

High-Speed Wireless Data Access Based on Combining EDGE with Wideband OFDM

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ABSTRACT The success of cellular services, combined with the increased presence of laptop computers and the rapid growth in the number of Internet users, indicates that wireless data should have a very bright future. Nevertheless, today the number of wireless data subscribers is small, with the most formidable obstacle to user acceptance being the performance limitations of existing services and products. This article discusses combining enhanced data rates for GSM evolution (EDGE) with wideband orthogonal frequency-division multiplexing in an asymmetrical solution to provide high-speed data rates, with wide-area coverage and good quality, for wireless packet data services.

The rapid growth of wireless voice subscribers, the growth of the Internet, and the increasing use of portable computing devices suggest that wireless Internet access will grow to be a major area of telecommunications services. Rapid progress in digital and RF technology is making possible highly compact and integrated terminal devices, and the introduction of sophisticated wireless data software is providing more value and making wireless Internet access more user-friendly. Data transmission rates are growing rapidly in fixed networks with the use of wavelength-division multiplexing (WDM) in backbone fiber networks, and the introduction of cable modems and high-speed digital subscriber line technology in fixed access networks. Increasingly demanding Internet applications and user expectations are emerging. Experience with laptop computers and personal digital assistants has shown that many end users desire their portable equipment to provide much of the same environment and applications they enjoy at their desks. Experience with wireless access has also demonstrated the singular importance of widespread coverage and anywhere/anytime access.

THE WIRELESS DATA OPPORTUNITY

Current cellular radio and paging services have been very successful in providing untethered communications. The introduction of the Global System for Mobile Communications (GSM) and other digital cellular technologies has accelerated the growth of wireless communications throughout the world, with more than 400 million digital wireless subscribers expected worldwide in the year 2000 with annual growth rates of 30–50 percent. Interest in wireless Internet access was initially generated by the opportunities for e-mail and messaging, but the explosion in popularity of the World Wide Web suggests broader long-term opportunities.

When you combine the success of cellular services with the increased presence of laptop computers and the rapid growth in the number of Internet users, wireless data should have a very bright future. Nevertheless, today the number of wireless data subscribers is small,

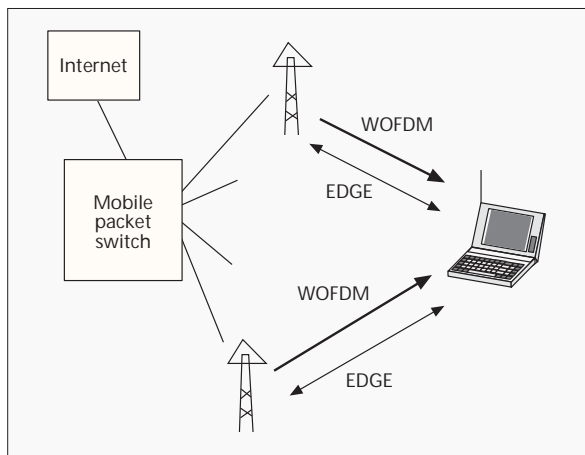
with the most formidable obstacle to user acceptance being the performance limitations of existing services and products, including link performance (data rate, latency, and quality), network performance (access, coverage, spectrum efficiency, and quality of service), and price. This article discusses combining enhanced data rates for GSM evolution (EDGE) with wideband orthogonal frequency-division multiplexing (WOFDM) in an asymmetrical solution to address the challenges of high-speed data rates combined with wide-area coverage and good quality for wireless packet data services.

THIRD-GENERATION SYSTEMS

The most extensive efforts to provide higher bit rates can be found among the third-generation (3G) projects around the world (e.g., see [1]). The International Telecommunication Union (ITU) program International Mobile Telecommunications in Year 2000 (IMT-2000), formerly called Future Public Land Mobile Telecommunications System (FPLMTS), was initiated in 1986 with a goal of producing a global standard for third-generation wireless access, using the frequency bands 1885–2025 MHz and 2110–2200 MHz.

