Performance Comparison of Radio Access Technologies for the UMTS

(Invited Paper)

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***Abstract*— In this paper, the three radio access technologies which have been chosen for the UMTS are evaluated both, by analytical calculations and by means of dynamic simulation. The most famous mode WCDMA or UTRA-FDD is compared to the two TDD modes with 3.84 Mcps (also known as TD-CDMA) and 1.28 Mcps which was developed based on the Chinese TD-SCDMA. A multi-service scenario in an urban environment is considered comprising voice and video data traffic.**

I. Introduction

The *Universal Mobile Telecommunications System* (UMTS) is currently being standardized providing three different kinds of *Radio Access Technologies* (RAT) for terrestrial access. Radio access is realized in a two-fold approach. Firstly, bidirectional communication is to be addressed by defining a suitable duplex scheme. Secondly, a multiple access scheme is to be defined which allows multiple communications simultaneously with the radio network protocols managing the different connections [1].

The duplex scheme aims to exclusively allocate parts of the available radio resources to *Downlink* (DL) or *Uplink* (UL) transmission direction. Two mechanisms are currently applied to mobile radio networks, *Frequency Division Duplex* (FDD) and *Time Division Duplex* (TDD). In FDD, frequency resources are identified for fixed usage in one of the transmission directions, where usually a lower part of the available spectrum is allocated to UL because of the better propagation conditions and the upper part is allocated to DL. Whereas for this scheme, paired frequency bands are mandatory, the TDD scheme divides the available single band spectrum in the time domain into the two transmission phases. Such allocation easily allows for adaptive and asymmetric allocation and serves better for data services with high traffic asymmetry as currently seen in mobile networks.

In the multiple access scheme, the available spectrum is divided into radio resources that can be allocated to an individual connection. This can be realized in the frequency domain by defining small frequency channels in the total bandwidth as *Frequency Division Multiple Access* (FDMA), in the time domain by splitting up the transmission in the time domain and defining time slots as *Time Division Multiple Access* (TDMA), or with the use of *Code Division Multiple Access* (CDMA). In the latter case, the whole spectrum is available to all users simultaneously and they are distinguished by using an individual code sequence. For a detailed introduction into CDMA please refer to [2, 3].

In the following, the radio access modes of UMTS are introduced. Within UTRA two duplex modes are foreseen. The FDD access is based on WCDMA enabling to allow multiple user access in the code domain. In TDD mode, a combination of TDMA and CDMA is specified. Both modes can be complemented by an FDMA scheme in case of multiple frequency bands of 5 MHz bandwidth allocated to an operator.

After an introduction to the physical layer structure in Sec. II with respect to the different technologies, Sec. III presents the overlaying *Radio Resource Management* (RRM) functionality. Analytical reflections and simulation results are described in Sec. IV and some final remarks are given in the conclusions.

II. Radio Access Technologies

In the following, the three different RAT for the UMTS are introduced. The main difference is not only the kind of duplex mode but also the chip rate at the physical transmission.

A. Frequency Division Duplex Mode

The FDD mode is planned to be applied for coverage of large areas [4]. Its symmetrical channel structure does not suit services with asymmetrical traffic on UL and DL very well. But especially packet services, which can be estimated to present a large fraction of overall traffic in the future, follow this imbalance in traffic because the most volume is downloaded in DL direction to the *User Equipment* (UE) whereas in UL only relatively small sized request or control messages have to be transmitted, e.g. acknowledgments and measurement reports.

The UTRA-FDD mode can be interpreted as a pure CDMA technique with *Spreading Factor* (SF) from 512 to 4. With an operator holding more than a single frequency band, it becomes a combination of CDMA and FDMA. A *Resource Unit* (RU) is then defined by the used spreading code and the center frequency of the allocated frequency band.

Within the UTRA-FDD mode, the time axis is structured into radio frames of 10 ms duration [5]. Each frame is divided into 15 time slots. These slots are only used to support periodic functionality and are not meant for TDMA. Since CDMA is employed, a global synchronization is not required. A radio frame contains 38400 chip resulting from the fixed chip rate of 3.84 Mcps. Transformed into the frequency space, this signal fits easily into a 5 MHz frequency band. The channel structure is shown in Fig. 1.

