Wireless Bandwidth in the Making

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ABSTRACT

Several emerging communication technologies hold the key to approaching the information theoretic limits of wireless multiple access channels. This article offers a brief review of those technologies and their promise to meet future demand for wireless data rate.

BANDWIDTH VS. "BANDWIDTH"

One of the defining features of the information technology industry is the unrelenting exponential growth of the "bandwidth," or data rate capacity, sustained by data communication networks and, in particular, the Internet. Likewise, the global demand for wireless "bandwidth" exhibits, now and in the foreseeable future, strong exponential growth. New wired network "bandwidth" is created when new physical resources (cable, fiber, routers, etc.) are added to the network. In sharp contrast, wireless communication requires sharing a finite natural resource: the radio frequency spectrum. The radio frequency (RF) bandwidth allocated by regulatory agencies to cellular wireless services has steadily grown in the last two decades. For example, in the United States, the 40 MHz allocated to first-generation cellular telephony in 1983 grew to 50 MHz with the advent of the second generation at the end of the 1980s, and to 170 MHz in 1995. While pressure will continue on regulatory agencies to release more and more bandwidth for wireless access, competing interests and fundamental physical laws dictate that the RF bandwidth allocated to mobile wireless services will cease to grow significantly in the not-too-distant future.

The exponential demand for wireless "bandwidth" coupled with the very limited supply of RF bandwidth direct a potent spotlight on physical-layer communications engineering. Although bandwidth is not equal to "bandwidth," they are intimately related through the laws of information theory. As shown by Claude Shannon in 1948, the maximum spectral efficiency (bits per second per Hertz) a channel can sustain depends on its statistical behavior and various design parameters such as transmitted power. The fundamental limitations on reliable data transmission posed by Shannon's capacity laws keep the realm of wireless communication beyond the reach of Moore's law on the exponential growth of computing capabilities. Fortunately, technological advances in integration enable designs whose data rates are closer and closer to the information theoretic limits. Those limits are much harder to analyze for wireless channels than for wired channels because not only are the channel models more complex but, as we will see later, the distributed nature of radio waves offers new challenges and opportunities.

ACHIEVING CAPACITY: WIRED VS. WIRELESS

The viewpoint of this article is that the bandwidth of wireless multi-user channels remains underutilized and much more spectrally efficient designs are feasible. This is in marked contrast to channels such as the voiceband telephone channel, in which current commercial modems operate fairly close to capacity. The technology transfer from theory to practice has occurred at a slower pace in wireless than in other systems. Indeed, most of the key coding/decoding and signal processing techniques used in existing commercial cellular systems were invented more than three decades ago. In contrast, the spectrally efficient technology of trellis-coded modulation invented in the early 1980s saw a remarkably rapid transfer from a research concept to a worldwide voiceband modem standard.

Accounting for the different state of progress in the wireless and wired worlds, we can identify the following major challenges faced by the wireless communication system designer:

- **Fading**: Mobile wireless channels are time-varying. The range of channel operating characteristics faced by wireless modems is much wider than in typical wired channels. The nonstationary nature of the channel has a large impact on spectrally efficient transmitter/receiver design as well as channel capacity. Achieving low-bit-error-rate data transmission is particularly challenging in rapidly varying channels subject to high Doppler spread.
- **Multi-user**: The users of the wireless medium are geographically separated and often uncoordinated. Spectral efficiency in cellular multipoint-to-point and point-to-multipoint communication is significantly more challenging than in single-user communica-

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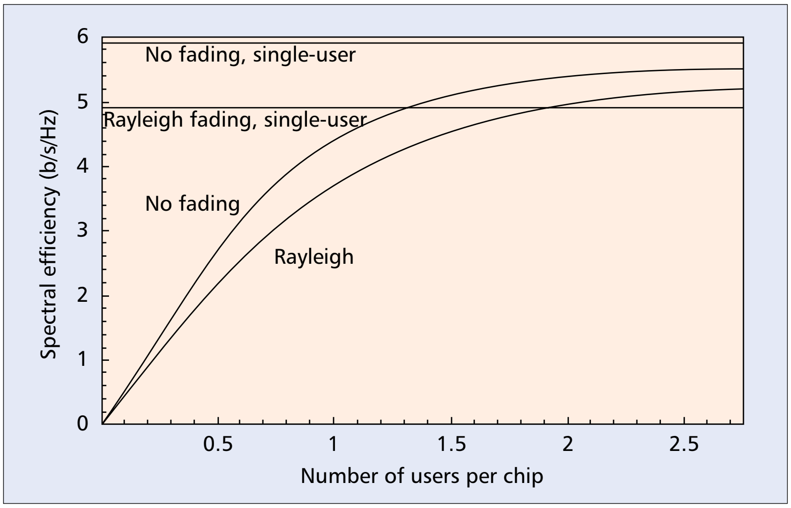


