Airlink Management in Point-To-Point Systems: An Examination of FDMA, FDD, and TDD

A White Paper for Telecommunications Service Providers Using the AIReach® 9000 System

This AIReach Broadband White Paper introduces and discusses concepts in airlink management used in point-to-multipoint (PMP) radio systems for broadband wireless access (BWA). It examines the frequency division multiple access (FDMA), frequency division duplexing (FDD), and time division duplexing (TDD) airlink management techniques including their underlying use of time division multiple access (TDMA). Its conclusion is that for the business markets being addressed by telecommunications service providers using BWA, FDD offers significant advantages over the other approaches. For these reasons, the Hughes Network Systems, Inc. (HNS) design team chose FDD for the AIReach 9000.

The intended audience of this paper is technical staff members of service providers taking advantage of AIReach for BWA networks or considering doing so.

1.0 Background

PMP systems employ a number of advanced technologies to make their application simple, reliable, effective, and competitive. How well a system meets these objectives is a function of many factors, a key one being the underlying system design and execution by its manufacturer.

Another key factor, decided by the manufacturer, is how the airlink is managed. In a PMP system, airlink management is the means by which radio spectrum is made available to users. Different airlink approaches have different effects on the system operator. The airlink management approaches used in PMP systems – FDMA, FDD, and TDD – are well established, used worldwide, and their relative merits are well understood.

This paper will use several terms commonly used in broadband wireless access, but not in other fields. These terms and their definitions are shown in **Figure 1-1** and include:

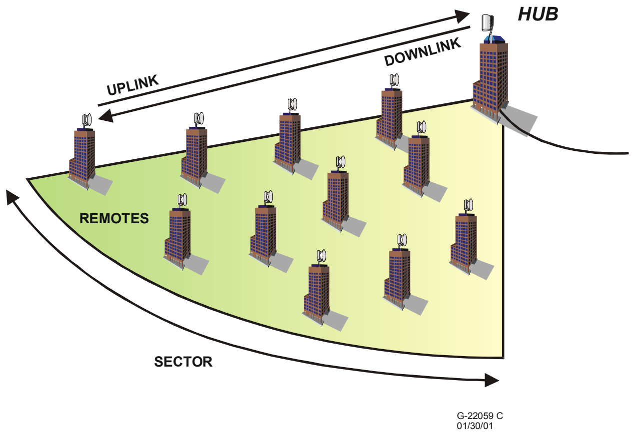

Figure 1-1. Definition

- Hub or Base Station: The building block of a PMP system is the hub, the central point in a radio coverage area. All PMP traffic flows through hubs.

- Remotes or Subscriber Terminals: Hubs communicate with remote terminals, which are located at the customer site. The airlink exists between hubs and remotes.
- Downlink and Uplink: Communications from the hub to the remote occur on the downlink. The uplink is communication in the opposite direction.
- Channel (not shown): The overall radio bandwidth is divided into units called channels. A channel is an amount of bandwidth with a known frequency allocation and managed as a single information stream.
- Sector: To concentrate power and increase range, the 360° coverage area of the hub is divided into sectors. PMP sectors typically range between 22.5° and 90°.

2.0 Frequency Division Multiple Access

FDMA is a fixed spectrum assignment system, which is based on the principles of frequency division multiplexing (FDM). While all airlink management approaches subdivide the available spectrum into fixed frequency channels, the fundamental premise of an FDMA system is that each channel is assigned and dedicated to a single subscriber or remote site unit in a PMP sector. This is depicted in **Figure 2-1.** Each channel is used for transmission in a single direction.

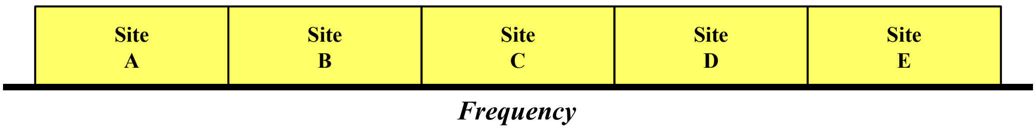

Figure 2-1.   Assignment of Uplink Channels in an FDMA System

PMP systems described as FDMA employ FDMA for the uplink and time division multiplexing (TDM) on the downlink. With the hub using TDM on the downlink, the channel is divided into timeslots. Timeslots can be flexibly addressed to any recipient as depicted in **Figure 2-2**.

