SIGNAL PROCESSING CHALLENGES FOR FUTURE WIRELESS COMMUNICATIONS

Ralf Irmer and Stanley Chia

Vodafone Group R&D, Vodafone House, Newbury, RG142FN, UK, {ralf.irmer , stanley.chia}@vodafone.com

1 ABSTRACT

The mobile internet has finally arrived with the sky-rocketing usage increase of HSPA. LTE, WiMAX and evolved WiFi are the upcoming wireless standards which are based on OFDM and MIMO. The mentioned standards have already started the evolution process with LTE-Advanced, IEEE 802.16m and IEEE 802.11n. New technology building blocks are on its way like cooperative MIMO, relaying and self-organizing networks. Increase of data-rate is one target, but the energy consumption both on the terminal and network side are important as well. This paper discusses the challenges imposed by developments in the wireless industry. Advanced signal processing can play a major role in addressing these challenges.

Index Terms— LTE, WiMAX, LTE-Advanced, Energy Consumption, Signal Processing

2 INTRODUCTION

The mobile internet has finally arrived:

a) with broad roll-out of HSPA (High Speed Packet Access) networks all over the world,
b) with the increasing availability of data-dongles, HSPA modules built into notebooks and mobile devices with large screens, and
c) with affordable tariffs and flat-rate price plans available from many operators.

Currently, the user data rate and the capacity in terms of number of users per cell (or within an area) are sufficient in most HSPA networks, but this is bound to change.
The ever increasing performance of fixed-line connections like VDSL sets higher expectations on the data rates for the mobile internet, more users will compete for the same resources and new data-hungry services like YouTube or the BBC iPlayer will appear.
3GPP LTE (Long Term Evolution) with its first release ("Release 8") is addressing some of these problems with higher peak rates, higher spectral efficiency and lower latency, but is causing new challenges. For a broad market adoption not only by a few pioneer customers in rich countries but for a mass-market penetration in developed and developing countries, the total cost of ownership of the network and the devices must be low – which is challenging given the advanced technical building blocks of LTE such as MIMO. The power consumption is also a major issue for mobile devices – the battery capacity is growing with a much slower slope than data rates. Power consumption is also increasingly a significant issue for network elements.
This paper outlines the developments of the wireless industry within the next years, and highlights some upcoming challenges, where signal processing could play a major role in resolving them.

3 UPCOMING WIRLESS COMMUNICATIONS STANDARDS

3.1 Operator Requirements on future wireless networks

The requirements on future networks were outlined by NGMN, the group of mobile operators, in [1]. These include average and cell edge spectral efficiency, low latency, simplicity, total cost of ownership, reliability, quality-of-service and seamless interworking with existing wireless standards. For the radio air interface, a unified evaluation methodology was established in [2] which allows for an apples-to-apples comparison of different standards and concepts.

3.2 LTE

LTE meets the essential requirements of NGMN[1], but still falls short on some preferred requirements such as cell-edge spectral efficiency in the uplink and downlink. LTE is based on OFDMA and MIMO, and allows for flexible bandwidths up to 20 MHz, increased peak rates of up to 150 Mbps with 2x2 MIMO. The LTE latency is between 5 and 10 ms; the connection setup latency ranges from50 to 80ms. The downlink spectral efficiency is 1.6 bits/s/Hz/sector with a 2x2 MIMO configuration. With 4x2 and 4x4 MIMO, the performance is 18% or 82% better, respectively. In the uplink, the spectral efficiency is 0.88 bits/s/Hz/sector. These figures are based on simulations with the above mentioned NGMN evaluation methodology. Trial activities are on the way in the industry to verify these performance predictions.