Figure 1. *Optimum CDMA spectral efficiency at an energy per bit per thermal noise level of 10 dB.*

tion, particularly when data rate requirements are heterogeneous. Although the rudiments of multi-user communication theory date back to the early 1970s, academic research in this area was not kindled until the 1980s, and mostly as a reaction to the wireless revolution.

- **Power limitation**: Since the majority of nomadic terminals are battery operated, power efficiency, in addition to spectral efficiency, is crucial. This applies not only to transmitted power but to circuit-dissipated power. As computational complexity translates into dissipated power, sophisticated designs required to approach capacity may not be advisable in a battery-operated terminal. Fortunately, the relentless advances in low-power-dissipation sub-micron complementary metal oxide semiconductor (CMOS) circuit design make increasingly complex designs not only feasible but preferable from the standpoint of power efficiency.

Capitalizing on the rapid pace of innovation in the integration and speed of computing and signal processing hardware, several emerging technologies promise important increases in wireless spectral efficiency. In the following sections we give a brief introduction to those key communication technologies that hold most promise to meet future demand for wireless data rate.[1]

Multiple Access Techniques

In cellular systems, the most straightforward way to make wireless "bandwidth" is to partition cells as customer demand increases. For example, third-generation systems include hierarchical cell structures with hot spots served by microcells. If cells could be subdivided *ad infinitum* there would be hardly any incentive to design more efficient air interfaces. Although in many geographical areas there is still much potential for further cell partitioning, very small cells are not always desirable due to both economic and engineering factors. The cost of base stations and their connection to the wired backbone is an important consideration. As the cell size shrinks it becomes increasingly difficult to locate the base station near the "center" of the cell, more areas of geographical coverage become fringe zones (where two or more base stations have similar strength), and increased intercell handoffs and interference are responsible for diminishing returns in the spectral efficiency gains achieved by cell partitioning.

Although spread spectrum techniques were originally conceived to buy robustness at the expense of spectral efficiency, there is a growing understanding that spread spectrum signaling does not have to lead to spectral inefficiency in multi-user wireless systems. This growing consensus is illustrated by the choice of wideband code-division multiple access (WCDMA) for the third-generation cellular standards. Moreover, recent information theoretic results [1, 2] indicate that the spectral efficiency of CDMA can be multiplied by a factor of roughly four by increasing receiver complexity and increasing the number of users per chip from 1/4 (typical of current systems) to 2 (Fig. 1). The economic incentive for more sophisticated receiver design required to accommodate such higher loads is clear.

At the same time, some CDMA wireless data transmission systems are starting to move away from the philosophy of simultaneous uncoordinated transmissions. This trend is fueled by the realization that power and spectrum efficiency dictates handling voice and data (with their contrasting latency and reliability requirements) in different ways. Qualcomm's High Data Rate system (see the article by Bender *et al.* in this issue) is a data multiplexing scheme that uses packet scheduling to avoid simultaneous transmissions. Downlink transmission epochs are scheduled on the basis of not only individual demand and delay, but also the instantaneous fade levels experienced by each user.

Enhancements to second-generation standards [3] boost the efficiency of time-division multiple access (TDMA) with dynamic channel assignment techniques [4]. In CDMA, resources such as spreading gain and power can be allocated dynamically in response to channel conditions and quality of service requirements [5]. Pricing for load balancing is having an impact on the design of wired networks; although at an incipient stage, the role of pricing in wireless resource allocation is already under current investigation [6].

