Abstract

In this article the authors examine the time-division duplex (TDD) mode of code-division multiple access (CDMA) communications. The differences from frequency-division duplex (FDD) are shown, and the advantages of using a TDD system are discussed. The TDD mode facilitates the implementation of several functions in the areas of power control, rake combining, and selection diversity combining, which can reduce the complexity of mobile units and improve system capacity.

Time-Division Duplex CDMA Communications

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Wireless and mobile communications has been the fastest-growing field in the electronics and telecommunications industry over the past ten years. The explosive growth in demand for mobile and cordless voice and data communications service has caused significant reductions in systems costs, which in turn has fueled further demand. To keep up with the demand, the technology has had to constantly evolve; resulting in numerous systems and methods which are presently in service or in the implementation phase; some even have come into service, had a short span, and are being gradually phased out.

The demography of mobile users and their demands have also changed greatly. The initial customers were mostly business users, who mostly required wide area connectivity and were not greatly concerned with the communications quality or size and cost of the mobile units. Nowadays, more and more ordinary citizens subscribe to these services. These new customers demand small, light, low-cost mobile units with low service charges. Moreover, business as well as private users now demand other services such as data and video communications along with telephony services. Furthermore, the growing demand will soon fully exhaust the limited allocated frequency bands unless ways are found to more efficiently utilize these resources. The present technological research is geared to find solutions to the above challenges, and the various present and proposed methods will be evaluated on the extent to which they address the above issues.

Mobile systems and services have been classified in a number of ways. Figure 1 shows some of these services to illustrate the emergence of new technologies [1, 2]. It is based on the approximate time they appeared in the market or are expected to appear. Presently, mobile communication systems are broadly divided into the first, second, and third generation of services, based on whether the system is analog or digital, and voice or multimedia (i.e., the extent of different services they provide). The first generation of mobile systems is already in the process of being phased out after some 10–15 years in service; the second-generation systems have been in operation for now some three or four years and are expected to be replaced by or evolve to the third-generation systems, which are presently in the process of being standardized. A general trend can be observed in the multiple access scheme utilized: from frequency-division multiple access (FDMA) to time-division multiple access (TDMA) and code-division multiple access (CDMA). The TDMA and CDMA developments are generally in response to the above-mentioned challenges. These systems have been shown to increase frequency utilization efficiency compared with FDMA [3, 4]. They are also capable of accommodating multirate services, one of the main requirements of future multimedia mobile communications.

An emerging trend can also be detected in the duplex mode of operation of mobile services. Time-division duplex (TDD) seems to be gradually utilized, gaining on the more broadly used frequency-division duplex (FDD) mode. The TDD systems are appearing in the low-power end of the domain, where simplicity and low cost are major concerns.

As shown in Fig. 1, most lower-power, small-area cellular systems (usually provided in microcells, with little round-trip propagation delays on the order of 10 μs) of the second generation use TDD as their duplex mode. In Europe the Digital Enhanced Cordless Telephone (DECT) standard is based on TDD-TDMA [5]; in Japan also, the Personal Handyphone System (PHS) is based on TDD-TDMA [1]. It is reasonable to expect that some of these systems will evolve into TDD-CDMA. In fact, one of the present technical ad hoc groups (TAG) in the United States, working on standards for personal communications services (PCS) systems, is concerned with TDD-CDMA (TAG-1) [6]. In addition, TDD-CDMA has been already developed for cordless telephones by Uniden [7]. TDD-CDMA is also increasingly the focus of research [8–10], and is being experimented with in combination with multicarrier CDMA for millimeter-wave communications [11].

