The 3G Long-Term Evolution – Radio Interface Concepts and Performance Evaluation

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***Abstract*—3GPP is in the process of defining the long-term evolution (LTE) for 3G radio access, sometimes referred to as Super-3G, in order to maintain the future competitiveness of 3G technology. The main targets for this evolution concern increased data rates, improved spectrum efficiency, improved coverage, and reduced latency. Taken together these result in significantly improved service provisioning and reduced operator costs in a variety of traffic scenarios. This paper gives an overview of the basic radio interface principles for the 3G long-term evolution concept, including OFDM and advanced antenna solution, and presents performance results indicating to what extent the requirements/targets can be met. It is seen that the targets on three-fold user throughput and spectrum efficiency compared to basic WCDMA can be fulfilled with the current working assumptions. More advanced WCDMA systems, employing e.g. advanced antenna solutions may however achieve similar performance gains. Enhancements for reduced latency and IP optimized architectures and protocols are further applicable to both LTE and WCDMA.**

I. BACKGROUND AND TARGETS FOR THE 3G EVOLUTION

The third generation WCDMA radio access technology approached 44 million subscribers worldwide in 2005, according to World Cellular Information Service, and is continuing to grow with an accelerated pace. However, to maintain WCDMA competitiveness in the long-term future, it is necessary to further develop today's standard. The first steps of this evolution have already been taken by the 3rd Generation Partnership Project (3GPP) through the additions of High Speed Downlink Packet Access (HSDPA) and Enhanced Uplink (EUL) to WCDMA [2], together denoted HSPA. The first products supporting HSDPA reached the market in 2005 and the corresponding EUL products should be available in 2006. HSDPA and EUL will clearly provide a platform that can meet the operator and user demands in the near and mid-term future.

In a longer time perspective it is, however, necessary to be prepared for further increasing user demands and an even tougher competition from new radio access technologies. To meet this challenge, 3GPP has initiated the study item *Evolved UTRA and UTRAN* [2], aiming at studying means to achieve additional substantial leaps in terms of service provisioning and cost reduction. As a basis for this work, 3GPP has concluded on a set of targets and requirements for this long-term evolution (LTE) [3], including e.g.

- Peak data rates exceeding 100 Mbps for the downlink direction and 50 Mbps for the uplink direction.
- Mean user throughput improved by factors 2 and 3 for uplink and downlink respectively.
- Cell-edge user throughput improved by a factor 2 for uplink and downlink
- Uplink and downlink spectrum efficiency improved by factors 2 and 3 respectively.
- Significantly reduced control-plane latency.
- Reduced cost for operator and end user.
- Spectrum flexibility, enabling deployment in many different spectrum allocations.

For the relative requirements on user throughput and spectrum efficiency, the reference system is a rather basic WCDMA system. To fulfill the requirements, new radio transmission technologies are being considered. Related work in this area is being done for the new fourth generation, 4G, mobile systems, see e.g. [4] [5] [6] and [7]. In addition to constituting valuable input, these similarities also facilitate that the LTE technical solutions will smoothly connect to the future 4G radio access technology.

This paper describes and evaluates radio interface constituents of the LTE concept: the use of orthogonal frequency division multiplexing (OFDM) [8], as a new transmission technology, frequency domain adaptation, and the support for employing advanced multi-antenna solutions. In the evaluation part special attention is paid to whether the 3GPP targets on user throughput and spectrum efficiency can be fulfilled. Other important building blocks for the long-term 3G evolution are a system architecture streamlined for packet services, and evolved quality of service, QoS, and link-layer concepts. These are described in [9].

II. RADIO INTERFACE CONCEPTS

The ability to provide high bit rates is a key measure for LTE. Multiple parallel data stream transmission to a single terminal, using multiple-input-multiple-output (MIMO) techniques, is one important component to reach this. Larger transmission bandwidth and at the same time flexible spectrum allocation are other pieces to consider when deciding what radio-access technique to use. The choice of adaptive multi-layer OFDM, AML-OFDM, in downlink will not only facilitate to operate at different bandwidths in general but also large bandwidths for high data rates in particular. Varying spectrum allocations, ranging from 1.25 MHz to 20 MHz, are supported by allocating corresponding numbers of AML-OFDM subcarriers. Operation in both paired and unpaired spectrum is possible as both time-division and frequency-division duplex are supported by AML-OFDM.