LTE implementation poses the following signal processing challenges in terms of performance, cost and power consumption:

- Data rate. Unfortunately, the growth of data rates is not matched by advanced in semiconductor structures, terminal power consumption improvements or battery lifetime improvements. New processing architectures and algorithms are needed to cope with these data rates.
- High performance MIMO receivers such as maximum-likelihood-like receivers, sphere decoders or interference rejection combiners offer substantial performance gains but impose an implementation challenge, especially when the high peak data rates are targeted.
- LTE utilizes precoding, which requires accurate channel estimation. Advanced methods like iterative decision directed channel estimation offer performance improvements, but pose again a complexity challenge.
- LTE has a large "toolkit" of MIMO schemes and adaptive methods. The selection and combination of the right method in a cell with heterogeneous devices, channel conditions and bursty data services is a challenge.

[1] Next Generation Mobile Networks Alliance , www.ngmn.org

- LTE roll-out will be gradual in most cases– interworking with other standards such as GSM or HSPA will be required for a long time. This imposes not only a cost and complexity issue. One of the reasons many early 3G terminals had poor power consumption was the need for 2G cell search and handover in addition to normal 3G operation. Reduced talk-time for dual-mode devices is not acceptable.
- "Dirty RF" challenges. OFDM systems cause problems with power amplifier nonlinearity, and are sensitive to frequency errors and phase noise. Digital compensation techniques are proposed for the transmitter and receiver, but innovation is needed to make them reality in low-cost devices.

3.3 Mobile WiMAX

Mobile WiMAX uses the same essential technical building blocks as LTE. WiMAX was initially focused on TDD (Time Division Duplex), but an FDD (Frequency Division Duplex) version is being developed. LTE is addressing both, FDD and TDD bands, with LTE FDD development having a lead in time-to-market over LTE TDD.

WiMAX development and first deployments started earlier, but the performance of WiMAX is lower than LTE. LTE can build on the huge GSM and HSPA ecosystem with more than 3 Billion and 50 Million subscribers, respectively and is expected to benefit from large economy of scale. But there are markets where WiMAX will play its role. Most challenges which are addressed in this paper for LTE also apply to WiMAX.

3.4 WiFi Evolution

The IEEE 802.11 family of wireless local area networks is designed for use in the 2.4GHz and 5GHz unlicensed frequency bands. Currently IEEE 802.11b/a/g radio products are widely available. IEEE 802.11n is a proposed amendment which improves upon the previous 802.11 standards by adding multiple-input multiple-output and channel-bonding operation to the physical layer, and frame aggregation to the medium access control layer. The technical workgroup TGn is not expected to finalise the amendment until December 2009. The Wi-Fi Alliance has started certifying IEEE 802.11n Draft 2.0 based products since 2007. Discussions are under way to enhance WiFi further by adding a 60 GHz mode.

The signal processing challenges for WiFi are similar to the ones described for LTE, but some are more relaxed due to less stringent power-consumption constraints in WiFi-form-factor devices such as notebooks. Also, the propagation conditions for indoor WiFi operation are less challenging than full-coverage outdoor solutions of LTE and WiMAX, which are essentially interference limited or link budget limited. The higher peak data rate of WiFi (up to 600 Mbps) is a major challenge which has to be addressed.

4 NOVEL TECHNICAL BUILDING BLOCKS IN LTE EVOLUTION

The ink is not yet dry on LTE, WiMAX and WiFi standards, but discussions on further improvements has already started. Further releases of LTE are addressed with "LTE-Advanced"; and IEEE802.16m is focusing on further WiMAX evolution. This section is focusing on some selected building blocks for LTE evolution. A full overview of all LTE-Advanced features und similar WiMAX innovations is beyond the scope of this paper.

4.1 Cooperative Multicell Algorithms

4.1.1 Topology Paradigms

The wireless research community went through different modeling approaches and came up with innovative concepts based on the understanding of these models.

- AWGN: Additive White Gaussian Noise models enabled advances in coding and modulation
- Frequency-flat fading and frequency selective fading capture the single-link radio much better. Spreading, advanced coding, iterative receivers, diversity combing and selective scheduling were developed.
- Multiple antennas on one side ("beamforming") and MIMO channels where eventually modeled and understood and theoretical and practical concepts such as spatial multiplexing were developed to exploit them. The focus was on a single user for a long time, ignoring interference from other users or base stations to a large extend.
- Multiuser detection and multiuser transmission address communications of multiple users within one cell. Concepts such as SDMA (Space Division Multiplexing), dirty paper precoding and advanced schedulers have appeared.
- The cooperation of neighboring cells is the next paradigm. Network coding theory helps to understand fundamental limits, and practical concepts such as distributed antennas are currently discussed.

