Broadband Wireless Internet Forum White Paper

Frequency Division Duplexing and Time Division Duplexing for Broadband Wireless Applications

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Notice

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Authors

Ender Ayanoglu
Cisco Systems

Michael Burgess
Fluor Global Services

Michael Pollack
Cisco Systems

Ali Zamanian
Fluor Global Services

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1 Introduction

With the advent of broadband wireless Internet access, discussions on Frequency Division Duplexing (FDD) versus Time Division Duplexing (TDD) have resurfaced. In this paper, we study this issue, with an emphasis on point-to-multipoint wireless Internet access service at microwave frequencies less than 10 GHz.

There are four major areas to consider:

1. The first set of issues is related to the specifics of implementing an FDD system, with regards to the guard band requirement, "wasting" the guard band, cost of duplexors, limitations in terms of frequency selection and ways to solve them, equipment provisioning, and identifying the channel.
2. The second set of issues is related to timing issues in TDD. The first such issue is a potential advantage of TDD, which is load balancing in the face of asymmetrical traffic. An important point we would like to raise in this paper is that this advantage, which is perhaps applicable in a wireline system, is not applicable in typical wireless access scenarios. In addition, we show that TDD systems require a guard time between their transmit and receive cycles, reducing system efficiency. Furthermore, we show that TDD introduces additional end-to-end delays in Media Access Control (MAC) and Automatic Repeat Request (ARQ) algorithms. Although it can be argued that TDD enables the implementation of transmit beamforming and therefore spatially multiplexed channels with increased system capacity, implementation of such a system requires the solution of major technical challenges.
3. The third issue we consider is hardware implications of choosing FDD versus TDD. There are multiple concerns that arise in designing the hardware with a TDD or FDD choice. For example, it is possible to share some components (and thereby reduce the cost) in TDD. But a TDD system suffers worse system sensitivity at equivalent data rates and requires additional switch timing signals within the system that are not trivial to implement. Also, TDD requires more expensive Analog-to-Digital and Digital-to-Analog Converters (ADC and DAC), as well as more complexity in implementing QAM equalization.

4. The fourth issue is the ability to use a given frequency reuse pattern. We will show that, with FDD, both desired signal and co-channel interference have non-line-of-sight (NLOS) propagation characteristics. For TDD, the desired signal is NLOS, while the co-channel interference is line-of-sight (LOS). We will show that, as a result, the signal-to-interference ratio (SIR) in a frequency reuse pattern is much higher with FDD as compared to TDD. In order to reach similar signal-to-interference ratios, TDD needs to reduce frequency reuse, thereby reducing spectral efficiency.

In the next four sections, we will elaborate on these issues and explain each one in detail. At the end of this paper we will summarize each area of discussion, and describe whether FDD or TDD should be preferable in a point-to-multipoint wireless Internet access system.

2 Frequency Duplexing

2.1 No Frequency Duplexing in TDD

An FDD system operates by allocating a certain part of the frequency spectrum to transmit and another part to receive. The front end of an FDD transceiver is shown in Figure 1 and that of a TDD transceiver is shown in Figure 2. As shown in both figures, the transmitter

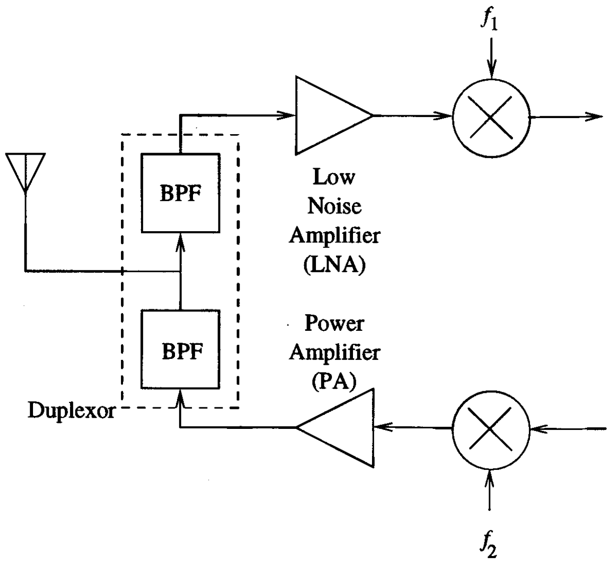

Figure 1: FDD transceiver front-end. BPF: Band-Pass Filter.

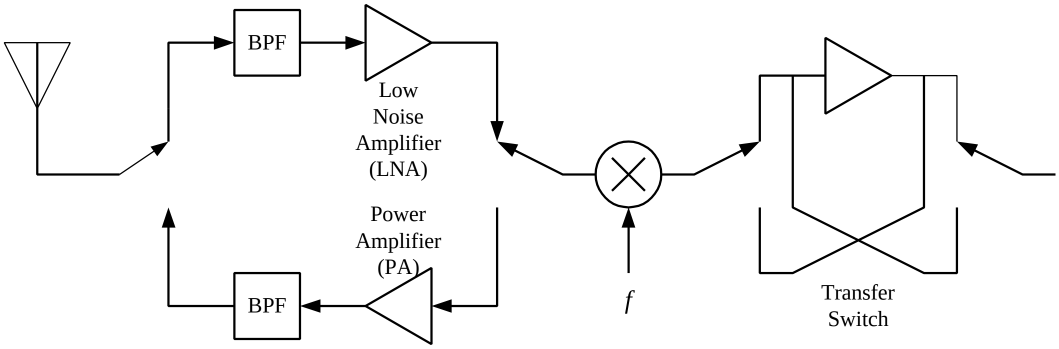

Figure 2: TDD transceiver front end. The two BPFs have much wider bandwidth as compared to the duplexor BPFs.

and the receiver typically use the same antenna (we will elaborate on this choice shortly). In FDD, this requires a coupled pair of RF filters known together as a duplexor. In addition to generally bandpass filtering the transmit and receive bands, the specific task of the duplexor is to prevent the co-located transmitter from degrading receiver performance. The transmit portion of the duplexor suppresses transmitter spurious signals in the receive spectrum and the receive portion suppresses the high power transmit signal to prevent the sensitive receiver front end (the Low Noise Amplifier, or LNA) from being overloaded (this is known as receiver desensitization). The duplexor requires sharp RF filtering at the transmit and receive frequency bands. This sharp RF filtering requirement has two consequences. First, due to the high Q requirement, the duplexor becomes a moderately expensive component. For example, in the MMDS band, for consumer applications, a duplexor can add $30 to the cost of a transceiver. Second, the transmit and receive bands cannot be contiguous since physically realizable filters require a nonzero frequency cutoff band. Consequently, a guard band is needed between the transmit and receive bands. This requirement is sometimes stated as a need in FDD to have some wasted spectrum. In reality, it is straightforward to choose the transmit and receive bands in FDD judiciously so that the guard band is not wasted. In a network with multiple links, separated by even moderate distances (multiple point-to-point links, or multiple base stations within a point-to-multipoint cellular network) one link may use a frequency that falls in another link's guard band. Therefore, no frequencies need to be wasted in the system. In fact, most frequency allocations (e.g., FWA) are made with this consideration by frequency allocating agencies. When a frequency allocation is made without this consideration, as in MMDS and UNII, it is often possible to design a frequency plan so that no frequency band is wasted. We will give examples of how this can be achieved later in this paper.

In passing, we would like to address whether separate transmit and receive antennas can serve the function of the duplexor. If this were possible, then the receiver desensitization problem could go away. Studies have shown that, for practical distances between the transmit and receive antennas, the best separation achievable by such spatially duplexed transmit and receive paths is about 20 dB short of what is actually needed. Thus, antenna separation per se is not sufficient to implement duplexing in FDD, although it can be used to enhance the separation achieved by a duplexor.