Several variations on classical multiple access signaling formats have been proposed in recent years. The time-division duplexed component of the third-generation cellular standard can be considered a hybrid of TDMA and CDMA [7, p. 84; 8]. Multicarrier CDMA [9] is a time-frequency dual of direct-sequence spread spectrum which does not require a contiguous frequency band and is also well suited to multirate applications. Orthogonal frequency-division multiplexing is a form of orthogonal CDMA that lends itself to fast signal processing at the receiver, and has shown promise as an efficient wireless interface for high-speed applications (see the article by Chuang and Sollenberger in this issue). For bursty users that send short packets to a satellite transponder, spread Aloha (see the arti-

[1] *Advances in data, speech, audio, image, and video compression have a direct impact on the efficiency with which bandwidth is used. However, source encoding methods fall outside the scope of this article.*

cle by Abramson in this issue) has been proposed as a spread spectrum variant of the classical random access protocol in which all users employ a common spreading sequence. Following the trend in cellular telephony, the benefits of increased frequency reuse will be realized in wireless packet-switched random access communication [10] as soon as effective methods to combat bursty multi-user interference become a reality.

An intriguing alternative which may eventually become practical, and even legal, for short-range communication between static terminals is ultra-wideband impulse radio [11]. Information is modulated by the position of a string of sub-nanosecond pulses. Multiple access is achieved by time-hopping. In fact, the principle of impulse radio is firmly grounded in information theory: maximum power efficiency is achieved by pulse-position modulation in an infinite bandwidth channel. With typical power spectral density values of 10^{-12} J/user, the utter spectral inefficiency of such a system is of little real consequence to any coexisting "narrowband" system. Conversely, although the whole band occupied by the transmission, say, from DC to a few gigahertz is "owned" by other systems, much of it is unused at any given time. Thus, reasonable receiver sensitivity can indeed be achieved with very low transmitted power.

Multi-User Detection

Wireless multi-user systems are subject to co-channel interference. TDMA users receive interference from overlapping slots originating in other cells, and from users in the same cell due to channel dispersion. Analogously, orthogonal synchronous CDMA transmissions lose their orthogonality once they go through the channel. Co-channel interference in asynchronous CDMA is unavoidable even in the absence of channel distortion or other-cell interference. Multi-access interference is usually a very significant contributor to the total interference seen at the receiver, whether at the mobile or at the base station. In second-generation systems, several strategies are used to mitigate multiaccess interference. In TDMA — Global System for Mobile Communications (GSM) and IS-136 — conservative frequency reuse patterns and guard times between consecutive slots incur an important penalty in efficiency. In CDMA (IS-95), tight equal-received-power control prevents any interferer from drowning the signal of the desired user in a near/far situation; highly redundant error-correcting codes for low signal-to-noise ratio channels are used to decode information reliably in the presence of multi-access interference which contaminates the output of the front-end adaptive matched filter. All second-generation systems treat multi-access interference as part of the background noise, and no signal processing countermeasures are taken to combat it. However, multi-access noise has considerable structure, and certainly much less randomness than white Gaussian background noise. By exploiting that structure, multi-user detection [7] can increase spectral efficiency, receiver sensitivity, and the number of users the system can sustain. In addition, the use of multi-user detection greatly reduces reliance on tight and accurate power control (which is infeasible in certain wireless applications). These gains are achievable with both long spreading codes (pseudorandom sequences with periodicity much longer than symbol duration) and short spreading codes (repeating every symbol). Although multi-user detectors suited to deal with long spreading codes do exist, short codes are preferable since they do not incur performance loss and make adaptive linear multi-user detectors a practical alternative.

