Time Division Multiple Access Methods for Wireless Personal Communications

TDMA is a classic approach to multiple access in digital cellular wireless communications systems and is the multiple access technique of choice for several digital cellular and PCS systems.

David D. Falconer, Fumiyuki Adachi, and Björn Gudmundson

Digital cellular and microcellular radio systems must incorporate multiple access schemes that make efficient use of the allocated bandwidth and radio cell infrastructure with minimum cost and maximum performance [1]. Time Division Multiple Access (TDMA) is the multiple access technique of choice for several digital cellular and PCS systems. For example, it is currently used in the European, North American and Japanese second generation digital cellular systems (GSM, IS-54, and PDC, respectively) [2, 3], and in several wireless personal communications systems: the European digital cordless system (DECT [2]), the Japanese personal wireless system (PHS [4]), and the wireless access system proposed by Bellcore (WACS [5] or PACS).

TDMA as a Multiple Access Technique

In a cellular radio system, a number of users in a cell communicate with that cell's base station, which in turn communicates with the rest of the world, generally through copper or fiber lines. Usually, the particular cell a user terminal belongs to is determined by which base station provides the highest signal power or signal to interference ratio. In a TDMA cellular radio system, several users time-share a common carrier frequency to communicate with the base station. Each user, transmitting low bit-rate digitized speech or other digital data, is allocated one or more timeslots within a frame in the downstream (base to users) and upstream (users to base) directions, as illustrated in Fig. 1. In the downstream direction, the base station broadcasts to the active users in a Time Division Multiplex (TDM) format. In the upstream direction, each active user terminal transmits to the base station only in its own assigned timeslot or slots. Inter-user interference is prevented by strict adherence to timeslot schedules, and by guard times and time-alignment procedures between upstream timeslots, in order to prevent overlaps due to different propagation times.

Note that each individual terminal's receiver and transmitter operates with a duty cycle of $1/N$ if there are N user terminals with equal bit rates sharing a common bit stream. Upstream and downstream traffic is separated either by using different carrier frequencies i.e., Frequency Division Duplex (FDD), or by alternating in time, i.e., Time Division Duplex (TDD). FDD requires less transmission bandwidth per radio and also less precise synchronization of upstream and downstream transmissions to minimize interference. On the other hand, TDD requires simpler radio duplex equipment and facilitates flexible bandwidth allocation between upstream and downstream traffic. The GSM, IS-54, PDC, and PACS systems all use FDD, while DECT and PHS use TDD.

TDMA is usually combined with Frequency Division Multiple Access (FDMA), as different carrier frequencies are used in different cells. Frequencies are only reused in cells sufficiently distant in order to minimize interference. Furthermore, there may be several carrier frequencies used in a cell, each with its own TDMA bit stream and set of user terminals.

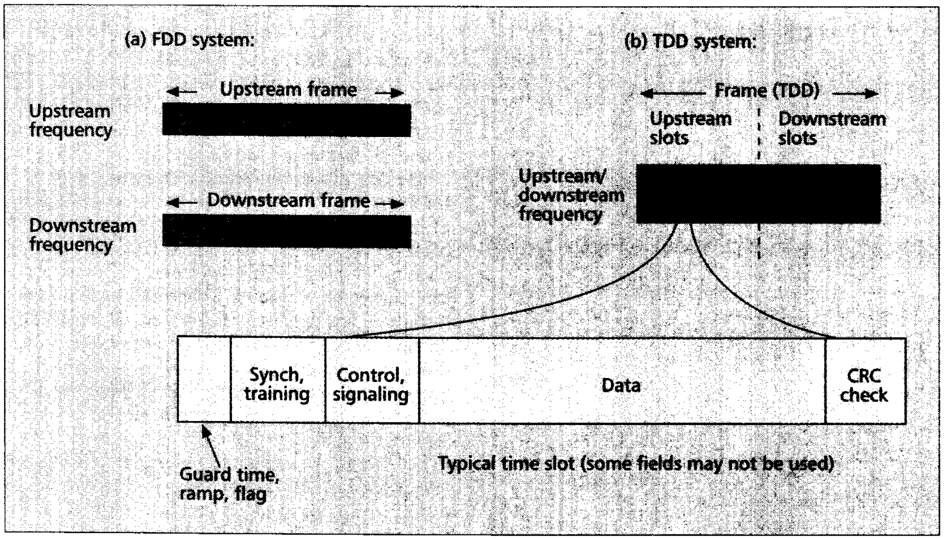
Each timeslot in a frame generally contains user data bits (which may include parity bits for error control), as well as extra bits for synchronization, adaptation, control, guard time, etc. The smaller the fraction of the frame devoted to these "overhead" bits, the more efficient is the TDMA frame design. For example, the GSM, PHS and DECT systems have roughly 30 percent of their total bit rates used for overhead, while the IS-54 and PDC systems have about 20 percent overhead. The major portion of the overhead in the GSM and IS-54 systems is used for adaptive equalizer training sequences, while in DECT, most of the overhead is used for system control. For a given amount of overhead, higher efficiencies could in principle be achieved by increasing the timeslot duration. However this can have the adverse effects of increasing the total transmission delay for time-sensitive traffic such as speech, and/or of hampering the system's ability to adapt to rapid changes in the propagation environment. Reference [2] provides a comprehensive description of the frame structures of

DAVID D. FALCONER is a professor in the Department of Systems and Computer Engineering at Carleton University.

FUMIYUKI ADACHI is with NTT Mobile Communications Network, Inc.

BJORN GUDMUNDSON is manager for the Radio Access and Signal Processing Research department at Ericsson Radio Systems.