A. Downlink – OFDM with Frequency-Domain Adaptation

The AML-OFDM-based downlink has a frequency structure based on a large number of individual sub-carriers with a spacing of 15 kHz. This frequency granularity facilitates to implement dual-mode UTRA/E-UTRA terminals. The ability to reach high bit rates is highly dependent on short delays in the system and a prerequisite for this is short sub-frame duration. Consequently, the LTE sub-frame duration is set as short as 0.5 ms in order to minimize the radio-interface latency. In order to handle different delay spreads and corresponding cell sizes with a modest overhead the OFDM cyclic prefix length can assume two different values. The shorter 4.7 ms cyclic prefix is enough to handle the delay spread for most unicast scenarios. With the longer cyclic prefix of 16.7 ms very large cells, up to and exceeding 120 km cell radius, with large amounts of time dispersion can be handled. In this case the length is extended by reducing the number of OFDM symbols in a sub-frame.

OFDM is suitable for broadcast services. To support such services the same information is transmitted from several (synchronized) base stations to the terminal. The total signal the terminal receives from the base stations will appear as multipath propagation and thus implicitly be exploited by the OFDM receiver. The longer cyclic prefix allows combining broadcast signals from a large number of distant base stations.

Techniques to exploit channel variations in the time domain have been successfully implemented for HSDPA. This has resulted in a substantial increase in spectral efficiency. For E-UTRA, the channel-based adaptation can be extended to also include transmission adaptation in the frequency domain thanks to the use of OFDM. When the radio channel varies significantly over the system bandwidth, large performance gains can be achieved.

B. Uplink – Single-Carrier FDMA with Dynamic Bandwidth

A key requirement for uplink transmission is that the transmission should allow for power-efficient user-terminal transmission to maximize coverage. To reach this, single-carrier frequency-division multiple access (FDMA) with dynamic bandwidth is a good choice. In order to achieve intra-cell orthogonality, the base station assigns a unique time-frequency interval to the terminal for the transmission of user data. This is done for each time interval. The users are separated primarily by time-domain scheduling; however, if the terminal has a limited transmission power or not enough data to transmit, also frequency-domain scheduling is used.

C. Multi-Antenna Solutions

Advanced multi-antenna techniques will play an important role in fulfilling the 3G LTE requirements on increased data rates and improved coverage and capacity. This includes both beamforming and multi-layer transmission solutions to better exploit the potential of using the spatial domain. This potential is large and not always fully exploited in existing radio access technologies.

Increasing data rates can be achieved by transmitting multiple parallel streams or layers to a single user. This Multi-layer transmission is often referred to as MIMO. The preferred use for MIMO is in conditions with favorable signal-to-noise ratio and rich scattering in the radio channel, e.g., small cells or indoor deployments. Multi-layer transmission may be applied for downlink as well as uplink transmission. The receiver has the possibility to separate the multiple data streams by using the channel properties and knowledge of the coding scheme. In order for the receivers to solve this task it is necessary to standardize the multi-layer transmission scheme selected for the long-term 3G. Selective per-antenna rate control (S-PARC) [10] is an interesting technique where the number of layers and the data rate per layer, is adapted to the instantaneous channel conditions.

Beamforming implies that multiple antennas are used to form the transmission or reception beam and, in this way, increase the signal-to-noise ratio at the receiver. This technique can both be used to improve coverage of a particular data rate and to increase the system spectral efficiency. The increased signal-to-noise ratio is not only due to a larger gain in the direction of the desired user, but also due to a better control of the spatial interference distribution in the cell. Beamforming can be applied both to the downlink and the uplink. It is possible to make beamforming transparent to the terminal, which would eliminate the need to standardize a particular solution. Instead, the exact algorithms can evolve over time and be tailored to particular needs. Alternatively, one could include some explicit support for a specific beamforming solution, especially if that would increase the efficiency of the system and enable low complexity implementations.