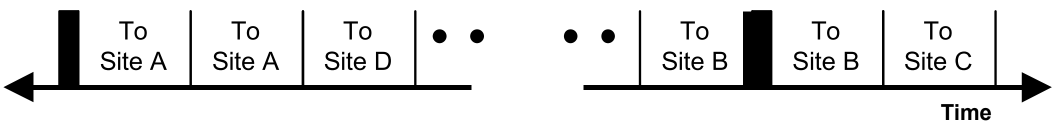

Figure 2-2.   TDM with the Hub Controlling the Channel

Note that FDMA operation in both directions is the defining characteristic of point-to-point radios. A point-to-point variant with multiple carriers in a single transmitter will suffer intermodulation interference and unpredictable ranges. Within an FDMA PMP system, once an uplink channel is assigned to a remote unit, it is dedicated to that unit.

The dedicated use of the channel is one of the primary drawbacks of an FDMA system. As a fixed assignment, no other users have access to the channel, even if it has capacity available. FDMA PMP systems also result in a large number of radio links or channels. Not only does this make frequency planning and capacity management much more difficult, but also the overall inflexibility of adding/ removing/modifying subscribers limits change management efficiency.

In large measure because of their inefficient use of spectrum, complex frequency planning and capacity management issues, and inflexibility in change management, FDMA systems are now widely regarded as unsatisfactory for PMP applications.

3.0 Time Division Multiple Access

TDMA was originally developed in the 1960s for satellite communications systems. It is a method used to manage the resource allocation of a *single* receiver (or receive channel) among *multiple* transmitters (or remotes in PMP). As will be discussed, in PMP systems TDMA is used on the uplink in FDD systems and on the shared uplilnk/downlink of TDD systems.

The principle of TDMA is that the full channel is available to all subscribers, but its momentary control or allocation is governed by their individual needs. The channel allocation is done in time, with the fixed, internal timeslot being the basic unit of allocation. Therefore, multiple sites transmit on the channel at their designated time for their allocated timeslots as shown in **Figure 3-1**. Seizure, control/transmission, and relinquishment of the channel must occur continually and across multiple sites with a high degree of precision, including accounting for propagation delay. Controlling this, however, means that some timeslots – and, therefore, resources – are consumed by system management traffic.

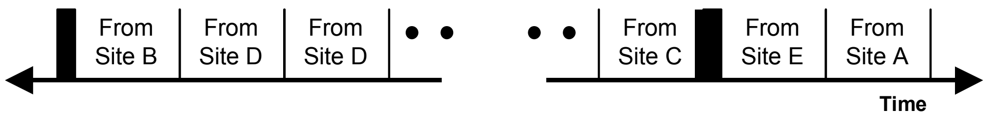

Figure 3-1. TDMA with Alternating Sites Controlling and Transmitting on the Channel

Attributes that can be stated or inferred about the use of TDMA in PMP systems include:

- Since resource is allocated as timeslots, the hub and subscriber units in a PMP system on the same carrier and in the same sector must be able to establish and maintain synchronization.
- Synchronization must account for propagation delay (3.3 µsec/km) as two transmissions may never overlap at the receiving unit (the hub in FDD or either hub or subscriber in TDD).
- System control is done from the hub.
- Remote units must have a means to convey their needs to the hub.
- A remote unit must be able to filter the traffic of other remote units.
- The management of TDMA adds channel-overhead, which detracts from payload capacity.

The true power of TDMA is its ability to dynamically assign resources according to need, a characteristic often called dynamic bandwidth allocation (DBA). Therefore, the resource of the frequency channel (which is divided in time) is used very efficiently across a subscriber population. This power, however, is accompanied by additional system complexity.

4.0 Frequency Division Duplexing

Duplexing schemes provide a means for managing upstream and downstream traffic flows. In FDD, these flows occur over two frequency channels, the uplink and the downlink. TDMA is used for resource allocation on the uplink. In PMP, only TDM needs to be employed on the downlink. In this mode, TDM is highly efficient and where it can be used gives all of the flexibility and benefits of dynamic bandwidth allocation with little of TDMA's complexity. Variants of FDD are widely used in radio and satellite systems.