2.2 Channel Selection Flexibility in TDD

As described above, a consequence of the need for duplexing in FDD and the absence of this need in TDD is that frequency bands for FDD need to be chosen judiciously with guard band considerations, whereas TDD can operate in any band. This is an advantage for TDD. Nevertheless, there are additional parameters to consider. When frequency allocations are made for wireless services, this issue is taken into account by frequency

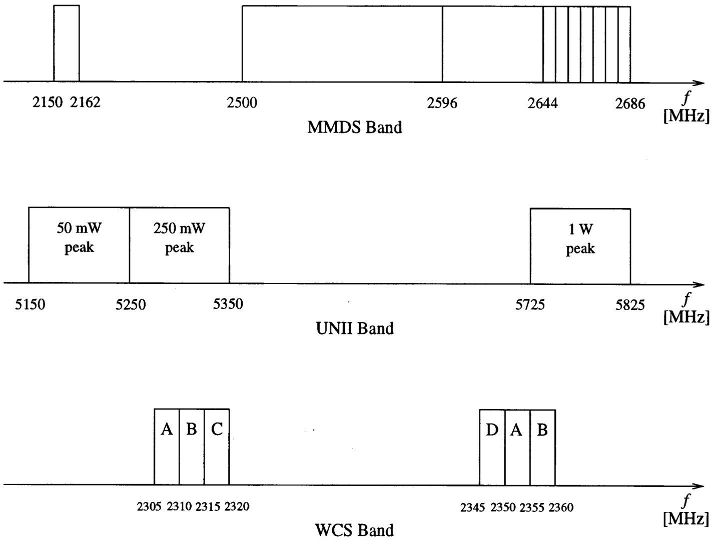

Figure 3: MMDS, UNII, and WCS bands. In WCS, A and B are allocated as FDD frequency pairs.

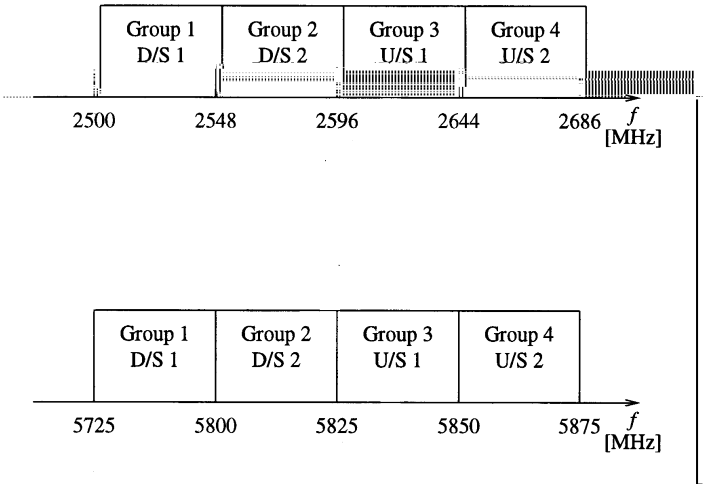

Figure 4: Only two sets of duplexors are necessary to cover the MMDS and UNII bands with no wasted bandwidth.

allocation granting agencies and in most cases allocations are made with FDD in mind. Examples of this are in FWA, mobile cellular bands, blocks A and B of the WCS band as shown in Figure 3, etc. When this is the case, the presence of a guard band is no longer an issue for FDD. Furthermore, in this case, TDD may in fact be at a disadvantage since building a TDD transceiver to operate in two noncontiguous frequency bands with a significant separation between them is not straightforward and complicates the design. On the other hand, the presence of an FDD guard band in a frequency allocation is not always the case. For example, in MMDS and the upper portion of UNII, this consideration is absent. However, FDD can be made to operate in these bands. In fact, frequency plans can be designed so that no spectrum is wasted with FDD.

For example, assume that an operator has access to all of the 31 MMDS channels between 2500 MHz and 2686 MHz. Consider the following frequency plan as shown in Figure 4

Group 1: The first set of 8 MMDS channels (2500-2548 MHz)
Group 2: The second set of 8 MMDS channels (2548-2596 MHz)
Group 3: The third set of 8 MMDS channels (2596-2644 MHz)
Group 4: The final 7 MMDS channels (2644-2686 MHz)

Now we will generate two sets of transmit and receive bands using these four groups. In the first set, use Group 1 for downlink and Group 3 for uplink. In the second set, use Group

2 for downlink and Group 4 for uplink. This makes Group 2 the guard band for the first set and Group 3 the guard band for the second set. This system now requires two duplexors, one for each set. Duplexors in the MMDS band with 48 MHz channel separation are available and the resulting system does not waste any bandwidth. The same principle is applicable to the UNII band as shown on the bottom portion of Figure 4.

2.3 Simpler Equipment Provisioning in TDD

Equipment provisioning in FDD may be complicated if there are multiple transmit and receive frequencies, as in a frequency reuse plan. Multiple bands require multiple duplexors. As a result, an FDD system requires keeping more than one duplexor in stock. Since a TDD system does not employ a duplexor, this consideration is absent. However, the number of duplexors can be minimized by careful design of the transmit and receive bands among the frequencies available. For example, the frequency band plan in the previous section requires only two duplexors.

Also, in some cases, there is a need for sharp cutoff filters even with TDD systems. Since many MMDS operators plan to colocate at existing ITFS or MDS sites, they have limited control over adjacent channel interference and antenna configuration. Because of limited antenna spacing and non-ideal filtering, it is very difficult to provide the high-level of isolation required between the adjacent channel transmitters and receivers at a colocated site. Thus, a guard band is required between a TDD channel and other non-TDD channels at a particular site. This guard band is required to prevent receiver degradation, due to adjacent channel interference and desensitization both from the adjacent transmitters to the TDD receiver, and from the TDD transmitter to the adjacent channel receivers. The minimum guard band requirement is a function of the frequency separation of transmitter and receiver, adjacent transmitter spectral emissions, transmit ERP, transmitter filtering, antenna spacing, and receiver filtering. Depending on the level of isolation between transmitters and receivers, the required guard band could be as little as 6 MHz [1] or as high as 48 MHz for ITFS/MMDS high-power video transmitters. Furthermore, a guard band is required on either side of the TDD channels in a site with mixed ITFS, FDD, and TDD channels.

In a non-colocated site, the owner has control over the adjacent transmit and receive equipment and antenna system. A dynamic Adaptive TDD (ATDD) system requires a guard band between each transceiver channel unless they are operated in a fixed frame mode (coordinated mode) which significantly decreases channel efficiency. This is a significant limitation for ATDD systems, since only a small number of channels can be used at any site. For example, assuming average transmitter/receiver filtering and antenna isolation, the TDD guard band required is 18 MHz, thus only one 6 MHz TDD channel could be assigned per each 24 MHz of spectrum at a particular site. This would result in a spectrum utilization of only 25% (6 MHz /24 MHz). On the other hand, an FDD system can utilize all of the spectrum with 18 MHz guard band by generating pairs of channel sets as described above.

