Recent Results on the Capacity of Wideband Channels in the Low-Power Regime

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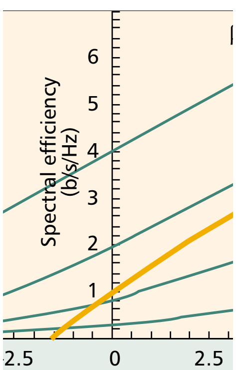


The tradeoff of spectral efficiency vs. energy-per information bit is the key measure of the capacity of channels in the power-limited regime. Many important communication channels operate in the region of low spectral efficiency in which is close to its minimum value for reliable transmission.

Abstract

This article gives a brief overview of recent results on the limits of reliable communication in the low-power wideband regime from the standpoint of information theory. Results on channel capacity and optimum signaling are reviewed for both point-to-point channels and multiuser channels.

Introduction

The technology of wideband communication is gaining ground in applications such as wireless personal communications, satellite, and sensor networks.

The interest in wideband channels was spurred mid-20th century by the antijamming capabilities of spread spectrum gained at the expense of spectral inefficiency. Ever since the 1960s, power-limited deep space communication has emerged as one of the main beneficiaries of advances in binary error correcting coding technology, as exemplified most notably by convolutional, turbo, and low-density parity check codes. The success of direct-sequence spread-spectrum code-division multiple access (CDMA)-based second-generation wireless telephony, developed in the late 1980s, led a decade later to the adoption of CDMA (in a wider-band format) for third-generation wireless personal communications [1, 2]. Recently, two major high-speed wireless systems based on orthogonal multiplexing coupled with spread-spectrum countermeasures against out-of-cell interference have been developed: time-division multiple access (TDMA)/direct sequence [3] and orthogonal frequency-division multiple access (OFDMA)/frequency hopping [4]. The increasingly popular unlicensed industrial, scientific, and medical bands are devoted to low-power spread-spectrum systems. Other examples of wideband channels receiving increasing attention are low-power low-data-rate sensor networks envisioned for future civilian and military applications, and communication based on ultra-wideband pulses (spanning from DC to gigahertz).

For reliable communication, the choice of the three primary performance parameters, bandwidth, power, and data rate (bits per second), must respect the fundamental information theoretic limit characterized by the region of achievable spectral efficiency (data rate divided by bandwidth) and energy per bit (power divided by data rate). In information theory, the "wideband" communication regime refers to the region in the maximal spectral efficiency vs. energy per bit curve where the spectral efficiency is low. Consequently, highly spectrally efficient broadband channels with high signal-to-noise ratio (SNR) lie outside the scope of our review.

The main driving forces behind the interest in wideband communications are:
- Ability to transmit at an energy per information bit close to the minimum
- Diversity against frequency-selective fading
- Ease of multiplexing/multiaccess
- Ability to coexist with other systems using the same band

Technological advances in very large scale integration (VLSI), error control coding, signal processing, and synchronization make information-theoretic fundamental limits on channel capacity increasingly relevant to communications engineering. The low spectral efficiency typical of wideband systems does not imply that the communication is wasteful of channel resources or that the system operates far from channel capacity. It all depends on how far from the fundamental trade-off of spectral efficiency vs. energy per bit the system operates. Furthermore, in multiuser channels, the spectral efficiency achieved by any one user may be small but the sum of the data rates may actually be near capacity.

Although the capacity of wideband channels has been studied since the inception of information theory, the last few years have seen a flurry of activity in the field leading to a body of results with interesting practical implications. The purpose of this article is to give a brief overview of those recent information theoretic results on the capacity of wideband channels.[1] Major issues of interest in this context are communication in the low-power regime (i.e., near minimum energy per bit), spread-spectrum multi-access, the effect of fading, optimum signaling, and power control.

The Low Power Regime

From Shannon's 1948 formula for the capacity of the ideal bandlimited additive white noise channel, it follows that the received energy per bit (ratio of power to data rate) divided by the one-sided noise spectral level N_0 required to achieve spectral efficiency equal to C b/s/Hz is given by

$$\frac{E_b^r}{N_0}(C) = \frac{2^C - 1}{C}. \tag{1}$$

As the bandwidth grows and the spectral efficiency vanishes, $C \to 0$, it can be seen from Eq. 1 that the minimum received energy necessary to transmit 1 bit of information reliably (by means of channel codes with growing blocklength) satisfies

