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TELEMETRY STANDARDS THAT IMPROVE LINK AVAILABILITY

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ABSTRACT

Inter-Range Instrumentation Group (IRIG) 106-17 is the latest release of the telemetry standard that defines many technologies that directly apply to increasing the link availability of aeronautical mobile telemetry (AMT) links. The Telemetry Group (TG) within the Range Commanders Council (RCC) has steadily worked with industry and government entities to develop standards that can be applied to the modern day serial streaming telemetry link that mitigate certain anomalies that exist in every airborne link in use today. Each of these technologies, or “tools” within the standard, are briefly addressed with real-world examples presented that directly show the benefit to the serial streaming telemetry link. The purpose of this paper is to not only increase awareness to the telemetry standard IRIG 106 but also provide some insight on when to apply these tools to increase link availability of a given telemetry link.

INTRODUCTION

Historically IRIG 106 has standardized best practices for modulation, recording, and multiplexing with the goal of ensuring interoperability. In response to decreasing AMT spectrum, recent additions to IRIG 106 have focused more on spectrally efficient modulations and techniques to increase the robustness of the link. Bandwidth efficient constant envelope modulation schemes Shaped Offset Quadrature Phase Shift Keying – Telemetry Group version (SOQPSK-TG) and Advanced Range Telemetry Continuous Phase Modulation (ARTM CPM) were included as were space-time coding, forward error correction, and smart diversity selection aimed towards increasing link performance. These technologies have all been laboratory and flight tested, standardized within the telemetry standard IRIG 106 [1], and productized by various vendors within the telemetry sector. This hardware is now finding its way onto test ranges allowing the telemetry engineer to optimize the telemetry link for differing test scenarios and link conditions.

In addition to the technologies just mentioned, tried and true methods utilizing spatial and frequency diversity have not been widely implemented due to the lack of a key enabling technology, namely metric driven robust diversity source selection. Recent advancements in this area have lead the RCC/TG to standardize upon a metric to assess link quality and pass this information along to a diversity source selector.

All these tools are standardized within IRIG 106, can they be put to practice in a cohesive manner with the goal of not only increasing the efficiency and robustness of the telemetry link but also provide the test engineer with error-free data?

IRIG 106 TELEMETRY STANDARDS

The Range Commanders Council (RCC) is dedicated to serving the technical and operational needs of U.S. test, training, and operational ranges. The RCC provides a framework wherein:

- Common needs are identified and common solutions are sought
- Technical standards are established and disseminated
- Joint procurement opportunities are explored
- Technical and equipment exchanges are facilitated
- Advanced concepts and technical innovations are assessed and potential applications are identified

The vehicle that serves this RCC framework are standards that ensure test range interoperability. The RCC is comprised of 11 groups. Some of the more familiar groups are the Telemetry Group (TG), the Frequency

Manager Group (FMG), and the Telecommunication and Timing Group (TTG). IRIG 106 is maintained by the Telemetry Group. The TG is comprised of five committees: the RF Systems Committee, Data Multiplex Committee, Telemetry Network Committee, Vehicular Instrumentation Committee, and Recorder Reproducer Committee. The topics discussed in this paper can be found in Chapter 2 “Transmitter and Receiver Systems” which is dedicated to standardizing technical characteristics and methods of improving the performance of the serial streaming telemetry link.

The main focus of IRIG 106 is to ensure interoperability, at a certain level of performance, of telemetry hardware between test ranges. This is done through technical standards dealing with frequency bands of operation, frequency tolerances, modulation scheme definitions, spectral masks, phase noise limits, etc. There are also appendices that standardize mitigation techniques for many of the link anomalies that exist in every aeronautical mobile telemetry link such as multipath, transmit antenna patterns, and telemetry links with limited link budgets.

Modulation Techniques

Prior to the need for more radio frequency (RF) spectrum by the commercial sector, pulse-code modulation frequency modulation (PCMFM, a form of continuous phase modulation CPM) was the only choice for modulating an RF carrier for telemetering test data for many, many years. PCMFM is an extremely robust waveform offering excellent detection efficiency at the expense of spectral efficiency.

Today, IRIG 106 has two additional choices of modulation schemes that trade spectral efficiency measured in terms of the 99% occupied bandwidth using the bit rate *R* for comparison with detection efficiency measured in terms of the ratio of bit energy to noise density (E_b/N_0) versus a bit error probability of $1e^{-5}$. See Table 1 for this comparison showing this inverse relationship. Spectral occupancy goes down and detection efficiency goes up as you go down in the table. These additional waveforms are SOQPSK-TG and ARTM CPM. All three waveforms in IRIG 106 are constant envelope waveforms specifically created to operate with non-linear amplification, a typical power amplifier design used in telemetry transmitters to decrease overall current consumption.