2.4 Single Channel to Learn in TDD

In a wireless system, the channel is time-varying and needs to be tracked continuously. This is needed for such signal processing purposes as channel equalization, power control, or spatial processing. In FDD, the transmit and receive channels are at different frequencies and this separation makes the two channels uncorrelated with each other. In TDD, since transmit and receive operations follow each other in the same frequency channel, the two channels are highly correlated. This provides a simplification for the signal processing functions mentioned above. For example, in QAM systems, training for equalization purposes can be simplified with the use of channel information feedback. Or, a fade level can be determined by the receiver of a subscriber unit based on its reception and thus the power control of this subscriber unit is simplified. On the other hand, with FDD systems, solutions to this problem exist. These solutions involve allocating a small amount of overhead and allowing a very manageable complexity increase in the hardware design. For example, for power control, the subscriber units can be forced to transmit periodic bursts and can be directed to change their power level. A version of this technique is employed in IS-95 CDMA systems.

2.5 Transmit Beamforming in TDD

In a TDD system, the downstream and upstream channels to/from a given Subscriber Unit (SU) are highly correlated with one another. This allows one to extract SU-specific downlink channel parameters from uplink channel estimates. Transmit beamforming at the base station is more easily implemented in a TDD system. The use of transmit beamforming in turn enables a higher downlink system capacity because one can then implement spatially multiplexed downlink channels. However, there are technical challenges to be solved before being able to implement such a system. In current fixed wireless access systems the downlink channel has a required broadcast period to let the subscriber units know their uplink transmission schedule or to declare collisions in the uplink contention channel. In a transmit beamforming system, this broadcast capability needs to be somehow duplicated. One possibility is to use an omnidirectional antenna pattern for a portion of the downlink transmission period. In order to implement this capability in a cellular system, the system designer must devise solutions to cope with the fact that the levels of co-channel interference from neighboring cells will be much higher during omnidirectional transmission periods. Thus, one needs a significantly specialized MAC algorithm, changes in the physical layer, and changes in the frequency plan as compared to a conventional system. The solution of these major design challenges may be possible, however, it requires a significant amount of research and implementation period. Therefore, we do not consider this advantage of TDD a realistic one today.

3 System Timing

3.1 Asymmetrical Traffic in TDD

Although conventional voice telephony traffic is symmetric (both directions have the same bit rate), Internet applications are typically asymmetric with the network-to-user direction carrying a higher bit rate. For example, Web traffic is from the server to the subscriber; similarly, audio or video broadcast applications are from the server to the subscriber. TDD offers the ability to accommodate any asymmetric traffic dynamically. This is known as Adaptive TDD (ATDD). FDD has a static ratio between the transmit and receive transmission rates and cannot easily accommodate changing this ratio dynamically. This is often suggested as a very important reason to prefer TDD. However, a close examination of the conditions in which a wireless system operates shows that this dynamic load balancing is extremely difficult to implement in real systems. This will be described in detail in the next section.

3.2 Need for Network Synchronization in TDD

In cellular wireless networks, base station antennas are located as above ground level as possible to increase coverage. As a result, base station antennas are typically located above the tree and roof line, such as on top of a hill or on an antenna tower. This results in base stations often being within line of sight of each other as shown in Figure 5.

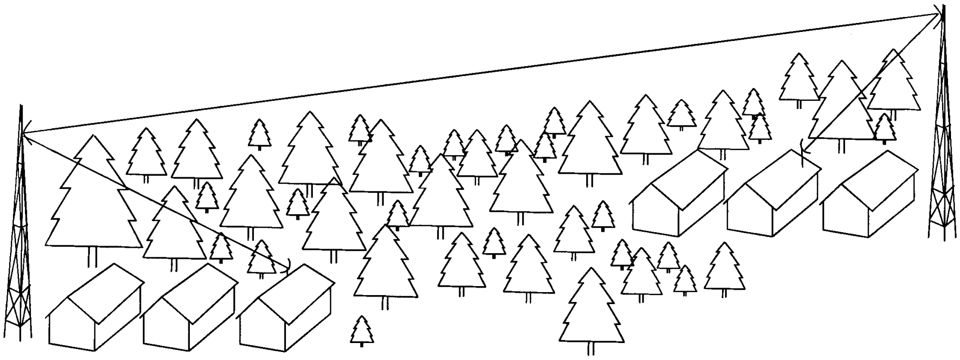

Figure 5: Although base stations and subscriber units may be on non-line-of-sight connections, base stations are typically at line-of-sight of each other.

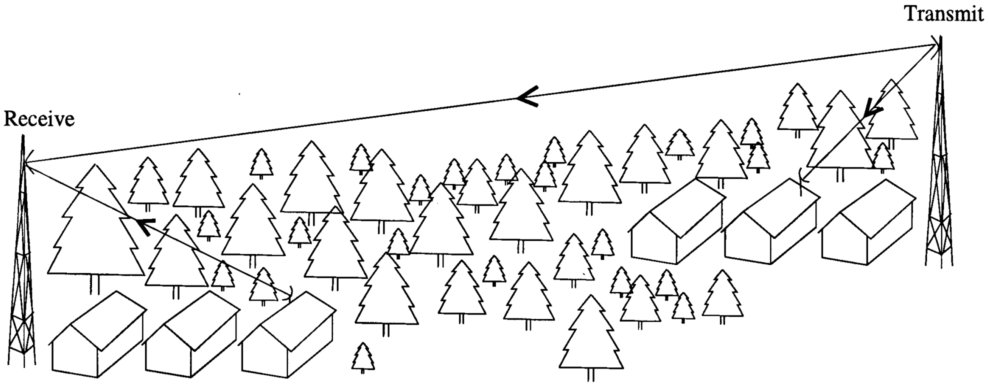

Figure 6: In a TDD system, if the base stations do not transmit and receive at the same time, cochannel interference can render reception from subscriber units impossible.

Meanwhile, efficient cellular RF network designs take advantage of the fact that, in general, the RF propagation path between the base station and the subscriber unit is NLOS. In a TDD system this requires the transmit and receive cycles of different base stations to be synchronized since otherwise co-channel interference from a neighboring base station can interfere with the uplink transmission from subscriber units in a cell as shown in Figure 6. (Even if the two base stations do not face each other as shown in Figure 6, the leaked back propagation from the same sector can overwhelm that of the local subscriber due to the propagation characteristics of LOS connections versus NLOS. We will quantify this effect in Section 5.)

This requirement for synchronization has a significant consequence. When all of the transmit and receive intervals for all base stations have to operate synchronously, one can no longer dynamically change the transmit and receive periods at a base station based on local traffic characteristics. Therefore, the dynamic load balancing advantage of ATDD is no longer applicable. This conclusion is valid even for systems with single, isolated cells. The reason is, as described before, physical antenna separation cannot provide the required signal suppression. Therefore, for isolated TDD systems that employ multiple sectors on a single tower, the transmit and receive cycles should be synchronized.

3.3 Need for Guard Time in TDD

Previously, we stated that in a cellular wireless TDD system the transmit and receive periods of all the base stations need to occur simultaneously. This is dictated by the fact that the base stations are often within LOS of each other. We will show in this section that, furthermore, this effect dictates a guard interval between the transmit and receive cycles. As shown in Figure 7, this guard interval enables the transmit signal from a distant base station to die out before the receive period begins so that the base station can hear subscriber units in its cell without co-channel interference. (Again, this conclusion holds even if the two base stations do not face each other, as will be shown in Section 5.) In a typical cellular frequency reuse plan, two base stations that employ the same frequency set can be, e.g., about 10 to 25 miles apart. This corresponds to approximately 50 to 125 μs of propagation time between the two base stations. This period should be equal to the guard time between the transmit and receive cycles. Due to delay considerations, there is a limit on the frame size (the sum of transmit period, receive period, and guard time). This limit is of the order of 1 ms. This guard time results in an efficiency loss of approximately 5% to 12.5% for TDD, which is not present in FDD. Note that in a similar fashion to the base stations, subscriber units can also generate cochannel interference to force transmit and receive cycle synchronization and guard time in TDD. Also note that even if we assume that there will not be interference from other cells, there is still a guard interval requirement to allow for upstream propagation time. If we assume the radius of a cell to be about 5 miles, then the required guard time is an additional 25 μs.

