RYSAVY RESEARCH

Mobile Broadband Explosion

The 3GPP Wireless Evolution

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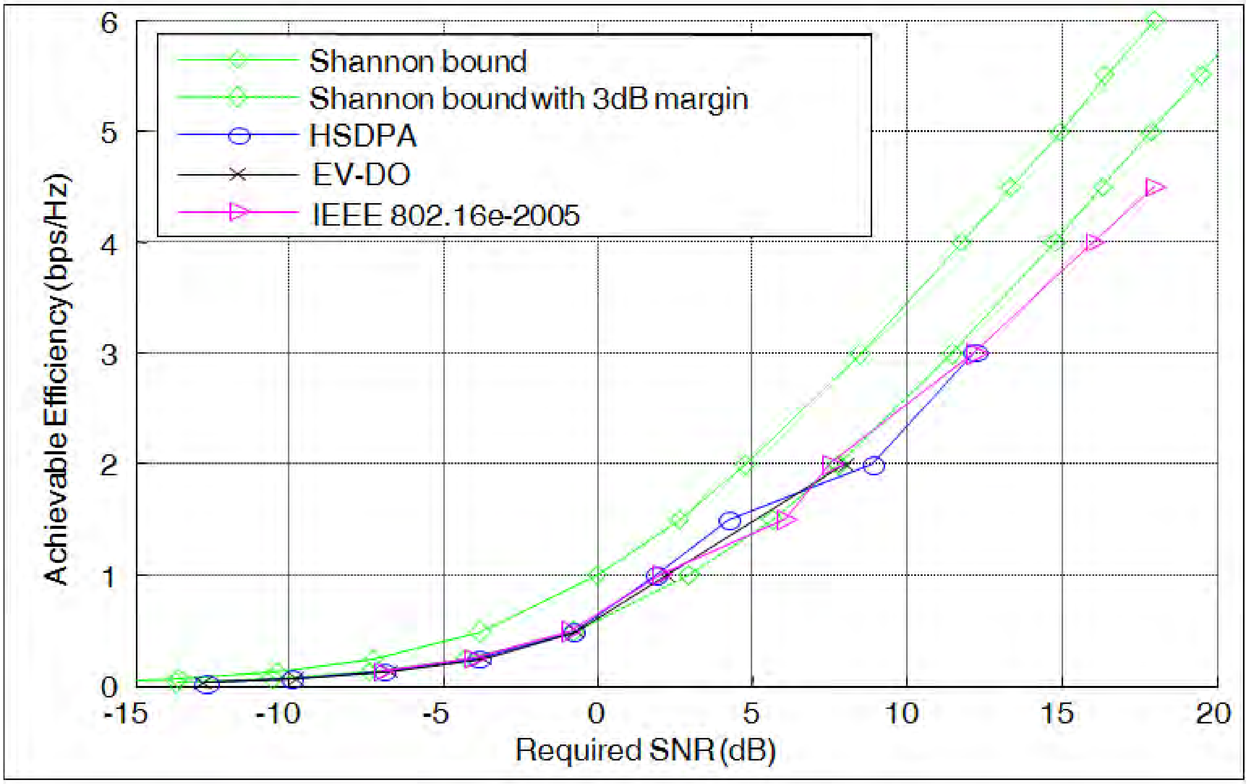
Spectral Efficiency

The evolution of data services is characterized by an increasing number of users with ever-higher bandwidth demands. As the wireless data market grows, deploying wireless technologies with high spectral efficiency is of paramount importance. Keeping all other things equal, including frequency band, amount of spectrum, and cell site spacing, an increase in spectral efficiency translates to a proportional increase in the number of users supported at the same load per user—or, for the same number of users, an increase in throughput available to each user.

Increased spectral efficiency, however, comes at a price because it generally involves greater complexity for both user and base station equipment. Complexity can arise from the increased number of calculations performed to process signals or from additional radio components. Hence, operators and vendors must balance market needs against network and equipment costs. OFDMA technologies are attractive because they achieve higher spectral efficiency with lower overall complexity, especially in larger bandwidths. The roadmap for the EDGE/HSPA/LTE family of technologies provides a wide portfolio of options that increase spectral efficiency.