The main design objective for 3G systems is to extend the services provided by current second-generation systems with high-rate data capabilities. Specifically, the goals are to provide 144 kb/s (preferably 384 kb/s) for high-mobility users with wide-area coverage and 2 Mb/s for low-mobility users with local coverage. The main application will be wireless packet transfer, in particular, wireless Internet access. However, supported services include circuit voice, circuit video, e-mail, short messages, multimedia, simultaneous voice and data, and broadband integrated services digital network (B-ISDN) access. In the search for the most appropriate multiple access technology for 3G wireless systems, a wide range of new multiple access schemes have been proposed to the ITU [2]. These efforts have resulted in proposals based on wideband code-division multiple access (WCDMA) and CDMA2000 using 5 MHz channels and EDGE using 200 kHz channels.

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■ Figure 1. EDGE combined with a WOFDM system.

Many manufacturers have been taking a revolutionary approach to provide higher-capacity data network solutions, but due to lack of backward compatibility to the existing technology and equipment, many wireless carriers are not fully committed to the technologies and their deployment. GSM and IS-136 combined support a total of about 200 million customers globally as of mid-1999. Current efforts and consensus among GSM carriers and IS-136 carriers to converge GSM and IS-136 onto a common platform of EDGE/general packet radio service (GPRS) creates the best backward compatibility among the 3G proposals with 600–800 million subscribers expected to be using GSM or time-division multiple access (TDMA) services by 2003. Moreover, the EDGE/GPRS 3G proposal requires the minimum spectrum for 3G services roll-out. Because of these advantages of EDGE/GPRS, IS-136 carriers such as AT&T Wireless Services and many GSM carriers have committed to and planned to deploy such systems to provide their customers with 3G specified services.

2 Mb/s and higher wireless data rates are likely to be needed eventually to meet requirements for applications such as high-resolution video, image transfer, large file transfer, interactive Web services and browsing, and general multimedia applications. OFDM is well known for its robust performance over heavily impaired channels, and its spectrum efficiency and flexibility to accommodate both narrowband and wide-band services efficiently. Robust performance, spectrum efficiency, and flexibility are crucial for wireless carriers to allocate minimum required spectrum to support high-rate multimedia and evolving Internet services, and to be able to deliver high-quality services to their customers at the lowest cost. A combined system of EDGE and WOFDM would leverage current 3G EDGE/GPRS developmental and manufacturing efforts, and significantly reduce the cost for a carrier to roll out high-speed mobility data services with data rates beyond 2 Mb/s.

A SUMMARY AND OUTLINE OF THE ARTICLE

In the remainder of this article, we will describe combining EDGE with a WOFDM downlink to achieve higher bit rates for future wireless packet data services. In the following section, the 3G technology EDGE, with target bit rates of about 384 kb/s provided with wide-area coverage, is briefly described. We then present a more detailed discussion of WOFDM downlinks supporting several megabits per second and solutions to combine WOFDM with EDGE. This combination is proposed to provide an asymmetrical wireless data access solution with similar properties to cable modems. An EDGE-based uplink is well-matched to the

battery and RF amplifier limitations of a portable device, and a WOFDM-based downlink is well-matched to the high-bit-rate needs of packet data downlinks. Figure 1 depicts this system architecture.

PACKET DATA ACCESS USING EDGE

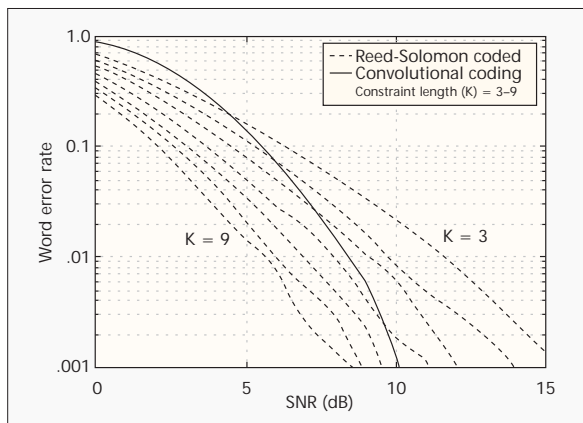
The GSM system is the most popular second-generation wireless system. It employs TDMA technology to support mobile users in different environments. This system, initially standardized and deployed in Europe, has been deployed worldwide. Each carrier is 200 kHz wide, which can support eight simultaneous full-rate circuit voice users using eight TDMA bearer slots. It also supports a circuit-data capability at 9.6 kb/s. To support higher data rates, the European Telecommunications Standards Institute (ETSI) has generated the GPRS standard [3], which employs variable-rate coding schemes and multislot operation to increase peak rates. Using packet access further enhances system throughput and spectrum efficiency. However, the peak rate for GPRS is limited to about 144 kb/s. ETSI is also developing the EDGE standard to enhance GSM packet data technology with adaptive modulation to support packet data access at peak rates up to about 384 kb/s, and the Universal Wireless Communications Consortium (UWCC) has also adopted EDGE to provide complementary wireless data access to IS-136 TDMA for voice and basic services [4, 5].