4.1.2 Cooperative MIMO

Cooperative MIMO has the largest potential in the uplink, where base stations can exchange information on received signals using the backhaul (i.e. fibre links or microwave) to address interference. The potential of spectral efficiency gains in average and on the cell edge are substantial. Signal processing can be centralized or distributed, i.e. with iterative information exchange (the "multi-base-station turbo receiver"). The signal processing burden can be reduced by clustering of cells and selective signal processing (only considering strong interferers), and the backhaul burden can be minimized by signal compression, quantization and by the right choice of exchanging quantized samples, hard bits, soft bits, or likelihood ratios. This leads to a complexity-performance trade-off which needs to be explored. Cooperation in the downlink is more challenging than in the uplink direction since channel estimates have to be made available before transmission for precoding. Other challenges of cooperative base stations are synchronization and delay.

One example of cooperative MIMO for LTE-Advanced is the system developed within the multi-site testbed of the EASY-C project[2] [3].

4.2 Relaying

It is economically difficult for most operators to build more base station sites – the inter-site distance is already very low. To increase coverage and capacity further, small and cheap base stations are attractive, i.e. if they are deployed on lamp-posts. One challenge is to provide backhaul – which can be addressed using in-band backhaul. Relaying is discussed in academia for a long time. An example is the system concept of the EU WINNER[3]

[2] www.easy-c.com

[3] www.ist-winner.org

project, which included relaying as an integral part. Relaying is getting to the stage of maturity now with standardization in the IEEE 802.16j and LTE-Advanced context. Challenges imposed by relaying include backwards-compatibility, resource management, routing, low-overhead signalling, delay minimization, MIMO-support, frame structure, and power control. The potential of relaying in example network deployments was shown in [4] in terms of coverage and capacity. To cover a large percentage of outdoor and indoor areas with sufficient data rates, the exiting macro site network would have to be complemented by more traditional sites, or alternatively with relays to achieve the same coverage. Business model studies suggest that relay solutions are more attractive. Beyond coverage improvement of urban areas there are further applications of relaying, such as range extension or support for moving cells such as trains.

4.3 Self Organizing Networks (SON)

Future networks should have minimal human interaction – the vision is to have "plug-and-play" base stations. Self-configuration, self-healing and self-optimization are key SON elements and success factors for the deployment of future networks, especially if they consist of macro cells, relays, femto cells and other new network elements. NGMN is driving the development of SON functionality. SON requires the definition of the right interfaces and good cross-layer design.

5 ENERGY EFFICIENCY

5.1 Handsets

Energy efficiency for a handset does directly impact battery endurance. Standby time and "talk" time of a handset have long been the benchmark for handset differentiation. With a mobile phone, a significant proportion of the battery power is consumed by the radio modem and the radio frequency power amplifier. As of today, industry has estimated that between 30% and 40% of the battery power is consumed by radio related functions. The second most demanding source of power consumption is the application processors, which amounts to typically around 20%. This is followed by memories, which may range from 7% to 20%, depending on the implementation. The audio and video components each may consume up to 10% of the battery power budget. The remaining 10% to 13% is consumed by other subsystems including Bluetooth and power management hardware. Thus power consumption at the system and processor level, which amounts to some 60% of the total energy consumption, is a dominant concern for handset designers.

5.1.1 Radio frequency power amplifier

Radio frequency power amplifiers have been historically the largest consumer of handset battery energy. Power amplifiers are frequently optimised for high efficiency in order to maximise talk time. For maximum efficiency, radio frequency power amplifiers are frequently connected directly to the battery and voltage regulators and DC-DC converters are usually avoided to eliminate loss. Battery voltage range is a critical factor and a flat discharge voltage characteristic, though not achievable with batteries, is ideal for power amplifier operation. It is believed that intelligent power amplifier control as a function of monitored battery voltage would be useful. For multimode handsets, this is particularly important as for each band of operation, the optimum saturated output power varies dependent on the post-power-amplifier loss for that band. Going forward, battery aware smart power amplifier control to prevent transmitting at highest power levels when battery is near end of discharge would be important.

