Broadband Wireless Internet Forum White Paper

BWIF - Bringing Broadband Wireless Access Indoors

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Notice

About the Broadband Wireless Internet Forum (BWIF)

BWIF, formed in July 2000, is an incorporated, non-profit association of industry-leading companies that will work together to ensure adoption of a single, unified broadband wireless access industry standard. Members of BWIF will drive product roadmaps that will lower product costs, simplify deployment of advanced services, and ensure the availability of interoperable standards-based solutions based on Vector Orthogonal Frequency Division Multiplexing (VOFDM) technology. BWIF members agree to cross-license to other BWIF members, the technologies required to implement the standard on a worldwide, royalty-free basis.

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1. Introduction

This white paper addresses the possibility of 3rd Generation (3G) mobile cellular wireless systems as the basis for fixed broadband wireless service. Currently 3G systems are in the process of evolution from 2nd Generation (2G) systems [1-8]. The 2G technology introduced digital voice into mobile cellular wireless voice communication, together with the optimization and the resultant capacity increase that digital technology enables. In mobile cellular wireless communication, 3G is defined as the introduction of data services as well as improvements in basic technology, such as better speech coding techniques. Data rates associated with 3G are targeted to be as high as 384 kb/s, even 2 Mb/s.

In this white paper we compare different aspects of 3G technologies with the technology developed by the Broadband Wireless Internet Forum (BWIF) (known as Vector Orthogonal Frequency Division Multiplexing (VOFDM)) to provide fixed broadband wireless Internet access. For a service provider whose goal is to provide Internet services in a competitive manner with Digital Subscriber Loop (DSL) and cable, networking performance as well as the Media Access Control (MAC) and physical layer (PHY) performance are very important. In this introductory section we will discuss general issues concerning networking and provide a summary of the results in the white paper. In subsequent sections, we will compare MAC issues and performance, as well as different physical layer aspects of the two technologies, such as spectral efficiency, frequency reuse, coverage, multipath and narrowband interference performance, time/frequency division duplexing, spatial processing, and requirements for timing acquisition, complexity, power control, frequency offset, phase noise, and amplifier nonlinearity in detail.

The goal of a fixed broadband wireless Internet service provider is to offer high quality Internet services. In the next few years, due to established user experience with DSL and cable, two outcomes are likely: 1) users will expect to see service at a high data rate (>Mb/s) to them, and 2) a number of new service offerings will become commonplace in broadband Internet access. Two examples of new applications are Voice over IP and IP multicast. Voice applications will drive Quality-of-Service (QoS) expectations higher. As a result, a fixed broadband wireless Internet service will need to address QoS needs of a variety of residential and business users. High throughput requirements will not only be driven by applications that demand high throughput themselves, but also, by the user experience with higher speed alternatives (DSL and cable). For example, the speed of response to Web queries is extremely important, a low-speed Internet connection reduces productivity and enjoyment. It is well-known from wireline access alternatives that users who are used to high-speed access do not want to go back to lower speed alternatives.

CDMA trades off processing gain (low transmission rates) against interference and therefore gets a frequency reuse advantage in voice mobile cellular communications. There are two clear implications of this: 1) Broadband upgrades of CDMA will give up processing gain and therefore will be similar to single carrier CDMA systems. Currently, the downlink configurations of 3G CDMA systems operate on this principle. In reality, since they do not use an equalizer and rely on a rake receiver without despreading, the performance of such systems are even worse than single carrier QAM whose fading channel performance is proven to be worse than VOFDM via extensive simulations and field trials. 2) Or, if the goal would be to provide interference rejection with omnidirectional CPE antennas, the processing gain will have to be high and the available transmission rates very low. Currently, the uplink configurations of 3G CDMA systems operate on this principle. Additionaly, CDMA cannot operate satisfactorily with several high-rate users transmitting simultaneously. Consequently, the transmission rates become unacceptably low. The paper shows these rates and specifically spectral efficiency and system efficiency figures in detail in Section 7.

Looking at a number of 3G and 3G-based alternatives, such as Wideband CDMA (W-CDMA), cdma2000, High Data Rate CDMA (HDR), and Time Division–Synchronous CDMA (TD-SCDMA), we see that in addition to low user throughput rates, QoS guarantees cannot be delivered. There are two reasons for this. First, physical layer properties of CDMA prevent multiple high data rate users. In addition, the degree of interference tolerable in a CDMA system is limited. As a result, the base station needs to police system interference and therefore the number and the rates of users; potentially reducing the rate it allocates to an individual user. Obviously, this makes guaranteeing QoS impossible. We are aware that there are claims of QoS support in 3G and 3G-based alternatives, but we believe these claims should be approached with a skeptical mind. There are fundamental assumptions in the design of CDMA that are best suited to providing circuit-switched voice service to a user population with identical rates. With data, these assumptions are broken and, in addition to becoming inefficient, the resulting system cannot provide QoS guarantees. Considering the fact that HDR, developed by the inventors of CDMA for high rate data applications does not support QoS should be an indication of the inherent difficulty of supporting QoS with CDMA. We will show that the peak rates achievable by 3G techniques are low. In addition, CDMA does not allow multiple high-rate users simultaneously. This results in an inability to serve broadband needs. Furthermore, user experience will be poorer (e.g., Web response times will be longer).

One reason 3G technologies are under consideration for fixed broadband wireless Internet access is the fact that today, most fixed broadband wireless systems are designed with outdoor antennas, typically on the rooftop, and some may require professional installation. Professional installation, which typically needs to be financed by the service provider, presents one of the biggest contributors to the cost of a fixed broadband wireless access system. On the other hand, mobile cellular wireless voice systems are designed to operate with large coverage and with simple, omnidirectional antennas. Since fixed wireless service is a special case of mobile wireless, a question is whether it would be possible to use the 3G infrastructure to build fixed wireless services so that installation is trivialized and professional installation is not required.

In this white paper we show that there are ramifications of moving an antenna from an outdoor configuration to indoors, in terms of reduced data rate or a smaller cell size requirement. Smaller cell sizes, in return, imply higher infrastructure deployment costs. The numbers provided by an example in this white paper show that moving an antenna from a rooftop configuration to indoors while keeping the data rates constant reduces the cell size by an order of magnitude, and at the same time, can increase the infrastructure cost by two orders of magnitude. On the other hand, for example, user installable under-the-eave antennas result in a much smaller penalty, about 30% in terms of cell radius.

TD-SCDMA employs Time Division Duplexing (TDD) in order to be able to use transmit beamforming. There are several problems with this approach. First, downlink and uplink transmissions of all base stations need to be synchronized. This takes away the adaptive TDD advantage, removing any link efficiency gain due to the use of TDD. Second, a guard interval between downlink and uplink transmissions becomes necessary to mitigate the base station to base station interference, reducing link efficiency.

The VOFDM system uses transmit and receive diversity for spatial signal processing with almost equal performance to transmit and receive beamforming. On the other hand, there are implementation limitations with transmit beamforming. First, transmit beamforming is not suitable for multicast or broadcast, limiting MAC performance and link efficiency. In addition, transmit beamforming prevents IP multicasting. IP multicasting is a desirable new service for service providers. Second, transmit beamforming forces the use of TDD, which is inefficient compared to FDD. Third, in order to achieve a beamforming downlink, one needs to employ uplink bandwidth, reducing system efficiency. We conclude that transmit beamforming may be a suitable technique for circuit-switched applications, but it is not appropriate for packet-switched data applications.

Another important consideration is directional antennas. 3G Customer Premises Equipment (CPE) antennas are omnidirectional. Without directional antennas, the interference tolerance of a cellular system is impacted and the system capacity is reduced. To make up for this loss, frequency reuse needs to be reduced. This results in increased spectrum requirements. An example studied in this white paper indicates the spectrum increase can be as high as 6 times.

Inherently, CDMA has lower system efficiency in terms of b/s/Hz/sector. System efficiencies of various CDMA techniques employing omnidirectional CPE antennas remain much lower than that of VOFDM. In this white paper, we provide a comparison of these system efficiency figures based on the required system engineering. The best performer, due to the use of turbo codes and synchronous CDMA, is TD-SCDMA; but even its system efficiency is an order of magnitude less than that of VOFDM.

When one compares a number of physical layer properties of CDMA and VOFDM, it turns out that VOFDM is usually superior. For example, the multipath, narrowband interference, and impulse noise performance of VOFDM is better, with less stringent requirements on timing acquisition, complexity, and power control. On the other hand, the amplifier linearity requirement of CDMA is slightly lower and its frequency offset and phase noise performance are better. This is one area where CDMA has an advantage but there are various low-cost solutions to these problems with VOFDM.

The rest of the paper is organized as follows. Section 2 discusses MAC layer performance comparisons of CDMA technologies with VOFDM. Section 3 provides an analysis of the antenna location. Section 4 describes the disadvantages of TDD. Section 5 is a comparison of spatial processing techniques beamforming and diversity. Section 6 quantifies the spectrum penalty due to omnidirectional antennas. Section 7 compares system and spectral efficiencies of VOFDM and various 3G CDMA alternatives. Section 8 is a comparison of various physical layer and implementation properties of VOFDM and CDMA. Finally, Section 9 provides a summary and conclusions.

2. MAC Layer

In this section, we will review the limitations of the MAC layers of 3G proposals, in particular for broadband access. We start with W-CDMA and cdma2000, and then consider HDR and TD-SCDMA with comparisons to the DOCSIS MAC layer of the VOFDM system.

W-CDMA and cdma2000 have two modes of packet operation: 1) Random access in uplink and downlink channels (abbreviated as RACH and FACH respectively), which are common control channels, and 2) circuit switched access in uplink and downlink dedicated traffic channels [1-4], [9]. Random access is applied for traffic with short random packets. Suggested access scheme for uplink is slotted ALOHA. Slotted ALOHA has low delay and good throughput with small number of users. Its maximum efficiency is limited to 36.8% [10]. This is less than half of the efficiency of DOCSIS MAC layer (around 80%), used in the VOFDM system. With 36.8% efficiency, a maximum aggregate throughput of 44 kb/s can be supported in W-CDMA’s 120 kb/s RACH channel [9]. The random access packet mode in the uplink can be suitable only for low traffic loads with small packets, such as messaging applications.

Higher data rates (384 kb/s for outdoor mobile, 2 Mb/s for indoor [1-4], [9]) can be obtained through the use of dedicated traffic channels, to transmit long or frequent packets. The channel rate can be changed according to the system load as well as intra-cell and inter-cell interference conditions. When the user has no packets to transmit, the traffic channel is released but the control channel is kept to maintain the link layer and network layer connections. An activity timer defines the duration after which the dedicated channel will be torn down. Throughout the connection, the packets are sent in circuit switching mode. Circuit switching is extremely inefficient for bursty data traffic as discussed in the white paper, "Media Access Protocols: Circuit Switching to DOCSIS" [11]. In [11], the analysis for typical Web use shows that packet switching (as in DOCSIS) has 15X advantage in throughput as compared to circuit switching. Milder throughput degradations can be achieved with the help of the activity timers, but the efficiency of these timers is very low, as traffic is never predictable. Both W-CDMA and cdma2000 proposals will suffer from delays due to setting up and tearing down of dedicated channels. Finally, scalability is a major concern when all users are using the system for data. Activity timers and set-up/tear-down operations might cause a large number of states and overhead, imposing a limit on the number of users that can be supported. Neither of the proposals suggests an efficient and scalable solution for data access at broadband rates.

HDR mode has been proposed within cdma2000 [5], [12] as an efficient means of supporting high data rates in the downlink (Due to highly asymmetric nature of today's consumer services, HDR focuses on the downlink.) Uplink packet access of HDR is similar to that of cdma2000, so it is inefficient with limited access capacity as discussed above. Downlink packet transmissions are time division and possibly code division multiplexed, and the data rates of users are varied by varying their assigned slot lengths, maintaining a target SNR for each user and an interference level for the sector [5], [12]. This, in the end, penalizes some of the users with lower throughput and larger delays as they are allocated fewer slots. Consequently, user rates are policed according to interference, and the HDR system cannot provide any QoS guarantees or Service Level Agreements (SLAs).

TD-SCDMA uses the MAC layer from UTRA (UMTS Terrestrial Radio Access) TDD mode proposal [7]. Uplink and downlink channels are duplexed in time. Frames of 5 ms are divided into 7 slots, which can be assigned to uplink and downlink channels in any configurations from 1 uplink and 6 downlink slots to 6 uplink and 1 downlink slots. TD-SCDMA is a hybrid of TDMA and CDMA, in which users can be multiplexed in time and/or code domain.

In addition to the existing two methods in W-CDMA and cdma2000, TD-SCDMA provides a reservation-based packet transport mechanism. A resource request message is sent prior to transmission, and the physical channel is allocated depending on the nature of the traffic. The allocations can be permanent (with activity check) or based on time or based on the amount of data [7]. This is a DOCSIS-like demand assignment scheme, with actual packet switching feature with two important limitations:

- Reservation requests are sent in the RACH channel. Maximum number of RACH channels in the system is 8 [8]. This can impose a limitation on the contention channel. For instance, in the case of 2/5 time slot uplink/downlink ratio, 32 uplink channels can be formed with 16 codes. In this case, the contention region is limited to 25% of the resources.
- In the case of a collision, a request is repeated after a random backoff time. MAC controls the timing of retransmissions on the transmission time interval level, which is a radio frame of 10 ms [11]. Hence, the backoff time is a multiple of 10 ms.

We performed simulations to quantify the MAC layer efficiency of the TD-SCDMA system and to compare it with the performance of our DOCSIS over VOFDM (DOCSIS/VOFDM) system. We made simple modifications to our DOCSIS model to account for the two limitations of the TD-SCDMA system.We assumed 2/5 uplink/downlink ratio as a typical setting for asymmetric traffic assumption. This limits the uplink contention channel to 25% of the channel bandwidth. For both systems, we assumed the same channel bandwidth and the same reservation based scheduling; packet transmissions were non-persistent and retransmissions were based on binary exponential backoff. As traffic sources, we employed the variable packet length distribution in [13] with exponential interarrival times to model variable length IP traffic. Figure 1 shows the throughput-delay curves obtained by simulating the two systems. In the experiments, subscribers were subject to the traffic sources from [13] and the global system load was increased by increasing the number of users. For each load level, the average throughput was recorded considering all successfully received packets at the base station, and the result has been normalized with respect to the total available uplink bandwidth, as shown by the x-axis in the figure. The access delay corresponds to the time interval from the instant a packet was created at a subscriber until it was successfully received at the base station. The access delay was averaged over all received packets at the base station and shown as the y-axis of the figure.