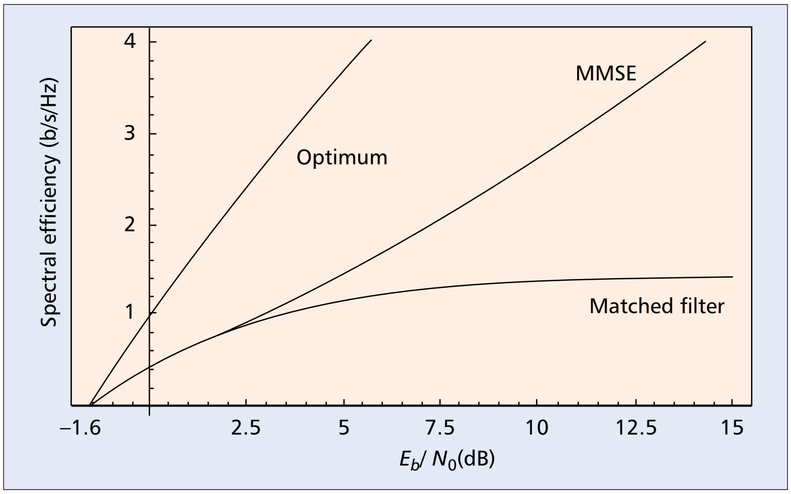
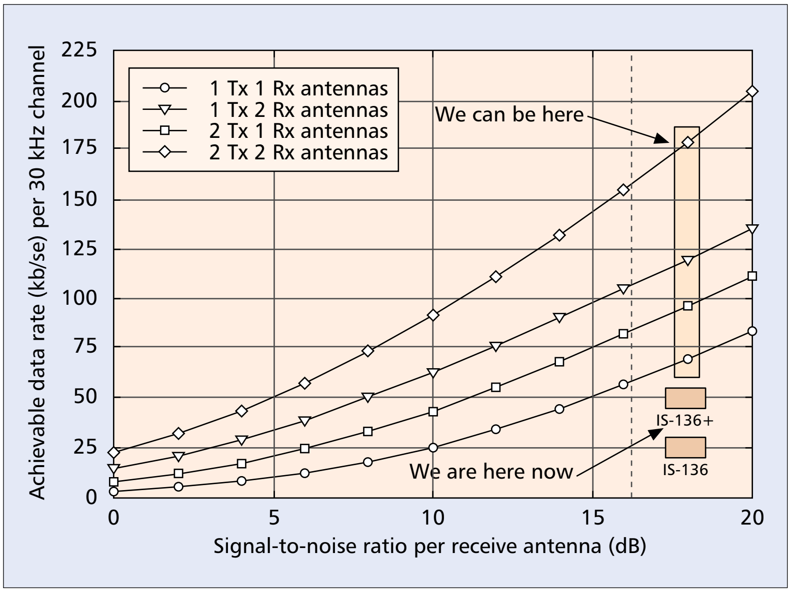


Figure 2. *CDMA spectral efficiencies with optimum coding-spreading trade-off.*

Partly because of a mistaken belief in some quarters of the spread spectrum community that little could be gained from receivers more sophisticated than the single-user matched filter, multi-user detection did not start developing until the early '80s. The last 15 years have witnessed a wide variety of signal processing techniques to combat multi-access interference. Successive cancellation, inspired by information theory, demodulates users sequentially by remodulating and subtracting the signals of users already demodulated. Linear multi-user detectors are modified matched filters that take into account the multi-access interference structure in order to mitigate its effect. Nonlinear detectors such as multistage, decision feedback, and maximum likelihood serve to attain various points in the performance/complexity trade-off curve.

Figure 2 [1] illustrates the gains in CDMA spectral efficiency that are achievable by using multi-user detection in conjunction with error-control coding. The x-axis is the energy per bit relative to background noise (not including multi-access interference). Although Fig. 2 assumes the best scenario for the single-user matched filter (equal received power), its spectral efficiency is bounded. Being limited by multi-access interference, the matched filter is unable to take advantage of low-noise linear amplifiers. At 9 dB, the spectral efficiency achieved by the matched filter can be doubled using linear minimum mean square error multi-user detection, or even quadrupled with an optimum nonlinear multi-user detector. In the absence of power control, even higher efficiency gains are achievable by multi-user detectors that exploit power imbalances.



■ **Figure 3.** *Data rates at 10 percent outage capacity.*

ANTENNA ARRAYS

Since the early days of radio, directive antennas have been used to concentrate energy in the direction of the receiver/transmitter. Directive antenna patterns provide a variety of benefits:

- They lower power requirements.
- They minimize interference to and from other antennas.
- They reduce delay spread.

Linear arrays of equispaced omnidirectional elements are one of the most common types of directive antennas. By adjusting the array weights, the array pattern can be steered electronically. *Smart antennas* adaptively adjust their patterns as a function of the location of the mobiles [12].

Since each mobile sees a different channel to the base station, it is beneficial to jointly adapt the receiver in the space domain and in the time domain [13], using multidimensional generalizations of classical scalar single-user linear channel equalization techniques.