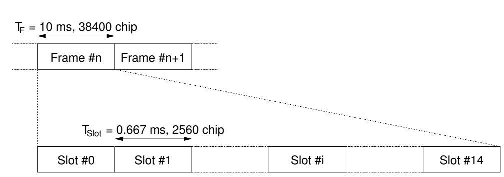

Fig. 1. Radio frame in UTRA-FDD and the TDD 3.84 Mcps option

In each time slot of 667 μs duration, 2560 chip with complex value can be transmitted. Since QPSK modulation is used, the real-valued chip will be transmitted on the I-branch of the modulation and the imaginary part is transmitted on the Q-branch.

B. *Time Division Duplex Mode with 3.84 Mcps*

The TDD technology separates DL and UL transmission in the time domain. Usually, a certain interval of a pre-defined radio frame belongs to DL (including necessary transmission of control data) and a remaining part for UL. However, multiple alternating intervals may also be possible.

In UTRA-TDD all well-known multiple access modes are combined. CDMA is enabled by supporting spreading with SF from 16 down to one, where the latter actually means no spreading and disables the CDMA. TDMA is realized by the definition of several time slots within the radio frame. Similar to the FDD mode, FDMA can be supported if an operator holds more than one frequency. An RU is entirely defined by the combination of code, time slot, and carrier frequency.

The 3.84 Mcps option uses a radio frame of 10 ms duration divided into 15 time slots each being able to carry a chip sequence of 2560 complex valued chips [6]. At least one slot has to be reserved for DL transmission to allow for broadcast information and one for UL transmission in order to realize customer's access to the system. The remaining slots can be arbitrarily distributed to either direction in order to adapt to the asymmetry of requested services [7]. However, the frame structure looks pretty much the same than for the FDD mode.

Between consecutive time slots, the transmission direction can be changed. The only restriction is to use the first slot for DL transmission and the last slot for UL transmission. However, due to the implementation complexity, a single switching point configuration is preferable. Hence, the first part of the radio frame will be used for DL and the remainder for UL.

C. *Time Division Duplex Mode with 1.28 Mcps*

As stated above, TDD enables the usage of a single frequency band for UL and DL transmission. The 1.28 Mcps option needs frequency bands of 1.6 MHz. Since UMTS is usually defined for a bandwidth of 5 MHz, three adjacent bands can be deployed within an operator's frequency band. Therefore, FDMA is an essential option for the multiple access and has to be considered for comparison of the different UTRA modes. Nevertheless, an RU is again defined by the combination of code, time slot, and frequency.

The 10 ms radio frame is divided into two sub-frames of 5 ms duration. Each of the sub-frames contains seven time slots. Transmission bursts fitting into a single slot contain 864 chip. The first time slot is always used for DL transmission, the latter six can be divided into UL and DL transmission adaptively, starting with the time slots used for UL. At least the second time slot (Slot#1) has to be allocated for UL. Unlike transmission in the 3.84 Mcps mode, the time slots used for transmission in a certain direction have to be grouped together so that no multiple switching points are possible. Between the first two slots in each sub-frame special pilot signals are included. The **DwPTS** is the DL *Pilot Time Slot* (PTS) which carries the DL pilot channel with the DL synchronization code. An additional main *Guard Period* (**GP**) is introduced at the first switching from DL to UL transmission. Afterwards, the **UpPTS** carries the UL pilot channel with the UL synchronization code. The radio frame setup is depicted in Fig. 2.

In order to re-use higher layer protocols, the radio frame is addressed in the same way as in the other RAT, i.e. every 10 ms. Therefore, the information data on MAC transport channels—which is almost the same for either mode—has to be distributed to both sub-frames. Hence, the same resources (code and time slot combinations) are used in both of the sub-frames and a frame can be reconfigured earliest after a 10 ms interval.