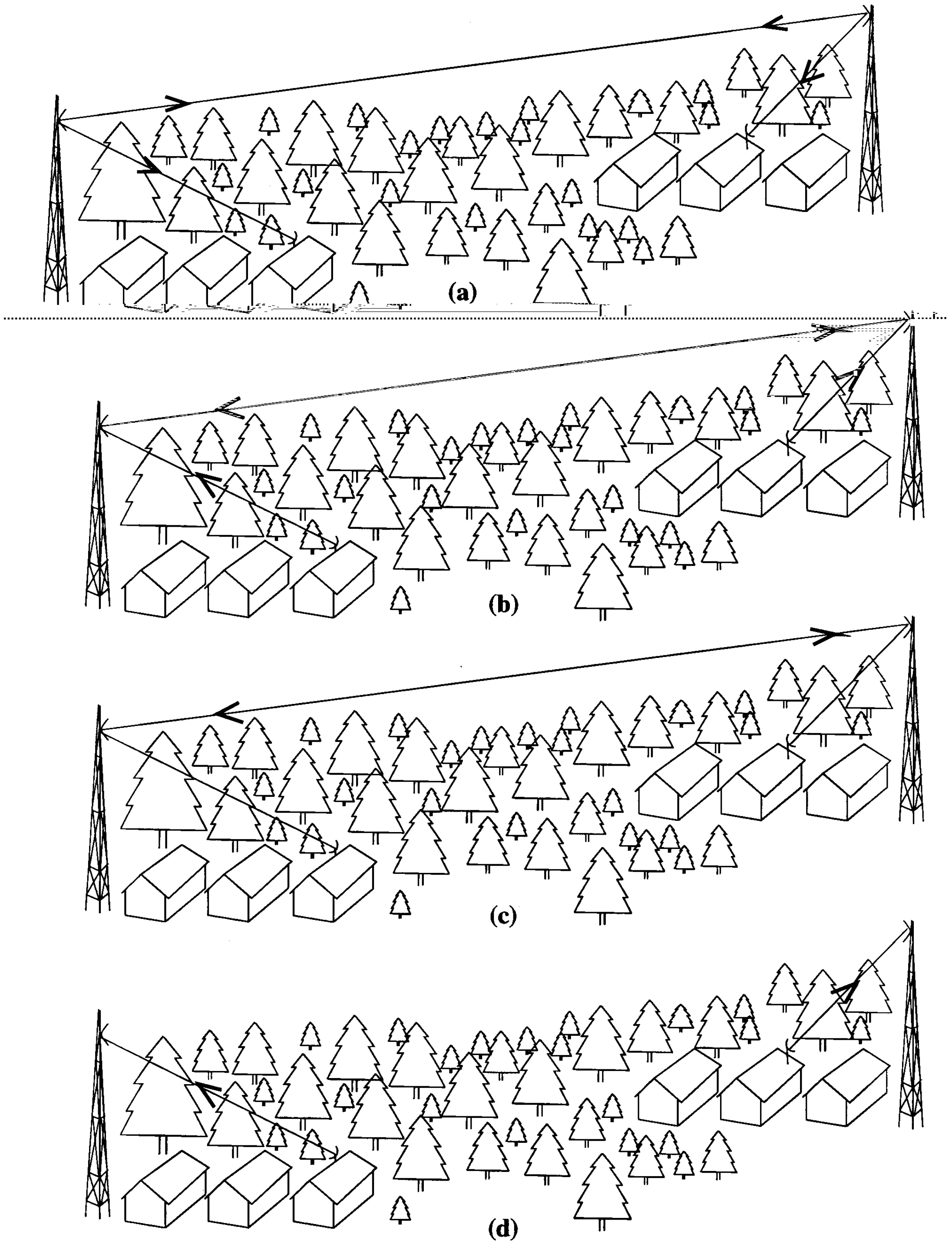

Figure 7: In TDD systems, receive and transmit intervals need to be separated by a guard interval. Otherwise, as shown in the sequence (a) and (b), cochannel interference impedes proper reception of subscriber units. Correct operation is sequence (a), (c), (d) so that cochannel interference dies out during the guard interval.

3.4 More Delay in MAC Timing in TDD

In all advanced wireless systems, MAC protocols employing demand assignment are being proposed to make the most efficient use of precious physical layer bandwidth. In systems that employ a demand assignment based MAC, TDD results in an added delay for channel access. In a demand assignment MAC the subscriber first goes through a reservation channel to request a time slot grant for transmission. Only when the allocation is granted can the user transmit its data at the time the grant is given. Thus, this process requires 1) waiting for the request opportunity (uplink), 2) waiting to find out the location of the grant (downlink), and 3) waiting for the allocated time slot for transmission (uplink). In a TDD system, these times are separated by sequential uplink and downlink transmission times. As shown in Figure 8, there is at least one downstream interval between the time a transmission request is made and the time the requested timeslot can be transmitted uplink. Whereas, in a well-designed FDD system, the uplink reservation request period is followed by a downlink grant broadcast (as in DOCSIS MAP message) period. Again, in a well-designed FDD system, this downlink grant broadcast period is immediately followed by the uplink transmit interval. Therefore, as shown in Figure 8, the time it takes to transmit an uplink request in a TDD system will inevitably be longer than the time it takes to transmit the same request in an FDD system.

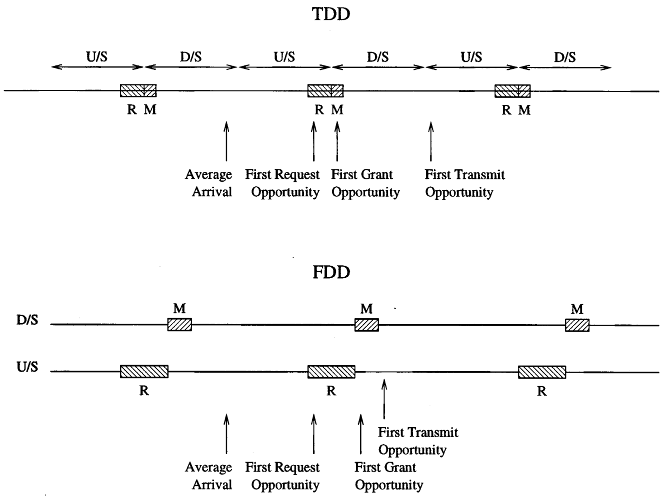

Figure 8: In TDD, demand-assignment MACs result in an inevitable delay of at least a downstream transmission period. In FDD, this inevitable interval is absent and the system can be optimized to minimize the delay. R: Reservation Request Period, M: Grant Descriptor (Map), D/S: Downstream, U/S: Upstream. Some protocols spread out the Reservation Request Period R. Observe from the above figure that this will not change the fact that with FDD, the transmit delay is shorter.

3.5 More Delay in ARQ in TDD

Protocols that employ Automatic Repeat Request (ARQ) will have increased latency due to the presence of the Transmit/Receive cycle. For example, in a point-to-point radio where every transmission block is subject to an acknowledgement (ACK) symbol, an errored transmission block will see an additional latency of a full receive period. This increased latency can reduce protocol performance.