TABLE I. MODELS AND ASSUMPTIONS

Traffic Models	
User distribution	Uniform, in average 10 users per sector
Terminal speed	0 km/h
Data generation	On-off with activity factor 5, 10, 20, 40, 60, 80, 100%
Radio Network Models	
Distance attenuation	L = 35.3+37.6*log(d), d = distance in meters
Shadow fading	Log-normal, 8dB standard deviation
Multipath fading	3GPP Typical Urban & Pedestrian A, independent between antennas
Cell layout	Hexagonal grid, 3-sector sites, 57 sectors in total
Cell radius	167m (500m inter-site distance)
System Models	
Spectrum allocation	5MHz for DL and 5MHz for UL (FDD)
Base station and UE output power	20W and 125mW into antenna
Max antenna gain	15dBi
Modulation and coding schemes	QPSK and 16QAM, turbo coding according to WCDMA Rel-6. Only QPSK for basic WCDMA uplink
Scheduling	Round robin in time domain
Basic WCDMA Characteristics	
Transmission scheme	Single stream in DL and UL
Receiver	2-branch antenna diversity with rake receiver, maximum ratio combining of all channel taps. 9dB noise figure in UE, 5dB in Node B
Advanced WCDMA Characteristics	
Transmission scheme	DL: 2 stream PARC UL: Single stream
Receiver	DL: GRAKE [12] with Succ. Interference Cancellation UL: GRAKE with 2-branch receive diversity, soft handover with selection combining between sites
LTE Characteristics	
OFDM Parameters	According to Section II, 300 subcarriers
Overhead	Bandwidth 28%, power 20%
Transmission scheme	DL: 2 stream PARC UL: Single stream
Receiver	DL: MMSE [13] with Succ. Interference Cancellation UL: MMSE with 2-branch receive diversity, soft handover with selection combining between sites

It is also possible to combine multi-layer transmission and beamforming. An example of this would be to transmit two data streams with two groups of antennas, where beamforming is employed within each group. Beamforming is then used to increase the received signal-to-noise ratio and multi-layer transmission is applied to convert the increased signal-to-noise ratio into a higher data rate.

III. MODELS AND ASSUMPTIONS

This section presents the models and assumption used to evaluate whether the 3GPP targets can be met. These are based on the guidelines in [11]. A summary grouped into traffic, radio network, and system models is provided in Table I. Three different systems are studied:

- A ‘basic’ WCDMA system, configured as the reference system in the 3GPP requirements, with single-stream transmission and simple receiver.
- A more ‘advanced’ WCDMA system with more sophisticated receivers, 2x2 MIMO for downlink, and 16QAM for uplink.

