Beyond 3G

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Beyond 3G is the official IEEE designation for the next stage of wireless technology that some people call 4G or fourth-generation radio. Over the years, every conceptual shift in wireless technology has been characterized as a generational change. With a good dose of hindsight, the generations of radio and major radio systems in each category are classified as shown in Table 1. Few first generation (or 1G) systems remain, except in the United States, where AMPS (Advanced Mobile Phone System) remains a background universal service. Most services are now second generation (or 2G) dominated by Global System for Mobile Communications (GSM) but also with widespread development of code-division multiple access (CDMA). CDMA is a conceptual advance on the 2G systems typified by GSM and so is commonly classified as 2.5G. Third generation (or 3G) offers a significant increase in capacity and is the optimum system for broadband data access. Third generation includes wideband mobile multimedia networks and broadband mixed wireless systems. The mobile systems support variable data rates depending on demand and the level of mobility. Typically 144 kb/s is supported for full vehicular mobility and higher bandwidths for pedestrian levels of mobility. Switched packet radio techniques and wideband CDMA-like systems (as the physical channel is) rather than assigned physical channel schemes (referred to as circuit switched) are required to support this bandwidth-on-demand environment.

There are two essential concepts beyond 3G. One of these is the provision of data transmission at rates of 100 Mb/s while mobile and 1 Gb/s while stationary. The other concept is that of pervasive networks where a handset supports many access technologies (e.g., cellular, UMTS, and WiFi) perhaps simultaneously and smoothly transitions between them. For example, to support