When determining the best area on which to focus future technology enhancements, it is interesting to note that HSDPA, 1xEV-DO, and IEEE 802.16e-2005 all have highly optimized links—that is, physical layers. In fact, as shown in Figure 23, the link layer performance of these technologies is approaching the theoretical limits as defined by the Shannon bound. (The Shannon bound is a theoretical limit to the information transfer rate [per unit bandwidth] that can be supported by any communications link. The bound is a function of the Signal to Noise Ratio of the communications link.) Figure 23 also shows that HSDPA, 1xEV-DO, and IEEE 802.16e-2005 are all within 2 to 3 decibels (dB) of the Shannon bound, indicating that there is not much room for improvement from a link-layer perspective.

Figure 1: Performance Relative to Theoretical Limits for HSDPA, EV-DO, and IEEE 802.16e-2005[1]



The curves in Figure 23 are for an Additive White Gaussian Noise Channel (AWGN). If the channel is slowly varying and the frame interval is significantly shorter than the coherence time, the effects of fading can be compensated for by practical channel estimation algorithms—thus justifying the AWGN assumption. For instance, at 3 km per hour, and fading at 2 GHz, the Doppler spread is about 5.5 Hz. The coherence time of the channel is thus 1 second (sec)/5.5 or 180 msec. Frames are well within the coherence time of the channel, because they are typically 20 msec or less. As such, the channel appears "constant" over a frame and the Shannon bound applies. Furthermore, significantly more of the traffic in a cellular system is at slow speeds (for example, 3 km/hr or less) rather than at higher speeds. The Shannon bound is consequently also relevant for a realistic deployment environment.

As the speed of the mobile station increases and the channel estimation becomes less accurate, additional margin is needed. This additional margin, however, would impact the different standards fairly equally.

The focus of future technology enhancements is on improving system performance aspects that reduce interference to maximize the experienced Signal to Noise Ratios (SNRs) in the system and antenna techniques (such as MIMO) that exploit multiple links

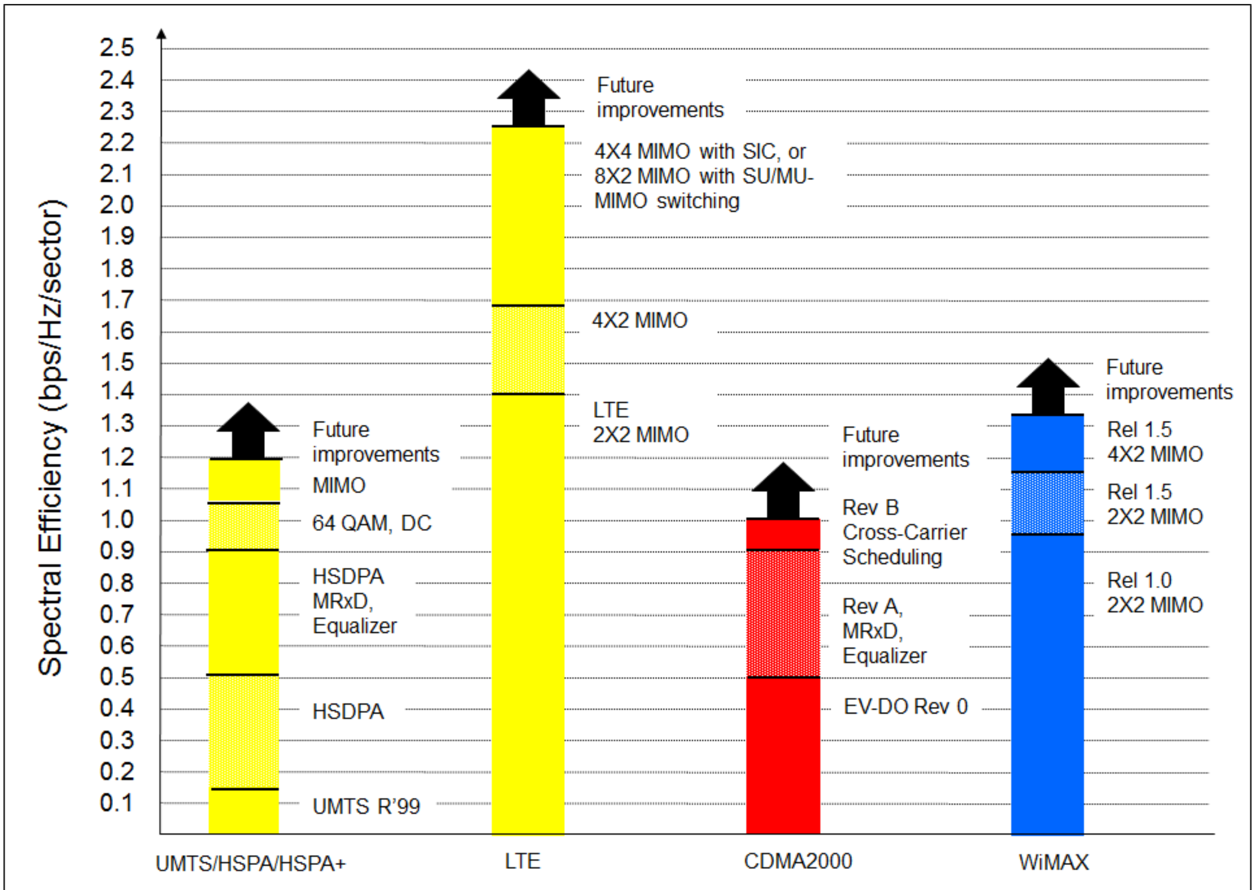
[1] Source: A 4G Americas member company.