Table 1 - IRIG 106 Waveform Comparison

Waveform	Spectral Occupancy (99% OBW)	Detection Efficiency (BEP=$1e^{-5}$)
PCMFM	**1.16****R***	**9dB/12dB**
SOQPSK-TG	**0.78****R***	**11dB**
ARTM CPM	**0.56****R***	**13dB**

Space-Time Coding

Space-Time Coding (STC) [2], a form of transmit diversity (spatial diversity coupled with temporal diversity), has been shown through theoretical studies [8, 9] and flight testing [13, 14] to mitigate the co-channel interference problem created by utilizing two antennas to transmit the same telemetry signal. This has also been referred to in literature as the “two antenna problem” and is a self-inflicted source of co-channel signal distortion. During a flight test mission, telemetry signal shadowing can exist under certain airplane-to-ground station geometries if only one transmit antenna is used. Conversely, using two transmit antennas mitigates shadowing but introduces another issue, a distorted composite transmit antenna pattern with deep nulls due to amplitude and phase imbalances between the transmitted signals. STC is designed to mitigate this distortion by space-time coding the baseband signal into two RF signals, S0 and S1. Each are at the same center frequency and transmitted each using two separate antennas. This specific Alamouti STC [12] is tightly coupled with SOQPSK-TG modulation and requires a specific transmitter than can construct the 128-bit pilot sequence coupled to a 3200-bit block of Alamouti-encoded data then provide the two RF signals (S0 and S1) for routing to the two transmit antennas.

Forward Error Correction Code

Forward error correction (FEC) is used to enhance transmitted data reliability by introducing redundant data (parity) prior to transmission. Forward error correction has been around for many years and comes in many different forms. The FEC code implemented within the telemetry community and standardized within IRIG 106 is Low-Density Parity Check (LDPC) [3] which is a “block” code. A block of information bits have parity added to them which aids in the correction of errors in the transmitted information bits once they are received at the ground station receiver/decoder. There are two information block sizes (1024, 4096) and three code rates (1/2, 2/3, 4/5) available in IRIG 106 which trade over-the-air bandwidth with coding gain. LDPC is a very powerful correction code offering gains in link margin exceeding 9dB when compared to an uncoded telemetry link. [10]

Diversity Selection – Data Quality Metric and Encapsulation

Spatial and frequency diversity techniques are not new to the flight test community or to the wireless communication community in general. Both are mitigation techniques to fight the effects of multipath on the transmitted signal given one general concept, multipath will not occur at the same time with the same severity on two or more diverse telemetry signals. These multiple diverse signals can be created temporally, in frequency or in space (geographically). Frequency diversity is created on the test article; the same data stream is transmitted on two (or more) separate frequencies, for example F1 and F2. On the ground station both frequencies are received and a choice is made, either by a combiner (operating in the frequency domain) or best source selector (operating in the time domain), as to the best signal to use. Spatial diversity uses several ground stations placed around the test range(s) to receive the signal(s), route these demodulated signals to a main control center, then make a decision on the best signal to use. A combination of the two techniques can also be used to provide a greater level of multipath immunity. [15]

The key enabling technology that allows the combined use of these diversity techniques is smart source selection, commonly called Best Source Selection (BSS). Up until recently there was not a robust method to assess link quality, time-align or correlate each source, and then choose the best source on a bit-by-bit basis. The key here is not correlation or the bit-by-bit selection, but the accurate assessment of individual link quality done at the receive site. Bit errors are the one defining figure of merit for instantaneous link quality. In order to determine if a bit is in error, the original data must be known. Without this knowledge, the next best assessment is the probability that a bit is in error, or more commonly bit error probability (BEP) [6]. IRIG 106 contains a standardized method of assigning a Data Quality Metric (DQM) to a block of bits based upon a real-time assessment of BEP. Coupled with DQM is a standard way of transporting this information after reception for BSS consumption and processing [5]. This packaging of the metric and data together is known as Data Quality Encapsulation (DQE). [11]

To summarize, there now exists a method to assess data quality at the telemetry receiver and send this information along with a block of data it applies to. A BSS can now take in many diverse telemetry streams with DQE, use DQM values to smartly decide which stream to choose, and present the best source to the end user. Diversity methods to fight telemetry channel anomalies can now be reliably implemented offering a huge step forward in end-user data quality.