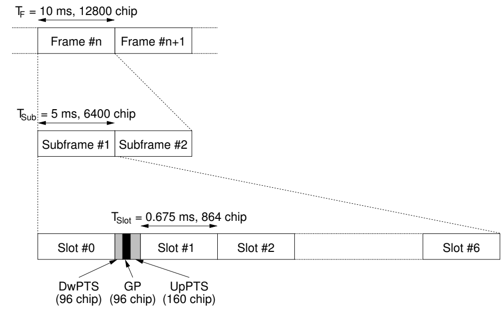

Fig. 2. Radio frame of the TDD 1.28 Mcps option

This mode generally defines two types of modulation, QPSK and 8PSK. Hence, the number of transmitted bit per time slot is additionally dependent on the modulation scheme used. Here, only QPSK modulation is considered. A comparative study of both TDD options is presented in [8].

III. Radio Resource Management Issues

RRM can be divided into resource allocation, scheduling, admission and congestion control. Furthermore, handover and power control are important management factors in CDMA networks. Channel allocation for TDD has already been widely studied, e.g. [9]. Scheduling performance in TDD is focussed in [10].

The main issue of RRM is to assign a suitable radio access bearer to meet the service requirements of a user at the right time and for an optimal interval. Obviously, for circuit-switched services the assignment has to be done immediately and lasts for the duration of the user's request. But the situation is different for packet-switched services. They are characterized by highly varying data rates and even contain idle periods where no data has to be transmitted, e.g. in web sessions. Shared channels and fast scheduling methods are options to optimally distribute the radio resources to the customers.

But RRM facilities and decisions are restricted by a limited choice of reference radio bearers with certain data rates, e.g. 32, 64, 128, 144, 384 kbps data channels. [11] provides an overview of some reference channels foreseen for all RAT. Based on an initial performance study of the UMTS RATs, we will derive challenges for efficient RRM strategies in the following.

IV. Performance Evaluation

Network capacity is defined with respect to certain QoS that is to be provided to all users in the network. [12] introduces the criteria for satisfied users if all of the following constraints are fulfilled.

- **Blocking**: The user is not blocked when arriving to the system. Blocking may result from resource limitation, i.e. no more available codes in the cell, or due to a admission control decision.
- **Dropping**: The user does not get dropped. For speech service, a connection is dropped when the BER is above 10^{-3} for more than 5 s consecutively. Connections may also be dropped due to failed handover or failed reconnection to the network in case of packet switched calls or as a result of congestion control algorithms.
- **Quality**: The user is experiencing sufficient quality throughout the complete service request. In case of speech service, sufficient quality is achieved if the BER is below the threshold of 10^{-3} for not less than 95% of the call duration. Packet data users usually get a BER far lower because of retransmissions of erroneous

TABLE I: Radio bearer parameters for speech and data services

Parameter	FDD mode DL	FDD mode UL	TDD modes DL	TDD modes UL
$SF_{12.2\,\text{kbps speech}}$	128	64	16	8
Codes per frame	1	1	2	1
$SF_{144\,\text{kbps data}}$	16	256	16	16
Codes per frame	1	1	9 and 16	1

packets. They are assumed to be satisfied if the active session throughput of the session is equal or greater than 10% of the requested service bit rate.

With these assumptions, the capacity of the network is analytically calculated and studied by means of dynamic simulations. The capacity is defined as the number of connections that can be supported by the system when there are 98% satisfied users.

A. Analytical Considerations

Limited resources in the network cause blocking of connections. The Erlang-B model allows to calculate the blocking probability P_B with respect to the number of offered connections to the network A and the number of available resources C in each cell by

$$P_B = \frac{\frac{A^C}{C!}}{\sum_{i=0}^{C} \frac{A^i}{i!}}. \quad (1)$$

Following the definition of the network capacity given above, the blocking probability P_B should be less than 2%. Resolving (1) the theoretical capacity of the network can be calculated. We therefore select speech service at 12.2 kbps as introduced in [12] as circuit-switched traffic (see also Tab. I).