In indoor or urban environments with significant local scattering, the energy from any given source does not arrive at the antenna predominantly from one direction. Although directive antennas are much less effective in those environments, antenna arrays can still play a crucial role in improving spectral efficiency. If the receiving array elements are sufficiently separated, the fading parameters at different elements become weakly dependent. Conversely, if the transmitter also has an antenna array with sufficiently separated elements, the fading coefficients due to each transmitting element are also weakly dependent. This transmitter/receiver diversity mechanism effectively creates a plurality of subchannels sharing the same RF bandwidth. Note that this creation of new degrees of freedom would be impossible in an unscattered free-space line-of-sight channel. Two major strategies have been recently proposed to deal with the unavoidable mutual interference among those subchannels: signal processing at the receiver and space-time error control coding.

If, as in the Bell Laboratories *BLAST* prototype [14], the transmitting antennas are fed independent data streams, the situation is akin to a multi-user spread spectrum system where the number of transmitting antennas plays the role of the number of users, and the number of receiving antennas plays the role of the spreading gain. Using nonlinear multi-user detection methods to separate the incoming signals at the receiver, the *BLAST* system has demonstrated spectral efficiencies on the order of 40 b/s/Hz with eight elements at both transmitter and receiver. This is more than 40 times the achievable data rate with single-element transmitting/receiving antennas using the same bandwidth and power. Moreover, in theory, the capacity of the system can grow *linearly* with the number of transmitting or receiving antennas (whichever is lower) [14], even if the transmitter makes no attempt to learn the fading coefficients. But such phenomenal growth assumes that the fading coefficients do not vary with time. If they do vary with time, there is no point, as far as capacity is concerned, in making the number of transmitting antennas exceed the number of symbols over which the fading is approximately constant [16, p. 599].

Coding redundancy can be introduced across the transmitting antennas adding the space dimension to the time dimension exploited in trellis-coded modulation. Practical low-complexity "space-time codes" geared to a few transmit/receive antennas developed at AT&T Research [15, p. 544] have already been incorporated in third-generation and enhanced second-generation wireless. With only two antennas at both transmitter and receiver, the spectral efficiency of narrowband TDMA second-generation channels can be multiplied by a factor of six (Fig. 3 = [16, Fig. 12]).

FADING COUNTERMEASURES

Fading is traditionally combatted with diversity in several domains:

- **Time**: The use of error control codes in conjunction with interleaving offers protection from the deleterious effects of channel error bursts by spreading the information contained in each raw bit across time.
- **Frequency**: Analogous to time diversity, spread spectrum modulation spreads the information contained in each raw bit over a wide band of frequencies. Frequency-selective multipath fading can be effectively harnessed at the receiver using the rake adaptive matched filter.
- **Space**: As mentioned earlier, sufficiently separated antenna elements can provide copies of received signals affected by independent fading. Polarization adds another degree of freedom to combat fading. In cellular systems, *macrodiversity* refers to the simultaneous reception and combining of a mobile transmission at several base stations.
- **Multi-user**: In certain fading channels, several transmitters may achieve higher spectral efficiency than a single transmitter with the same total power [2]. For example, we

see in Fig. 1 that for sufficiently high load and in the presence of Rayleigh fading, a CDMA channel may have higher spectral efficiency than a single user with the same total transmitted power.

High-speed wideband signal processing is receiving increasing attention to counter time-varying intersymbol interference and Doppler [17]. In the last few years, several researchers have investigated the capabilities of receivers that perform diversity combining at several of the aforementioned dimensions simultaneously. In particular, receivers that adapt not only to the multipath profile but to the Doppler profile have been proposed recently [18]. Even with relatively moderate Doppler spreads, unexpected power savings are reported by taking advantage of the Doppler diversity at the receiver.