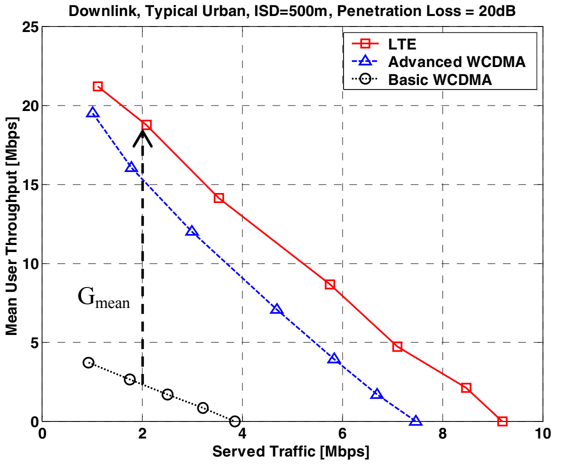

Figure 1. Mean user throughput versus served traffic, TU channel

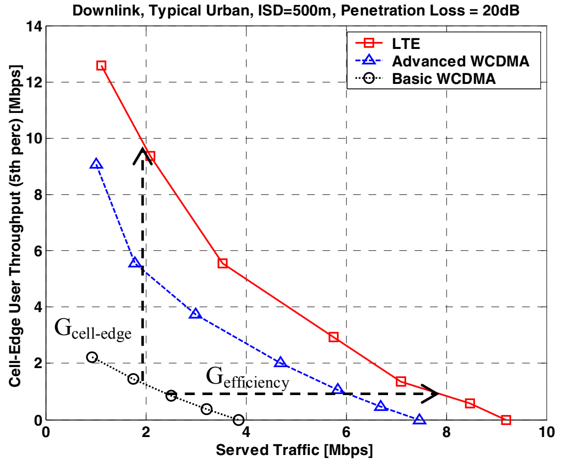

Figure 2. Cell-edge user throughput versus served traffic, TU channel

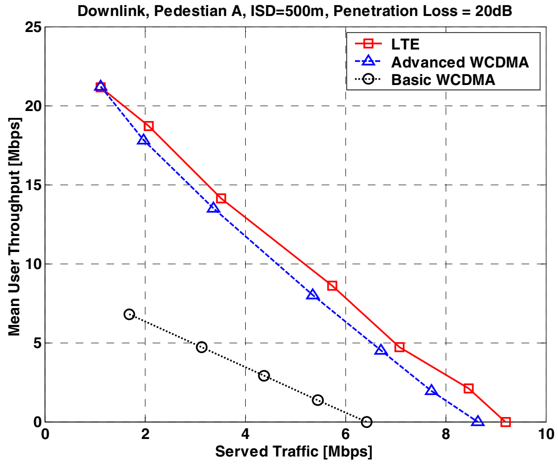

Figure 3. Mean user throughput versus served traffic, Ped. A channel

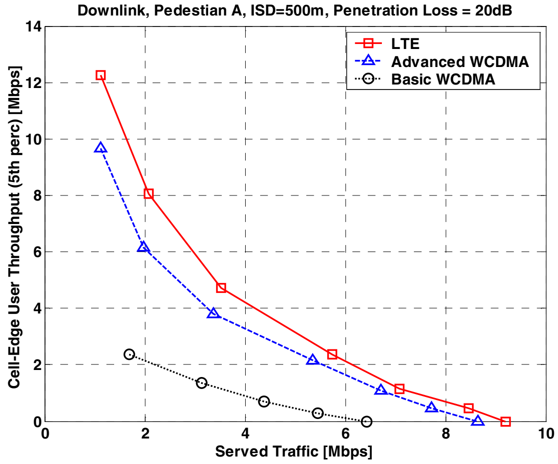

Figure 4. Cell-edge user throughput versus served traffic, Ped. A channel

- An LTE system, configured according to the 3GPP requirements, with 2x2 MIMO for downlink.

The ambition is to achieve relative assessments of the gains associated with OFDM and MIMO. Frequency-domain adaptation and other higher-layer improvements of the LTE concept are not included in the evaluation. It should also be noted that many control plane and user plane protocol aspects above the physical layer are omitted, yielding optimistic absolute values.

A simple static simulation-based evaluation methodology is used. In each iteration of the downlink (and uplink) simulation, terminals are randomly positioned in the system area, and the radio channel between each base station and terminal antenna pair is calculated according to the propagation and fading models. To study different system load levels, base stations are randomly selected to be transmitting (or receiving) with an activity factor f ranging from 5 to 100%. In cells with active base stations, a single receiving (or transmitting) user is selected independently of channel quality. This models channel independent time domain scheduling, e.g. round robin. The total number of active users for activity factor f is denoted $U(f)$. Based on the channel realizations and the active interferers, a signal-to-interference and noise ratio (SINR) is calculated for each terminal (base station) receive antenna. Using the mutual information model of [14], the SINR values are then mapped to active radio link bitrates R_u, for each active user u. In the case of MIMO, R_u is modeled as the sum of the rates achieved per MIMO stream. Note that R_u is the bitrate that user u gets when scheduled. The bitrate experienced above the MAC layer, after sharing the channel with other users, is denoted user throughput S_u. According to processor sharing theory [15] this can be calculated as

$$S_u = R_u(1\text{-}f). \tag{1}$$

Active base stations and users differ between iterations, and statistics are collected over a large number of iterations.