The UTRA-FDD system is assumed to be resource limited in DL direction because almost infinite codes are available in UL since the code tree is re-used at every UE by using different scrambling codes. The DL capacity is assumed to be $C = 128 - 2$ codes available at SF 128 because at least 4 control codes at SF 256 will be used fixed in each cell. Moreover, an additional *Soft Handover* SHO overhead has to be taken into account. Hence, the available capacity is reduced by the average active set size of all users which may range from 1.0 for no users in SHO up to 2.0 in case of worse parameterized algorithms. Realistic values may be approximately $1.3 \ldots 1.4$ as derived in [13, 14].

In UTRA-TDD, network capacity has to be divided into DL and UL direction. Voice traffic is usually symmetric and therefore, the optimal allocation of capacity would also be symmetric. But the odd number of time slots only allows for quasi-symmetric allocation of slots to the transmission directions. Since more control channels are needed in DL, a distribution of 7 time slots to UL for the 3.84 Mcps option and 3 time slots in 1.28 Mcps mode is assumed as the limiting factor. Hence, $C = 7 \times 8 = 56$ resources at SF 8 for the speech service are considered in the 3.84 Mcps mode.

To allow for a fair comparison with the other modes, three carrier frequencies are considered for the UTRA-TDD 1.28 Mcps mode. Being UL code limited, $C = 3 \times 3 \times 8 = 72$ RU are available at SF 8.

Fig. 3 shows the resulting blocking probability for 12.2 kbps speech service provided by the different UTRA modes. SHO overheads of 20%, 30%, 40%, 50%, and 60% are taken into account for the FDD mode.

Obviously, UTRA-FDD offers the highest voice capacity of all access modes but it uses also twice the spectrum. Moreover, with in-

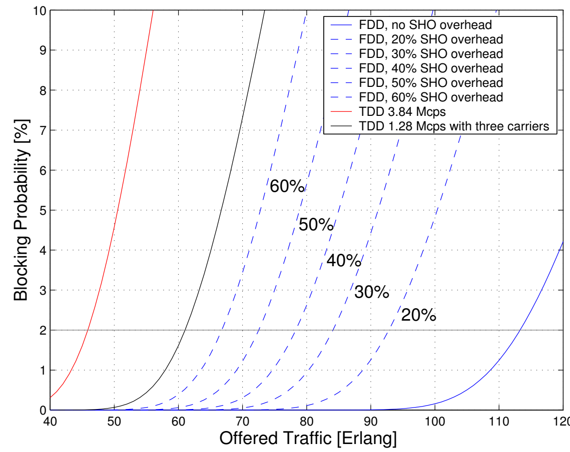

Fig. 3. Erlang-B blocking probability for speech service in UTRAN

creasing SHO overhead the network capacity decreases. For realistic values of 40%, up to 78 Erlang can be carried with sufficient QoS. This results in a spectrum efficiency ν for 12.2 kbps voice in both, DL and UL direction of

$$\nu_{\text{FDD,speech}} = \frac{78 \times 2 \times 12.2\,\text{kbps}}{10\,\text{MHz}} = 190\,\text{kbps/cell/MHz}.$$

The 3.84 Mcps TDD option is able to carry up to 46 Erlang in a single frequency band of 5 MHz which results in a spectrum efficiency of

$$\nu_{\text{TDD 3.84,speech}} = \frac{46 \times 2 \times 12.2\,\text{kbps}}{5\,\text{MHz}} = 224\,\text{kbps/cell/MHz}.$$

UTRA-TDD with 1.28 Mcps performs most efficient as it is able to support up to 61 connections within 5 MHz bandwidth. The spectrum efficiency for speech is then

$$\nu_{\text{TDD 1.28,speech}} = \frac{61 \times 2 \times 12.2\,\text{kbps}}{5\,\text{MHz}} = 298\,\text{kbps/cell/MHz}.$$

These figures are theoretical bounds for the speech capacity of a UMTS network. The Erlang model lacks consideration of handovers which mean additional arrival and departure rates of calls in the cellular network. However, it gives a first upper estimate of the network performance.

