources for this kind of control signalling. Dropped or not detectable packets are caught by timeouts. After the disassociation is completed, the UT sends an association_req to the target RN via the for the time being error-free RACH,

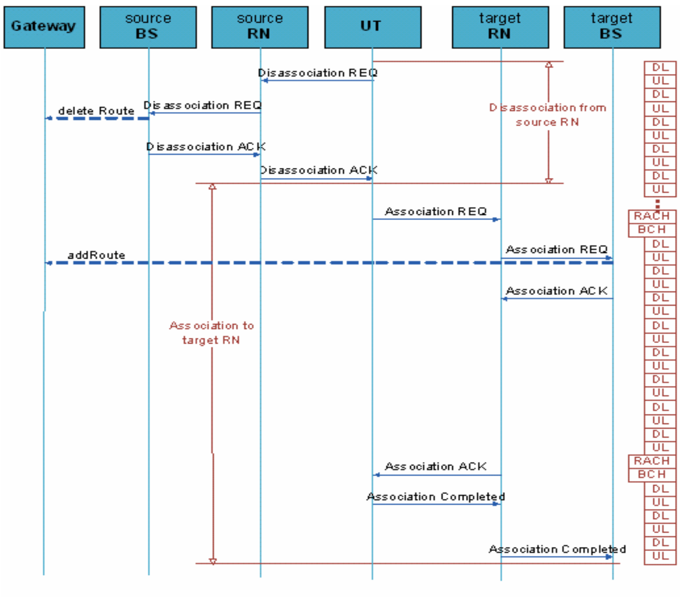


Fig. 3 Association procedure

because currently there are no other resources available which it could use for communication with the new RAP. The target RN forwards the request to its BS and the new BS informs the GW about the update. So, the GW can send DL packets to the correct BS. The BS confirms the successful association by sending an association_ack to the target RN and the RN forwards the acknowledgement to the UT in the BCH. For the acknowledgement the BCH is chosen, because it is the only resource a RAP can communicate with the UT in this phase. Alternatively this could be another DL channel in case it is a broadcast one. Finally after receiving the association_ack the UT sends an association_completed message to the new BS via the new RN, so that the BS is knows it can start to send user data in the DL. The purpose of this “three-way-handshake” is to avoid sending user data in DL too early. If the association_completed message was not sent, it would be possible that user data arrives at the UT before the association_ack, i.e. before the UT knows the association procedure was successful. The reason for this is that association_ack messages can only be sent in the BCH.

2.3 Flow Management

In order to be able to distinguish different flows and hence support QoS requirements, a mechanism to uniquely identify flows must be used. Unfortunately flows cannot be distinguished with the information available in the data link layer not to mention in the physical layer. Information from higher layers is needed, in order to be able to decide when a new flow or synonymously connection shall be established and released respectively. One possibility to identify different flows uniquely is the quadruple of source IP address, destination IP address, source port number and destination port number. This approach would make it necessary to have a kind of convergence layer, which is able to look into the TCP/IP- and UDP/IP-headers respectively. Furthermore it has to be provided a cross-layer interface for QoS aware requests by e.g. the application on top of the TCP/UDP/IP protocols. Even if it is decided how to distinguish the different flows, it is still a challenge to handle, i.e. establish and release the flows, especially in the case supporting multiple hops and in addition multiple modes. For the time being there is only one flow between a UT and a BS, also in the case of being connected via a RN. The End-to-End ARQ in the RLC of the BS and UT respectively handles its instances based on this flow. Since there is only one flow between a UT and a BS, this flow is directly established during the association procedure. In case of a handover it is distinguished between an intra-cell and an inter-cell handover. In case of an inter-cell handover all packets in the ARQ buffers belonging to the current flow are deleted. A possible ARQ mechanism in the higher layers, e.g. in TCP would be in charge of re-requesting them. A more sophisticated handover procedure could send these packets to the new BS via the backbone. However, in case of an intra-REC handover, i.e. inter-mode with the same RAP or between a RN and its serving BS and vice versa, the packets in the ARQ buffer are preserved, since the flow does not change in this case.