If the transmitter is able to obtain information on the instantaneous fade level suffered by the received signal, it can make use of several adaptive techniques. The best known technique is power equalization (namely, equal received power), which was already mentioned earlier. Recently, the analysis of the Shannon capacity of various multi-user channels has yielded important insights on the design of power control strategies that boost the overall spectral efficiency.[2] Among those insights, we can highlight the fact that it is better not to control power at all than to equalize the fade level. As shown in [19], the optimum strategy for an average-power-limited receiver is characterized by a channel signal-to-noise ratio threshold below which no energy is transmitted, and above which the received power is an affine function of the channel gain. In effect, instead of trying to fight it, optimum power control operates in unison with the fading. Unless the signal-to-noise ratio is low, constant transmitted power (i.e., no power control) is almost optimal in single-user channels. In multi-user channels, various forms of power control offer substantial power savings even for high signal-to-noise ratios [2]. Likewise, unequal received power control has the potential to afford important gains in cellular systems [15, p. 615]. In multiuser narrowband channels with centralized power control it is optimum to maintain the foregoing optimum single-user power control strategy while allowing at most one (the strongest) user to transmit [15, p. 602].

Under a variety of models and assuming perfect knowledge of the fading parameters at the receiver, it is known that, as the degrees of diversity go to infinity, the fading channel is equivalent from the standpoint of coding and capacity to an unfaded additive white Gaussian noise channel. However, recent information-theoretic results [15, p. 592] point out that too much spreading (or, in general, too many degrees of diversity) may actually decrease the spectral efficiency of time-varying channels because of the need to estimate more and more unknown fading parameters with less and less energy devoted to each. Under those time-varying conditions, it is actually preferable to concentrate the energy of the codewords in a small region of the available time-frequency plane.

Channel Error Control Coding

In addition to modulation/demodulation and signal processing, reliable communication hinges on effective ways to add redundancy to the data in order to protect it from the random disturbances introduced by the channel.

The last five years have witnessed a revolution in error control coding led by the invention of *Turbo* coding/decoding in 1993. Originally introduced for error correction in low signal-to-noise ratio channels not subject to fading, Turbo coding achieves performance very close to Shannon capacity at the expense of complexity which is well within the capabilities of current very large scale integration (VLSI) technology. Gains of 0.8–1.5 dB have been reported [21, p. 509] when Turbo codes were used in lieu of the convolutional error control codes adopted in the GSM and IS-95 second-generation standards. Although Turbo iterative decoding is plagued by an inherent decoding delay which hinders its use in real-time voice telephony, its enormous potentials are under active exploration not only in error control decoding, but also in multi-user detection and other signal processing techniques.

Error control coding for fading channels has traditionally relied on burst error correction and interleaving. Schemes tuned to Rayleigh fading that emphasize codeword separation in the Hamming sense have also received attention [15, p. 620]. Bit-interleaved coded modulation [15, p. 626] is a robust spectrally efficient technique that performs well in both faded and unfaded channels. Recently, considerable interest has arisen in adaptive coding strategies that vary the number of bits per transmitted symbol as a function of the channel fade level [21].

The two-way nature of wireless channels can naturally be exploited by error control coding. Rudimentary end-to-end acknowledgment/repetition schemes are typical in wired networks to boost data transmission reliability. For spectrally challenged wireless channels, more efficient interactive redundancy schemes would be highly desirable. The first steps in that direction have been taken with schemes such as *packet combining* [21, p. 314] and *incremental redundancy coding* [16, p. 547].

Concluding Remarks

The emerging technologies reviewed in this article are at various stages of development. Some have already been implemented in enhancements to second-generation systems; others are under active consideration for the third generation. The effective implementation of sophisticated receiver design concepts is likely to occur initially in the more benign environments of fixed wireless and low-mobility applications. Although not each of the reviewed technologies is advisable or even applicable to every wireless scenario, it is likely that future designs will capitalize on the synergistic effects of signal processing in the time, frequency, and space domains.

We have seen several illustrations of the usefulness of information theory, not only as a tool to compute the ultimate achievable performance, but as a design driver. In channels where bandwidth and power are scarce resources, critical

In channels where bandwidth and power are scarce resources, critical choices in transmitter design and receiver design are increasingly driven by information theory.

[2] *Different conclusions are reached if, rather than maximizing the overall channel capacity, it is desired to minimize the maximum individual outage probability.*

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choices in transmitter design (e.g., modulation, power control, multi-access, and diversity techniques) and receiver design (e.g., countermeasures against fading and co-channel interference) are increasingly driven by information theory.

As wireless access quickly emerges as the major bottleneck of the information highway, the enormous economic incentives for efficient wireless spectrum utilization are spurring a flurry of physical channel research and development activities. With the feasibility of increasingly sophisticated transmitter/receiver designs, conquering wireless channel capacity is likely to become a reality in the not-too-distant future.

