Computer Communications 33 (2010) 1894–1906

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

LTE, the radio technology path towards 4G

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ARTICLE INFO

Article history:
Available online 7 July 2010

Keywords:
EUTRA
LTE
Radio Access Network
Radio Resource management
Performance evaluation

ABSTRACT

Evolved Universal Terrestrial Radio Access (EUTRA), known as the Long Term Evolution (LTE) technology, brings cellular communication to the fourth generation (4G) era. In this article, we discuss the most important characteristics of LTE; its simplified network architecture which allows ultimate means for adaptation of the radio transmission to the Internet packet traffic flows and to the varying channel states. LTE radio resource management is based on time–frequency scheduling, fast feedback between the transmitter and receiver, and nearly optimal adaptation of transport formats. Yet, the radio system is simple and cost efficient to manage from the evolved packet core network, having a server architecture with IP tunnels. The mobility states and resource allocation allow power save operation of the User Equipment when not actively communicating. In addition, we brief the key results on the LTE baseline performance for paired and unpaired frequency bands, i.e. the two duplex modes.

1. Introduction

The term “Long Term Evolution” (LTE) stands for the process to generate a novel air interface by the 3rd Generation Partnership Project (3GPP), and for the specified technology. Earlier, the 3G Wideband Code Division Multiple Access (WCDMA) provided a new, high capacity, air interface including transport of packet traffic, and the Radio Access Network (RAN) designed to be compatible with the second generation GSM and GPRS core networks. WCDMA allows multiplexing of voice and variable rate data services, and its evolution to High Speed Packet Access (HSPA) [1,2] further enhances the high rate packet capabilities as a set of new transport channels.

LTE was initiated as a study item and its technical requirements were agreed in June 2005 [3]. The targets of LTE included reduced latency, higher user data rates, improved system capacity and coverage and reduced cost of operation. LTE was required to become a stand-alone system with packet-switched networking. The study item was reported the first time in the technical report [4], where it was decided that LTE is based on a new air interface, different from the WCDMA/HSPA enhancements. The actual specification work resulted in a complete set of approved standard specifications [1,5] that are mature enough for product implementation. The evolution of the LTE system, its architecture, protocols and performance are described widely e.g. in [6–9].

The salient characteristics of LTE are as follows: a flat architecture based on distributed servers, LTE base stations having transport connections to the core network without intermediate RAN network nodes (such as radio network controllers). Simplified and efficient radio protocols, where channel state information is available at the radio protocol peers to optimize the access and to minimize the overhead. A physical layer design favouring frequency domain processing for efficiency, enabling high data rate transmissions e.g. by multiantenna transmission methods, and alleviating interference conditions by intracell orthogonality. Radio resource management enabling scalability of transmission bandwidth (BW), and a high degree of multiuser diversity e.g. by time–frequency domain scheduling. Efficient operation in power saving modes as a designed fundamental property of the User Equipment (UE).

In this paper, we discuss LTE technology and how its solutions will meet the targets that were set for the International Mobile Telecommunication (IMT) systems. Even more, LTE meets the targets also for IMT-Advanced [10] in certain evaluation scenarios, and is the foundation of new releases of LTE specification [11], aiming to meet the IMT-A local area environment targets. The 3GPP approach to 4G systems is thus based on LTE.

The paper is organized as follows: The architecture of LTE is discussed in Section 2 and the protocols in Section 3. The physical layer solutions are presented in Section 4, and the Radio Resource Management principles in Section 5. System performance results are briefed in Section 6 and the paper is concluded in Section 7.

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doi:10.1016/j.comcom.2010.07.001

2. LTE architecture

2.1. UE states of operation

In LTE, the UE may operate in two states, the LTE_Idle or the LTE_Active state, in relation to the *non-access stratum* which connects the UE and the core network. In the radio access network, these correspond to the Radio Resource Control (RRC) states RRC_Idle and RRC_Connected, respectively [1]. The mobility state machine is considerably simplified from 3G/WCDMA UTRAN (with at least four states). Discontinuous transmission and reception modes apply to both states, enabling efficient UE power saving.

In the LTE_Idle state, the location of the UE is not known at cell accuracy. The UE camps on the system at the resolution of a Tracking Area, consisting of a large number of sites, applying the cell_reselection (or cell_change) procedures. UE mobility is controlled by the core network. The UE may initiate activity by a random access procedure and the network may request UE activity by a paging procedure. The random access parameters and paging cycles are indicated in a broadcast channel, which is scheduled to allow power saving and appears frequency multiplexed with a shared data channel.

When becoming active, the UE gets a cell Radio Network Temporary Identity (c-RNTI) for resource allocations and scheduling by the serving base station. After having the c-RNTI granted, the UE changes into the RRC_Connected state, and it may attach and register to the core network, which changes the UE to the LTE_Active state. The procedures will setup the default bearer to the core network and establish transport tunnels between the base station and the serving gateway. At the UE request, the network will have a primary context openend to the gateway, and the procedure completes the IP connectivity of the UE to the Internet. In the LTE_Active state, the mobility procedures and handover are executed for seamless operation. However, parametrised discontinuity periods may be defined at the air interface, which means that the UE is mandated to decode the downlink signalling channels only at given subframe intervals instead of every subframe. This allows significant power saving opportunity for the UE also while in the active state.

2.2. Evolved packet system

The system architecture evolution of the Universal Mobile Telecommunications System (UMTS) is called the Evolved Packet System (EPS) [1,8]. It operates fully in the packet domain and allows the LTE base station (evolved NodeB, eNodeB) route both control plane and user plane packets via the IP tunnels to the core network. The Mobility Management Entity (MME) operates in the control plane and handles idle mode mobility, paging, authentication and bearer setup procedures. MME contacts Home Subscriber Server (HSS) for subscriber information, and it is capable of storing the UE mobility context with cellular identifiers (Temporary Mobile Subscriber Identity, S-TMSI) and IP addresses. The architecture of LTE and the interfaces of the EPS are shown in Fig. 1.

In the user plane, the eNodeB packet routing and transfer functions implement the EPS bearer and connectivity to the serving Packet Data Network (PDN) gateways. These gateways have connectivity and routing capability of the Internet, and they contain the Packet Data Protocol (PDP) context that the UE requests to be opened and configured for service connectivity and quality of service (QoS) handling. QoS functions are applied on the PDP context ports, where they may provide subscriber differentiation or traffic differentiation by the QoS parameters of the EPS bearer. The QoS traffic classes are commonly known as conversational, streaming, interactive and background treatment classes.

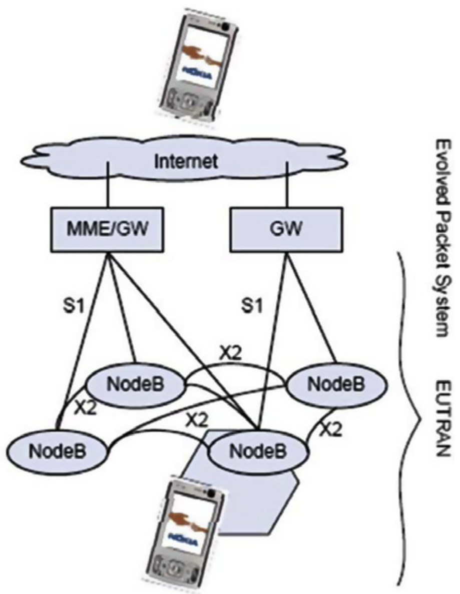

Fig. 1. EUTRAN architecture and interfaces.

2.3. LTE interfaces

LTE provides a simplified architecture compared to UTRAN, because macro diversity gains are not relevant in EUTRAN, and hence a centralized radio controller is not needed. Thus all decisions related to communication over the air interface are taken at a transmitting or receiving network node, making ultimate adaptation both to traffic and channel conditions possible. Control plane communication is executed as the application protocol over the S1-interface between the serving eNodeB and the MME. User plane communication is executed as the transport protocol over the S1-interface between the eNodeB and the serving gateway.

In LTE, fast handovers are necessary because of the lack of macro diversity, which may cause the Signal to Interference plus noise ratio (SINR) suddenly decrease due to UE moving at high velocity. Therefore, an interface called X2 is defined between the eNodeBs. An application protocol may be run over the X2 for handover preparation and execution, and to control transfer of the user plane packet buffers between the eNodeBs at handover. Also Inter-cell Interference Coordination may be performed over X2. The signaling solution between eNodeBs appears much lighter compared to the control and reconfiguration of the transport by a centralized node.

2.4. Addressing

Internet addressing in EPS is implemented either by IP version 4 (IPv4) or IP version 6 (IPv6) or both. This is known as the dual-stack approach, and sufficient network support exists to operate with both formats. The key principle is always-on IP connectivity for the UE (users), which is enabled by the default EPS bearer that is established already during the Initial Attach procedure.

