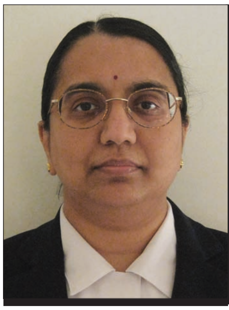
LTE PART II: RADIO ACCESS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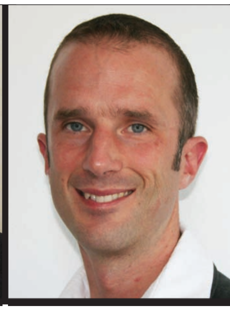
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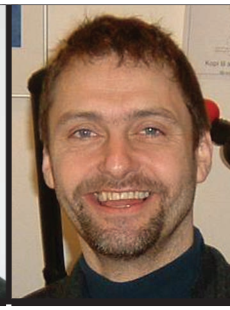
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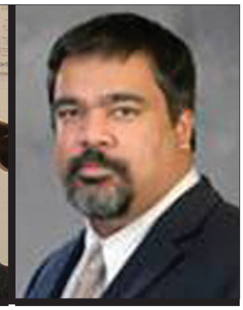
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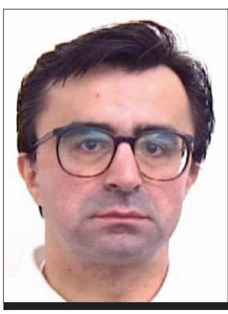
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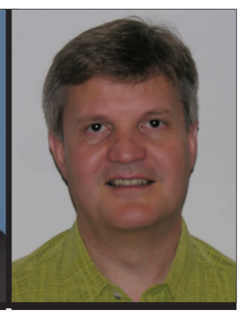
Zoran Zvonar

The recent rise in data traffic volumes being carried by mobile communication networks is tremendous. Some mobile communication networks have already turned from voice dominance to data dominance in terms of carried traffic volume. In 2008 the increase was up to a factor of five, and large operators' networks are now carrying on the order of 5–10 Tbytes/day. This boom in mobile data traffic has been enabled by several factors: flat rate pricing, 3G offering digital subscriber line (DSL)-like data rates, the availability of USB mobile data modems for PCs, and Web-friendly mobile terminals. In the wake of these headlines, mobile operators are evaluating evolved network infrastructures that can simultaneously provide lower cost per bit and greater flexibility in the pricing structures of end-user services. The Third Generation Partnership Project (3GPP) has responded to these challenges with the creation of the Release 8 specification including the long term evolution (LTE) and evolved packet core (EPC) set of standards.

In Part I of this Feature Topic published in the February 2009 issue of *IEEE Communications Magazine*, we investigated the technologies behind EPC. In this issue we provide insight into the inner workings of the LTE air interface.

From a technical point of view, some of the fundamental targets of LTE are to offer higher data rates — 100 Mb/s for down- and 50 Mb/s for uplink transmission, to increase the cell average and cell edge spectral efficiency by a factor of 2–4 compared to HSPA Release 6, and to provide flexible channel bandwidth for operators in both paired and unpaired spectrum. Another important target was to reduce user plane latency to less than 10 ms and control plane latency to less than 100 ms.

The multiple access techniques selected for LTE are orthogonal frequency-division multiple access (OFDMA) for downlink and single-carrier frequency-division multiple access (SC-FDMA) for uplink. These multiple access schemes provide several advantages over wideband code-division multiple access (WCDMA), including flexible bandwidth configurations from 1.4 up to 20 MHz.

With OFDMA, the data is transmitted over a large number of orthogonal narrowband channels. By insertion of a cyclic prefix, the received signal, even after undergoing multipath propagation, can be detected by a low-complexity single tap equalizer in the user equipment (UE). This complexity reduction (compared to a multitap equalizer) becomes especially important in combination with spatial multiplexing multiple-input multiple-output (MIMO) techniques. OFDMA also provides easy bandwidth scalability via configuration of the number of subcarriers. Lastly, OFDMA in combination with frequency-dependent channel state information gives the opportunity to benefit from frequency domain channel aware user diversity packet scheduling.