2.4 Mode Detection, Selection and Switching

Availability of a mode means that both the UT and the RAP support this mode so that they can communicate with each other via this mode. To know whether one of its supported modes is also available at the RAP, the UT listens to the BCHs. Different RAPs transmit their BCH on different OFDMA sub-carriers, so that UTs can receive them simultaneously. The BCH is mode dependent. The RAP sends broadcast messages via the BCH at the beginning of each super frame. The UT listens and evaluates each received BCH. Thus, for each mode the UT can have a set of received BCHs from different RAPs. The criteria used for the BCH evaluation is the SNR. The UT stores every received BCH with the SNR and the RAP ID and periodically, here every 0.01s, determines the best RAP. There are two thresholds for the mode detection, one for the detection (here: 0dB) and one for the disassociation (here: -1dB). The hysteresis avoids so called “ping-pong handovers”. As a consequence of the mode detection information the detected mode is stored and deleted respectively and if necessary a mode selection and switching is done. Assuming that TDD is to be used in metropolitan area and FDD in wide area scenarios [10], the mode selection strategy is as the following. TDD is chosen if available, otherwise FDD is used. As a result of the mode selection the mode switching can be triggered by either the detection of a new mode, i.e. with the above assumptions inter-mode handover from FDD to TDD, or by the loss of coverage of the active mode, i.e. with the above assumptions inter-mode handover from TDD to FDD.

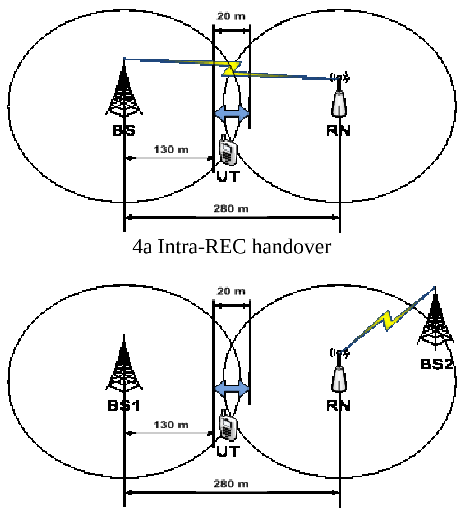
3. Simulations

3.1 Parameters

The multi-mode capability of the MAC protocol shall be shown by simulative performance evaluation of delay, throughput and handover durations in different handover scenarios. General simulation parameters are listed in Tab. 1. They are taken from [10].
Specific parameters for the two considered modes FDD and TDD are listed in Tab. 2 and 3 respectively.

3.2 Scenarios

There is a wide range of possible handover scenarios in a Multi-Hop Multi-Mode capable system. One level is the handover regarding the modes, namely inter-mode between the modes or intra-mode retaining the mode and changing the RAP. The other level is concerns the type of RAPs involved. Changing the RAP in a so called Relay Enhanced Cell (REC), i.e. from a BS to one of its RNs or vice versa, is an intra-REC handover. The other possibility is an inter-REC handover where the new serving RAP belongs to another REC. In order to proof the feasibility of the proposed protocol performance metrics in the following three handover scenarios will be shown; TDD intra-mode handover in both an intra-REC and an inter-REC scenario (Fig. 4) and an inter-mode handover between TDD and FDD in an intra-REC scenario (Fig. 5). In order to efficiently simulate and evaluate the performance of the handover mechanisms, the mobility of the UT is set to move straight across the border between two RAPs



4a Intra-REC handover
4b Inter-REC handover
Fig. 4 TDD intra-mode handover scenarios

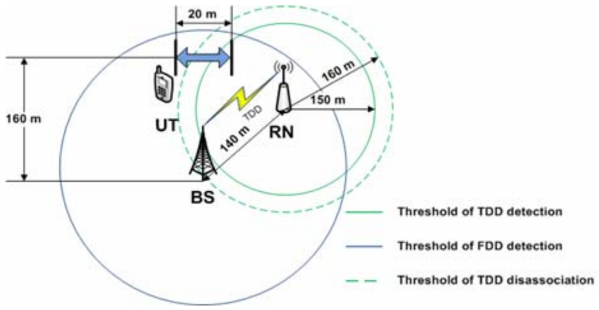


Fig. 5 Inter-mode intra-REC handover scenario

Parameter	Value	Unit
Antenna type	omni-directional	
Power control	None	
Number of UTs	1	
Mobility	3	m/s
Distribution of packet inter arrival time	Poisson	
Packet size	1024	Bit
Traffic rate above IP (DL / UL)	5 / 5	MBit/s
MCS preamble	BPSK 1/2	
Frame length	0.6912	ms
Preamble duration	0.36	ms
Super-frame length	5.8896	ms

