Beyond 3G: Wideband Wireless Data Access Based on OFDM and Dynamic Packet Assignment

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Abstract

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 rise rapidly over the next few years. 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 making wireless Internet access more user-friendly and providing more value. Transmission rates are currently only about 10 kb/s for large cell systems. Third-generation wireless access such as WCDMA and the evolution of second-generation systems such as TDMA IS-136+, EDGE, and CDMA IS-95 will provide nominal bit rates of 50–384 kb/s in macrocellular systems. [1] This article discusses packet data transmission rates of 2–5 Mb/s in macrocellular environments and up to 10 Mb/s in microcellular and indoor environments as a complementary service to evolving second- and third-generation wireless systems. Dynamic packet assignment for high-efficiency resource management and packet admission; OFDM at the physical layer with interference suppression, space-time coding, and frequency diversity; as well as smart antennas to obtain good power and spectral efficiency are discussed in this proposal. Flexible allocation of both large and small resources also permits provisioning of services for different delay and throughput requirements.

Introduction

Wireless Internet access is expected to grow rapidly, because of the maturing of digital cellular, portable computing, and fixed Internet technologies. 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 (HDSL) technology in the fixed access networks. In parallel with the expanding availability of high-speed transmission capabilities, increasingly demanding Internet applications and user expectations have emerged. Experience with laptop computers and personal digital assistants (PDAs) has shown that many end users desire their portable equipment to provide essentially the same environment and applications they enjoy at their desks with few compromises. Experience with wireless access has demonstrated the singular importance of widespread coverage and anywhere/anytime access. Wireless packet data access in macrocellular environments at peak rates beyond 2 Mb/s is likely to be needed in the near future to provide users with an application environment with few compromises from fixed environments. Challenges for the high-speed wireless data access future are transmission speeds at 100–1000 times existing rates; costs of a few cents per minute for access; RF power transmission efficiency that is 10–20 dB better than existing systems; and substantially increased spectral efficiency.

Two important business drivers for complementary packet data access at speeds above 2 Mb/s are:

• Integration of wireless data services across macrocellular, microcellular, and private indoor systems, and with other services

• High spectrum efficiency

Wireless service providers pay dearly to acquire spectrum. Efficiency of spectrum usage is always a strong factor in a decision on wireless technology. Spectrum efficiency becomes crucial for very high-speed data services (e.g., > 2 Mb/s). By taking advantage of improvements in digital signal processing (DSP) and radio frequency (RF) technologies, orthogonal frequency-division multiplexing (OFDM) provides the possibility to provide > 2 Mb/s packet data at a cost and with a spectrum efficiency that allow wireless providers to compete with wireline carriers for data services. Integrated services also provide significant billing advantages for both customers and service providers. Based on customers’ preferences, telecommunications companies such as AT&T are moving in the direction of delivering integrated services which cover local residential and business, long distance, and both wireline
and wireless services. Integrated services also include voice services, circuit data, and packet data with transmission rates from 30 kbps to a few hundred megabits per second. Providing nomadic customers in areas such as airports, hotels, and other public areas with the same user experience they have in their office is the key driver to deploy such high-rate complementary packet data services.

Wideband code-division multiple access (WCDMA) will use 5 MHz channels, and it is a leading candidate for third-generation wireless access [1]. However, it will be limited to about 384 kbps (nominal) peak data rates for macrocellular wireless access (up to 2 Mbps rates are proposed for indoor environments). Global System for Mobile Communications (GSM) enhancements based on Enhanced Data Rates for GSM Evolution (EDGE) using adaptive modulation will provide bit rates up to 384 kbps in the near future. [1] Second-generation wireless systems will evolve with complementary packet data solutions that generally use frequency channels separated from circuit voice and circuit data access. Time-division multiple access (TDMA) and CDMA systems are being considered in which circuit and packet access share a common frequency channel and access modes are separated by time slots or spreading codes. However, the expected demands for high peak-rate Internet access are motivating increasing consideration of complementary access based on separate frequency channels to provide maximum peak rates and to allow optimization for packet data transmission alone.

