Parallel Operation of Half- and Full-Duplex FDD in Future 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 duplex (FDD) and time-division duplex (TDD). In general each of these methods has its benefits and drawbacks. However, both schemes have their scenarios where they perform best. 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. In general TDD is more appropriate for dense metropolitan area scenarios whereas FDD has benefits in wide area environments. If an FDD terminal which transmitted and received simultaneously, it would need an expensive duplex-filter, in order to separate UL and DL channels. Half-duplex terminals do not need such a filter. Therefore, half-duplex FDD appears to be attractive in terms of cost.**

A Relay is a promising concept for next generation systems. It allows enlarging the cell coverage range and is increasing the total cell capacity. A Relay is not connected by wire, but works in a decode-and-forward principle and consequently is a cost-efficient alternative to Base Stations. This paper introduces a protocol to support parallel operation of half- and full-duplex FDD terminals in a Relay capable system.

Index Terms— **Half-Duplex, Full-Duplex, FDD, B3G, 4G, MAC, WINNER, LTE**

I. Introduction

In next generation mobile radio systems 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. Furthermore these systems will demand quality of service, like high data rate and low delay. The EU FP6 project WINNER (Wireless World Initiative New Radio) and its successor WINNER II [1, 2] have specified 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. Such a system requires an amount of solutions each tailored for specific environments and the ability to select a tailored solution. Regarded candidates for such solutions are the duplex procedures Time Division Duplex (TDD) and Frequency Division Duplex (FDD). Both duplex schemes have their pros and cons [3]. The main advantage of FDD is the absence of a duplex guard interval, which is needed in TDD and is longer the larger the cell radius is. Therefore TDD is less appropriate for larger cell sizes than FDD. However, full-duplex FDD terminals are more expensive than TDD ones, because they transmit and receive at the same time and so require an expensive, high quality duplex-filter to separate transmission and reception signals. A duplex filter needs to be of high quality with sharp edges and high attenuation of out of band signals. A cheaper alternative are half-duplex FDD terminals, which alternately receive and transmit. These terminals theoretically reach only half the throughputs of full-duplex terminals. Both full-duplex and half-duplex FDD modes are not new but are in use in present mobile radio systems like GSM/GPRS, UMTS and WiMAX. GSM/GPRS uses a half-duplex FDD scheme [4]. UMTS offers full-duplex FDD [5, 6]. 3GPP LTE favours FDD [7] and WiMAX has full-duplex FDD operation as an option [8], but de facto only TDD is used. The WINNER project has proposed to integrate both schemes TDD and FDD in a future mobile broadband system. Recent work about half-duplex FDD is in [9] for 3GPP LTE and in [10] for WiMAX, but both without any performance evaluation and in case of [10] without considering multi-hop.

The aim of this work is to show what functions must be provided in a Medium Access Control (MAC) protocol, in order to support the coexistence of half- and full-duplex FDD terminals.

This paper is organised as follows. In Section II the integration of half- and full-duplex FDD operation into a MAC protocol is presented. Section III extends this to the relaying support. Section IV describes simulation scenarios and related parameters and presents performance analysis results. The paper concludes with an outlook on future work.

II. Concept

The implementation of half-duplex FDD operation as part of a MAC protocol mainly relates to the resource scheduling. The resource scheduler as part of a MAC protocol is the instance to decide what resources in the frequency and time domain are to be assigned to a certain User Terminal (UT) associated with to a Base Station (BS). Therefore the resource scheduler needs to know whether a half-duplex terminal can be reached at a certain point in time or not. A full-duplex terminal can transmit and receive all the time so that it can always be reached. Fig. 1 shows the so called MAC super-frame structure of the WINNER system for half-duplex