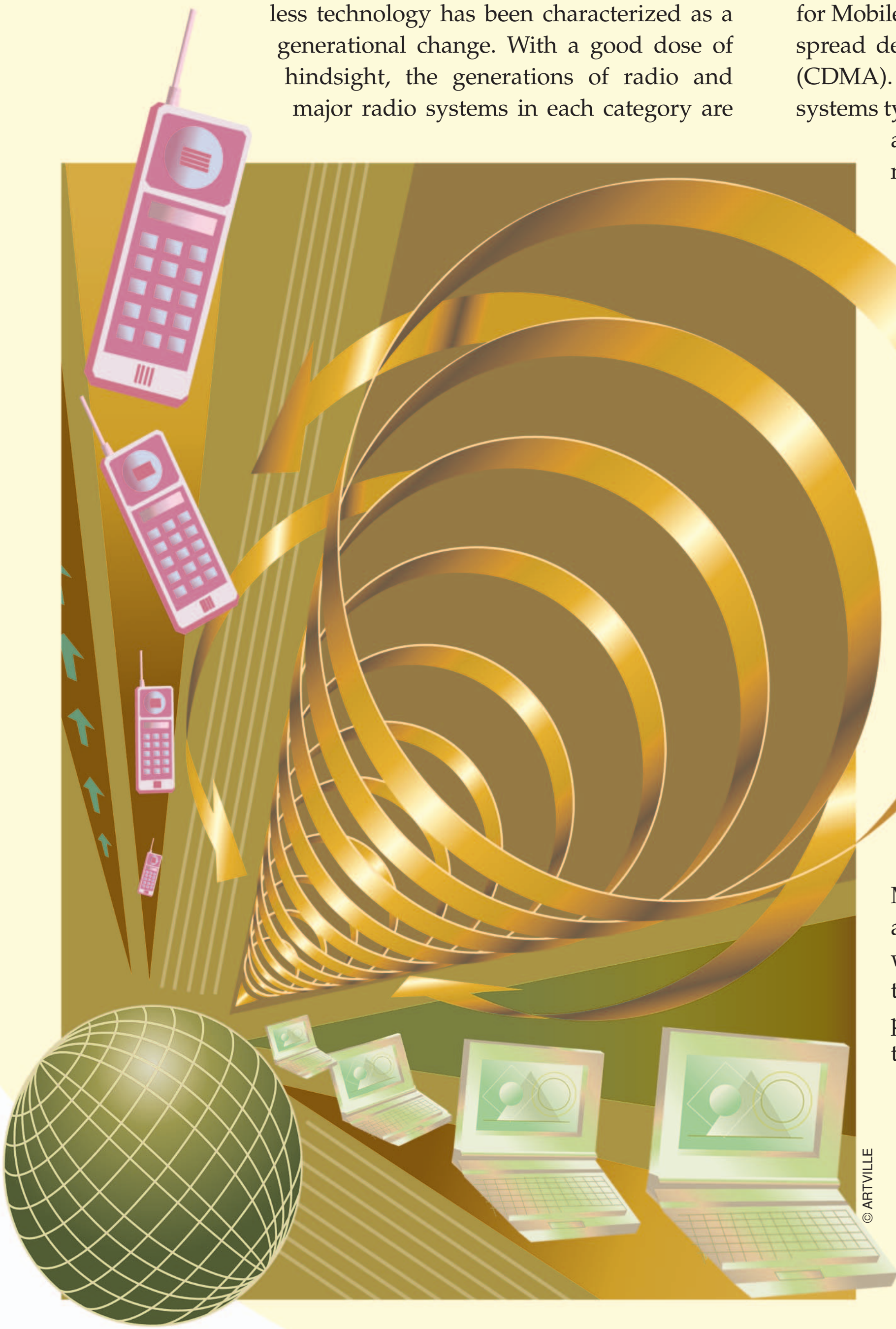

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TABLE 1. Major mobile communication systems with year of first widespread use.		
System	**Year**	**Description**
0G		Broadcast, no cells, few users, analog modulation
MTS	1946	Mobile Telephone Service, half duplex, operator assist to establish call, push-to-talk
AMTS	1965	Advanced Mobile Telephone System, Japan, full-duplex, 900 MHz
IMTS	1969	Improved Mobile Telephone Service, full duplex, up to 13 channels, 60–100 km (40–60 mile) radius, direct dial using DTMF (dual tone multi-frequency) keypad.
0.5G		FDMA, analog modulation
PALM	1971	(also Autotel) Public Automated Land Mobile radiotelephone service, used digital signaling for supervisory messages, technology link between IMTS and AMPS.
ARP	1971	AutoRadioPuhelin (Car Radio Phone), obsoleted in 2000, used cells (30 km radius) but not hand-off. 80 channels at 150 MHz, half-duplex and latter full duplex
1G		Analog modulation, FSK for signaling, cellular, FDMA
NMT	1981	Nordic Mobile Telephone, 12.5 kHz channel, 450 MHz, 900 MHz
AMPS	1983	Advanced Mobile Phone System, 30 kHz channel
TACS	1985	Total Access Communication Systems, 25 kHz channel, widely used up to 1990s, similar to AMPS
Hicap	1988	NTT's mobile radiotelephone service in Japan
Mobitex	1990	National public access wireless data network, first public access wireless data communication services including two-way paging network services, 12.5 kHz channel, GMSK
DataTac	1990	Point-to-point wireless data communications standard (like Mobitex), wireless wide area network, 25 kHz channels, max bandwidth 19.2 kb/s (used by the original BlackBerry device)
2G		Digital modulation
PHS	1990	Personal Handyphone System, originally a cordless phone, now functions as both a cordless phone and as a mobile phone
GSM	1991	Global System for Mobile Communications (formerly Groupe Spécial Mobile), TDMA, GMSK, constant envelope, 200 kHz channel, max. 13.4 kb per timeslot (at 1900 MHz), 2 billion customers in 210 countries
DAMPS	1991	Digital AMPS, narrowband, (formerly NADC for North American Digital Cellular and prior to that as USDC for U.S. Digital Cellular), *pi*/4DQPSK, 30 kHz channel
PDC	1992	Personal Digital Cellular, Japan, 25 kHz channel
cdmaOne	1995	Brand name of first CDMA system known as IS-95. spread spectrum, CDMA, 1.25 MHz channel, QPSK
CSD	1997	Circuit Switched Data, original data transmission format developed for GSM, max. bandwidth 9.6 kb/s, uses a single timeslot
2.5G		Higher data rates
WiDEN	1996	Wideband Integrated Dispatch Enhanced Network, combines four 25 kHz channels, max. bandwidth = 100 kb/s
GPRS	2000	General Packet Radio System, compatible with GSM network, used GSM time slot and higher-order modulation to send 60 kb per time slot, 200 kHz channel, max. bandwidth = 171.2 kb/s
HSCSD	2000	High-Speed Circuit-Switched Data, compatible with GSM network, max. bandwidth = 57.6 kb/s, based on CSD, higher quality of service than GPRS
2.75G		Medium bandwidth data—1 Mb/s
CDMA2000	2000	CDMA, upgraded cdmaOne, double data rate, 1.25 MHz channel
EDGE	2003	Enhanced Data rate for GSM Evolution, compatible with GSM network, 8PSK, TDMA, max. bandwidth = 384 kb/s, 200 kHz channel
3G		Spread spectrum
FOMA	2001	Freedom of Mobile Multimedia Access, first 3G service, NTT's implementation of WCDMA
UMTS		Universal Mobile Telephone Service, 5 MHz channel, data up to 2 Mb/s
• WCDMA	2004	Main 3G outside China
• OFDMA	2007	Evolution to 4G (downlink high bandwidth data)
1xEV-DO		(IS-856) Evolution of CDMA2000, max. downlink bandwidth 307 kb/s, max. uplink bandwidth 153 kb/s.
TD-SCDMA	2006	Time division synchronous CDMA, China. Uses the same band for transmit and receive, base stations and mobiles use different time slots to communicate, 1.6 MHz channel
GAN/UMA	2006	Generic access network, formerly known as unlicensed mobile access, provides GSM and GPRS mobile services over unlicensed spectrum technologies (e.g., Bluetooth and WiFi.)
3.5G		
HSDPA	2006	High-speed downlink packet access, high download speeds up to 14.4 Mb/s, incorporated in UMTS
3.75G		
HSUPA	2007	High-speed uplink packet access, high upload speeds up to 5.76 Mb/s, incorporated in UMTS
4G		Low latency (e.g., for VoIP) + MIMO + OFDM + wireless broadband (WBB, > 100 Mb/s) + software defined radio

