

Reprint

W. Tong, E. Sich, P. Zhu, and J.M. Costa, "True broadband multimedia experience", *IEEE Microwave Magazine*, Vol. 9, No. 4, pp. 64-71, August 2008.

Copyright © 2008 IEEE. Reprinted from the *IEEE Microwave Magazine*, Vol. 9, No. 4, pp. 64-71, August 2008.

This material is posted here with permission of the IEEE. Internal or personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution must be obtained from the IEEE by sending an email message to

pubs-permissions@ieee.org

By choosing to view this document, you agree to all provisions of the copyright laws protecting it.

For instance, the first instantiation of 4G—the rollout of worldwide interoperability for microwave access (WiMAX) systems—is already well under way in the networks of many wireless operators, and several new entrants are planning nationwide and even continent-wide networks based on WiMAX. The 4G evolution of the universal mobile telecommunications system (UMTS) standard, called the long term evolution (LTE) project, is now being specified within the Third-Generation Partnership Project (3GPP). Similarly, 3GPP2 has specified the ultramobile broadband (UMB) standard to improve code division multiple access (CDMA) [1] for 4G applications and requirements.

As this pace continues, many in the industry consider the year 2010 to be the inflection point for 4G mobile broadband—the point at which 4G will be noticeably adding to second-generation (2G) and 3G infrastructures.

Numerous technology innovations that will fundamentally rewrite the economic equation for wireless access infrastructures are being developed and will pave the way for ubiquitous deployment of networks that support true broadband. From the compact 4G

base station, to new antenna designs, sophisticated scheduling algorithms, backhaul techniques, and multihop relay, this article describes the technological progress that will dramatically lower the cost per bit of over-the-air transmission while boosting data rates, capacity, coverage, reach, and throughput and improving spectral efficiency. For operators of all kinds—whether traditional 3G and 2G operators or new entrants—these technologies form the underlying pillars for evolving to and rolling out high-performance, multimedia 4G wireless networks and, ultimately, to supporting an affordable true broadband experience anywhere.

Enhancing the Broadband Wireless Experience

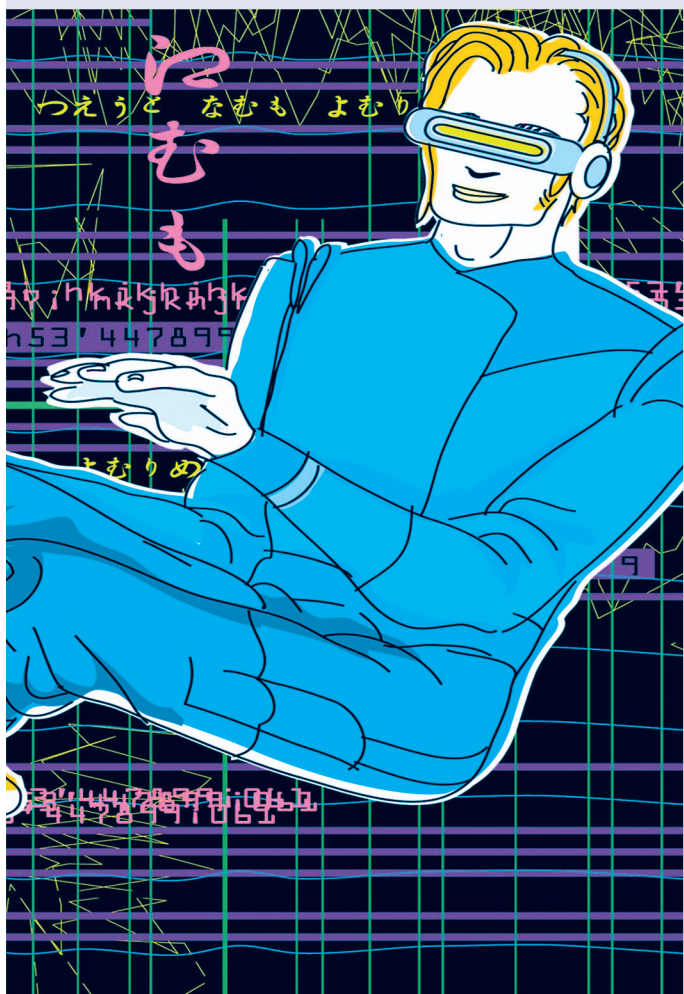
The drive to 4G is being fueled by the promise of access speeds of 1 Gb/s for low mobility such as nomadic/local wireless access users and 100 Mb/s for vehicular mobility. These speeds are part of the International Telecommunication Union (ITU) long-term vision (2010–2015) for systems beyond International Mobile Telecommunications–2000 (IMT-2000) [2], now referred to as IMT-Advanced [3]. The roadmap toward development of IMT-Advanced is described in another article in this issue of *IEEE Microwave Magazine* [4], as is a specific evolution from the IEEE 802.16 standard to IMT-Advanced [5].

