Ethernet via Bidirectional Packet Based Telemetry – Frequency Division Duplex (FDD) vs. Time Division Duplex (TDD)

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ABSTRACT

An analysis of the implementation and application of two approaches to bidirectional packet-based telemetry: Frequency Division Duplex (FDD) and Time Division Duplex (TDD). The dual channel FDD system approach has two parallel links providing low latency with co-site interference considerations. The TDD Switched Telemetry System (SwTS) approach requires only one frequency which completely eliminates the co-site interference issue though introduces packet latency, transmitter switching and receiver synchronization considerations. This paper includes analysis of these two approaches including measured networked telemetry data from lab testing. How each of these two systems are configured based on a set of application specific requirements will be covered as well as the performance results when they are subjected to the same RF impairment and user traffic conditions.

INTRODUCTION

Transferring bidirectional Ethernet packets between a test article and ground station over a pair of frequency diverse serial streaming telemetry links has been successfully deployed over the past decade. Consolidating from a dual channel frequency diverse link to a single shared RF channel using time division has become an area of interest for both spectrum efficiency as well as co-site interference mitigation. A TDD bidirectional communications link can be a viable solution though introduces additional packet latency associated with transmitter switching times that may need to be considered. With both FDD and TDD solutions capable of providing bidirectional packet based data over a telemetry link this paper provides a comparison of an implementation of the two approaches with the goal of providing useful information to aid in the selection process. The first chapter reviews packet based telemetry systems. The second chapter provides a description of bidirectional FDD and TDD systems. The next chapter then dives deeper into technical issues which should be considered when deploying either FDD or TDD systems. The fourth chapter describes the test bed used to evaluate the FDD and TDD systems performance. Lastly, the final chapter presents some of the notable test results.

CHAPTER 1 - PACKET-BASED TELEMETRY

Traditionally, telemetry systems involve the sending of a continuous stream of data formatted as a custom solution to an application or more commonly following a standard such as the IRIG-106 PCM data format [1]. As packet-based systems were introduced the standards were expanded to provide a way to encapsulate packet data in existing PCM data streams [2]. More recently applications have appeared in which there is a design advantage to match the packet-based networks of the test article and ground systems. Two examples of packet based telemetry systems which have been introduced to the test range applications and other long distance aerospace applications are the iNET program developed TmNS transceiver [3] and the wireless Ethernet Telemetry EVTM configurable family of solutions [4]. The EVTM receiver and transmitter approach was used in this evaluation since it supported TDD and FDD modes. A high-level representation of the data flow in the EVTM based systems is shown in Figure 1. The EVTM system has been in use since 2015 [5] providing packet based down-links and up-links. A comparison of the EVTM and the TmNS link types can be found in [6]. A common application of deployed FDD packet-based systems has been the introduction of a control up-link allowing the ground system to control the selection of the down-link data source.

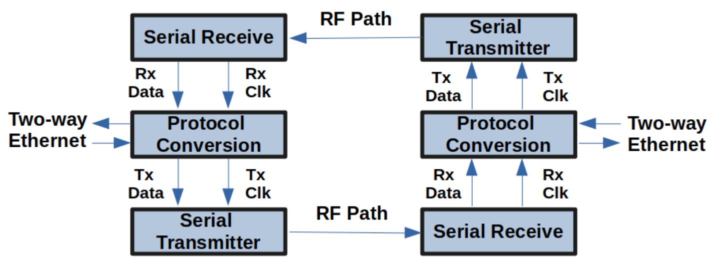

Figure 1: EVTM High-level Data Flows

CHAPTER 2 - BIDIRECTIONAL PACKET BASED TELEMETRY

Bidirectional Systems Overview

The bidirectional systems described in this paper consist of single carrier modulated waveform which employ two separately configured RF channels as shown in Figure 2. With the FDD system, some amount of frequency separation is required for isolation, unlike the single frequency TDD systems. The TDD also allows the reuse of a single RF channel by alternating the transmit directions between the up and down links. Each approach has fully independent up/down communications links each configured with the center frequency, modulation, data-rate, and power