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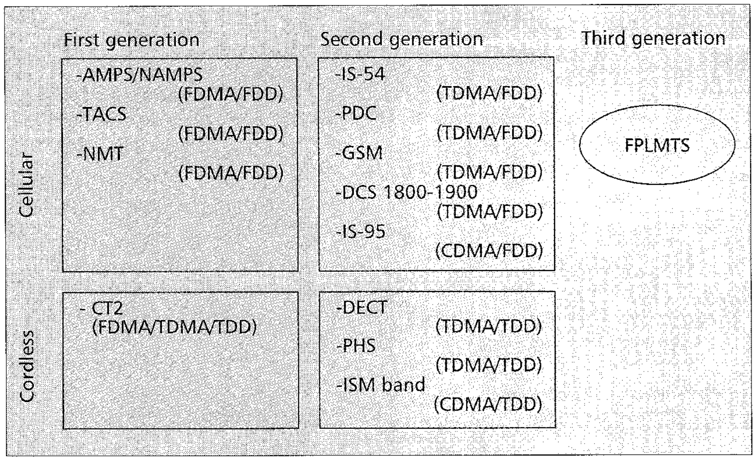


■ **Figure 1.** *The evolution of mobile communication systems and services.*

The main difference between the two modes, as shown in Fig. 2, is that duplex transmission is carried in alternate time slots for the TDD mode in the same frequency channel, whereas FDD uses two separate channels for continuous duplex transmission. In FDD systems a guard frequency is required between the forward and reverse links' allocated frequencies to minimize mutual interference. On the other hand, a guard time in TDD systems is required to reduce mutual interference between the links. Its length is decided from the longest round-trip delay in a cellular system.

One of the advantages of using TDD over FDD is the simplicity of its devices, since only one set of electronics (filters, oscillators, etc.) is required at both mobile and base stations for both forward and reverse links. This is significant in the low-power, small-size mobile communications market.

However, the most important advantage of TDD over FDD is that since the same frequency channel is used, reciprocity exists between the links' channel characteristics. This fact can be used to implement a number of important functions in an open loop fashion, including power control, signal pre-emphasis and shaping, and diversity transmission (as compared to diversity reception) to respond to unfriendly urban mobile channel conditions. All these functions will help further reduce the complexity of the portable mobile unit, resulting in less costly devices.

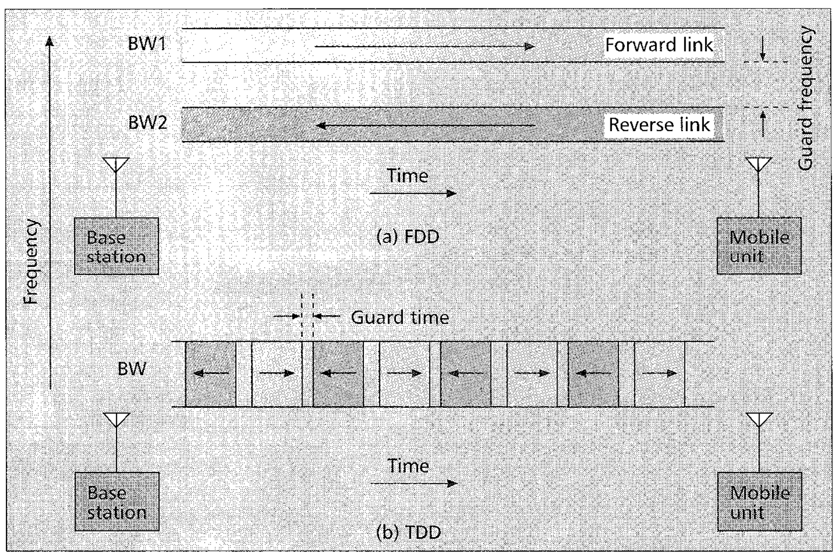
The cellular mobile channels are characterized by signal fading due to the vector summation of multiple received signals at the receiver antenna, each signal being a distinct reflection of the transmitted signal from physical objects in the communications channel. As a result, the received signal power level changes widely as a mobile unit moves in the cell. The signal also undergoes shadowing fade caused by the blockage of signal by buildings. To reduce the fading effects, diversity reception and power control must be utilized.

Considering the unfriendly conditions of cellular mobile channels, using the TDD mode in CDMA is more than just combining two technologies. TDD facilitates very accurate power control in CDMA, a field extremely important for the provision of greater capacities. In packet-switched data communications, fading power control can only be implemented in TDD: it is impossible or very inefficient to implement power control in FDD systems for short-length transmissions. It also provides diversity transmission to CDMA mobile units where the unit is only a simple nondiversity combining receiver, thereby helping to keep the mobile units small and low-cost. The TDD and CDMA combination, the authors believe, will be crucial to the success of CDMA mobile systems, in particular to low-end devices.