4 Hardware

4.1 Sharing Analog Components in TDD

A TDD system operates as either a transmitter or a receiver at a given time. This enables the sharing of some system components between the transmitter and the receiver. For example, because the frequency plan is usually the same for the transmitter and the receiver in a TDD radio, the number of local oscillators can be reduced. Similarly, filters and amplifiers can be shared. As a result, system cost can potentially be reduced. On the other hand, this sharing requires transfer switches or transmit/receive switches as shown in Figure 2, which increases the system cost. Consequently, there is not a clear superiority in either way, with perhaps TDD with shared analog components having a slight cost advantage. However, as it will be stated in more detail in Section 4.3, maintaining proper timing of these switches, particularly in wireless systems that have outdoor and indoor RF electronics, is not trivial.

4.2 Transmit/Receive Switch Loss in TDD

As described above, there are cost advantages due to sharing analog components. This involves using Transmit/Receive (T/R) switches. A problem with the presence of T/R switches in TDD systems is the insertion losses involved at microwave frequencies. High isolation, low loss, higher power handling RF switches are expensive above 2 GHz. Consequently, the cost advantage due to the sharing of analog components is either offset by the cost of the T/R switches or by the reduction in system performance (sensitivity, output power, etc).

4.3 Transmit/Receive Switch Timing in TDD

Another, less obvious, design problem with the presence of T/R switches is their timing. The requirement is the occurrence of the switching signal at precise instants in time across the system. In particular, the signal must be transmitted to the RF unit, which may be remotely located and connected to the main unit by a single wire connection. The multiplexing of the control signal while maintaining the precise switching time requirements is a small increase to the complexity of the system. The reason for this is the nontrivial, relatively high bandwidth of the signal to be transmitted and the circuitry required to implement the transceivers for this signal. Although in some FDD systems a control signal may also need to be transmitted in a similar fashion, the timing and therefore the bandwidth requirements of these signals can vary by up to an order of magnitude.

4.4 Receiver Sensitivity

Consider a TDD system and an FDD system operating at the same data rate. Since the receiver of the TDD system is operational half the time that the FDD system is, the TDD signal occupies twice the bandwidth (although overall bandwidth is the same since FDD uses transmit and receive bands). As a result, the noise power at the TDD receiver is twice that of the FDD receiver. Therefore, for equivalent conditions, the signal-to-noise ratio for a TDD system is 3 dB worse than an FDD system. As a result, an FDD radio has approximately 3 dB more sensitivity.

In reality, this difference is slightly more than 3 dB. This is due to three distinct reasons. In TDD, RF filter and switch losses amount to approximately 1 dB of insertion loss in both transmit and receive modes. In FDD, there is a loss due to the duplexor. The duplexor to be used at the subscriber unit must be inexpensive. A duplexor with about 2 dB insertion loss satisfies this requirement. The duplexor at the base station need not be inexpensive and a 1 dB duplexor can be employed. Therefore the total duplexor loss in an FDD system is approximately 3 dB. In addition, since a TDD system operates at twice the bandwidth, there is more spectral regrowth. This results in larger power backoff, specifically, the output power needs to be reduced by approximately 3 dB. This effect is shown in Figure 9.

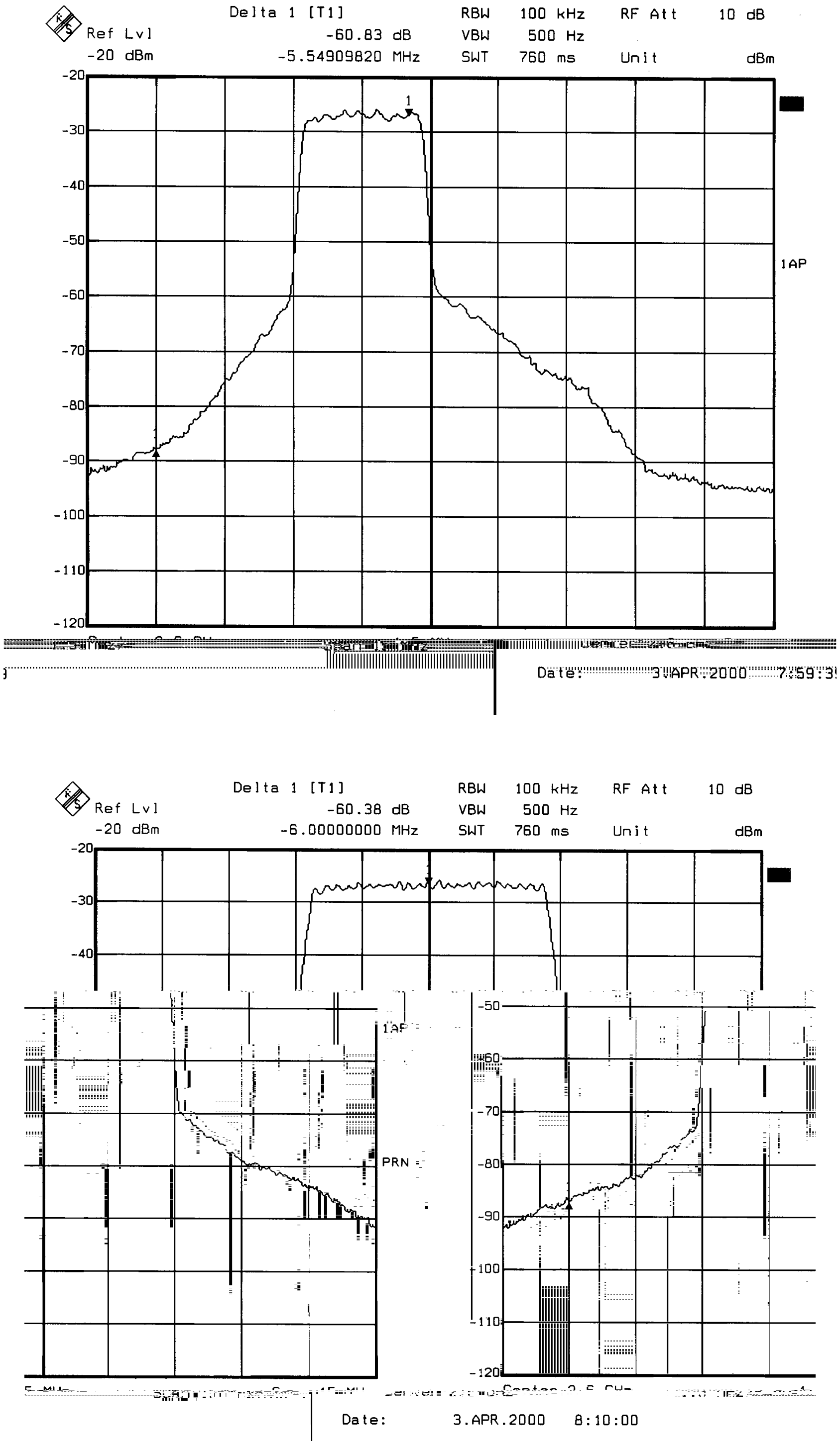

Figure 9: The FCC spectral regrowth specification for the MMDS band requires that the output power level be at –60 dB from the center of the MMDS band to the adjacent one. In the plots above, we evaluate the total output power required to satisfy this specification for systems that operate at 3 and 6 MHz within the 6 MHz MMDS band. The upper plot corresponds to the 3 MHz system. As specified in measurement values, the FCC requirement is satisfied. It should be clear that the power difference between the two systems is 3 dB since the power spectral density levels are about the same while the bandwidth changes by a factor of two between them.

Cause of the Loss	TDD	FDD
Bandwidth	-3 dB	
Switch	-2 dB	
Duplexor		-3 dB
Spectral Regrowth Backoff	-3 dB	
Total	*-8 dB*	*-3 dB*

Table 1: System gain comparison of TDD and FDD.