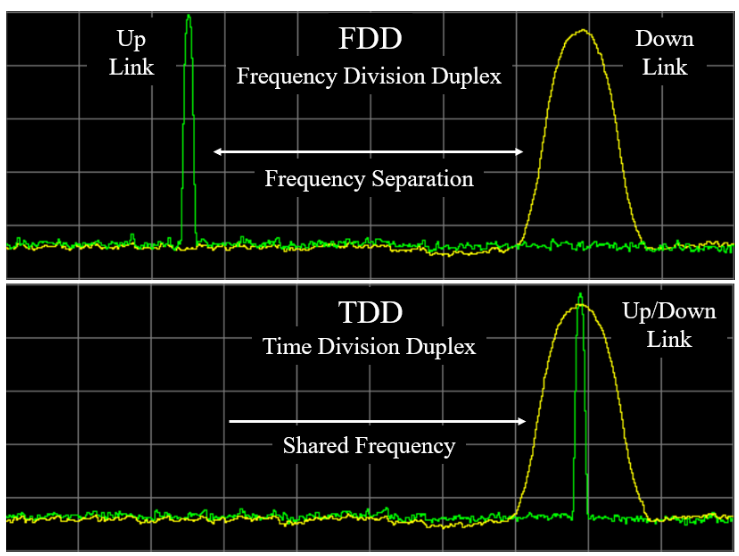

Figure 2: FDD and TDD RF Spectrum Usage

level based on the requirements for each direction. For example, a downlink may be a higher bandwidth relative to the uplink to provide higher throughput from the test article.

Frequency Division Duplex (FDD)
This approach consists of a pair of independent continuous streaming one-way links. Each end of an FDD link has local co-site receiver interference concerns that need to be addressed to maintain desired receiver sensitivity performance. Isolation requirements are met by inclusion of low-loss high Q filters in both transmit and receive paths. One key advantage of the FDD approach is that it provides a lower packet end-to-end latency than TDD links due to the simultaneous bidirectional nature of the FDD continuous streaming approach.

Time Division Duplex (TDD)
This approach uses a single frequency with a sequenced transmit event employing two or more transmitters. The method of providing timing for transmit access can be based on synchronized timing present at all transmitters typically derived from a GPS receiver connection for the test article and by way of a wired based timing protocols to a common time source for the ground system. An alternative approach is to have a single transmitter provide timing as a schedule master for the other transmitters in the network thus relaxing the need for a common network synchronization implementation. Typically, in the alternative approach the schedule master would be the test article in a telemetry system with ground antennas receiving up-link transmission timing from the test article. In both approaches the channel access is set by a transmit schedule at each end of the link. A transmit schedule can be defined by specifying the epoch time, slots per epoch, and slot allocation. An epoch is one complete receive/transmit cycle, a slot is a division of the epoch that is used for setting the transmit slot rate and the slot allocation is how many transmit slots are allocated to a link in any given direction. The slot allocation can be expressed as a ratio of the number of slots allocated in an epoch to the total number of slots in an epoch. For example, Figure 3 details a transmit schedule utilizing a 100 ms epoch time with 10 slots per epoch. In the example shown there is one uplink channel, with one slot allocated to that channel. The uplink Slot Allocation in this example is 1/10 = 10% and the downlink slot allocation is 9/10 = 90%. The channel slot allocation will need to be considered when determining how much bandwidth (BW) is required for transferring data in each direction. Transmit switching schedules may be modified to meet application specific requirements. Switching efficiency becomes a critical factor in low BW applications or where there are multiple uplinks with slot allocations.

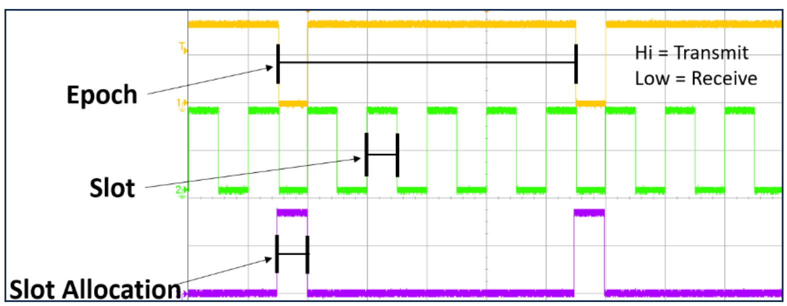

Figure 3: TDD Transmit Access Schedule

CHAPTER 3 - SYSTEM DEPLOYMENT CONSIDERATIONS

Overview

The selection of a bidirectional approach for an application typically starts with a trade-off requirement analysis between approaches. Primary areas of interest include co-site interference, packet latency, TDD switching efficiency, and antenna tracking performance.