The Future Public Land Mobile Telecommunication Services (FPLMTS) standards are now in the process of being decided. Several of the systems shown in Fig. 1 or their evolved systems are strong candidates to become the universal standard. It is very likely, however, that multiple standards will evolve from the present operating systems because of economical and political as well as technical considerations. It seems reasonable to expect that TDD will start to dominate the low-power systems, whereas FDD will be used in high-power digital cellular mobile. An evolution is likely to be seen from TDD-TDMA systems to TDD-CDMA systems; thus, these systems will become more and more common. It is also likely that dual-mode TDD-FDD systems will come to exist, operating in both microcell and macrocell mobile, since the addition of a TDD-style receiver to FDD devices can be done at minimum cost.

Organization

This article discusses the combination of TDD and CDMA, and some of the advantages of using this system. The following is divided into three parts, the first on power control in TDD-CDMA and its efficiency compared with the FDD-CDMA power control. The results are used to discuss capacity of the two systems. Next, the preselection diversity is discussed, followed by an explanation of pre-rake CDMA. It is shown that both these systems can significantly reduce the complexity of mobile units.



■ **Figure 2.** *FDD and TDD systems frequency allocation.*

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Power Control in TDD

CDMA systems are very sensitive to changes in transmitted power and channel and terrain characteristics [12, 13]. In contrast to TDMA and FDMA systems, where user capacity is mainly dependent on allocated frequency bandwidth (BW), CDMA capacity is dependent not only on BW, but also heavily on co-channel interference. To reduce this, each user must transmit at the lowest possible power level necessary for an acceptable performance, and transmit in a way that its received power at the base station deviates minimally from the desired level. It is well known that power control errors can significantly reduce total user capacity [12–14]; and it is believed that the promised high capacities of the CDMA technique are only achievable if a very efficient power control method is applied, and the received power level at mobile unit and base station is kept with minimum deviation. It has been shown that fading power control can improve system performance significantly in channels with multipath fading characteristics [15].

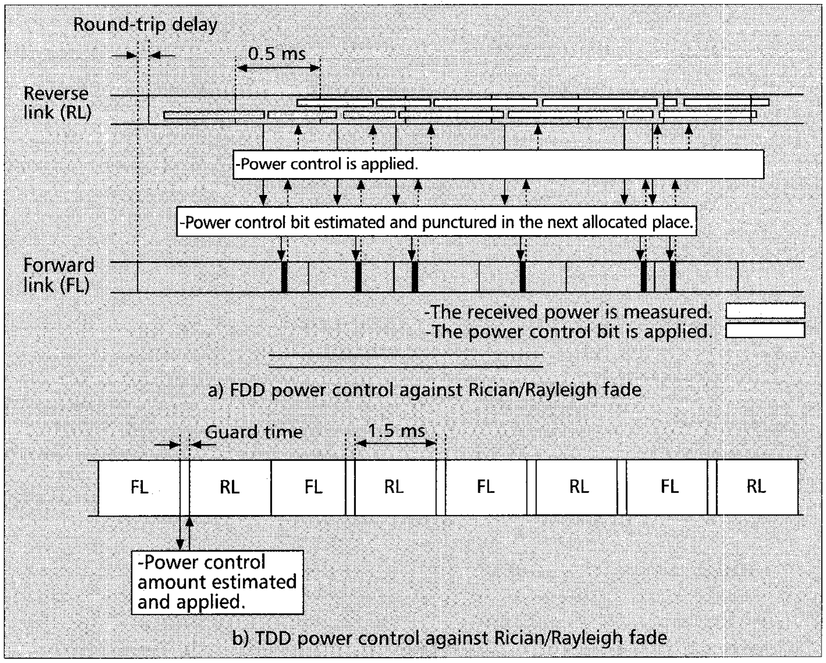

Figure 3. *Power control against fast fading in FDD and TDD systems.*

The received signal in a mobile communication system is the convolution of the transmitted signal and the channel characteristics, and can be written as

$$r(t) = h(t) * s(t),$$

where $h(t)$ represents a user's channel impulse response.