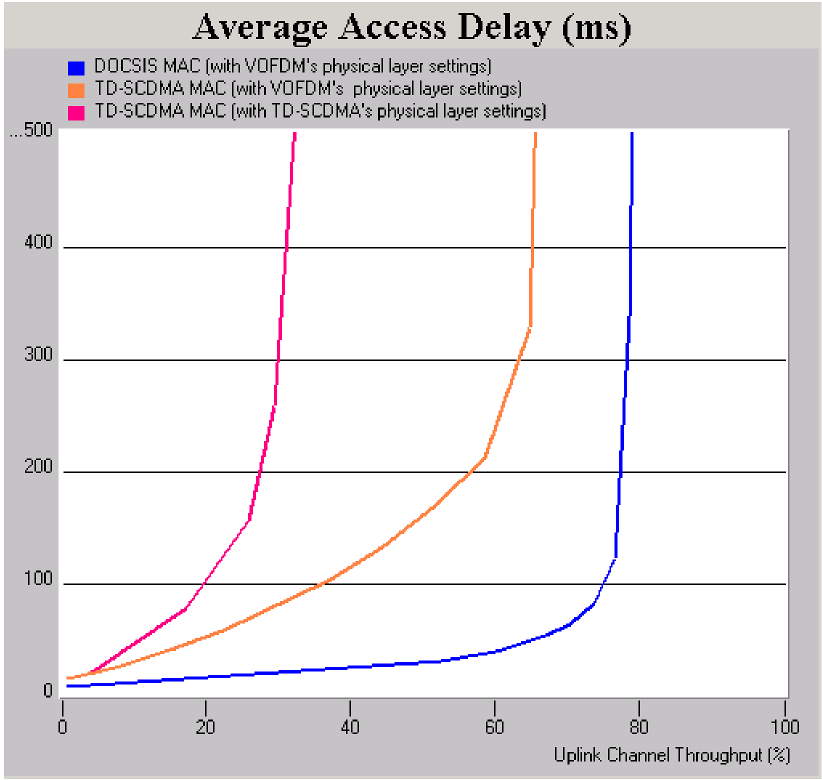

Figure 1: Comparison of DOCSIS/VOFDM and TD-SCDMA

As it can be inferred from Figure 1, concentrating on VOFDM physical layer settings for the time being (two curves on the right) the DOCSIS/VOFDM system outperforms the TD-SCDMA system. For example, considering a 100 ms delay goal, the maximum throughput of DOCSIS/VOFDM can be obtained as 80% while TD-SCDMA is limited to about 35%. This is due to the limited contention region in TD-SCDMA. Moreover, the access delay of the TD-SCDMA system is significantly larger than the access delay of the DOCSIS/VOFDM system. Similar throughput values (up to 60%) can be obtained with both systems, at a delay cost an order of magnitude larger for TD-SCDMA than for DOCSIS. This is due to increased backoff durations in TD-SCDMA. These two curves assumed identical physical layer parameters for both systems, to compare the access layer efficiency only. Since TD-SCDMA's channel rates are much lower than VOFDM, considering the system as a whole, the delay degradation is even further and available user rates are much lower as shown in Figure 1 (the curve on the left). In this case, the maximum throughput of TD-SCDMA at 100 ms target is 20% (compared to 80% for VOFDM). Also, final throughput value of the TD-SCDMA system is 30% of the uplink channel rate (compared to 80% for VOFDM).

Another important issue we would like to point out is the impact of Adaptive Transmit Beamforming (ATB) of TD-SCDMA on MAC. TDD systems, like TD-SCDMA, often incorporate ATB, which can be used advantageously on the downstream to direct antenna “beams” towards particular subscribers to overcome downstream path loss and perhaps building penetration loss. In some implementations, antenna “nulls” are steered to in-cell or out-of-cell interferers thereby improving the SINR at the subscriber’s receiver. However, ATB comes at a cost to the MAC layer: Directing an antenna beam to particular subscribers necessarily means that one or more other subscribers will not receive sufficient power to demodulate their received signal. This means that transmit beamforming severely limits and possibly precludes IP multicast and IP broadcast services. If these services are to be implemented in a system with ATB, then the base station will be required to simulate them via re-broadcast techniques. Re-broadcasting has a negative impact on downstream throughput and transmission delay. The impact may be severe if the multicast group is large. MAC messages requiring broadcast services, such as system information elements, will suffer similar inefficiency. One possibility to regain efficiency for IP multicast/broadcast messages is to not use ATB when these services are required. This has obvious disadvantages. Cell radius cannot be extended by the extra gain possible by ATB because it will not be present on all transmissions. Also, if ATB is employed to reduce the average out-of-cell interference levels, then the advantage will not be present when IP multicast/broadcast packets are transmitted.

All our comparisons show that existing 3G proposals can accommodate data at much lower rates with much lower MAC efficiency as compared to the DOCSIS/VOFDM system. In 3G, data is an “add-on service” for applications such as short message services or limited web access for emergency services. Whereas, the DOCSIS/VOFDM system targets and supports true broadband access.

In this section, so far we have considered and compared systems in terms of packet access for data applications. There is an increasing demand for services with QoS requirements and support of service differentiation. W-CDMA and cdma2000 have very poor QoS support, with negotiations only in terms of peak rate; and they are subject to limitations due to circuit-rate adaptation mechanisms to combat interference. HDR has an improved way of rate adaptation on the downstream via time division multiplexing but still, user rates are adaptively changed according to channel and interference conditions. In these systems bandwidth guarantees cannot be maintained, SLAs cannot be provided, users can be severely throttled or even unvoluntarily placed in an inactive state. DOCSIS has major advantages as a QoS framework, such as, ability to efficiently handle multiple service types for scheduling upstream traffic, support of QoS guarantees and Service Level Agreements (SLAs), fragmentation of data packets for controlled latency without violating stringent delay guarantees for real-time services, Payload Header Supression (PHS) for reduced overhead, etc. DOCSIS also has enhanced security, privacy and authentication as well as network management functions [10]. TD-SCDMA MAC specifications resemble DOCSIS, and claim to provide some similar QoS features (fragmentation, concatenation, PHS). However, this set of specifications is not as mature and robust as DOCSIS. In addition, since the basic interference limitations of CDMA are shared by all flavors of 3G CDMA, we question the ability of 3G-based technologies to deliver QoS, including TD-SCDMA although it may have a set of DOCSIS-like MAC specifications. Furthermore, DOCSIS chips have been developed, debugged, and heavily tested, and they have been widely deployed and verified by several vendors over the course of many years. A DOCSIS-like MAC implementation will likely take a comparable time.

3. Coverage

Although Customer Premises Equipment (CPE) with indoor antennas are very attractive from the viewpoint of reducing the installation effort, they are at a significant disadvantage in terms of coverage area or data rate. Reducing the coverage area substantially increases the infrastructure expense. Reducing the data rate means the system cannot provide broadband performance, leaving the fixed wireless system little advantage over incumbent dial-up services.

The following tables show Carrier-to-Noise (*C/N*) link budget typical for a VOFDM 7.4 Mb/s downstream data mode. This mode requires a *C/N* of 8 dB, based on its specific modulation and forward error correction profile. We require a fading margin of 5 dB with dual antenna transmit and receive diversity. At this point we assume the CPE antenna is on the rooftop at a height of 8 meters. With the parameters in the link budget below, the Sprint-B pathloss model results in a pathloss exponent of approximately 4.4.

Parameter	Units	
Transmit		
Headend Transmit Power	dBm	40
Headend connector/cable losses	dB	-4
Headend Antenna Directivity	dBi	18
Headend EIRP	dBm	54
Receiver		
Required C/N	dB	8
Fade Margin w/ Tx&Rx Diversity	dB	5
Required C/N with Fading	dB	13
Noise		
noise figure	dB	7
bandwidth	MHz	6
noise	dBm	-99.2
Required received level		
SU Antenna Directivity	dBi	15
Macrodiversity gain	dB	3
Required received level	dBm	-104.2
Building penetration loss	dB	0
Allowable pathloss	dB	**158.2**
frequency	MHz	2600
HE height	meters	30
SU height	meters	8
range -Sprint-B	km	8.0

Table 1: Typical link budget for the VOFDM downstream data mode at 7.4 Mb/s.

We will illustrate the system impact as the CPE "outdoor" antenna is progressively moved to easier installation configurations from the rooftop to under-the-eave, then to indoor in a windowsill, and then finally to a portable indoor unit with a low-gain antenna. The table below lists the parameters that are modified as the antenna is moved. The fade margin assumes a Rayleigh fading channel.

	Number of Receive Antennas	SU Antenna Gain (dBi)	Fade Margin (dB)	SU Height (m)	Building Penetration Loss (dB)
Rooftop	2	15	5	8	0
Under-the-eave	2	15	5	3	0
Indoor - window sill	2	12	5	1	6
Indoor - portable	1	3	10	1	12

Table 2: Antenna assumptions used in the analysis.

We assume that the indoor portable CPE has a broad beam, low gain antenna. In addition, the unit only has one antenna, increasing the necessary fade margin. From [14], 12 dB is an average value for building penetration loss. Penetration loss through a window is 6 dB less, for the indoor unit placed in a windowsill.

The link budget above demonstrated performance with a medium throughput rate of 7.4 Mb/s. In this study we will compare the performance of different CPEs for five data rates. Since we know their parameters and the required *C/N* values through extensive simulations and measurements, we will use five VOFDM settings for this purpose. The table below gives the five modes and the link budget parameters that are modified for each mode.

Data Rate (Mbps)	Required C/N (dB)	Bandwidth (MHz)	Max Tx Power (dBm)
19.2	18	6	40
14.7	15	6	40
7.4	8	6	40
4.9	4	6	40
1.1	8	1.5	43

Table 3: VOFDM data modes used in the analysis.

The required *C/N* values are shown for dual antenna receive diversity. The portable indoor CPE will require a 3 dB higher *C/N* s we assume it only has a single antenna, and its fade margin will be 5 dB higher because it does not have a diversity receiver.

Figure 2 below illustrates the performance for each type of CPE. The indoor portable CPE will only be able to achieve the highest data rate of 19.2 Mb/s at a range of 500 meters from the headend. In addition, with the indoor portable CPE, at the lowest data rate of 1.1 Mb/s the range only extends out to 1.4 km. With a rooftop configuration, the CPE can achieve a range of 13 km with a 1.1 Mb/s data rate, and a data rate of 19.2 Mb/s can be attained up to a distance of 4.7 km from the Headend. We would like to note that although this analysis has focused on the downstream, similar reduction in performance will apply to the upstream.

We understand and appreciate the issues associated with customer installability of CPE antennas. However, when customer installability is used on a desktop configuration, the associated penalty in data rate or coverage radius is enormous. We note that the windowsill antenna configuration is slightly better, while user installable under-the-eave antennas may provide the best compromise of coverage (range) and capacity.

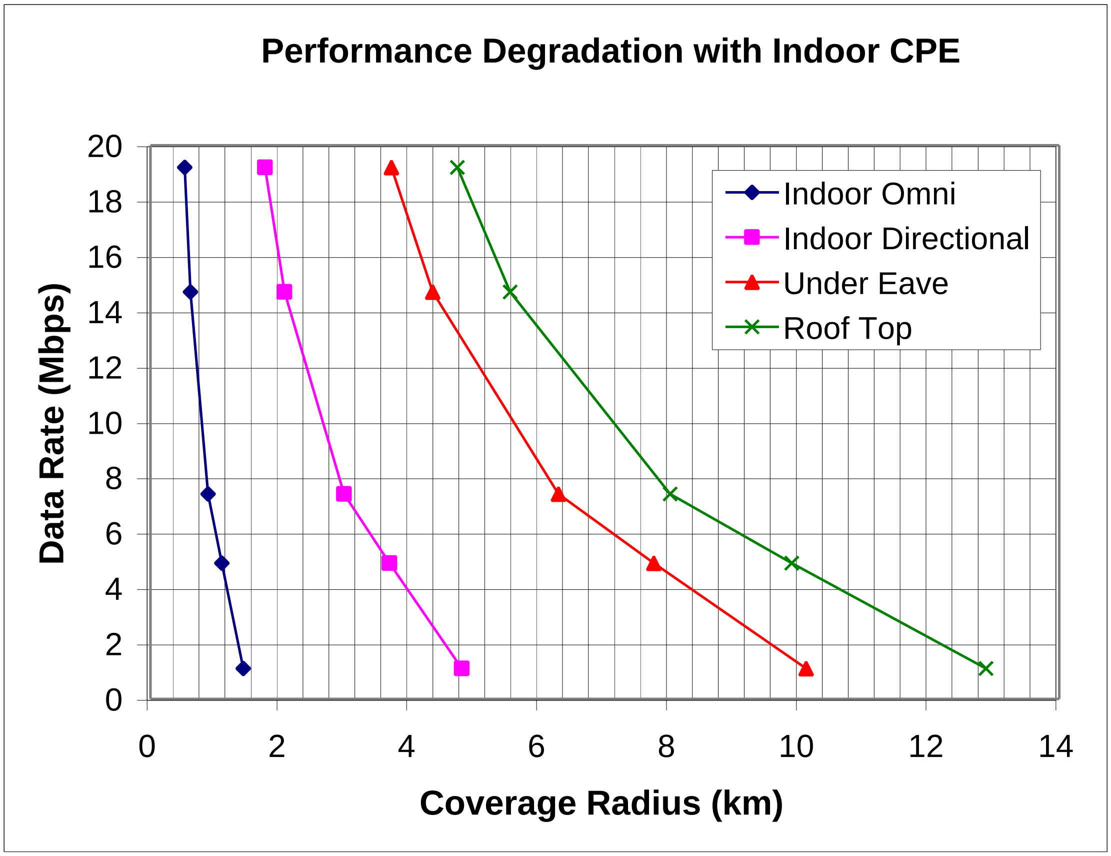

Figure 2: Performance degradation with indoor CPE.

Since the area relates to the radius in a squared fashion, the drastically reduced ranges lead to substantial increases in infrastructure costs. For example, the Chicago metropolitan area is approximately 3,000 km^2. The following table shows the number of base stations that would be necessary to provide 7.4 Mb/s per sector downstream service to the entire Chicago metropolitan area, assuming the propagation environment throughout Chicago is Sprint-B.