FLIGHT TEST DESCRIPTION

The mitigation techniques standardized in IRIG 106 provide a means for the telemetry engineer to increase the efficiency and robustness of the telemetry link. Prior to any of these technologies appearing in IRIG 106, significant testing was accomplished comparing performance against a baseline. (Example: When new modulation schemes were being evaluated, PCM/FM was the comparative baseline.) But how do we know the affect these technologies can have on the telemetry link? The metric used to assess increased link performance or to evaluate the effectiveness of these technologies is known as Link Availability.

Link Availability

In addition to the random errors caused by receiver noise, error bursts due to multipath propagation, signal blockage, RF interference, receiver synchronization loss, antenna track loss, etc. are common occurrences during flight testing. Consequently, making an assessment of link quality based solely in terms of a bit error rate is not representative of link performance. The metric that best describes how well a telemetry link functions over time, or in this case during a test run, is called Link Availability (LA) [4]. This metric accounts for all sources of link outages. Link Availability, expressed as a percentage, is calculated using the following equation:

$$LA(\%) = \frac{[TotalTime - (SES + PLS)]}{TotalTime} * (100\%) \quad (1)$$

where:

TotalTime is the time of the test run in seconds

SES is Severely Errored Second, a second where the BER $\geq 1.0e^{-5}$

PLS is Pattern Loss Second, a second where synchronization was lost

Link Availability characterizes the data quality the end user observes and places a number to that observation. It is now the universal metric used for determining telemetry link performance and assessing link improvements.

Mitigation Techniques Put To Practice

The objective of any telemetry link design is to provide the control room user with the best possible data. Using the mitigation techniques now in IRIG 106, dedicated real-world flight testing has been accomplished providing the opportunity to systematically improve the data quality. At each stage of the testing, from a baseline configuration to a system configuration using all of the tools available to improve the link, data quality improvement was assessed so a clear progression of increased link availability could be illustrated.

In order to provide a challenging environment in which to test, a helicopter was chosen as the test platform coupled with a flight path designed to incorporate elements of the test range that stressed the transmission channel. The test range can be characterized as a valley with surrounding mountains enabling a multipath rich environment. Three geographically diverse receive sites were chosen throughout the range which were outfitted for signal reception, signal monitoring and data logging during the flight testing. Data reduction was accomplished at the end of each flight ensuring the data captured provided results justifying test progression to the next mitigation technique. [7]

The helicopter test platform incorporated an STC-enabled transmitter with LDPC forward error correction. One of the transmitters RF outputs was connected to an upper telemetry antenna and the other RF output to the lower telemetry antenna. An important feature of this particular STC-enabled transmitter, when not operating in STC mode, is that it can operate as two independent telemetry transmitters. This is important for this type of testing as it provides the capability to perform comparative link testing incorporating different mitigation techniques such as frequency diversity.

On the ground side, three geographically diverse telemetry sites (Site 1, Site 2, Site 3) were each outfitted with a dual channel telemetry receiver with data logging and bit error statistics capture and recording capabilities. When frequency diversity was implemented in the helicopter, each of the channels in the receivers were coupled to the same antenna polarization (RHCP). When STC was flown, channel 1 was coupled to RHCP, channel 2 to LHCP. In both cases each channel operated separately and the combined output was not used. Site 2 and 3 also had a telemetry over internet protocol (TMoIP) capability using existing range infrastructure to allow channel 1 and channel 2 received data to be sent to a central location via a dedicated IP connection.

Site 1 was the central location which housed the Best Source Selector with internal data logging, and a bit error rate tester (BERT) for logging error statistics of the output of the BSS. In addition, Site 1 housed all of the equipment necessary to control all of the remote ground station test assets located as Site 2 and 3. Though not sent to the BSS, each receiver's combiner bit error statistics were logged for later analysis. Figure 1 illustrates the entire test set-up.

A pseudo-random bit sequence, length 2^{23}-1 (PRBS23) was used to simulate random data allowing bit error rate statistics to be captured at each site and at the output of the BSS. This information was then used for the calculation and determination of Link Availability enabling an assessment of link improvements for each flight. Table 2 shows the progression of flights starting with determining baseline telemetry link performance and progressing to applying diversity and coding techniques to mitigate channel impairments. The same flight path was flown for each flight, allowing comparisons of the results between flights, see Figure 2. The flight path selected was intended to stress the telemetry link and provide a means to show the benefits of each mitigation method. Data from each flight was not only viewed real-time at Site 1 but also logged, reduced, and analyzed after each flight. A diagram showing where and how the data was captured is included in Figure 1.