0163-6804/95/$04.00 1995 © IEEE



■ **Figure 1.** *Illustration of TDMA frames and timeslots.*

TDMA is a well-understood access technology, which has been successfully used in a number of wired and wireless digital transmission systems.

several TDMA systems. Table 1 presents a comparison of a number of features of contemporary TDMA systems. Figure 1 illustrates possible frame and timeslot structures for generic FDD and TDD systems.

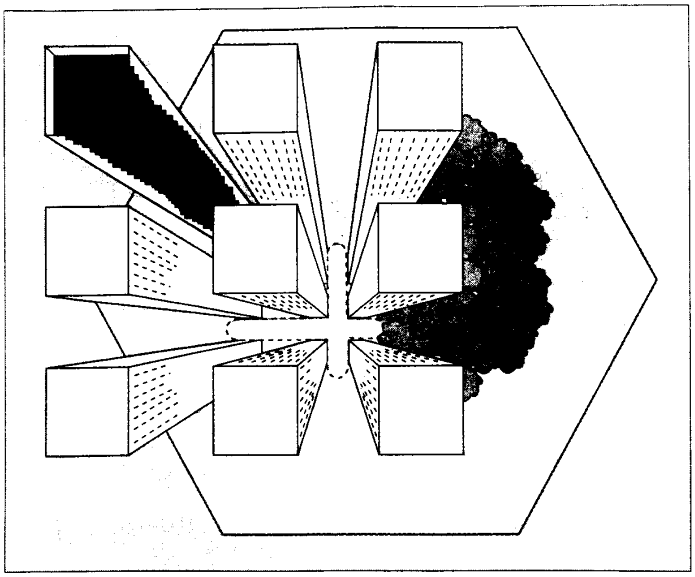
Comparison with Other Multiple Access Techniques

TDMA has several advantages relative to alternative multiple access techniques, such as FDMA and Code Division Multiple Access (CDMA). One advantage is that common radio and modem equipment, at a given carrier frequency, can be shared among N users at a base station. Another advantage with respect to FDMA is that bit rates to and from each individual user terminal can be easily varied according to current user needs, by allocating more or fewer timeslots to the user. This is especially advantageous for integrated service applications. With respect to CDMA, TDMA has the advantage of much less stringent power control requirements, since interuser interference is controlled by timeslot and frequency allocation instead of by processing gain resulting from coded bandwidth spreading. Another important advantage relative to FDMA and CDMA is that the timeslot structure gives time for measurements of alternative slots, frequencies, and ports in order to support mobile assisted or mobile controlled handoff.

TDMA also has some disadvantages with respect to FDMA and CDMA. Because user terminals have a $1/N$ duty cycle, they have a periodically pulsating power envelope. This presents a challenge to designers of portable RF units. Frequency and timeslot assignment and management entail a certain extra complexity in TDMA systems, which is not found in CDMA systems. Also, the N times higher bit rate means that TDMA may require equalization against multipath, which is generally avoided with FDMA.

TDMA can also be advantageously combined with packet-type multiple access schemes in integrated voice/data applications, involving perhaps several different types of traffic with different bit rates and on/off characteristics. One example is Packet Reservation Multiple Access (PRMA) [2], a dynamic slot allocation procedure in which idle timeslots are requested by users on a contention basis. If a user is successful in reserving one or more slots in a frame, that slot or slots is reserved for that user as long as required. When a slot is relinquished by a user (at the end of a speech burst or data packet), it is open for contention and reservation by other users. Asynchronous transfer mode (ATM) can also be incorporated in a TDMA-based wireless system [6]. TDMA is a well-understood access technology, which has been successfully used in a number of wired and wireless digital transmission systems. This has no doubt contributed to its adoption in second-generation digital cellular and PCS systems.

Objective comparisons of spectrum efficiency or capacity of FDMA, TDMA and CDMA systems are difficult to make since it is almost impossible to have similar assumptions for different systems. Furthermore, most comparisons are made between different systems, at different evolutionary stages, and not between the access methods themselves. If one were to compare two optimized systems, with different access methods, their capacities would likely be similar. Capacity in a cellular based personal wireless communication systems can be expressed as cell capacity or system capacity. Cell capacity, or radio capacity, depends on the radio link performance, i.e., at how low carrier-to-interference ratio (C/I) the system can operate, at acceptable quality. This in turn depends on the system requirements for speech quality (for a given digital speech compression technique) or data reliability. Cell capacity is measured in Erlang/MHz/Cell, and is traditionally used when analyzing the capacity of a system. Both the modulation efficiency (bits per second per Hz) and the frequency reuse factor must be taken into account. System capacity, on the other hand, depends on the feasibility of supporting small cells (micro cells and pico cells) and the cell capacity. System capacity is measured in Erlang/MHz/km^2, which means quite naturally that the capacity increases with decreased cell size.



■ Figure 2. *Illustration of hierarchical cell structures, which shows a system with three layers of cells: one macrocell to give coverage, one street microcell to increase capacity, and a number of indoor picocells. All these cells give different types of coverage to the same geographical area.*

Capacities for various types of cellular systems can also be compared roughly and simply, on the basis of the number of user terminals they can support in a fixed bandwidth, given the C/I requirements of each system. As an example, consider a comparison of the GSM digital cellular system with the North American AMPS analog cellular system. The latter accommodates one user in a 30-KHz bandwidth, requires about 18 dB C/I for satisfactory quality, and generally requires a cellular frequency reuse factor of 7, with 3-sector antennas. The GSM system, aided by slow frequency hopping and coding, requires about 9 dB C/I, a frequency reuse factor of 3, with 3-sector antennas, and in its initial version, accommodates eight users in a 200-KHz bandwidth. Thus the GSM capacity is about (30 x 7) divided by (3 x 200/8) = 2.8 times that of AMPS. Similar calculations [7] suggest that the IS-54 digital cellular system can exceed the AMPS capacity by a factor of about 3.5 to 6.3, and that the PDC digital cellular system can exceed the AMPS capacity by a factor of about 4.2 to 7.6. Each of these systems' factors can (and will) be approximately doubled by the use of half-rate speech coders. These upper and lower bounds on improvement factor correspond to pessimistic and optimistic frequency reuse factors of 7 and 4, respectively.