Bounds for packet data users can be derived in a similar way if it would be possible to capture the effects of packet data connections into a stationary process for the duration of a session. The Erlang-C model with infinite sources and call queuing serves for estimating the soft capacity for packet switched connections. It is expressed as

$$P_C = \frac{\frac{A^C}{C!} \cdot \frac{C}{C-A}}{\sum_{i=0}^{C-1} \frac{A^i}{i!} + \frac{A^C}{C!} \cdot \frac{C}{C-A}}, \quad (2)$$

where P_C is the probability that a customer will have to wait for resources, i.e. will experience a non zero delay in obtaining a resource. A is the number of connections offered to the cell and C the number of available resources for the particular service. A packet data application provided in DL at an average data rate of 144 kbps is considered.

One code with SF 16 is needed in DL UTRA-FDD (see Tab. I). The total DL capacity, i.e. the number of remaining codes at this spreading layer is $C = 15$. SHO overhead is considered with 20%, 40% and 60%.

In the UTRA-TDD 3.84 Mcps option up to 14 time slots can be allocated to DL. The 144 kbps data service requires 9 codes in one

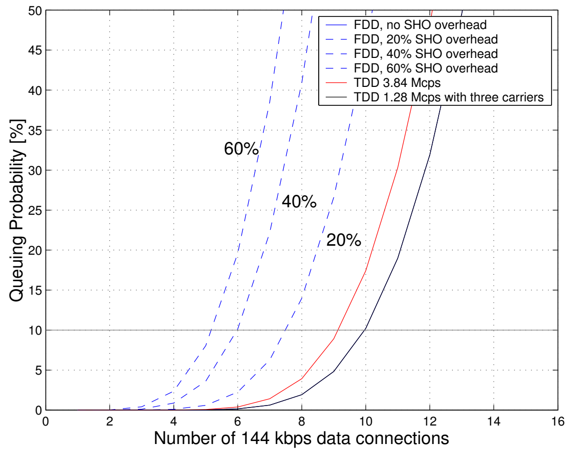

Fig. 4. Erlang-C queuing probability for 144 kbps data service in UTRAN

time slot at SF 16 in DL. Therefore, the capacity is $C = 14$ leaving enough resources for the control channels. The UL feedback channel may be realized with a single SF 16 code on the remaining UL time slot.

The 1.28 Mcps option provides a DL 144 kbps data service with the use of 8 codes at SF 16 in each of two time slots. Taking into account the three carriers available in 5 MHz bandwidth and a maximum of 6 time slots in DL, the capacity is $C = 18$. Since in this case all DL resources may be occupied by the data service and no control channel can be established, one data channel in every sub-band remains unused. This gives a maximum capacity of $C = 15$ data service channels.

The waiting probability according to (2) is plotted in Fig. 4. Sufficient QoS for the data service is assumed with queuing probabilities below 10%.

The worst capacity is offered by UTRA-FDD. Even if a SHO overhead of only 20%—assuming the packet data users quite stationary—is taken into account, only 7 connections at 144 kbps can be supported. This gives a spectrum efficiency of

$$\nu_{\text{FDD,144 kbps}} = \frac{7 \times 144\,\text{kbps}}{10\,\text{MHz}} = 101\,\text{kbps/cell/MHz}.$$

The main drawback is that the UL capacity remains unused. Moreover, the SHO overhead additionally reduces the capacity. Without the necessary SHO overhead the FDD DL frequency band would offer the same capacity than the TDD 1.28 Mcps option.

The 3.84 Mcps TDD option is able to carry up to 9 simultaneous data connections in a single frequency band of 5 MHz which results in a spectrum efficiency of

$$\nu_{\text{TDD 3.84,144 kbps}} = \frac{9 \times 144\,\text{kbps}}{5\,\text{MHz}} = 259\,\text{kbps/cell/MHz}.$$

UTRA-TDD with 1.28 Mcps performs again most efficient as it is able to support up to 10 connections within 5 MHz bandwidth. The spectrum efficiency for streaming data at rate 144 kbps is then

$$\nu_{\text{TDD 1.28,144 kbps}} = \frac{10 \times 144\,\text{kbps}}{5\,\text{MHz}} = 288\,\text{kbps/cell/MHz}.$$

Once more, the UTRA-TDD mode with 1.28 Mcps offers the highest spectral efficiency.