For each activity factor, the served traffic $T(f)$ is calculated as the sum of the active radio link bitrates for the active users

$$T(f) = \sum_{u=1}^{U(f)} R_{\mathrm{u}}. \tag{2}$$

This assumes that user are scheduled an equal amount of time. The mean and the 5th percentile of the user throughput are used as measures of average and cell-edge user quality respectively. Note that as the activity factor increases, individual user bitrates decrease because of increased interference and thereby decreased SINR, and less frequent access to the shared channel. The served traffic however increases as the number of active users increases.

IV. NUMERICAL RESULTS

Fig. 1 and Fig. 2 show the mean and 5th percentile (cell-edge) downlink user throughput (S_u) versus served traffic (T) for a Typical Urban (TU) channel. It is seen that as compared to the basic WCDMA system, the LTE system yields signifi-

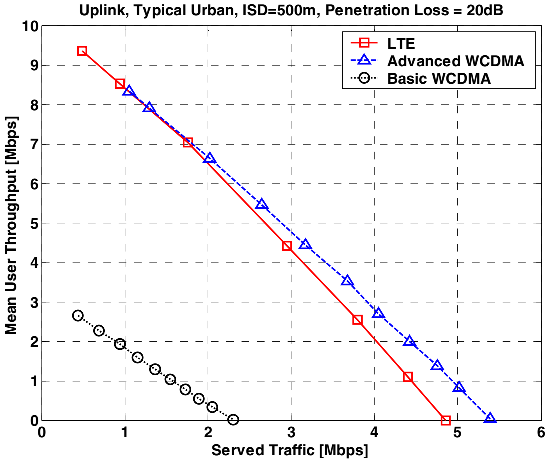

Figure 5. Mean user throughput versus served traffic, TU channel

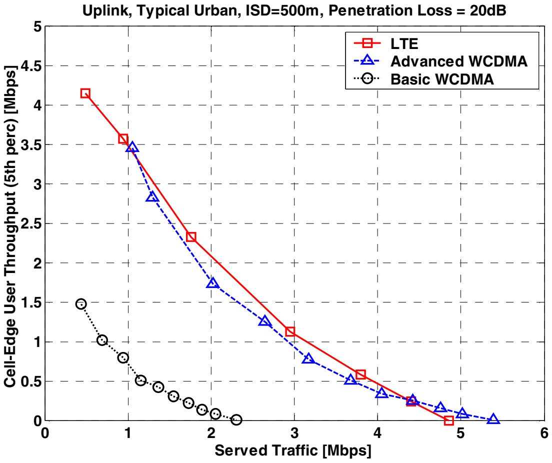

Figure 6. Cell-edge user throughput versus served traffic, TU channel

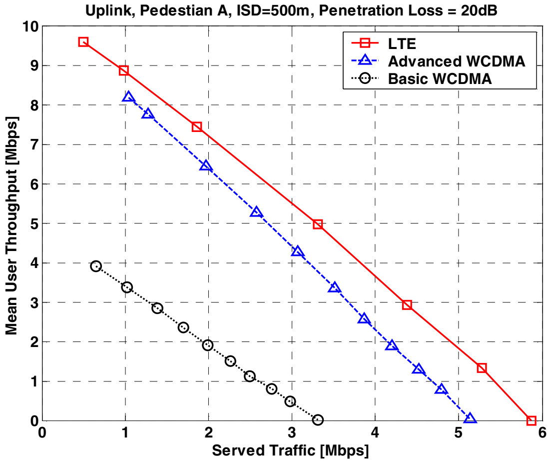

Figure 7. Mean user throughput versus served traffic, Ped. A channel.