5.1.2 Application processor

With the exception of hardware accelerators and run-time environments, the majority of the tasks in a handset touch on its operating system at some point. To properly facilitate power management the operating system needs to be continuously kept informed of the power demand across the unit, especially the application processors. Symmetric multiprocessing that involves a multiple processor architecture allows more processing power per clock cycle compared to a single core approach. It can help to reduce power consumption at the expense of a more complex operating system and potentially more complex application software.

Continual advancements in smaller silicon geometries have enabled lower operating voltages in microprocessors. Operating voltages for processor cores are now as low as 1.2V and quickly migrate to 0.8V. The opposing requirements of the power amplifier that demands high voltage for best efficiency and the low voltage for reducing power consumption among the application processors have presented challenges for deriving energy from the same battery source without introducing DC-DC converters.

5.1.3 Peripherals

Audio components and video displays also consume a significant amount of battery energy. New technologies to reduce power consumption are emerging and we shall give a couple of examples here: the use of piezo-ceramic speaker for high-volume audio output as well as micro-electromechanical system (MEMS) based reflective display. Piezo-ceramic speakers have an ultra thin profile but have lower audio quality compared to traditional dynamic speakers. However, with a multi-layered design, the frequency response is substantially improved compared to earlier single layer products.

MEMS based reflective display using light reflection can effectively eliminate the backlight requirements in good ambient light conditions, thus reducing the power consumption requirements significantly. The bi-stable memory gives near zero power consumption for static image and thus further eliminates battery drain.

5.1.4 Battery technology

Batteries will remain a simple, integrated energy storage and delivery device for mobile handsets for some time to come. It provides a reasonably good balance between power and energy density as well as reasonable reliability. Improvement on storage battery technology has been slow. Energy density gains for lithium based batteries over past ten years were driven by packaging and process optimisation. It is expected there will be limited improvement headroom with conventional lithium-ion batteries. Continued gains required shift to new chemistries and new nano-technology, such as using high energy materials of nickel-based metal oxides for the cathode and silicon or tin alloys and composites for the anode.

5.2 Network Infrastructure

Network energy consumption is a major cost element for mobile operators, especially at remote sites which have to be powered by diesel generators. It is also a large contributor to CO_2 emissions, which impact our environment and contribute to climate change.

Mobile operators have started initiatives to reduce the energy consumption of base stations, and to use renewable energy sources such as solar and wind power. The GSMA, the global trade body for the mobile industry, has launched a "Green power for Mobile" programme to power 118,000 new and existing off-grid base stations in developing countries with alternative energy supplies by 2012 . Vodafone has pledged to reduce its global CO_2 emission by 50%, against the 2006/2007 total, by 2020. To achieve these goals, the most important measures such as switching-off air conditioning when it is not necessary are relatively low-tech. Ones these sources of energy-waste are eliminated, innovation is necessary to improve the energy-efficiency further – where signal processing will play a very important role:

5.2.1 Core Network

As more traffic generated by end user energy consumption by switches, application servers, data centres and their associated cooling will continue to escalate. In order to reduce the energy demand, newer generation of servers tend to reduce the number of interfaces through software and hardware integration, adoption of more energy efficient processors as well as adding dynamic power management techniques to wake up clusters of servers only when required. Processors also employ technology such as frequency and voltage scaling and aggressive circuit gating. Blocks of cache and floating point unit may be turned off while the server is idle and then turn on quickly when called into action.