B. Simulation Results

The event-driven simulator GOOSE developed at ComNets is used for dynamic network simulation purposes. The Manhattan-like scenario following [12] is chosen as well as propagation and traffic modeling, except the video streaming model which is derived from [15]. The latter is used to generate a 144 kbps data service with highly variable data rate.

Network interference is a critical factor in CDMA networks. Therefore, the resulting average interference in DL and UL direction with respect to the offered traffic is evaluated in Fig. 5 and 6. The background noise level including receiver noise figure marks the lower bound for the interference. Because of superior receivers at the Node B, the UL noise is lower. The smaller bandwidth for the TDD 1.28 Mcps option causes the 5 dB reduced noise level [8]. The plots show the mean interference for the link with respect to the number of offered connections at each cell. The standard deviation of the measured interference values is given additionally as bars above and below the mean value to allow for an estimation of the interference variation.

We can clearly see that both TDD modes benefit from an interference-aware channel allocation scheme which assigns the least interfered resources to a connection keeping the overall network interference low (see also [16]). Moreover, application of joint detection techniques in the TDD modes is a major advantage of these RAT. FDD suffers from the permanent power on the broadcast channels in DL and the missing code orthogonality in UL direction.

Along with the higher interference comes the demand for higher transmission powers at both, the UE and the Node B. Fig. 7 illustrates the power requirements for UE providing voice services in UMTS. Whereas both TDD modes enable Tx powers between -40 and -10 dBm almost independent of the offered traffic, the necessary UE power in FDD is increasing with increasing traffic. This complicates efficient radio network planning and RRM optimization.

Another drawback of UTRA-FDD is the overhead necessary for SHO. The simulations show an average active set size between 1.26 and 1.29 independent of the offered traffic which is a little less than estimated for the macro-cellular urban environment in [14]. Fig. 8 illustrates the good agreement of the analytical study with the simulation results concerning the blocking of circuit-switched speech connections.

It is obvious that UTRA-FDD can handle all offered connections at the expense of high interference (compare Fig. 5 and 6). Thus, although enough resources are available, the RRM is in charge of controlling the users' access to the network to prevent instabilities and quality degradation. The actual limitation in FDD is due to transmission power and interference bounds at approximately 65 Erlang [14].

Additionally, a 144 kbps video streaming data service is evaluated. Firstly, Fig. 9 presents the DL power per code. As a result of the higher interference in FDD we can clearly see the demand for higher powers almost reaching the power capacity of the Node B. In TDD, higher power compared to the speech service is needed to guarantee the higher SIR targets.

In the following, RRM tasks for the video data service are discussed. If the RRM assigns a radio bearer that matches the average required data rate, high delays for the video frames are experienced as a result of waiting for large packets to get transmitted. Fig. 10 presents the complementary cumulative distribution function (CCDF) of the frame transmission delay. Such weak performance with average delays of several seconds requires large buffers to offer sufficient quality in terms of service continuity to the user. Therefore, a temporary allocation of higher rate radio bearers for multiple users using some kind of shared channel seems advantegeous. Here, we can expect faster transmission of large packets and lower average delays.