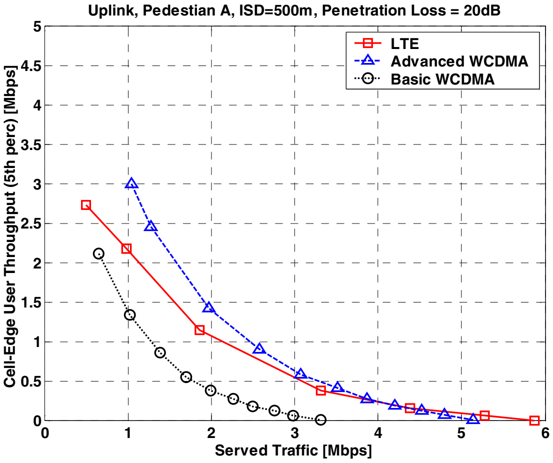

Figure 8. Cell-edge user throughput versus served traffic, Ped. A channel

cantly improved user throughput for both average and cell-edge users. The advanced WCDMA system however performs almost as well as the LTE system.

More specifically, looking at the 3GPP requirements, improvements in mean and cell-edge user throughput can be estimated by comparing the throughputs achieved by the different systems at the same traffic load. It is seen that a mean user throughput gain (G_{mean}) of the required factor three is achieved for the range of studied traffic loads. For example, at a served traffic of 2Mbps per sector, basic WCDMA achieves a mean user throughput of about 2.5Mbps, as compared to about 18Mbps for LTE. Note that the advanced WCDMA system here reaches 15Mbps. The large difference is due to a double effect of the faster links of the LTE and advanced WCDMA systems: (i) for a given SINR a higher throughput is achieved, and (ii) for the same served traffic, this results in a lower link utilization, and thereby less interference. Also the cell-edge throughput gain ($G_{cell\text{-}edge}$) exceeds the targeted factor two for the range of traffic loads. Spectrum efficiency gains ($G_{efficiency}$) can be estimated by comparing the served traffic for a given requirement on cell-edge throughput. For example, for a cell-edge throughput requirement of 1Mbps, basic WCDMA can serve some 2.5Mbps per sector. The corresponding number for LTE is 8Mbps, i.e. more than a factor three higher. For lower cell-edge throughput requirements however the requirement is not met. In a fully loaded network, the served traffic is about 4Mbps and 9Mbps for basic WCDMA and LTE respectively, i.e. only a gain of a factor two.

Fig. 3 and Fig. 4 show similar results for a Pedestrian A channel. For this less time dispersive channel WCDMA systems perform better, especially the basic system, whose simple receivers suffer more from time dispersion. Despite this, gains of the targeted factors three and two are achieved in mean and cell-edge user throughputs respectively. A gain in spectrum efficiency of a factor three is also achieved provided that the cell-edge user throughput requirement is at least 2Mbps.

Uplink results are presented in Fig. 5 and Fig. 6 for a Typical Urban channel and in Fig. 7 and Fig. 8 for a Pedestrian A channel. It is seen that the requirements of a factor two in mean user throughput are met and exceeded. The cell-edge throughput requirements are also met, but with a smaller margin for the Pedestrian A channel. The spectrum efficiency target is not met for the Pedestrian A channel. This is partly due to lack of soft handover.

Although based on simple models and excluding higher layer protocol improvements, the results indicate the high potential of LTE and advanced WCDMA/HSPA to improve user quality, capacity and coverage, thereby reducing overall infrastructure cost in both coverage and capacity limited scenarios.

V. CONCLUSIONS

Promising technologies to fulfill the requirements of the long-term 3G evolution include an AML-OFDM-based physical layer supporting multi-antenna solutions, which together enable high bitrates and high capacity. Performance results indicate that the concept including the proposed technologies indeed fulfill the 3GPP targets on user throughput and spectrum efficiency. These requirements are partly formulated as relative comparisons to a rather basic WCDMA system. A more advanced WCDMA system, employing MIMO and GRAKE receivers, reaches performance similar to that of the LTE concept. The LTE physical layer does however have benefits in terms of broadcast, spectrum flexibility, and the possibility for frequency domain adaptation. The LTE concept is not limited to the physical layer. Architecture and higher-layer protocol enhancements are also included. These are equally applicable to LTE and WCDMA/HSPA.

In summary, it should be noted that many of the improvements in the 3G LTE also will be applied in the WCDMA/HSPA evolution, and that the 3G evolution will include both HSPA and the new LTE physical layer.

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