4G is not solely about data rates, and it is certainly not faster 3G. Today's cellular 2G or 3G networks offer excellent quality for mobile voice, narrowband data in the form of text messaging and emails, and even rudimentary Web browsing and video transmission. This next wireless generation—the first to be based on an all-internet protocol (IP) network and thus the first to support all types of traffic on a single converged infrastructure—will substantially alter the definition and experience of mobile communications.

The 4G user experience will be characterized by seamless, high-bandwidth network connectivity, with access to any application regardless of device and location. High-quality and reliable delivery of unified communications sessions, virtual reality experiences, real-time video streaming, high-speed data, multimedia messaging, and high-definition mobile television will all become commonplace and affordable for wireless subscribers.

The transition to 4G will also be critical for supporting what is fast becoming a hyperconnected communications environment. More and more devices and machines, many of them mobile, are becoming IP-enabled and connected to the network, potentially far exceeding the number of humans using the network.

Wen Tong, Edward Sich, Peiyang Zhu, and José M. Costa are with Nortel Networks, Ottawa, Canada.



© DIGITAL VISION

As this trend continues, we will see an exponential growth in the number and types of users, applications, and services and a greater drive toward much richer experiences and more extensive mobile lifestyles.

The plethora of new, rich, mobile applications and services that can be made possible with 4G is, not surprisingly, attracting many players—both existing and new. Traditional wireless carriers are being joined by new entrants that are acquiring spectrum in new ways and moving into the broadband wireless space, including operators such as cable and satellite providers that are extending their infrastructures into the wireless world.

At the same time, Internet and information technology (IT) companies are coming to the wireless arena with entirely new business models. 2G operators also are keenly interested in accelerating the transition to 4G and evolving to true broadband using technology that allows them to leapfrog the incremental step to 3G to preserve their existing network investment.

4G Network Technology Challenges and Solutions

All of these existing players and new entrants have their eyes on opportunities being brought on by the transition to 4G, with its unprecedented jump in bandwidth, capacity, and multimedia capability. As 4G technologies and standards mature, the industry will take a giant step closer to realizing the long-held vision of a single, converged, packet-based “fat pipe” that will carry all wireless multimedia services with high quality and reliability, will scale easily to accommodate subscriber growth, and will provide users with whatever bandwidth they need, wherever they need it, simply and cost-effectively. Most importantly, 4G promises a true broadband experience, where mobile services will be delivered with enough capacity and transparency that users will be unaware of the underlying network.

This next era in the wireless industry is an exciting one from a technology perspective. The capabilities of 4G will not be achieved through a series of incremental improvements in capacity, spectral efficiency, and throughput.

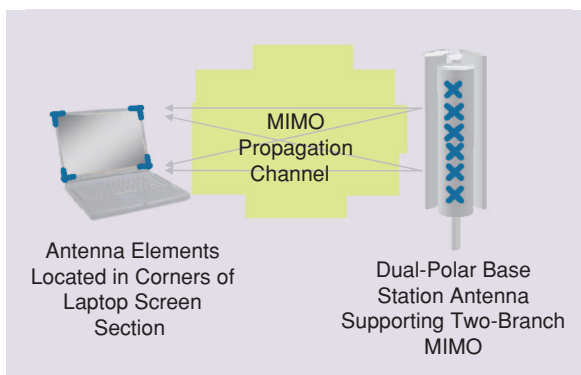


Figure 1. Example of MIMO transmission configurations.

Rather, the disruptive shift to a 4G architecture affords the opportunity to rethink and revamp nearly every function in the wireless access network, from the radio, antennas, base station, transport network (i.e., backhaul) all the way up to the core networks.

Interestingly, there are as many different schools of thought on 4G as there are providers. For some, 4G means high-capacity metro hot spots. For others, 4G is about enabling cheaper voice service, or achieving a better user experience in viewing or uploading video clips. Still others are looking to 4G for mobile video, broadband for the extended enterprise or home, or as a digital subscriber line (DSL) replacement. 4G is about enabling all of these scenarios by developing a common technology base to support all future 4G configurations, interoperability standards, and deployment strategies.