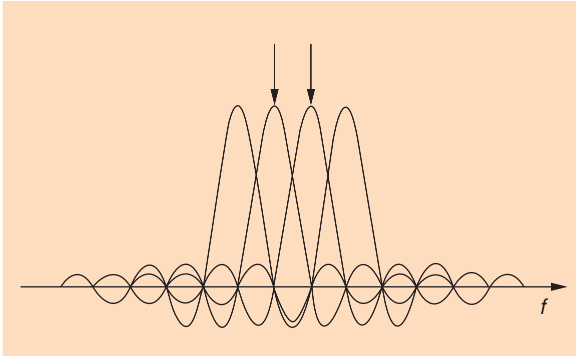

Figure 1. *OFDM spectrum showing orthogonality.*

high-speed data, it is more efficient to use an available WiFi network than a UMTS network.

Two technological advances that enable the high-data-rate concept are the bases of the evolution of cellular communications and wireless networks. One advance is OFDM, for orthogonal frequency division multiplexing, which sends multiple relatively slow bit streams with one of the bit streams on each of a large number of carriers. OFDM reduces the impact of fading as symbols are spread out over relatively long periods of time. The other advance is MIMO, for multiple input, multiple output, which relies on multipath to send multiple versions of several bit streams transmitted from several antennas. These schemes are discussed below and with them it is possible to greatly increase spectral efficiency.

OFDM

In OFDM, data is simultaneously sent over multiple channels or subcarriers with the special property that the subcarriers are orthogonal and precisely spaced in frequency. Each subcarrier is modulated independently so each becomes a subchannel carrying its own data stream. This is shown in the spectrum of Figure 1 where the arrows at the top indicate sampling points for two subcarriers. The subcarriers are ideally orthogonal. This can be seen in part by noticing that the peak of one subcarrier is at the zeros of the other subcarriers. When one subcarrier is sampled, the contribution from all other carriers is zero—they are orthogonal. The spectra of the subcarriers overlap but this does not matter. This scheme enables high-speed data transmission over possibly hostile channels of an unregulated band. OFDM is a spread-spectrum technique as data is spread over a large number of subcarriers. The impact of the multipath is mitigated as each subcarrier has a relatively narrow bandwidth or, in time, a long duration. Thus, having in effect many relatively slow bit streams, the impact of multipath on can be reduced relative to a single high-speed bit stream. Signal strength and interference, and hence signal-to-interference ratio (SIR), can differ for each channel, and this can be compensated for by having different bit rates in each subchannel and adjusting the power level in each subchannel.