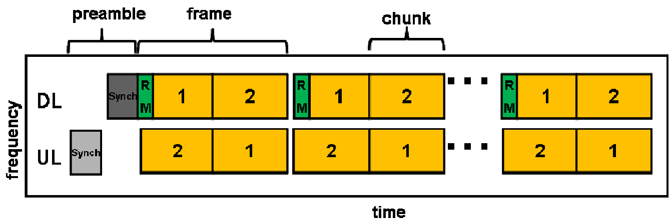

Fig. 1 WINNER MAC super-frame and half-duplex groups

operation [12]. It comprises a preamble for synchronisation followed by eight frames each containing two so called chunks. Each frame begins with a resource map (RM) where the resource allocation information, i.e. what time and frequency slot is reserved for what UT, is broadcasted to the UTs associated to a BS. The chunks are used to realise the half-duplex operation of a link. There are two half-duplex groups, say 1 and 2. UTs belonging to the group 1 receive in the first half of a frame and transmit in the second half whereas UTs of group 2 do it the other way round. Full-duplex terminals of course may transmit and receive all the time. Obviously, in this concept a UT of group 2 can never receive the resource map, since it is always transmitting during the resource map broadcast. This concept in addition is unfair concerning the resource distribution between the two groups, since group 1 gets fewer resources on the DL than group 2. Both drawbacks would be avoided if group 2 UTs received too during the RM map broadcast, but then the UL resources during this phase would be wasted. Assuming that a waste of resources should be avoided, one way to enable half-duplex scheduling is to precede group 2 in the DL by a RM too to

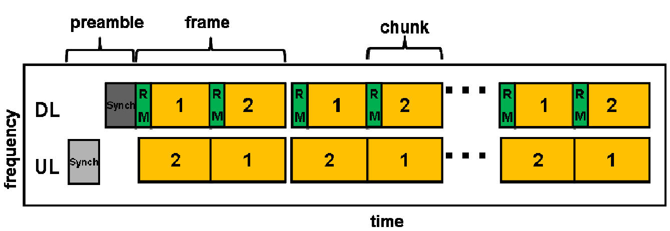

Fig. 2 Super-frame with two resource maps per frame

ensure UTs in group 2 are able to receive resource allocation. This is shown in Fig. 2 where a second RM is inserted before the second chunk in a frame.

Since the RM is what differs a frame from a chunk the super-frame structure in Fig. 2 has twice as many frames compared to Fig. 1, while the duplex groups switch from frame to frame. This can lead to a waste of resources, if a few terminals operate in half-duplex FDD mode, because full-duplex terminals do not need RM differentiation into two

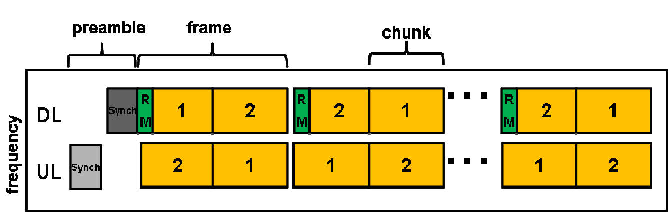

Fig. 3 Super-frame with duplex groups alternating in frames

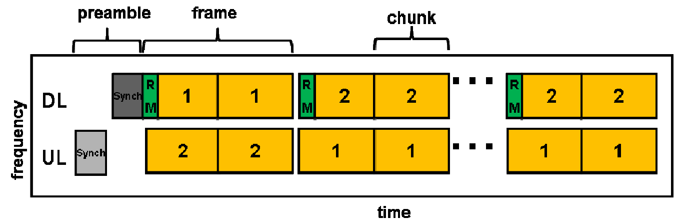

Fig. 4 Super-frame with alternating order of duplex groups over frames

groups, so that one RM per frame is enough and the resources spent for the second map are wasted. To reduce the overhead to only one resource map per frame, the order of the duplex groups could be alternated from frame to frame, i.e. in frame N duplex group 1 would receive the resource map and in frame N+1 group 2 receives the map, see Fig. 3. According to Fig. 3 information contained in the RM spans the contents of two chunks.

The concept shown in Fig. 3 can be further developed interchanging chunks of consecutive frames leading to Fig. 4. Each group receives a resource map every other frame and both chunks in a frame belong to the same group.