The foundational technology for 4G is based on the orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO) antenna processing technology. The use of the OFDM signaling for the macro cell and mobility is a fundamental change of the air-interface technologies; in addition, the use of multiple antenna technology at base station and user equipment device can significantly increase the spectrum efficiency and increase the peak user data rate. Moreover the combined OFDM-MIMO air interface can be implemented at even lower cost and reuse most of the existing cellsite infrastructure. Figure 1 shows an example of a downlink (DL) 2X2 MIMO configuration.

Researchers at Nortel's Wireless Technology Lab (WTL) are building a set of fundamental technologies that will establish a flexible base upon which to not only achieve the promise of mobile multimedia and high bandwidth, speed, and capacity across all 4G technologies, but also significantly alter the economic paradigm for mobility solutions to meet the following challenges [6]:

- *Provide dramatically lower operating expenditures (OpEx) and capital expenditures (CapEx):* A top priority for operators is to provide their subscribers with mobile broadband multimedia services that are both affordable and ubiquitous. Operators are faced with rising consumer pressure for mobile services delivered at the same prices that they pay for similar services in the wireline domain. Consumers are increasingly pushing the market, expecting to be able to do much more with their mobile devices than ever before, but with no increase in service price. For instance, consumers have come to expect a growing richness of functionality from the network and their devices, so that they can upload photos and movies, surf the Internet, engage in social networking by interacting with friends and colleagues via instant messaging, and so on—and they expect the price of these services to fall further over time. Increasingly, they also expect to be able to access those services everywhere they roam.

This requirement leads to an interesting technology challenge: provide a significant leap in capability and performance, while at the same time driving out cost and complexity to keep network capital and operating costs equal to, or preferably lower than, those of today's 3G networks. Certainly, OFDM-MIMO brings a significant improvement in spectral efficiency. As well, leveraging new silicon technologies (taking advantage of the ongoing progression of Moore's Law) and advances in materials technologies will be instrumental from the standpoint of lowering overall cost of ownership.

- *Support a wide variety of spectrum bands:* Spectrum is a key challenge for 4G systems, because of both the differing bandwidth requirements and the spectrum bands available globally. Whereas previous wireless generations all globally operate roughly in two major spectrum ranges (806–960 MHz and 1.7–2.2 GHz), new spectrum is spread across five additional bands—specifically, in parts of the 400- and 700-MHz bands and in the 2.3-, 2.5-, and 3.5-GHz bands. Therefore, unlike previous generations of wireless, 4G systems will not lend themselves to a single product in a globally coordinated agreed-upon band. As a result, radio frequency (RF) technology for 4G must be deployable in different markets and adjustable to a wide range of different frequency bands. Moreover, these new frequencies have completely different over-the-air transmission characteristics compared to the well-established mobile bands, raising new challenges in ensuring high quality of service.
- *Develop cost-effective high-performance cell-site solutions:* 4G will demand extremely high levels of performance and capability from the cell-site equipment. Multibranch antennas, for instance, will be required at the cell site to provide the greater coverage and range needed to support the growth in both subscribers and capacity. Adding antennas, however, raises significant issues with cabling from the base station to support those antennas. In conventional systems, such additions would place an impractical burden on the cell tower itself. There is an opportunity, therefore, to devise new cell-site architectures and technologies that integrate the base station with the antenna for placement at the tower top, thereby reducing and even eliminating the need for extra cabling.
- *Enable higher capacity for hot-spot deployment:* In a 4G-enabled wireless environment, the amount of high-bandwidth high-speed data traffic is expected to soar, especially for the high concentrations of users in dense urban environments and in-building office scenarios.
- *Provide more bandwidth in the backhaul portion of the network:* Network backhaul remains a traditionally lower-capacity technology, with backhaul

typically via microwave-based T1 and E1 links [7]. But as higher-bandwidth multimedia traffic from greater numbers of subscribers continues to crowd the airwaves, traffic levels at the point of backhaul will also rise. To cope with this growing traffic, a very-high-bandwidth backhaul solution will be required. Compounding this challenge is the fact that backhaul solutions are relatively expensive in terms of network build-out. As well, in certain regions, notably the United States, backhaul arrangements are typically lease arrangements, leased by operators from separate cable or cell-tower companies. New backhaul solutions therefore need to reach a much lower cost point, using a combination of optical and wireless solutions.