FDD Co-site Interference

Local receiver degradation often occurs when operating a high-powered transmitter and a sensitive receiver with a single or two antenna approach [7] as shown in Figure 4. An application may have both transmit and receive signals connected to a single broadband antenna using a diplexer as the primary source of transmitter/receiver isolation. An alternative approach is to use separate antennas where isolation then is a summation of filter selectivity, cable losses, antenna frequency

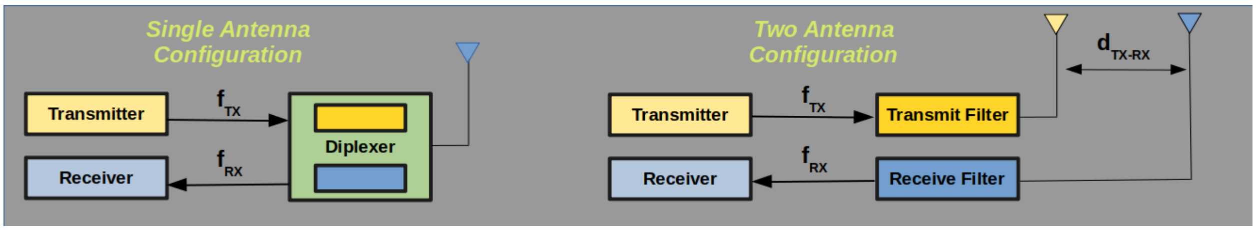

Figure 4: FDD Single or Dual Antenna Approaches

responses and path loss due to any antenna separation. The critical isolation for both approaches occur at both transmit and receive frequencies (f_{TX} and f_{RX}). Co-site interference can degrade receiver performance in two ways with the first being the high-power output level from the transmitter overloading the local receiver's front end. Receiver desensitizing starts to affect operation typically with an out of band signal of approximately -30 dBm. The transmit power at the antenna must be attenuated back to the receiver to guarantee that less than -30 dBm be allowed into the receiver input. For example, using a 10-Watt (+40dBm) transmitter, a receiver would typically require 40 - (-30) = 70dB of rejection to f_{TX}. Since the receiver needs low insertion loss at the receive frequency (f_{RX}), this requirement is often met by the insertion of filter into the receive path. The second source of receiver degradation is from broadband noise interference generated by the transmitter showing up in the receiver's front end. A typical 10 Watt (+40dBm) transmitter transmits broad band noise at all reasonable frequencies at a level of approximately -150dBc/Hz or -110dBm/Hz potentially impacting local receiver performance. Figure 5 details receiver sensitivity degradation due to additive noise impinging on the receiver's input. Assuming 0.5 dB allowable sensitivity degradation, the -110dBm/Hz transmit broad band noise would need to be attenuated by a minimum 70dB at f_{RX}. Since the transmitter needs low insertion loss at the transmit frequency (f_{TX}), this requirement is met by

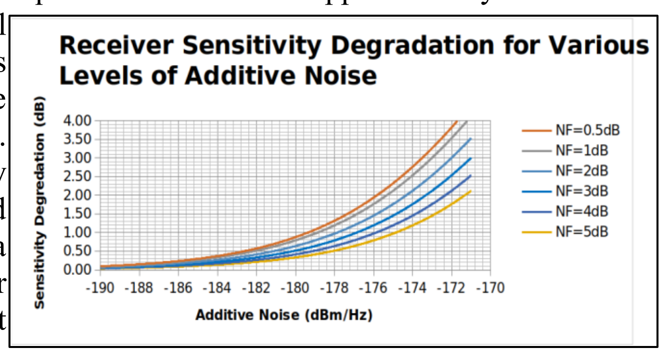

Figure 5: Receiver Sensitivity Degradation

insertion of a filter in the transmit path. In summary, typical FDD isolation requirements include 70 dB of rejection from the transmitter to the receiver at the receive frequency (transmit filter) in addition to 70 dB of rejection from the transmitter to the receiver at the transmit frequency (receive filter).