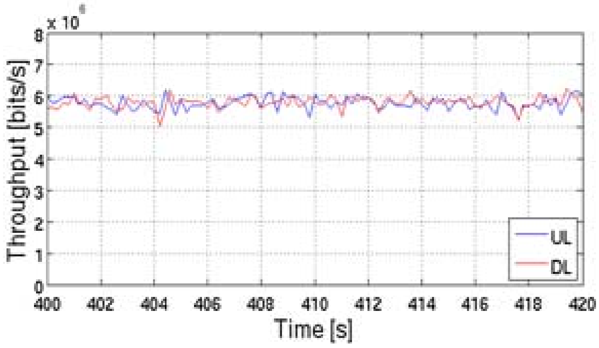
Tab. 1 General simulation parameters coming from [10]

forwards and backwards within a range of 20 meters.

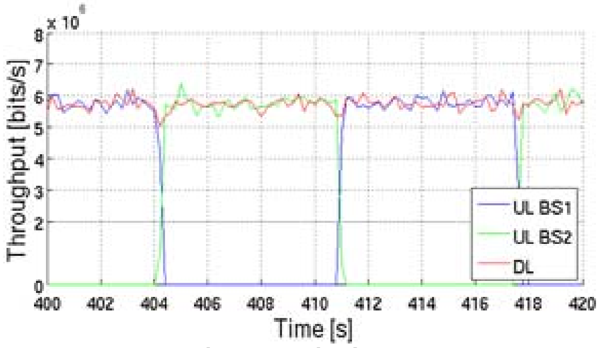
3.3 Results

Fig. 6 shows the UL and DL throughput over the time during TDD intra-mode intra-REC and inter-REC handovers. Three handovers occur in the considered time interval. In botch cases the offered traffic can be carried and it can be seen that the UT is continuously connected. The reason for the slightly higher carried traffic compared to the offered traffic (5 MBit/s) is that the offered traffic is measured on top of the IP layer whereas the carried traffic is right below IP, so that the carried traffic also contains the IP overhead. In the right figure it can be seen that the UT is alternately connected to BS1 and BS2 via the RN.

In Fig. 7 the according DL delay of the two scenarios can be seen. In both cases the delay behaviour is similar. When connected directly with the BS the delay is nearly half as high as when connected via a RN. This is obviously caused due to the additional second hop. Furthermore, in the left curve, i.e. in the intra-REC handover case, a delay peak after the handover is observable. The higher delay can be traced back to the packets which were preserved in the ARQ buffers during the handover. This is possible because in case of an intra-REC handover the End-To-End flow between the BS and the UT does not change (compare Section II.C). In case of an inter-REC handover these packets are simply deleted. The UL delay values of these two scenarios are shown in Fig. 8. The structure of the curves is similar to the DL. Also the effect of the delay peaks after a handover can be distinguished between the intra- and inter-REC handover. However, the variance of the delay values in UL is higher than in the DL. The reason for this is the lower transmitting power in the UL. This causes a lower SNR at the RAP and therefore packet errors occur in the UL. These packets are then retransmitted by the ARQ mechanism and consequently the delay is higher.



6a Intra-REC handover



6b Inter-REC handover

Fig. 6 Throughput during TDD intra-mode handover

Parameter	Value (FDD / TDD)	Unit
Multiplexing scheme	TDMA-OFDMA	
Mid frequency	4.2 (UL) / 3.95 4.45 (DL) / 3.95	GHz GHz
Signal bandwidth	2 x 45 / 89.84	MHz
OFDMA symbol duration	28.8 / 22.48	µs
Transmitting power (fixed per subband)	24.416 / 13.382 15.416 / 6.382 2.416 / 0.382	dBm dBm dBm
Duplex guard time	0 / 8.4	µs

Tab. 2 FDD and TDD specific parameters coming from [10]

	Mode	Mean	Variance
DL packet delay	TDD	1.3133 ms	6×10^{-7}
DL packet delay	FDD	1.6743 ms	7×10^{-7}
UL packet delay	TDD	1.6055 ms	1.9×10^{-6}
UL packet delay	FDD	1.6542 ms	2×10^{-7}
Handover duration	TDD	15.6 ms	6.8309×10^{-6}
Handover duration	FDD	16.2 ms	6.8584×10^{-6}