The default EPS bearer is established, whenever the UE switches from the LTE_Idle state to the LTE_Active state and connects to a PDN i.e. opens the PDP context. Additional EPS bearers that are established to the same PDN are referred to as a dedicated EPS bearers. The PDN gateway selection function uses subscriber information to allocate the PDN gateway that is favoured for the UE in its mobility context, or the PDN is selected from the PDN pool area e.g. by taking network load into account.

2.5. Quality of service

In EUTRAN architecture, QoS is provided by the Differentiated Services (DiffServ) mechanisms, PDP context procedures, transport tunneling and EPS bearer parameters.

The default PDP context does not provide QoS differentiation. It offers a context port for Session Initiation, for TCP request/response messages, and possibly best effort services. Any number of secondary PDP contexts may be opened for defined QoS classes.

EPS bearer parameters are defined in [1,8] and are shortly discussed below. QoS Class Identifier (QCI) is the primary parameter of EPS bearer quality. It controls bearer level packet forwarding treatment e.g. scheduling weights, admission thresholds, queue management thresholds, link layer protocol configuration that have been preconfigured by the operator, who owns the eNodeB. These QCI characteristics describe the packet forwarding treatment in terms of resource type i.e. guaranteed or non-guaranteed bit rate, priority, packet delay budget and packet error rate. In LTE, these values are valid to ensure that applications (services) mapped to a QCI get the same QoS through the entire delivery over the EPS, even in a multivendor deployment.

Example services of different QCI values include conversational voice, conversational video, streaming, real-time gaming, IMS signalling, interactive gaming, interactive web browsing, as well as best effort traffic applications running on Transmission Control Protocol (TCP) like email, chat, ftp and rich media [12]. On the radio and S1-interfaces, each packet is indirectly associated with one QCI via the bearer identifier.

Allocation and Retention Priority (APR) takes an action only for the bearer establishment and modification, occasionally also for bearer dropping. Once successfully established, ARP has no impact on packet level forwarding (e.g. scheduling and rate control). Each EPS bearer may have additional parameters for the Guaranteed Bit Rate (GBR) and for the Maximum Bit Rate (MBR). All non-guaranteed bit rate services have instead the Aggregate Maximum Bit Rate (AMBR) parameter that applies to a group of EPS bearers that share the same PDN connection and which may share capacity dynamically.

3. EUTRAN protocols

EUTRAN radio protocols and their peer-to-peer relationship are shown in Fig. 2. EUTRAN architecture includes the Radio Resource Control (RRC) protocol in the control plane for radio resource management functions, see Section 5. In the user plane, EUTRAN includes the Packet Data Convergence Protocol (PDCP) which handles the Internet packet buffers and is terminated in the eNodeB. This architecture allows coupling of the segmentation decisions not only to the packet (SDU) sizes of traffic flows in the Internet but also to the channel state information, short term channel dependent scheduling decisions and transport format adaptation. Flexible segmentation tends to minimize the overhead in providing the best fit of the packet sizes in the queue to the best fit of the transport block size. Transport channel switching (see UTRA) is neither a problem, because LTE transport resources are shared for all logical channels of a UE. For voice and video packets, segmentation is preferably avoided completely. This creates less protocol overhead and allows strict scheduling that satisfies the packet delay requirements of the real-time transport. For data packets, segmentation is preferably tailored to the amount of data in the transmission buffer rather than to the size of individual packets. This creates less overhead per packet and allows scheduling by greed throughput weighting algorithms.

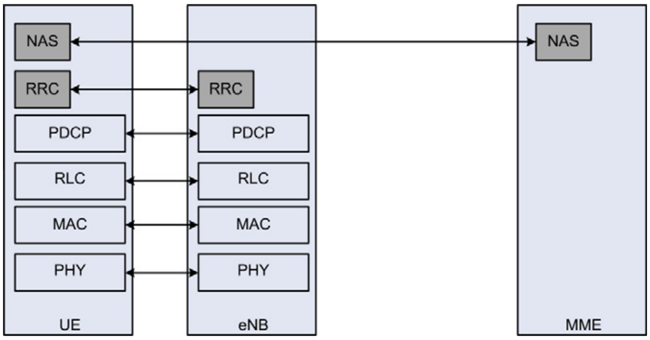

Fig. 2. Radio protocols and their peer-to-peer relationship in LTE.

The efficiency of EUTRAN is reached mainly by the protocol architecture and logical channel flow of layer 2, in addition to the advanced physical layer processing. The structure of layer 2 processing in the User Equipment is shown in Fig. 3. The physical layer provides signal processing algorithms for the transmitters and receivers, where the computation is executed in the transform domain. Layer 2 protocols enable the presence of channel state information in all critical decisions of segmentation, scheduling, and transport format selection.

Header compression at the PDCP may be critical for the voice service, which is delivered as Voice over the Interent protocol (VoIP). The voice packet payload is small compared to the large networking headers generated by Real-Time Transport Protocol (RTP), User Datagram Protocol (UDP) and the IP Protocol. Header compression avoids regular transmission of redundant (or static) header fields, whose contents can be saved to the compression context instead. At each packet interval, only dynamic parts of the header are transmitted, i.e. at least the Sequence Number of RTP. When packet sequences are irregular due to Internet, longer information fields have to be transmitted, whereas during good regularity, a single byte dynamic field is sufficient. For IPv4 in general and for IPv4 or IPv6 for video packets, the need for header compression is disputable, because the ratio of the payload and networking headers is not as dramatic as for VoIP with IPv6. Also for TCP/IP sessions, header compression is typically used, because the header information is static and its compression context does not have any of the complexity present for the dynamic IP/UDP/RTP protocols of VoIP.

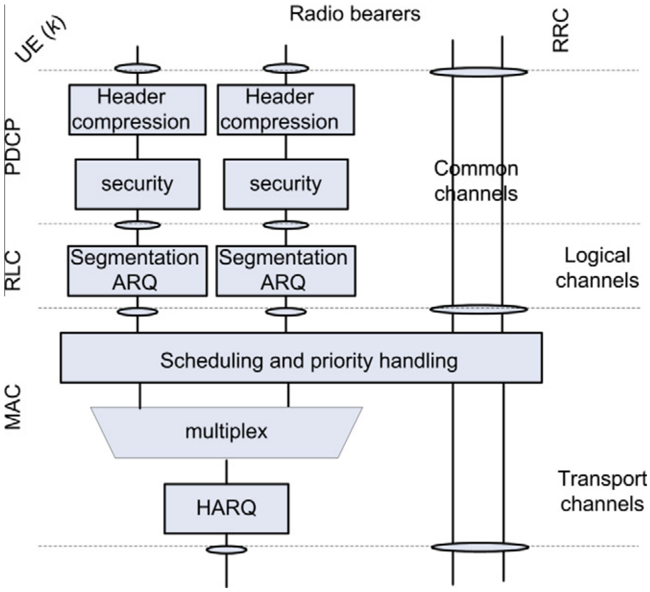

Fig. 3. The structure of Layer 2 processing in the User Equipment.

In EUTRAN, security is also implemented in the PDCP layer, because it guarantees long sequence numbers for packets, which may be preserved during handovers as well. This ensures security and yet enables each packet processed individually.

The Radio Link Control (RLC) protocol handles segmentation and windowing of packets. It further takes care of SDU retransmissions whenever requested, in case physical layer retransmissions are not sufficient. Proper RLC parametrisation may reduce the probability of (end-to-end) TCP retransmissions, which are slow and are known to have a dramatic impact on TCP flow management and network loading. In contrast, the impact of RLC remains local to the radio interface.

The Medium Access Control (MAC) and the physical layer of EUTRAN are fully different from those specified for 3G/UTRAN. The OFDMA and SC–FDMA techniques of LTE enable fast channel dependent scheduling both in the time and frequency domains at high resolution, comparable to the coherence time and bandwidth of the channel. MAC implements scheduling on one hand by quality and priority requests of the traffic flows from the higher layers, and on the other hand from the fair and efficient share of instantaneous physical resources relative to the channel conditions.

Transport format adaptation provides instantaneous optimization of expected throughput relative to the channel conditions. Link adaptation includes the choice of modulation alphabet, the choice of effective code rate per payload, as well as retransmissions with combining of code blocks. These adaptive algorithms have the capability to tune the instantaneous throughput relative to the channel state information, and provide tolerance to the Block Error Rate (BLER) variation by a flexible amount of retransmissions. The expense of retransmissions is an increase of packet delay as a function of the number of requested transmissions for the correct decoding of the code block. The retransmissions of EUTRAN are very fast (in minimum cycles of 8 ms) and the scheduler may decide to use retransmissions outside channel coherence by changing the frequency of allocated resources for the retransmissions.