The attenuation factor, included in $h(t)$, directly affects the received power and depends on three factors: propagation distance, shadowing, and multipath fading. These factors vary as a mobile unit moves in a cell. The power control units in both the mobile unit and the base station track the changes in received power, estimate the total attenuation, and adjust their transmission power to compensate for the changes. The first two factors, distance and shadowing, vary slowly and can easily be compensated for. The rate of change of the fading factor depends on the velocity of user movement and the transmission frequency. It is relatively difficult to track and compensate for the changes in signal power due to fading, especially at high mobile speeds.

In the FDD mode of transmission, the shadowing factor is highly correlated between the forward and reverse links. The fading factor, however, is uncorrelated since the links' allocated frequencies are different. In the TDD mode the fading factor also is highly correlated. This fact can be used to implement open loop power control in the TDD CDMA systems, whereas the FDD systems must use closed loop power control.

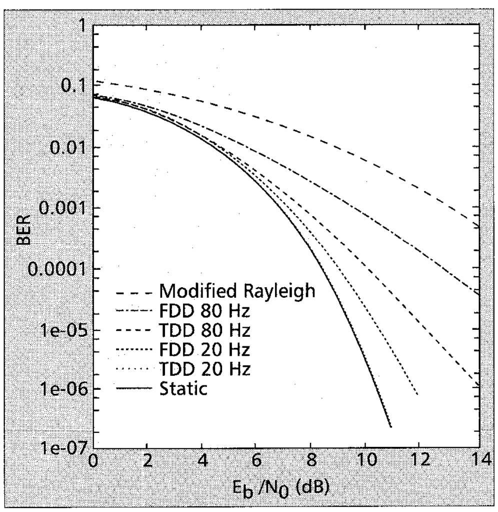

Figure 4. *BER curves for the FDD and TDD power control modes at BW = 5 MHz.*

To ensure the reception of a signal with little or no fading, the transmitted signal must be multiplied by a factor inversely proportional to the attenuation factor. This factor must be estimated prior to transmission based on information obtained from the transmission channel.

TDD and FDD Fading Power Control

Since the fading patterns of the reverse and forward links are uncorrelated in the FDD mode, closed loop power control is implemented; this is illustrated in Fig. 3a. Upon receiving the reverse link signal, a base station determines whether a mobile unit should decrease or increase its transmission power to combat fading. In this example, the decision is conveyed to the mobile unit by puncturing one bit in the data frame and substituting it by the power control command [3, 16].

In the TDD mode open loop power control is implemented. An extrapolation process is used to estimate the fading level of the next frame. Based on this information, the transmitter unit modifies the power control factor (Fig. 3b.) Compared with the FDD method, variations in the TDD power control signal can vary greatly and are not restricted to increase/decrease; no capacity is lost due to power control data transmission; and little processing delay exists between the calculation and implementation of power control.

In the simulations of [17], the FDD mode power control bits are transmitted on average every 500 μs for a total of 2000 b/s or 6.7 percent reduction in data transmission efficiency. In the TDD mode transmitted data are organized in frames, each 1.5 ms in length. Guard times of 50 μs

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Fading rate	FDD PC gain over no PC	TDD PC gain over no PC
20 Hz	6.2 dB	6.4 dB
40 Hz	6.0 dB	6.3 dB
80 Hz	3.7 dB	5.7 dB
120 Hz	2.5 dB	4.6 dB

■ **Table 1.** *A comparison between the FDD and TDD power control (PC) gains at BW = 5 MHz.*

One path		Two paths (TDD)		Three paths (TDD)	
FDD	TDD	PC	Diversity	PC	Diversity
3.2 dB	4.6 dB	3.9 dB	1.9 dB	3.8 dB	3.2 dB

■ **Table 2.** *The power control (PC) and diversity gains of the multipath systems over a single-path, no-power-control system (average over 20–200 Hz).*

(equivalent to a round-trip of 15 km) are placed between the forward and reverse link frames, resulting in a 3.3 percent reduction in data transmission efficiency. It should be noted that smaller frame lengths have been suggested; for example, Miya *et al.* use a frame length of 625 μs with a guard time of 62.5 μs, a loss in efficiency of 9.1percent [10]. The shorter the TDD burst, the faster the power control process can be performed, which results in better performance at higher fading rates.