Capacity Enhancement and Evolutionary Scenarios

Both large cells (macro cells or umbrella cells) and small cells are needed simultaneously. The large cells are used to get coverage, and sometimes also to support hand-offs between small cells. The small cells are used to achieve high capacity, to get coverage in certain places, e.g., tunnels and garages, and also to provide access to users with low power portables. This whole scenario can be described as hierarchical cell structures (HCS); as shown in Fig. 2. The definition of HCS is that different cell types exists simultaneously in different cell layers, covering a common geographical area. To get very high system capacity the requirement is that HCS must be supported [8].

Before discussing the consequences of HCS for TDMA systems, we look into the possibilities of increasing the cell capacity via either or both of Adaptive Channel Allocation (ACA)[1] and Frequency Hopping (FH). The idea of ACA is to avoid interference by allocating channels based on the instantaneous signal-to-interference situation. This means that there is no fixed reuse distance. Sometimes the co-channel user is very close; e.g., when the mobile/portable is close to the base station. Sometimes the operating conditions for one user are very difficult; then the co-channel users are forced to be distant. Also when the traffic conditions are varying, channels can be "moved" to the peak-traffic cells. The capacity increase with ACA can be as much as 100 percent, compared to the same system using a fixed channel allocation. In [9], ACA is shown to be able to increase the capacity of IS-54 on the order of 30 percent. ACA is also part of the DECT standard [10].

Another way to increase the cell capacity is to use random FH, which can either be fast, (hopping rate on the order of the bit rate), or slow, (hopping between bursts of data). Slow FH (SFH) is part of the GSM standard. In a SFH system, the users inside a cell have the same hopping sequence, but offset from one another such that they do not interfere; i.e., the users within any cell are orthogonal. The hopping sequences in different cells are random, which means that the interference from other cell users is averaged. The averaging is made possible through interleaving and powerful channel coding. In GSM for example, the interleaving is done over 8 bursts, and a convolutional code of rate $R = 1/2$, and constraint length $K = 5$, is used [11]. The combination of interleaving and channel coding give the effect that a number of bursts can be completely wiped out, and the information can still be recovered. In GSM, approximately two out of eight bursts can be wiped out without loss of information. See [12-14] for further information on capacity in FH-TDMA systems.

Note that a FH-TDMA system really can be considered as a CDMA system, with the code as the hopping sequence. The increase in capacity comes from the fact that the interference is averaged, which means that one can design the system closer to the average interference situation, compared to non-hopping systems. The frequency reuse factor can be reduced to one, by reducing the cell load (fractional loading). This is very similar to direct sequence (DS) CDMA systems, with the extra benefit that the users inside a cell are orthogonal to one another.

Another benefit of FH is increased robustness (diversity) against fast fading, due to multipath propagation, especially for slowly moving users. The principle is that the total hopping bandwidth is sufficiently large that the different hopping frequencies are not too highly correlated. Improved performance results because only a few of the frequencies will be subject to deep fading at the same time instant.

As discussed earlier, to really increase the system

---

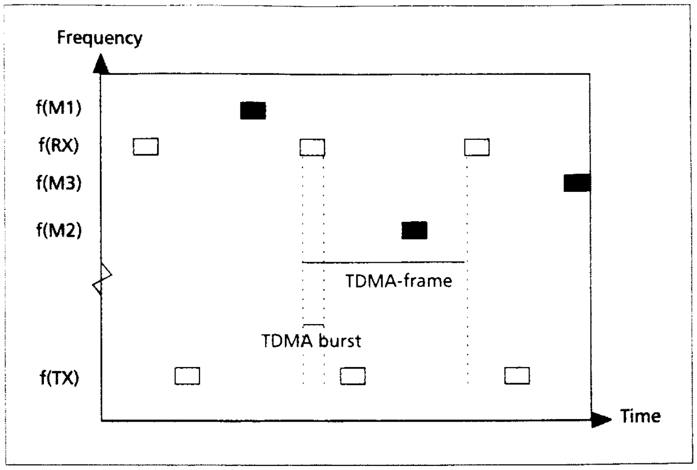
[1] *ACA is also frequently called Dynamic Channel Assignment (DCA).*

capacity, a hierarchical cell structure (HCS) is required and not only for capacity, but also for coverage and operational flexibility. To support HCS, reliable hand-off between cell layers is required. Furthermore, hand-off should not be forced between cell layers, i.e., it should be up to the operator to choose the hand-off strategy [8]. In HCS systems the different layers need to use different RF-carriers, so the different cell types are orthogonal to each other. This is due to near-far effects, e.g., mixing low power micro cells and high power macro cells, and the requirement that hand-off should not be forced between layers. Mobile assisted hand-off (MAHO) is therefore required between different RF-carriers. This is the normal operating mode for TDMA systems, as shown in Fig. 3, where measurements on other RF-carriers are made at the mobile station during the free time after the receive and transmit bursts. As indicated in Fig. 3, the mobile measures one other frequency in each frame, cycling through all possible alternative frequencies during the succession of frames. The MAHO process is part of all TDMA standards.