This system will have a baud equal to the GSM rate of 270.833 kbaud, and it will adapt between Gaussian minimum shift keying (GMSK) and 8-phase shift keying (PSK) modulation with linearized GMSK pulse shaping. It will use up to eight different channel coding rates to support packet data communications at high speeds on low interference/noise channels and at lower speeds on channels with heavy interference/noise. The linearized GMSK pulse shaping for the 8-PSK modes results in a low peak-to-average power ratio of the transmitted signal of only 2.5 dB, which is particularly advantageous for terminal RF power amplifiers.

EDGE can be deployed with conventional 4/12 frequency reuse, that is, the same set of frequencies is reused every four base stations or 12 sectors, as for GSM. However, 1/3 reuse is also proposed to permit initial deployment with only 2×1 MHz of spectrum (which provides two guard channels as well as three operating channels). A combination of adaptive modulation/coding (referred to as link adaptation or LA), partial loading, and efficient automatic repeat request (ARQ) permits operation with very low reuse factors. Incremental redundancy (IR) or type II hybrid ARQ has been proposed to reduce the sensitivity of adaptive modulation to errors in estimating channel conditions and to improve throughput. [6]

A challenge for 1/3 reuse is the operation of control channels which require robust performance. Control channels include broadcast information which is transmitted without the benefit of a reliable link protocol. A reliable control channel can be provided by synchronizing the frame structures of base station transceivers throughout a network and using time reuse and discontinuous downlinks to achieve adequate protection for control channels. One of the complications of these arrangements is the requirement that a terminal must achieve initial base station selection and synchronization on downlink channels which are not continuous.

In summary, a major feature of EDGE is the feasibility of initial packet data deployment with peak data rates of about 384 kb/s with 1/3 reuse requiring only 2×1 MHz of spectrum. Another major feature of EDGE is that it builds on very mature GSM technology. Frame synchronization of



■ Figure 2. Performance of a wideband OFDM radio link.

base stations and time reuse provides for robust control channels, and partial loading with hybrid ARQ or IR and link adaptation are used for traffic channels. Some of the challenges for EDGE include equalization with 8-PSK modulation, accuracy in link adaptation, and robust performance with slow Rayleigh fading.

PACKET DATA ACCESS USING WIDEBAND OFDM DOWNLINKS

This section considers the possibility of a future high-speed wireless packet data system with a wideband 5 MHz channel using OFDM modulation to mitigate multipath fading while providing peak data rates up to about 5 Mb/s. A frequency reuse of one is considered with dynamic resource management to achieve high spectrum efficiency for packet data access.

PHYSICAL-LAYER LIMITATIONS

The radio link performance in a mobile environment is primarily limited by propagation loss, fading, delay spread, and interference. Here, we concentrate on the link budget and dispersive fading limitations. Because of the large path losses encountered in wide-area coverage systems, the link budget is challenging for multimegabit-per-second data rates. For example, consider a target data rate of 4 Mbaud, which is about 100 times that of a TDMA cellular voice circuit. Since the signal-to-noise ratio (SNR) is inversely proportional to the baud, this corresponds to a 20 dB increase in the required transmitted power to achieve the same bit error performance and cover the same area as a typical cellular voice circuit. Clearly, the coverage and performance of such systems will be severely limited without the introduction of new techniques.

In addition to the link budget limitations, the bit rate is also limited by the multipath nature of the radio environment. Physically, the received signal can be considered as the summation of a large number of signals which have traveled different paths to the receiver, and therefore have different time delays, amplitudes, and phases. Depending on the extent of the channel impulse response, called the delay spread, and the resulting intersymbol interference (ISI), the maximum data rate can be severely limited. This delay spread, in a macrocellular environment, could be as large as 20–40 μ s, limiting the data rate to about 5–10 kbaud if no measures are taken to counteract the resulting ISI. In addition, the channel is time-varying, with Doppler rates as high as 200 Hz if operating in the 2 GHz personal communications services (PCS) band for vehicles traveling at highway speeds.