TDD Co-site Interference

In TDD systems with either a single or dual antenna as shown in Figure 6, co-site transmit to receiver interference is not a concern due to the transmit schedule allocating channel access to only

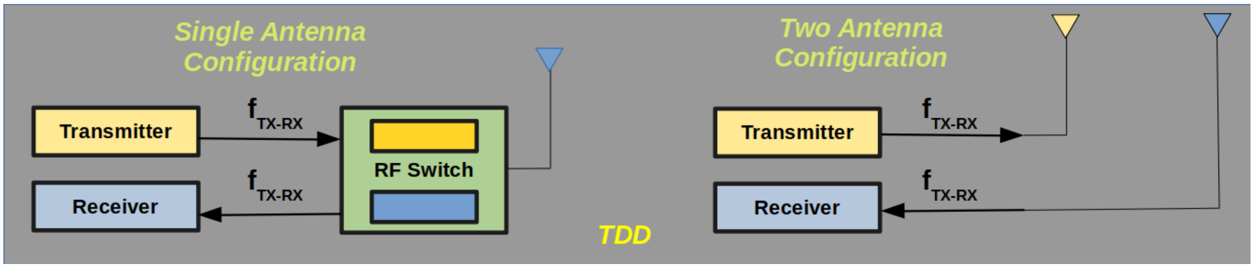

Figure 6: TDD Single or Dual Antenna Approaches

one transmitter at a time ensuring the local transmitter is off during receive windows to avoid receiver degradation. This allows for maximum flexibility in frequency management and system integration for TDD systems as the transmit and receive filter requirements are eliminated.

FDD Continuous Transmit Packet Latency

FDD link latency is primarily affected by the Ethernet to serial conversion and will vary with packet size and the serial stream clock rate as shown in Figure 7. RF characteristics such as modulation type and link distance have a less significant impact in overall packet latency. Forward Error Correction (FEC) will add additional link latency. One way packet latency for various data rates and LDPC block sizes are shown.

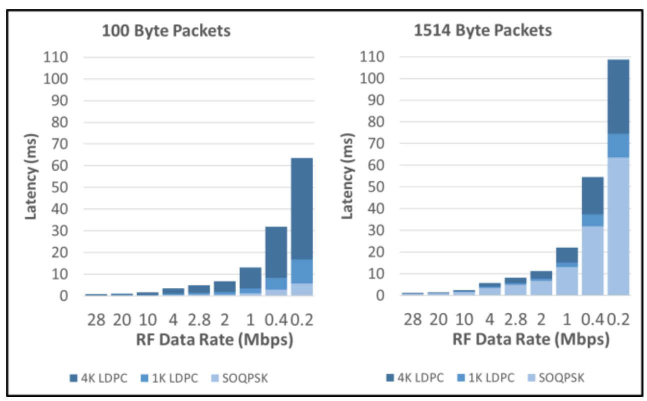

Figure 7: Single Direction Packet Link Latency vs. RF Data Rate

TDD Packet Latency

In a TDD link, the packet latency is a sum of the continuous transmit packet latency seen in the FDD link, as well as the transmit packet buffering delays introduced during receive event windows. Packets arriving during a transmit window [1,3] as shown in Figure 8, are sent across the link with the same latency as FDD continuous transmit systems. Packets arriving at the end of a transmit window [2,4] and during receive windows will be held in queue until the next transmit opportunity occurs making both epoch time and slot allocation factors in overall packet latency. Transmit switching schedules can be modified to meet latency requirements as needed. For example, applications requiring low latency in both directions such as VoIP may favor a balanced slot allocation schedule while the "Netflix model" of a high BW payload downlink with low BW command and control uplink may prefer a slot allocation schedule that favors a downlink with maximum throughput and minimal latency.