The evolution of TDMA systems not only means increased capacity. Probably even more important is the aspect of increased flexibility in frequency planning. The use of ACA means that the system is self-planning, continually adapting to changing conditions.

Modulation and Detection Approaches

Consideration of the frequency reuse factor and C/I (carrier to interference ratio) required by multilevel modulation schemes lead to the conclusion that four-level modulation schemes such as QPSK or its variants are appropriate choices in many cellular environments [1]. Beyond four levels in these environments, the effect of decreased required bandwidth is more than offset by the larger frequency reuse factor needed for sufficient C/I. However the reasoning in [1] leads to the conclusion that modulation schemes with more levels may be more appropriate if cells are physically isolated by walls, or if the attenuation-versus-distance exponent is high (six or more). Multilevel modulation is also useful in proposed systems whose instantaneous bit rate can vary to accommodate fading. An example is differentially encoded amplitude phase shift keyed modulation (DAPSK or star QAM) [15], which can be detected coherently or differentially.



■ Figure 3. *MAHO process (RX-TX measure):* f(TX), f(RX) *and* f(Mn) *are the transmission, reception, and measurement frequencies (on base station* n*), respectively, in the mobile station.*

Table 1 summarizes several representative current TDMA second generation cellular systems, including their modulation parameters. Most use two- or four-level modulation schemes. As examples of four-state modulation applications, the North American [16] and Japanese digital cellular systems [3] use π/4-shifted differential QPSK (DQPSK), with either coherent or differential detection. The GSM and DECT systems use Gaussian Minimum Shift Keying (GMSK), which can be considered a form of binary frequency

	GSM	IS-54	PDC	DECT	PHS
Bit rate	270.8 Kb/s	48.6 Kb/s	42 Kb/s	1.152 Mb/s	384 Kb/s
Bandwidth (carrier spacing)	200 KHz	30 KHz	25 KHz	1.728 MHz	300 KHz
Time slot duration	0.577 ms	6.7 ms	6.7 ms	0.417 ms	0.625 ms
Upstream slots per frame	8 (16 with half-rate coder)	3 (6 with half-rate coder)	3 (6 with half-rate coder)	12	4
Speech coding	13 Kb/s RPE-LTP	7.95 Kb/s VSELP	6.7 Kb/s VSELP	32 Kb/s ADPCM	32 Kb/s ADPCM
FDD or TDD	FDD	FDD	FDD	TDD	TDD
Percent payload in time slot (not including coding parity bits)	73 %	80 %	80 %	67 %	71 %
Modulation	GMSK	π/4 DQPSK	π/4 DQPSK	GMSK	π/4 DQPSK
Coding	3 classes: Coded (r = 1/2, K=5 convol.); or coded +CRC; or uncoded	3 classes: Coded (r=1/2, K=5 convol.); or coded +CRC; or uncoded	2 classes: Coded (r=9/17, K=5 convol.) + CRC or uncoded	CRC only	CRC only
Adaptive equalizer	Mandatory	Mandatory	Optional	None	None

■ Table 1. *Characteristics of contemporary TDMA systems.*

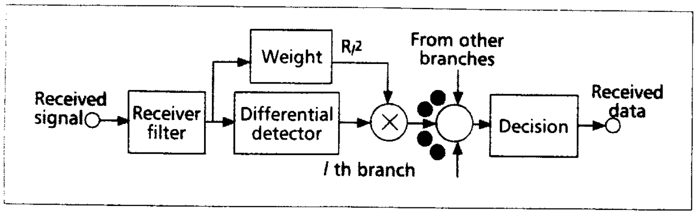


Figure 4. *Optimal post-detection diversity receiver.*

modulation, or also as a version of offset QPSK (its modulation bandwidth efficiency is closer to that of QPSK than to that of BPSK). The PACS system proposed by Bellcore [5, 17] uses coherent QPSK.

The choice of coherent or noncoherent modulation depends on the relative time variability of the radio channel and on cost and processing power considerations. Conditions of higher time variability tend to favor the use of differential or other noncoherent detection. Lower time variability and more stringent performance or spectral efficiency requirements tend to favor coherent detection approaches. Furthermore, reference-directed equalizer adaptation algorithms in effect supply the carrier phase estimate. In this case it requires very little extra hardware complexity to include coherent demodulation.

Differential detection of differentially encoded phase modulated signals is a form of noncoherent detection which has the advantages of fast synchronization, high robustness to multipath fading, and reduced hardware complexity. Conventional differential detection for M-ary DPSK detects the phase difference between the two successively received signal samples and then decides which symbol was transmitted. Since the phase reference is corrupted by noise and interference, the bit error rate (BER) performance is inferior to that with ideal coherent detection.

Decision feedback differential detection is a simple and practical method of improving the performance of differential detection to approach that of coherent detection[18]. Feeding back the past L detected symbols, it reverse-modulates the stored, past received signal samples and generates a reliable reference signal. If the past decisions are all correct, the reverse-modulated signal components are all in phase and can be coherently added. This modulation and addition process increases the reference signal SNR by $10 \log L$ dB. The fast synchronization property of differential detection is still maintained. Differential detection is susceptible to frequency offset between the transmitter and receiver, but the frequency offset can be estimated by correlating the detector output waveform with the feedback detected symbol sequence. Then the detector output is inversely phase-rotated before the decision circuit so as to cancel the effect of the frequency offset.