rather than on investigating new air interfaces that attempt to improve link-layer performance.

MIMO techniques using spatial multiplexing to increase the overall information transfer rate by a factor proportional to the number of transmit or receive antennas do not violate the Shannon bound because the per-antenna transfer rate (that is, the per-communications link transfer rate) is still limited by the Shannon bound.

Figure 24 compares the spectral efficiency of different wireless technologies based on a consensus view of 4G Americas contributors to this paper. It shows the continuing evolution of the capabilities of all the technologies discussed. The values shown are reasonably representative of real-world conditions. Most simulation results produce values under idealized conditions; as such, some of the values shown are lower (for all technologies) than the values indicated in other papers and publications. For instance, 3GPP studies indicate higher HSDPA and LTE spectral efficiencies. Nevertheless, there are practical considerations in implementing technologies that can prevent actual deployments from reaching calculated values. Consequently, initial versions of technology may operate at lower levels but then improve over time as designs are optimized. Therefore, readers should interpret the values shown as achievable, but not as the actual values that might be measured in any specific deployed network.

Figure 2: Comparison of Downlink Spectral Efficiency[2]



The values shown in Figure 24 are not all possible combinations of available features. Rather, they are representative milestones in ongoing improvements in spectral efficiency. For instance, there are terminals that employ mobile-receive diversity but not equalization.

The figure does not include EDGE, but EDGE itself is spectrally efficient at 0.6 bps/Hz using mobile receive diversity and potentially 0.7 bps/Hz with MIMO. Relative to WCDMA Release 99, HSDPA increases capacity by almost a factor of three. Type 3 receivers that include Minimum Mean Square Error (MMSE) equalization and Mobile Receive Diversity (MRxD) effectively double HSDPA spectral efficiency. The addition of dual-carrier operation and 64 QAM increases spectral efficiency by about 15%, and MIMO can increase spectral efficiency by another 15%, reaching 1.2 bps/Hz. HSPA+ exceeds WiMAX Release 1.0 spectral efficiency. Dual-carrier HSPA+ offers a gain in spectral efficiency from cross-carrier scheduling with possible gains of about 10%.[3] With Release 8,

[2] Joint analysis by 4G Americas members. 5+5 MHz FDD for UMTS-HSPA/LTE and CDMA2000, and 10 MHz TDD DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.

[3] Source: 4G Americas member analysis. Vendor estimates for spectral-efficiency gains from dual-carrier operation range from 5% to 20%. Lower spectral efficiency gains are due to full-buffer traffic assumptions. In more realistic operating scenarios, gains will be significantly higher.

operators can deploy either MIMO or dual-carrier operation. With Release 9, dual-carrier operation can be combined with MIMO.

Some enhancements, such as 64 QAM for HSPA, are simpler to deploy than other enhancements, such as 2X2 MIMO. The former can be done as a software upgrade, whereas the latter requires additional hardware at the base station. Thus, the figure does not necessarily show the actual progression of technologies that operators will deploy to increase spectral efficiency.

Beyond HSPA, 3GPP LTE will also result in further spectral efficiency gains, initially with 2X2 MIMO, and then optionally with SIC, 4X2 MIMO, and 4X4 MIMO. The gain for 4X2 MIMO will be 20% more than LTE with 2X2 MIMO; the gain for 4X4 MIMO in combination with successive interference cancellation will be 60% more than 2X2 MIMO, reaching 2.25 bps/Hz. This assumes a simplified switched-beam approach defined in Release 8. This same spectral efficiency of 2.25 bps/Hz is also achievable in Release 10 using 8X2 MIMO in combination with SU/MU MIMO switching (which provides a 60% gain over 2X2 MIMO). CoMP, discussed in the appendix, provides a minimal contribution to spectral efficiency.