Regulatory authorities assign spectrum for PMP systems in blocks. These assignments are typically block pairs (which are nonfrequency-contiguous). PMP system providers subdivide these blocks into channels of equal bandwidth. In FDD systems, the channels are divided equally between uplinks and downlinks. These are paired with each pair having the same frequency separation. This arrangement for contiguous and noncontiguous frequency assignments is shown in **Figure 4-1**.

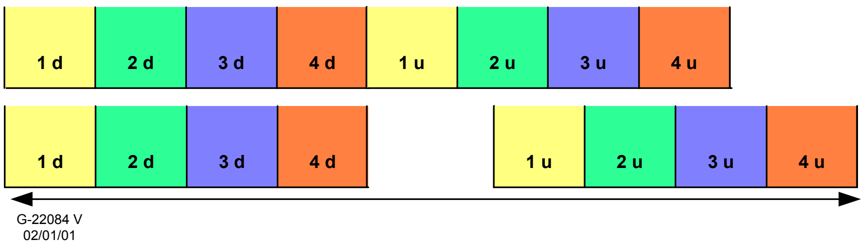

Figure 4-1. FDD PMP Frequency Plan for Contiguous (above) and Noncontiguous (below) Spectrum Assignments (Downlink (d) and Uplink (u) Channel Pairs Have a Constant Frequency Offset)

Using Channel 1 in the figure as an example, the hub transmits to its remotes on Channel 1d using TDM. All remotes in the sector filter the traffic intended for them. All remotes transmit on Channel 1u using TDMA, but do so at their assigned timeslots as discussed previously. The timeslot assignments vary according to the momentary needs of each remote site.

In an FDD system, the resource assignments on the uplink and downlink are independent. For example, over some time period the instantaneous allocation for a particular site could be 75% of the uplink bandwidth (i.e., timeslots), while on the downlink it could be only 10%. Furthermore, FDD channel *pairs* are independent. For instance, channel pair 1 (1d and 1u) is independent of channel pair 2 in terms of both allocations *and* TDMA or TDM timeslot timing. This even holds in the AIReach system when adjacent channels (e.g., channel pairs 1 and 2) are operating in the same sector.

5.0 Time Division Duplexing

In TDD, uplink and downlink traffic is conveyed on the same channel. Here, using TDMA, channel resources are assigned between all remote units and the hub in both directions. TDD systems have also been employed for many years.

The same spectral allocation discussed above for FDD is shown below in **Figure 5-1**, but is now showing a channel plan for TDD. Notice that the total amount of bandwidth consumed between TDD and FDD is the same.

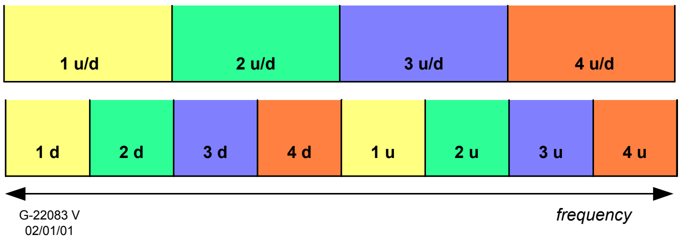

Figure 5-1. TDD PMP Frequency Plan (Upper) with a Corresponding FDD Plan

Similarly to FDD, TDD can flexibly allocate resources to support needs in two directions. However, we will see that TDD's flexibility is considerably limited by other factors.

6.0 Comparison of Airlink Management Approaches in PMP Systems

Having introduced FDMA, FDD, and TDD as they are used in PMP systems, we can now compare the three approaches.

6.1 Schematic Comparisons

Figure 6-1 is a schematic comparison of potential channel plans for the three approaches. In all cases, the downlink is broadcast to the remote units in the sector. As previously indicated, sectors in PMP systems typically range between 22.5° and 90°.