Install type	Cell Radius (km)	Cell Area (km^2)	Total Cells
Rooftop	8.0	201.3	15
Under-the-Eave	6.3	124.0	24
Indoor - Windowsill	3.0	28.0	107
Indoor - Portable	0.9	2.5	1208

Table 4: Infrastructure of different antenna configurations.

Due to the small number of cells, the costs to roll out service in Chicago are reasonable for rooftop and under-the-eave installations. The initial infrastructure costs are significantly higher for indoor windowsill antennas, since almost 10 times as many cells are required. The infrastructure costs associated with indoor portable CPE antennas are almost 100 times higher than for rooftop antennas, and approximately 50 times higher than under-the-eave installs!

4. Time Division Duplexing

The issue of Time Division Duplexing (TDD) versus Frequency Division Duplexing (FDD) is addressed in the white paper [15] in detail. There are a number of issues that need to be considered in the selection of TDD or FDD. We consider two of these most significant:

1. Need for network synchronization in TDD
2. Need for guard time in TDD

As explained in [15], due to the fact that the base station antennas are at more than 30 m height, there is a line-of-sight (LOS) connection from one base station to the other. This results in free-space propagation among the base stations while the base station to subscriber unit (and vice versa) transmissions remain Non-LOS (NLOS). This interference among base stations is the cause of the two results stated above.

First, because of the overwhelming power coming from a transmitting base station to receiving base station, base stations need to be operated synchronously. This synchronous operation requires all base stations transmit simultaneously and receive simultaneously. This takes away the ability to have an Adaptive TDD (ATDD) operation where each base station adapts its transmit/receive cycles with respect to traffic.

To illustrate this point, one can compare the co-channel interference figures of FDD and TDD systems. This issue is addressed in Section 5 of [15]. There, it is shown that with a 4x3 reuse scheme, and a cell radius of 5 miles, the Signal-to-Interference Ratio (SIR) of an FDD system is 21.7 dB, whereas for a TDD system, the corresponding SIR is –1.1 dB. The difference is due to the fact that for FDD, the co-channel interference is essentially due to the subscriber units that transmit in neighboring cells, whereas for TDD the base stations contribute to the co-channel interference. Since the base stations are at LOS, their contribution overwhelms the base station receiver under consideration.

One can calculate these values with parameters closer to those being discussed for 3G systems. Let us take a cell radius of 3 miles, and assume a frequency reuse pattern of 1x3. Performing the calculations in [15], the SIR of FDD is 19 dB, while that of TDD is 1.8 dB. QPSK requires 6 dB SIR. In order to reach a 6 dB SIR figure, the frequency reuse required by TDD needs to be increased to 7x3, resulting in a spectrum penalty of 7 times!

The second issue is the guard interval requirement in TDD. In order for the last part of the transmit signal from one base station to the other to cross the distance between two base stations, a guard time interval needs to be placed between downlink and uplink transmission intervals of the base stations. No transmissions take place during this interval. According to [8], there is a total 275 μs guard and synchronization interval in one TDD frame of the TD-SCDMA system. One TDD frame of this system is 5 ms long. This is a 5.5% overhead.

5. Spatial Processing

Spatial diversity techniques improve the performance of wireless systems. In this section we will compare two such techniques in terms of their performance, i.e., beamforming and diversity. The diversity techniques we consider are BWIF VOFDM diversity techniques of transmit delay diversity and receive diversity with optimal ratio combining. We will make comparisons based on simulations as well as providing general observations on the two techniques. Our comparisons will first concentrate on receive processing. We contend that receive processing operations for beamforming and diversity are similar and therefore their performance is comparable. For transmit processing, our simulations indicate some gain for beamforming against diversity, however, we will show that this gain is small. The limitation of beamforming techniques for broadband wireless Internet access arises from implementation. We illustrate in the sequel that while transmit beamforming may be a good technique for circuit-switched applications, it has serious limitations for packet-switched applications.

Receive Processing

The operations involved in receive beamforming and VOFDM receive diversity signal reception are very similar. In both cases, the receive processing proceeds as follows:

1. Signals are received on multiple antennas.

2. The received signals are correlated with a known signal structure. This signal structure may be a spectral spreading sequence, a training sequence, or training tones. The output of this correlation yields a channel response matrix.
3. The signal power, signal quality, channel magnitude and channel phase are estimated for each receive channel.
4. Those channel quality estimates are used for optimal channel combining.

There may be minor differences in the procedures and the results between Single Carrier QAM, VOFDM, and CDMA due to slightly different structure of the signals, however the receive processing and associated processing gain should be identical.

Transmit Processing

During this subsection, we will limit the discussion to the comparison of two-element transmit diversity and transmit beamforming. Figure 3 shows the effective directivity gain for a diversity transmitter operating in a flat unfading channel against a single element directional antenna. In this simple case, two transmitters are transmitting at maximum power rather than one. The signal for the second antenna is a delayed version of the first one, which just creates a small amount of additional delay spread. This additional delay spread is removed by the VOFDM receiver. The delay-diversity prevents coherent signal interference from the two transmitters. As a result, the signal received at a subscriber unit will be 3 dB higher than for one transmitter.

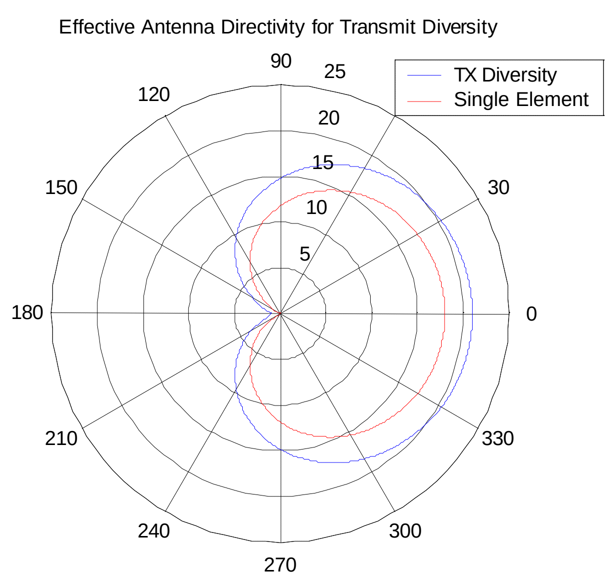

Figure 3: EIRP gain for transmit diversity.

Figure 4 shows the gain in directivity that can be achieved by transmit beamforming for a flat unfading channel. In this example two power amplifiers are transmitting at maximum power. Their signals are sent to transmit antennas spaced 10 wavelengths apart. As a result the antenna array pattern has 40 lobes as predicted by theory. Assuming that the transmitted signals arrive at the subscriber unit with the same phase, the gain at boresight over a single antenna is 6 dB.

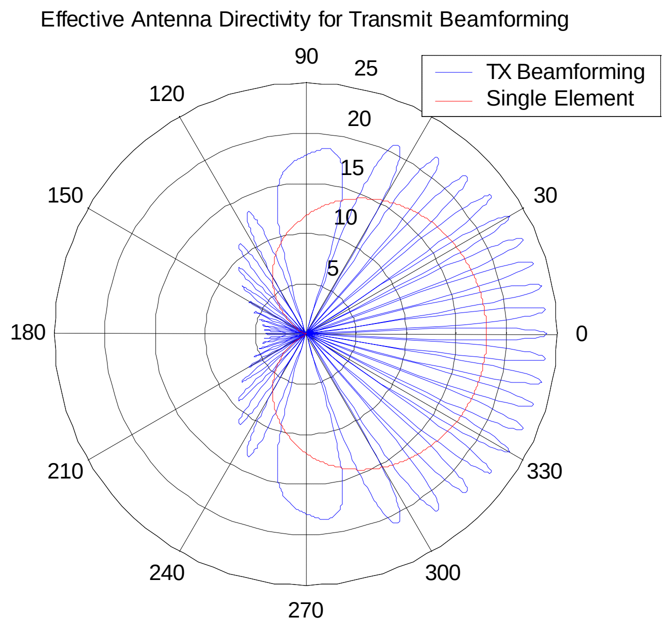

Figure 4: EIRP gain for transmit beamforming.

This comparison indicates that under the best operating conditions for both systems, transmit diversity provides a 3 dB gain over a single antenna system, while transmit beamforming offers a 6 dB gain. The difference between transmit diversity and transmit beamforming is only 3 dB under these idealized conditions. Note the narrow beam that result due to beamforming. Clearly, this narrow beam has increased sensitivity to time varying multipath.

In field deployments, the idealized flat unfading channel conditions will not hold. To figure out the performance improvement in field deployments by both techniques, a series of computer simulations were carried out. describes the simulation parameters. The modulation rate determines the bandwidth of the downstream signal. Wider bandwidth signals offer improved robustness to fades due to frequency diversity. The Sprint/Stanford SUI-3 multipath fading channel model was chosen because it yields the deepest fades of all Sprint channel models. The simulation was run over a period of 1200 seconds at a sample rate of 1000 Hz, yielding 1.2 million power measurements to obtain probability distributions.

Each tap was simulated as the summation of 50 sinusoids with random phase and random frequency. Delay Diversity of 0.33 μs was used for the Transmit Diversity case. The transmit beamforming used estimates of relative phase between the two channels. The phase of the second channel was shifted to maximize the resulting power seen at the CPE.

Simulation Parameter	Parameter Value
Modulation Rate and Type	6 MHz, 64 QAM
Sprint Channel Type	Sprint/Stanford SUI-3 Tap magnitudes: 0, -5, -10 dB Tap delays: 0, 0.5 1.0 usec Tap K factors: 0 0 0 Tap Doppler Rates: 0.4, 0.4, 0.4 Hz Tap Antenna Correlation: 0.25, 0.25, 0.25
Simulation Duration	1200 seconds
Simulation Sample Rate	1000 Hz
Number of Rays simulated for each tap	50
Doppler Spectrum Shape	Rounded
Number of Antennas	2
Transmit Diversity Type	Delay Diversity of 0.33 usec
Transmit Beamform Type	Phase-Shift Beamforming to maximize RX Power
Transmit Beamform Update Period	1 msec

Table 5: Simulation parameters.

Figure 5 shows a plot of relative received power vs. time for three different transmission schemes during a 15 s period of the simulations:

1. Single antenna transmission
2. Transmission using two channel transmit diversity
3. Transmission using beamforming to maximize the downstream received power.

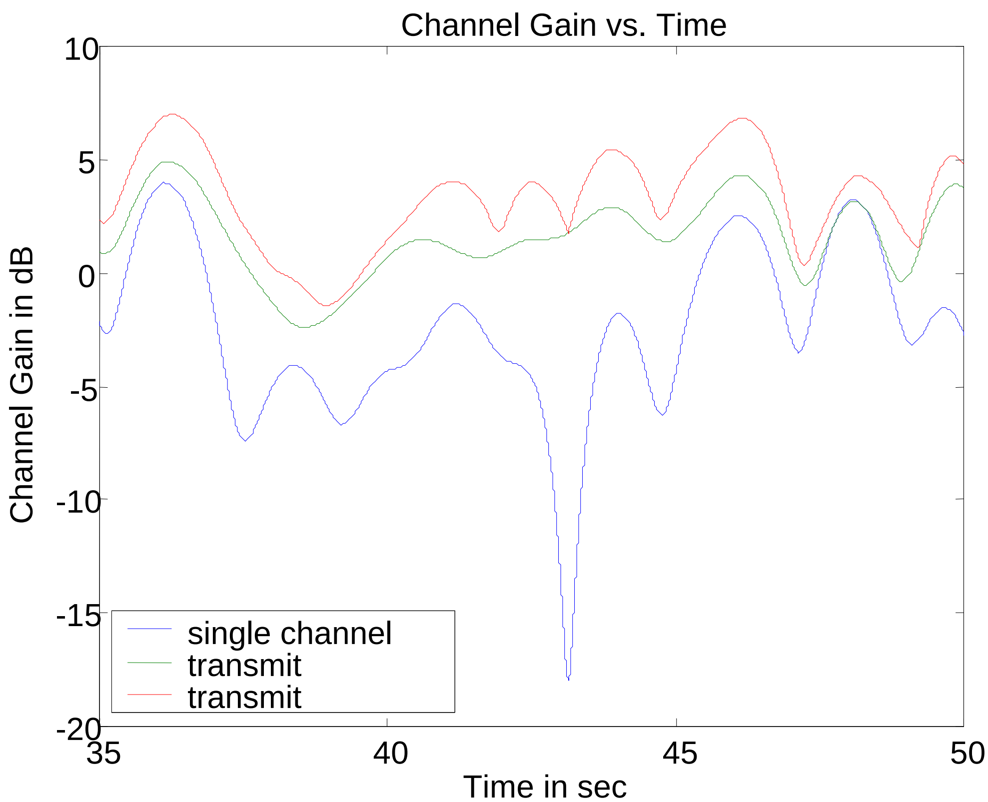

Figure 5: Sample time-domain power.

This 15 s period of the simulation is presented to illustrate both transmit diversity and transmit beamforming are effective during a deep fade, providing in this case more than 20 dB gain. Slightly more gain is achieved by transmit beamforming. However, the important observation is that deep fade performance of the two systems is essentially similar.

We can summarize by looking at averages obtained during the simulation. Figure 6 shows the distribution of received power at the subscriber unit using the three different transmission schemes. The reference power level is the average power received from an single-channel transmitter.