OFDM was proposed for digital cellular systems in the mid-1980s [2]. OFDM has also been shown to be effective for digital audio and digital video broadcasting at multimegabit rates in Europe, and it has been incorporated into standards by the European Telecommunications Standards Institute (ETSI). The IEEE 802.11 standards group recently chose OFDM modulation for wireless LANs operating at bit rates up to 30 Mbps at 5 GHz. In this article, OFDM modulation combined with dynamic packet assignment with wideband 5 MHz channels is proposed for wireless access in macrocellular and microcellular environments, supporting a family of peak bit rates ranging from 2 to 10 Mbps. OFDM can largely eliminate the effects of intersymbol interference for high-speed transmission rates in very dispersive environments, and it readily supports interference suppression and space-time coding to enhance efficiency. Dynamic packet assignment can support excellent spectrum efficiency and high peak-rate data access.

Wideband OFDM

WCDMA is now recognized as one of the leading candidates for third-generation wireless access. Based on direct-sequence spread-spectrum with a chip rate of 3.84 Mcips/s, it occupies a bandwidth of about 5 MHz. It will support circuit and packet data access at nominal rates up to 384 kbps in macrocellular environments, and provide simultaneous voice and data services. An advanced cellular Internet service (ACIS) concept based on OFDM signaling and dynamic packet assignment (DPA) has been proposed, with the potential to provide 384 kbps data services in macrocellular environments using only 1 MHz of spectrum [3]. It is possible to expand this ACIS concept into a wideband context in 5 MHz while providing a complementary service to third generation systems such as EDGE and WCDMA. This wideband OFDM system would support an order of magnitude higher peak data transmission rate in macrocells at 2 to 5 Mb/s and up to 10 Mb/s in microcells. IS-136, GSM or WCDMA would provide circuit voice and other circuit-based services and basic data services. A complementary high-speed packet data mode would provide fast wireless packet data access to meet the demand for wireless data in the future that provides access performance similar to wideband fixed access. Since portable equipment is power-limited, strongly asymmetrical traffic should be supported, and uplink transmission rates should be allowed to adapt downward as necessary to support the required link budgets. Wideband OFDM wireless access might also be configured to introduce new broadband capabilities using OFDM only on the downlink, which is then integrated with emerging wireless packet data systems such as General Packet Radio Service (GPRS), EDGE, or WCDMA to provide two-way access. An example of such a system with the EDGE uplink is discussed in [4].

There are a number of reasons to consider such a high-rate complementary packet data capability for downlinks. Wireless Internet usage is likely to be downlink-limited. Furthermore, for data services, peak bit rate is very important in determining overall system performance, because of the highly bursty nature of Internet traffic. GPRS, EDGE, and WCDMA solutions will support transmission rates of 144–384 kbps in macrocellular environments. To achieve rates in the megabits-per-second range for all environments using 5 MHz spectrum is challenging for both the physical layer and radio resource management design. Single-carrier TDMA solutions are limited in supportable transmission bit rate by equalizer complexity. Even though new techniques such as interference suppression and space-time processing are promising, the interactions of these techniques with equalization significantly lower achievable bit rates in hostile operating environments for single-carrier solutions. Low spreading gain or intercode interference at high bit rates limits CDMA solutions. The use of OFDM with sufficiently long symbol periods of 100–200 μs for packet data transmission addresses these issues. It supports a high bit rate in time delay spread environments with performance that improves with increasing delay spread up to a point of extreme dispersion. Another reason to consider a complementary packet data solution is to use optimized admission procedures for packet data access that is fairly aggressive in order to achieve high spectral efficiency. An aggressive admission policy will result in high word error rates (WERs) that can generally be managed for Internet services using automatic repeat request (ARQ) techniques but are problematic for delay-sensitive voice services. Therefore, a com-

OFDM can largely eliminate the effects of intersymbol interference for high-speed transmission rates in very dispersive environments, and it readily supports interference suppression and space-time coding to enhance efficiency.

1Peak rates exceeding 1 Mbps under limited conditions for very few simultaneous users are also considered for some systems.