- *Support voice over IP (VoIP) applications:* Voice, which has been the *raison d'être* of cellular and wireless communications since the beginning of the industry, is also undergoing a transformation. With 4G, voice transmission will, for the first time, be carried over the same infrastructure as all other traffic. No longer will separate parallel circuit-switched and packet-switched networks be required for voice and data. Instead, all traffic will be carried on a single all-IP wireless network. Even more, 4G air interfaces, such as LTE or UMB, can deliver VoIP capacity that is three times greater than that of 3G interfaces. To reach these capacity levels, however, and to meet and even exceed the quality and reliability that users have come to expect in the 2G and 3G worlds, several difficult technical challenges need to be met to accommodate the different traffic behaviors and to deliver real-time voice and video. Here, innovations are required in the area of digital signal processing and scheduling algorithms.
- *Provide a cost-effective 4G evolution path from 2G and 3G:* Regardless of their starting points—whether 2G, 2.5G, or 3G—operators require an evolution path to 4G that is cost-effective and does not require a “rip and replace” of existing equipment. 4G solutions, therefore, need to coexist with today's infrastructures to enable operators to preserve their spectrum and extend their existing investments.

4G Technologies

The following are the key areas of the 4G technologies development that will have high impact on the 4G network development:

- new base station technologies
- advanced antenna designs, integration strategies, and configurations
- novel backhaul methods
- advanced digital signal processing techniques
- solutions for multihop relay.

Base Station Technologies

The focus on new base station technologies is a major priority in the industry, primarily because the base station represents the majority of the costs—both CapEx and OpEx—of the entire wireless infrastructure.

Compact 4G BTS Platform

By using advanced silicon technology, efficient power amplifiers and a new network timing and synchronization solution, a simpler, more cost-effective base station architecture can be achieved, the integrated 4G base transceiver station (BTS) represents a major departure from traditional base station design, and offers a dramatically smaller footprint that gives operators more flexible deployment options, along with a significant reduction in cell-site operations costs. As well, the BTS needs to support many different frequency bands to provide the flexibility for deployment in different markets and for various carriers.

Innovations in Antenna Design

4G systems are fundamentally based on MIMO technology, which essentially allows the creation of multiple parallel data streams between the multiple transmit and receive antennas. By exploiting the multipath phenomenon to differentiate among the multiple parallel signal paths between MIMO antennas, MIMO technology achieves a multifold user throughput gain and/or multiple aggregated capacity increase compared to current 3G macro-cellular networks.

The adoption of multiple antenna technology means that 4G systems will require new antenna designs that enable a range of deployment scenarios depending on operators' needs. For instance, incumbent operators with many existing cell sites would most likely be interested in antenna deployments that increase the capacity at each site. By contrast, new entrants deploying new cell sites would be looking to maximize capital investments by building as few sites as possible but equipping them with antennas that increase range. As well, because of the typically high costs involved with leasing cell sites, all players are demanding antennas that are compact and require a smaller footprint than previous generations.

Adaptive Antenna Technology

Technology is being developed that enables antennas to be directed at each user and to ensure that the transmission and reception of every packet is optimized for that user. This technology involves adaptive

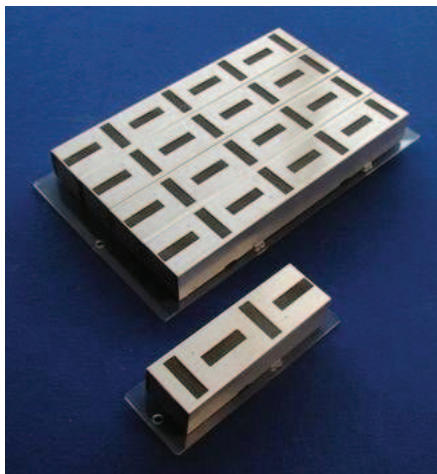


Figure 2. Prototype LCLW modular antenna for use in a Hex-MIMO solution.

beamforming techniques based on spatial division multiple access (SDMA). Adaptive algorithms that steer a beam toward the target user can be developed, effectively optimizing the transmission of each packet delivered to each user. The schedulers for assigning users and determining priorities for transmission can be developed. Earlier research demonstrated that OFDM-MIMO with multibeam technology can provide ten times higher capacity on the DL than current 3G baseline system deployments—and at one-tenth the cost [8].

Hex-MIMO

Another technology being actively pursued for a variety of 4G applications is a concept called Hex-MIMO, a configuration that uses compact, lightweight antenna arrays to provide six sectors per cell site versus the typical three, delivering valuable capacity and coverage gains in urban hot-spot deployments. This concept is based on both MIMO and SDMA techniques. Depending on the scenario, a Hex-MIMO solution can offer DL and uplink (UL) capacities in excess of two and one-half times that of conventional deployments. Figure 2 shows a prototype of Nortel's low-cost lightweight (LCLW) modular antenna design for use in a Hex-MIMO solution [9].