The total effect of four factors described above make FDD at a net SNR advantage of about 5 dB as compared to TDD. This is detailed in Table 1 above.

However, we would like to note that, for a given channel bandwidth and a given delay spread (or, equivalently, coherence bandwidth), doubling the system bandwidth can in fact improve the reliability of the channel due to increased frequency diversity. This can offset the effect of system gain as described above. Let us compare an FDD link using a non-contiguous pair of 6 MHz MMDS channels against a TDD link using two contiguous channels to form a 12 MHz RF channel. If we further assume that the physical environment yields relatively short channel delay spread values (e.g., 0.5 μs), then the increased frequency diversity seen by the TDD system is estimated to produce a 3 dB improvement in system gain.

4.5 Sampling Rate for ADC and DAC

The sampling rates for Analog-to-Digital and Digital-to-Analog Converters are halved in FDD. This reduces the cost, DC power consumption, and increases the number of available products. It also enables higher interpolation/decimation ratios.

4.6 QAM Requires Twice Longer Equalizer with TDD

Since the sampling rate is doubled with TDD, in QAM, the equalizer length is also doubled. Together with the doubling of the sampling rate, the symbol rate is also doubled. Thus, with TDD, in QAM, the number of operations per second while the system is in operation is quadrupled. Or, since the receiver is in operation half the time, the number of operations is doubled as compared to an FDD QAM system. Note that this also increases the training overhead.

In OFDM, similarly, the number of samples corresponding to the delay spread is doubled due to increasing the sampling rate. This can be handled with an FFT of size 2*N* as opposed to size *N*. This choice keeps the burst size and the overhead the same, whereas reducing the number of FFTs performed by 2. Thus the number of operations performed increases from *N*log*N* to *N*log2*N*, or the increase in the number of operations is by a factor of log2*N*/log*N* = 1 + 1/log*N.* This number is slightly larger than 1. The number of operations per second is increased by a factor of 2 + 2/log*N,* or slightly larger than 2; due to performing operations in half the time. We summarize these results in Table 2 below.

	QAM	OFDM
Number of Operations in a Transmit/Receive Cycle	x2	x1 (approx.)
Number of Operations per Second	x4	x2 (approx.)

Table 2: The increase in the number of operations for a TDD system as compared to an FDD system of the same transmission rate.

4.7 FDD is Easier to Operate at Other Bands

Most frequency allocations by regulating agencies are made in FDD pairs. Therefore, it is easier to use the basic FDD design in other bands. The advantage of this from a system point is the fact that one can design a single FDD system and can operate it in multiple bands by changing local oscillator and duplexor frequencies. This single design drives the cost down.

5 Frequency Reuse

As discussed previously, systems based on ATDD access technology have recently been offered as the ultimate solution for the emerging broadband fixed wireless market. These systems reportedly are able to increase the efficiency of the radio spectrum by varying the upstream and downstream bandwidth of a channel in accordance with the traffic pattern.

While systems using ATDD access technology are considered to be capable of improving channel efficiency in many LOS systems, they have severe Carrier-to-Interference Ratio (CIR) and frequency reuse penalties when used for NLOS systems. Since the typical business model for MMDS deployment is based on NLOS systems to minimize the cost of transmitter sites and infrastructure, each MMDS system should be carefully evaluated before ATDD technology is selected.

Since the MMDS frequency spectrum is limited and expensive, the fixed wireless system must be capable of maximizing resources via effective frequency reuse to support the system capacity requirements. The frequency reuse plan must also support the business plan, which typically maximizes the Return on Investment (ROI) by providing the highest system capacity for the minimum capital investment.

Co-channel cells must be physically separated to provide the necessary co-channel interference isolation. The minimum distance between co-channel cells is dependent on several factors, including the co-channel interference objective and the path propagation. For example, a much greater distance between neighboring co-channel cells is required if there is a LOS path between the cells.

In a cellular system with similar size cells, the co-channel interference is a function of the radius of the cell (R) and the distance to the center of the nearest co-channel cell (D). Increasing the D/R ratio increases the spatial separation between co-channel cells relative to the coverage area; consequently, the co-channel interference is reduced by increasing the D/R ratio. The cellular channel reuse and overall system capacity, however, is decreased when the D/R ratio is increased to reduce co-channel interference. Cell sectoring and directional antennas are generally employed in high-capacity MMDS systems to meet minimum co-channel interference requirements.

The co-channel interference is typically expressed as the Carrier-to-Interference Ratio (C/I or CIR) or Signal-to-Interference Ratio (S/I or SIR). A system using a high-efficiency digital modulation scheme to maximize channel bandwidth, such as 64 QAM requires a very high SIR. Depending on the amount of error correction, a typical 64 QAM SIR requirement may be 19-20 dB. On the other hand, a typical 4 QAM system may operate with a SIR as low as 6-7 dB. It can be seen that the system capacity is a function of both the frequency reuse and co-channel interference.

A brief analysis follows to compare the CIR and frequency reuse performance of ATDD/TDD and FDD systems in MMDS systems.

5.1 Co-channel Interference for FDD Systems

FDD systems utilize different transmit frequencies for the Base Transceiver Station (BTS) and Customer Premises Equipment (CPE). Refer to Figure 10. This diagram shows potential interference from a CPE transmitter in Cell B interfering with a CPE transmission in Cell A. Note that 120 degree sectored cells and directional CPE antennas have been used to minimize co-channel interference. The worst-case potential interference for an FDD system is CPE transmitters in neighboring co-channel BTS cells interfering with transmissions from the local CPE sites.

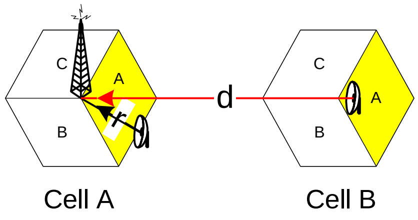

Figure 10: FDD cochannel interference.

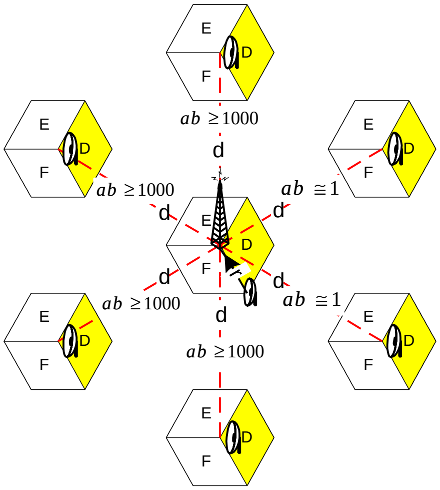

Figure 11: FDD Tier 1 interference.

Although the BTS sites in many MMDS systems commonly use tall towers to maximize the cell coverage area, the CPE sites typically use antennas mounted at or below roof level. The distant, low-elevation CPE transmissions will likely be attenuated with the same or greater propagation exponent as the local sites. For example, the co-channel interference will typically be attenuated with a propagation exponent of either 3 or 4 in an NLOS MMDS system. FDD systems, therefore, are capable of effectively using conventional cellular reuse techniques to increase the system capacity.

The interference from the Tier 1 neighboring co-channel cells is shown in Figure 11. The joint antenna discrimination, $\alpha\beta$, is shown for each path to the neighboring co-channel cell. A joint $\alpha\beta$ discrimination for a 120° sector BTS antenna and a 20° planar array CPE antenna is typically 1000 (30 dB); this value has been assumed for the analysis.