III. Integration of Relaying

Relay Nodes (RN) are useful to extend the coverage area of a BS in a cost-efficient way [11] or to increase the throughput capacity of a cell, but increase the complexity of half-duplex scheduling. In the WINNER system concept [1, 2] it is assumed that RNs behave like a UT towards the BS and behave towards their UTs like a BS. Accordingly, two consecutive task phases of RNs can be identified that switch from frame to frame, namely BS and UT. RNs are supposed to operate in full-duplex mode. Therefore the link between RN and BS is easy to schedule. The BS must only ensure that the RN is in a phase where it is acting as a UT when it is scheduled by the BS to receive the resource map. Fig. 5 depicts the super-frame structure of a RN. The RN alternates its role from “BS” to “UT” frame by frame. During the BS phase the RN schedules UTs of the associated half-duplex groups. In the phase marked “UT” the RN operates as UT to the BS. The interesting phase is “BS” where the RN acts as a BS. Since scheduling is done not only for one frame, but it must consider future frames too, the RN scheduler must take into account the time according to it is in BS role. A half-duplex UT that is scheduled must not switch from frame to frame as shown in Fig. 4 for UTs directly connected to a BS, but it must switch from BS phase to BS phase of its serving RN. Since it is in general possible that this BS task pattern is not fixed, the resource scheduler must switch the UT group to be scheduled, independently, from absolute frame numbers within a super frame. This becomes clear from Fig. 6.

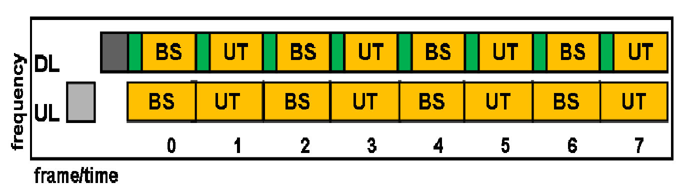

Fig. 5 Alternating task phases of a RN

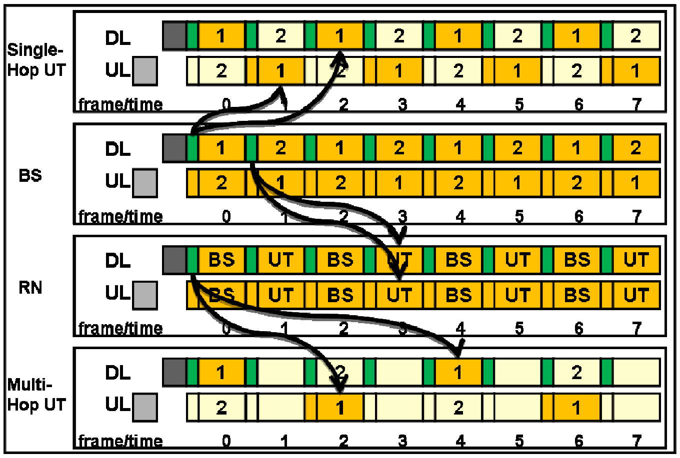

Fig. 6 Frame structures of all station types and their dependencies

The arrows point to the frames that are scheduled during the RM phases. For UTs that are directly served by a BS the duplex groups alternate from frame to frame as visible from the first row in Fig. 6. However, for UTs served by a RN the duplex groups alternate on the basis of the BS task phase of the RN. This is illustrated in the bottom row in Fig. 6. Clearly there is a gap of one frame between the uplink and downlink phases of both duplex groups and a gap of three frames between consecutive DL and UL phases, respectively. This leads to an increased delay and a lower maximum data rate for UTs owing to the gaps mentioned.

The concept introduced can easily be extended to serve more hops.

IV. Scenarios, Simulations and Results

This section describes the simulation scenarios considered to evaluate the half-duplex scheduling concept in Fig. 6 and presents and discusses the results.

A. Scenarios

The evaluation of the half-duplex FDD concept is done in two steps. First the scheduling is analysed in simple test scenarios to validate the correct functioning of the resource scheduler handles. In the second step more complex and more realistic simulation scenarios are considered to study the behaviour of half-duplex terminals within a multi-hop environment that supports both half- and full-duplex UTs.