OFDM can be implemented by using separate modulators and demodulators for each subcarrier. It is also possible and more practical to replace the separate modulators and demodulators by a fast Fourier transform (FFT) and an inverse FFT (IFFT), respectively, implemented in a digital signal processor (DSP). This FFT/IFFT implementation of OFDM is called discrete multitone (DMT) or OFDM/DMT. Here the subcarriers share a common carrier and the frequency outputs of the FFT of the data stream are the subcarriers. Generally each subcarrier has its own bit stream, and the total bit stream is carried on perhaps 256 subcarriers. With forward error correction (FEC) coding, a large fraction of the bits could be lost (because individual subcarriers collide with other signals) but the data stream can still be recovered.

Unfortunately the peak-to-average power ratio (PAR) of OFDM is large. As a result, nonlinear distortion in the RF front end is more of a problem than with other signal types and hence the need for more linear amplifiers. An approximation of the problem is to view an OFDM signal as the composite of a large number of tones. In practice the PAR is reduced through clipping of the signal in DSP (and hence some data is lost). However, using coding it is possible to recover from these errors and regenerate the missing bits. In the ideal situation the subcarriers are orthogonal, but timing and frequency offsets cause the subchannels to interfere with each other. This interference can be reduced by limiting the number of subchannels and also by using special pulse shapes that are more robust to timing errors.

OFDM is the transmission method for digital radio, digital TV, high-speed wireless local and metropolitan area networks [WLAN and WMAN respectively, e.g., WiFi (specifically IEEE 802.11a WLAN standard achieving 54 Mb/s [1]–[3]) and WiMax (specifically IEEE 802.16 WMAN standard achieving 18.36 Mb/s [4]–[6])], and broadband Internet over phone lines in a digital subscriber line (DSL). OFDM achieves close to maximum spectral efficiency. The OFDM system implemented in IEEE Standard 802.11a, one form of WiFi, uses several modulation formats with different throughputs; see Table 2. The difference between the number of data bits per symbol and the number of coded bits per symbol is the coding added in the DSP for error correction and to provide additional information about the channel. The ratio of the number of data bits to the number of code bits is the coding rate.

The system described in IEEE Standard 802.16, generally known as WiMax, also uses OFDM. It is designed to cover a wide geographical area and hence is designated as a WMAN. It is a cellular system implementing universal frequency reuse with cells that are typically a few kilometers in diameter. The downlink throughput typically averages 3 Mb/s over a 5-MHz bandwidth when there is a single antenna at the receiver and with a trisector transmit antennas. In the same 5-MHz bandwidth, 7 Mb/s can be achieved with two receive antennas and with six-sector cells (and hence lower interference from other cells). WiMax uses several modulation formats as shown in Table 3. Higher-order modulation such as 64-QAM can only be achieved when interference is low.

Capacity

The concept of spectral efficiency is important in contrasting different radio and modulation systems. Spectral efficiency has its origins in Shannon's theorem that expresses the information carrying capacity of a channel as

$$\hat{C} = B_c \ln(1 + S/N) \qquad (1)$$

where $\hat{C}$ is the capacity in units of bits per second, B_c is the channel bandwidth in hertz, and S and N are signal and noise powers so S/N is the signal-to-noise ratio (SNR). N is assumed to be Gaussian noise so interference that can be approximated as Gaussian can be incorporated by adding the noise and interference powers and then it is more appropriate to use SIR. Then Shannon's capacity theorem (1) becomes

OFDM reduces the impact of fading as symbols are spread out over relatively long period of time.

$$\hat{C} = B_c \ln[1 + S/(N + I)] = B_c \ln(1 + \text{SIR}). \qquad (2)$$

Shannon's theorem cannot be proved but is widely accepted as the upper limit on the information carrying capacity of a channel. So the stronger the signal, or the lower the interfering signal, the greater a channel's information carrying capacity. Indeed if there is no noise and no interference, the information carrying capacity is infinite. Shannon's capacity formula (2) tells us that increasing the interference level, and hence resulting in a lower SIR, has a weakened effect on the decrease in capacity than may initially be expected. That is, doubling the interference level does not halve $\hat{C}$. This is the conceptual insight that supports the use of closely packed cells and frequency reuse as the resulting increase in interference, and its moderated effect on capacity is offset by having more cells.

TABLE 2. Modulation formats of the OFDM WLAN system denoted IEEE Standard 802.11a generally known as WiFi [1]–[3].