$$\frac{E_b^r}{N_0}_{\min} = \ln 2 = -1.59\text{dB}. \tag{2}$$

Operation at very small SNR per degree of freedom allows maintaining E_b/N_0 close to its minimum value at the expense of low (but nonzero) spectral efficiency (bits per second per hertz). Subsequent work in the 1960s showed that Eq. 2 is not only a feature of the ideal band-limited additive white noise channel, but also holds when the channel is subject to frequency-flat fading, even if the fading coefficients are unknown at the receiver [5]. It has been shown recently [6] that Eq. 2 is actually a feature of any fading channel as long as the background noise is Gaussian. It is indeed possible to obtain a lower value of

$$\frac{E_b^r}{N_0}_{\min}$$

if the additive noise is non-Gaussian [6, 7].

Up until recently, the only information-theoretic guidance on the capabilities of wideband communication was offered by the infinite bandwidth capacity (or equivalently, minimum energy per bit) results (e.g., [5–8]). In particular, [7] gives a formula computable even in cases where the Shannon capacity is unknown. It is natural to extrapolate information-theoretic results obtained for the infinite bandwidth (zero spectral efficiency) regime to the wideband regime. This leads to conclusions such as:

- Wideband capacity is not affected by fading.
- Receiver knowledge of fading coefficients cannot increase capacity, and consequently there is no capacity loss due to noncoherent reception.
- On-off signaling such as pulse position modulation is near optimal.

However, it has been shown recently [6] that these conclusions are unwarranted. The crucial point is that operation in the regime of low spectral efficiency does not imply disregard for the bandwidth required by the system. On the contrary, with the possible exception of ultra wideband pulse communication, given a certain power and data rate, it is of interest to minimize the required bandwidth (to the extent allowed by the given complexity constraints). Even if we operate at an energy per bit close to Eq. 2, the bandwidth required to achieve a given data rate turns out to be very sensitive to receiver side information and to the nature of the fading.

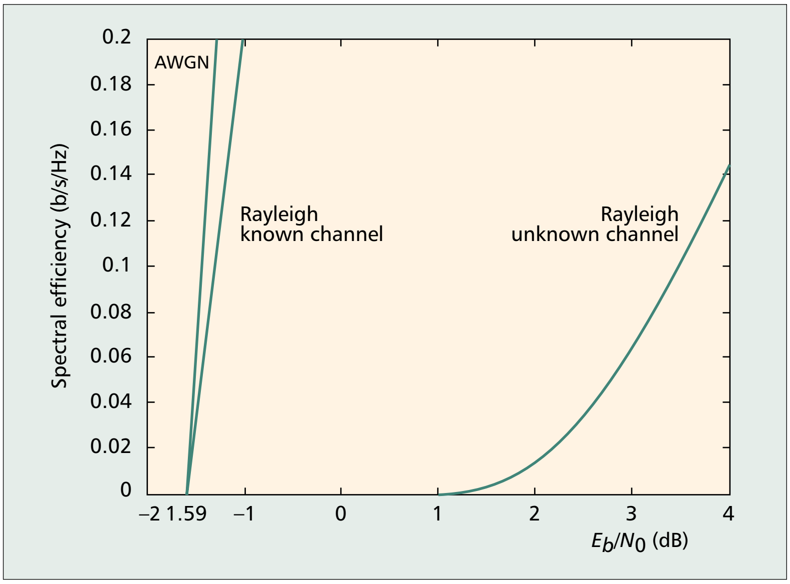


Figure 1. *Spectral efficiency of the AWGN channel and the Rayleigh flat fading channel with and without receiver knowledge of fading coefficients.*

If the receiver knows the fading coefficients and coherent communication is feasible, quadrature phase shift keying (QPSK) has been shown [6] to attain optimal spectral efficiency in the wideband regime, whereas in those conditions on-off signaling is distinctly suboptimal, requiring more than six times the minimum bandwidth. The minimum bandwidth turns out to be proportional to the *kurtosis*[2] of the fading amplitude distribution [6]. Thus, Rayleigh fading requires twice the bandwidth required in the absence of fading, and the bandwidth required with log-normal fading grows exponentially with the dB variance.

In the noncoherent regime where the channel is not fully known at the receiver, attaining channel capacity at low power requires *flash* signaling, an asymptotic form of on-off signaling where the on level has unbounded energy and the duty cycle is vanishingly small [6]. Furthermore, the lack of precise knowledge of channel coefficients makes operation near

$$\frac{E_b^r}{N_0}_{\min}$$

prohibitively expensive in terms of bandwidth and complexity.