4. Physical layer

In this section, we discuss the main principles of LTE physical layer design, which lead to new Radio Resource Management (RRM) opportunities that are significantly different from the ones applied in GSM and WCDMA/HSPA. LTE is primarily optimised for slow moving users in a wide coverage area. The leading principle is to solve intersymbol and in-cell interference problems that limit the high data rate coverage of the WCDMA/HSPA.

Downlink WCDMA/HSPA ideally provides orthogonal transmission of channelization codes. In practice, however, orthogonality is partially lost after multipath propagation. Uplink WCDMA/HSPA is designed to be in-cell non-orthogonal. LTE keeps in-cell orthogonality both for downlink and uplink even in a multipath propagation environment, because the channel dispersion is contained in the signal extension part of the received symbols. For this, the multiple access design is based on in-cell orthogonality and cyclic signal extensions, which enable frequency domain processing—in particular, frequency domain equalization is important for efficient and accurate computation. This design further enables the use of advanced multiantenna techniques because the spatial processing can be done in a frequency selective manner.

Reflecting the optimization criteria for slowly moving users, the multiple access scheme and the multiantenna techniques enable extensive use of instantaneous channel state information at the transmitter.

4.1. Channel characterization

LTE is optimized for wide area deployments. Most importantly this means large delay spreads [13] and severe frequency selective fading. Thus in LTE design and in performance evaluation, channel models with large delay spreads have been considered [4]. One example is the Typical Urban (TU) channel, which has a relatively long delay spread corresponding to a path length difference of 1.5 km between the longest and the shortest transmitter–receiver path. The coherence bandwidth is respectively about 200 kHz. The impulse response and an example power profile in frequency domain are depicted in Fig. 4.

Three evaluation scenarios in [4] are for mobile speeds of 3 km/h and one for 30 km/h, corresponding to coherence times of ≈ 100 ms and 10 ms respectively. These assumptions allow significant gains from using instantaneous channel state feedback.

4.2. Cyclic prefix

For WCDMA/HSPA, time-domain equalization turned out to be a computational challenge. Transversal filter chip equalizers never provide perfect equalization. Combined with inaccuracy in channel estimation this leads to throughput loss, especially in frequency selective channels with high SINR. Frequency domain equalization, inherent in LTE, is preferable due to efficient implementations of the Fast Fourier Transform (FFT).

Adding a Guard Interval between the blocks of transmitted symbols is an effective way of cutting the intersymbol interference, as long as the Guard Interval is longer than the delay spread of the channel. Furthermore, filling the Guard Interval with a Cyclic Prefix (CP) of the symbol block enables an orthogonal transform to the frequency domain. A CP is a copy of the samples at the end of the symbol block, see Fig. 5. The CP makes the signal inside a receiver window a cyclic convolution of the transmitted signal and the channel. This is visible in Fig. 5 in that the two-path received signal is periodic over the block length inside the receiver window. Cyclic convolutions lead to computationally effective equalization because they can be diagonalized with the Fourier transform. Accordingly, transforming a block of received signal samples to the frequency domain, inter-symbol interference can be perfectly removed with a single-tap frequency domain equalizer.

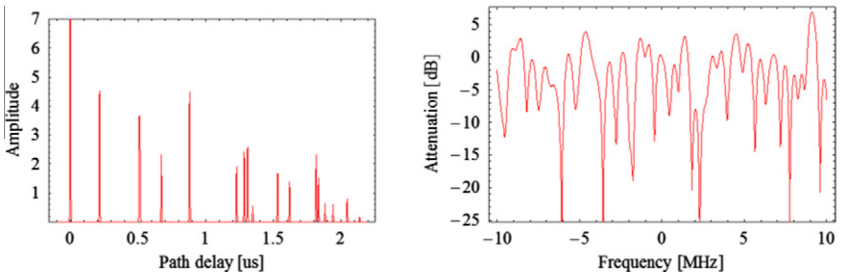

Fig. 4. The absolute value impulse response of the Typical Urban Channel and an example power profile over an LTE band.

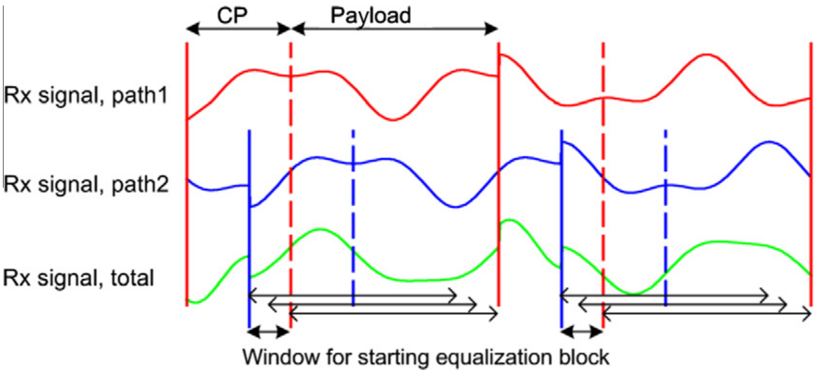

Fig. 5. Example of received signal for transmission with Cyclic Prefix in a two-path channel.

To benefit from this property, LTE applies a cyclic prefix in both downlink and uplink block transmissions formats, solving the Inter-symbol Interference problems pestering high rate HSPA transmissions. Chip equalization of long, multipath propagated sequences in time domain is in general a more complex and inaccurate operation than the equalization of a periodic signal in the frequency domain.

4.3. Downlink: OFDMA

LTE downlink modulation is based on multicarrier transmission of subcarrier signals, i.e. Orthogonal Frequency Division Multiplexing (OFDM). As long as the channel delay spread remains within the CP, the subcarriers are orthogonal. In the transmitter, the subcarrier signals are generated in the frequency domain by an Inverse FFT. In the receiver, FFT is used, after discarding the CP, to recover the transmitted signals. In LTE, the data of different users is multiplexed in the frequency domain, and accordingly the downlink is characterized as Orthogonal Frequency Division Multiple Access (OFDMA).

4.4. Uplink: SC–FDMA

LTE uplink is designed to be in-cell orthogonal. This is contrary to the WCDMA/HSPA uplink, which is non-orthogonal and targets at randomizing the intracell interference by long scrambling sequences. Non-orthogonal multiple access is in theory superior to orthogonal, if ideal multiuser detection is used. However, channel estimation imperfections limit the multiuser efficiency, especially at high load and high SNR, see e.g. [14]. 3GPP systems have been traditionally designed for full load, see e.g. evaluation principles in [4]. Accordingly, investing in multiuser detection would not pay off, when the target is high user data rates in a high load system. Also, we shall see in Section 6, comparing LTE uplink to a non-orthogonal uplink with a conventional (RAKE) receiver, that the gains from reduced interference due to in-cell orthogonality are greatest for cell edge users.

Another important feature underlying the selection of the LTE uplink transmission technique is the need to sacrifice power and symbol resources for the channel estimation. Spreading the transmission over the whole bandwidth is not sensible for transmitters with limited power resources—the wider the bandwidth, the larger the overhead needed for the pilot signals.

Together with the bandwidth flexibility target of LTE, these arguments lead to selecting Frequency Division Multiple Access (FDMA) as the basis for uplink user multiplexing. To keep the peak-to-average power ratio small, a Single Carrier transmission format was adopted. In this respect, LTE uplink returns to the GSM principle of utilizing power efficient modulation, which was partially sacrificed in uplink HSPA. To solve the equalization problems, a Single Carrier FDMA (SC–FDMA) transmission format with a cyclic prefix was adopted. This allows for a power efficient modulation, yet equalizable in the frequency domain [15]. If the transmitted signal is generated in the frequency domain, SC–FDMA can be interpreted as DFT-spread OFDMA.

4.5. Multiantenna techniques

Gains from multiantenna techniques remained a perennial promise in WCDMA/HSPA, but will become realizable in LTE due to the novel design of the physical layer. Multiantenna techniques are covered widely e.g. in [16].

Transmit diversity in WCDMA came in two flavours, open loop and closed loop transmit diversity. Open loop methods do not use channel information to adapt the transmission, whereas closed loop methods are based on adapting the transmission using suitable antenna weights, which are selected based on the feedback from the receivers. WCDMA transmit diversity has not proven to be too successful, and has been of little relevance for HSPA. First, open loop diversity does not combine well with greedy scheduling algorithms, which are of primary importance for the packet radio, see [17]. The reason for this is that open loop diversity methods reduce the effect of fading by reducing channel variability. In addition to removing deep fades, essential to improve performance in a circuit switched system, this removes cases when the channels are strong, which are the cases exploited by a greedy scheduling algorithm in a packet switched system. Second, the closed loop transmit diversity modes of WCDMA suffer from multipath propagation, which often makes the best transmission weight frequency selective. Using a single weight for the whole transmission band (5 MHz) to a user makes array gains small. Another reason for the poor performance of WCDMA closed loop diversity is that the feedback bits in WCDMA are without channel coding, so that they are prone to errors.