LTE is even more spectrally efficient with wider radio channels of 10+10 MHz and 20+20 MHz, although most of the gain is realized at 10+10 MHz. LTE TDD has spectral efficiency that is within 1% or 2% of LTE FDD.[4]

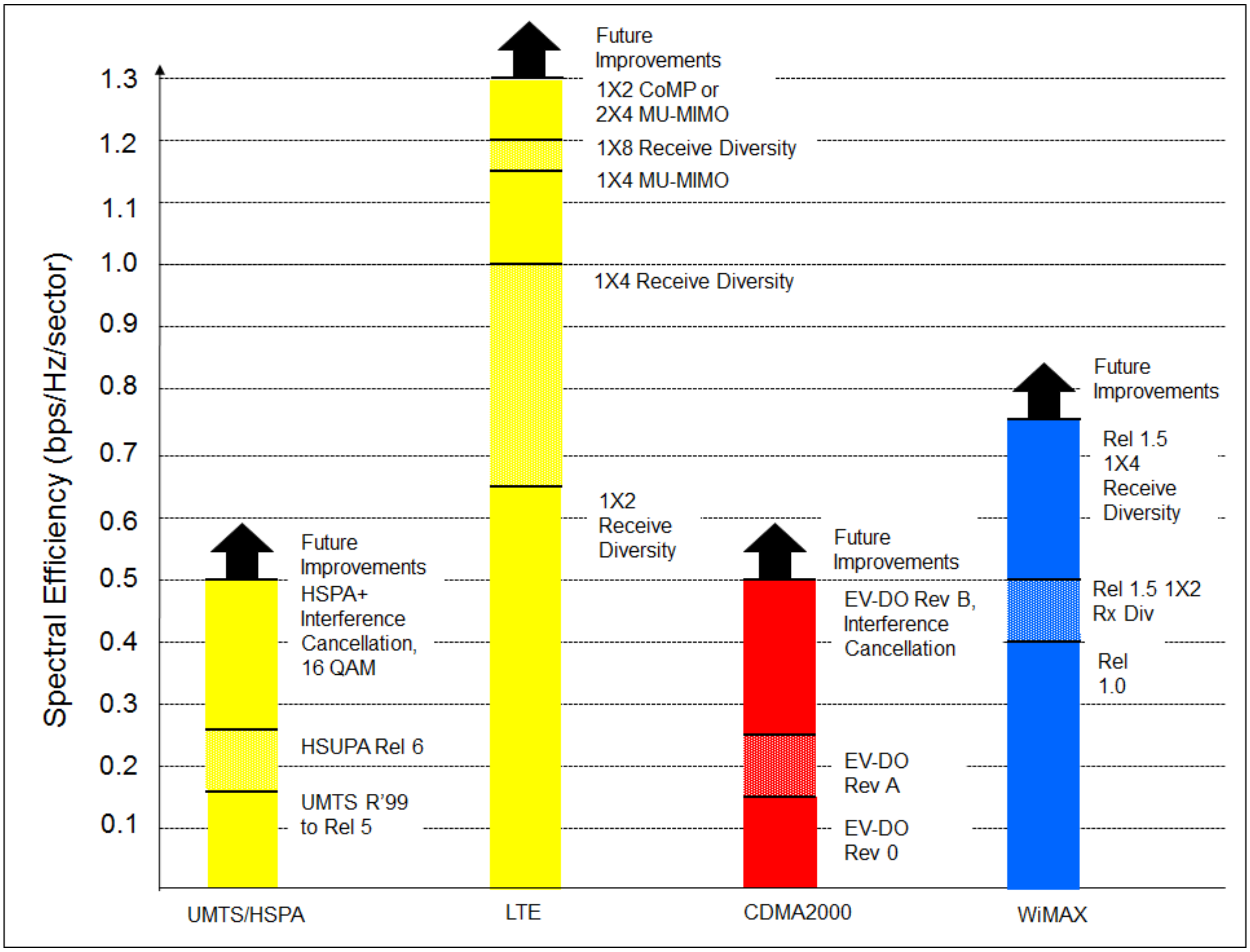
Similar gains to those for HSPA and LTE are available for CDMA2000. CDMA2000 spectral efficiency values assume seven carriers deployed in 10+10 MHz. The EV-DO Rev. 0 value assumes single receive-antenna devices. As with HSPA, spectral efficiency for EV-DO increases with a higher population of devices with mobile-receive diversity. These gains are assumed in the Rev. A spectral-efficiency value of .9 bps/Hz.