Figure 4 shows the bit error rate (BER) results for the FDD and TDD modes with TDD frame lengths of 1.5 ms at two fading frequencies, 20 and 80 Hz. The power control gains for the FDD and TDD modes at BER = 10^{-3} are listed in Table 1. These results exhibit a significant improvement in system performance for fading conditions for both the TDD and FDD modes [17]. TDD performance is always better (slightly at low-fading rates and significantly in faster-fading environments) than FDD. However, it should be remembered that for most short packet data services no fading power control can be provided in FDD systems, which represents a significant disadvantage from the TDD mode.

Preselection Antenna Diversity

Diversity combining techniques are used to shorten the fading periods of the channel in mobile radio communications. In the selection diversity combining technique the receiver measures the received signal level from independent paths and selects the best path for data reception. Such a receiver is necessarily more complicated; and although the base station can accommodate this increase in complexity to achieve superior performance, it is undesirable for inexpensive handheld mobile units. However, in some environments, space (antenna) diversity is the only way to provide the mobile with diversity reception.

In the TDD CDMA communication it is possible to provide diversity reception by preselecting the best transmission path to a mobile based on the information obtained from the reverse link signal. Since fading patterns are the same for both forward and reverse links, a base station can estimate the strongest available path by measuring the received signal power at each of its antennas, and estimate and select the most suitable antenna for the next frame transmission (Fig. 5). In this way the advantages of diversity reception can be realized on the forward link while mobile units remain identical to ones used for a single-path case.

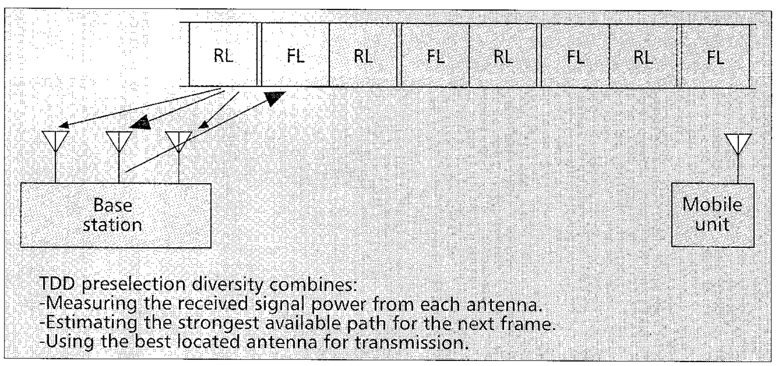
Here, the power control factor is set to the estimated inverse of the fading parameter of the estimated best path. The path (in this case antenna) selection is done completely at the base station; the mobile unit remains unaware of which antenna is being used for communication.

Some BER results of TDD power control in three-path selection, and the power control and diversity gains for multipath systems are summarized in Table 2. More detailed analysis can be found in [18]. It can be seen that power control gain remains significant even when diversity reception exists.

Pre-Rake Combining Diversity

One interesting feature of CDMA systems is the use of rake receivers in multipath environments to achieve a multipath diversity gain [19]. These receivers, however, require significant signal processing and power supply consumption, which increase the cost of the receiver, where it is desirable to reduce the size, power consumption, and cost of the portable mobile unit.