Spatial multiplexing Multiple-Input-Multiple-Output (MIMO) techniques were standardized for the HSPA downlink in Release 7. These schemes are based on the closed loop feedback, but the problems related to the WCDMA feedback quality were solved by protecting the feedback bits with channel coding.

At the receiver, OFDM allows separation of multipath (frequency domain) equalization and equalization in the multiantenna (spatial) domain, removing the main complexity obstacle for the use of advanced multiantenna methods in a frequency selective manner. First, related to receiver antenna processing, OFDM allows Maximum Ratio Combining (MRC) at the subcarrier level. Also Interference Rejection Combining (IRC), where interference is rejected in the multiantenna combiner in a frequency selective menner, is possible. If a spatial multiplexing transmission is used to increase the date rate, subcarrier-by-subcarrier spatial equalization enables almost optimum performance with realizable complexity.

LTE downlink multiantenna transmission may happen from one, two or four antenna ports. The transmission schemes come in three flavours.

- Open loop transmit diversity.
- Closed loop spatial multiplexing (including closed loop transmit diversity).
- Open loop spatial multiplexing.

LTE open loop transmit diversity is intended for control channels, and to increase the coverage for fast moving users—the problems indicated in [17] have not changed since HSPA.

Closed loop spatial multiplexing of the LTE OFDMA solves the inherent problems of WCDMA/HSPA closed loop transmit methods. OFDMA enables the use of narrowband, frequency selective, closed loop transmission weights, and LTE further enables reliable feedback with channel code protection against errors. In LTE, the feedback weights are called precoders, and the set of weights are called codebooks. The spatially multiplexed transmission streams are called layers. For closed loop spatial multiplexing, matrix codebooks have been defined for two and four transmit antennas with the number of layers ranging from one up to the number of transmit antennas. Closed loop transmissions in LTE are realized based on Precoding Matrix Indication (PMI) feedback.

LTE open loop spatial multiplexing is based on a randomization principle, where the frequency selective interference and channel qualities of the multiple spatial multiplexing layers are averaged. It applies for fast moving users, for which feedback is unreliable due to latency, and when closed loop feedback overhead is considered too heavy.

4.6. Modulation and channel coding

The set of modulation alphabets used is a system design choice due the requirements posed on the implementation of the transmitter–receiver chain. The dynamic range, sensitivity and decoding complexity are key issues as well as requirements for the linearity, Error Vector Magnitude (EVM) and noise figure of the receiver.

In LTE, QPSK, 16QAM and 64QAM modulations may be used both in downlink and uplink. For amplitude modulated multicarrier symbols, the peak power varies depending on the instantenous choices of modulated symbols. In the eNodeB transmitter, where the linear range of the amplifier can be large, the power limiter cuts the highest power peaks to the wideband noise. The probability of the highest power peaks is fairly small due to a large number of modulated subcarriers, thus the power-density of the inband noise remains small, and 64QAM transmissions may be possible. In the UE transmitter, the linear region of the power amplifier sets constraints for the choice of modulation. In practise, uplink transmissions at least up to 16QAM are feasible. The benefits of 64QAM transmission are disputable, because its coverage-area probability remains small in mobile reception. For short range communications, it however may provide gain.

The channel codes used in LTE are convolutional and Turbo codes. Convolutional codes provide higher coding gain for small information blocks, e.g. in control signalling, whereas Turbo code [18] is best for larger information blokcs of high data rates. Low Density Parity Codes (LDPC) were studied as an alternative for LTE, but were not selected due to their rate matching properties [19]. Decoding complexity and decoding latency are critical for LTE receivers, especially when Turbo decoding is iteratively coupled to the channel equalizer with soft-decisions and if that is yet to be applied for multiantenna reception. This kind of receiver structure, however, provides superior decoding performance.

4.7. Numerology and frame structure

The radio parameters in LTE are designed to enable reliable equalization even in macrocellular environments with long delay spread. The downlink subcarrier separation was chosen to be 15 kHz, corresponding to a 66.7 μs symbol duration. A strong reason for this selection of parameters is the compatibility with WCDMA—there is a rational relationship between the 15 kHz clock and the WCDMA clock. The same symbol duration is used in uplink.

Reflecting the packet optimization of LTE, there is Time Division Multiple Access (TDMA) in both link directions. The unit of TDMA is a *subframe* of 1 ms. The structure of broadcast and synchronization channels is determined in terms of radio frames consisting of 10 subframes. In typical environments, there are 14 symbols per subframe, leaving ~ 4.8 μs for the CP. This corresponds to a typical wide area environment with about 1.5 km path length differences. In harsh environments with very long delay spreads, an alternative subframe format is available with 12 symbols and 16.7 μs CP.

Instead of suffering from multipath-induced frequency selectivity, LTE turns it to an opportunity. For this, the radio resources have been divided into *Physical Resource Blocks* (PRBs) of 180 kHz (12 downlink subcarriers). This is roughly the coherence bandwidth in a typical urban environment.

The basic unit of allocating frequency resources in LTE is the PRB. User scheduling, Channel Quality Indication (CQI) and precoding feedback may happen at the accuracy of a PRB, enabling multiuser diversity in the frequency domain. When reliable frequency selective information is not available, *distributed* frequency domain transmission is possible. This is realized by in-band frequency hopping, the transmission hops from one PRB to another in the middle of a subframe. This yields frequency diversity of diversity order two, which was considered sufficient for a packet radio system—LTE has in addition time diversity due to HARQ, and receive diversity due to the multiple receive antenna elements.

The downlink subframe shown in Fig. 6 consists of a control region and the shared channel. The control region is parametrizable from one to three symbols and the shared channel spans over the rest of the subframe. The control region is time-multiplexed in order to shorten the reception time of the control signalling. This allows shorter roundtrip times due to shorter delays in starting shared channel processing. Also, power saving of the receiver is enabled, whenever there are no PRBs to decode. The reference symbols (RS) are multiplexed to the time–frequency symbol positions in an interlaced manner. The control region of the subframe includes the code blocks of the control channels for all downlink and uplink allocations of all UEs in that subframe. The code blocks are separately formed for each signalling entity of an allocation. Every code block present in the control region of the subframe is dispersed over the full bandwidth in the form of control channel elements and their coded aggregations to maximize the frequency diversity of each signalling code block.

The uplink subframe shown in Fig. 7 consists of the control channels and the shared channel. These are frequency multiplexed to the subframe. In one subframe a UE transmits on only one of these channels. The motivation for frequency multiplexing is to provide large coverage by having continuous transmission, and by containing all transmit power of the UE to the allocated PRBs. The demodulation reference symbols (DMRS) are time-multiplexed to the given symbol positions in the allocated PRBs, in order to maintain the single carrier transmission property for any adaptive transmission bandwidth. The souding reference symbols

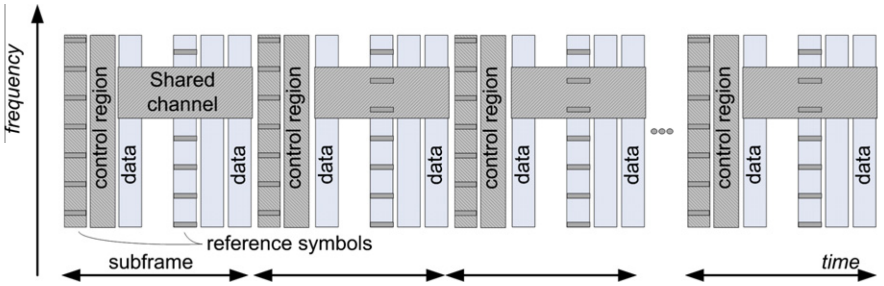

Fig. 6. The downlink subframe structure with the control channels and frequency selective shared channels.

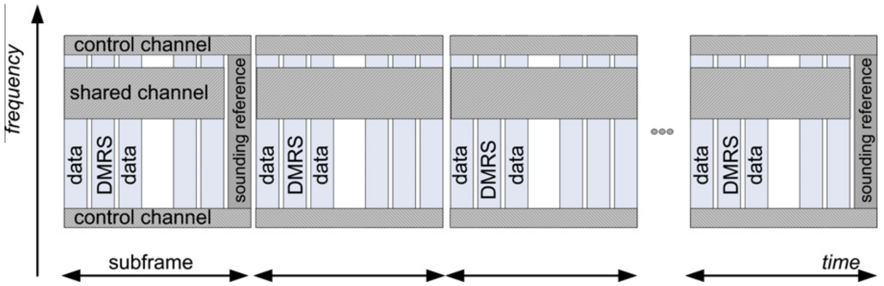

Fig. 7. The uplink subframe structure with the control channels and frequency selective shared channels.

represent a defined measurement bandwidth during the last symbol of the subframe. (see Fig. 8)

A transport block on the shared channel consists of the symbol resources in all those PRBs that are allocated to a user in the data region. If spatial multiplexing MIMO is applied, there may be at most two transport blocks, known as codewords (CW), transmitted to a user per subframe on the up to four MIMO layers. Spatial multiplexing re-uses the same symbol resources for the two transport blocks.