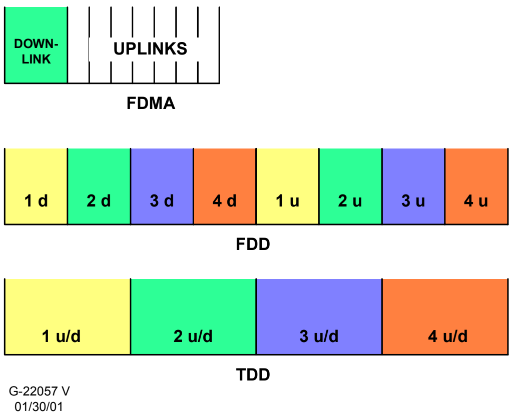

Figure 6-1. Channel Plans for FDMA, FDD, and TDD PMP Systems

Recall that in FDMA each uplink channel has fixed bandwidth and is dedicated to a single remote location. The FDMA downlink uses TDM and is broadcast from the hub and received by all the remote sites in the sector.

In FDD, the downlink is also broadcast from the hub to the remotes in a TDM mode.

A schematic of the channels operating for the three approaches is shown in **Figure 6-2**. In FDMA and FDD, separate transmit and receive frequencies are used in the uplink and downlink. The two frequencies are easily separated right at the antenna by a simple duplexer. (The manufacturer's cost of the duplexer is about $50 but it also contains filters.)

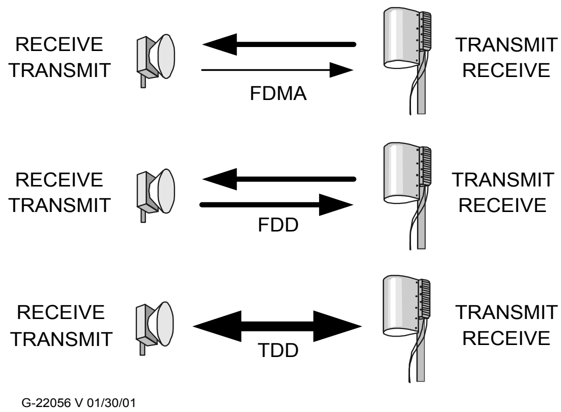

Figure 6-2. Schematic of Transmission Between Hub (Right) and Remote (Left)

With TDD, the hub and remote share a single channel in time. There is no frequency separation needed; instead, there is a separation in time. The transmit and receive functions must actively be switched on and off. The cost to do this is about the same as with a duplexer.

6.2 Guard Bands and Guard Time

In any radio system where spectrum is divided into channels, there are boundaries between adjacent channels. These boundaries are called guard bands and examples are shown in **Figure 6-3** for an FDD system and a TDD system. These systems are depicted as having similar total bandwidth definitions per duplex channel. (FDMA systems also have guard bands.)

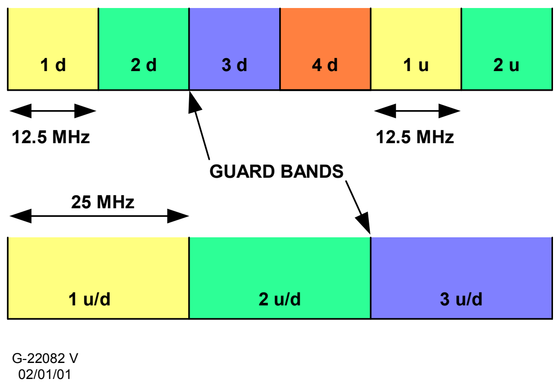

Figure 6-3. Guard Bands and Channel Bandwidths for Similar FDD (Top) and TDD (Lower) Systems

The significance of guard bands is not that they exist, as they do by definition, but how closely the spectral energy between adjacent channels can be spaced before the channels interfere with each other. The spacing is a function of several factors including the channel spectrum generated in the modem, the sharpness of various filters, phase stability in conversion stages, and linearity of the amplifiers. These factors come into play in all PMP systems and indeed all radio systems.

Figure 6-4 depicts two systems with different guard bands. If the bandwidth of the main spectral energy is the same in both cases, then the system on the left with the narrower guard band would have a closer channel spacing than the one on the right, all other things being equal. In practice, the channel spacing might be the same (the spectra on the right would have to move toward each other) but the system on the left with the narrower guard band would have a greater throughput because it would have less adjacent channel interference. In the HUGHES AIReach Broadband PMP system, the guard band is actually narrow enough that adjacent channels can operate in the same sector and throughput or capacity on a 12.5 MHz channel is 45 Mbps of payload (or in 25 MHz of spectrum, 90 Mbps of total payload).