THE PHYSICAL-LAYER SOLUTION

Asymmetric Service — Since portable terminals must be powered by batteries and their transmit power is limited to about 1 W, achieving transmission rates beyond 50–384 kb/s in large-cell environments is impractical. On the other hand, base stations are usually powered from commercial main power systems, and can transmit with higher power; subsequently, bit rates of 2–5 Mb/s may be possible. Web browsing and information access, which have caused the recent explosion in Internet usage, are highly asymmetrical in transmission requirements. Only the transmission path to the subscriber needs to be high-speed. Also, thin client-server computing architectures may be attractive for mobile applications in which primarily display information is transmitted to mobile terminals and applications reside within a fixed corporate or public network. This results in highly asymmetrical transmission speed requirements, which matches the limitations of practical terminals. Only video telephony and large file transfers in the direction from a terminal toward the network are envisioned to require high-speed transmission from terminals. Therefore, we consider an asymmetric service: a high-speed downlink with 2–5 Mb/s peak data rates for macrocellular environments and up to 10 Mb/s for microcellular environments, and a lower speed, 50–384 kb/s on the uplink based on EDGE.

Multicarrier Modulation — One possibility for overcoming the delay spread limitations on the downlink is to use a single-carrier system modulated at about 4 Mbaud with equalization and coding. The equalizer could require 80–100 taps and must be updated at the highest Doppler rate. In addition, the extensive period required to train the equalizer could be a major source of inefficiency in a packet-based system.

An alternative approach, and the one taken here, is to use a multicarrier system. The basic concept is to divide the total bandwidth into many narrowband subchannels which are transmitted in parallel. The subchannels are chosen to be narrow enough so that the effects of multipath delay spread are minimized. The particular multicarrier technique used here is OFDM [7, 8] and is the standard for digital audio broadcasting (DAB) in Europe [9] and asymmetric digital subscriber line (ADSL) in the United States; it has been proposed for many other applications.

To ensure a flat frequency response within a subchannel and achieve the desired bit rate, 400–800 subchannels are required, each modulated at 5–10 kbaud. With 5–10 kbaud subchannels and guard periods of 20–40 μ s, delay spread as large as 40 μ s can be accommodated with little or no ISI, so equalization is not needed.

Diversity and Coding — To reduce the link budget shortfall in the downlink, techniques for reducing the required SNR must be incorporated. To eliminate some of the 20 dB link budget shortfall, two-branch antenna diversity can be used at the mobile. Also, switched-beam base station transmit antennas can be used, with each 120° sector containing four beams. With a transmit bandwidth of 5 MHz, the fading is significantly randomized across the OFDM bandwidth.

To realize gain from the frequency diversity potential of the wideband signal, Reed-Solomon or convolutional coding is used across subchannels. With two receive antennas at the mobile combined with the frequency diversity of a wideband OFDM signal, the required SNR at the mobile receiver can be reduced by about 12 dB compared to a TDMA cellular radio link (5 dB SNR vs. 17 dB SNR for a word error rate of about 3 percent). Figure 2 shows the results of simulations of an OFDM downlink with two-branch receiver diversity, coherent

detection of quadrature PSK (QPSK) using robust channel estimation and several alternatives for 1/2-rate channel coding. The Reed-Solomon coding case is based on Galois Field of size 64 (GF(64)). A coding block was set equal to one OFDM block of 120 tones. The channel fading rate was 40 Hz with a two-ray model with 20 μ s delay between the paths. The use of four-beam antennas at a base station can provide up to 6 dB gain on a downlink, and the total transmitted power can be increased to realize an additional 8 dB gain total to offset the link budget shortfall. The use of switched beam antennas would also about double spectrum efficiency by reducing interference.