4.8. Bandwidth and duplexing

The system bandwidth in LTE is flexible. An LTE system may be deployed in any of the variants of 1.4, 3, 5, 10, 15 and 20 MHz bandwidth. The corresponding number of PRBs are 6, 15, 25, 50, 75 and 100. The bandwidth efficiency for all but the lowest bandwidth alternative is 0.9, which compares favourably with 0.78 of WCDMA/HSPA. The improved efficiency is due to improved frequency domain filtering enabled by the robustness against intersymbol interference.

Bandwidth flexibility impacts the cell detection, synchronization and access procedures. To keep these procedures independent of the variable system bandwidth, the synchronization channels and system broadcast information are condensed to the six PRBs at the center of the carrier. The synchronization sequences appear at constant time intervals, periodic in the 10 ms radio frame. A pair of primary and secondary sequences allows faster cell detection and forms a physical cell identity in the family of (504) codes. The cell identity informs the position of the reference symbols in frequency domain, needed for decoding of the primary system information block, which indicates the system bandwidth and the system frame number. The consequent system information blocks follow a system information schedule that scales in time and frequency as needed but whose size and contents remain constant over a long period.

LTE has two duplex modes that fit the transmission either to paired band allocations having downlink and uplink carriers separated by a duplex gap, or to unpaired band allocations having downlink and uplink on the same carrier frequency but at different frame periods. LTE design targets at commonality of protocols and processing blocks between the duplex modes. The main impact of the duplex modes is different interference conditions and different timing of signalling events.

In the Time Division Duplex (TDD) mode, the receiver may suffer from severe interference from a transmission in the opposite link direction. For example, a UE receiving a weak signal from a distant base station may be disturbed by another UE transmitting on the adjacent carrier with high power. These interference conditions typically require coordinated network designs so that transmission subframes and downlink–uplink switching periods are synchro-

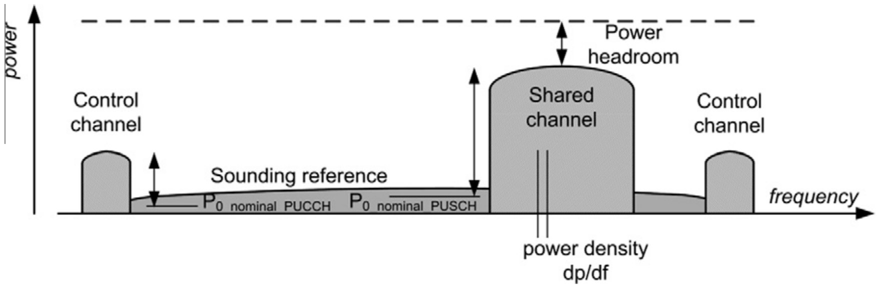

Fig. 8. Power Control in LTE uplink.

nized on adjacent carriers to the accuracy of a fraction of the cyclic prefix. This is most feasible inside a single operator network or if a common timing may be agreed between operators. An alternative is to arrange frequency isolation between time duplexed adjacent carriers of different operators. However, in small cells or in indoor propagation environments with wall isolation to distant signal sources, time duplexing interference conditions may be significantly alleviated. In small cells the power dynamics are smaller and power differences between transmissions accordingly smaller. Also good propagation isolation (walls) between wide area cells and local area cells alleviates interference conditions.

The implementation of time duplex UEs is considered less expensive, due to the need of less RF components. Time duplexing may further gain in multiple antenna transmission schemes due to channel reciprocity. Despite of its potential implementation benefits, time duplex mode suffers from increased latency over the air interface, and the potential risk of badly interfered channels remain.

5. Radio resource management

5.1. Power control

LTE power control applies to a burst transmission per subframe. As several UEs are multiplexed to the same physical downlink shared channel, there may be a UE specific power offset between the allocation and the reference symbols. In LTE uplink, the shared data channel transmit power of a UE is

$$P = \min\{P_{\max}, 10 \cdot \log M + P_0 + \alpha_{\mathrm{PL}} PL + \Delta_{\mathrm{TF}} + f\} \qquad (1)$$

where P_0 is the nominal power, M the allocated bandwidth, and Δ_{TF} the power headroom for the transport format used. Pathloss is fractionally compensated up to the factor α_{PL}, and finally a short term power adjustment f may be used, which may be an absolute or an accumulated relative update. The cell-specific and UE-specific control parameters may be defined by higher layer (RRC) signalling. The short term adjustment f may be given inside the signalling entry per allocation in the downlink shared control channel. The transmit power of the control channel is set in reference to the nominal power and relative to at least the pathloss and control channel signalling format. The transmit power of the sounding reference symbols is controlled relative to at least the cell specific shared data channel power reference, bandwidth and fractional pathloss.

5.2. Link adaptation

The link adaptation algorithm selects proactively the modulation and channel code rate, the rank (in downlink), and the transmission bandwidth (in uplink), that form the most feasible combination to maximize the instantaneous link throughput. In addition, adaptive retransmissions can be considered a reactive link adaptation function.

Link adaptation requires knowledge of the channel state at the receiver fed back to the transmitter in terms of Channel Quality Indication (CQI) and Rank Indication in downlink, scheduling grants in uplink, and acknowledgment bits in both link directions. The measurement delay, reporting delay and finite reporting resolution always have an impact to the accuracy of channel state information.

5.2.1. Adaptive coding and modulation

The link throughput is a function of the received signal quality and BLER of the decoded transport block. The selection of the modulation alphabet and code rate depend on the received SINR and the expected BLER. At high SINR, a high modulation order with a high code rate is possible, allowing a large transport block and a high instantaneous throughput. On the other hand, at low SINR, lower order modulation and lower code rates are applied.

The SINR behavior depends on the multiple-access technique, intercell interference mechanisms and transmission scheme (e.g. MIMO). The higher SINR is required, the smaller is its probability in a selective channel, and the smaller is the coverage area, where it can be experienced.

Rate matching is a further part of code rate adaptation, necessary to match the Information Block Length to the physical resource grid.

5.2.2. Rank adaptation

For high rate transmissions in downlink LTE, rank adaptation becomes necessary, i.e. selecting the number of spatially multiplexed MIMO layers. Acquiring a high rate using single stream 64QAM requires a diversity reception mode, where modulation symbol energy is summed at least from two antenna branches before decoding. If the transmitter has two transmission branches, better performance may be obtained by spatially multiplexing multiple 16QAM modulated symbols. Both 64QAM and multistreamed 16QAM require sufficiently high SINR and low EVM of the transmitter–receiver chain. Multistreaming additionally requires sufficiently high channel rank up to the number of streams.

LTE MIMO transmission indirectly benefits from frequency selectivity. When a transmission to a user is scheduled to the best set of resources for a the user, the subband SINR is increased compared to the wideband SINR. Therefore, frequency selective allocations act as an enabler for utilizing a high channel rank and gaining from MIMO.

For rank adaptive MIMO, the rank is selected in a wideband manner, but the precoding matrix selection may still be frequency selective. Precoding feedback may be provided per subband, with the subband smaller than the coherence bandwidth of the channel This yields significant gain in downlink throughput, but on the other hand it increases the channel feedback overhead of the reverse link.

5.2.3. Adaptive retransmissions

Automatic retransmission protocols (ARQ) with channel coding (HARQ) provide link adaptation by adding received channel power and symbol redundancy as increments of retransmissions. A target BLER may be reached at close to the optimal channel power with a small transmission delay. Retransmissions efficiently use channel resources, add time and frequency diversity and provide soft symbol combining gains. HARQ allows initial transmission at a higher nominal BLER and integrates channel power for correct decoding. Symbol vectors of retransmitted replicas are combined before decoding, providing soft combining gains. The transmitted replica can be modified, e.g. by changing the redundancy bits transmitted (incremental redundancy). For any HARQ combining scheme, the information block (i.e. the transport block) of transmitted instances is mandated to be bit-exact, even if the symbol mapping or code rate would adapt. The design choices of HARQ include Chase combining and Incremental Redundancy. Chase combining is favourable for its property of self-decodable transport blocks and minimum delay. Incremental redundancy is favourable for its increasing coding gain. For simplicity, the number of redundancy versions in LTE was reduced compared to WCDMA/HSPA, without a net impact on performance.

5.2.4. Adaptive transmission bandwidth

Adaptive Transmission Bandwidth (ATB), enabled by LTE uplink, is a further link adaptation method. Because of UE transmission power constraints, transmission power may get limited. When coverage is critical, the bandwidth has to be decreased to reach a sufficient symbol energy over thermal noise (E_s/N_o) at the receiver. Condensing the limited transmit power to a narrow subband increases power spectral density compared to a wideband transmission. ATB provides gains especially when transmission resources can be scheduled into subbands having good channel state and a higher than average SINR.