2In [4] we focused on the architecture of such a system in a macrocellular system. This article provides a detailed discussion of the design considerations under different conditions. However, the numerical results shown in [4] were based on an improved radio link design using convolutional codes to achieve even better performance.
Physical Layer Techniques and Deployment Scenarios

This section discusses how wideband OFDM can be implemented in both macrocells and microcells to provide ubiquitous broadband services. Most of the techniques discussed next for macrocells are also applicable to enable wideband OFDM in microcells with potential for even higher rates.

Wideband OFDM in Macrocells

Physical Layer Techniques — In typical wireless-line applications, communication channels are generally static over the connection period. In this case, OFDM subchannel power and bit allocation can be optimized through measurement and feedback in the initial link setup process. Measurement errors and feedback delay significantly reduce the performance of this technique in time-varying wireless fading channels. In wireless channels, good link performance can be achieved by OFDM when combined with diversity, interleaving, and coding [2]. OFDM inherently provides frequency diversity over subchannels, which introduces an opportunity for interleaving in the frequency domain. However, adjacent subchannels may still be highly correlated. Sony has proposed an OFDM-based scheme [5] using time-domain interleaving combined with frequency hopping to enhance performance. This system also uses frequency hopping to achieve interference averaging.

However, when high peak rate is desired while bandwidth is limited, there may generally not be enough “clusters” of subchannels to use for frequency hopping. Reference [3] proposed the application of multiple transmit antennas for sending adjacent subchannel signals to achieve frequency diversity without requiring frequency hopping or interleaving in the time domain, which introduces delay. More advanced transmitter diversity can be achieved by transmitting the same OFDM symbols on multiple antennas with delayed transmission times. With the wider bandwidth discussed in this article, many subchannels are available, which provides a possibility to achieve good performance by exploiting time and frequency diversity without using multiple transmit antennas.

Assume a bandwidth of 5 MHz is divided into about 20 radio resources of 200 kHz each with 1 MHz reserved for guard bands. Every 200-kHz radio resource can be constructed by grouping a cluster of (25) 8-kHz subchannels. Frequency diversity can be achieved by hopping over different clusters on different time slots. The same hopping pattern is repeated once every frame of 8 slots. Up to 20 users can be simultaneously assigned, one resource each, using different hopping patterns that are free from collisions. High-rate users can be assigned multiple or all resources. Date rates equivalent to a fraction of a nominal radio resource can also be assigned by scheduling transmission in the time domain. We will discuss assignment of large and small resources for different applications. A key feature of a 5 MHz bandwidth is the availability of diversity and interleaving in both time and frequency domains, which enables high coding gain to achieve performance enhancement using a single transmit antenna.

OFDM has been proposed for the physical layer for ACIS in macrocells with 1–2 b/s/Hz channel coding using mode adaptation with quadrature phase shift keying (QPSK) and 8PSK modulation to support peak bit rates up to 1 Mb/s in about 800 kHz channels [3]. This allows for various overheads to account for up to 50 percent of the total available bandwidth. With a 4 MHz bandwidth, similar to WCDMA, up to 5 Mb/s can be supported. OFDM provides good support for interference suppression and smart antennas [7] because the effects of dispersion can be removed at a receiver easily by first processing each antenna’s signal with a discrete Fourier transform (DFT) before combining with an interference suppression algorithm. Packet data wireless access tends to be dominant-interference-limited, so linear interference suppression techniques are effective to increase capacity with a two-branch receiver. These techniques support operation near 0 dB signal-to-interference (S/I) and at about 5 dB signal-to-noise ratio (SNR) for 1 b/s/Hz coding [7].