Closed-Loop MIMO Beamforming

For dense urban indoor and rural environments, researchers are working on antenna solutions that utilize four-branch receive and closed-loop MIMO transmission, also called closed-loop Eigen beamforming [10]. Essentially, Eigen beamforming concentrates radio signals and aims them at the targeted user in the complex propagation clutter environment, enabling high-quality signals to be delivered to users who are located in areas of weak or poor radio reception, such as indoors. Here, designers are developing a new algorithm and scheduler that can determine the optimum mode of transmission for each user's reception conditions. "Closed loop" refers to the feedback loop created by the continuous communication of channel information between the mobile and base station, thus enabling the base station to direct the virtual beam to a particular user, as illustrated in Figure 3 [10]. This contrasts with open loop whereby signal transmissions are spread more broadly.

Remote Radio Head

Another critical requirement in the antenna domain is ease of deployment. Because there typically is not much space on the cell-site towers to accommodate large antennas, next-generation antennas must therefore be much

more compact, while still offering higher capacity and throughput. The solution that integrates the antenna with the necessary electronics for deployment on the tower top is typically referred to as a remote radio head (RRH). This solution essentially puts a small, lightweight, highly reliable carrier-grade base station on top of the tower. The small size of the remote radio head brings new levels of flexibility for operators deploying 4G networks [11].

New Ideas for Backhaul

Wireless backhaul is another important area not only because equipping and operating the backhaul portion of the network consumes a significant portion of an operator's infrastructure costs, but also because the backhaul requirements in a 4G world will be an order of magnitude greater than in today's 3G networks. Indeed, if the bandwidth and cost challenges are not addressed, the point of backhaul has the potential to become a serious bottleneck in a 4G network. Wireless access backhaul, then, represents an important opportunity for new technology designs that lower overall costs and introduce greater levels of capacity and bandwidth. Several recent advancements in the carrier Ethernet area can be used. In particular, the provider backbone transport (PBT), as well as the provider link state bridging (PLSB) protocols for Ethernet radio-based wireless backhaul, to achieve carrier-grade availability and resiliency [12]. In addition, PLSB has strong potential for use in backhaul configurations, to optimize multimedia broadcast and multicast services.

Signal Processing

Digital signal processing (DSP) software—in the form of advanced scheduling algorithms—controls and optimizes the transmit and receive signals to and from the user's mobile device. This optimization is a diffi-

cult challenge in over-the-air environments, where channel quality can not be guaranteed and is much more vulnerable to undesirable channel fading, delay, and jitter than traffic in wireline environments. To date, signal processing in the wireless access portion of the network has focused on meeting the individual traffic characteristics of separate circuit-switched and packet-switched cellular voice and data networks.

A 4G wireless access system that supports all types of traffic (voice, data, video) on a single converged IP network and directs this multimedia traffic through a single interface brings new DSP-related challenges. Not only must the software overcome the inherent over-the-air transmission characteristics, but it must also meet the different traffic behaviors and requirements of new types of services and a variety of user devices. For example, to ensure that users are provided with optimal transmission and reception for a particular service—whether real-time voice, real-time high-bandwidth streaming video, or lower-priority data, for instance—the scheduler must now determine priority for multiple types of traffic, change the coding modulation depending on the channel conditions, and change the MIMO transmission modes according to both the robustness and throughput needed for each service and user type.

The development of a new scheduling algorithm, along with new adaptive coding modulation schemes and radio resource management software are critical enablers for supporting voice over IP and delivering a high quality of service.

Mobile Multihop Relay

Mobile multihop relay is an emerging technology that will enhance coverage and capacity for 4G deployments, such as WiMAX.