FREQUENCY REUSE AND SPECTRUM EFFICIENCY

Very high spectrum efficiency will be required for WOFDM, particularly for macrocellular operation. First-generation cellular systems used fixed channel assignment. Second-generation cellular systems generally use fixed channel assignment or interference averaging with spread spectrum. Wideband CDMA (WCDMA) will also use interference averaging. Interference avoidance or dynamic channel assignment (DCA) has been used in some systems, but generally as a means of automatic channel assignment or local capacity enhancement, not as a means of large system-wide capacity enhancement. Some of the reasons for not fully exploiting the large potential capacity gain of DCA are the difficulties introduced by rapid channel reassignment and intensive receiver measurements required by a high-performance DCA or interference avoidance algorithm. OFDM is promising in overcoming these challenging implementation issues. It was shown by Pottie [10] that interference averaging techniques can perform better than fixed channel assignment techniques, whereas interference avoidance techniques can outperform interference averaging techniques by a factor of 2 to 3 in spectrum efficiency.

For existing second-generation systems, the achieved spectrum efficiency measured in bits per second per Hertz per sector (assuming three sectors per cell) is much lower than most of the results in [10], which were obtained under idealized conditions. IS-136 TDMA today provides a spectrum efficiency of about 4 percent ($3 \times 8 \text{ kb}/30 \text{ kHz} \times 1/21$ reuse). GSM also provides a spectrum efficiency of about 4 percent ($8 \times 13 \text{ kb}/200 \text{ kHz} \times 1/12$ reuse). IS-95 CDMA provides a spectrum efficiency of 4–7 percent ($12\text{--}20 \times 8 \text{ kb}/1250 \text{ kHz} \times 1$ reuse $\times 1/2$ voice activity). DCA combined with circuit-based technology can provide some benefits. However, it cannot provide large capacity gains because of the dynamics of interference in a mobile system as well as the difficulty of implementing rapid channel reassignments. In circuit-based systems, channel variations, especially those caused by the change of shadow fading, are frequently faster than what can be tracked by the slow assignment cycle possible in the circuit services. To achieve the potential of DCA gain, channel reassignments must take place at high speed to avoid rapidly changing interference. Dynamic packet assignment (DPA) is proposed, which reassigns transmission resources on a packet-by-packet basis to overcome these problems [11]. One of the benefits of DPA based on interference avoidance is that it is relatively insensitive to errors in power control, and it provides good performance without power control. Even without power control, interference avoidance can outperform interference averaging with power control. This is particularly advantageous for packet transmission, where effective power control is difficult (even though it can potentially improve performance) due to the rapid arrival and departure of interfering packets.

A DYNAMIC PACKET ASSIGNMENT PROTOCOL COMBINING WOFDM WITH EDGE

The protocol for DPA for a downlink comprises five basic steps:

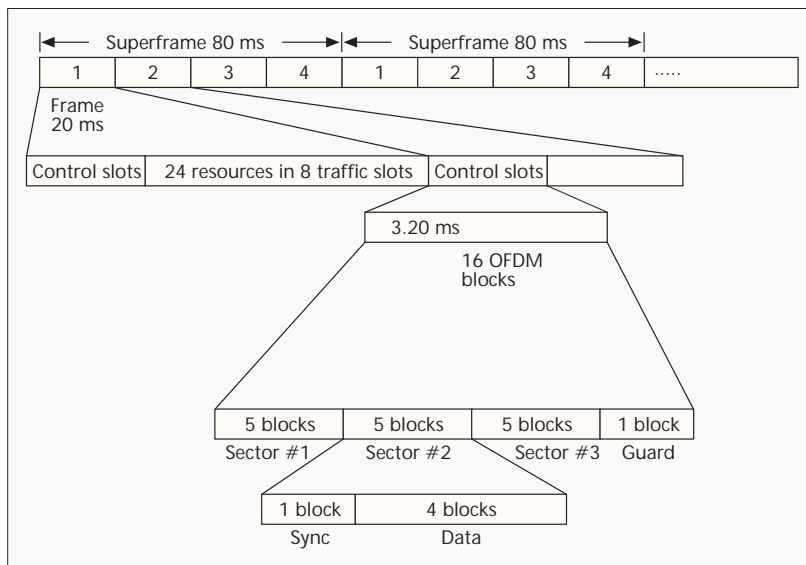
- Mobiles would report path loss measurements made on WOFDM downlink control channels for all nearby base stations to a serving base station using an EDGE uplink on a regular basis at a rate of about once per second.
- Serving base stations would forward those measurements to all neighboring base stations to allow each base station to build a database of all nearby mobiles and their path losses to both serving and nearby base stations.
- Base stations would maintain a second database of occupancy of each resource in nearby base stations.
- Base stations would allocate resources for packet transmission to mobiles using both databases to minimize interference created for other transmissions and to minimize received interference for the desired transmission.
- Base stations would forward information about the occupied resources to all neighboring base stations.