One of the strong challenges of providing up to 5 Mb/s transmission rates on downlinks for packet data in macrocells is the link budget. RF power amplifier cost is a major factor in base station cost, and it is a major contributor to power supply requirements, heat management, and equipment size. An IS-136 channel delivers about 24 kb/s of coded user data with acceptable quality on a fading channel at about 17 dB SNR.
Therefore, 2.5 Mb/s would require 100 times as much transmit power (20 dB) unless additional techniques are introduced. Smart antenna technology using four switched 30° beams in a 120° sector is now a well-developed technology with some early deployment. This technology provides up to 6 dB in link budget improvement and also improves capacity. Terminal two-branch receiver diversity combined with concatenated convolutional/Reed-Solomon coding supports receiver sensitivities of less than 5 dB SNR with 1 b/s/Hz coding. Space-time coding can provide SNR gain based on transmit diversity. By combining smart antenna technology at base stations with terminal receiver sensitivities of less than 5 dB SNR, the downlink for wideband OFDM can support peak transmission rates of 2–5 Mb/s with about the same transmit power and coverage as a single transceiver for IS-136 TDMA or analog cellular technologies.

MAC-Layer Techniques — Very high spectrum efficiency will be required for wideband OFDM, 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. WCDMA will also use interference averaging. Interference avoidance or dynamic channel assignment (DCA) has been used in some systems, generally as a means of automatic channel assignment or local capacity enhancement, but not as a means of large systemwide 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 promises to overcome these challenging implementation issues. It was shown by Pottie [8] 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. However, 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 problematic due to the rapid arrival and departure of interfering packets.

The basic protocol for a downlink comprises four basic steps:

- A packet page from a base station to a terminal
- Rapid measurements of resource usage by a terminal using the parallelism of an OFDM receiver
- A short report from the terminal to the base station of the potential transmission quality associated with each resource (a unit of bandwidth that is separately assignable)
- Selection of resources by the base and transmission of the data

This protocol could be modified to move some of the over-the-air functions into fixed network transmission functions to reduce wireless transmission overhead at the cost of more demanding fixed network transmission requirements. The frame structures of adjacent base stations are staggered in time (i.e., neighboring base stations sequentially perform the four different DPA functions outlined above with a predetermined rotation schedule). This avoids collisions of channel assignments (i.e., 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 mode (bit rate) adaptation based on measured signal quality.

Figure 1 shows the performance of this algorithm with several modulation/coding schemes and with either two-branch maximal-ratio-combining or two-branch receiver interference suppression using packet traffic models based on Internet statistics [9]. Results with interference suppression for space-time coding are not included because each transmitted signal appears as multiple signals, which significantly limits the...
suppression of interference. These results are based on an OFDM radio link with a bandwidth of about 800 kHz, and the bit rates in the following discussion are scaled up for an occupied bandwidth of 4 MHz. A system is considered with three sectors per base station, each having a transceiver. All base stations share one wideband OFDM RF channel by using DPA to avoid co-channel interference. DPA enables frequency reuse in the time domain among all radio transceivers. Occupancy is defined to be the fraction of slots being used. As traffic intensity increases, occupancy increases, which results in higher interference and more retransmissions. Power control was not used to obtain these results. Simulation results based on the wideband set of parameters will be presented following a description of a possible frame structure. These results show that good performance is obtained with 1 b/s/Hz coding even at an average occupancy per base station of 100 percent (33 percent per sector). With two-branch interference suppression and 1 b/s/Hz coding, the average retransmission probability is only about 3 percent throughout the system with the average delivered bit rate of about 2.5 Mb/s per base station. Using ARQ at the radio link layer will permit Internet service at this retransmission probability with good quality of service (QoS). Higher retransmission probability may be acceptable at the expense of longer packet delay. Peak rates up to 5 Mb/s are possible with lower occupancies using 2 b/s/Hz coding. Finally, in addition to interference suppression at the receiver, beam switching smart antenna techniques, performed by the transmitter, can also be applied to reduce interference, thus achieving good performance at 5 Mb/s even at 100 percent occupancy per base station.

WIDEBAND OFDM IN MICROCELLS

For microcell deployment, very compact radio ports with low power requirements are desirable to permit convenient siting on existing poles and building walls. In addition, high bit rates are desirable to provide a capability as near to that of wired access as possible. For indoor and private system access, unlicensed spectrum at 5 GHz or higher may be desirable, where large bandwidths are available. For these environments, small antennas are required. Because of the large angular spread experienced at radio ports located in the clutter of buildings and trees, simple omnidirectional or low-gain antennas are appropriate. In that environment, antenna beam switching provides limited gains in performance, but adaptive antenna arrays and/or space-time coding can be very effective. For example, in a 5 MHz channel, peak rates of 10 Mb/s could be supported using two transmit and two receive antennas for the radio link with space-time coding of 16-quadrature amplitude modulation (QAM) to achieve a 4 b/s/Hz coding rate while allowing for about 50 percent overhead. Mode adaptation to 5 or 2 Mb/s would support appropriate link budgets for robust coverage.