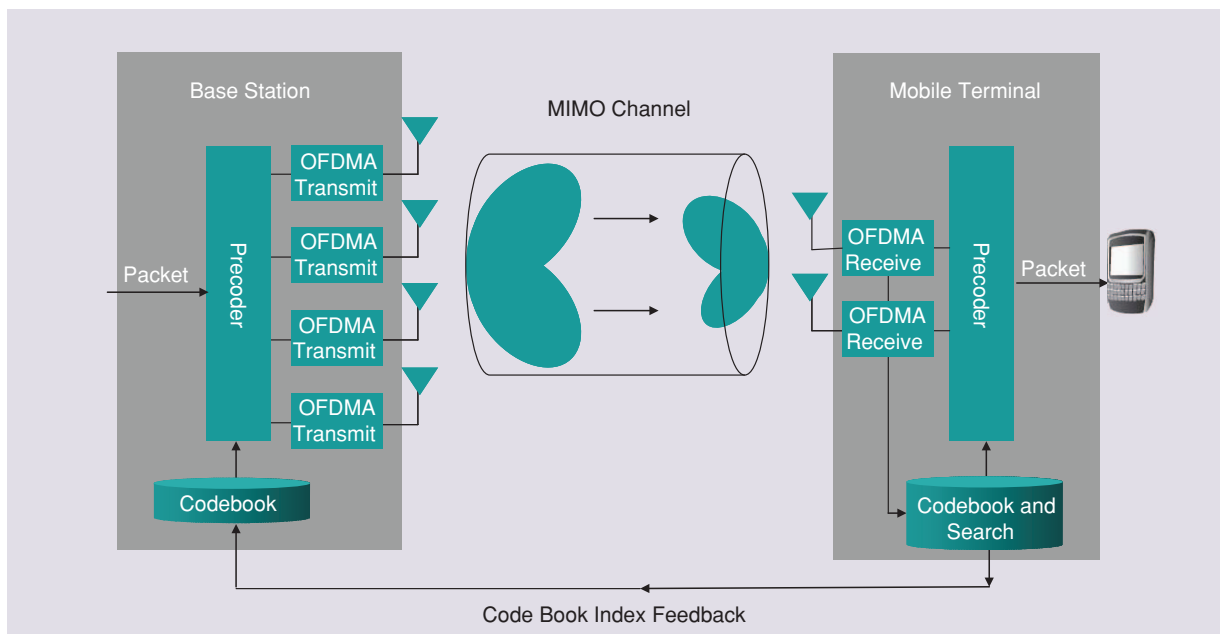


Figure 3. Architectural view of closed-loop MIMO beamforming.

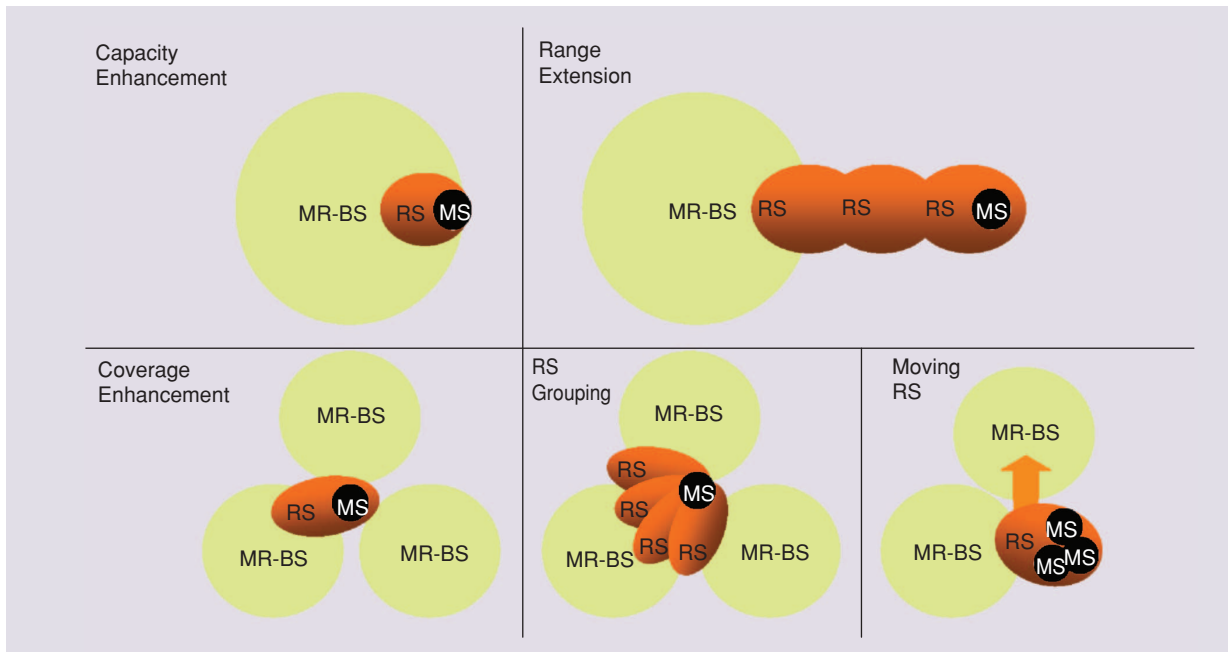


Figure 4. Various multihop relaying modes.