5.3. Inter-cell RRM

As the spectral efficiency requirements are very high, the target is to design RRM schemes which operate in frequency reuse one networks. This means that all carrier frequencies of the allocated bandwidth are available in all cells. This is not realized in the circuit switched TDMA systems, where convolutional forward error correction is in use, and the SINR requirement therefore is high. As a result, co-channel interference had to be avoided so that cells using the same frequency had to be at sufficient propagation distance and geographically neighboring cells had to avoid using the same frequency by increasing the reuse factor. This decreases spectral efficiency by the factor of the inverse of the reuse.

WCDMA and HSPA operate in frequency reuse one network, which is enabled by using turbo coding, together with the spreading and scrambling operations. Spreading makes it possible to distribute the transmission of a low information rate over a wide channel bandwidth using a long spreading code. Spreading adds processing gain and hence increases the symbol energy for the decision of an information bit in the decoder. In HSPA, however, spreading looses its gains in a multicode transmission. Scrambling randomizes cross correlation interference to resemble Gaussian white noise. It does not make the long term average interference smaller, but it reduces interference variation, which increases the reliability of decoding.

In LTE, the operation in deep negative SINR conditions is feasible by the cell-specific independently fading frequency components, link adaptation and frequency domain scheduling. All this means that even if the average wideband SINR is negative, some subband frequency components may have much higher SINR. Further, frequency selective interference, even if remaining high on a subband, may be rejected efficiently by multiantenna receiver techniques such as IRC, because the interference more likely arrives from a single dominant source to the subband. Wideband interference arrives typically from many sources, and rejection of many (non-dominant) interferers is known to require complex algorithms, and it does not gain as much compared to the rejection of a dominant interferer.

As a consequence, intercell radio-resource management is primarily left to the individual eNodeBs, and the system targets at high spectrum efficiency with reuse 1 operation.

5.4. Scheduling

In LTE, almost all resources may be dynamically scheduled in each subframe. The only exception is VoIP-optimization by semi-persistent scheduling. A flexible size transport block is generated per subframe and the scheduler acts both in time and frequency domains, see Fig. 9. LTE schedules in a high resolution of one subframe (1 ms) and one PRB (180 kHz). If accurate channel state information is not available e.g. due to high mobility, scheduling gains will reduce, but even then fast blind scheduling (e.g. block frequency hopping) may capture the gains of channel diversity. An example time–frequency scheduler function is

$$\mathbf{m}' = \arg\max_{\mathbf{m}}\{P_{\mathbf{m},b}(n)\}, \tag{2}$$

where $P(n)$ depends on the utility function of the scheduler, which includes the priority metrics. The user $\mathbf{m}'$ with the highest priority metric is selected among the candidate users $\mathbf{m}$ to be scheduled to physical frequency resources b during scheduling period n. Typical reference schedulers used for system evaluation are Round Robin schedulers and channel dependent Proportional Fair schedulers. Sometimes priority based QoS schedulers or delay constrained schedulers are used. In reality, the schedulers may have to include variety of priority metrics like weighting of users, weighting of traffic flows, weighting of perceived quality (e.g. delay) and fairness of resource use. The relative importance and aggressiveness of each criterion is subject to a set of scheduling policies. The utility function may consist of soft weighting algorithms and may further include tight constraints as cut-off values (e.g. voice packet delay).

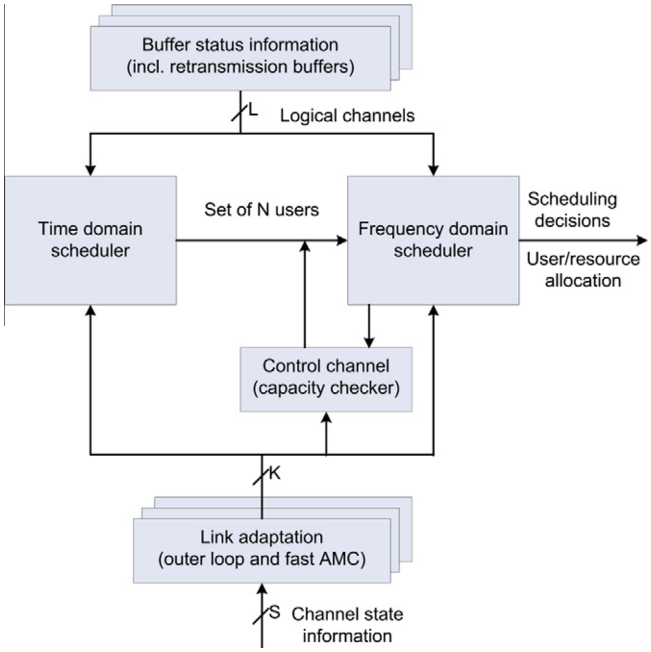

Fig. 9. Interaction of schedulers and link adaptation in the LTE radio.

5.5. Handover

In WCDMA, soft handover operates by adding radio links into the active set, which includes all cells (sectors) that transmit identical signals, up to cell specific scrambling, to be combined at the receiver. Soft combining of downlink signals is arranged in the network and executed in the UE receiver. Uplink signal combining is done in the network. Due to active set adaptation, the cell edge is typically at about 0 dB SINR. If SINR were below 0 dB, interference sources would be converted to signal sources. In order to avoid too frequent active set updates, handover margins and triggering thresholds are set both in terms of the received pilot power and triggering time windows.

In LTE, OFDMA combines multipath propagated signals inherently, as all signal energy windowed inside the cyclic prefix contributes additively in the Fourier transform despite of its relative propagation delay. For hard handover in a frequency reuse one network, the signals to be received may, however, reach a strongly negative SINR regime. Typically, the cell edge reception is assumed at about −5 dB SINR, and due to handover margins and delays reception at about −7 dB needs to be possible.

LTE handover is controlled by the network by the Handover Command procedure, and is assisted by the UE measurements. Hard handover happens locally between two cells and it does not require a long preparation phase, therefore it has less impact on the network procedures than the active set update of WCDMA.

HSPA transport channels in WCDMA may have similar hard handover as LTE. However, the performance difference of LTE to HSPA is large. Most of the cell edge performance enhancing mechanisms discussed in Section 5.3 do not apply to HSPA.

5.6. Power saving modes

The discontinuous transmission and reception scheme of LTE allows time multiplexed, parametrized windows (On Duration) for periods when a UE is mandated to decode subframes. Signalling for the UE may only appear in these subframes, and that signalling may initiate further activity. Power saving is possible, whenever the UE is not mandated to decode the control region of subframes. Lighter power saving is feasible during subframes, whose control region was decoded but where no allocations were indicated for the UE. Uplink traffic may be initiated by the random access procedure or by transmitting a scheduling request in the physical uplink control channel.

Because of the efficient power saving modes it is possible to switch the UE from the LTE_Idle state to the LTE_Active state and stay always-on. This means that after the initial network access (Attach procedure), the PDP context, the EPS default bearer and the IP transport tunnels can be established. This provides readiness for communication between the UE and the PDN gateway. Any higher layer signalling (seen as user plane traffic) or initiation of traffic can be delivered via the EPS default berarer. More PDP contexts may be opened for different media types, and additional dedicated EPS bearers may be activated when QoS differentiation is needed.

6. System performance

In this section, baseline performance is given for LTE as the cumulative throughput experienced in a cellular network serving multiple users per cell. Baseline here means that moderate antenna configurations are used at the base station sites, and the UE capability includes two receive antennas. Multiuser MIMO technologies, enabled by the LTE control channel structure, are not used. These technologies have an effect on the cell throughput, as select resources may be non-orthogonally used by multiple users. The schedulers work on the best effort full load, which allows a fair metric of system throughput converted to the measure of spectral efficiency. This type of analysis also reveals fairness among the served UEs. When special emphasis is placed on the cell edge user throughput, the mean throughput will not reach its highest value. In cellular networks, cell edge performance is often valued because it is the most challenging regime of signal processing and signalling, and the region where the interference limitation of cellular networks is most strongly felt. For a uniform geographical user distribution, relatively large number of users get served at cell edge areas.

6.1. About the modeling and simulations

The performance results presented in this article are produced by link and system level simulation according to widely adopted methods. The link simulator models operate in symbol resolution and include transmitter & receiver algorithms, and communication over multipath, time variant, frequency selective channels. The link results are mapped to SINR statistics by the exponential effective SNR mapping (EESM) or the Actual Value Interface (AVI) interface to the system simulator. Both EESM and AVI are capable of modeling short term BLER as a function of SINR and the transport format of the symbol block.