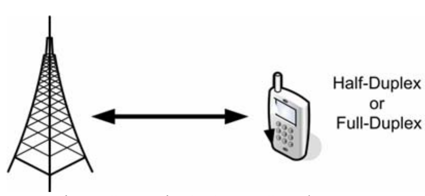

Fig. 7 Scenario 1: One BS and one UT

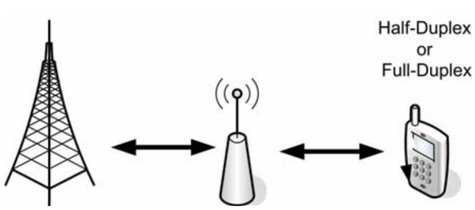

Fig. 8 Scenario 2: One BS, one RN and one UT

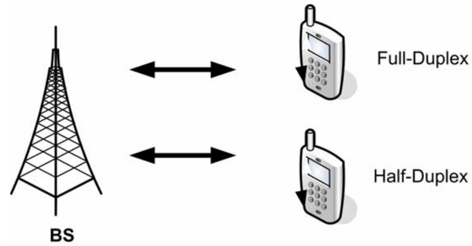

Fig. 9 Scenario 3: One BS and two UTs

The first investigated scenarios can be seen in Fig. 7 and 8. They consist of either one BS or one RN and one UT. The UT operates either in half-duplex or in full-duplex, i.e. the obtained results belong to different simulation runs.

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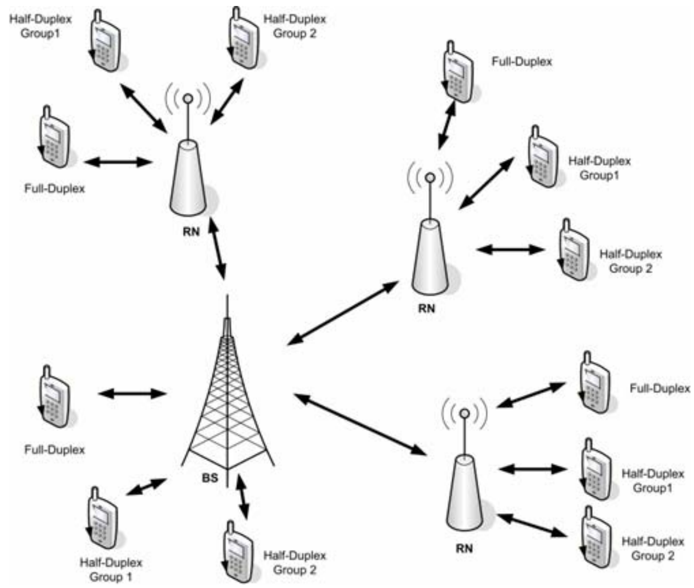

Fig. 10 Scenario 4: One BS, three RNs and twelve UTs

the next scenarios the effects of the different duplex groups on each other in terms of throughput and delay will be investigated. For this purpose the scenarios in Fig. 9 and 10 will be considered. Scenario 3 consists of one BS and two UTs one operating half-duplex and the other full-duplex. The purpose of this scenario is to show the influences of the two duplex groups on each other whereas the purpose of the last scenario is to point out the effects of additionally having multi-hop terminals. The last scenario (Fig. 10) consists of one BS, three RNs and altogether twelve UTs. The BS and each RN serves three UTs, one of them being a full-duplex UT and the other two being half-duplex terminals belonging to different duplex groups referred to as duplex group 1 and 2 in section III.

B. Parameters

The following parameters will be adjusted in each simulation run according to the before mentioned scenarios.

- Traffic rate
- Number of UTs directly connected to the BS
- Number of RNs
- Number of UTs connected via a RN

Furthermore, there are parameters which will be fixed for all simulations. They are mainly from [12] and are listed in Tab. 1. The distances between BS, RNs and UTs are such that the highest PhyMode (modulation&coding) QAM64-½ is used for every resource.