In a multipath fading channel a conventional rake receiver is often used. A rake receiver consists of a number of correlators, each synchronized to one of the channel's paths. The outputs of the matched filters are then coherently added for maximally efficient reception. In FDD systems, the receiver in both the base station and the mobile unit must be equipped with a sufficient number of correlators and must estimate the channel impulse response. In TDD systems we can utilize the fact that for a period of time the channel impulse response is the same for the forward and reverse links. In this case only the base station needs to estimate the channel impulse response. In the forward link the base station multiplies the signal to be sent to a user by the time-inverted complex conjugate of the reverse link channel impulse response of that user. When the pre-rake signal is transmitted, it is convolved with the channel impulse response of the user. This produces a strong peak at the output of the channel which is equivalent to the rake receiver's output. Therefore, the receiver of the mobile unit does not need to estimate the channel impulse response and can only use one matched filter and tune to this peak. The pre-rake concept is shown graphically in Fig. 6 for a transmitted impulse signal. The advantage of the pre-rake combining technique is that rake receiver function and circuitry is removed from the portable unit to the base station, while pre-



■ **Figure 5.** *Base station selected multipath diversity.*

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serving diversity gains. The result is again simple, low-cost units, ideal for the low end of the market.

A more detailed description of the base station and mobile unit block diagrams can be found in [20], where it is also shown that the performance of the rake and pre-rake systems are identical for single-user spread-spectrum systems under ideal conditions (i.e., when the channel impulse response is accurately measured, and rake and pre-rake parameters are ideally set).

In a CDMA environment the performance of rake and pre-rake are not equal. This is because the pre-rake process affects the amount of co-channel interference. The received signal at a mobile unit's rake receiver consists of the desired and coherent multi-user interference signals. The rake combining process thus not only enhances the desired signal, but also the interference. In the pre-rake process, however, the transmitted signals from the base station are incoherent, and as a result the interfering signals are not enhanced at the mobile unit's receiver, resulting in a better performance for pre-rake systems.

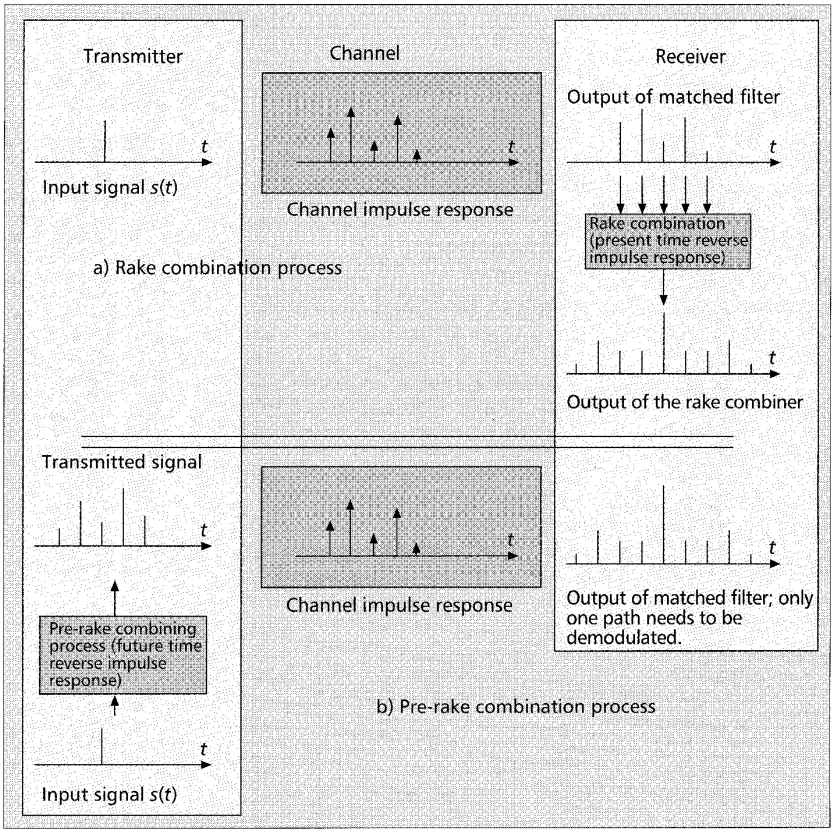

Figure 6. *Rake and pre-rake combination process.*

Figure 7 shows the probability of error versus the E_b/N_0 for the rake and pre-rake systems with four paths for a TDD CDMA system with 20 users and psuedo-noise code length of 63. It can be seen that the receiver significantly outperforms the rake receiver since the latter enhances the interference as well. Figure 8 shows the probability of error versus the number of users with E_b/N_0 = 15 dB and 4 diversity paths. The same observation of the previous figure can be seen here. For details and the derivation of BER formulas the reader is referred to [21].