Mobile WiMAX also experiences gains in spectral efficiency as various optimizations, including mobile receive diversity (MRxD) and MIMO, are applied. WiMAX Release 1.0 includes 2X2 MIMO. Enhancements to WiMAX come with Release 1.5 and IEEE 802.16m. Because there are no commitments by any operators to deploy IEEE 802.16m networks at this time, the analysis does not include this technology.

Figure 25 compares the uplink spectral efficiency of the different systems.

[4] Assumes best-effort traffic. There is a difference in performance between LTE-TDD and FDD for real-time traffic for the following reasons: a.) The maximum number of HARQ process should be made as small as possible to reduce the packet re-transmission latency. b.) In FDD, the maximum number of HARQ process is fixed and, as such, the re-transmission latency is 7ms. c.) For TDD, the maximum number of HARQ process depends on the DL:UL configurations. As an example, the re-transmission latency for TDD config-1 is 9ms. d.) Because of higher re-transmission latency, the capacity of real-time services cannot be scaled for TDD from FDD based on the DL:UL ratio.

Figure 3: Comparison of Uplink Spectral Efficiency[5]



The implementation of HSUPA in HSPA significantly increases uplink capacity, as does Rev. A and Rev. B of 1xEV-DO, compared with Rel. 0. OFDM-based systems can exhibit improved uplink capacity relative to CDMA technologies, but this improvement depends on scheduling efficiency and other factors, as well as the exact deployment scenario.

With LTE, spectral efficiency increases by use of receive diversity. Initial systems will employ 1X2 receive diversity (two antennas at the base station). 1X4 diversity will increase spectral efficiency by 50% to 1.0 bps/Hz and 1X8 diversity will provide a further 20% increase from 1.0 bps/Hz to 1.2 bps/Hz. These receive diversity improvements could also be implemented on HSPA+ and CDMA2000 networks.

It is also possible to employ Multi-User MIMO (MU-MIMO), which allows simultaneous transmission by multiple users on the uplink on the same physical resource to increase spectral efficiency. MU-MIMO will provide a 15% to 20% spectral efficiency gain, with

[5] Joint analysis by 4G Americas members. 5+5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.

actual gain depending on how well link adaptation is implemented. The figure uses a conservative 15% gain, showing MU-MIMO with a 1X4 antenna configuration increasing spectral efficiency by 15% to 1.15 bps/Hz and 2X4 MU-MIMO a further 15%, to 1.3 bps/Hz.

In Release 11, uplink CoMP using 1X2 will double spectral efficiency from .65 bps/Hz to 1.3 bps/Hz. Many of the techniques used to improve LTE spectral efficiency can also be applied to HSPA since they are independent of the radio interface.

Figure 26 compares voice spectral efficiency.

Figure 4: Comparison of Voice Spectral Efficiency[6]