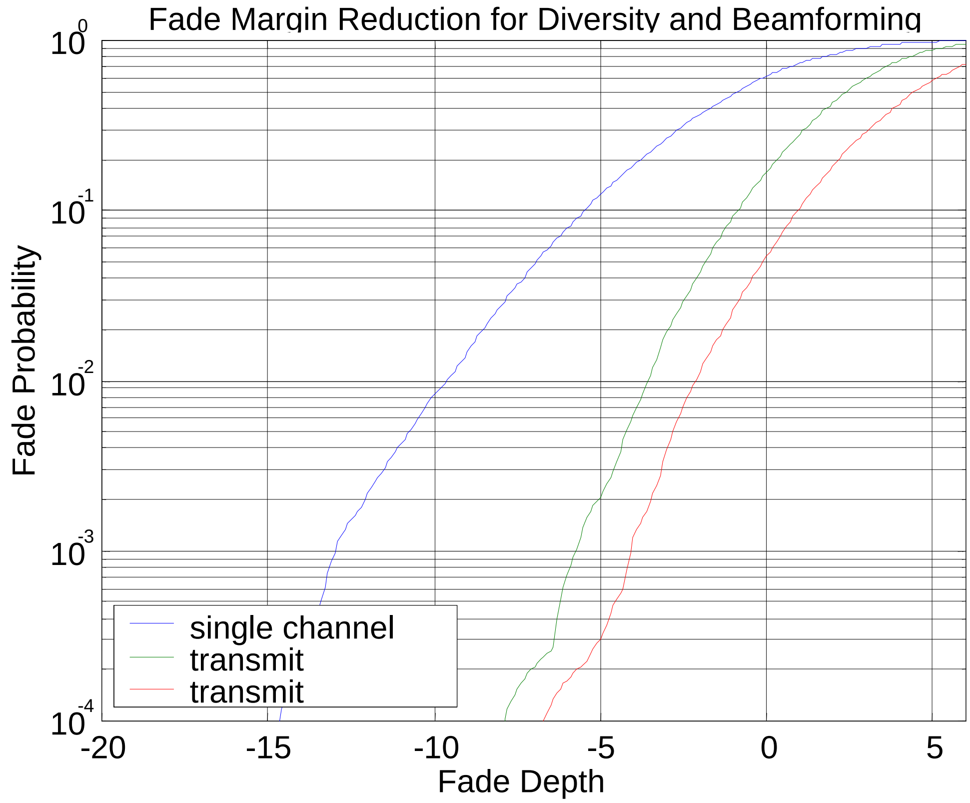

Figure 6: Received power distributions.

summarizes the gain obtained from transmit diversity and transmit beamforming against a single antenna system.

Transmit Type	.999 Fade RX Power	.999 Fade Gain over Single Antenna TX
Single Antenna	-12.9	0
Transmit Diversity	-5.7	7.2
Transmit Beamforming	-4	8.9

Table 6: Relative performance (in dB) of transmit diversity and transmit beamforming against single antenna.

For three-nines fades, transmit diversity achieves a gain of 7.2 dB, while transmit beamforming achieves 8.9 dB over a single antenna element. The difference of 1.7 dB is insignificant for link budget considerations with link budgets of the order of 140-180 dB.

We should point out that as the number of antennas in the transmit beamforming system is increased, the gain due to beamforming will increase. However, there are practical limitations to the number of antenna elements in a transmit beamforming system due to 1) cost of extra transmitters and amplifiers, 2) wind loading conditions on antenna towers.

In addition, there are implementation limitations with transmit beamforming that makes it unsuitable for packet-switched applications (data applications).

The first issue was discussed in Section 2 on the MAC Layer. Transmit beamforming severely limits IP multicast and IP broadcast services since directing an antenna beam to a subscriber implies there will be subscribers who will not receive sufficient power. In addition, MAC broadcast messages will suffer. There are two potential solutions to this problem: 1) rebroadcasting, which severely reduces link efficiency, 2) not to use transmit beamforming for broadcasts, which defeats the purpose of beamforming since it will not provide any advantage against coverage or cochannel interference.

The second issue is the fact that we are not aware of a way to implement transmit beamforming with FDD in a fading multipath environment. Beamforming requires the knowledge of the channel response matrix. With FDD, the transmit and the receive channel are at widely separated frequencies, therefore any information from the receive channel is almost useless for the transmit channel. Learning the receive channel parameters indirectly from the receiver requires a periodic transmit training interval which has an associated link efficiency problem.

On the other hand, in TDD the receive and the transmit channels are the same, therefore the channel response matrix for the transmit beamformer can be learned from the receive transmissions, as long as the receiver knows it has been scheduled a downlink transmission. There are two ways to ensure that the channel response matrix is current for each downtream signal transmission, the TDD base station must schedule an upstream burst before transmitting data downstream, or the channel matrix estimates must be maintained via regular upstream messages (such as power control messages). Both techniques add overhead to the upstream channel, particularly when there are a large number of subscribers per sector.

In summary, although transmit beamforming is a powerful tool for circuit-switched TDD applications where the base station gets periodic estimates of the channel so that it can continuously optmize its beamforming weights; for packet-switched applications where the upstream traffic is stochastic in nature, the base station must use upstream bandwidth to optimize its downstream transmissions. Upstream bandwidth is usually a more precious resource than downstream bandwidth, so the minor improvement in downstream signal strength is achieved at a very high cost in terms of link efficiency and implementation complexity.

Finally, we wish to reiterate that even though the link efficiency and the implementation complexity problems of transmit beamforming are ignored, transmit or receive diversity essentially captures the performance gain that transmit or receive beamforming achieves as illustrated by the simulations presented in this section.

6. Capacity

In Section 3, we have discussed performance based on *C/N*, the coverage limited case. The tolerance to self-interference will dictate the system capacity since the frequency reuse pattern is set based on the allowable interference level. The portable indoor CPE with an omnidirectional antenna will receive interference from other cells in all directions. Whereas, a CPE with a directional antenna will reject interference out of the antenna main lobe. Therefore, with a system using the portable indoor CPE, the other interfering CPEs must be kept much farther away. This results in much higher frequency reuse factors, and much lower system capacity.

The following analysis will illustrate the impact of CPEs with an omni-directional antenna on system capacity. The total carrier-to-interference ratio is defined as

$$\frac{C}{I} \equiv \frac{C}{\sum_k I_k} \tag{1}$$

where I_k represents the interference power from *k*th interfering cell. Assuming equal transmit power from all Headends (HE) and an omni-directional antenna at the HE and CPE, the total Carrier-to-Interference ratio can be expressed by

$$\frac{C}{I} = \frac{R^{-a}}{\sum_k D_k^{-a}} \tag{2}$$

where R is the distance between the CPE and the main HE, D_k is the distance between HE from each interfering cell and the CPE, and a is the path loss exponent.

Assuming hexagonal cells; if we approximate the distance between the SU and each of the six HE's from the first tier of interfering cells as D, and ignore the interference contribution from the interfering cells which are further away [16]

$$\begin{aligned}\frac{C}{I} &= \frac{R^{-a}}{6 \cdot D^{-a}} \\ &= \frac{1}{6 \cdot \left(\frac{D}{R}\right)^{-a}}\end{aligned} \tag{3}$$

where D/R is termed the co-channel reuse ratio [14].

As the next step, we include the contributions of the second and third tier interferes, assuming for the time being, omnidirectional antennas. We approximate the distance from each of the six second and each of the six third tier interfering HE's to the CPE as $2D$. Therefore

$$\begin{aligned}\frac{C}{I} &= \frac{1}{6 \cdot \left(\frac{D}{R}\right)^{-a} + 12 \cdot \left(\frac{2D}{R}\right)^{-a}} \\ &= \frac{1}{\left(6 + 12 \cdot 2^{-a}\right)\left(\frac{D}{R}\right)^{-a}}\end{aligned} \tag{4}$$

For hexagonal geometry $D/R = \sqrt{3N}$, where N is the frequency reuse factor [14]. From this and (4) for C/I, we determine N as a function of D/R

$$N = \frac{1}{3}\left[\left(6 + 12 \cdot 2^{-a}\right)\frac{C}{I}\right]^{2/a} \tag{5}$$

In order to take directional antennas into account, (4) can be modified to provide an approximation for the performance of a sectorized cell system with directional HE and CPE antennas

$$\begin{aligned}\frac{C}{I} &= \frac{G_C \cdot R^{-a}}{\left[\sum_{k=1}^{6} G_{I,k}\right] D^{-a} + \left[\sum_{k=1}^{12} G_{I,k}\right] (2D)^{-a}} \\ &= \frac{1}{\left[\left(\sum_{k=1}^{6} \frac{G_{I,k}}{G_C}\right) + 2^{-a}\left(\sum_{k=1}^{12} \frac{G_{I,k}}{G_C}\right)\right]\left(\frac{D}{R}\right)^{-a}}\end{aligned} \qquad (6)$$

where $\frac{G_{I,k}}{G_C}$ is the relative antenna gain between the *k*th interfering HE and the CPE. For a three-sector cell with a directional HE antenna, the resulting expression for frequency reuse factor with an omnidirectional CPE is

$$N = \frac{1}{3}\left[\left(3.9 + 7.7 \cdot 2^{-a}\right)\frac{C}{I}\right]^{2/a} \qquad (7)$$

For a CPE with a 20° antenna, the resulting expression for frequency reuse factor is

$$N = \frac{1}{3}\left[\left(0.4 + 1.6 \cdot 2^{-a}\right)\frac{C}{I}\right]^{2/a} \qquad (8)$$

With (7) and (8), we can determine the increase in frequency reuse which corresponds to a decrease in capacity

$$\text{Capacity Improvement} = \left[\frac{\left(3.9 + 7.7 \cdot 2^{-a}\right)\left(\frac{C}{I}\right)_{Omni}}{\left(0.4 + 1.6 \cdot 2^{-a}\right)\left(\frac{C}{I}\right)_{Directional}}\right]^{2/a} \qquad (9)$$

Since the portable indoor CPE only has a single antenna and because of the lack of diversity combining in a multipath environment, the required *C/I* will be 8 dB higher. As a result, with α = 4.4 (from the link budget in Table 1), the capacity per base station of a system with CPEs using directional antennas is 6 times greater than a system with CPEs using omnidirectional antennas.

As an example, we will use the same 7.4 MHz downstream data mode, 30 m base station height, 3m and 1m CPE antenna height, Sprint-B propagation environment. We will then calculate the frequency reuse for a dual-channel 20° receiver and a single-channel omni receiver.

Receiver Type	**Diversity Directional**	**Single Omni**
Required Single-Channel Unfaded *C/I*	13	13
Adjustment for Number of Receiver Channels	-3	0
Fade Margin	5	10
Macro Diversity Gain	-3	-3
Required Mean *C/I*	12	20
Frequency Reuse Factor	2.7	16.5

Table 7: Required frequency reuse factors from (7) and (8).

This example shows that at the 7.4 Mb/s data rate, a diversity directional receiver can support a 3x3 frequency reuse, and a single omnidirectional receiver will require a 17x3 frequency reuse.

The figure below illustrates a 3x3 frequency reuse pattern.

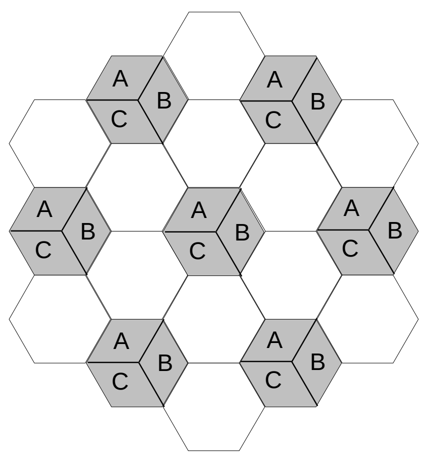

Figure 7: A 3x3 frequency reuse pattern.

In order to tessellate – to connect without gaps between adjacent cells – the geometry of hexagons is such that the number of cells per cluster, *N*, can only have values which satisfy

$$N = i^2 + ij + j^2$$

where *i* and *j* are non-negative integers [14]. Therefore, the nearest reuse factor greater than or equal to 17 would be 19 ($i = 3$, $j = 2$). The figure below illustrates a reuse factor of 19x3.

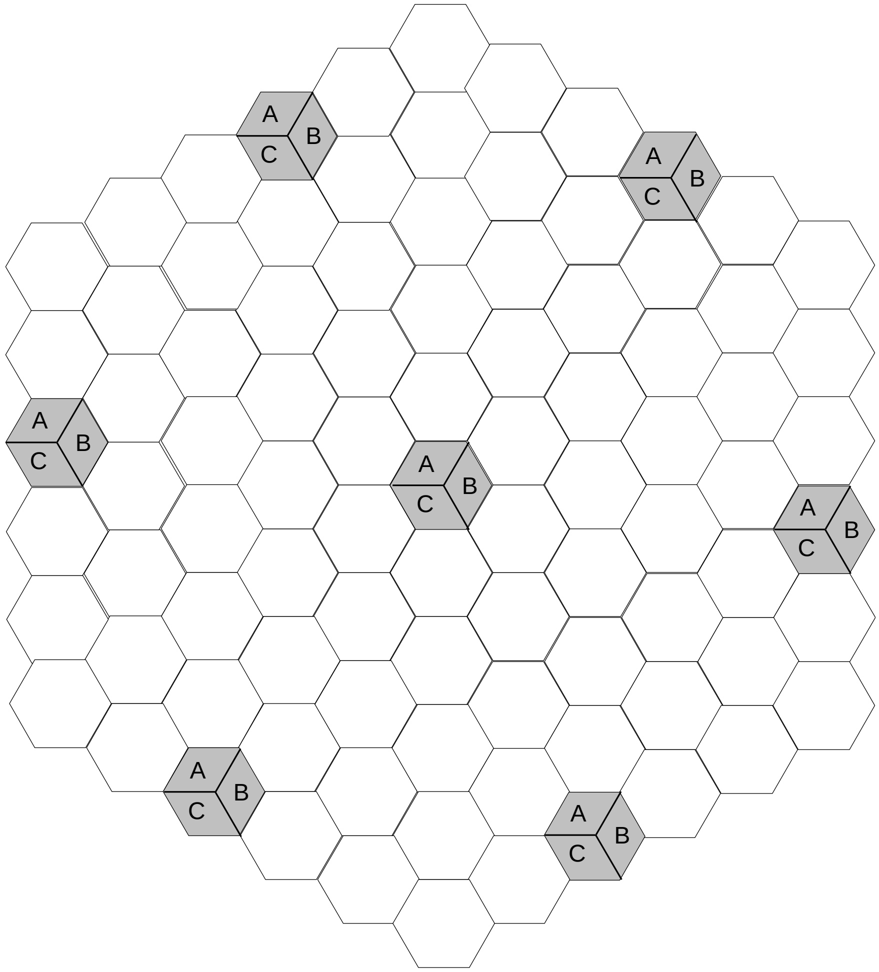

Figure 8: A 19x3 frequency reuse pattern.