5.2.2 Macro Base Stations

Many techniques have been used to reduce energy consumption of conventional macro base stations over the past decade. These include the use of more efficient radio frequency power amplifiers, introducing solar shielding to the equipment, utilising natural convection cooling rather than the traditional forced cooling, elimination of the air conditioner, as well as adding intelligence to selectively switch-off radio channels and baseband circuitries during times of low traffic volume. Remote radio heads and amplifiers integrated directly into antennas are upcoming technologies with the potential to reduce power consumption. In addition, more power efficient electronic components have to be designed into the subsystems to enable lower power consumption. The overall system-integration of often heterogeneous systems including backhaul has to take this into account.

5.2.3 Micro Base Stations and Relays

The current generation of macro base stations are mostly optimised for wide area coverage. However, as we evolve to higher data rate applications, we need much smaller cells to support the increased data rates. The flexibility of such deployment would be dependent on the power supply as well as backhaul. To solve the power supply issue, the energy demand for these small network elements should be sufficiently low such that it can be powered by sustainable energy sources such as small solar panels. Likewise backhaul may need to be provided through a self-contained relay network using either in-band or out-of-band radio relays. This will eliminate the need to access fibre at every base station but only at locations that is either collocated with a fibre drop or have access to a fibre point of presence.

5.2.4 Femto Base Stations

Femto base stations exploit the proliferation of fixed DSL and cable modem deployment in urban and suburban areas to provide indoor radio coverage. Femto base stations are small, low power cellular base stations, typically designed for use in residential and business environments. It connects to the service provider via fixed broadband access. As femto base stations are deployed in indoor locations, it does not have to circumvent high building loss. Thus, low output power is sufficient to provide adequate indoor coverage. By the nature of the small cell structure, it can improve both network capacity and coverage. There are, however, known challenges associated with femto base station deployment that include spectrum allocation, interference handling, access control, lawful interception, emergency calls and equipment location, quality of service, handover and network integration. In addition, the requirement of access fixed broadband precludes the deployment of femto base stations in many of the emerging markets where fixed infrastructure is effectively non-existent.
Smart signal processing solutions have the potential to solve some of the femto cell issues.

5.2.5 Off-grid locations

Providing sustainable energy source to base station infrastructure at locations beyond the power grid is particularly challenging. Conventional methods of using diesel generations and lead-acid batteries are relatively low cost but cause high maintenance overhead and environmental impact. The industry is looking to renewable energy sources including solar and wind as the primary energy sources and regenerative fuel cell technology as a means of backup. More specifically, a fuel cell normally requires some kind of fuel, such as hydrogen, to generate electricity and provide water as a by-product. Regenerative fuel cells are designed to recycle the water output and through the use of electrolysis to extract the hydrogen. Together with oxygen from the air, and power supplied by the solar and wind, a near-closed cycle can be formed. The process is completely environmentally friendly but the economics of such a setup has yet to be refined before it can be sufficiently attractive to compete with lower cost conventional solutions. Interworking between power supply, power storage and network equipment power demand poses a challenge with the need for innovative solutions.

Energy efficiency (both infrastructure and terminals) needs to be considered as an inherent feature of next generation standards and products, which is reflected on the way the physical layer, radio resource management and network management are designed. The Green Radio project[4] is showing one way of addressing these issues.

11. REFERENCES

[1] H. Akhavan, V. Badrinath, T. Geitner, H. Lennertz, Y. Sha, T. Utano, B. West: *"Next Generation Mobile Networks Beyond HSPA and EvDO"*, NGMN Alliance White Paper, www.ngmn.org, 3.0, December 2006

[2] R. Irmer,S. Abeta, G. Liu, J. Krämer, T. Sälzer, E. Jacks, G. Wannemacher, A. Buldorini, S. Xiadong: *"Next Generation Mobile Networks Radio Access Networks Evaluation Methodology*", NGMN Alliance White Paper, www.ngmn.org, 1.3, January 2008

[3] C. Jandura, P. Marsch, A. Zoch and G. Fettweis. „*A Testbed for Cooperative Multi Cell Algorithms*", Proc. TRIDENTCOM, Innsbruck, Austria, March 2008

[4] R. Irmer and F. Diehm: *"On Coverage and Capacity of Relaying in LTE Advanced in Example Deployments*", In Proc. IEEE PIMRC, September 2008

[4] www.mobilevce.com