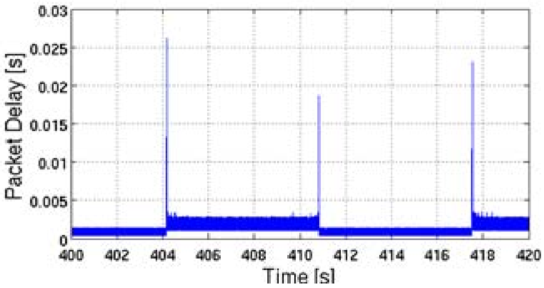
Tab. 3 Intra-mode intra-REC handover between a BS and a RN: Delay and handover durations

	Mode	Mean	Variance
DL packet delay	TDD	1.2970 ms	5×10^{-7}
DL packet delay	FDD	1.6665 ms	5×10^{-7}
UL packet delay	TDD	1.4999 ms	1.7×10^{-7}
UL packet delay	FDD	1.5922 ms	4×10^{-7}
Handover duration	TDD	15.6 ms	6.8309×10^{-6}
Handover duration	FDD	16.2 ms	6.8584×10^{-6}

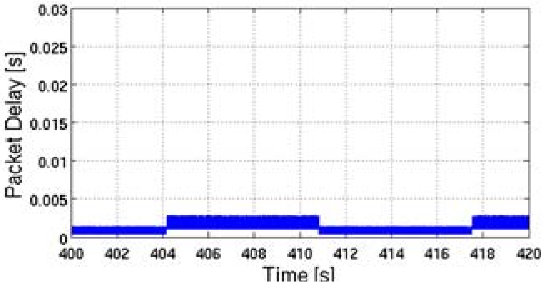
Tab. 4 Intra-mode inter-REC handover between a BS and a RN: Delay and handover durations

	Mean	Variance
DL packet delay	1.5098ms	4×10^{-7}
UL packet delay	1.5251ms	5×10^{-7}
Handover duration	15.9ms	8.0618×10^{-6}

Tab. 5 Inter-mode intra-REC handover between a BS and a RN: Delay and handover durations