This protocol has similarities to a protocol proposed for Advanced Cellular Internet Service (ACIS) [12]. The frame structures of adjacent base stations are staggered in time, that is, neighboring base stations sequentially perform the different DPA functions outlined above with a predetermined rotational schedule. This avoids collisions of channel assignments, that is, the possibility for adjacent base stations to independently select the same channel thus causing interference when transmissions occur. In addition to achieving much of the potential gain of a rapid interference avoidance protocol, this protocol provides a good basis for admission control and link mode (bit rate) adaptation based on measured signal quality. The remainder of this section focuses on organization of an OFDM signal into flexible radio resources and DPA based on combining over-the-air measurements with a network-centric algorithm to efficiently manage those resources.

RADIO LINK RESOURCE ORGANIZATION

Considerations for organization of resources are the resolution of resource size, the overhead required to allocate individual resources, and the expected size of objects to be transmitted over a resource. Minimization of overhead can be achieved by organizing the available bandwidth into large resources, but if many objects are relatively small in size or if higher-layer protocols generate small objects that the lower layers must carry, there will exist a need to allocate small resources to achieve good efficiency. Also, streaming data may require resources that are small locally in time to avoid the need for buffering source bits before transmission, which causes delay. A 2 Mb/s system with 20–25 resources would support about 80–100 kb/s rates locally in time. This rate would be suitable for high-bit-rate data services. If supporting about 10 kb/s locally in time were desirable (e.g., voice or audio streaming services of 8 kb/s with additional coding for error correction in wireless channels), that would be equivalent to about 200 resources.

For large resources, a total of 624 subchannels (3.96 MHz) are organized into 24 clusters of 26 subchannels (165 kHz) each in frequency and eight time slots of 10.5 OFDM blocks each within a 20 ms frame of 100 blocks. This allows flexibility in channel assignment while providing 16 blocks of control overhead to perform control and DPA procedures. This arrangement of tone clusters is similar to the arrangements in the band-division multiple access (BDMA) proposal by SONY [13]. Each tone cluster would contain 24 individual modulation tones plus two guard tones, and an OFDM block would have a



■ Figure 3. A staggered frame structure for a WOFDM downlink with DPA.

time duration of $157.5 \mu\text{s}$ plus $42.5 \mu\text{s}$ for guard time and ramp time to minimize the effects of delay spread up to about a $20\text{-}\mu\text{s}$ span. Of the 10.5 OFDM blocks in each time slot, 1.5 blocks are used as overhead, which includes a leading block for synchronization (phase/frequency/timing acquisition and channel estimation) and a trailing 1/2 block as guard time for separating consecutive time slots. A single radio resource is associated with eight different tone clusters spread in frequency and possibly in time to obtain frequency diversity. This arrangement supports 24 resources that can be assigned by DPA. A peak data rate of 2.07 Mb/s is available for packet data services using all 24 large radio resources for 1/2-rate coded QPSK and a peak rate of 4.14 Mb/s using 2/3-rate coded 8-PSK.

Small resources have a frame structure similar to large resources. A difference is that the time slots are further divided into two mini-slots. A group of four small radio resources can be obtained by allocating one large radio resource. A small radio resource uses a mini-slot from every other tone cluster in the large radio resource frame. Of the 10.5 OFDM blocks in each time slot, 2.5 blocks are used as overhead. This includes a total of two leading blocks (duration of one block for each of the two mini-slots) for synchronization and a trailing 1/2 block (0.25 block for each of the two mini-slots) as guard time for separating consecutive mini-slots. A peak data rate of 1.84 Mb/s is available using all 96 small radio resources for 1/2 rate coded QPSK or 3.68 Mb/s is available using 2/3 rate coded 8-PSK.