Data Rate (Mb/s)	Modulation	Coding Rate	Coded Bits per Subcarrier	Code Bits per OFDM Symbol	Data Bits per OFDM Symbol
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	64	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	1/2	4	192	144
48	16-QAM	3/4	4	288	192
54	64-QAM	2/3	6	288	216

TABLE 3. Modulation formats of the OFDM WLAN system denoted IEEE Standard 802.16d with a 5 MHz bandwidth generally known as WiMax [4]–[6].

Data Rate (Mb/s)	Modulation	Coding Rate	Coded Bits per Subcarrier	Code Bits per OFDM Symbol	Data Bits per OFDM Symbol
1.89	BPSK	1/2	0.5	176	88
3.95	QPSK	1/2	1	368	184
6.00	QPSK	3/4	1.5	512	280
8.06	16-QAM	1/2	2	752	376
12.18	16-QAM	3/4	3	752	568
16.30	64-QAM	2/3	4	1140	760
18.36	64-QAM	3/4	4.5	1136	856

OFDM is a spread-spectrum technique as data is spread over a large number of subcarriers.

Shannon's capacity-carrying limit has not been reached but today's radio systems are very close. Different modulation and radio schemes come closer to the limit, and two quantities are introduced to describe the performance of different schemes. From the capacity formula we can define a useful metric for the performance of modulation schemes. This is the channel efficiency (or channel spectrum efficiency, or sometimes channel spectral efficiency)

$$\eta_c = R_c/B_c \tag{3}$$

where R_c (as bits per second) is the bit rate transmitted on the channel so η_c has the units of bits per second per hertz (b/s/Hz). The unit b/s/Hz is dimensionless as hertz has the units of s^{-1} but using b/s/Hz is a reminder of the meaning of the quantity. (Similarly decibels is dimensionless but is an important qualifier.)

In a cellular system, the numbers of cells in a cluster must also be incorporated to obtain a system metric [7]. The available channels are divided among the cells in a cluster, and a channel in one cell appears as interference to a corresponding cell in another cluster. Thus the SIR is increased, and the capacity of the channel drops. System throughput increases, however, because of closely packed cells. So the system throughput is a function of the frequency reuse pattern. The appropriate system metric is the radio spectrum efficiency η_r which incorporates the number of cells K in a cluster

$$\eta_r = \frac{R_b}{B_c K} = \frac{\eta_c}{K}\frac{R_b}{R_c}. \tag{4}$$

Here R_b is the bit rate of useful information and discounts the channel bit rate R_c (R_c is higher than R_b because of coding). Coding is used to enable error correction, assist in identifying the start and end of a packet, and provide orthogonality of users in some systems that overlap users as with CDMA. The units of η_r are bits per second per hertz per cell or b/s/Hz/cell. The decrease in channel capacity resulting from the increased SIR associated with fewer and thus closer cells in a cluster, i.e., lower K, is more than offset by the increased system throughput.

There are two definitions of spectral efficiency; one is the channel spectrum efficiency η_c that characterizes the efficiency of a modulation scheme and the other the radio spectrum efficiency η_r that incorporates the added interference that comes from frequency reuse. Indeed the frequency reuse interference dominates noise in a cellular system, and background noise is often ignored in evaluating performance. Commonly both measures of efficiency are referred to as spectral efficiency and then only the units distinguish which is being referred to. In summary:

- $\hat{C}$ is a theoretical maximum channel bit rate for a given set of conditions.
- R_c is the actual channel bit rate for a given set of conditions.
- R_b is the actual channel bit rate for a given set of conditions minus overhead associated with coding.

MIMO

MIMO technology uses multiple antennas to transmit and receive signals. The MIMO concept was developed in the 1990s [8]–[10] and implemented in a variety of WLAN systems and evolving cellular communications standards. There are several aspects to MIMO. First, each transmit antenna sends different data streams simultaneously on the same frequency channel as used by other transmit antennas. Then the most interesting feature is that MIMO relies on signals traveling on multiple paths between an array of transmit antennas and an array of receive antennas. In a conventional communications system, the various paths result in interference and fading, but in MIMO these paths are used to carry more information. In a MIMO system, each path propagates an image of one transmitted signal (from one antenna) that differs in both amplitude and phase from the images following other paths. Each image arrives at one of the receive