Figure 1 compares the spectral efficiency of the unfaded (additive white Gaussian noise) channel with the spectral efficiency of the Rayleigh channel in the wideband regime. If the channel coefficients are known at the receiver, it can be seen that the slope of the spectral efficiency curve is half of that in the unfaded case. If the channel coefficients are unknown at the receiver [9], despite what may appear from Fig. 1, Eq. 2 still holds. However, the slope is equal to zero, and nonnegligible spectral efficiency requires much higher levels of energy per bit.

One of the conclusions drawn from the results of [6] is that the traditional paradigm of the voiceband telephone channel that maximizes data rate for given power and bandwidth may be an invitation to inefficient design in the wideband regime.

[1] Seventy percent of the references in this article have appeared within the last three years.

[2] Fourth moment divided by second moment squared.

From the standpoint of practical design, where a judicious assessment of the complexity-performance tradeoff is always necessary, the benefits of additional complexity (or the costs incurred by channel impairments) are particularly apparent when bandwidth is minimized for given rate and power.

A more sensible approach is to minimize bandwidth for a given rate and power. This may appear surprising since once any two parameters from {power, bandwidth, rate} are fixed, Shannon capacity determines the third one. However, from the standpoint of practical design, where a judicious assessment of the complexity-performance trade-off is always necessary, the benefits of additional complexity (or the costs incurred by channel impairments) are particularly apparent when bandwidth is minimized for given rate and power. For example, consider a Rayleigh channel operating at

$$\frac{E_b^r}{N_0} = 1.25 \text{ dB}.$$

Without incurring the complexity necessary to track the channel at the receiver, the spectral efficiency is equal to 0.0011 b/s/Hz (Fig. 1). Tracking the channel buys a 92 percent improvement in rate for fixed bandwidth and power, or a decrease in power of 2.8 dB for fixed bandwidth and rate. As substantial as these improvements are, they pale in comparison to the reduction in bandwidth for fixed power and rate: a factor of 1000. If we go deeper into the wideband regime, that is, we start from

$$\frac{E_b^r}{N_0} < 1.25 \text{ dB},$$

the bandwidth savings (with fixed power and rate) due to coherence is greater and the rate improvement (with fixed bandwidth and power) smaller.

If instead of allowing flash signaling, the channel inputs are subject to peak-to-average limitations, and there are no specular components or other knowledge at the receiver, then the input-output mutual information grows as the square of the per-symbol SNR and is proportional to the kurtosis of the input for low SNR [10, 11]. As a consequence, the lower the allowed input burstiness, the further away from the

$$\frac{E_b^r}{N_{0\,\min}} = -1.59 \text{ dB}$$

point (achievable by flash signaling) we must operate [6].

A popular type of wideband signaling that has small peak-to-average ratio is direct sequence spread spectrum. One of the oft-cited advantages of this format is its ability to harness multipath and use it as a source of diversity. Recent results [12] have shown that this is only true provided that the number of significant resolvable paths is not too high. Otherwise, mutual information is, in fact, inversely proportional to the number of resolvable paths (assuming the paths have equal power and the receiver does not have side information to aid it in the acquisition of the fading coefficients). This severe limitation stems from the fact that since the overall power (sum of the individual path powers) is fixed, as the number of paths increases, the per-path SNR decreases, and, more crucially, the ability to measure reliably the amplitude/phase of the individual paths is increasingly compromised. Other works that assess the impact of imperfect channel estimation at the receiver in the wideband regime include [13, 14].

Since the pioneering information-theoretic observations in [15, 16], there has been much interest in the evaluation of the gains in spectral efficiency that can be achieved by using multiple transmit and receive antenna elements. In multi-antenna systems where the transmitter knows the channel matrix, the optimum signaling in the low-power regime concentrates all its energy in the maximal-singular-value eigenspace of the channel matrix [6, 17, 18]. If the multi-antenna transmitter has no information about the channel, it feeds all the antenna elements with independent equal-power streams in order to maximize capacity. In this case, sometimes it is claimed that in the low-power regime capacity is not affected by the number of transmit antennas [19]. In fact, while

$$\frac{E_b^r}{N_{0\,\min}}$$

is indeed independent of the number of transmit antennas, and inversely proportional to the number of receive antennas, for every 3 dB increase in energy per bit, the spectral efficiency in bits per second per hertz grows as twice the harmonic mean of the number of transmit and receive antennas [6], whereas in the high spectral efficiency regime the slope is equal to the minimum of the number of transmit and receive antennas [15].