A FRAME STRUCTURE FOR DYNAMIC PACKET ASSIGNMENT

The frame structure described in this section supports both control information, which is needed to perform the DPA procedure, and the bearer traffic. A frame is 20 ms . The control part uses a staggered schedule, in which only one base station at a time, from a group of four adjacent base stations, transmits information for DPA. The bearer traffic, on the other hand, is transmitted on the assigned radio resources ("channels") without a staggered schedule. To implement the staggered schedule, four frames (80 ms) are grouped as a "superframe." Effectively, this achieves a reuse factor of 4 for the control information while allowing a reuse factor of 1 for bearer traffic by using DPA (i.e., all traffic channels can be used everywhere). A reuse factor of 4 and three sectorized antennas in each base station provide extra error protection

for the control channels, whereas interference avoidance based on DPA with admission control provides good quality for the traffic channels.

DOWNLINK SIMULATION PERFORMANCE RESULTS

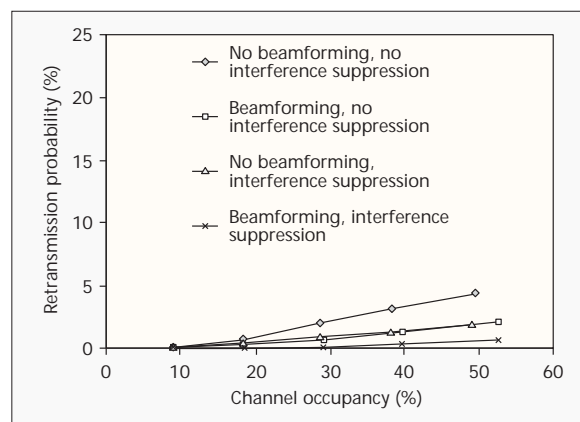
To characterize the DPA performance, a simulation system of 36 base stations arranged in a hexagonal pattern is used, each having three sectors. The same channel can be used in different sectors of the same base station as long as the signal-to-interference ratio (SIR) at the DPA admission process exceeds 7 dB . Based on the downlink frame structure shown in Fig. 3, four base stations in each reuse area take turns performing the DPA procedure and the assignment cycle is reused in a fixed pattern. In the propagation model, the average received power

decreases with distance d as d^{-4} and the large-scale shadow-fading distribution is log-normal with a standard deviation of 10 dB . A data service traffic model, described in [11], based on wide area network traffic statistics, which exhibit a "self-similar" property when aggregating multiple sources, was used to generate packets. ARQ is employed for retransmission when a packet ("word") is received in error. If a packet cannot be successfully delivered in 3 s, which may be a result of traffic overload or excessive interference, it is dropped from the queue. The control messages are assumed to be error-free in the designated control slots, and only large resources are used in this study.

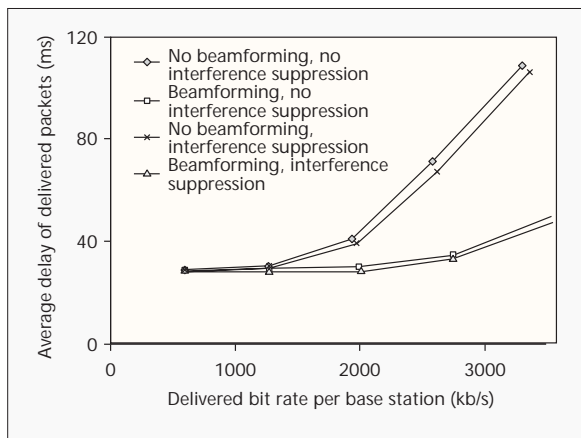
We consider two radio link enhancement techniques to study DPA performance:

- Beamforming
- Interference suppression

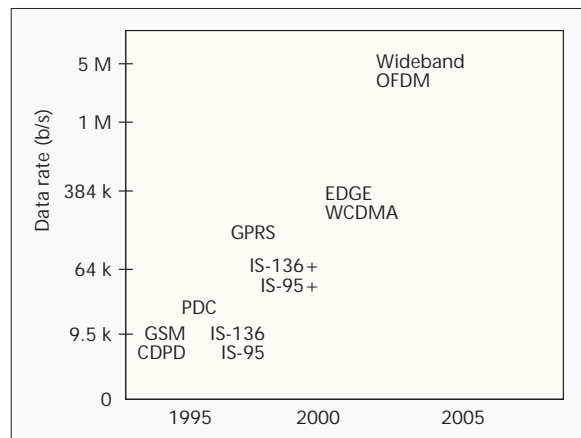
Both beamforming and interference suppression employ two receive antennas, and minimum mean square error (MMSE) combining is used in the case of interference suppression to improve SIR. Downlink beamforming is performed at the base station using four transmit antennas to form four narrow beams. By using narrow beams to deliver packets for



■ Figure 4. Average retransmission probability as a function of occupancy.