The drawback of OFDMA is the relatively large peak to average power ratio (PAPR), which tends to reduce the efficiency of the radio frequency (RF) power amplifier. Hence for uplink, SC-FDMA has been selected mainly to improve RF transmission power efficiency in the UE. By inserting a cyclic prefix, as in OFDMA, the received signal after multipath propagation can still be detected by a low-complexity equalizer at the enhanced NodeB. SC-FDMA can be treated as a discrete Fourier transform (DFT) precoded OFDMA signal, and hence provide the same scalability advantages as OFDMA. SC-FDMA, however, requires transmission in consecutive bands, and thus introduces restrictions on the frequency domain packet scheduling for individual users compared to OFDMA. Compared to wideband code-division multiple access (WCDMA), intracell orthogonality is preserved between users by using timing advance such that the users are received synchronously. This provides significant coverage and capacity gain in the uplink over WCDMA.

LTE Release 8 supports spatial multiplexing with two codewords and up to four parallel streams in the downlink. In combination with 64-quadrature amplitude modulation (QAM), the peak data rates in downlink exceeds 300 Mb/s. LTE also supports user specific beamforming. The corresponding uplink peak data rate is approximately 75 Mb/s using single-stream transmission. Spatial multiplexing in the uplink is introduced in a second phase of LTE, and is part of the LTE-Advanced Study Item.

A detailed overview of the LTE radio interface, including both frequency- and time-division duplex (FDD and TDD) techniques, is described in the article "LTE: The Evolution of Mobile Broadband" by David Astely, Erik Dahlman, Anders Furuskär, Ylva Jading, Magnus Lindstrom, and Stefan Parkvall. In addition to transmission scheme, the authors have outlined details associated with spectrum flexibility covering transmission bandwidth and duplex schemes, multi-antenna transmission, power control and intercell interference coordination. Current activities within 3GPP, often referred to as LTE-Advanced, are briefly introduced in terms of several technology components including carrier aggregation, relaying, extended multi-antenna transmission, and coordinated multipoint transmission/reception (CoMP).

The challenge in designing the LTE link layer protocol is to provide a simplified architecture considering high data rates of the LTE physical layer while having strict latency requirements. An overview is provided in the article "The LTE Link Layer Design" by Anna Larmo, Magnus Lindstrom, Michael Meyer, Ghyslain Pelletier, Johan Torsner, and Henning Wiemann. The underlying principle in design approach is an efficient interaction among different layers. The resulting LTE link layer consists of three sublayers: packet data convergence protocol (PDCP) responsible for IP header compression and ciphering, radio link control (RLC) protocol covering mainly automatic repeat request (ARQ) functionality and supporting data segmentation and concatenation, and medium access control (MAC) protocol, which provides hybrid ARQ functionality and is responsible for scheduling operation. The relevant functionality is described in an intuitive manner focusing on the key aspects of the standard. In retransmission handling a fundamental design choice for LTE has been not to propagate any bit errors to higher layers but rather to drop the entire data unit. A scheduling request (SR) mechanism allows the UE to request uplink transmission resources from the eNodeB through either random access SR or dedicated SR. LTE supports discontinuous reception (DRX) to enable UE power savings by shutting down a portion of, or possibly the whole, receiver. With respect to scheduling, the challenge is to provide desired quality of service (QoS) on a shared channel. LTE does not provide any dedicated channel, and it is up to eNodeB implementation and schedulers to assign radio resources in a way to obtain the agreed QoS characteristics. The overhead analysis and performance result indicate that the LTE link layer is highly efficient to meet and even exceed the requirements of mobile broadband users in the future with low overhead, while still being flexible enough to provide support to TCP services as well as real-time services such as voice over IP (VoIP).

LTE can expect some distinct deployment challenges. LTE users should be able to make voice calls from their terminal and have access to basic data services even when they are in areas without LTE coverage. LTE therefore allows smooth, seamless service handover in areas of CDMA, 1xEV-DO, HSPA, WCDMA, or GSM/GPRS/EDGE coverage. Furthermore, LTE/SAE supports not only intra- and intersystem handovers, but also interdomain handovers between packet and circuit switched sessions. These issues are examined in the article "Coexistence Studies for 3GPP LTE with Other Mobile Systems" by Man Hung Ng, Shen-de Lin, Jimmy Li, and Said Tatesh. It provides an overview of the coexistence studies, and system simulation methodology and assumptions used in the studies. In addition, they show some simulation results for the possible impacts with different system parameters such as adjacent channel interference ratio (ACIR).