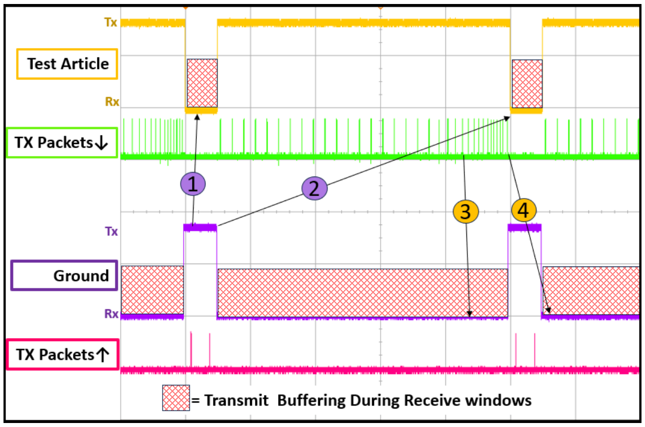

Figure 8: TDD Packet Latency Sources

TDD Switching Efficiency

Switching from transmit to receive has time components associated with switching times, synchronization, and control messaging. Switching efficiency can be calculated by the following:

Total time used for switching:

TTsw = (Trfsw + Trxsync + Tctrlmsg)

Efficiency of the use of the channel in TDD mode:

*EFTDD = 1 – TTsw * Nswepoch * Nepoch*

Switching overhead increases with decreased epoch time and additional transmit slots within the epoch. Also, a system performance trade-off is required between latency and efficiency of sending data. Latency can be lowered with additional slot allocations though at a cost of efficiency due to additional source transmit transition times.

Bidirectional Antenna Systems

Telemetry tracking antennas generate steering information from a continuous streaming downlink signal. In FDD systems, traditional tracking techniques are able to be applied as the downlink tracking signal is always present. In TDD systems using traditional tracking methods, the outages introduced from transmitter switching will present erroneous tracking signals to the ACU. Current implementation of TDD switched telemetry systems rely on steering information to be provided from an external source such as a separate system tracking on a Serial Streaming Transmitter (SST) downlink signal. The adoption of modern telemetry tracking antenna systems has introduced the possibility of tracking on an intermittent TDD downlink signal. When building link budgets for both FDD and TDD applications the downlink availability typically has the benefit of a high gain parabolic reflector while the uplink signal may be limited due to frequency management restrictions and/or system limitations resulting in an imbalanced RF link budget. With uplink applications typically requiring much lower bandwidth than the payload downlink data, the uplink RF data rate can be scaled back proportionate to the downlink rate in efforts to balance link budgets.

CHAPTER 4 - EVALUATION TEST BED

The evaluation hardware consisted of a transmitter, receiver, and node controller at each end of the link. The FDD link test setup shown in Figure 9, had separate RF paths each connected with separate attenuators.

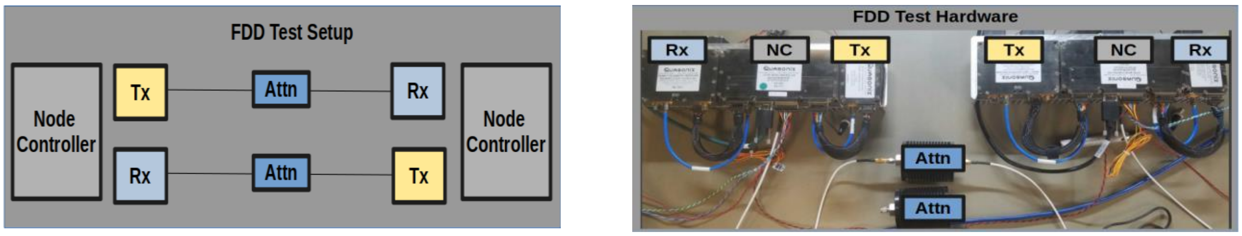

Figure 9: FDD Test Setup

The TDD test setup shown in Figure 10, made use of the RF switch contained in the Node Controller assembly to multiplex transmit and receive signals onto a single RF connection. In both configurations the Node Controller provided the serial to packet interfaces.