The traffic model parameters are listed in Tab. 2.

Finally, in order to allow the usage of RNs, the DL and UL bands are divided between the BS and the RNs during their BS task phase to avoid interference between these stations. Since the so called resource partitioning is not in the main scope of this work, it is kept as simple as possible and therefore is configured statically for each simulation. The resource partitioning is depicted in Fig. 11 for the case of one, two and three RNs.

As mentioned in section III, the RN task phase switches from frame to frame. Therefore only one of two consecutive frames is divided. The yellow sections belong to the BS while the others are assigned to the RNs.

C. Analytical Results

With the given prerequisites in the previous section the expected outcome of the simulations, especially upper bounds of the throughput in simple scenarios can be calculated analytically. Equations 1 and 2 show the theoretical maximum gross throughput for UL and DL respectively.

Parameter	Value
Super-frame **(SF)** length	5.8896 ms
Number of frames **(Fr)** per super-fame	8
Preamble duration	0.36 ms
Frame length	0.6912 ms
Multiplexing Scheme	TDMA/OFDMA
Duplexing scheme	FDD
Carrier frequency	3.95 GHz DL / 3.7 GHz UL
Channel bandwidth	2 x 50 MHz
OFDM symbol duration	28.8 µs
Number of sub-channels **(SC)**	1152 for both DL and UL
Number of OFDM symbols **(Sym)** per frame for data	21 in DL and 24 in UL
Number of OFDM symbols for resource map (only DL)	3
MCS for data	64QAM1/2
MCS for resource map	BPSK1/2

Tab. 1 General simulation parameters

Parameter	Value
Packet size distribution	Synthetical typical IP traffic
Mean packet size	2056 Bit
Packet inter-arrival time distribution	Negative exponential with mean = $\frac{2056 Bit \cdot NumberOfUTs}{TrafficRate}$

Tab. 2 Traffic model parameters

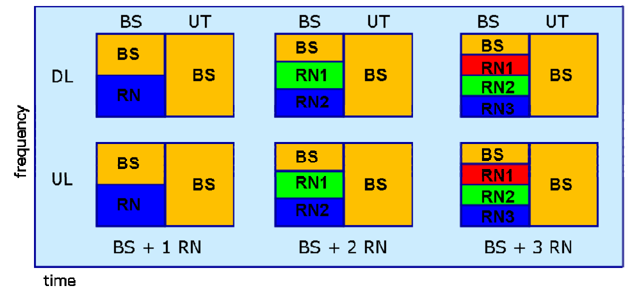

Fig. 11 Resource partitioning between BS and RNs

$$MaxThroughput_{UL} = \frac{\frac{1}{2}\cdot 6\frac{Bit}{Sym}\cdot 1152\,SC\cdot 24\frac{Sym}{Fr\cdot SC}\cdot 8\frac{Fr}{SF}}{0.0058896\frac{s}{SF}} = 112.6 MBit/s \quad (1)$$

$$MaxThroughput_{DL} = \frac{\frac{1}{2}\cdot 6\frac{Bit}{Sym}\cdot 1152\,SC\cdot 21\frac{Sym}{Fr\cdot SC}\cdot 8\frac{Fr}{SF}}{0.0058896\frac{s}{SF}} = 98.6 MBit/s \quad (2)$$

However, the actual data rates are expected to be lower. Although the overhead caused by the preamble phase and the resource map were already taken into account in the above equations, there is still some more overhead caused by functionalities like Cyclic-Redundancy-Check (CRC) or wasted, i.e. unused resources due to packets which do not fully fit into the assigned resources.

Nevertheless it can be expected that the maximum achievable throughput of a single-hop half-duplex terminal will be 50% of a single-hop full-duplex terminal. The same is valid for a multi-hop full-duplex terminal, because it can also only be served every second frame due to the alternating task phases of its serving RN. Finally the multi-hop half-duplex terminals will have a maximum throughput of 25% of the single-hop full-duplex terminal. These expectations apply for the first two scenarios. The more interesting case is the one where different types of UTs are connected to the same BS/RN. Fig. 12 shows the expected resource assignments for the case of three UTs (full-duplex, half-duplex group 1 and group 2) connected to a BS/RN.