Delay Spread Mitigation Requirements

Delay spread or time dispersion is a physical phenomenon due to multipath propagation. The transmitted signal will travel through a multipath environment, and will arrive dispersed in the receiver. The rms delay spread is a measure of the standard deviation of the channel impulse response duration. It tends to increase with the propagation path length and antenna heights. Thus it is typically higher for large-cell systems than for indoor microcellular systems. How much intersymbol interference (ISI) a given amount of delay spread causes depends on the symbol time. If the rms delay spread exceeds about 10 percent to 20 percent of the symbol time, delay spread mitigation is necessary [19], typically either diversity or equalization, or both. TDMA radio systems with larger relative delay spreads, where the transmission bandwidth significantly exceeds the channel's coherence bandwidth, can achieve a form of frequency diversity by using adaptive equalization. The same kind of benefit is realized by large-bandwidth CDMA systems which use RAKE receivers. The resulting relative diversity gain would be expected to be higher for CDMA systems when the channel delay spread is small compared to the data symbol interval, but might be roughly equal for TDMA and CDMA systems whose signal bandwidth greatly exceed the channel's coherence bandwidth.

The GSM and IS-54 digital cellular systems both require adaptive equalization. The requirements on delay spread mitigation are defined quite differently in these systems. In GSM a number of typical channel models (delay profiles) have been postulated. Roughly speaking, in GSM impulse responses of any shape, with a width of up to around 18-20 μs, should be handled. In IS-54 the different channel models are characterized as a two-ray model, with ray separation as a parameter. The maximum separation between the two rays is 40 μs; i.e., one symbol time.

The ISI in the two systems will also differ quite significantly, and consequently the equalizer requirements. With a time dispersion width of 18 μs in GSM, 5 bits might interfere with one another. GSM is an example of a TDMA system whose transmission bandwidth typically exceeds the channel coherence bandwidth by a considerable amount. In IS-54 two symbols will interfere, since the symbol time is the same as the time dispersion width requirement (40 ms). Further spreading results from transmitter and receiver band limiting filters, but the ISI span in symbol intervals is still less than that of GSM. So the GSM equalizer itself will be more complex than that for IS-54. Delay spread conditions requiring equalization and/or diversity will also be encountered in most indoor wireless systems operating with bit rates above about 2 Mb/s.

Diversity and Channel Coding

Antenna diversity reception is basically classified into two types: predetection and postdetection combining. Predetection combining either requires the careful co-phasing of all the received signals that experience fast random phase variations, or is done simply by selecting the "best" of the antenna outputs for demodulation, and discarding the others. Postdetection diversity is simpler to implement than co-phasing (but more complex than selection since it requires the duplication of receivers) and matches noncoherent receivers [20], since all the differential detector outputs can be easily combined; this is because the detection process removes the random phase variations.

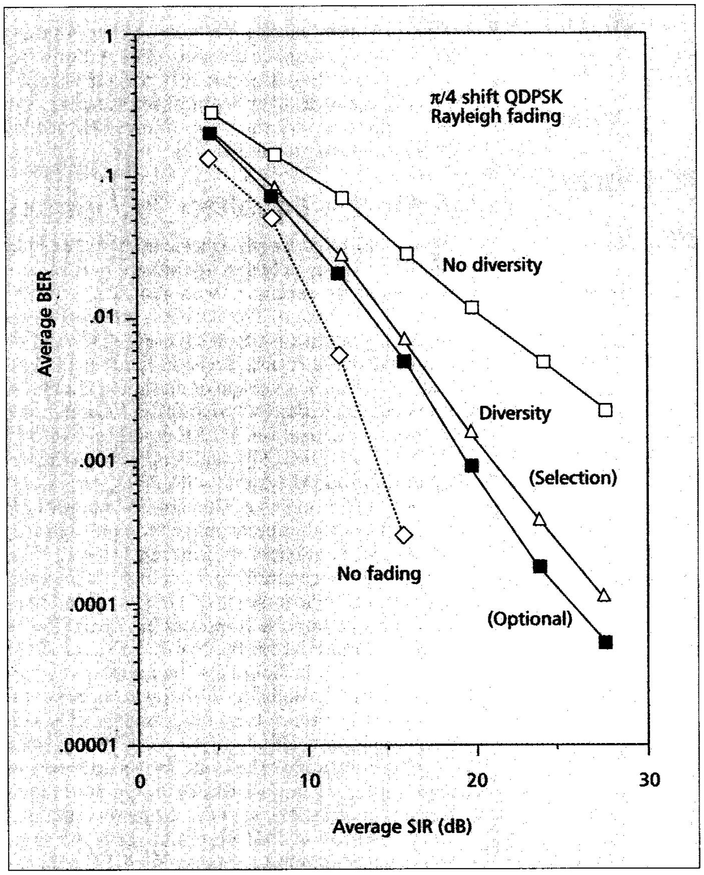
A block diagram of an optimal postdetection diversity receiver with differential detection is shown in Fig. 4. The detector outputs are weighted before combination according to the time varying channel condition of each branch. The weight is in proportion to the square of the received signal envelope R (if a limiter is not used before differential detection, no weight function is required) to weaken contributions from weaker signal branches. Performance results, shown in Fig. 5, were measured for independent Rayleigh fading of desired and interfering signals, with a normalized maximum Doppler frequency $F_D T = 0.00125$. The results show that a 1 percent BER can be achieved at below an average SIR of 14 dB (which is about 1 dB smaller than with selection combining) with simple two-branch diversity. This permits a frequency reuse factor of four if a three-sectored cell is used.

Since ISI due to delay spread becomes larger as the signal becomes weaker, diversity combining can reduce the effect of delay spread. The Japanese PDC system relies on diversity to combat ISI, and generally does not use adaptive equalization. For example, the tolerable rms delay spread for 1 percent BER can be increased to nearly 20 percent of the symbol time by using two-branch diversity. This corresponds to 9.5-μs rms delay spread for the Japanese PDC using 21 ksymbol/s. To cope with delay spreads beyond this value, diversity can be combined with base station antenna beam tilting to weaken multipath signals travelling from long distances.