In a multihop relay architecture, communication between the base stations and mobile terminals can be extended and improved through a number of intermediate relay stations; various multihop relaying modes are shown in Figure 4 [13]. These relays enable signals to hop between them, without having to communicate back to the base station. In this way, relays can be used in a variety of deployments to provide many advantages. For instance, relays can help extend the network, allowing operators to effectively reduce the

number of cell sites needed for coverage—a solution that is especially attractive to new entrants. Relays can also be deployed to fill holes or shadowing caused by environmental obstacles (such as buildings, or corners within buildings), which can lead to weak signal reception and thus lower data rates.

Technology Roadmap and Summary

Table 1 shows the capabilities and several key performance metrics for various generations of wireless

TABLE 1. Characteristic performance metrics of representative wireless access technologies.									
		TDMA	CDMA		OFDMA + 2 × 2 MIMO (4G)				
		EDGE	1 × EV-DO Rev. A	HSPA (Rel.6)	WiMAX		UMB	LTE	
Channel Bandwidth (MHz)		0.200	1.25	5	1.25, 2.5, 5, 10, 20, 3.75, 7, 8.75		1.25 to 20	1.4, 1.6, 3, 5, 10, 15, 20	
TDD (2:1)/FDD		FDD	FDD	FDD	TDD (10 MHz)	FDD (5 + 5 MHz)	FDD (5 + 5 MHz)	TDD (10 MHz)	FDD (5 + 5 MHz)
Peak data rate (Mbit/s)	DL	0.384	3.1	10.8	37.44	28.63	37.25	47.48	37.5
	UL	0.384	1.8	5.76	5.04	7.56	19.5	9.33	12.5
Aggregate per carrier-sector throughput (Mbit/s)	DL	0.16	0.95	2.6	7.88	5.25	8.1	11.93	7.95
	UL	0.16	0.45	1.5	2.55	3.83	4.0	2.5	3.75
Spectral efficiency (bits/s/Hz/carrier-sector)	DL	0.1	0.76	0.52	1.28		1.62	1.59	
	UL	0.1	0.36	0.3	0.72		0.8	0.79	

access technologies. The metrics for both the CDMA and OFDMA (with 2×2 MIMO) technologies are based on the following assumptions. Frequency division duplex (FDD) assumes a 5-MHz bandwidth in the DL, and 5 MHz in the UL. Time division duplex (TDD) is based on a total 10-MHz bandwidth with DL:UL ratio 2:1. For OFDMA, the peak data rate in the DL is based on 64 quadrature amplitude modulation (QAM), and in the uplink, 16 QAM. For CDMA, the DL is 16 QAM and the UL is based on quadrature phase-shift keying (QPSK). Spectrum reuse for both CDMA and OFDMA is equal to 1, and signaling overheads are included. Furthermore, since the standards are evolving the values in the table may be different for future versions of the specifications.

While the different 4G air interfaces, notably WiMAX and LTE, meet different market needs and are marching down separate evolution paths, our development is to deliver a single converged platform that will support both of these technologies. This convergence is made possible by the fact that all 4G technologies are built upon the same foundations—OFDM and MIMO.

With the advance of the enabling technologies, the common architectures, technologies, and platforms that will underpin and support all flavors of 4G and easily adapt to support evolved 4G technologies that will appear in the future.

With WiMAX and LTE following different evolution paths, a similar evolution of technologies to support them is expected over the next five years. We also expect the development of new hot-spot technologies and new network elements, including nodes that support relay technology [14] and femto cells, which can be realized by means of Home NodeBs (HNBs) [15].

With respect to LTE, standards work is scheduled to be completed by the end of 2008, with a complete set of specifications developed by the 3GPP technical specification groups (TSGs) Radio Access Network (RAN), Services and System Aspects (SA), and Core Network and Terminals (CT). These specifications will cover the end-to-end LTE system—from the air interface to network evolution [16].

Another exciting technology revolution in the 4G landscape is occurring in the end-user mobile terminal and handset industry. Many vendors in the consumer electronics mass market are recognizing the tremendous potential of 4G connectivity and are quickly developing open devices, open source software, and open applications, which will give subscribers easy access to the richness of the broadband multimedia services and facilitate a true broadband experience.

As technology innovations progress and standards mature, the 1-Gb/s (nomadic) and 100-Mb/s (vehicular mobility) access speeds envisioned by the ITU will become reality. Soon, it will become second nature to expect that the same advanced broadband multimedia and communications-enabled capabilities offered in the

wireline environment will also be available and affordable in the wireless world, providing users with a ubiquitous true broadband experience.