Figure 12 shows a 4x3 reuse pattern. Co-channel interference to cell number 1 in the center is caused by cells numbered 1. As shown in the figure, there are 6 such first tier cells at a distance $d_1 = d$. This distance can be calculated from

$$d / r = D / R = (3\,N)^{1/2} = (12)^{1/2} = 3.464.$$

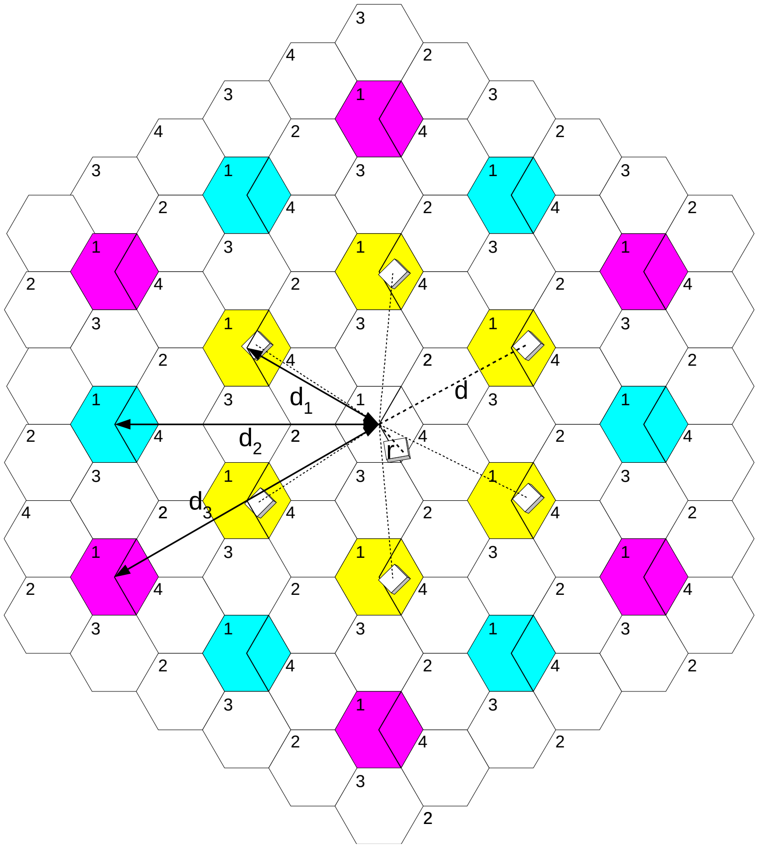

Figure 12: A 4x3 reuse pattern and Tier 1, 2, and 3 interferers.

Assuming r = 5 miles, the formula above yields

$$d_1 = 17.32 \text{ miles.}$$

In the figure above there are 6 cells at a distance d_2 that result in co-channel interference for cell 1. This distance is

$$d_2 = (3)^{½}\ d_1 = 30 \text{ miles.}$$

In the figure, there are 6 third tier cells that cause co-channel interference which are at a distance d_3. This distance is

$$d_3 = 2\ d_1 = 34.641 \text{ miles.}$$

We note that, out of the 6 first tier cells, 2 are in front view and 4 are in the back view for a given sector. For the second tier, there are 3 in front view and 3 in back view. For the third tier, 2 cells are in front view and 4 are in back view.

The worst-case co-channel SIR is calculated below for the 4x3 cellular reuse pattern, assuming a cell radius of 5 miles and directional CPE antennas. NLOS propagation is assumed between the local CPE sites and the associated BTS site; NLOS is also assumed between the BTS site and the neighboring co-channel CPE sites. Uplink power control can be used effectively with FDD systems to reduce the co-channel interference. In systems with uplink power control, the transmitter power at each CPE location is adjusted to the minimum level required to meet the SINR objective. The signal from each CPE location, regardless of the path length, is maintained at the same level at the BTS site, as long as the path loss does not exceed the link objectives. Consequently, it can be shown that the interference from a CPE transmitter near the BTS is reduced to the same level as that from a CPE transmitter at the cell boundary. In other words, the co-channel separation distance is effectively increased to d + r for any CPE transmitter in the neighboring co-channel sector. Since MMDS systems often use relatively tall towers, the SIR calculation will be expanded to include co-channel interference from the second and third tiers of interferers. The co-channel interference for an FDD system with uplink power control can be calculated as follows

$$\mathrm{SIR} = 10\ .\ \log\left[\frac{r^{-4}}{2\cdot\left(d_1+r\right)^{-4}+4\cdot G\cdot\left(d_1+r\right)^{-4}+3\cdot\left(d_2+r\right)^{-4}+3\cdot G\cdot\left(d_2+r\right)^{-4}+2\cdot\left(d_3+r\right)^{-4}+4\cdot G\cdot\left(d_3+r\right)^{-4}}\right]$$

where $G = (\alpha\beta_{ant})^{-1} = 1/1000$. The numerical value of SIR is

$$\mathrm{SIR} = 21.672\ \mathrm{dB}.$$

Note that the first two terms in the denominator of the above equation represent interference from Tier 1, the next two terms from Tier 2, and the last two terms from Tier 3 interferers. The terms without G in the denominator correspond to interference within the base antenna beamwidth. The terms with G in the denominator represent interferers that have been attenuated by the composite BTS/CPE antenna discrimination.

The above example shows that a 4x3 cellular reuse plan could support a 64 QAM system with a minimum SIR objective of 20 dB. A 4x3 pattern permits the same frequency to be reused in every 4th cell. Note that a confidence factor of 1 dB to 3 dB is usually added to the SIR objective in an actual system design. Additional cell sectoring and better quality CPE directional antennas could be used to increase the SIR. For example, a 4x6 reuse pattern would increase the SIR by approximately 3 dB.

5.2 Co-channel Interference for ATDD Systems

ATDD systems use the same transmit frequency for both BTS and CPE sites. ATDD systems use traffic-adaptive time slots, rather than fixed time slots, for upstream and downstream transmissions. This permits the ATDD systems to allocate traffic capacity to the upstream or downstream, on a flexible, channel by channel basis. Flexible ATDD systems, however, do not coordinate BTS and CPE transmissions between co-channel cells. Therefore, the local BTS site is subject to interference from both neighboring co-channel BTS and CPE transmitters. Refer to Figure 13. This diagram shows interference from the co-channel transmissions in Cell B interfering with a CPE transmission in Cell A.

The worst-case co-channel interference for an NLOS ATDD system can be shown to be the BTS transmitters in neighboring BTS cells interfering with transmissions from the local CPE sites. Refer to Figure 14. The BTS sites in MMDS systems generally use tall towers to maximize the cell coverage area; consequently, these towers increase the likelihood of LOS propagation between the BTS sites of neighboring co-channel cells. This problem is exacerbated in NLOS MMDS systems where LOS does not exist between the local BTS and CPE sites. In addition, the BTS transmitters generally transmit at higher power levels than CPE transmitters and are active approximately 50% of the time.

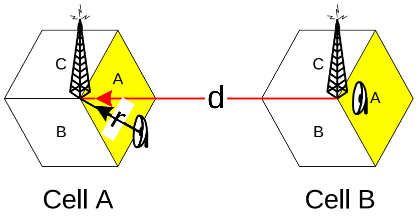

Figure 13: ATDD co-channel interference.

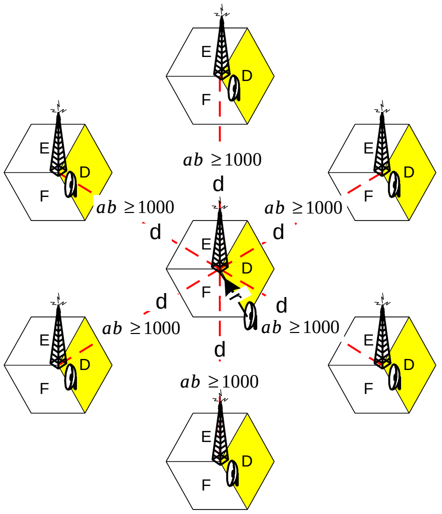

Figure 14: ATDD Tier 1 interference.