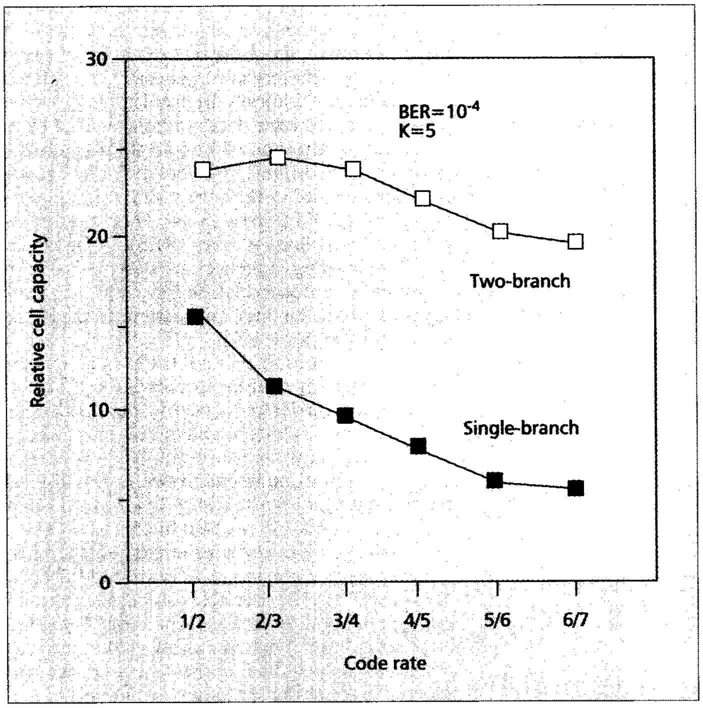
Convolutional coding is a powerful technique for reliable data transmission in mobile fading environments. Decoding can be applied to the output of the postdetection combiner in Fig. 4. Soft decision Viterbi decoding with interleaving is itself a form of postdetection combining, and thus can increase the effective diversity order without increasing the number of antenna elements . This is of practical importance, especially for hand-held portables. For ideal interleaving, the equivalent order of diversity is the number of space diversity branches times the effective code length (ECL), which may be defined as the shortest symbol error event path length of the code [21].

The theoretically predicted relative cell capacity of QDPSK with two-branch space diversity and constraint length $K = 5$ punctured codes, compared to a system with no diversity and no coding, is shown in Fig. 6 for $\mathrm{BER}=10^{-4}$ [21]. Although conditions for this result were ideal (interference but no noise, hexagonal cell layout, ideal bit interleaving, zero delay spread and doppler), it illustrates the substantial contribution to system capacity from coding and diversity.

Symbol (or bit) interleaving is used to change slow fading into forced fast, independent fading to yield the maximum power of channel coding. For ideal interleaving, the required interleaving depth (the transmission time separation between two consecutive coded symbols), is on the order of $0.38/f_D$., where f_D is the maximum Doppler frequency, determined by the terminal speed and carrier wavelength. This corresponds to 4.6 ms in time and 73 symbols for a transmission rate of 16 Ksymbol/s at a 900 MHz carrier frequency and a 100 km/h terminal speed. A shorter interleaving depth, about half the above value, can be used with a slight performance degradation. The effect of



■ **Figure 5.** *BER performance.*



■ **Figure 6.** *Cellular spectrum efficiency.*

imperfect interleaving is similar to that of fading correlation in a space diversity system. For a frequency selective high bit rate indoor wireless channel, coding, even without interleaving, can also help to reduce the order of diversity needed to limit outage probability [22].

The GSM and North American digital cellular systems have chosen adaptive equalization, applied at the receiver, to combat severe multipath delay spread.

Adaptive Equalizer Techniques

The GSM and North American digital cellular systems have chosen adaptive equalization, applied at the receiver, to combat severe multipath delay spread. The wireless channel's frequency response is often severely distorted by multipath; as a result, decision feedback equalization (DFE) or a version of maximum likelihood sequence estimation (MLSE) are used in preference to linear equalization. MLSE equalizers with 32 states [23] and DFE [24] equalizers have been implemented for GSM systems with delay spreads on the order of 5 bit intervals. The choice between MLSE and DFE is usually a performance/complexity tradeoff. MLSE equalizers are inherently better than DFEs, but are generally more complex. However, relatively simple versions of MLSEs, which handle truncated impulse responses have been shown to be very effective for the North American IS-54 system [25-27]. It should also be noted that adaptive equalizers also have an ability to suppress cochannel interference from other transmitters with the same bit rate [28].

The function of the equalizer's adaptation algorithm is to acquire and track the required equalizer parameters. The set of parameters that must be estimated for a MLSE equalizer is the sampled channel impulse response. The DFE requires a set of forward and feedback tap coefficients, which can be adapted directly, or computed from the estimated channel impulse response.

Since in a TDMA system the channel response to or from a particular terminal may have changed significantly since the last timeslot, acquisition of the equalizer parameters must generally start afresh in each timeslot. Typically the acquisition algorithm is based on reference data symbols derived from a training sequence of known data symbols. Adaptation algorithms with very fast convergence are required due to the very short training periods (26 b for GSM, 28 b for IS-54). The classic example is recursive least squares (RLS). In GSM and IS-54 the training sequences are designed to have impulse-like autocorrelation functions, so that a simple correlation operation estimates the channel impulse response [23].