The full-duplex terminal will be assigned 50% of all resources of its BS/RN whereas the two other stations will each get only 25% of the resources, but this is highly dependent on the type of resource scheduler used. Here a memoryless Round-Robin scheduler is used which provides fairness on frame basis, i.e. the scheduler takes only those stations into account which are currently reachable. Since the full-duplex terminal is available twice as often, it gets twice as much resources as a half-duplex terminal. Another type of scheduler, e.g. a Proportional Fair scheduler, which also takes into account the past scheduling decisions, is expected to be fair over all frames. The last considerations are valid for

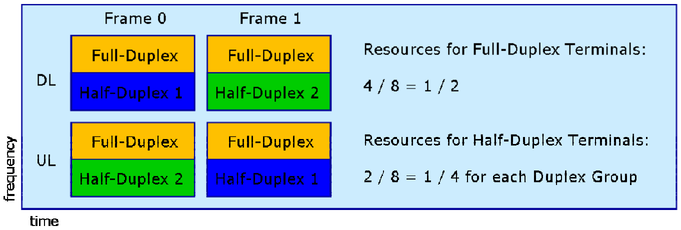

Fig. 12 Resource assignment to different kinds of UTs

scenario 4, namely for each single BS/RN and its UTs. In scenario 3 due to the absence of a second half-duplex group the full-duplex terminal will even get 75% of all resources.

D. Results

Fig. 13 shows the carried traffic over the offered traffic for above described scenario 1. It consists of one BS and one UT either half-duplex or full-duplex. These and all following results are results for the DL, although in all simulations symmetric traffic in DL and UL was applied. The UL results are pretty much the same except that the absolute values are higher due to the absence of a resource map in the UL (see also analytical results). The upper curve obviously belongs to the full-duplex terminal, the lower one to the half-duplex terminal. In both cases the offered traffic can be carried until the throughput goes into saturation. As expected the maximum achievable throughput for the full-duplex terminal is twice as high as for the half-duplex terminal. The expectation that the actual maximum throughput is lower than the analytically calculated one is also fulfilled. The full-duplex terminal reaches a maximum net throughput of about 86 MBit/s whereas the gross calculations added up to about 98 MBit/s. This is an overhead of about 12%. Consequently the throughput of the half-duplex terminal goes into saturation at about 43 MBit/s. The according UL values are 99 and 49.5 MBit/s respectively.

These results are confirmed also in the multi-hop case. The results can be seen in Fig. 14.

Again the upper curve belongs to the full-duplex terminal and the lower one to the half-duplex terminal. As expected the maximum throughput of the multi-hop full-duplex terminal corresponds to the value of the single-hop half-duplex terminal and the multi-hop half-duplex terminal reaches a half of this value.