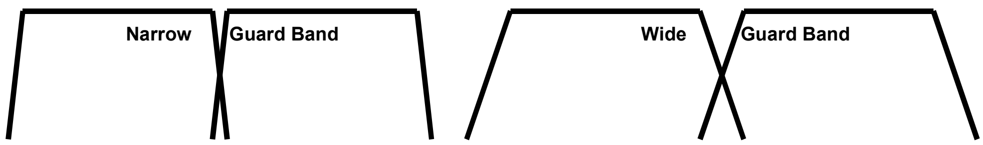

Figure 6-4 Narrow and Wide Guard Bands (The width of the guard band is a function of many design and engineering factors. All things being equal, for a given channel spacing the system with the narrower guard band will have a greater throughput.)

Guard time is an inherent overhead penalty in TDMA. It is the spacing in time between TDMA bursts and is a cushion to allow for inherent imperfections in such characteristics as synchronization, propagation delay, signal acquisition time, and TDMA framing. Because they use TDM, guard time is virtually non-existent in the downlink of FDMA and FDD systems. However, it does extract a penalty on the TDMA uplink side of FDD systems. Where guard time becomes significant is in TDD systems.

In TDD, additional time must be left to allow for the switchover between transmit and receive, called channel turnaround time. Turnaround time has two components. The first is the actual switchover between the transmit and receive functions. This occurs quickly however relative to the second component, accounting for propagation delay. The penalty due to propagation delay in TDD systems arises since sites must always account for the delay when they transmit, but face the paradox that they can never transmit and receive simultaneously. Having to transmit “in advance” but receive “in delay” is an impediment that can only be overcome by adding additional time cushion, which is a penalty on system capacity and spectral efficiency. We will also see that the propagation delay issue has an additional impact on intrasystem interference in TDD.

6.3 Spectral Efficiency

Spectral efficiency is a measure of the overall payload capacity across the assigned spectrum. It is impacted by factors such as guard band, guard time, link management overhead, and coding bits. On a practical basis, traffic profiles for the customer base being served must also come into play. A discussion or comparison of spectral efficiency assumes that link factors such as channel bandwidth, modulation, transmit power, and antenna gain, are constant. The latter is a good assumption in comparing FDD and TDD PMP systems. A related metric, frequency reuse, will be discussed later.

Without the overhead associated with TDMA, and if the site traffic patterns somehow matched very well with the channel assignments, an FDMA PMP system could have very good efficiency. However, since such matches do not occur practically and since there is no sharing of channels between remote units, FDMA systems have poor spectral efficiency. This is a key reason why the industry has moved away from FDMA PMP systems. Accordingly, the comparisons going forward will not always include FDMA.

Comparing FDD and TDD systems using the same bandwidth (e.g., a 12.5 MHz FDD channel pair and a 25 MHz TDD channel), the additional guard time and management required by TDD results in an approximate 10% advantage for FDD. To the point, in the AIReach system each 12.5 MHz channel carries 45 Mbps of user traffic or 90 Mbps (45 Mbps full duplex) in a pair of 12.5 MHz channels. This is a spectral efficiency of 3.6 payload bits/Hz. The superior spectral efficiency is one of the reasons why the HUGHES engineers chose FDD over TDD.

Because traffic profile is a practical factor in efficiency, highly asymmetric traffic carried on a very narrow channel would be advantageous to TDD. Business traffic, however, is highly symmetrical, especially when averaged over several sites as is done in PMP systems. This is another reason why HUGHES opted for FDD.