If neither the transmitter nor the receiver know the channel coefficients, the results in [20] apply to an ideal setting where time is slotted in blocks of T symbols and within each block fading is constant, independent from block to block. It is shown in [20] that capacity does not increase by having more transmit antennas than T. The optimal strategy is to modulate orthogonal T-vectors at each antenna. As in the single-antenna case, the slope at

$$\frac{E_b^r}{N_{0\,\min}}$$

of the spectral efficiency curve is zero [6]. On the other hand, for any SNR, as the number of transmit antennas and T grow to infinity, capacity converges to the case with full receiver knowledge [21].

If the transmitter knows the channel fading coefficients instantaneously, it can, in principle, adjust its transmitted power so that no power is wasted in signaling dimensions affected by severe fades. Pioneered in [22], optimal power control is only marginally useful at high SNRs but it can theoretically (for unbounded fading distributions, e.g., log-normal, Rayleigh, Rice) lead to reliable communication no matter how low the transmitted energy per bit (Fig. 2), provided that a long enough delay is tolerated. Optimal power control with delay constraints has been studied in [23–25].

Multiuser Channels

Suboptimality of TDMA

One of the simplest ways to engineer multipoint-to-point (multi-access) or point-to-multipoint (broadcast) links is to use TDMA, whereby each user is assigned nonoverlapping time slots during which it is the only active transmitter. Begun in the early 1970s, multiuser information theory is the discipline that studies the capacity of multi-access, broadcast, and other multiuser channels.

An early discovery of multiuser information theory was that in additive white Gaussian noise multi-access channels, an arbitrary number of users can achieve the same aggregate data rate as a single user whose power is equal to the sum of the powers. Furthermore, there is some flexibility as to how rates and powers are apportioned among the users to achieve such a total capacity. Regardless of the individual powers, it is possible to find a rate allocation so that the single-user capacity can be achieved by TDMA. This fact would seem to leave little room for the consideration of superposition strategies (e.g., CDMA) where users transmit simultaneously overlapping in time frequency even in a nonorthogonal way. However, aside from practical considerations such as the need for synchronism and the fact that TDMA suffers from performance-limiting multiuser interference because of channel distortion and out-of-cell interference, several information-theoretic results favor superposition strategies:

- The capacity regions (set of achievable rates) of multi-access channels and of broadcast channels are not achieved by TDMA.
- Whereas in both multi-access and broadcast channels [26], TDMA achieves the same

  $$\frac{E_b^r}{N_0}_{\min}$$

  as in the single-user channel reviewed in an earlier section, superposition requires less bandwidth than TDMA [27] when used in conjunction with joint multiuser detection.
- When users in a multi-access channel are affected by independent fading, they can achieve higher aggregate rate with superposition than with TDMA, as a simple consequence of the concavity of channel capacity as a function of SNR [28].
- In cellular models where each base station neglects the structure of the out-of-cell interference, superposition coding (possibly coupled with so-called intercell time-sharing protocols, if the out-of-cell interference is sufficiently high) offers higher capacity than TDMA in the presence of fading [29].