REFERENCES

[1] S. Verdú and S. Shamai (Shitz), "Spectral Efficiency of CDMA with Random Spreading," *IEEE Trans. Info. Theory*, vol. 45, no. 2, Mar. 1999, pp. 622–40.

[2] S. Shamai (Shitz) and S. Verdú, "The Effect of Frequency-Flat Fading on the Spectral Efficiency of CDMA," *IEEE Trans. Info. Theory*, submitted, 1999.

[3] N. R. Sollenberger, N. Seshadri, and R. Cox, "The Evolution of IS-136 TDMA for Third Generation Wireless Services," *IEEE Pers. Commun.*, June 1999, pp. 8–18.

[4] I. Katzela and M. Naghshineh, "Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey," *IEEE Pers. Commun.*, June 1996, pp. 10–31.

[5] S. Jordan, "Resource Allocation in Wireless Networks," *J. High Speed Networks*, vol. 5, no. 1, 1996, pp. 23–4.

[6] D. Famolari *et al.*, *A New Framework for Power Control in Wireless Data Networks: Games, Utility and Pricing*, Kluwer, 1999.

[7] S. Verdú, *Multi-user Detection*, New York: Cambridge Univ. Press, 1998.

[8] G. W. Wornell, "Spread-Signature CDMA —Efficient Multi-User Communication in the Presence of Fading," *IEEE Trans. Info. Theory*, vol. 41, no. 5, pp. 1418–38, Sept. 1995.

[9] S. Hara and R. Prasad, "Overview of Multicarrier CDMA," *IEEE Commun. Mag.*, vol. 35, no. 12, Dec. 1997, pp. 126–33.

[10] J. P. M. G. Linnartz, "On the Performance of Packet-Switched Cellular Networks for Wireless Data Communications," *Wireless Networks*, vol. 1, no. 2, 1995, pp. 129–36.

[11] M. Z. Win and R. A. Scholtz, "Impulse Radio: How It Works," *IEEE Commun. Lett.*, vol. 2, Jan. 1998.

[12] J. H. Winters, "Smart Antennas for Wireless Systems," *IEEE Pers. Commun.*, vol. 5, no. 1, Feb. 1998, pp. 23–27.

[13] A. J. Paulraj and B. C. Ng, "Space-Time Modems for Wireless Personal Communications," *IEEE Pers. Commun.*, vol. 5, no. 1,Feb. 1998, pp. 36–48.

[14] G. J. Foschini, "Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas," *Bell Labs Tech. J.*, Autumn 1996, pp. 41–59.

[15] E. Biglieri, J. Proakis, and S. Shamai (Shitz), "Fading Channels: Information Theoretic and Communications Aspects," *Information Theory: Fifty Years of Discovery*, S. Verdú and S. MacLaughlin, Eds., IEEE Press, 1999.

[16] R. Calderbank, "The Art of Signaling: Fifty Years of Coding Theory," *Information Theory: Fifty Years of Discovery*, S. Verdú and S. MacLaughlin, Eds., IEEE Press, 1999.

[17] D. P. Taylor *et al.*, "Wireless Channel Equalisation," *Euro. Trans. Telecommun.*, vol. 9, no. 2, Mar.-Apr. 1998, pp. 117–43.

[18] A. M. Sayeed and B. Aazhang, "Joint Multipath-Doppler Diversity in Mobile Wireless Communications," *IEEE Trans. Commun.*, vol. 47, no. 1, Jan. 1999, pp. 123–32.

[19] A. J. Goldsmith and P. P. Varaiya, "Capacity of Fading Channels with Channel Side Information," *IEEE Trans. Info. Theory*, Nov. 1997, pp. 1986–92.

[20] D. J. Costello, J. Hagenauer, H. Imai, and S. B. Wicker, "Applications of Error-Control Coding," *Information Theory: Fifty Years of Discovery*, S. Verdú and S. MacLaughlin, Eds., IEEE Press, 1999.

[21] A. J. Goldsmith and S. G. Chua, "Adaptive Coded Modulation for Fading Channels," *IEEE Trans. Commun.*, vol. 46, May 1998, pp. 595–602.

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