6.4 Operating Range and Coverage

Simply stated, within the context of the comparison (e.g., equal channel bandwidth, modulation, transmit power, antenna gains, receiver sensitivities and noise figure, and system availability), an FDD PMP system enjoys an approximate 12% operating range advantage over a TDD system. This equates to some 25% advantage in coverage area for a given PMP hub.
The reason for FDD's advantage is straightforward: Because the same channel is used for uplink and downlink, TDD modems must operate at twice the symbol rate (hence twice the bandwidth) of FDD modems to achieve the same throughput. Not only does this increase the cost of the TDD modem, but doubling the symbol rate halves the energy per bit (a 3 dB reduction in E_b/N_0 at any range). This degradation translates into an approximate 12% reduction in operating range at the 25-40 GHz frequencies used in broadband PMP systems. To compensate for this, a TDD system could double transmitted power, but additional power at millimeter wave frequencies — if it is even available — is perhaps the most costly element in PMP systems. This penalty in range and coverage was yet another reason HUGHES chose FDD over TDD.

6.5 Frequency Planning and Reuse

Frequency planning is one of the most important considerations in implementing PMP wireless networks. Spectrum is a valuable resource that must be managed for maximum reuse within the operating area. Frequency reuse in particular is a function of several factors including modem quality, filter sharpness, antenna sharpness, and dynamic power controls. These factors are much more functions of the manufacturer's design and execution than of the airlink management approach. However, there is another key factor, interference, where the differences between FDD and TDD are significant, and strongly favor FDD.

Figure 6.5a illustrates the core of a typical frequency plan for an operating region. The figure shows four frequencies: A, B, C, and D (four pairs in FDD) representing frequencies operating from hubs (the circles) with four sectors. Hubs face outward into the sectors;

remotes in the sectors face their hub. This discussion extends to larger numbers of frequencies and sectors.

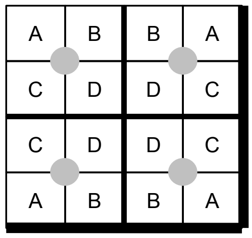

Figure 6-5a. Basic Four-hub, Four-frequency Operating Plan Building Block

As the coverage area increases, the pattern begins to repeat, and the potential for system interference comes into play. Interference arises as a remote in one sector can also “see” a hub other than its own operating on the same frequency. Interference represents a form of noise to a receiver.

Figure 6-5b depicts this situation for FDD. Here, the remote in the upper left-hand corner of the figure can also see the hub in the lower right hand corner. The relationship of the desired carrier to an interfering one is expressed by the C/I ratio. In this case, C/I can be determined based on the ratio of the distances between the remote and its primary and interfering hubs. Shown along the diagonal line, this ratio is 5:1, which equates to a C/I ratio of 14 dB. This means that for this particular location of a remote, higher order modulations (16-QAM, 64-QAM) are not available because of insufficient C/I. In the case of AIReach, the system will fall back to QPSK for this site only because of the AIRmatch™ Dynamic Modulation Matching feature. Note that as the location of the remote changes within the sector, the remote sees less interference (because of its narrow beam antenna and/or its close proximity to its own hub) and the C/I improves dramatically.

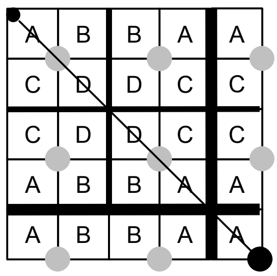

Figure 6-5b. The Pattern Begins to Repeat (Interference Consideration)

The interference situation for TDD is significantly worse. Because units transmit and receive on a single frequency, the potential distance between interfering units is less than in the FDD case. This is depicted in **Figure 6-5c**, where the distance ratio is shown as 4:1. This equates to a C/I ratio of 12 dB, which begins to limit even QPSK operation. The remote in the lower right could actually be closer to its own hub, which degrades matters further.

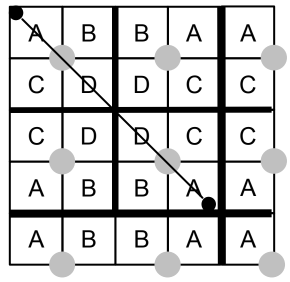

Figure 6-5c. Interference for TDD

Even the less sophisticated frequency plan depicted in **Figure 6-5d** suffers an interference problem with TDD. Here, the problem is intrahub interference. The sidelobes and backlobes of one hub antenna (sector 3) pick up the signal from the hub behind it (sector 1). While these lobes are down 40 dB or more, they are competing with very low power levels being received at the sector 3 hub. This is another interference problem.