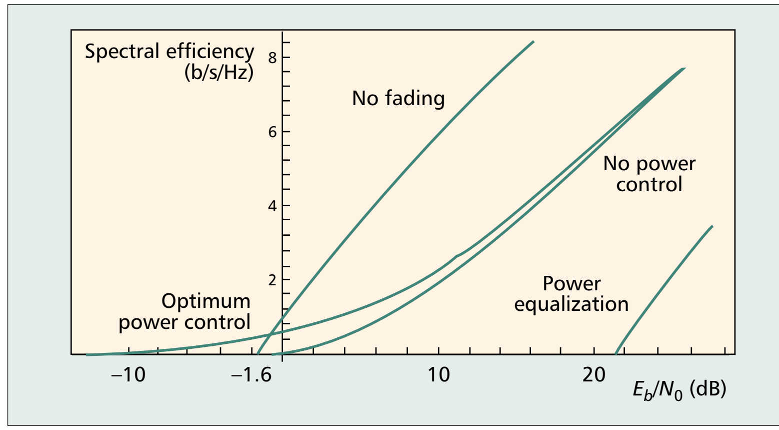
CDMA

The most common superposition strategy is CDMA. Both orthogonal CDMA (primarily for point-to-multipoint channels) and nonorthogonal CDMA have found practical use. The capacity of CDMA channels as a function of arbitrary signature waveforms was found in [30]. This result can be used to choose an optimum set of signature waveforms for a given number of users and spreading gain. The key parameter is the load, defined as the number of users divided by the spreading gain. If the load is less than or equal to one, orthogonal CDMA (e.g., with Walsh spreading sequences) is optimum and achieves single-user capacity (with power equal to the aggregate power). If the load is greater than one, the optimal set of signature waveforms was found in [31] as a function of the allocated individual powers, generalizing the earlier optimal design in [32] which showed that Welch-bound-equality signals achieve single-user capacity when the received powers are identical. However, practical nonorthogonal CDMA systems such as those found in second- and third-generation wireless use pseudorandom spreading codes rather than optimized signature waveforms. The capacity of CDMA with random spreading was analyzed in [33–38]. In particular, the spectral efficiency of CDMA subject to fading was obtained in [35] for three major receiver structures: matched filter (which ignores multiuser interference), optimum linear multiuser detectors (modified matched filters that take into account the interfering spreading codes to maximize SNR [39]), and optimum nonlinear multiuser detectors. Furthermore, the results of [35] are asymptotic in the number of users and spreading gain, keeping the load fixed. Results for arbitrary number of users are given in [6]. While even the simple matched filter achieves single-user

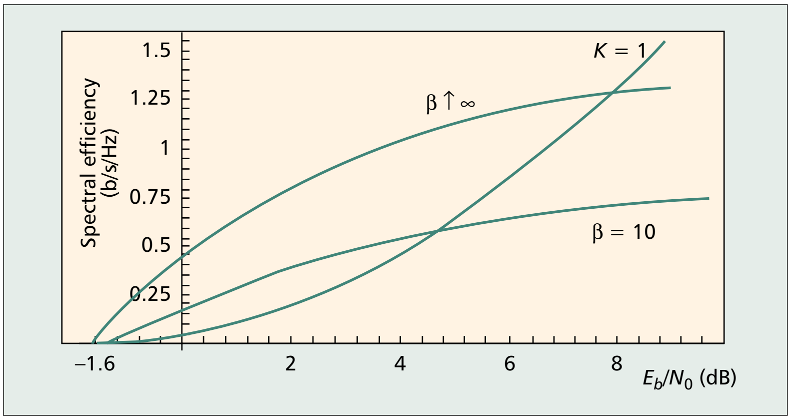
$$\frac{E_b^r}{N_0}_{\min} = -1.59 \text{ dB},$$

it achieves only half of the spectral efficiency achieved by the optimum receiver in the low-power regime for any type of fading. Thus, even in the region where the background noise (rather than multi-access interference) is dominant, taking into account the structure of the multi-access interference through multiuser detection has the potential of halving the required bandwidth. Furthermore, while the spectral efficiency of the matched filter converges to a constant as the SNR increases, the spectral efficiency achieved by multiuser receivers shows quite a different behavior. Using the optimum load (coding-spreading tradeoff), the optimal linear receiver spectral efficiency grows without bound with the SNR. As the load grows, and thus the synchronization and signal processing complexity, the optimal receiver is able to counteract, to a large extent, the loss incurred by nonorthogonal CDMA. The higher the SNR, the lower the load required to achieve a given percentage of the single-user capacity.

The increase in CDMA spectral efficiency due to the capability of having L receive antennas is also studied in [35]. For the optimum linear receiver, [40] identified the phenomenon of resource pooling, which renders the effective spreading gain equal to the product of the actual spreading gain times L. However, in the low-load low-power regime the improvement in spectral efficiency due



■ Figure 2. *Spectral efficiencies for a single user channel with log-normal fading σ_P = 10 dB.*



■ Figure 3. *Single-user vs. multiuser spectral efficiencies with matched filter and log-normal fading σ_P = 10 dB; load is denoted by β.*

to diversity is very slight unless the kurtosis of the fading distribution is large [35]. For high load, spectral efficiency is multiplied by a factor of L. A CDMA-based scheme that uses orthogonal spreading sequences to exploit transmitter antenna diversity without requiring knowledge of the channel at the transmitter is given in [41].