Supporting vertical handover (VHO) between different networks requires the provision of ubiquitous mobile services. The article "Data Loss Preventive Optimized Vertical Handover Technology for 3GPP and Mobile WiMAX Communications" by William Song, Jong-Moon Chung, Daeyoung Lee, Chaegwon Lim, and Sungho Choi addresses VHO between 3GPP and mobile WiMAX networks. They introduce a new network entity named the data forwarding function (DFF) to resolve the data loss problem in existing techniques. They show through simulation experiments that the loss of data can be significantly reduced by applying the proposed optimized VHO scheme.

A second deployment challenge involves the presence of interference between eNodeBs and within an eNodeB's coverage. A combination of high- and low-power subchannels can be exploited to increase the overall capacity of the network compared to networks which use the same transmission power for all subchannels. This approach is known as fractional frequency reuse (FFR) as all base stations use the same frequency band and low-power subchannels, but only a fraction of the high-power subchannels. Additional techniques are used to cancel interference using a variety of advanced decoding principles. These technologies are reviewed in the article "Interference Coordination and Cancellation for 4G Networks" by Gary Boudreau, John Panicker, Ning Guo, S. Vrzic, Reid Chang, and Neng

Wang. It provides an overview of techniques that can be employed to mitigate interference in fourth-generation (4G) OFDM systems with specific relevance to LTE. Viable approaches include the use of fractional power control, static and adaptive fractional frequency reuse, opportunistic spectrum access, intra- and inter-eNodeB interference cancellation, MIMO, SDMA, adaptive beamforming, and network MIMO as well as advanced coding theory concepts such as dirty paper coding. They suggest combinations of approaches that provide gains in short-term and long-term perspectives.

To ensure a smooth transmission from standardization to commercialization, a global group of equipment vendors and operators have formed the LTE/SAE Trial Initiative (LSTI). The first trial results compiled by LSTI are included in this edition as an invited article by Julius Robson, Chair of LSTI's proof of concept group, entitled "The LTE/SAE Trial Initiative: Taking LTE/SAE from Specification to Rollout." LSTI is coordinating and reporting progress on trial activities to ensure that everyone has a realistic understanding of a) what performance and functionality to expect from LTE, and b) the readiness of the technology for commercial rollout. Apart from reporting measurement results on raw data rates, the article also reports measurement results for packet latency and idle to active time.

The editorial team would like to thank Editor-in-Chief Nim Cheung for providing the opportunity to present this Feature Topic and guiding the process toward publication. The team would also like to thank the reviewers who helped us select the best papers. Last but not least, the editorial team would like to thank our companies for providing support in this initiative that will help engineers to get a basic understanding of LTE technology and the associated networking concepts.

BIOGRAPHIES

KALYANI BOGINENI (Kalyani.Bogineni@VerizonWireless.com) is principal architect at Verizon Communications with extensive experience in architecture and design of telecommunications networks for wireless and wireline technologies as well as various application technologies. She has published extensively in IEEE/ACM peer-reviewed journals and conferences. She has been on the Technical Program Committees for several conferences, and has been a reviewer for various IEEE journals and magazines for over 18 years. She is an active speaker on next-generation converged networks at various conferences and panels. Recently she has been active in the development of 3GPP standards for 4G technologies focused on the development of converged networks for multiple access technologies with IP-based mobility management mechanisms, policy-driven roaming architectures, and converged security architectures. She has B.Tech and M.E. degrees in electrical engineering, an M.S. degree in computer engineering, and a Ph.D. in electrical and computer engineering.

REINER LUDWIG received his Diploma and doctoral degree in computer science from the University of Technology, Aachen, Germany, in 1994 and 2000, respectively. He joined Ericsson in 1994 working within the Research Department on cross-layer aspects of wireless packet-based networks. He has worked within the Internet Engineering Task Force (IETF), where he co-authored standards on operating end-to-end protocols across wireless access networks. More recently, he has been actively involved in the standardization of the policy and QoS framework of the 3GPP EPS, including link layer aspects of the LTE radio access. He currently holds an expert position in the Systems and Technology Department of Ericsson's Business Unit Networks, where he is responsible for policy and QoS control for fixed and mobile access networks.