The system simulator calculates SINR values in subcarrier resolution based on the modeled channel and the scheduled resources. The received SINR depends on the RRM algorithms discussed in Section 5. The pathloss and the shadow fading distributions are calculated from the experimental models; e.g. in [4,20], the shadow correlation process is included. The system simulator includes realistic resource reservation for signalling channels, seen as overhead from the user throughput point of view. The overhead of reference and channel measurement symbols are taken into account as well. Further, the reporting delay and measurement inaccuracy of the feedback are included.

Simulation results depend on many modeling assumptions and parameters, e.g. propagation, channel and traffic models, transmitter and receiver structures, signalling formats, algorithms and their parametrisation. Many of these models are statistical processes that require measurements for proper action during the simulation. The simulation models and parameters can be found in Tables 1 and 2. See [21] for more discussion.

In system simulation, short term statistics for the Transport Blocks per UE and per cell are collected over a simulation area. The results are presented as cumulative distribution functions (cdf) of the user throughput and cell throughput, which allows analysis of the mean, the cell edge and the peak performance. In downlink, throughput of user data, experienced at the IP layer above the radio stack is reported, with the observations for the distributions collected per user device. In uplink, cell throughput, observed for all served users in a cell, is measured.

6.2. Spectral efficiency and capacity analysis

Performance results depend on the scheduler, multiantenna transmission schemes, system bandwidth, and number of users

Table 1
Most important traffic, protocol, and system assumptions.

Traffic models and protocols, VoIP	
Voice codec	AMR 12.2 kb/s
L3–4 protocols	RTP/UDP/IP
Radio protocols	PDCP/RLC/MAC/PHY
Header Compr.	ROHC, profile RH-0
Payload with overhead	40 byte for AMR 12.2 2×{40,28}, packet bundling
SID overhead	15 byte once per 160 ms
Voice activity	50%
Talk-spurt	exponential duration, mean 2 s
Traffic models and protocols, Best Effort (BE)	
Source model	Full buffer, infinite queue
L3–4 protocols	TCP/IP (included as payload)
Radio protocols	PDCP/RLC/MAC/PHY
Payload with overhead	max Transport Block size exact fit to PRB allocation
System simulation	
Number of cells	19 sites (or 7 sites), 3 cells per site
Carrier frequ.	2.0 GHz
Intersite dist.	500 m, 1000 m, 1500 m
System BW	10 MHz (if otherwise not stated)
Frequency reuse	1
Active users per cell	VoIP: variable (outage criterion) BE: 10 users, uniformly distributed
Allocations	PRB resolution
Cell selection	best cell, 0 dB margin
Path loss	{Min Coupl., Penetr.} loss {70,20} dB
Shadow fading-correlation	log-normal, std 8 dB sites 0.5, cells 1.0, distance 50 m
Fast fading	UE velocity dependent Jakes
UE velocity	3 km/h
Channel model	SCM-C
Channel estim.	2D Wiener filter

Table 2
Most important link-specific assumptions.

Downlink simulation	
Transmit power	{43,46}dBm for {5,10} MHz
RS overhead	{4.55, 9.09,12.12}% for {1, 2, 4}-tx
Tx schemes	precoded MIMO, 2 CW, rank adaptation
Receivers	1 CW: MRC/IRC, 2 CW: LMMSE
Power control	Equal transmit power per PRB
Rx power dynamics	22 dB
Control overhead	1–3 symbols/ subframe (12–21%)
CQI	realistic delay, Gaussian accuracy
Link Adaptation	Fast, CQI based
HARQ	8 channels (asynchronous, adaptive)
Uplink simulation	
max UE Tx power	24 dBm
RS overhead	2 DMRS, 1 fullBW SRS/ subframe
Receivers	LMMSE/ antenna branch; MRC combining; FDE
Power control	open loop, Eq. (1); α_{PL} = [0.6,0.7]
Rx power dynamics	17 to 20 dB
Control overhead	VoIP (5 MHz): 2 PRB PUCCH (8%)
(Layer1/Layer2)	BE (10 MHz): 4 PRB PUCCH (8%)
Channel Sounding	realistic, Gaussian accuracy
Link adaptation	Fast, channel sounding based
ATB	min BW fixed 6 PRB
HARQ	8 channels (synchronous, non-adaptive)
Both link directions	
Modulation	{QPSK,16QAM,64QAM}
Coding	Turbo code, variable rate
Allocations	PRB resolution

Table 3
Downlink cell mean and cell edge spectral efficiency [b/s/Hz/cell] for various antenna configurations (transmit x receive), MRC/IRC receivers (rx) and RR/PF schedulers (scd). The reference (ref) is HSPA given in [22].

Best Effort traffic				
	scd	rx	CM	CE
ref			0.53	0.020
1 × 2	RR	MRC	1.03	0.029
		IRC	1.18	0.036
	PF	MRC	1.54	0.056
		IRC	1.69	0.063
2 × 2	PF	MRC	1.64	0.061
		IRC	1.82	0.076
4 × 2	PF	MRC	1.73	0.065
4 × 4	PF	MRC	3.03	0.110

Table 4
Uplink cell mean and cell edge spectral efficiency [b/s/Hz/cell] for various antenna configurations, FDE/MRC receivers and RR/PF schedulers. The reference is HSPA given in [24].

Best Effort traffic			
	scd	CM	CE
ref	–	0.33	0.009
1 × 2	RR	0.72	0.030
	PF	0.86	0.036
1 × 4	RR	1.03	0.045
	PF	1.22	0.058

in the cell. Tables 3 and 4 classify results and scale the numbers for comparison to spectral efficiency values. Round Robin (RR) scheduler results are shown for reference, whereas Proportional Fair (PF) results represent achievable performance in full load conditions. The downlink multiantenna schemes are fairly advanced with adaptive precoding and rank adaptation ranging from single stream diversity transmissions to multistream transmissions. IRC based on sample matrix inversion is modeled. FDD downlink results are summarized in Table 3 and uplink results in Table 4. The full distributions of observations can be found in Fig. 10. For TDD, summary results are shown in Fig. 11.

The tabulated spectral efficiencies are given both for the cell mean (CM) and for the cell edge (CE) [21]. The CM spectral efficiency is the average user throughput divided with the system bandwidth, multiplied with the number of served users per cell. The CE spectral efficiency is the throughput of the user at the 5% point of the cdf, divided by the system bandwidth. Note that this is not literally a link spectral efficiency; the bandwidth used per user is not factored in. RR and PF schedulers, however, are resource fair. Thus multiplying the reported CE spectral efficiency with the number of users per cell, one gets the link spectral efficiency of transmissions to/from cell edge users on the resources actually used for these transmissions.

Peak data rate measures are sometimes valued in the literature and are given for LTE in [23]. The peak data rate depends on the UE capability category, and is defined as the number of layer 2 (transport channel) information bits that can be instantaneously processed. For example, a UE with two receive antennas and one transmit antenna may reach peak data rates of 150 Mb/s in downlink and 50 to 75 Mb/s in uplink. Peak data rates can in theory exceed 300 Mb/s for UEs in the highest capability category. The time and coverage probability of the peak data rates depend on the channel properties, number of receive antennas and on the implementation quality (EVM). According to link budget calculations,

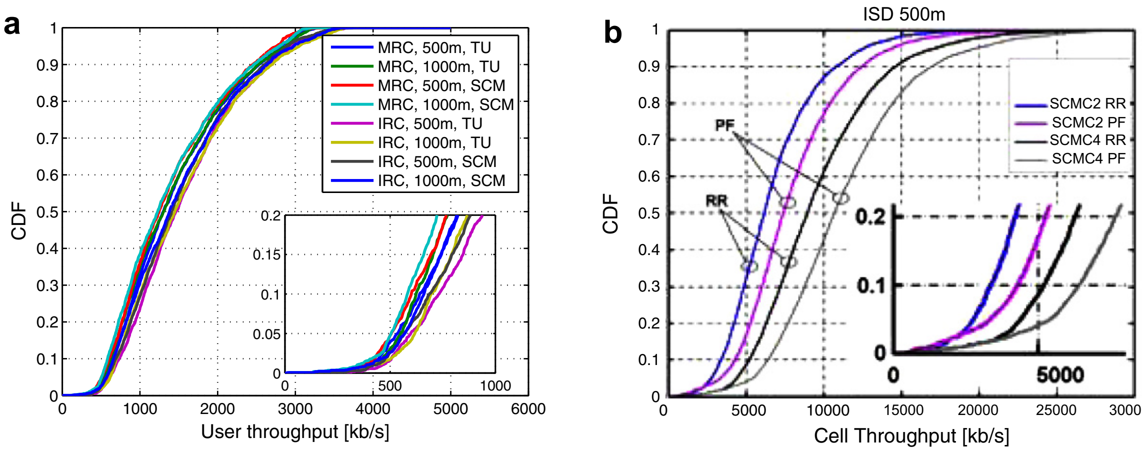

Fig. 10. (a) Downlink (FDD) user throughput with Proportional Fair channel dependent scheduler, MRC and IRC receivers in 1 × 2 antenna configuration. SCM-C in addition to TU channel models. (b) Uplink (FDD) cell throughput with Round Robin and Proportional Fair channel dependent schedulers in 1 × 2 and 1 × 4 antenna configurations.