The interference from neighboring co-channel CPE transmitters is present, as with the FDD systems; however, it is significantly less than the interference from the BTS transmitters in NLOS systems. The CPE interference, therefore, has not been included in this analysis. It should be noted that the co-channel interference in both LOS and NLOS ATDD systems will always be worse than similar FDD systems, since ATDD systems experience interference from both BTS transmitters and CPE transmitters.

The co-channel calculation for an ATDD system includes both LOS elements, with a path loss exponent of 2, and NLOS elements with a path exponent of 3 to 4. In the calculations below, we will use the power loss formula given as [2]

$$P_r = P_0 \,(d / d_0)^{-n}$$

where P_r is the received power at a distance d from a transmitter as shown in Figure 6. P_0 is the power received at a distance d_0 from the transmitter. The distance d_0 is called the interception distance, the interception point is the boundary where the path loss slope changes from LOS to NLOS. For a transmitter antenna the interception distance corresponds to the largest sphere where free-space formulation is valid. In [2] the distance

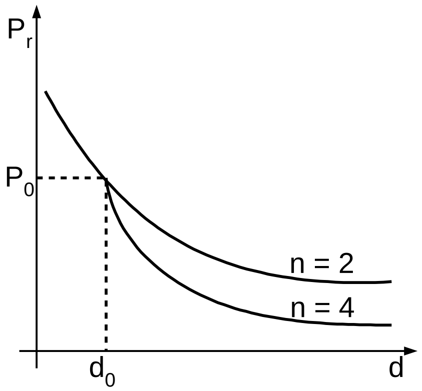

Figure 15: LOS and NLOS power loss formulation of [2] and the interception distance d_0.

d_0 is stated to be tens of meters. A 200 meter (0.124 mi.) interception distance is considered to be typical for an MMDS system in a suburban area and will be used in the ATDD SIR calculation.

The worst-case co-channel signal-to-interference ratio (SIR) is calculated for a 4x3 cellular reuse pattern, assuming a directional antenna discrimination of 1000 (30 dB) for each co-channel interferer and a cell radius of 5 miles. Non-line-of-sight (NLOS) propagation is assumed between the CPE and associated BTS site; line-of-sight (LOS) propagation is assumed between the three tiers of co-channel BTS sites. Note that a path loss exponent of 2, corresponding with line-of-sight (LOS) propagation, is used in the denominator of the following equation. A path loss exponent of 4, NLOS propagation, is used in the numerator.

$$\mathrm{SIR} = 10\cdot\log\left[\frac{\left(\frac{r}{r_0}\right)^{-4}}{\left[6\cdot G\cdot\left(\frac{d_1}{r_0}\right)^{-2} + 6\cdot G\cdot\left(\frac{d_2}{r_0}\right)^{-2} + 6\cdot G\cdot\left(\frac{d_3}{r_0}\right)^{-2}\right]}\right]$$

This formula yields

$$\mathrm{SIR} = -1.096\ \mathrm{dB}.$$

It is possible to reduce frequency reuse and achieve a higher SIR. However, this does not result in a practical system. It can be calculated that, for r = 5 miles, the distance d should be equal to about 196 miles in order to reach a 20 dB SIR objective! In addition to this unrealistic d, it would require an unrealistically large number of cells and channels to implement the reuse plan. Another possibility is to reduce r, resulting in a denser network with higher capital expenses.

5.3 Comparison of TDD and FDD Spectral Efficiency

Although ATDD systems may increase the channel efficiency by dynamically allocating bandwidth resources, it can be seen from the previous co-channel interference calculations that frequency reuse is less effective in NLOS systems. Consequently, the spectral efficiency of an uncoordinated ATDD can be shown to be significantly less than that of an FDD system in a typical MMDS system.

6 Summary

FDD requires duplexors and the presence of a guard band. It is true that duplexors add to the cost of an FDD system. However, for TDD systems, there are corresponding costs, such as the cost of two times faster ADC and DAC, and that of requiring two times larger number of operations. In a similar fashion, it is true that some expensive components can be shared in TDD, thus reducing the cost. However, this reduction in cost is offset by a corresponding reduction in receiver sensitivity and a more complicated design due to the complexity of timing signals to perform this sharing.

It is true that frequency duplexing requires a guard band. However, frequency allocating agencies often grant operating frequency licenses with FDD in mind, and in that case the band is not wasted. When the band is split for FDD, the design of a TDD system presents extra difficulties since designing an efficient wireless system that simultaneously operates in two noncontiguous bands is a design challenge. Even if the frequency allocation was not made for FDD (such as in MMDS), there are ways to come up with frequency plans so that while there are guard bands, no frequency band is wasted; namely, by using spatial separation within a larger frequency reuse plan. Such frequency plans enable a large degree of channel selection flexibility and reduce equipment provisioning needs in FDD. Furthermore, TDD requires a guard interval between transmit and receive cycles, thereby reducing system efficiency. Also, there are occasions where both FDD and TDD receivers require as high Q front-end filters to cope with strong interference that is close to the RF carrier frequency. One very real example of such an intereferer is an MMDS broadcast video channel.

TDD adds delay to protocols that involve a response from the base station. Examples of such protocols are time slot grants or collision feedback from the base station in MAC protocols and acknowledgement messages in ARQ systems. These delays reduce protocol efficiency. In FDD systems such delays are absent and therefore protocol efficiency is preserved.

Several recent articles in the trade press as well as in vendor announcements make the observation that the Internet traffic is asymmetric and TDD is therefore better suited for Internet access. According to this reasoning, one can dynamically change the transmit and receive cycles in TDD systems based on instantaneous traffic characteristics. This results in a better efficiency of the overall system. We agree that this would have been a good advantage if it could be realized in practical wireless systems. In reality, because of base-station-to-base-station interference, transmit and receive cycles of base stations need to be synchronized. Therefore, this major advantage of TDD goes away.

FDD systems can be shown to provide superior performance to ATDD and other TDD access schemes using non-coordinated base station transmissions in MMDS NLOS environments.

ATDD and other TDD access schemes are susceptible to interference between the neighboring co-channel base stations and have a significant frequency reuse disadvantage when compared to FDD access schemes. Since the antennas are usually mounted on structures much higher than the surrounding environment to permit communications with as many users as possible in a given area, LOS propagation conditions are likely to exist between the base stations. Large separation distances are required between neighboring co-channel cells when LOS propagation exists. These systems do not effectively support frequency reuse techniques.

FDD access schemes, on the other hand, are not susceptible to base station to base station co-channel interference. The principal co-channel interference in FDD systems is from the user (CPE) antennas that are typically mounted at or below roof level. The desired and co-channel interference signals in FDD systems experience the same propagation conditions, i.e. NLOS. Consequently, FDD systems are able to utilize conventional cellular frequency reuse techniques to maximize the system capacity and performance in NLOS environments.

Based on the observations above, FDD is still more advantageous as compared to TDD in wireless Internet access systems.

References

[1] J. B. Schwartz, “The risk of converting to two-way ITFS operation and strategies for mitigating them,” (http://www.itfs.org/articles/Two_Way_Risks.htm).

[2] T. S. Rappaport, *Wireless Communications,* Prentice Hall PTR, Upper Saddle River, NJ, 1996.