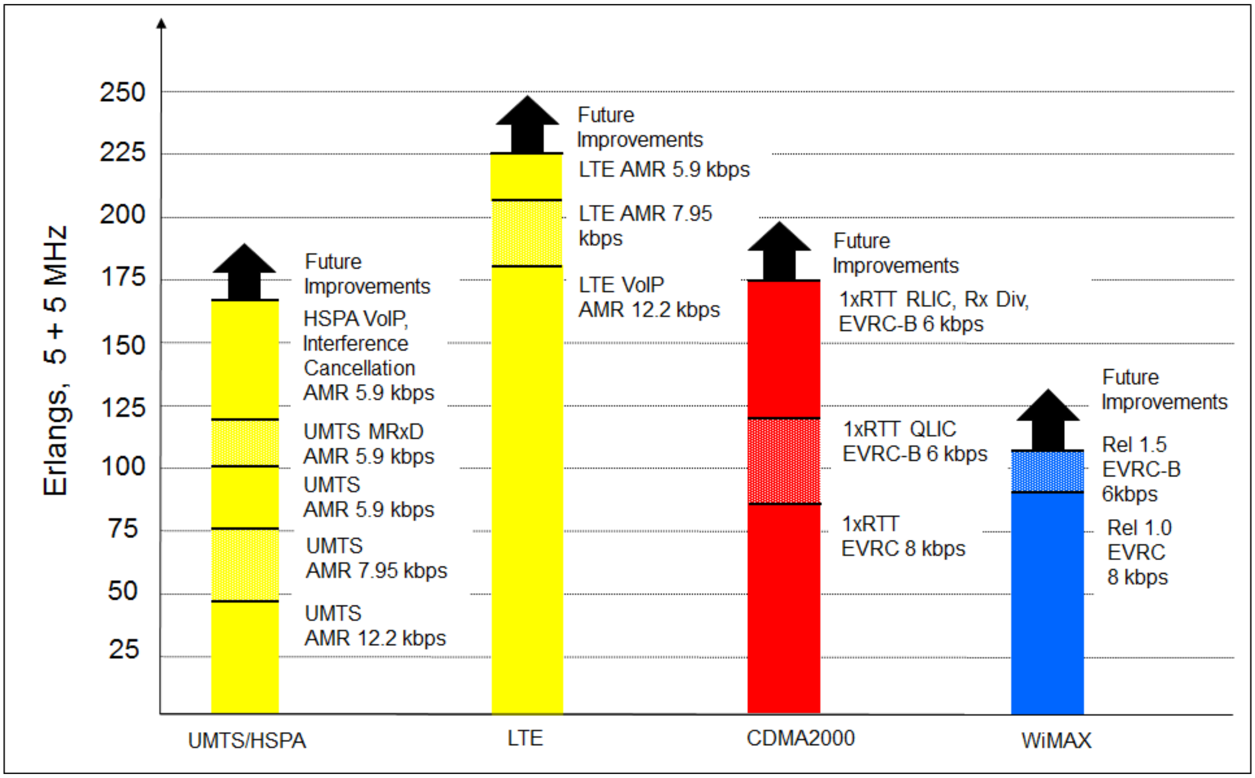


Figure 26 shows UMTS Release 99 with AMR 12.2 Kbps, 7.95 Kbps, and 5.9 Kbps vocoders. The AMR 12.2 Kbps vocoder provides superior voice quality in good (for example, static and indoor) channel conditions. UMTS has dynamic adaptation between vocoder rates, enabling enhanced voice quality compared with EVRC at the expense of capacity in situations that are not capacity limited. With the addition of mobile receive diversity, UMTS circuit-switched voice capacity could reach 120 Erlangs in 5+5 MHz.

Opportunities will arise to improve voice capacity using VoIP over HSPA channels. VoIP Erlangs in this paper are defined as the average number of concurrent VoIP users that can be supported over a defined period of time (often one hour) assuming a Poisson arrival process and meeting a specified outage criteria (often less than 2% of the users

[6] Source: Joint analysis by 4G Americas members. 5 + 5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz TDD DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.

exhibiting greater than 1% frame-error rate). Depending on the specific enhancements implemented, voice capacity could double over existing circuit-switched systems. These gains do not derive through use of VoIP, but rather from advances in radio techniques applied to the data channels. Many of these same advances may also be applied to current circuit-switched modes.

LTE achieves very high voice spectral efficiency because of better uplink performance since there is no in-cell interference. The figure shows LTE VoIP spectral efficiency using AMR at 12.2 Kbps, 7.95 Kbps and 5.9 Kbps.

1xRTT has voice capacity of 85 Erlangs in 5+5 MHz with EVRC-A and reaches voice capacity of 120 Erlangs with the use of Quasi-Linear Interference Cancellation (QLIC) and EVRC-B at 6 Kbps.

CDMA2000 1X Advanced significantly increases voice capacity. The figure shows two features that will provide enhancement prior to the full feature set of 1X Advanced: Reverse Link Interference Cancellation (RLIC) and receive diversity in the devices, which increase voice capacity to 175 Erlangs.

VoIP for LTE can use a variety of codecs. The figures show performance assuming specific codecs at representative bit rates. For Enhanced Variable Rate Codecs (EVRCs) the figure shows the average bit rate.

WiMAX voice capacity is shown at 90 Erlangs for Release 1.0 and 105 Erlangs for Release 1.5. Changing the Downlink:Uplink (DL:UL) ratio from 29:18 to 23:24 increases spectral efficiency by 50% because now 18 data symbols per frame are allocated for the UL compared with 12. Persistent scheduling and changing the DL:UL from 23:24 to 20:27 delivers a further gain of 15%.[7] Changing this ratio, however, may not be practical if the same carrier frequency must support both voice and data. Alternatively, voice and data can operate on different radio carriers using different TDD ratios.

[7] Source: IEEE Communications Magazine, Mo-Han Fong and Robert Novak, Nortel Networks, Sean McBeath, Huawei Technologies, Roshni Srinivasan, Intel Corporation, “Improved VoIP Capacity in Mobile WiMAX Systems Using Persistent Resource Allocation,” October, 2008.