In the above analysis, simplifications were made in order to derive equations that give us a feel for performance differences between omnidirectional and directional CPE antennas. Now we present results from a frequency reuse simulation, which incorporates many more effects. For example, log-normal shadow fading with a standard deviation of 8 dB and macrodiversity are included. In addition, CPEs are uniformly distributed in the cell. The figure below illustrates the coverage probability as a function of *C/I* with omnidirectional antenna CPEs. Simulations were run for a variety of frequency reuse patterns. Note that the figures represent the probability of CIR in the cell being larger than the x-axis, not the coverage for CIR equal to the x-axis.

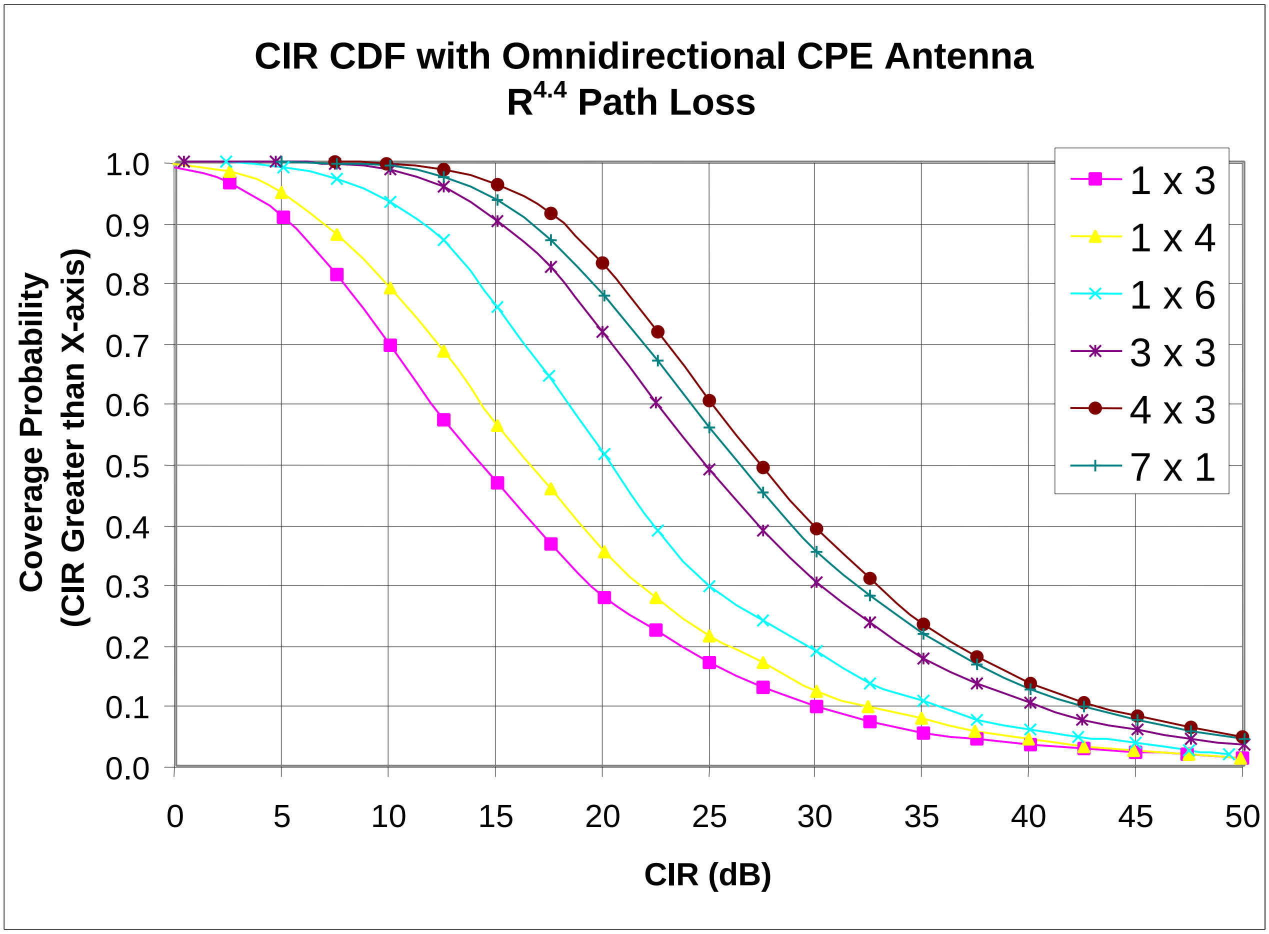

Figure 9: CDF of *C/I* with omnidirectional CPE antenna. The vertical axis corresponds to Prob(CIR in cell with given reuse configuration > x-axis).

We require a *C/I* of 20 dB. From the figure above, with omnidirectional antennas, even with a 4x3 frequency reuse, only 82% of the cell would be covered.

The following figure illustrates the coverage probabilities with directional antennas.

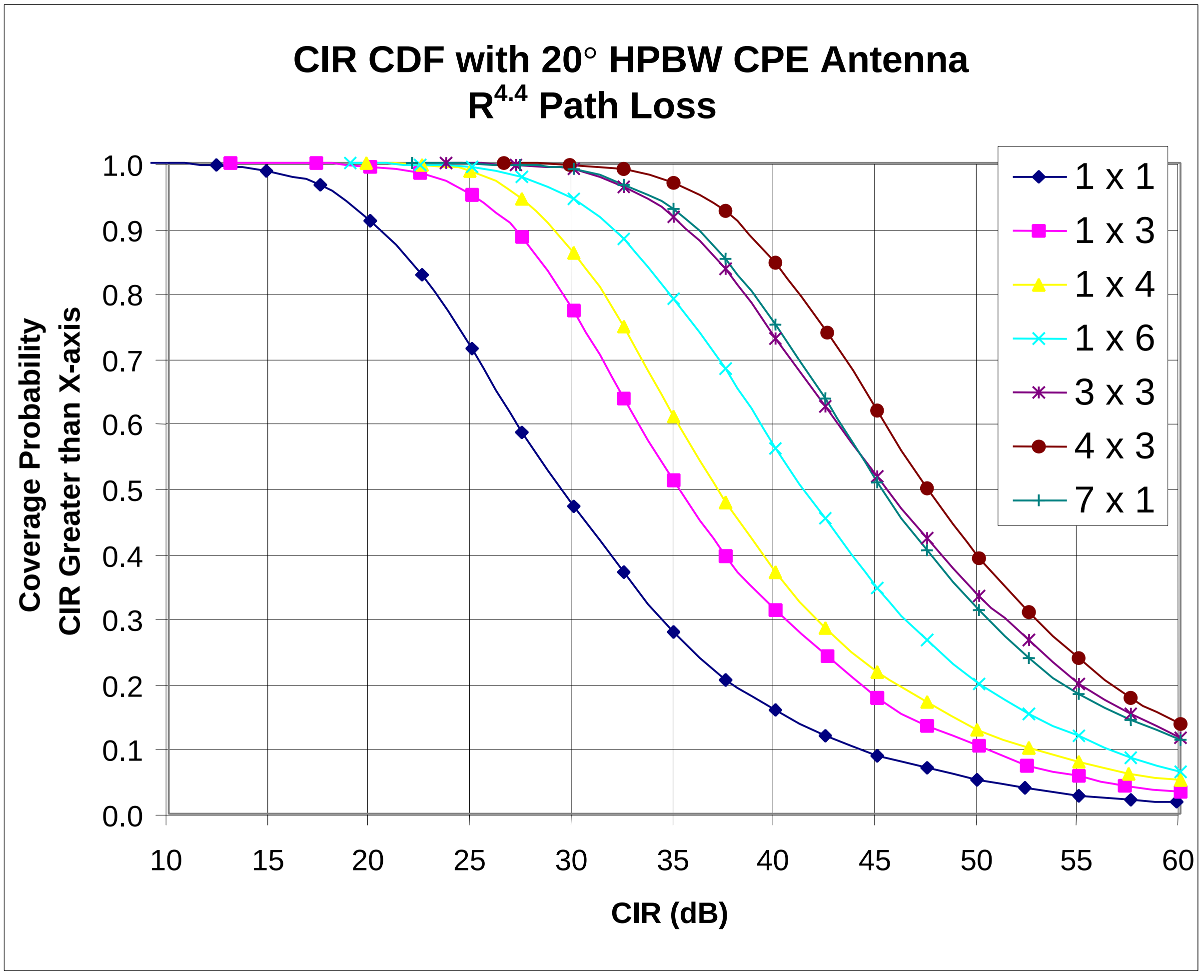

Figure 10: CDF of *C/I* with 20° HPBW CPE antenna. The vertical axis corresponds to Prob(CIR in cell with given reuse configuration > x-axis).

We see that with directional antennas we achieve a tremendous reduction in reuse factor. With 20 dB *C/I*, complete cell coverage can be obtained with all frequency reuse schemes except 1x1. A required *C/I* of 12 dB results in almost complete cell coverage with a reuse factor of one.

7. Spectral and System Efficiency

The capacity of CDMA and TDMA systems has been a topic of considerable debate in the literature for mobile telephony [17-22]. In this section we will apply the analysis for mobile telephony to estimate the spectral efficiencies of broadband CDMA systems and compare them to VOFDM.

In [22], simulations were performed to measure the efficiency of a CDMA mobile phone system. The quality of the calls is dictated by the level of the required Signal-to-Interference ratio (SIR).

Since a CDMA mobile phone system is typically designed with a frequency reuse of one (achievable with large processing gain), the system is interference limited. Therefore, increasing the required SIR means that less interference is allowed in the system which reduces the capacity or efficiency of the system. In [22] efficiency is defined as the number of simultaneously active users of a particular bit rate, divided by the available channels. Results are presented in [21] which illustrate the decrease in efficiency as the required SIR is increased. The figure below is adapted from the results given in [22].

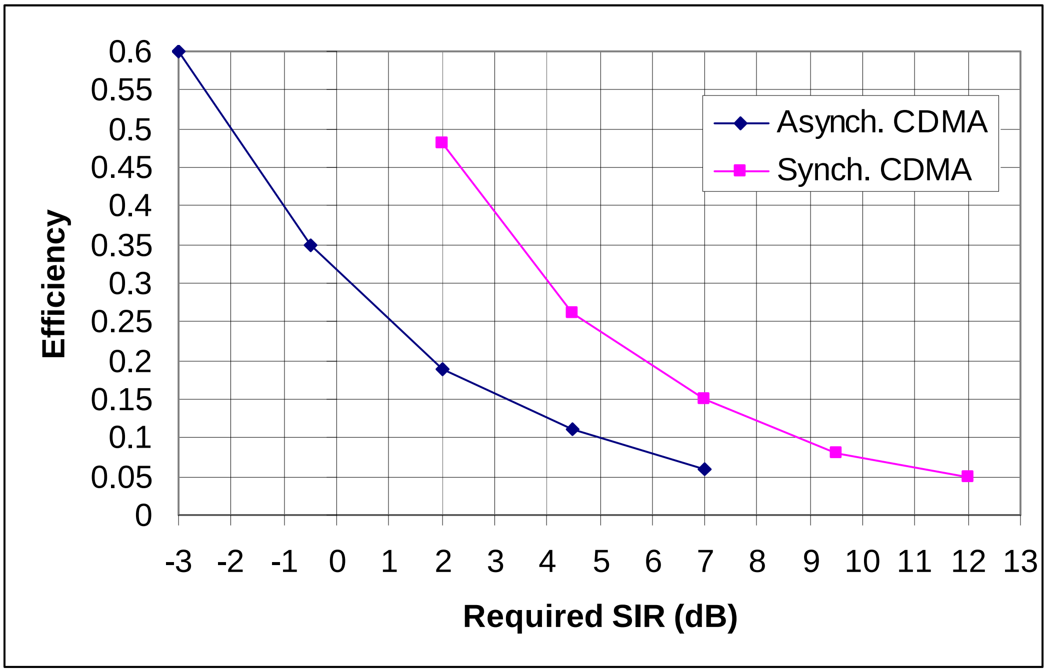

Figure 11: Efficiency of synchronous and asynchronous CDMA system.

We can apply these results to broadband systems by using the required SIR corresponding to the modulation and coding schemes for these systems. First we will illustrate how to estimate the spectral efficiency of an IS-95 CDMA system. IS-95 uses PSK modulation with one bit/symbol efficiency and half rate convolutional encoding. The required E_b/N_0 for AWGN is 4 dB [23]. Recalling E_b is energy per information bit, we convert E_b/N_0 to normalized SIR as given below.

$$\mathrm{SIR} = \frac{\mathrm{Eb}}{\mathrm{No}} + 10\log\left(\frac{\mathrm{bits}}{\mathrm{symbol}} \cdot \mathrm{code\ rate}\right)$$
$$= 4 + 10\log\left(1 \cdot \frac{1}{2}\right) = 1\,\mathrm{dB}$$

Using the figure above, an SIR of 1dB yields an efficiency of 0.25 for an asynchronous CDMA system according to the "Asynch. CDMA" curve. In order to meet out-of-band emission requirements, spectral shaping must be employed. We have assumed a spectral shaping factor of 1.2 for these calculations. We convert this to system spectral efficiency (b/s/Hz) as follows

$$\text{Spectral Efficiency} = \frac{\text{Users}}{\text{Channels}} \cdot \frac{\text{bits}}{\text{symbol}} \cdot \text{code rate} \cdot \frac{1}{\text{spectral shaping}}$$
$$= 0.25 \cdot 1 \cdot \frac{1}{2} \cdot \frac{1}{1.2} = 0.10$$

where Users/Channels is the Efficiency of [22] as described above. In the table below we present modes for two broadband CDMA systems: HDR [12] and TD-SCDMA [6, 8]. These systems use turbo codes to achieve lower required E_b/N_0. The HDR system is an asynchronous CDMA system. Accordingly, we use the "Asynch. CDMA" curve in the figure above. The TD-SCDMA system is synchronized. Therefore the "Synch. CDMA" curve is used to determine the efficiency. However, as described in [22], the synchronous CDMA system was simulated assuming perfectly synchronized and orthogonal codes resulting in no intra-cell interference. Therefore, these results will be an upper bound for a practical synchronous CDMA system.