When it comes to channel tracking an important issue is whether one has to track during the burst, or not. With a carrier frequency of around 900 MHz, and assuming a vehicle speed of 100 km/h, we get a maximum doppler frequency of f_D = 83 Hz. The minimum time between two fading dips is therefore roughly 6 ms ($1/2f_D$). In GSM the burst length is around 0.58 ms, and furthermore, since the synchronization word is in the middle of the burst, the maximum variation time is around 0.29 ms. This means that the channel is practically constant during the burst. In IS-54 on the other hand, the burst length is 6.7 ms; i.e., of the same order as the time between dips. This means that one will experience severe channel variations during the burst and highly optimized tracking algorithms are needed. On the other hand, for broadband indoor wireless systems, where doppler is small and the data rate is relatively large, tracking and coherent demodulation pose little problem.

Fast tracking algorithms utilizing receiver decisions to provide a reference introduce problems of error propagation; decision errors can rapidly direct the equalizer parameters towards the wrong values. Furthermore, in the case of MLSE equalizers, the MLSE decision algorithm introduces a significant delay in the receiver's decisions, which can hamper a fast decision directed algorithm. One way to circumvent these problems is to dispense with decision-directed tracking altogether, estimate the channel impulse response or equalizer coefficients during periodic training periods, and *interpolate* these estimates between training periods. This strategy has proven effective and robust, for sufficiently frequent training intervals [29]. It can be used for example in the base to mobile direction in IS-54, with a phase-alignment procedure to allow for differential coding [26].

Conclusions

TDMA is a classic approach to multiple access in digital cellular wireless communications systems. We have summarized a number of frequency and timeslot allocation techniques for enhancing the capacity and flexibility of TDMA-based systems. We have also described how the problems of fading, delay spread, time variability and interference affect TDMA systems, and how they may be countered and even exploited by appropriate techniques of detection, diversity, coding, adaptive equalization and slow FH. It is worth emphasizing that the use of one of these techniques, slow random FH, results in a system that is in effect a hybrid of TDMA and CDMA.

References

[1] D. C. Cox, "Universal Digital Portable Radio Communications", *Proc. IEEE*, vol. 75, no. 4, April 1987, pp. 436-477.

[2] D. J. Goodman, "Trends in Cellular and Cordless Communication," *IEEE Comm. Mag.*, vol. 29, June 1991, pp. 31-40.

[3] RCR STD-27B, "Personal Digital Cellular Telecommunication System."

[4] RCR STD-28 "Personal Handy Phone System."

[5] "Generic Criteria for Version 1.0 Wireless Access Communications System (WACS)," Bellcore Technical Advisory TA-NWT-001313, Issue 1, July, 1992.

[6] H. M. Hafez *et al.*, "Fundamental Issues in Millimeter Wave Indoor Wireless Networks," Conference Record, Wireless '93 Conference, Calgary, July 1993.

[7] K. Raith and J. Uddenfeldt, "Capacity of Digital Cellular TDMA Systems," *IEEE Trans. Vehic. Technol.*, vol. 40, no. 2, May 1991, pp. 323-332.

[8] H. Eriksson *et al.*, "Multiple Access Options for Cellular Based Personal Communications," Proc. Vehic. Technol. Conf., May 1993, Secaucus, New Jersey, pp. 957-962.

[9] H Andersson *et al.*, "Adaptive Channel Allocation in TIA IS-54 System," Proc. Vehic. Technol. Conf., May 1992, Denver, Colorado, pp. 778-781.

[10] ETS 300-175-3, "Radio Equipment and Systems (RES) Digital European Cordless Telecommunications (DECT) Common Interface, Part 3 Media Access Control Layer," Oct. 1992.

[11] ETSI/GSM 05.02, "Multiplexing and Multiple Access on the Radio Path."

[12] B. Gudmundson, J. Sköld and J. Ugland, "A Comparison of CDMA and TDMA Systems," Proc. Vehic. Technol. Conf., May 1992, Denver, Colorado, pp. 732-735.

[13] S. Chennakeshu, A. Hassan, J. Anderson, "Capacity Analysis of a Mixed Mode Slow Frequency Hopped Cellular System," Proc. Vehic. Technol. Conf., May 1993, Secaucus, New Jersey, pp. 540-543.

[14] R. Meidan, "Frequency Hopped CDMA and the GSM System," Proc. DMR-5, Helsinki, Dec. 1992, pp. 343-345.

[15] W. T., Webb, L. Hanzo, and R. Steele, " Bandwidth efficient QAM schemes for Rayleigh fading channels, " *IEE Proc.*-I, vol. 138, pp. 169-175, June 1991.

[16] TIA/EIA/IS-54, "Dual-Mode Mobile Station - Base Station Compatibility Standard."

[17] N. R. Sollenberger *et al.*, "Architecture and Implementation of an Effi-

cient and Robust TDMA Frame Structure for Digital Portable Communications," Proc. IEEE Vehic. Technol. Conf., May 1989, San Francisco, pp. 169-174.

[18] F. Adachi and M. Sawahashi, "Decision feedback differential detection of 16DAPSK signals," *IEE Electron. Lett.*, vol. 29, pp.1455-1457, Aug. 1993.

[19] J. C-I Chuang, "The Effects of Time Delay Spread on Portable Radio Communications Channels with Digital Modulation," *IEEE J. Sel. Areas in Communication*, vol. SAC-5, June 1987, pp. 879-889.

[20] F. Adachi, " Postdetection optimal diversity combiner for DPSK differential detection, " *IEEE Trans. Veh. Technol.*, vol. 42, pp. 326-337, Aug. 1993.

[21] T. Matsumoto and F. Adachi, "Combined convolutional coding/diversity reception for QDPSK land mobile radio," *IEICE Trans.*, vol. E74, pp. 1522-1530, June 1991.