Microcell radio ports could be implemented that provide little more than radio modem functions to allow for very small radio ports. One possible approach is to use a combination of dual antennas at each port and multiplex processing per user at a centralized headend. For example, if a user delivers, on average, a strong signal to M ports, the dual-branch signals back-hauled from the M “best” ports can be processed at the central site using selection or combining techniques. Simulation studies have shown that grouping of microcell ports in this way can yield impressive results in link reliability and capacity due to macroscopic diversity. Moreover, this approach requires a minimal amount of processing at the ports, thus keeping them simple. The processing at the central site can also be fairly simple if the signals being combined are not dispersed by significant multipath propagation. The grouping approach is therefore compatible with the use of OFDM, wherein each frequency (or subgroup of frequencies) can be processed with parameters optimized for that frequency. This kind of processing works best with time-division duplexing (TDD), which requires using the same carrier frequency for transmission and reception. This is consistent with the planning for very high-speed micro- and picocellular services in third-generation systems.

Backhaul could be a significant cost issue in microcellular systems. Various innovative ways to use fiber, coax, microwave radio, and millimeter-wave radio can be envisioned to make this part of the system reliable. The key requirements are to deploy microcells only in areas where there is a strong expectation of high-speed service demand and to provide wide-area coverage with a compatible technology.

DPA requires low delay between the air interface and resource assignment function, so any architecture that minimizes radio port functionality would need to consider that constraint. This also means that DPA should allow some margin in timing for delay in microcellular transmission equipment.
The frame structure described in this section supports both control information, which is needed to perform the DPA procedure, as well as 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 a staggered schedule, four frames (80 ms) are grouped as a “superframe.” Effectively, this achieves a reuse factor of 4 for 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.

The total bandwidth is divided into 8-kHz subchannels (“tones”). In the time domain, this can be constructed by grouping OFDM blocks (blocks of OFDM subchannels) with a 125 μs signaling interval and a 31.25 μs guard time to accommodate significant delay spread in macrocells. In the following discussion, the duration of an OFDM block (or simply “block”), 156.25 μs, is used as the basic time unit in the discussion of the frame structure. A frame of 20 ms is equivalent to 128 blocks. This corresponds to a 6.4 kbaud block rate. Also, a total of 528 subchannels are considered, resulting in a 4.224 MHz bandwidth. The discussion below focuses on the case of QPSK modulation and 1/2-rate coding (1 b/s/Hz), resulting in a total rate of 3.3792 Mb/s without considering other overheads. Coding and modulation schemes with higher efficiency could provide higher rates, especially for microcellular environments.

Considerations for organization of resources are the resolution of resource size, the overhead required to reserve 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 higher-layer protocols generate small objects that the lower layers must carry, there will be 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 services of 8 kb/s with additional coding for error correction in wireless channels), this would be equivalent to about 200 resources. In the following resource assignment is considered using only one of the 8 slots in a 20-ms frame. Frequency hopping over different slots is employed to gain frequency diversity for large resources. To achieve this frequency diversity for small resources a slot is divided into mini-slots, at the cost of reduced efficiency due to TDMA overhead.

**HIGH-PEAK-RATE DATA SERVICES: LARGE RADIO RESOURCES**

528 subchannels (4.224 MHz) are organized into 22 clusters of 24 subchannels (192 kHz) each and 8 time slots of 13 OFDM blocks each within a 20-ms frame of 128 blocks. Figure 2 shows this resource allocation scheme. The control channel functions are defined in [3]. This allows flexibility in channel assignment while providing 24 blocks of control overhead to perform the DPA procedures.