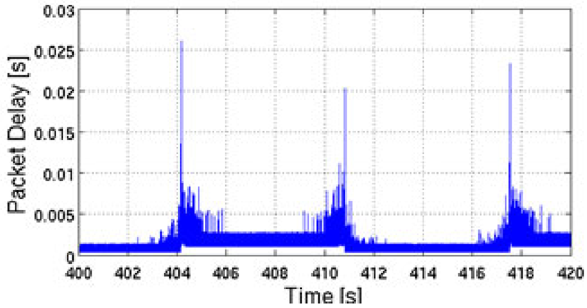


7a Intra-REC handover

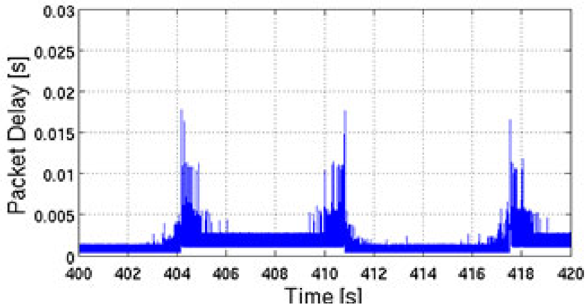


7b Inter-REC handover

Fig. 7 DL delay during TDD intra-mode handover



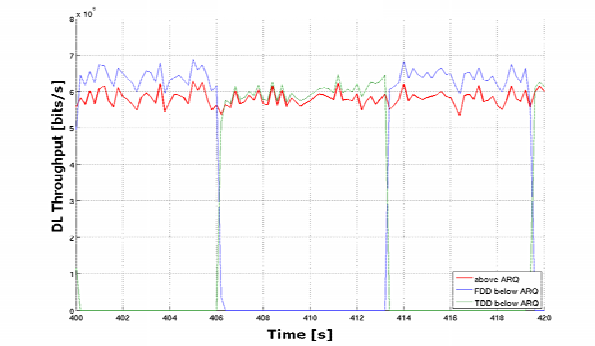
8a Intra-REC handover



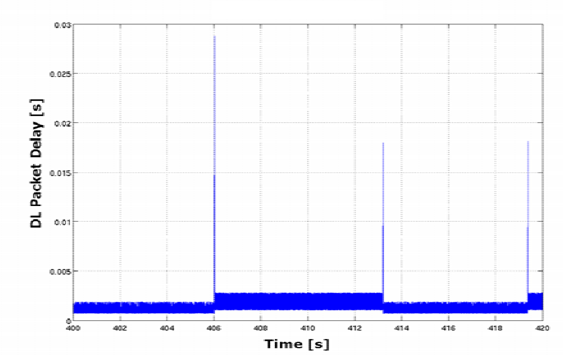
8b Inter-REC handover

Fig. 8 UL delay during TDD intra-mode handover

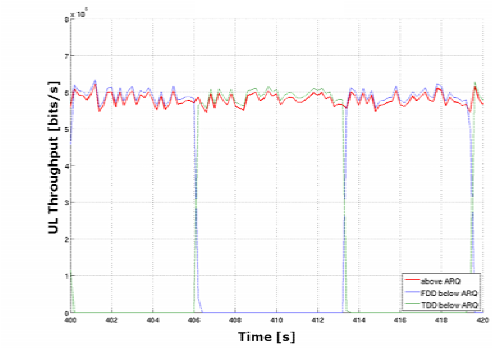
The exact delay values and handover durations for the intra- mode intra-REC and inter-REC handovers also for FDD are listed in Tab. 3 and 4 respectively. Due to the higher UL transmitting power in FDD than in TDD there is nearly no difference between UL and DL delay values in FDD. The DL and UL throughput curve of the third scenario depicted in Fig. 5 can be seen in Fig.9. The red line in both DL and UL shows the throughput over ARQ. In both cases the UT is continuously connected alternately with the BS using the FDD-mode and with the RN through the TDD-mode. The effect of the carried traffic below IP being slightly higher than the offered traffic above IP (5MBit/s) has already been explained in the TDD intra-mode scenario. The blue line shows the throughput via FDD below ARQ and the green one the throughput via TDD below ARQ respectively. It can be



9a DL

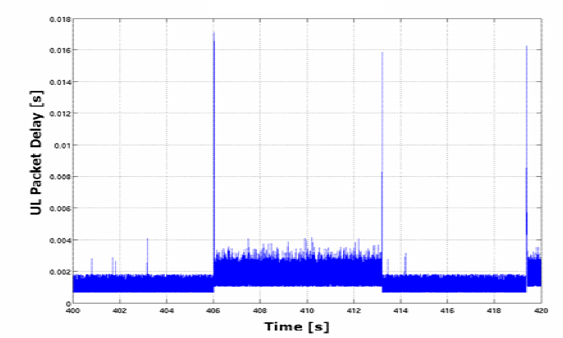


10a DL



9b UL

Fig. 9 DL and UL throughput during inter-mode intra-REC handover



10b UL

Fig. 10 Delay during inter-mode intra-REC handover seen that the FDD DL-throughput is slightly higher than the throughput above ARQ. The reason for this is that the FDD-mode is used in wide area scenarios [10]. This means that the UT is quite at the cell-edge in this scenario (see Fig.5) resulting in a relatively bad SNR in the UL due to the lower transmitting power compared to the BS. As a consequence there are acknowledgements in the UL which cannot be decoded correctly, so that a retransmission in the DL is necessary. This, of course, leads to an increase of the DL traffic below ARQ. The according delay curves of this scenario are shown in Fig. 10. Since this is an intra-REC handover scenario again the delay peaks after a handover occur. Again, the delay in the two-hop case is about twice as high as in the single-hop case. Different in DL and UL is the variance of the delay. The reason for this was explained before. It is due to the worse SNR in the UL than in the DL. So, more transmission attempts are necessary in the UL which heightens the delay. The exact delay values and handover durations for this scenario are listed in Tab. 5. In all scenarios the handover duration is about 15-16 ms, i.e. in the range of 2-3 super-frame lengths. The reason is that some of the (dis-)association signalling is sent in the preamble phase of the super-frame. The handover duration could be shorter, if there were exclusive control channels for this purpose in between the frames.

4. Conclusions and Future Work

In this paper it has been shown that parallel operation of different modes in a relay capable MAC protocol is feasible and therewith that it is possible to integrate the two duplex schemes FDD and TDD in one MAC protocol for future mobile radio systems. It is possible to detect, select and switch the modes dynamically based on a given strategy. The proof of concept has been done by investigating handovers in different Multi-Mode scenarios. According the handover it has been shown that the handover duration in a relay capable system is dependent on the number of hops and used physical channels. In the future more sophisticated handover procedures reducing the handover duration and preserving the context also in case of an inter-REC handover shall be investigated.

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