[22] C. L. B. Despins, D. D. Falconer, and S. A. Mahmoud, "Compound Strategies of Coding, Equalization and Space Diversity for Wide Band TDMA Indoor Wireless Channels, *IEEE Trans. Vehic. Technol.*, vol. 41, no. 4, Nov. 1992, pp. 369-379.

[23] R. D'Avella, L. Moreno and M. Sant'Agostino, "An Adaptive MLSE Receiver for TDMA Digital Mobile Radio," *IEEE JSAC*, vol. 7, Jan. 1989, pp. 122-129.

[24] G. D'Aria, R. Piermarini, and V. Zingarelli, "Fast Adaptive Equalizers for Narrow-Band TDMA Radio with CEPT/GSM Characteristics," *IEEE Trans. Vehic. Technol.*, vol. 40 No. 2, May 1991, pp. 392-404.

[25] G. Larsson, B. Gudmundson and K. Raith, "Receiver Performance for the North American Digital Cellular System," Proc. IEEE Vehic. Technol. Conf., May 1991, St. Louis, pp. 1-6.

[26] R. D. Koilpillai, S. Chennakeshu and R. L. Toy, "Low Complexity Equalizers for U.S. Digital Cellular System," Proc. IEEE Vehic. Technol. Conf., May 1992, Denver, Colorado, pp. 744-747.

[27] W. P. Chou and P. J. McLane, "16-State Nonlinear Equalizer for IS-54 Digital Cellular Channels," Proc. ICUPC, Ottawa, Oct. 1993, pp. 436-442.

[28] D. D. Falconer *et al.*, "Advances in Equalization and Diversity for Portable Wireless Systems," *Digital Signal Processing*, vol. 3 no. 3, July 1993.

[29] N. W. K. Lo, D. D. Falconer and A. U. H. Sheikh, "Adaptive Equalization and Diversity Combining for Mobile Radio Using Interpolated Channel Estimates," *IEEE Trans. Vehicular Technol.*, Vol. 40, Aug. 1991, pp. 636-645.

Biographies

DAVID D. FALCONER [SM '83] received the B.A. Sc. degree in engineering physics from the University of Toronto in 1962 and S.M. and Ph.D. degrees in electrical engineering from M.I.T. in 1963 and 1967, respectively. After a year as a postdoctoral fellow at the Royal Institute of Technology, Stockholm, Sweden he was with Bell Laboratories, Holmdel, New Jersey from 1967 to 1980, as a member of the technical staff and later as group supervisor. During 1976-77 he was a visiting professor at Linköping University, Linköping, Sweden. Since 1980 he has been at Carleton University, Ottawa, Canada, where he is a professor in the Department of Systems and Computer Engineering. His interests are in digital communications and communication theory, with particular application to wireless communications systems. He was editor for Digital Communications for the *IEEE Transactions on Communications* from 1981 to 1987. He is a member of the Association of Professional Engineers of Ontario and was awarded the Communications Society Prize Paper Award in Communications Circuits and Techniques in 1983 and again in 1986. He was a co-recipient of the IEEE Vehicular Technology Transactions Best Paper of the Year Award in 1992. He was a consultant to Bell-Northern Research, working on ISDN access, in 1986-87 and to Codex/Motorola, working on cellular CDMA techniques, in 1990-91, during sabbaticals. He is currently leading a research project on broadband indoor wireless communication, involving several universities, sponsored by CITR (Canadian Institute for Telecommunications Research).

FUMIYUKI ADACHI was graduated from Tohoku University in 1973 and was awarded Doctorate in Engineering from the same university in 1984. In 1973, he joined the Nippon Telegraph & Telephone Corporation (NTT) Laboratories in Japan and in 1992, he transferred to NTT Mobile Communications Network, Inc. Since joining NTT, he has been researching in the areas of CDMA/TDMA mobile radio communications systems and digital signal processing including bandwidth efficient modulation/demodulation, diversity reception, and channel coding. During the academic year of 1984/85, he was a United Kingdom SERC Visiting Research Fellow at the Department of Electrical Engineering and Electronics of Liverpool University. He is a co-recipient of the IEEE Vehicular Technology Society Paper of the Year Award in 1980 and 1990. He has been a secretary of IEEE Vehicular Technology Society Tokyo Chapter since 1991.

BJÖRN GUDMUNDSON [M '85] received an Ms.Sc. from the Royal Institute of Technology, Sweden, in 1981, an Ma.Sc. from Stanford University in 1985, and a Ph.D. from the Royal Institute of Technology, Sweden, in 1988, all in electrical engineering. In 1981 he joined Ericsson Radio Systems, working primarily with development of Private Land Mobile Radio Systems. During 1984 to 1988 he studied Adaptive Equalization Techniques for Mobile Radio Channels, both as part of the Ph.D. research and for the pre-development of the GSM signal processing at Ericsson Radio Systems. In 1988 he joined the research department at Ericsson Radio Systems, engaged in the Mobile RACE project, primarily studying microcellular techniques. In 1990 he became manager for a research unit on radio access/radio transmission techniques. From 1992 has been manager for the research department "Radio Access and Signal Processing Research," including also Speech Coding and Echo Cancellation.

> *It is worth emphasizing that the use of slow random frequency hopping results in a system that is in effect a hybrid of TDMA and CDMA.*

Upcoming Features in
IEEE Communications Magazine
February 1995

A Multi-faceted Approach to Forecasting Broadband Demand and Traffic

Methods of Forecasting Long Term Demand for Wideband and Broadband Services in the Residential Market

Forecasting Broadband Demand Between Geographic Areas