■ Figure 5. Average delay of the delivered packets as a function of the throughput per base station.



■ Figure 6. The evolution of wireless packet data access.

mobile stations (MSs), SIR is enhanced. For beamforming, each 120° sector is simply divided into four 30° beams (with a 20 dB front-to-back ratio and idealized antenna pattern), and the assumption is made that a packet is delivered using the beam that covers the desired MS. The parameters used in this study are similar to those discussed earlier, but are not identical.

Figure 4 shows the overall average probability of packet retransmission as a function of occupancy. With a 3–6 percent target retransmission probability, 15–50 percent occupancy per radio in each sector is possible with this DPA scheme, depending on the use of MMSE antenna combining at the terminal and beam-switching at the base station. This result is significantly superior to the efficiency provided by current cellular systems. Figure 5 shows packet delay versus system load. Notice that both interference suppression and downlink beamforming are effective in improving retransmission probability. However, the improvement in packet delay for interference suppression is somewhat limited (even though the packet dropping rate is improved significantly) because interference suppression is not employed in SIR estimation, which is used for admission control.

Specifically, some of the packets are delayed if the SIR estimated during resource assignment does not exceed 7 dB, although the SIR may be acceptable with interference suppression which is performed in the demodulation process after admission is granted. This could be addressed by considering SIR after interference suppression for admission control. Based on the results of Fig. 4, it appears that the reasonable operating region of occupancy is about 25–40 percent and 40–60 percent occupancy per radio for cases with and without beamforming, respectively.

Under this condition, interference suppression and/or beamforming can achieve acceptable retransmission probability, providing good QoS. If neither enhancement is employed, the traffic capacity must be lowered to ensure good performance. When both techniques are employed, three radios in three sectors can utilize over 100 percent of the radio resources in every base station. Finally, Fig. 5 shows that 2–3 Mb/s can be successfully delivered by each base station with an average delay on the order of 40–120 ms. This indicates that WOFDM and DPA combined enable a spectrally efficient air interface for broadband services, even for macrocell environments, providing complementary high-bit-rate data services beyond what third-generation systems can offer. Adaptive modulation has not been considered in this study, and its use is expected to improve throughput to 4–5 Mb/s

per base station. It is reasonable to expect that an 8-PSK-based modulation can deliver about 5 Mb/s in peak rate packet data access as well as increase throughput. The WOFDM technology discussed here can provide high peak rates with robust performance that is not achievable in second- or third-generation technologies. However, it is a less mature technology that requires more research and development effort. A possible evolutionary roadmap for packet data services is shown in Fig. 6. Combining a high-speed OFDM downlink with a 3G wireless system such as EDGE appears to be attractive, providing an asymmetrical access arrangement, requiring new spectrum only for downlinks, and leveraging the convergence of IS-136 and GSM with GPRS/EDGE.

CONCLUSIONS

The rapid growth of wireless voice subscribers and the Internet, and the increasing use of portable computing devices suggest that wireless Internet access will grow to be a major part of telecommunications. Today, the number of wireless data subscribers is small, with the most formidable obstacle to user acceptance being the performance limitations of existing services and products, including link performance (data rate, latency, and quality), network performance (access, coverage, spectrum efficiency, and quality of service), and price. Early wireless packet data access technologies providing about 10 kb/s transmission rates over wide areas are expected to evolve or be replaced by technologies providing 40–144 kb/s peak data rates with IS-136+, IS-95+, and GPRS technologies. In the 2001–2003 time frame, the introduction of EDGE and WCDMA technologies will provide access rates up to about 384 kb/s. WOFDM is expected to support peak bit rates of 2–5 Mb/s in large-cell environments and up to 10 Mb/s in microcellular environments for downlinks. Combining WOFDM with EDGE could provide an attractive approach for future packet wireless access based on uplink techniques that are friendly to the limitations of a terminal's RF amplifier and limited battery power; providing a downlink capability with peak rates up to 5 Mb/s; and providing an evolutionary path for the convergence of IS-136 and GSM based on GPRS/EDGE.

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