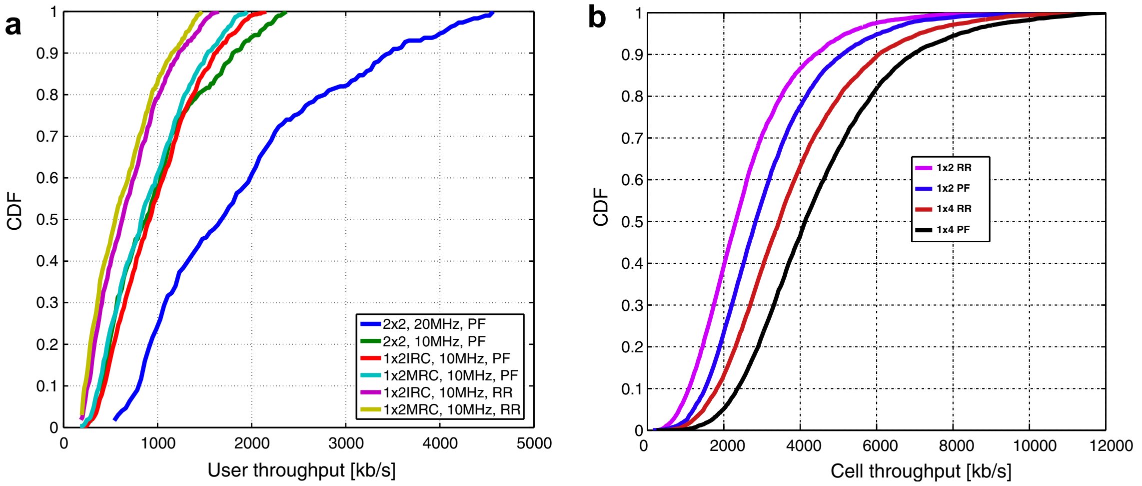

Fig. 11. (a) Downlink (TDD) user throughput with Proportional Fair channel dependent scheduler, MRC and IRC receivers. For system bandwidths 10 and 20 MHz. (b) Uplink (TDD) cell throughput with Round Robin and Proportional Fair channel dependent schedulers in 1 × 2 and 1 × 4 antenna configurations. The asymmetry ratio between the downlink and uplink subframes was 3:2.

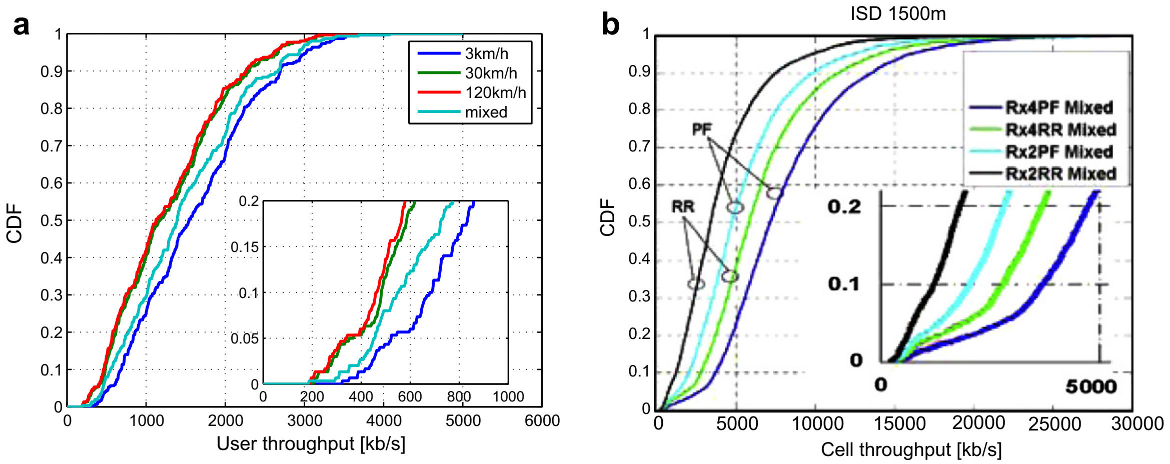

Fig. 12. User throughput (FDD) for the mixed velocity scenario with large intersite distance. (a) Downlink results with Proportional Fair channel dependent scheduler and IRC receivers in 1 × 2 antenna configuration. (b) Uplink results with Proportional Fair channel dependent schedulers in 1 × 2 and 1 × 4 antenna configurations. ITU modified PedB and VehA channel models [20].

Table 5
VoIP capacity, number of satisfied users per cell. Fully dynamic scheduler, control channel overhead 3 symbols. Uplink mean IoT 13–14 dB.

VoIP traffic, AMR12.2 kb/s, 5 MHz BW			
Downlink	#PDCCH channels	6	8
	FD scheduler, no bundling	203	272
	FD scheduler bundling	375	488
Uplink	#PDCCH channels	6	8
	FD scheduler	206	248

the coverage probability of LTE peak data rates is expected to be notable.

Further results are available for macro cells, where UEs may move at different velocities, see Fig. 12. Velocity impacts channel coherence time, and consequently many dynamic system processes. LTE performs well also for high velocity links because of its Doppler-tolerant parametrisation, frequency selective channel estimation which remains accurate also in channels with short coherence time, and the high density of demodulation reference symbols. However, the presence of high velocity links necessarily decreases the system throughput at full load due to increasing link adaptation overhead, inaccuracy of scheduling, and degradation of channel sounding accuracy. With the assumed mixed velocities of {3, 30, 120} km/h with probabilities {60, 30, 10}%, respectively, the performance degradation was below 10% in downlink and up to 30% in uplink, compared to the baseline performance with velocity 3 km/h for all links. These results did not yet include velocity dependent optimisations that may improve performance.

As voice traffic will remain important in wide area systems, mechanisms for packet transmission of voice (VoIP) have been specified in LTE. VoIP has high overhead of headers due to the RTP/UDP/IP protocols. LTE VoIP capacity, however, is extremely high due to the efficient payload adaptation and efficient signalling of small packets. In a wideband LTE transmission, VoIP capacity was shown to reach over 70 satisfied users per MHz in downlink and 46 satisfied users in uplink, in FDD mode. Detailed results can be found in Table 5. In TDD mode, the equivalent VoIP capacity in downlink and uplink may be more balanced, reaching about 53 to 60 satisfied users per MHz.

7. Conclusions

The LTE process led to rapid research and innovation for the EU-TRA technology to radically bring the 3G networks to a new 4G performance era. The technical targets set in [3] required an iterative development process, where simultaneous innovations in the design of the physical layer, radio protocols, resource management algorithms and network architectures support each other. Hence, increasing the cell edge throughput and spectral efficiency had to happen yet reducing the air interface latency, which requires advanced receiver algorithms and efficient signalling protocols. Despite of the high performance at highly aggressive scheduling events, the UE is able to activate its power saving modes for the moments of low activity. This shows as increased battery activity times and yet provide fast transitions to the active state of communications, because the IP connectivity is maintained to the serving gateway on the “always-on” EPS bearer. The cost factors, flexibility and reliability of the network are improved due to the server based distributed architecture and due to the lack of centralized control in the radio access network.

The LTE standard Release 8 (series_36) [1] is complete and several field trials are on-going or planned by the mobile network operators with the mobile device vendors. Targets for launching commercial operations in the near future have been published, and the first openings are expected to begin in year 2010. After the first launches, LTE deployments are expected to increase rapidly, because the network upgrades suit to the existing 3G sites. Also in regions, where 3G is not widely spread, LTE technology is expected to offer the next major upgrade. Hence, LTE will clearly be the future technology for the wide area mobile data coverage in dense traffic areas globally.

In longer term, local access is expected to gain more momentum, because the forecasted increase of traffic volumes cannot fully be satisfied by wide area deployments with large cell ranges. This observation motivates new local area studies e.g. by scaling the LTE technology for small cells and to implement local networking for low cost of operation.

LTE reaches the targets set for IMT-Advanced [10] in wide area evaluation scenarios. New releases of LTE [11], including technology components such as uplink MIMO and carrier aggregation, will improve LTE performance in local area scenarios, and factually realize a Gbit/s peak rate, often seen as a rate characteristic of 4G systems.

Acknowledgments

We thank collaegues—past and present members of the Nokia & NSN LTE teams—for collaboration over the years, and acknowledge 3GPP partners for creating technology proposals to the standard specifications. In particular, we thank Pekka Soininen for posing the 4G challenge of 1 Gbps on 100 MHz, on an autumn afternoon in 1999.

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