	Modulation	bits/ symbol	Coding Rate	spectral shaping	Eb/No	Normalized SIR	Efficiency (users per channels)	System Spectral Efficiency (bits/sec/Hz)
IS-95 [9]	BPSK	1	0.5	1.2	4	1.0	0.25	**0.10**
HDR [10]	QPSK	2	0.25	1.2	2	-1.0	0.35	**0.15**
	QPSK	2	0.5	1.2	3	3.0	0.18	**0.15**
	8PSK	3	0.5	1.2	5.5	7.3	0.05	**0.06**
	16QAM	4	0.5	1.2	6.5	9.5	0.025	**0.04**
TD-SCDMA [10,11]	QPSK	2	0.5	1.2	3	3.0	0.3	**0.25**
	8PSK	3	0.5	1.2	5.5	7.3	0.15	**0.19**
	16QAM	4	0.5	1.2	6.5	9.5	0.1	**0.17**

Table 8: System spectral efficiency comparisons of IS-95, HDR, and TD-SCDMA.

The conclusion we draw from this analysis is that TD-SCDMA has significantly better system spectral efficiency as compared to HDR and IS-95. With this observation, we close the spectral efficiency analysis based on Figure 11 and [22]. In the rest of this section, we will derive the spectral efficiency of TD-SCDMA for high rate applications. We will then compare that figure with the corresponding one for VOFDM.

The spectral efficiencies in the table above are based on a mobile telephony simulation. In such a system, many users are distributed uniformly in cells, all with a large spreading factor for large processing gain. In this manner, a CDMA system can achieve a frequency reuse factor of one. The TD-SCDMA system uses a spreading factor of 16 for low data rate modes. Our spectral efficiency analysis would apply to the system operation in this manner. In this mode, the maximum data rates of TD-SCDMA will be limited to less than V.90 analog modems as illustrated by Table 9. Consumers can at present access the Internet with analog modems with a number of free Internet service providers. Therefore, it is more important to compare system efficiencies with high data rate modes.

Processing Gain	Downlink Data Rate (4 slots, 16QAM) Mbps	Uplink Data Rate (3 slots, QPSK) Mbps
1	1.126	0.422
2	0.563	0.211
4	0.282	0.106
8	0.141	0.053
16	0.070	0.026

Table 9: Uplink and downlink maximum data rates of TD-SCDMA.

To calculate the maximum data rates of TD-SCDMA we first describe the burst and frame structure of the TD-SCDMA system in Table 10 [8]. We also calculate the spectral efficiency in terms of coded symbols/sec/Hz with a spreading factor of 1.

TD-SCDMA Parameter [12]	Value	Units
Subframe Length	5.00E-03	sec
Burst Length	6.75E-04	sec
Slots/Frame	7	
Frame Efficiency	0.95	
Data Symbols/Burst	704	symbols
Usable Symbol Rate	9.86E+05	symbol/sec
Bandwidth	1.60E+06	Hz
Efficiency (PG=1)	0.62	symbol/sec/Hz
Code Rate	0.5	
Efficiency (PG=1)	0.31	coded symbol/sec/Hz

Table 10: Burst/frame structure and the spectral efficiency of TD-SCDMA.

Note that the rates and the spectral efficiency figures tabulated on Table 9 and Table 10 are based on the frame structure only, and are independent of previous results based on [22].

Consider a coverage limited scenario for calculating the maximum data rates for TD-SCDMA. QPSK modulation will be used on the uplink since it requires the least SNR. Since we have more transmit power on the downlink than uplink, we will set the downlink modulation to 16QAM. We consider a traffic scenario whereby the downlink requires roughly three times the throughput as the uplink. Therefore the downlink will be allocated 4 time slots per frame and the uplink will be allocated 3 time slots per frame. This results in a downlink to uplink throughput ratio of 8/3. With this scenario, the maximum data rate with a processing gain of 16 is 70 kb/s on the downlink and 26 kb/s on the uplink. With a processing gain of 1, the maximum data rate is 1.1Mb/s on the downlink and 422 kb/s on the uplink. These maximum data rates for all processing gains are given in Table 9.

To provide high data rates in TD-SCDMA, the spreading factor is reduced by powers of 2 from 16 down to 1. A number of issues arise in this mode. High data rate modes have little or no processing gain for signal separation from interferers. This is equivalent to a TDMA system and will require comparable reuse factors. In other words, if a high data rate user is near a cell boundary, it will cause a large amount of interference into neighboring cells. A code reuse or frequency reuse factor would be required comparable to a TDMA system. Therefore, the system spectral efficiencies in the table above would be reduced by the reuse factor. In another approach, which maintains the system spectral efficiency, high data rate users could be restricted to the interior of the cell. But then, large capacities cannot be made available under coverage guarantees [24].

A significant problem arises with signal detection in high data rate mode. As previously stated, with a processing gain of one, the signaling of TD-SCDMA is comparable to Single Carrier QAM (SC-QAM) systems. However, the rake receiver will perform worse than a linear equalizer in a multipath environment with no processing gain. Therefore link performance in TD-SCDMA will be worse than SC-QAM and substantially worse than VOFDM. In addition, with an omnidirectional antenna the delay spread will be much longer than VOFDM with a directional antenna. And without receive diversity the CPE will experience much deeper fades requiring more fade margin. This will further worsen SNR performance in a TD-SCDMA system.

As described in the previous section, we calculate the required *C/I* in a fading environment for VOFDM and for TD-SCDMA.

	Mode	Required Single Channel Unfaded C/I	Adjustment for Number of Receiver Channels	Fade Margin	Required C/I
	BW (MHz) Data (Mbps)				
VOFDM	6 5.7	8	-3	5	10
	6 8.5	13	-3	5	15
	6 22	24	-3	5	26
	6 7.4	13	-3	5	15
TD-SCDMA	QPSK	3	0	10	13
	8PSK	7.3	0	10	17.3
	16QAM	9.5	0	10	19.5

Table 12: Required *C/I* for VOFDM and TD-SCDMA.

With the values for required *C/I* in fading environment, we can generate the required reuse factor from the coverage probability figures (Figure 9 and Figure 10) in the previous section. We choose the 90% coverage probability as the metric for comparison of the two systems. We pick the reuse factor from Figure 9 and Figure 10 based on 90% coverage probability and Required SIR with Fading from the above table. With the spectral efficiency and the reuse factor, we calculate the system spectral efficiency. The results are given in the table below.

	mode		Modulation (bits/symbol)	Spectral Efficiency (bits/sec/Hz)	Required SIR w/ fading	Frequency Reuse Factor	System Spectral Efficiency (bits/sec/Hz)
VOFDM	BW (MHz)	Data Rate (Mbps)					
	6	5.7	2	0.94	10	1	0.94
	6	8.5	4	1.41	15	1	1.41
	6	22	6	3.70	26	3	1.23
	6	7.4	4	1.22	15	1	1.22
TD-SCDMA	QPSK		2	0.62	13	7	0.09
	8PSK		3	0.92	17.3	12	0.08
	16QAM		4	1.23	19.5	> 12	< 0.10

Table 13: System spectral efficiency of VOFDM and TD-SCDMA.

The VOFDM system provides better than 10 times system efficiency compared to TD-SCDMA.

8. Physical Layer Properties of VOFDM and CDMA

In this section, we consider the physical layer attributes of typical OFDM and CDMA systems and specify the advantages or disadvantages of either system. Due to practical limitations existing in a real-world implementation, the performance of OFDM and CDMA are significantly different. These limitations include channel impairments such as multipath and time variation, non-white noise and interference, system limitations such as timing and latency restrictions, complexity, cost, and power consumption. In the following, we shall compare the VOFDM-based radio specified by BWIF (Broadband Wireless Internet Forum) and a typical CDMA system with respect to a variety of such impairments and limitations.

- **CDMA versus SCM TDMA/FDMA**

The original purpose of CDMA was to provide a multiple access system that is more tolerant of interference compared to Single Carrier Modulation (SCM) TDMA/FDMA systems. This was in exchange of losing spectral efficiency since with a frequency reuse of one, a CDMA network must operate at far less than 100% loading[1] in order to meet the required performance (see Section 7). For current CDMA systems this translates to moderate data rates.

On the other hand, a broadband system requires high data rate channels for maximum efficiency. Since it is not feasible to just increase the CDMA chip rate due to bandwidth and spectral efficiency limitations, broadband CDMA systems need to assign many code channels to each user and operate close to 100% loading.

In addition to having frequency reuse and spectral efficiency issues, it can be shown that a 100% loaded CDMA signal *is a unitary linear transformation* of a SCM signal whose symbol rate is the same as the CDMA chip rate. If we assume that similar channel estimation techniques are used in the two cases, this is equivalent to saying that the two signals would have the same error statistics under any linear estimation method in time-invariant channels and Gaussian white noise. Moreover, in general, the receiver for 100% loaded CDMA system *cannot perform any better* than the corresponding SCM receiver.

[1] A CDMA cell is at P% loading if P% of the code channels have been assigned. In particular it is 100%loaded if all the code channels are used to transmit data.

In order to show the above claim, let s^1 be the baseband samples of a CDMA signal with spreading factor of G and 100% loading, and s^2 be the baseband samples of a SCM signal with the same total power. We can represent these signals as

$$s^1_{Gt+k} = \frac{1}{\sqrt{G}} \sum_{j=1}^{G} q_{Gt+j} w_{kj} p_{Gt+k}$$
$$s^2_{Gt+k} = q_{Gt+k}$$

for k = 1,…, G, t = 1, 2, …, where q_k are the data symbols, w_{kj} is the *k*th chip of the *j*th orthogonal spreading code, and p_k are the scrambling PN code chips. This formulation can be explained as follows: Let $\mathbf{w}_j = (w_{1j}\ w_{2j}\ \ldots\ w_{Gj})^T$ be the *j*th codevector. Each codevector $\mathbf{w}_j$ is multiplied by a different bit q_{Gt+j} to be transmitted. Each element of $q_{Gt+j}\ \mathbf{w}_j$ is a chip, the *k*th element is to be transmitted at time $Gt+k$. Before transmission, each chip is multiplied by a scrambling PN codechip p_k or p_{Gt+k} so that the contribution of the *j*th code at time $Gt+k$ is the *k*th element of $q_{Gt+j}\ \mathbf{w}_j\ p_{Gt+k}$. There are G codes and they are all transmitted at the same time, so that the resultant signal at time $Gt+k$ is proportional to $\sum_{j=1}^{G} q_{Gt+j} w_{kj} p_{Gt+k}$. The proportionality constant is $1/\sqrt{G}$ for normalization. The above can be simplified as

$$S_t^1 = \begin{bmatrix} s^1_{Gt+1} \\ \vdots \\ s^1_{G(t+1)} \end{bmatrix} = \frac{1}{\sqrt{G}} Diag(p_{Gt+1}, \ldots, p_{G(t+1)}) \underbrace{\begin{bmatrix} w_{11} & \cdots & w_{1G} \\ \vdots & \ddots & \vdots \\ w_{G1} & \cdots & w_{GG} \end{bmatrix}}_{W} \underbrace{\begin{bmatrix} q_{Gt+1} \\ \vdots \\ q_{G(t+1)} \end{bmatrix}}_{Q_t} = H_t Q_t$$

$$S_t^2 = \begin{bmatrix} s^2_{Gt+1} \\ \vdots \\ s^2_{G(t+1)} \end{bmatrix} = \begin{bmatrix} q_{Gt+1} \\ \vdots \\ q_{G(t+1)} \end{bmatrix} = Q_t$$

Note that $p_k p_k^* = 1$ and W is a unitary matrix. Hence, $S_t^1 = H_t S_t^2$ where H_t is a unitary transformation; $H_t H_t^* = H_t^* H_t = I$, and it can be said that s^1 is a unitary transformation of s^2.

Since a unitary transformation does not change the statistics of Gaussian white noise, any linear estimation algorithm in white noise would result in the same estimation error for both signals. Moreover, any detection method applied to s^1 (CDMA) can clearly be applied to s^2 (SCM) as well resulting in the same error statistics, while the reverse is not necessarily true. This is due to the fact that s^1 needs to be processed in blocks of G symbols while s^2 can be processed either every symbol or in blocks. Consequently, the optimum detection algorithm for CDMA *cannot perform any better* than the optimum method for SCM. This is based on the implicit assumption that the same channel estimates are available for the two systems and the signals are not affected by any nonlinearity. Note that the two signals have different statistics and as shown later in this section, have very different PMPRs (Peak-to-Mean Power Ratios).

In a similar manner, we can show that a CDMA signal with a spreading factor of G and $M\,K$ code channels is a linear unitary transformation of a CDMA signal of the same total power with spreading factor of G/K and M code channels.

The result of above discussion is that for high data rate usage it makes sense to use lower processing gain and fewer code channels for better receiver performance. Moreover, at high data rate, the performance and efficiency of a CDMA system approaches that of a SCM system even though its implementation is more complex.

- **Channel Fading and Time-Selectivity**

The performance of both OFDM and CDMA systems deteriorate in a time-selective channel. Consider the case where the Doppler frequency, f_D, is small compared to the CDMA symbol rate and the OFDM burst frequency. In other words, we have

$$CDMA\ Symbol\ Rate = \frac{CDMA\ Chip\ Rate}{Spreading\ Factor} >> f_D$$

$$OFDM\ Burst\ Freq. = \frac{OFDM\ Symbol\ Rate}{FFT\ Size} >> f_D$$

Then, under flat fading (frequency non-selective) channel conditions, the performance of both receivers will be worse than the AWGN case by almost the fading margin. That is to say, with similar FEC schemes and symbol constellations, OFDM and CDMA have similar coded Bit Error Rates (BERs) for the same E_b/N_o. The implicit assumption is that optimal channel estimation algorithms have been used and the signals are not affected by any nonlinearity.

Now, let us assume that both systems require the same frequency bandwidth, W. This means that the CDMA chip rate and OFDM symbol rate are roughly equal to W. Then the above conditions imply that if the CDMA spreading factor is less than the OFDM FFT size, which is often the case under BWIF VOFDM specifications, then the CDMA system is less sensitive to time variations than the VOFDM counterpart. Reducing the OFDM burst (FFT) size will improve the situation, but on the other hand will limit the delay spread that the OFDM system can handle as explained below.

We should point out that for fixed wireless networks the maximum Doppler frequency will be in the order of 2 Hz, and the above conditions are easily met for both systems. Moreover, for the existing CDMA specifications such as IS95, 3GPP W-CDMA, cdma2000, HDR, and TD-SCDMA, the CDMA pilot symbol rate, which is needed for channel estimation, is of the same order as OFDM burst frequency. So overall, for the systems subject to our study CDMA holds no advantage. TD-SCDMA, in particular, transmits pilot symbols in a short interval every burst with a burst frequency of about 1.5 KHz. Therefore, its channel estimation is in fact more sensitive to fast fading than VOFDM. See [8], [12], [24], and [25].