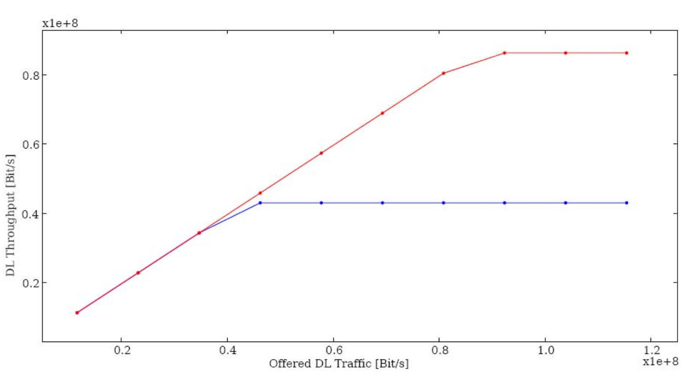

Fig. 13 DL throughput for scenario 1, one BS and one UT

In the previous two cases the relation of the theoretical maximum throughput of half- and full-duplex terminals was shown. However, the next results show the influence of the two kinds of stations in one and the same scenario. In Fig. 15 the maximum throughput for the above described scenario 3 can be seen. It consists of one BS and two UTs, one half-duplex and one full-duplex. The upper curve, which shows the sum of the values of both terminals, is nearly the same as the full-duplex maximum throughput in scenario 1, obviously the maximum capacity of the cell. Moreover the diagram can be divided into three sections. To the left none of the UTs has reached its maximum data rate and the throughput of both stations increases simultaneously. At the point where the offered traffic load reaches the maximum (at 84 Mbit/s) the

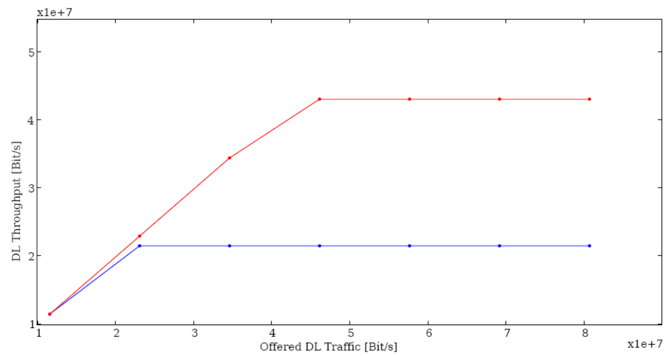

Fig. 14 DL throughput for scenario 2, one RN and one UT

half-duplex terminal can carry the full-duplex terminal's throughput still continues to rise and the one of the half-duplex terminal begins to decrease until both UTs reach their saturation at about 63MBit/s and 21MBit/s respectively. The saturation value for the full-duplex terminal (middle curve) is as expected exactly three times as high as the one for the half-duplex terminal (lower curve), because the half-duplex terminal gets half of all resources every second frame and no resources at all the other frame. In the low traffic cases the full-duplex terminal does not call on all of the 50% resources that are entitled to it in the frames it shares with the half-duplex terminal, since the resources in the other frame are sufficient to carry its traffic. In these cases the half-duplex

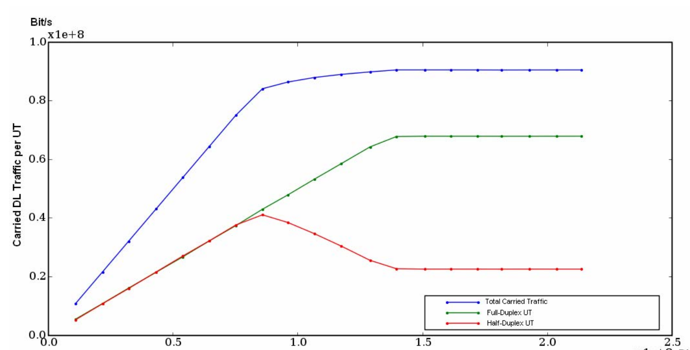

Fig. 15 DL throughput for scenario 3, one BS and two UTs

terminal can get more than half of the available resources in its duplex group frame. But as soon as the full-duplex terminal needs more resources, it accesses them up to the saturation point, so that the resources reserved for the half-duplex terminal decrease down to 50% every second frame and accordingly 25% in total. As described before this can be traced back to the scheduling strategy which provides fairness on a frame basis. The according delay results of this scenario in Fig. 16 confirm the throughput values. In the low traffic cases the delay is constant, nearly the same for half- and full-duplex terminals, namely about 2 ms and of course slightly higher for the half-duplex terminal due to transmissions in only every second frame. But as soon as the full-duplex terminal demands more resources, the delay for the half-duplex terminal increases. The delay for the full-duplex terminal increases not until the saturation throughput is reached. The reason for the upper bounds of the delay of about 14 ms the half-duplex terminal and about 5 ms for the full-duplex one is the transmitter-site limited queue size which lead to queue overflows and so limit the delay. Otherwise the delay values would increase ad infinitum beyond the saturation load point, of course.