This arrangement of tone clusters is similar to the arrangements in the band-division multiple access (BDMA) proposal by Sony. Figure 3 depicts this operation. Each tone cluster would contain 22 individual modulation tones plus 2 guard tones, and an OFDM block would have a time duration of 156.25 μs with a 31.25 μs guard time and ramp time to minimize the effects of delay spread up to about a 20-μs span. Of the 13 OFDM blocks in each traffic slot, two blocks are used as overhead, which includes a leading block for synchronization (phase/frequency/timing acquisition and channel estimation) and a trailing block as guard time for separating consecutive time slots. A single radio resource is associated with a frequency-hopping pattern, by which the packets are transmitted using eight different tone clusters in each of the eight traffic slots. Coding across eight traffic slots for user data, as shown in Fig. 3, exploits frequency diversity which gives sufficient coding gain for performance enhancement in the fading channel. This arrangement supports 22 resources in frequency that can be assigned by DPA. Taking into account overhead for OFDM block guard time, synchronization, slot separation, and DPA control, a peak data rate of 2.1296 (3.3792 x 22/24 x 11/13 x 104/128) Mb/s is available for packet data services using all 22 radio resources, each 96.8 kb/s.

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3 The grouping can be configured similar to conventional frequency planning for reuse factor 4 using a regular and repetitive pattern, for example, with timing groups 1 and 2 alternating in the odd rows and groups 3 and 4 in the even rows.

4 The word “resource” is used to emphasize that the assignment of radio channels for traffic bearers can be a general combination of time slots, frequency sub-carriers and user codes. The user code controls the sequence by which a given user access different frequency sub-carriers at different time slots.
For the base station, where uplink transmission for all radio resources is asynchronous, a receiver may separate 192-kHz clusters with filters followed by independently synchronized demodulators. For the mobile terminal, where downlink transmission for base station radio resources is typically synchronous, a receiver may use a single demodulator with receiver windowing to result in strong attenuation of undesired clusters. However, adjacent clusters may be asynchronous if transmitted by different base stations. The receiver structure requires further study.

**LOW-DELAY SERVICES: SMALL RADIO RESOURCES**

Similar to the previous section, 528 subchannels (4.224 MHz) are organized into 22 clusters of 24 subchannels (192 kHz) each and 8 time slots of 13 blocks each within a 128-block (20 ms) frame. A difference is that these time slots are further divided into four mini-slots for frequency hopping, and one slot is assigned per frame as a basic radio resource. Therefore, the frame structure is the same as shown in Fig. 2 except that there are 176 (8 x 22) small resources, and each resource bit rate is reduced by additional TDMA overhead needed at the beginning and end of a mini-slot. The same control channel can be used to assign both large and small resources using staggered frame DPA.

Figure 4 depicts the coding scheme for small resources. Each tone cluster would contain 22 individual modulation tones plus 2 guard tones. Of the 13 OFDM blocks in each traffic slot, three blocks are used as overhead. This includes a total of two leading blocks (duration of one-half block for each of the four mini-slots; this can be realized by using one block in every other tone) for synchronization and a trailing block (one-fourth block for each of the four mini-slots) as guard time for separating consecutive mini-slots. A single radio resource is associated with a frequency-hopping pattern, by which the packets are transmitted using four different tone clusters in each of the four mini-slots. Coding across four mini-slots for user data, as shown in Fig. 4, exploits frequency diversity. However, it should be noted that when large and small resources are simultaneously assigned in different clusters of a given slot, the frequency range over which small resources can hop to achieve frequency diversity might be limited. Mixed assignment of large and small resources is a topic for further study. Taking into account overhead for OFDM block guard time, synchronization, slot separation, and DPA control, a peak data rate of 1.936 (3.3792 x 22/24 x 10/13 x 104/128) Mb/s is available using all 176 radio resources, each of 11 kb/s.