PREBEN MOGENSEN received his M.Sc.E.E. and Ph.D. degrees in 1988 and 1996, respectively, from Aalborg University (AAU), Denmark. Since 1999 he has been a part time professor in the Department of Electronic Systems, AAU, where he heads the Radio Access Technology (RATE) research section. He also holds a part time position as principal engineer at Nokia Siemens Networks, Aalborg, where he is involved in LTE and LTE-Advanced standardization research. He is author or co-author of more than 170 technical publications within a wide range of areas, including radio wave propagation, advanced antenna technologies, receiver design, frequency assignment, radio resource management, and packet scheduling.

VISH NANDLALL is the chief technical officer for Carrier Networks at Nortel. He is responsible for Nortel's technology vision in 4G and in particular LTE, and has shaped Nortel's product and standards strategy in this field, advocating seamless intertechnology handoff and flat network topologies. He has spent the last 15 years in architecture roles within Nortel, most recently as chief architect for Nortel's CDMA and EVDO wireless access division, contributing to the launch of high-speed data services in North America and Eastern Europe. Prior to his life in wireless, he contributed to Nortel's Metro Optical and DMS product lines, providing key technologies in core computing and private line services. His current research is in cross-layer design for cellular interference control and scheduling in direct relay systems.

VOJISLAV VUCETIC received his Ph.D. degree from Imperial College, London, United Kingdom. In 1988 he joined AT&T Bell Laboratories, where he worked on software design and software architecture for data communications systems, and network designs for data carrier networks internationally. In 1998 he joined Cisco, where he worked as a consulting engineer supporting U.S.-based and international service providers. He also contributed to metro Ethernet and cable-based VoIP development activities. Currently he is a senior manager in the Carrier Standards and Architecture group. He leads a group that is responsible for coordinating industry and standards activities with Cisco carriers' development organizations and service providers. His current focus is on architecture and protocols for access-agnostic IP-based networks to support 3GPP, 3GPP2, WiMaX, and other access technologies.

BYUNG K. YI, senior executive vice president of LG Electronics, has over 32 years of experience in research and development of communication and space systems. He has been working on 3G and 4G wireless communication systems. He served as TSG-C chair of 3GPP2 for two terms, developing cdma2000 air interface specifications, and served as a co-chair of Working Group 5 of 3GPP2 TSG-C, developing 1xEV/DV wireless standards. Under his leadership, TSG-C published three important air interface standards, cdma2000 Rev. D, and High Rate Packet Data (HRPD) Revs. A and B. He is currently heading the LGE North America R&D center, developing mobile terminals for North American carriers. He was in charge of small satellite system engineering for distributed low earth orbiting telecommunication and remote sensing applications at Orbital and CTA as a chief engineer. He taught graduate courses for nine years at George Washington University as an adjunct professor. His current interests are wireless and space communication systems, iterative decoding, and space system engineering. He holds eight U.S. patents and five international patents in the areas of iterative decoding and handoff schemes for cellular-based systems.

ZORAN ZVONAR is director of systems engineering, MediaTek Wireless, and a MediaTek Fellow. He received a Dipl.Ing. in 1986 and an M.S. degree in 1989 from the Department of Electrical Engineering, University of Belgrade, Serbia, and a Ph.D. degree in electrical engineering from Northeastern University, Boston, Massachusetts, in 1993. From 1994 to 2008 he pursued industrial carrier within Analog Devices. He was a member of the core development team for the baseband platform and RF direct conversion transceiver wireless product families, and has been a recipient of the company's highest technical honor of ADI Fellow. Since January 2008 he has been with MediaTek focused on the design of algorithms and architectures for cellular standards, with applications to integrated chip set solutions and real-time software. He is the Editor of the Radio Communications Series in *IEEE Communications Magazine* and has served as Guest Editor and the member of the editorial boards for a number of professional journals in wireless communications.