The results of the last scenario where the influences of single-hop and multi-hop, half- and full-duplex terminals on each other can be seen is shown in Fig. 17. The scenario consists of one BS and three RNs each of them serving one full-duplex and two half-duplex terminals belonging to different half-duplex groups. The total DL throughput is 61.5

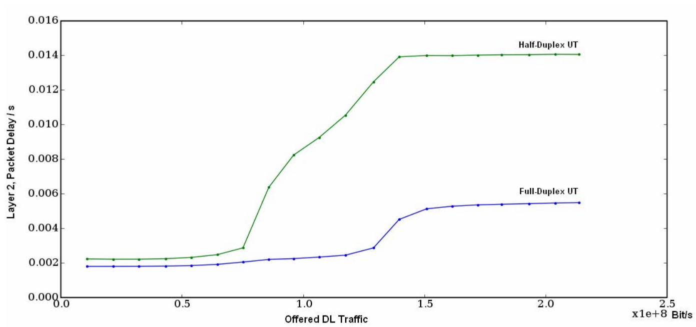

Fig. 16 DL delay for scenario 3, one BS and two UTs

MBit/s and is thus lower than the cell capacity due to the multi-hop overhead. The effect which appeared in scenario 3 where half-and full-duplex terminals had to share the resources among each other can also be seen here, namely between the terminals served by the same BS/RN. The only difference is that the full-duplex terminal now gets only twice as much resources as the half-duplex terminals, because now there are two of them, namely exactly one in each frame. Moreover, the effect of first increasing and afterwards decreasing slightly for the half-duplex terminals' throughput also arises in this scenario, exactly like in scenario 3. The exact values of the different saturation throughputs are 15.4 MBit/s for the full-duplex single-hop terminal and half of it for the half-duplex ones and 5.2 MBit/s for the multi-hop full-duplex terminals and again half of it for the half-duplex ones. When summing up these values and considering that the multi-hop data has to be sent twice, namely once for each hop,

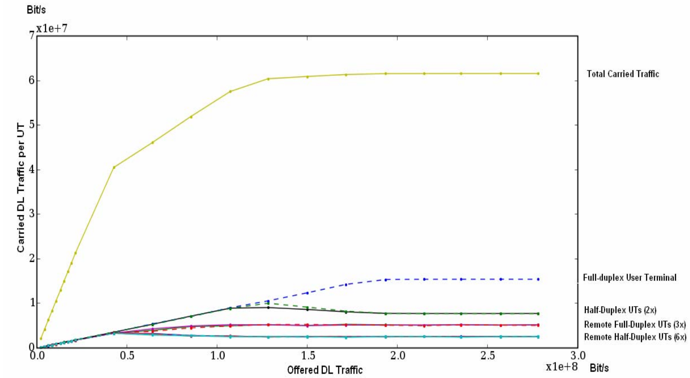

Fig. 17 DL throughput for scenario 4, one BS, three RNs and twelve UTs

the total capacity of the cell is 93.2 MBit/s. This is closer to the analytically calculated value than the maximum throughput in scenario 1 with one BS and one full-duplex terminal and can be traced back to trunking gain due to an increased number of UTs.

V. CONCLUSION AND FUTURE WORK

In this paper a concept has been introduced how to integrate half-duplex FDD in parallel to full-duplex FDD in future cellular multi-hop mobile radio networks. The resource scheduler has been identified as the key component which has to be able to consider the capabilities and availability of the terminals as well as of the connected relay stations. A simulative performance evaluation of half-duplex FDD terminals in single- and multi-hop scenarios has been conducted and the results have been verified by means of comparison with analytically calculated results.

In the future the resource scheduler which provides fairness on a frame basis shall be enhanced, in order to be able to provide a more general fairness, so that all terminals get the same amount of resources provided that they can use it. Expected results should be that expensive full-duplex and cheap half-duplex terminals only differ in the theoretical maximum throughput.

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