Note that an additional implication of CDMA symbol rate being of the same order as OFDM burst rate is that *each* CDMA code channel will need more time (in the order of spreading factor) to transmit the same amount of information compared to an OFDM system with similar symbol constellation. Hence, under these conditions the throughput delay is significantly longer for the CDMA network.

- **Multipath and Frequency Selectivity**

Multipath delay spread:

OFDM systems are specifically known to be robust with respect to multipath propagation. This is in particular true if the OFDM burst cyclic prefix is at least as long as the multipath delay spread. Furthermore, the BWIF VOFDM standard specifies n training tones among the OFDM tones for the purpose of estimation of the multipath channel coefficients, where n is the size of the cyclic prefix. Naturally, both the cyclic prefix and the training tones are part of the overhead.

We will shortly make a comparison of OFDM and CDMA in terms of multipath delay spread resistance. But we first wish to state that the VOFDM system is designed to tolerate 7 μs of delay spread while thousands of measurements carried out by AT&T Labs, Motorola, Sprint, and Cisco using directional antennas have never indicated a delay spread value larger than 3 μs. Thus, we are confident that the multipath performance of the VOFDM system is excellent. In the following, we will also show, working from the fundamentals, that VOFDM has inherently better multipath performance as compared to CDMA.

For a given design, the maximum delay spread Δ that can be tolerated by the OFDM receiver is less than n ($\Delta \leq n$). Hence, to increase robustness of the OFDM system with respect to delay spread, one must increase n. In order to keep the overhead constant, one must increase the OFDM burst size by the same proportion. But increasing the burst size, or reducing the burst frequency, increases sensitivity of the OFDM system with respect to channel time-variation, frequency offset, and phase noise, as stated above.

On the other hand, a CDMA system poses no system-based restriction on the length of the delay spread. In fact, any limitation would be a direct result of the specific implementation such as buffer sizes.

Every CDMA system uses a rake receiver structure composed of N rake fingers to coherently detect and combine at most N different received signal paths. Hence, the rake receiver architecture limits the number of paths that can be combined to the number of fingers, while OFDM estimates the multipath frequency response and hence takes into account the energy of all paths within the delay spread limit. When the multipath channel is composed of more than N non-negligible distinct transmission paths, the CDMA system uses only a portion of the received signal energy for the purpose of detection and can achieve a worse performance than OFDM. The unused portion of the received signal will in fact act as interference.

BWIF VOFDM systems use directional antennas at the subscriber end, which reduce the length of delay spread. Hence, these systems are robust with respect to delay spread length for typical fixed wireless applications. As mentioned above, OFDM systems are also better than CDMA systems in detecting the energy of all multipath components for a given delay spread. Therefore, one can say that regarding multipath delay spread, BWIF VOFDM performs better than a typical CDMA system.

Multipath Self-Interference:

As mentioned earlier, CDMA rake receiver achieves perfect diversity gain from multipath reception if it can perfectly decouple the different paths. In practice however, each path acts as interference for other paths. This interference becomes especially significant if the CDMA signal is transmitted over many code channels or the spreading factor is small.

More precisely, let I be the sum of interference from other sources, assumed to be white noise, P be the transmitted signal power, S be the received signal power, G be the spreading factor, M be the number of code channels for this signal, and H_i be the channel gain for the *i*-th path. Then, E_s/N_o, where E_s is the received energy per symbol and N_o is the received interference power density at the output of the rake[2], is given by

$$\frac{E_s}{N_o} = \frac{\sum_i H_i^2 P}{\left(\frac{\sum_{i \neq j} H_i^2 H_j^2}{\sum_i H_i^2} M\, P + I \right) \Big/ G} = \frac{G\, S}{x\, M\, S + I}$$

$$\text{with} \qquad x = \frac{\sum_{i \neq j} H_i^2 H_j^2}{\left(\sum_i H_i^2 \right)^2}$$

From the above equation, it is clear that even when $I = 0$, i.e. no outside interference is present, E_s/N_o would still be a <u>non-zero</u> value equal to $G/x\,M$. Clearly, the multipath self-interference will be most significant if $G/M = 1$, in other words when the spreading factor is equal to 1 or the signal is using all the existing code channels. Note that with a spreading factor of 1, CDMA simply becomes a SCM system.

The following figures in particular show the significance of the multipath interference for a simple test case, where the multipath is composed of 2 Rayleigh fading paths with equal average power.

Such a case can particularly be experienced in urban areas or in regions where reflections from mountains can occur by a receiver with an omnidirectional or wide-beam antenna. In fact, the same test case has been specified by various mobile CDMA and TDMA standards. Based on Figure 12, in the absence on any other interference, raw BER of a CDMA signal using more than 40% of the code channels is more than 0.5% for all spreading factors (up to 4.5% for a fully loaded system). For Ricean channels, it can be shown that this figure increases to 1% BER or more. For conventional FEC schemes these raw BER figures translate to 10^{-5} codeword error rates or more. Note that this error rate is exclusively due to multipath self-interference when any other form of interference is absent, in other words is a lower bound on error rate for such channel conditions. On

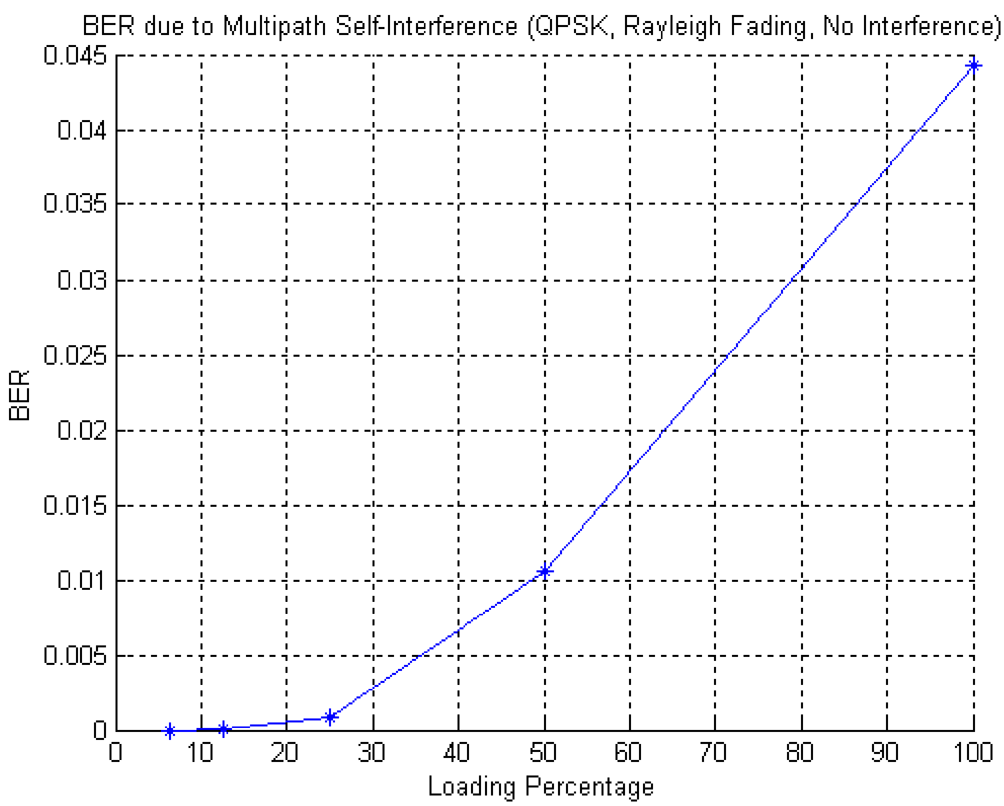

Figure 12: CDMA raw BER due to multipath self-interference.

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[2] Note that E_s is equal to (Received-Power / Symbol-Rate) and N_o is equivalent to (Interference-at-Rake-Output/Chip-Rate).

the other hand, BWIF VOFDM receiver has ideal performance (i.e., no error) under such conditions. This is particularly significant for high data rate systems where codeword error rates of 10^{-6} and 10^{-7} are required. Figure 13 shows the simulated Noise-to-Signal ratio at the output of rake receiver, i.e. $a\, M/G$, for various loading factors.

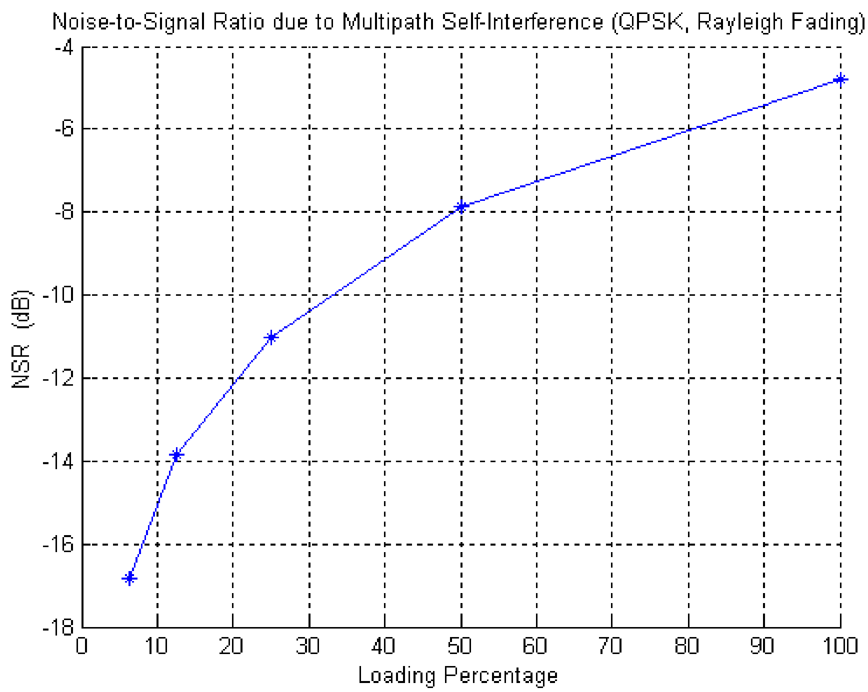

Figure 13: CDMA Noise-to-Signal ratio due to multipath self-interference.

CDMA multipath self-interference can be equalized by using MUD (Multi-User Detection) based rake receiver/equalizers. See [27] for an introduction to various MUD-based equalization methods and architectures[3]. The implementation of these algorithms is however very complex. Moreover, in most cases the optimized algorithm can still not perfectly equalize the channel and eliminate the self-interference, and this is true even in absence of external noise. Furthermore, one of the primary advantages of CDMA over TDMA systems was that CDMA receivers did not require equalizers.

[3] These algorithms are combination of successive or parallel cancellation techniques used in MUD, and decision-feedback or linear equalization methods.

On the other hand, multipath does not cause any self-interference for OFDM systems, which is a very significant advantage of such systems. Note that existence of the cyclic prefix prevents any inter-burst interference. In addition, OFDM frequency-domain equalization is very simple in comparison and ideally can achieve perfect channel equalization.

- **Narrowband Interference**

Without coding OFDM will be more sensitive to narrowband interference because a strong narrowband interference could corrupt certain data tones and result in a substantial increase in raw BER. On the other hand, a CDMA receiver spreads the narrowband interference over the whole bandwidth.

With optimal channel coding and interleaving, OFDM outperforms CDMA in the presence of narrowband interference. If the interference is sufficiently narrow such that it can corrupt only a few tones, adequate interleaving and coding can ensure that the errors are corrected and coded BER does not increase at all. But, because of averaging (despreading), coded BER of a CDMA receiver will increase proportional to the increase in raw BER. It should be pointed out that the mentioned narrowband interference is typically due to the carrier frequency power in analog transmissions, and hence covers only a few OFDM frequency tones as specified by the BWIF VOFDM standard.

An example of such interference seen in practice is the video interference. Experimental results have shown the robustness of the BWIF VOFDM system with respect to such interference.

- **Impulse Noise**

OFDM spreads the energy of an impulse noise over an OFDM burst. This means that instead of a few symbols being lost the noise level slightly increases over a burst, which may not cause any increase in the error-rate.

On the other hand, CDMA absorbs the energy of an impulse noise over a few CDMA symbols that will be lost. For low data rates, coding and interleaving will correct the errors, but for high data rates this can translate into an increase in coded BER. Note that for high data rates, the average impulse noise interval covers more than a few symbols.[4]

- **Amplifier Nonlinearity**

One of the most well-known disadvantages of OFDM is its high PMPR (Peak-to-Mean Power ratio). The high PMPR is caused by the summation of many sinusoids in the transmitted waveform. The resulting time-domain waveform has a probability distribution that is nearly Gaussian. A high PMPR means that the transmitter RF power amplifier needs to have a working point with adequate backoff from the saturation point such that the probability of the signal being clipped is negligible. If PMPR increases, the backoff needs to be increased by the same amount. For the BWIF VOFDM system the backoff is in the order of 10 dB, provided that no PMPR reduction algorithm is used.

This 10 dB backoff for VOFDM appears to be large compared with the 2 or 3 dB backoff required for a single-carrier QPSK signal. However wide-bandwidth CDMA signals, with large constellations sent over multiple code channels and/or multiple carrier channels, suffer from the same problem, at nearly the same level of magnitude.

In Figure 14, we compare the minimum PMPR with probability distribution of a VOFDM signal with 512 carriers to the PMPR distribution of a QPSK modulated wideband CDMA signal with 1, 2, 4, 8, and 16 codes. These results hold for 1, 2, 4, 8, and 16 carriers, or the combinations of codes and carriers. These PMPR probability distributions were calculated for baseband samples for both the VOFDM system and the multi-code QPSK system. Note in the figure that the distribution for a single code QPSK does not appear; it is a constant modulus signal, with a baseband PMPR of 0 dB. As the number of codes increases from 2 to 16, the PMPR distribution rapidly approaches the distribution for VOFDM. See [27] for a more detailed analysis of PMPR of CDMA systems.

[4] Narrowband interference in frequency-domain is the dual of impulse noise in time-domain. Nevertheless, OFDM has better performance in both cases because for high data-rates, symbol interval is much shorter than the average impulse noise interval and the average narrowband interference bandwidth is also much smaller than the OFDM burst rate.