Multiuser Diversity

In wireless channels, the transmission schemes incorporate one or several diversity mechanisms in order to combat fading. Diversity may be present in the time domain (e.g., using redundant error control codes in conjunction with interleavers), the frequency domain (e.g., using spread spectrum signaling), or the space domain (e.g., using several sufficiently separated antennas at transmitter and/or receiver). The phenomenon of multiuser diversity arises in certain scenarios because of the beneficial effects of allocating power among several transmitters subject to independent fading, even if the transmitters have no knowledge of the channel. In CDMA, sometimes the multiuser diversity gain can offset the performance loss incurred by a simple receiver that neglects multiuser interference [35]. Within the context of the single-user matched filter, the beneficial effects of multiuser diversity occur in the low-power region, with fading distributions that have sufficiently high kurtosis, and increase with the load (Fig. 3).

In the context of the optimum linear multiuser receiver, fading sometimes has a net positive effect by reducing the number of "effective" interferers seen at the receiver. For sufficiently large load, the optimum nonlinear receiver wipes out the penalties in spectral efficiency due to fading and random CDMA spreading. Thus, it achieves better efficiency than a single-user system operating at the same E_b/N_0 and subject to the same fading distribution.

Power Control

From the standpoint of channel capacity the strategy of equalizing received powers at the base station (so-called perfect power control) used in second-generation wireless CDMA is very power hungry (Fig. 2). (That choice is dictated by the lack of multiuser detection at the receiver, thus rendering the system very sensitive to the near-far problem.) According to single-user channel capacity, no power control whatsoever is a much better strategy and asymptotically optimal as the SNR increases. Of course, in practice, a modicum of power control is a necessity to limit the dynamic range of signals at the receiver. For CDMA channels where transmitters are only aware of their individual instantaneous path losses, the optimal power control laws have been obtained for several receivers in [35]. For the matched filter receiver, optimum power control can eliminate the penalty in spectral efficiency due to fading. For the optimum linear multiuser detector, optimum power control is particularly helpful in channels where the load is high. The optimum receiver with optimum power control can even outperform the single-user channel without fading (Fig. 4).

If the transmitters are aware of the path losses suffered by all the other transmitters (or in downlink where the base station knows the instantaneous losses of each mobile), centralized power control is feasible. The gains achievable over the decentralized control described above depend on the multi-access scheme. For the randomly spread CDMA channel with an optimum receiver, it was shown in [42] that knowledge of other users' channel conditions does not increase capacity. In contrast, for narrowband multiaccess channels, [43] showed that the optimum strategy is to let only one user[3] — the strongest — transmit at a time using the single-user power control law of [22]. If there are many independently faded users, significant gains are feasible relative to channels without fading — another manifestation of the phenomenon of multiuser diversity seen previously. The practical exploitation of this source of diversity is limited by the fact that if the fading varies too slowly, users may have to wait a prohibitively long time before they can transmit. Scheduling algorithms that take fairness and latency into account have been implemented in commercial systems [3, 4], with the latter system incorporating multiple antennas fed with slightly offset carriers in order to accelerate the fading dynamics [45]. The statistical independence of the fading affecting different transmitters is a benefical source of multiuser diversity. This provides yet another reason in favor of wideband communication, as the multiuser diversity benefits of centralized power control grow with the number of users.

[3] *In the narrowband setting with decentralized power control the optimum number of simultaneously active users turns out to be the logarithm of the number of users if the fading is Rayleigh distributed [44].*

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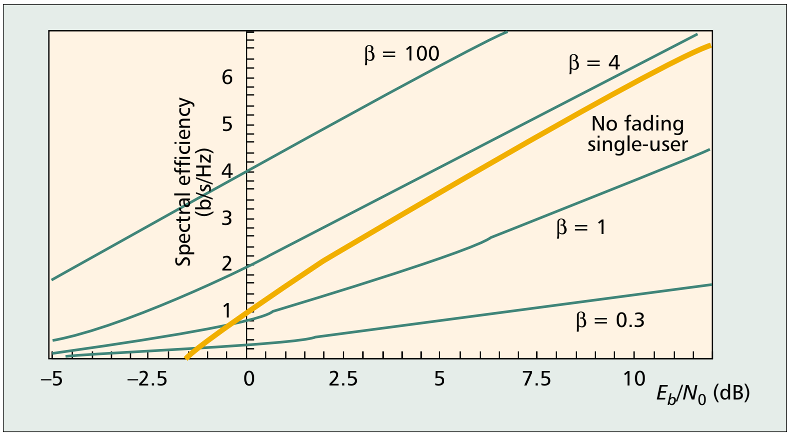

■ Figure 4. *Optimum power control with Rayleigh fading and CDMA with load β.*

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Biographies

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