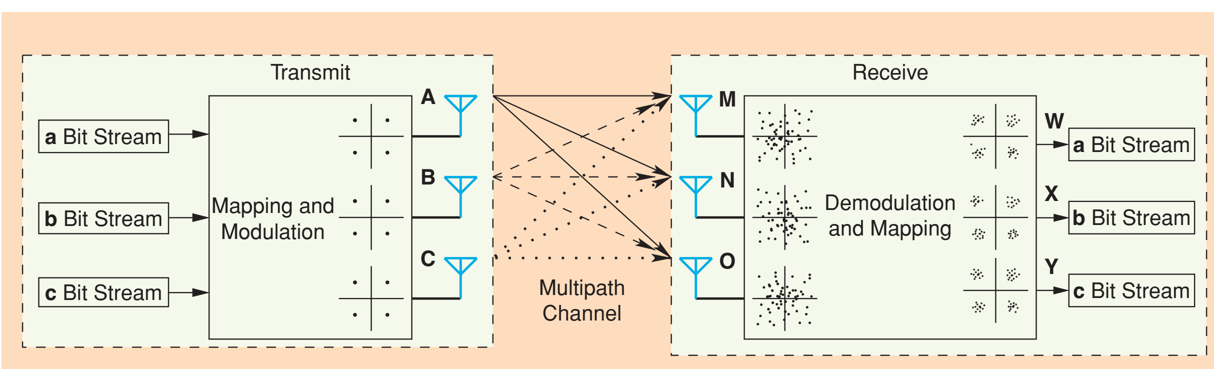

Figure 2. *A MIMO system showing multiple paths between each transmit antenna and each receive antenna.*

antennas at slightly different times and the phase differences are used to differentiate between them. Effectively there are multiple connections between each transmit antenna and each receive antenna; see Figure 2. For simplicity three transmit antennas and three receive antennas are shown here. MIMO, however, can work with as few as two transmit and one receive antennas but the capacity is much higher with more. The high-speed data stream is split into several slower data streams shown in Figure 2 as the **a**, **b**, and **c** data streams. The bit streams are mapped so different versions of the data streams are combined, modulated, and sent from each transmit antenna with the constellation diagrams labeled **A**, **B**, and **C**. The signal from each transmit antenna reaches all of the receive antennas by following different paths.

The output of each receive antenna is a linear combination of the multiple transmitted data streams with the sampled RF phasor diagrams labeled **M**, **N**, and **O**. (It is not really appropriate to call these constellation diagrams.) That is, each receive antenna has a different linear combination of the multiple images. In effect the output from each receive antenna can be thought of as the solution of a linear equation with each path corresponding to an equation. Continuing the analogy, the signal from each transmit antenna represents a variable. So the set of simultaneous equations can be solved to obtain the original bit streams. This is accomplished by demodulation and mapping with some knowledge of the channel characteristics yielding the original transmitted signals modified by interference. The result is that the constellation diagrams **W**, **X**, and **Y** are obtained. The composite channel can be characterized using test signals. Special coding called space-time (or spatiotemporal) coding embedded in the transmitted data stream also enables estimation of the communication matrix. Space-time coding encodes each transmitted data stream with information that can be used to assist in reconstructing the signals on the others. This is more robust than characterizing the channel with test signals sent at a different time.

OFDM is the transmission method for digital radio, digital TV, high-speed wireless local and metropolitan area networks, and broadband Internet over phone lines in a digital subscriber line.

With the advent of MIMO, it is necessary to modify Shannon's capacity limit as MIMO systems can exceed the Shannon limit defined for a single channel. Shannon's capacity limit for a MIMO system becomes

$$\hat{C} = B_c \ln(1 + \mathrm{SIR} \times H) \quad (5)$$

where H is a MIMO capacity factor that depends on $\min(M, N)$ and effectively multiplies the SIR [12].

TABLE 4. Capacity of MIMO schemes with PSK modulation for different received SIRs (signal-to-interference ratios) compared to the maximum capacity of a conventional non-MIMO scheme. M is the number of transmit antennas, N is the number of receive antennas. Data is from [11].