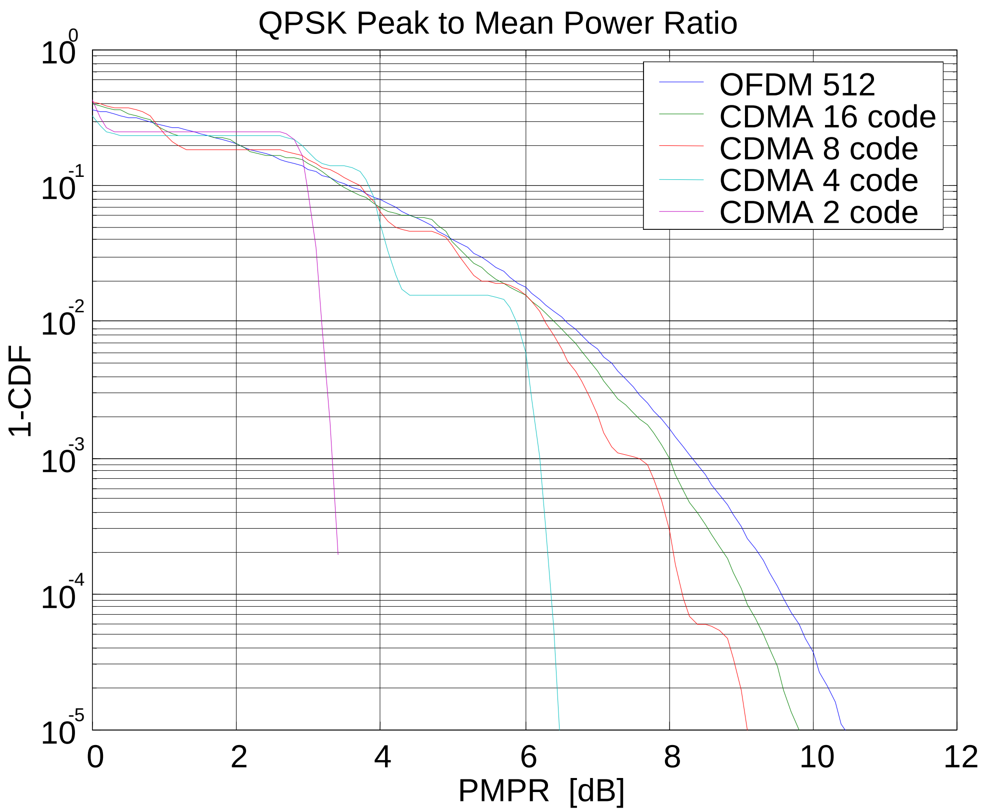

Figure 14: Cumulative distribution of VOFDM and CDMA signal PMPR for spreading factor of 64 and QPSK modulation.

The above figure clearly shows that CDMA PMPR increases with the number of codes. The CDMA PMPR also increases with constellation size, particularly when few codes are used for signal transmission. Figure 15 shows cumulative distribution functions of the PMPR of a wideband CDMA signal with 16 QAM modulation for 1 to 16 codes, and compares it to that of the VOFDM system using 16 QAM modulation. Note that the distributions for VOFDM, and 16 CDMA codes change very little, but the PMPR distributions for 1 and 2 codes changes a great deal. It should be noted that pulse shaping, frequency up-conversion, and the corresponding bandpass filtering at the transmitter increase the PMPR by another 2-3 dB regardless of the system.

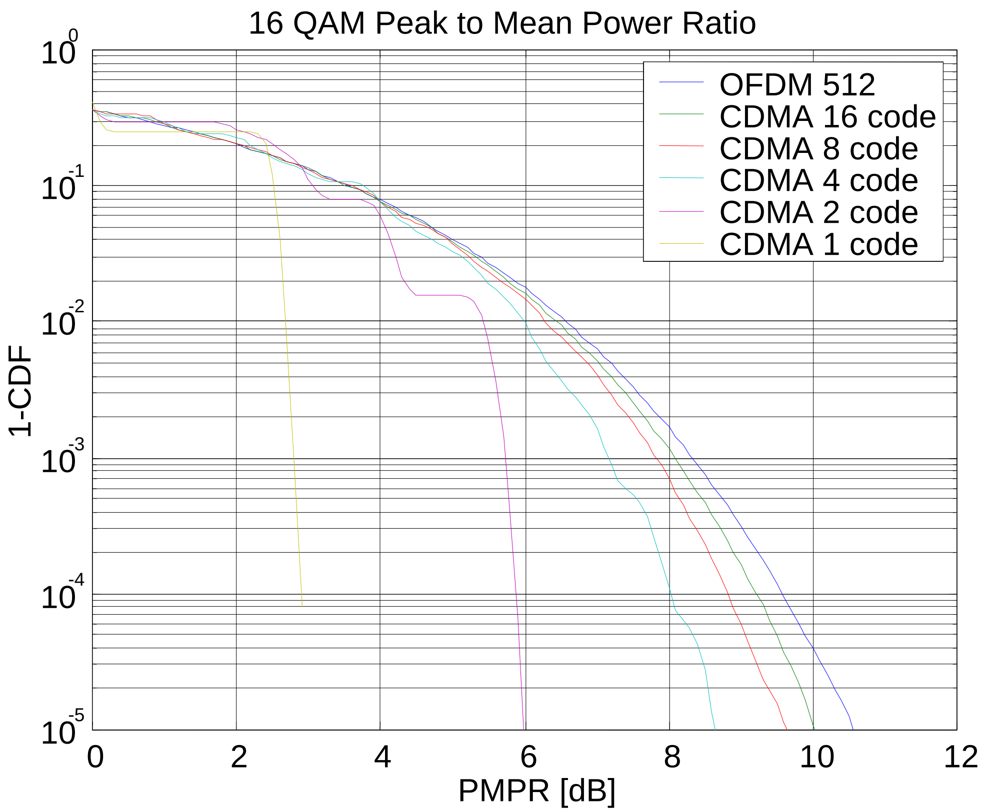

Figure 15: Cumulative distribution of VOFDM and CDMA signal PMPR for spreading factor of 64 and 16QAM modulation.

It is observed from Figure 14 and Figure 15 that for large numbers of codes, CDMA PMPR differs from VOFDM PMPR by less than 1 dB. Thus, based on Figure 14 and Figure 15, one can assume that a practical broadband multiple-service CDMA system would still need to accommodate transmission of RF signals with PMPRs of up to 8-9 dB.

- **Frequency Offset and Phase Noise**

It is well-known that OFDM is very sensitive to frequency offset and phase noise with increasing sensitivity as OFDM burst rate decreases. This is due to the fact that OFDM processes and detects the signal in the frequency domain. In the same manner, a CDMA system would be very sensitive to timing offset and jitter.

Nonetheless, CDMA is very tolerant of frequency offset as long as the offset is smaller than the CDMA symbol rate. CDMA is also more tolerant of phase noise than OFDM, even though phase noise does affect the orthogonality of the CDMA spreading codes.

- **Quantization & Precision**

In CDMA, despreading process in the rake receiver averages the quantized received signal over the duration of a symbol, which reduces the quantization noise power. Hence, CDMA rake receivers normally require rather low precision input signals. On the other hand in OFDM, FFT, which is at the digital front end, usually requires high precision input signals in order to function at the required performance levels. Having said that, we should point out that 3G systems based on CDMA give up processing gain in order to reach broadband transmission rates. When that is the case, the averaging advantage of CDMA goes away and the precision requirements of VOFDM and CDMA-based 3G systems become the same.

- **Timing Acquisition**

Mobile networks in general require relatively fast acquisition times in a time-varying environment and CDMA performance in particular is very sensitive to small timing offsets. Hence, CDMA systems employ complex schemes in order to ensure fast and precise timing acquisition in a mobile scenario. These schemes use significant overhead that decreases the system efficiency and necessitate complex receiver implementations. See [26] and [28].

Fixed wireless networks on the other hand do not require fast acquisition times, or complex schemes to achieve that, and BWIF VOFDM falls in the same category. Therefore, one can say that the timing acquisition overhead and complexity of CDMA systems is a disadvantage.

- **Digital Receiver Complexity**

Even though FFT needs more precision than the rake receiver does, practically the rake receiver structure requires a considerably more complex and costlier implementation than the OFDM digital front end. See [28]. Thus, one can say that for the same production volume, OFDM chipsets can be less expensive than corresponding CDMA chipsets.

Equalization, Interference Cancellation and Adaptive Antenna Array Complexity:

In OFDM, equalization, interference cancellation and adaptive antenna array algorithms are carried out in the frequency domain where instead of convolution in time domain, only multiplication and division are needed. Therefore, implementation of these algorithms in OFDM is simpler than in CDMA. There are proposals in the literature to perform such operations for CDMA in the frequency domain. In addition to requiring transformations to frequency domain and back, none of these proposals provide an alternative as simple as OFDM.

- **Power Control**

CDMA requires fast and precise power control in frequency reuse of one because its capacity is interference-limited and therefore highly sensitive to received signal and interference power levels. This requires rather elaborate MAC and physical layer power control schemes. In spite of these schemes, CDMA system is still very sensitive to rather small changes in received power levels due to abrupt changes in the propagation channel, and can easily lose efficiency, capacity, or coverage because of these fluctuations. In order to maximize capacity and coverage, even more complex power control schemes are required. See [28].

OFDM, on the other hand, needs much simpler power control algorithms for optimum performance and is much less sensitive to received power variations.

The following table summarizes the points made in this section:

Limitation	Advantage	Remarks
Multipath	OFDM	CDMA can tolerate longer delay spreads but captures only a fraction of the energy of the multipath signal compared to OFDM because of limited number of rake fingers. OFDM captures the total energy within a limited delay spread length. Multipath self-interference affects CDMA but not OFDM.
Narrowband Interference	OFDM	Only a few tones are affected or lost in OFDM, but in CDMA the interference affects all symbols.
Impulse Noise	OFDM	OFDM spreads the impulse noise over a burst reducing its effect, but in CDMA multiple symbols may be lost.
Timing Acquisition	OFDM	CDMA is very sensitive to timing and requires fast acquisition resulting in complex algorithms and overhead as opposed to OFDM.
Complexity	OFDM	Overall the CDMA rake receiver is more complex than OFDM digital front end. Implementation of equalization, interference cancellation, and adaptive antenna array algorithms is simpler in OFDM.
Power Control	OFDM	CDMA requires fast and precise power control and is very sensitive to received power fluctuations as opposed to OFDM.
Time Variation	None	For mobile networks CDMA has slight advantage but for fixed wireless systems robustness with respect to time variation is not very critical.
Quantization & Precision	None	CDMA rake receiver requires less precision than OFDM digital front end (FFT). However, 3G CDMA techniques do not have this property.
Amplifier Nonlinearity	CDMA	CDMA PMPR is less than OFDM PMPR, hence CDMA requires smaller backoff. But for high spreading factors and large constellation sizes CDMA PMPR approaches that of OFDM.
Frequency Offset & Phase Noise	CDMA	OFDM is more sensitive because it processes the signal in frequency domain. Orthogonality of CDMA codes is also affected by phase noise. Inexpensive solutions for OFDM exist.

Table 14: Comparison of OFDM and CDMA performance against limitations.

9. Summary and Conclusions

In this paper we studied the feasibility of systems based on 3G mobile cellular wireless technologies in fixed broadband wireless access. A summary of the results reached in this paper is as follows.

1. The peak rates achievable by CDMA-based techniques are low. This will result in poor user experience compared to higher peak rate systems (e.g., DSL, cable, VOFDM).

2. CDMA-based techniques have poor MAC performance. W-CDMA and cdma2000 have essentially circuit-switched MACs for messages other than short ones. HDR has improved downlink packet transmission by time and code division multiplexing, but it still cannot provide any QoS guarantees as user rates are changed according to interference conditions. TD-SCDMA has a MAC specification which resembles DOCSIS. However, it allows for a random access channel only during a fraction of the uplink period and it has a long backoff period. Simulations indicate a heavy delay penalty (hundreds of ms, as opposed to tens!) and about a 15% throughput penalty due to these limitations. Also, it is worthwhile to consider the development time: the time it took to develop, verify, and test DOCSIS chips is in terms of years.

3. There are substantial path loss penalties in moving a CPE antenna indoors. As a result, both the cell size and the available data rates suffer substantially. The calculations indicate that for the same data rate, the cell radius reduces by a factor of 10 in going from a rooftop antenna to a low-gain desktop antenna. This results in an increase of two orders of magnitude in base station costs! Whereas, a user installable under-the-eave antenna results in a much smaller penalty (about 30% in cell radius).

4. TDD has multiple limitations. It requires network-wide base station synchronization of uplink and downlink periods. This takes away the claimed traffic-based adaptability advantage of TDD. Also, TDD carries a significant overhead due to its guard interval requirement.

5. Receive beamforming and optimal receive diversity techniques are basically the same with identical performance. Two-element transmit beamforming and transmit diversity techniques have similar performance. On the other hand, there are implementation limitations with transmit

beamforming. First, transmit beamforming is not suitable for multicast or broadcast, limiting MAC performance and link efficiency. Second, transmit beamforming requires the use of TDD, which is inefficient. Third, transmit beamforming requires uplink bandwidth to optimize downlink beamforming, reducing system efficiency. Transmit beamforming may be suitable for circuit-switched applications, but it is not for packet-switched applications.

6. Both analysis and simulations indicate that an omnidirectional antenna at the CPE results in substantially more cochannel interference. To compensate for the increased cochannel interference, frequency reuse needs to be reduced. In other words, more spectrum needs to be used. Analysis shows the increase in spectrum can be more than a factor of 6!

7. Spectral efficiencies (in terms of b/s/Hz) of systems based on CDMA are typically low. In a cellular system, a high data rate user at the boundary of two cells results in interference in the cell neighboring its own. To prevent this effect, frequency reuse needs to be introduced. By taking fading into account, calculating required *C/I* ratios, and using simulations to determine feasible frequency reuse values, one can compute the system spectral efficiency in terms of b/s/Hz/sector. Calculations show CDMA-based techniques have much lower (about an order of magnitude!) system spectral efficiency as compared to VOFDM.

8. VOFDM has better multipath, narrowband interference (such as analog TV signals), impulse noise, timing acquisition, and power control performance at a lower complexity than CDMA. It is true that basic CDMA is superior in terms of amplifier nonlinearity performance, but with broadband versions of CDMA, that advantage disappears. There are additional advantages of CDMA in frequency offset, phase noise, and quantization precision, however, these advantages are not sufficient to overcome the VOFDM advantages stated above.

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