Conclusions

The results of the previous sections indicate that the TDD mode is better suited to low-end mobile communications systems than FDD. The main advantage is the reciprocity of forward and reverse links, which facilitates the implementation of a number of power control and diversity techniques without increased complexity, resulting in simpler mobile units. Further simplicity of TDD systems results since both mobile and base units use a single frequency band, because of which many of the electronic devices can be used jointly for both forward and reverse link operations. The simplicity and low cost are major concerns, and the advantages provided by TDD are very important. Frequency utilization efficiency can be also much higher in TDD systems, especially when the operation frequencies are allocated in one single band, as is the case with system operating in the Industrial, Scientific, and Medical (ISM) band.

In addition, more efficient power control can be applied in TDD systems. In single-path transmission channels, the TDD open loop power control method has an advantage over the FDD over a range of fading frequencies, which translates into higher reverse link user capacities. Also, FDD systems are not able to provide fading power control for short packet data transmissions, which further puts them at a disadvantage.

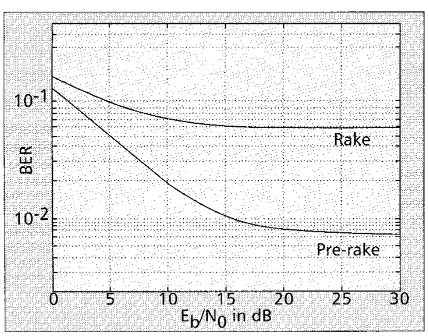

Figure 7. *BER vs. SNR.*

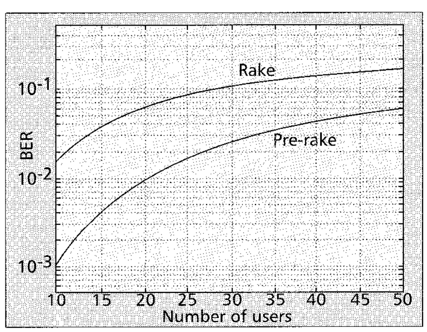

Figure 8. *BER vs. the number of users.*

Fading can severely degrade the performance of mobile systems. To shorten the fading periods, diversity reception must be implemented. One way to make this possible is by utilizing space/antenna diversity methods. While TDD facilitates forward link diversity reception at the mobile unit by transmission antenna preselection at the base station, diversity reception in FDD is only possible if multiple antennas are used, while it is necessary to keep the size and cost down. Considering the size

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of a mobile unit, it may not even be possible to place two antennas on the device.

In multipath channels, TDD facilitates the implementation of a unique diversity combining method, called pre-rake. Since the forward and reverse links are on the same carrier the base station can estimate the channel impulse response and pre-emphasize (pre-rake) the signal before transmission to the portable unit. With a simple matched filter at the portable unit, the diversity effect is achieved. This greatly reduces the size and cost of the portable unit. It has been shown that the pre-rake receiver's performance can be better than that of the rake receiver.

The FPLMTS standards aim for a single mobile unit that can provide access to communication services anywhere. This may not be possible with single-mode devices. An easier and more efficient approach may be the combination of two present systems, in which case a TDD-FDD system is a very attractive solution which also helps to keep the costs down. The TDD part will provide efficient, inexpensive service for low-fading-rate microcell communications (it should be noted that TDD operation efficiency is limited by the guard time between forward and reverse link frames, which is determined based on cell size; thus, TDD systems are most suitable in microcell environment), and the FDD mode will be used for the macrocell communications. In any case, the TDD is the emerging choice for the low-end market where simplicity and low cost are the main concerns.

References

[1] D. M. Balston and R. C. V. Macario, *Cellular Radio Systems*, Artech House, 1993.

[2] D. C. Cox, "Wireless Network Access for Personal Communications," *IEEE Commun. Mag.*, Dec. 1992, pp. 96–115.

[3] K. S. Gilhousen, *et. al.*, "On the Capacity of a Cellular CDMA System," *IEEE Trans. VT*, May 1991, pp. 303–12.