	Capacity (b/s/Hz—bits per second per Hertz)				
	Non-MIMO $M = 1$,	MIMO with $M = 2, N = 2$			
Modulation Scheme	$N = 1$ Maximum	SIR 0 dB	SIR 10 dB	SIR 20 dB	SIR 30 dB
BPSK	1	1.2	2	2	2
QPSK	2	1.6	3.7	4	4
8PSK	3	1.6	4.8	6	6
16PSK	4	1.6	4.9	7.5	8

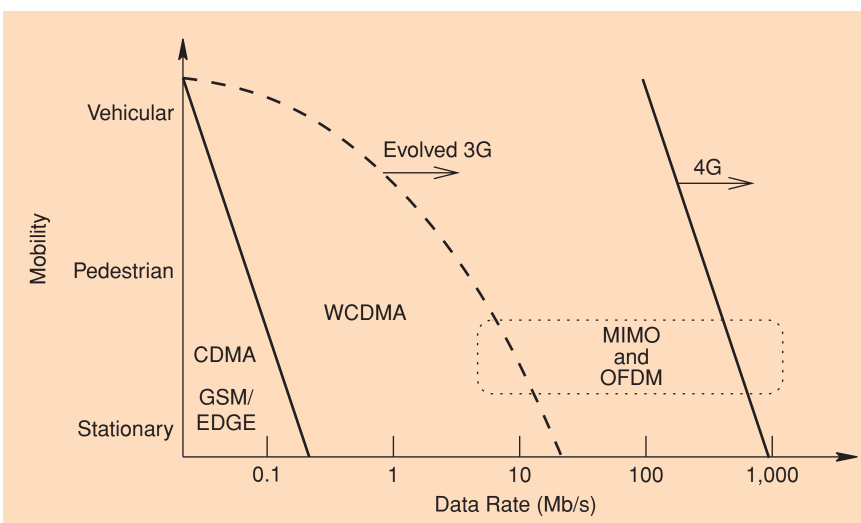

Figure 3. *Data rate capacity of evolved 3G and beyond cellular communications.*

In a MIMO system, each path propagates an image of one transmitted signal that differs in both amplitude and phase from the images following other paths.

The capacity of a MIMO system with high SIR scales approximately linearly with the minimum of M and N, $\min(M, N)$, where M is the number of transmit antennas and N is the number of receive antennas (provided that there is a rich set of paths) [12], [13]. So a system with $M = N = 4$ will have four times the capacity of a system with just one transmit antenna and one receive antenna. With less than optimum conditions, only slightly less capacity is obtained. Table 4 presents the capacity of a MIMO system with ideal phase-shift keying (PSK) modulation (i.e., without modifications to control PAR) and two transmit and two receive antennas. This is compared to the capacity of a conventional (non-MIMO) system. The capacity is presented in bits per second per hertz, and we see that significant increases in throughput are obtained when SIR is high. MIMO is incorporated in the WiMax (IEEE 802.16d) and WiFi (IEEE 802.11n) standards where spectral efficiencies of 6.35 b/s/Hz have been achieved in commercial systems.

In summary, MIMO systems achieve throughput and range improvements through four gains achieved simultaneously:

1) Array gain resulting from increased average received SNR obtained by coherently combining the incoming and outgoing signals. To exploit this, the channel must be characterized. This increases coverage and quality of service (QoS).
2) Diversity gain obtained by presenting the receiver with multiple identical copies of a given signal and this combats fading. This also increases coverage and QoS.
3) Multiplexing gain by transmitting independent data signals from different antennas to increase throughput. This increases spectral efficiency.
4) Cochannel interference reduction. This increases cellular capacity.

MIMO can be combined with spreading to obtain a scheme denoted MIMO-CDMA. MIMO-CDMA achieves greater capacity than MIMO-OFDM when SIR is low, generally below 10 dB [14]. At high SIR, however, MIMO-OFDM achieves higher capacity than MIMO-CDMA.

Summary

There seems little doubt that Beyond 3G cellular communication technologies will be based on a combination of OFDM and MIMO (MIMO-OFDM) or a combination of MIMO and CDMA (MIMO-CDMA). There is a tremendous increase in channel-carrying capacity especially when the SIR is high. The data-rate capacity of 2G systems (GSM and CDMA) is contrasted with the capacity of 3G (WCDMA) and what are called evolved 3G and 4G systems in Figure 3. Evolved 3G (evolved third-generation cellular) incorporates many of the features of 4G. Fourth generation is the implementation of MIMO and OFDM or CDMA technologies with space-time coding. To be an effective RF hardware designer, engineers need to become intimately familiar with the properties of signals and understand the concepts behind increasingly sophisticated communications.

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