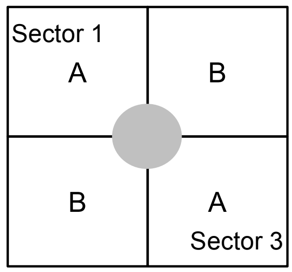

Figure 6-5d. Simple, Alternate Frequency Plan

To mitigate these situations, TDD systems synchronize transmit and receive systemwide as best they can in an attempt to restrict any remote unit or hub from transmitting when another is receiving on the same frequency. (Note that the significance of propagation delay increases because distances between interferers is greater.) This transmit/receive synchronization locking carries a significant penalty in limiting the flexibility of TDMA and dynamic bandwidth reassignment — in fact, defeating its whole purpose. Additionally, TDD systems pay a price in restricted frequency reuse or interference, which translates to “dead zones” and significantly more difficult frequency planning and operations planning and coordination. Not surprisingly, the major TDD systems in the world — Personal Handyphone System in Japan, and Digital European Cordless Telephone systems in Europe — operate with system-wide synchronization to avoid interference and they mainly carry voice traffic, which is tolerant of high bit error rates.

Interference is yet another reason why the HUGHES engineers chose FDD when they designed the AIReach system.

6.6 Summary Table

The distinctions between FDD — as implemented by HNS with AIReach — and TDD systems are summarized in **Table 6-1**.

Table 6-1. Comparison Summary of FDD in AIReach and TDD Systems

Comparison Metric	AIReach FDD System	TDD Systems
Guard Band: Frequency border or spacing between channels, some loss of spectrum.	Present in FDD systems. AIReach's very narrow guard bands even permit adjacent channels to operate in the same sector.	Present in TDD systems. With wider channels, TDD systems have fewer guard bands. Band widths depend on design and implementation.
Guard Time: Some loss of capacity due to needed time margin between TDMA slots.	Present in AIReach as it uses TDMA for channel management. Guard time is less of an issue on the unshared downlink.	Guard time inherent due to use of TDMA. Loss of capacity from guard time more severe in TDD due to channel turnaround time.
Spectral Efficiency: All other factors being equal, the net payload capacity across assigned spectrum.	Less guard time and other factors give AIReach superior efficiency at 3.6 payload bits/Hz. Permits 45 Mbps in 12.5 MHz channel.	Increased guard time and other factors limit spectral efficiency compared with FDD systems.
Operating Range/ Coverage:	All factors equal, FDD systems have about a 12% range/25% coverage advantage over TDD. AIReach has unique receiver technology to extend range about another 5%.	All factors equal, TDD systems pay a 3 dB penalty in E_b/N_0 due to the higher symbol rate on the channel. This is an inherent range penalty.
Frequency Planning and Reuse: Impacted by manufacturer's product design and execution, and by C/I issues.	AIReach's design and execution allow the best frequency reuse in the industry. Because of uplink and downlink frequency separation, FDD systems inherently offer better interference protection.	TDD systems are more susceptible to interference and result in poorer frequency reuse, more "dead zones," and more complex planning. System synchronization improves matters, but limits flexibility.

7.0 Conclusions

This AIReach Broadband White Paper has introduced concepts in airlink management used in PMP systems and has examined the advantages and disadvantages of each. FDMA was introduced but, as it has proven unsatisfactory in PMP applications, the discussion focused on FDD and TDD.

As stated in the introduction, both FDD and TDD are long-established technologies and their relative merits are well known and understood. Both take advantage of TDMA for dynamic allocation of capacity resources across the subscriber set. While a properly designed TDD system can have advantages in highly asymmetric traffic flows, business traffic is highly symmetrical, especially when averaged over several sites as is done in PMP systems. *This situation favors FDD, which also has sizable advantages over TDD in virtually every category that affects operators.*

When Hughes Network Systems, Inc., which has unparalleled experience in radio systems, considered design approaches for a PMP system, it evaluated numerous design approaches. Its conclusion was that FDD with TDMA was the clear choice for broadband wireless access serving business markets. The resulting product, AIReach, is now recognized as the PMP system offering the unique value proposition of limiting capital and operating expenditures, protecting the investment in spectrum, and increasing revenue opportunities.

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