Acknowledgments

The authors are grateful to the guest editor of this special issue, Dr. Ferdo Ivanek, for his guidance and constructive suggestions.

References

- [1] 3GPP2. (2007, Sept.). 3GPP2 publishes Ultra Mobile Broadband (UMB) Specification. Press Release. [Online]. Available: http://www.3gpp2.org/Public_html/News/Release_UMBSpecification_24SEP2007.pdf
- [2] ITU. (2003). Framework and overall objectives of the future development of IMT 2000 and systems beyond IMT 2000. Recommendation ITU-R M.1645 [Online]. Available: <http://www.itu.int/rec/R-REC-M.1645/en>
- [3] ITU (2007). Naming for International Mobile Telecommunications. ITU-R Resolution 56. [Online]. Available: <http://www.itu.int/publ/R-RES-R.56/en>
- [4] A. Hashimoto, H. Yoshino, and H. Atarashi, "Roadmap of IMT-Advanced Development," *IEEE Microwave Mag.*, vol. 9, no. 4, pp. 80–88.
- [5] R.B. Marks, J.M. Costa, and B. Kiernan. "The Evolution of WirelessMAN," *IEEE Microwave Mag.*, vol. 9, no. 4, pp. 73–80.
- [6] V. Nandlall, Ed Sich, W. Tong, and P. Zhu. (2008, Mar.). Advanced technologies for 4G: Mobile broadband multimedia everywhere. *Nortel Tech. J.* [Online]. no. 6, pp. 4–20. Available: http://www.nortel.com/corporate/news/collateral/ntj6_wireless.pdf
- [7] J.M. Costa, "DS1 Services and Standards," in *The Froehlich/Kent Encyclopedia of Telecommunications*, vol. 6. New York: Marcel Dekker, 1993, pp. 361–382 [Online]. Available: <http://people.itu.int/~costa/pub/DS1.pdf>
- [8] S. Beaudin, D. Choi, B. Lehman, and B. Morris. (2008, Mar.). Technology innovations behind Nortel's WiMAX base station: The industry's most compact and efficient 4G platform. *Nortel Tech. J.* [Online]. no. 6, pp. 8–10. Available: http://www.nortel.com/corporate/news/collateral/ntj6_wireless.pdf
- [9] D. Adams and A. Jeffries. (2008, Mar.). High-performance Hex-MIMO antenna technology for cost-effective 4G. *Nortel Tech. J.* [Online]. no. 6, pp. 11–13. Available: http://www.nortel.com/corporate/news/collateral/ntj6_wireless.pdf
- [10] C. Chan and W. Tong. (2008, Mar.). Closed-loop MIMO beamforming: Taking MIMO transmission the "extra mile". *Nortel Tech. J.* [Online]. no. 6, pp. 14–15. Available: http://www.nortel.com/corporate/news/collateral/ntj6_wireless.pdf
- [11] Nortel. (2008). Solution Brief—Nortel WiMAX 802.16e Portfolio. [Online]. Available: <http://www.nortel.com/solutions/wimax/collateral/nn116820.pdf>
- [12] D. Allan, P. Ashwood-Smith, and N. Bragg. (2008, Mar.). New innovations in ethernet: Provider link state bridging. *Nortel Tech. J.* [Online]. no. 6, pp. 21–30. Available: http://www.nortel.com/corporate/news/collateral/ntj6_plsb.pdf
- [13] H. Zhang and P. Zhu. (2008, Mar.). The many advantages of mobile multi-hop relay technology. *Nortel Tech. J.* [Online]. no. 6, pp. 16–18. Available: http://www.nortel.com/corporate/news/collateral/ntj6_wireless.pdf
- [14] R.B. Marks, M. Nohara, J. Puthenkulam, and M. Hart. (2006, Mar.). IEEE 802 Tutorial: 802.16 mobile multihop relay. IEEE 802.16mmr-06/006. Presented at IEEE 802.16 Session #42, Denver, CO. [Online]. Available: http://wirelessman.org/sg/mmr/docs/80216mmr-06_006.zip
- [15] Nortel and Vodafone. (2007, Aug.) Open and closed access for home NodeBs. R4-071231. Presented at 3GPP TSG-RAN WG4 Meeting #44, Athens, Greece. [Online]. Available: http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_44/Docs/R4-071231.zip
- [16] 3GPP. (2007). TSG Organization. 2007 [Online]. Available: <http://www.3gpp.org/tb/home.htm>