**A FRAME STRUCTURE FOR DYNAMIC PACKET ASSIGNMENT**

The downlink structure is shown in Fig. 5. The uplink structure is similar, but the control functions are slightly different. At the beginning of each frame, the control channels for both the uplink and downlink jointly perform the four DPA procedures described earlier sequentially with a predetermined staggered schedule among adjacent base stations. Some control channel overhead is included to allow three sectors to perform DPA at different time periods, thus obtaining additional signal-to-interference ratio (SIR) enhancement for the control information. For traffic channels, spectrum reuse is achieved by interference avoidance using DPA to avoid slots that can cause potential interference; a reuse of 1 is achieved with this intelligent “partial loading.” This frame structure permits SIR estimation on all unused traffic slots. The desired signal is estimated by the received signal strength from the two OFDM blocks used for paging, while the interference can be estimated by measuring three blocks of received pilot signals. The pilot channels are generated by mapping all the radio resources currently in use onto corresponding pilot subchannels, thus providing an “interference map” without monitoring the actual traffic subchannels [3]. The OFDM scheme can process many subchannels in parallel, which provides a mechanism

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**Figure 3. Coding of a large radio resource with clustered OFDM and frequency hopping in a frame; radio resource mapping onto OFDM’s time/frequency structure provides interleaving, which is required for effective error-correction coding.**

<table>
<thead>
<tr>
<th>Code work ordering</th>
<th>Radio resource mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8</td>
<td>104 OFDM blocks in 8 slots</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Bit index (within a word)</th>
<th>Frequency</th>
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<td>x x x x</td>
<td>x x x x</td>
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</table>

| 1 2 3 4 5 6 7 8 | 528 tones divided into 22 24-tone clusters |

**Figure 4. Assignment of a small radio resource with clustered OFDM and frequency hopping in four mini-slots within a slot.**

- B: 1 OFDM block
- G: Guard equivalent to 0.25 OFDM block in duration
for very fast SIR estimation. In addition, since a total of 528 subchannels are available to map 22 large resources and 176 small sources over three OFDM blocks, significant diversity effects are achieved to reduce measurement errors. The estimated SIR is compared to an admission threshold (e.g., 10 dB in our example), so channel occupancy can be controlled to achieve good QoS for the admitted users. QoS provisioning for different services is an area for further study. To reduce time delay for small resource assignment, this frame structure can be modified to allow assignment of 1/4 resources per frame.

**DOWNLINK PERFORMANCE FOR HIGH-PEAK-RATE DATA SERVICES**

In the following, downlink performance is studied by large-scale computer simulations. Only the downlink simulation results are shown here since downlink transmission requires a higher RF bandwidth, and its information bandwidth demand in popular applications (e.g., Web browsing) is also higher. Although uplink efficiency could be reduced by collisions, downlink spectrum efficiency is the crucial factor in system deployment.

**THE SIMULATION MODEL**

To characterize DPA performance, a system of 36 base stations arranged in a hexagonal pattern is assumed, each having three sectors using idealized antennas with $120^\circ$ beamwidths and a 20-dB front-to-back ratio. The mobile antennas are assumed to be omnidirectional. In each sector, one radio provides eight traffic slots to deliver downlink traffic packets. The same channel can be used in different sectors of the same base station as long as the SIR at the DPA admission process exceeds 10 dB. Based on the downlink frame structure shown in Fig. 5, four base stations in each reuse area take turns performing the DPA procedure, and the assignment cycle is reused in a fixed pattern. The co-channel-interference-limited case is considered; that is, noise is ignored in the simulation. 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. Rayleigh fading is ignored in the channel assignment, which approximates the case where antenna diversity is employed and sufficient averaging in both time and frequency domains is achieved in signal and interference estimations.

Uniformly distributed mobile stations (MSs) receive packets, which are generated from the network and arrive at different base stations. A data service traffic model, described in [9], based on wide-area network traffic statistics, which exhibit a “self-similar” property when aggregating multiple sources, was used to generate packets. A radio resource (“channel”) is statistically multiplexed to deliver packets for different MSs. MSs are fairly allocated as many unused radio channels as possible provided the SIR exceeds 10 dB for resources. When the number of pending packets exceeds the number of channels assigned, they are queued for later delivery. The assigned channels are reserved for the same MS.
until all packets are delivered or the DPA reassigns radio channels in the next superframe. ARQ is employed, assuming perfect feedback, to request base stations for retransmission when a packet (“word”) is received in error, which is simulated based on the WER curve obtained in [3] using differential demodulation with four transmit-diversity and two receive-diversity antennas. Recent simulations of the clustered OFDM scheme described earlier found that almost the same WER can be obtained using coherent demodulation with one transmit and two receive antennas. Therefore, the results shown can be achieved by using one transmit and two receive antennas. 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.