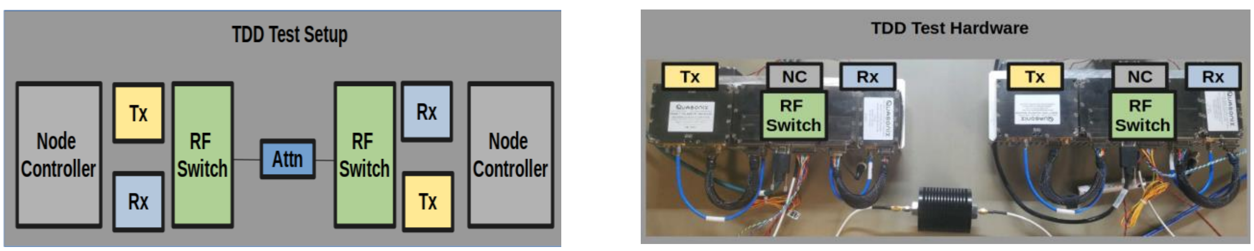

Figure 10: TDD Test Setup

Hardware Used

Transmitter (2)	QSX-VJR2-1111-20-04-05AB-HR-LD-VP
Receiver (2)	QSX-RDMS-1C15-A1-1111-EQ
Node Controller (2)	QSX-EVTM-NCR-RF

Test List

1: Packet to Serial Conversion Overhead
2: Packet Loss Rate vs E_b/N_0
3: Equalizer Performance

Link Parameters

Center Frequency (MHz): TDD 4915.5, FDD F_1 4915.5, FDD F_2 4700.
Modulation: SOQPSK-TG
Encoding: LDPC rate = 2/3, 1K & 4K Block sizes.
RF Bit Rate (Mbps): 28, 20, 10, 4, 2.8, 2, 1, .4, .2
Ethernet BW (Mbps): 0.1-25
Packet size (Bytes): 98, 1514

CHAPTER 5 – ADDITIONAL TEST RESULTS

Packet to Serial Conversion Overhead

The Ethernet packet to serial protocol will insert a minimum 1 Flag, 0x7E (1byte) + CRC (4byte) = 5 Bytes to the Ethernet frame. These 5 bytes account for the fixed portion of conversion overhead making packet size a positive variable in overhead efficiency. Bit stuffing accounts for the variable portion of overhead and will change based on the data presented. Bit stuffing works by inserting a '0' whenever five '1's are detected in the packet data so that the 0x7E HDLC flag is unique to non-packet data. This results in a bit stuff rate as high as 1/5 or 20% when all 1's are presented to the interface and as low as 0% when the packet data contains no lengths of 1's greater than four. The overhead of serializing the packet stream is shown in Figure 11 for a link containing different packet types. The all 1's test case was used as a reference of maximum bit stuffing and is not expected to occur in real-world environments.

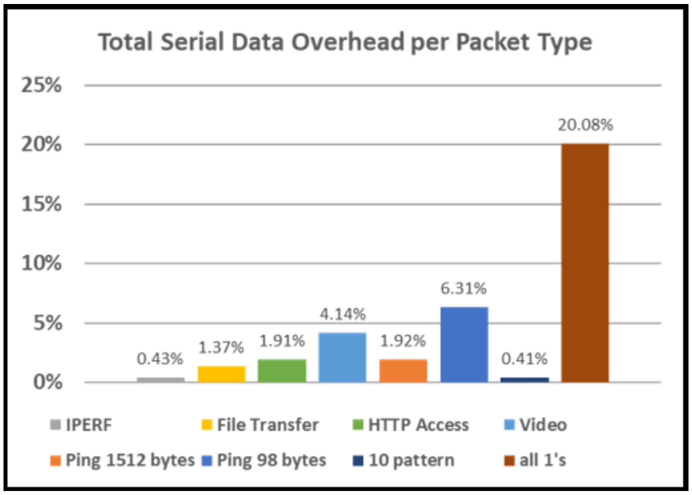

Figure 11: Packet Serialization Overhead

Packet Loss Rate vs E_b/N_0

In packet-based systems, a single bit error could result in losing an entire Ethernet packet. Errors within the Ethernet header, Flag Byte or FCS will result in the entire packet being dropped. Static AWGN tests were performed to compare Bit Error Probability (BEP) against Packet Loss Rate (PLR) when presented in a static AWGN condition. Measured results are shown for a 28Mbps downlink. A shift to the right in PER when compared to the BEP for a given static condition indicates the impact of errored bits within Ethernet frames. Introducing FEC significantly reduces the impact of an errored bit within an Ethernet frame.