[4] J. Skold, B. Gudmundson, and J. Farjh, "Performance and Characteristics of GSM-Based PCS," *Proc. IEEE VTC*, Chicago, IL, July l995, pp. 743–48.

[5] D. J. Goodman, "Trends in Cellular and Cordless Communications," *IEEE Commun. Mag.*, June 1991, pp. 31–40.

[6] L. Goldberg, "Personal Communication Systems: Seven Methods for U.S. Standards," Japanese translation cited in *Nikkei Elect.*, no. 633, June 10, 1995, pp. 135–43.

[7] K. Tanaka, *et. al.*, "Development of Spread Spectrum Cordless Telephone," IEICE Tech.Rep. IT93-88, ISEC93-90, SST93-83 (1993-12), vol. 93, no. 381, Dec. 16, 1993, pp. 67–72 (in Japanese).

[8] G. J. R. Povey, "Capacity of a Cellular Time Division Duplex CDMA System," *IKE Proc. Commun.*, vol. 141, no. 5, Oct. 1994, pp. 351–56.

[9] K. Akabane, R. Esmailzadeh and M. Nakagawa, "Hybrid DS/SFH-TDD System," IEICE Tech. Rep. SST94-14, June 1994 (in Japanese).

[10] K. Miya *et al.*, "A Base Station Based Diversity Scheme for CDMA/TDD Systems," IEICE Tech. Rep. RCS94-73, Sept. 1994 (in Japanese).

[11] H. Takahashi and M. Nakagawa,: "Antenna and Multi-Carrier Pre-Diversity System Using Time Division Duplex in Selective Fading Channel," IEICE Tech. Rep. RCS9545, July 1995 (in Japanese).

[12] F. Behebahani and H. Hashemi, "Performance and Capacity Evaluation of CDMA Mobile Radio Systems — Reverse Link Analysis," *Proc. IEEE VTC,* Stockholm, Sweden, June 1994, pp. 65–69.

[13] M. R. Heath and P. Newson, "On the Capacity of Spread Spectrum CDMA for Mobile Radio," *Proc. IEEE VTC*, Denver, CO, May 1992, pp. 985–88.

[14] E. Kudoh, "On the Capacity of DS/CDMA Cellular Mobile Radios Under Imperfect Transmitter Power Control," *IEICE Trans. Commun.*, Aug. 1993, pp. 886–93.

[15] R. Esmailzadeh and M. Nakagawa, "Time Division Duplex Method of Transmission of Direct Sequence Spread Spectrum Signals for Power Control Implementation," *IEICE Trans. Commun.*, vol. E76-B, no. 8, Aug. 1993, pp. 1030–38.

[16] S. Ariyavsitakul and L. F. Chang, "Signal and Interference Statistics of a CDMA System with Feedback Power Control," *Proc. IEEE GLOBECOM*, Phoenix, AZ, Dec. 1991, pp. 1490–95.

[17] R. Esmailzadeh and N. Doi, "A Comparison on the Performance of the FDD and TDD Modes of B-CDMA Communications," *Proc. IEEE ICUPC '95*, Tokyo, Japan, pp. 339–43.

[18] R. Esmailzadeh and M. Nakagawa, "Time Division Duplex Transmission of Direct Sequence Spread Spectrum Signals in Multipath Channels," *Proc. IEEE VTC*, Stockholm, Sweden, May 1994, pp. 1572–76.

[19] G. L. Turin, "Introduction to Spread-Spectrum Antimultipath Techniques and Their Application to Urban Digital Radio," *Proc. IEEE*, vol. 68, no. 3, Mar. 1980, pp. 328–53.

[20] R. Esmailzadeh and M. Nakagawa, "Pre-Rake Diversity Combination for Direct Sequence Spread Spectrum Mobile Communications Systems," *IEICE Trans. Commun.*, vol. E76B, no. 8, Aug. 1993, pp. 1008–15.

[21] R. Esmailzadeh, E. Sourour, and M. Nakagawa, "Pre-Rake Diversity Combining in Time Division Duplex CDMA Mobile Communications," *Proc. IEEE PIMRC '95*, Toronto, Canada.

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