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

• Beamforming
• Interference suppression

Both beamforming and interference suppression employ two receive antennas for signal processing to improve SIR. Downlink beamforming is performed at the base station using four transmit antennas to form four narrow beams. By using different beams to deliver packets for MSs inside the desired beamwidth, SIR is enhanced. Interference suppression, on the other hand, relies on two MS receive antennas to suppress interference. For beamforming, each 120° sector is simply divided into four 30° beams (with the same 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. It is important to note that the case of beamforming shown in the following requires implementation of four narrow-beam transmit antennas at the BS, but each active link still uses one transmit and two receive antennas, as discussed above.

**Performance Results**

Figure 6 shows the overall average probability of packet retransmission as a function of occupancy. With a 3–6 percent target retransmission probability, about 15–50 percent occupancy per radio in each sector is possible with this DPA scheme. This result is significantly superior to the efficiency provided by current cellular systems. The corresponding average packet dropping probability is shown in Fig. 7. Notice that both interference suppression and downlink beamforming are effective in improving retransmission probability. However, the improvement in packet dropping probability for interference suppression is somewhat limited 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 10 dB, although SIR may be acceptable with interference suppression performed in the demodulation process after admission is granted. Based on the results of Fig. 7, it appears that the reasonable operating region of occupancy is about 20–25 and 30–35 percent occupancy per radio for cases without and with 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 100 percent of radio resources in every base station. Finally, Fig. 8 shows that 2–3 Mb/s can be successfully delivered by each base station with an average delay on the order of 60–120 ms. This indicates that OFDM 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.

Based on the performance shown here and the coding/modulation alternatives discussed earlier, it is reasonable to expect that an 8-PSK-based modulation can deliver 5 Mb/s in peak-rate packet data access. The wideband OFDM
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.

CONCLUSIONS

Peak bit rates of 2–5 Mb/s are likely to be desirable for future packet wireless data service for Internet applications with widespread macrocellular coverage to enable anywhere/anytime access. Adaptive modulation will be important to achieve maximum efficiency and allow for the more limited transmit power levels of portable terminals. The 5 MHz channelization discussed can support packet data bit rates of 2–5 Mb/s in macrocellular environments in a complementary packet data mode. Bit rates up to 10 Mb/s can be supported in microcellular and indoor environments using space-time coding with two transmit and two receive antennas. Space-time coding may also be applicable in macrocellular environments. Private indoor systems should probably use unlicensed spectrum for high-speed wireless data access, because of the need for large amounts of spectrum and emerging wireless LAN standards, including the IEEE 802.11 standard at 5 GHz based on OFDM. Dynamic packet assignment, an OFDM physical layer, adaptive modulation and coding, space-time coding and interference suppression, and smart antennas are proposed as techniques to provide wideband OFDM packet wireless data access in macrocellular and microcellular environments. The target bit rates are substantially higher than what third-generation systems can achieve in macrocellular environments, and can reduce the gap between wireline and wireless data rates and applications. Areas for further study include receiver structures and implementations, resource assignment, and QoS provisioning for mixed services, as well as many other issues not discussed here.

ACKNOWLEDGMENTS

The concepts in this article are based on the work and ideas of a number of colleagues within AT&T as well as others. Lek Ariyavisitakul and Larry Greenstein contributed to concepts on microcells. Len Cimini and Ye Li contributed to the OFDM techniques that were discussed. Vahid Tarokh, Nambi Seshadri, and Rob Calderbank contributed to space-time coding concepts. Hong Zhao contributed to concepts for applications and requirements for high-speed data services.

REFERENCES


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Figure 8. Average delay of the delivered packets as a function of the throughput per base station.