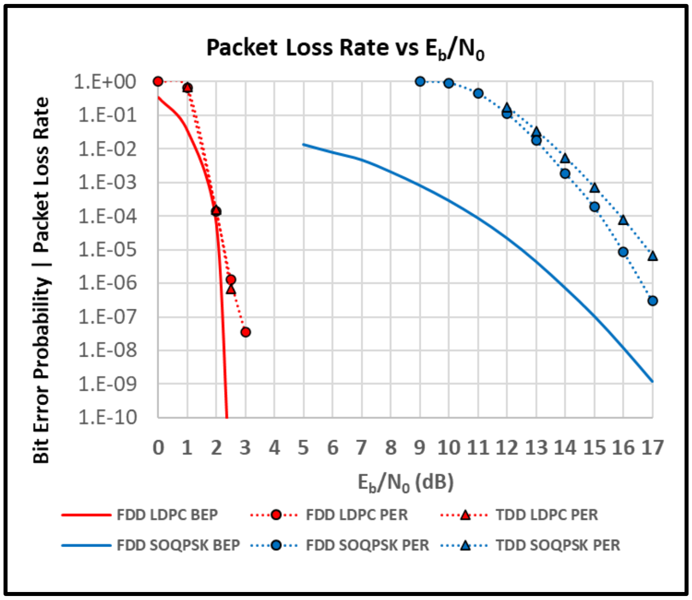

Figure 12: Packet Loss Rate

Equalizer Performance

Multipath as shown in Figure 13, is a common source of signal degradation in real-world test environments. In TDD applications, transmitter switching causes an intermittent receive signal that could potentially impact the receiver's ability to achieve maximum equalizer performance. Equalizer test methods [8] were used to evaluate the equalizer performance in a TDD link. For this test, a severe 2-ray multipath channel was created on the 28Mbps downlink signal at 20dB E_b/N_0. Measured BEP showed that the adaptive equalizer provided essentially the same multipath mitigation improvement in both FDD and TDD systems.

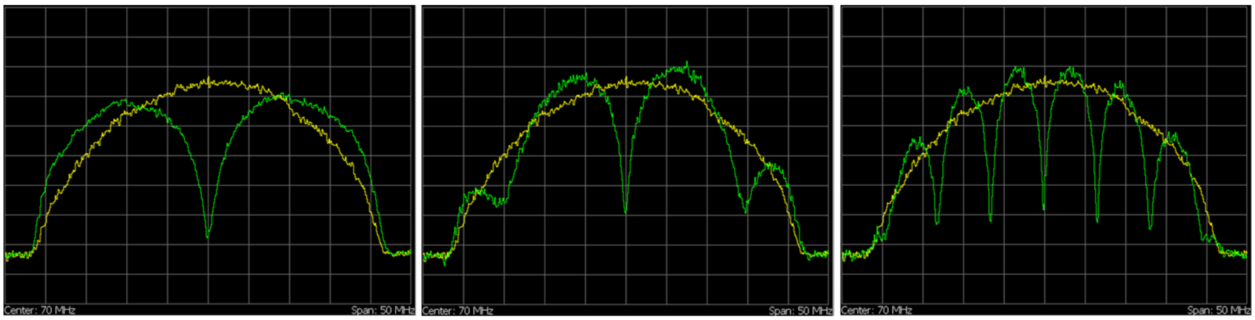

Figure 13: Multipath Test Conditions

FDD/TDD Summary

Table 1 summarizes some of the key aspects for the FDD and TDD link types.

Link Type	RF Channels	Isolation Requirements	Link Latency	R-T Switching Overhead	Antenna Trackable
FDD	2	Transmitter >70dB from F_{RX} Receiver >70dB from F_{TX}	Lowest available	None	Yes
TDD	1	None	FDD + Rx window time	Yes	Presents tracking implementation challenges

Table 1: FDD vs. TDD Comparison

CONCLUSION

We have identified some key tradeoff areas to be considered when selecting between two bidirectional telemetry link approaches. The FDD implementation has been an effective solution for bidirectional packet transfer, though has transmitter to receiver isolation requirements that need to be met in order to achieve optimal receiver sensitivity performance. The TDD implementation relieves the isolation requirement by setting a transmit access schedule, though has additional latency that comes from packet buffering during receive windows. Results from lab testing of each approach have been presented.

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