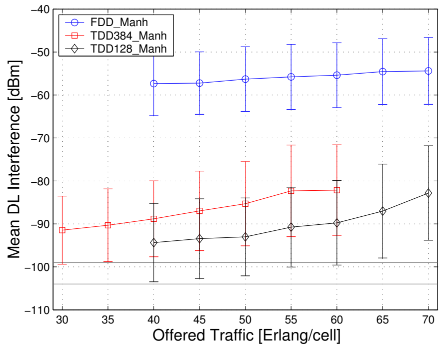

Fig. 5. Measured DL interference

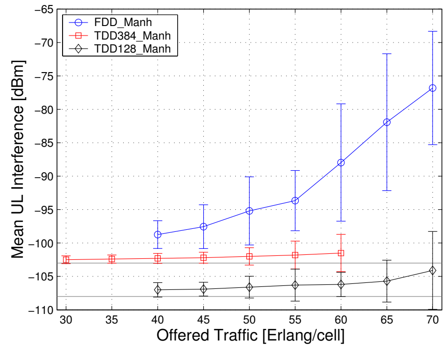

Fig. 6. Measured UL interference

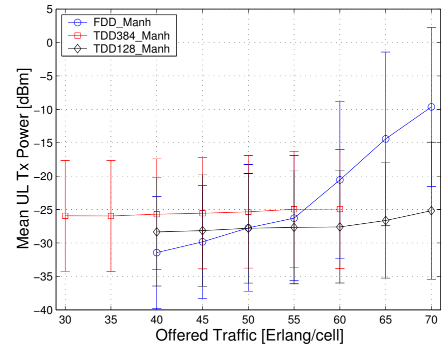

Fig. 7. Transmission power used in UL

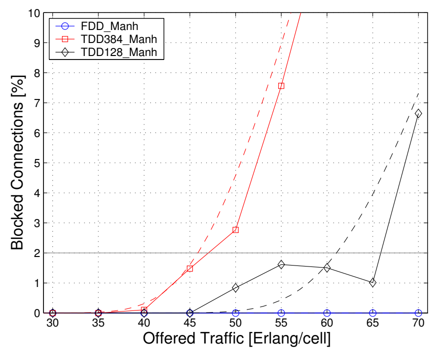

Fig. 8. Blocking probability for speech service

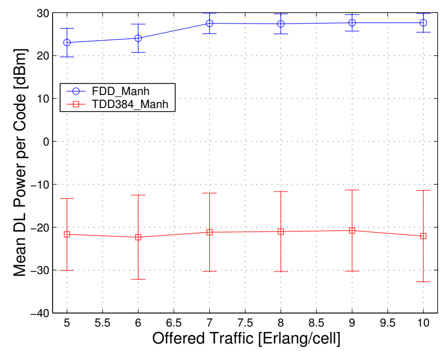

Fig. 9. Tx power per code in DL

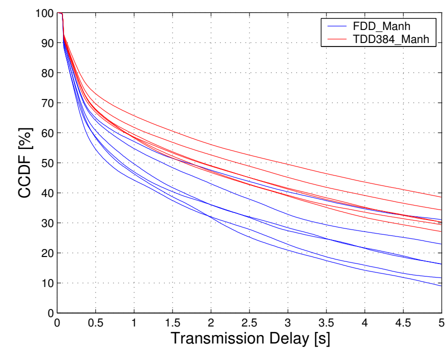

Fig. 10. Transmission delay for video data packets

Consider an average I-frame size of 8 kByte. Such a data packet will take about 0.5 s to get transmitted over a 144 kbps radio bearer. If a 384 kbps could be allocated, the transmission delay can be reduced below 200 ms. Afterwards, the channel should be given to other users following a scheduling strategy that serves the waiting request with earliest due date and longer queue length first. It is known, that such a scheduling strategy may not be optimal for the delay and throughput but it might help reducing the buffer requirements because of the faster transmission of large packets and might keep delays according to the service's requirements.

V. Conclusion

From the analytical study and the performance evaluation by means of dynamic simulation we can clearly state, that RRM algorithms will still be the major challenge to optimize the different UMTS RAT. Whereas voice and other circuit-switched services restrict the freedom of RRM decisions, packet-switched data services enable a high degree of flexibility to efficiently share the scarce radio resources.

However, the TDD modes offer even more flexibility because of their TDMA component for the radio access and the multi user detection capabilities. Especially the 1.28 Mcps deployed in a 5 MHz band with three independent carriers looks like the most promising RAT. Future studies in different kind of scenarios and with various traffic types have to prove, if it is worth to accept the more complicated and expensive RAT aiming at higher spectrum efficiency, more satisfied customers and higher revenues for the network operators.

Acknowledgment

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