Table 2 – Flight Tests

Flight	Configuration
Flight 1 Test 1	PCMFM F1/F2 5Mbps
Flight 2 Test 1	SOQPSK-TG F1/F2 5Mbps
Flight 3 Test 1	SOQPSK-STC/LDPC F1 5Mbps

FLIGHT TESTING RESULTS

Baseline link performance testing for PCMFM modulation and SOQPSK-TG modulation both at 5Mbps were performed first. Since frequency diversity was one of the mitigating techniques under investigation, baseline link performance was further broken down on a per transmit antenna basis, upper versus lower transmit antenna. Once the baselines were determined, mitigation techniques to better the link performance were incrementally added. Test progression was as follows:

1. Baseline Link Performance – Link Availability on a per modulation and transmit antenna basis.
2. Single Site Frequency Diversity – Link Availability at each receive site utilizing frequency diversity.

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3. Frequency Diversity coupled with Spatial Diversity – Link Availability using frequency diversity coupled with best source selection of spatially diverse receive sites.
4. Single Site STC coupled with LDPC – Link Availability at each receiving site on a per receive polarization basis using STC to mitigate the nulling in the composite transmission antenna pattern coupled with LDPC for error correction.
5. STC/LDPC coupled with Spatial Diversity – Link Availability using STC with LDPC coupled with best source selection of spatially diverse receive sites signals.

PCMFM Baseline

Tables 3-5 show the baseline performance of a PCMFM link operating at 5Mbps for each transmission frequency at each receive site. These results are typical PCMFM link performance in a helicopter environment without any mitigation techniques applied. These will be the LA numbers used for comparison purposes for PCMFM. At each receive site, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz) and channel 2 was tuned to the lower antenna frequency (2260.5MHz). Link Availability was then calculated for both of these signals at each site.

Table 3 - Site 1 PCMFM Baseline

PCMFM Baseline Link Availability		
Flight	Upper Antenna (F1)	Lower Antenna (F2)
PCMFM	**86.1%**	**93.6%**

Table 4 - Site 2 PCMFM Baseline

PCMFM Baseline Link Availability		
Flight	Upper Antenna (F1)	Upper Antenna (F1)
PCMFM	**77.0%**	**87.0%**

Table 5 - Site 3 PCMFM Baseline

PCMFM Baseline Link Availability		
Flight	Upper Antenna (F1)	Lower Antenna (F2)
PCMFM	**83.3%**	**90.1%**

SOQPSK-TG Baseline

The LA results in Tables 6 through 8 are the baseline performance of an SOQPSK-TG link on a per receive site basis. Again, at each receive site channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz) and channel 2 was tuned to the lower antenna frequency (2260.5MHz). Link Availability was calculated for both of these signals at each site. The calculated LA numbers will be used as the baseline link performance for SOQPSK-TG when assessing link improvement techniques.

Table 6 - Site 1 SOQPSK-TG Baseline

SOQPSK Baseline Link Availability		
Flight	Upper Antenna (F1)	Lower Antenna (F2)
SOQPSK-TG	**76.7%**	**86.2%**

Table 7 - Site 2 SOQPSK-TG Baseline

SOQPSK Baseline Link Availability		
Flight	Lower Antenna (F2)	Upper Antenna (F1)
SOQPSK-TG	**72.9%**	**80.5%**

Table 8 - Site 3 SOQPSK-TG Baseline

SOQPSK Baseline Link Availability		
Flight	Lower Antenna (F2)	Upper Antenna (F1)
SOQPSK-TG	**81.4%**	**81.5%**

PCM/FM Implementing Frequency Diversity

Table 9 tabulates Link Availability when frequency diversity is implemented using PCMFM modulation. Whereas Tables 3-5 show LA for each individual receiver channel, Table 9 shows the LA results when the receiver's IF combiner at each site is allowed to choose between channel 1 and channel 2 as to the best signal. For this test, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz), channel 2 was tuned to the lower antenna frequency (2260.5MHz) and the receiver's internal maximal ratio combiner was used to select the best signal.

Table 9 - PCMFM Frequency Diversity LA

PCMFM F1/F2 Combined		
Site 1	Site 2	Site 3
99.3%	**96.2%**	**97.0%**

SOQPSK Implementing Frequency Diversity

The numbers in Table 10 show Link Availability when frequency diversity is implemented using SOQPSK-TG modulation. For this test, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz), channel 2 was tuned to the lower antenna frequency (2260.5MHz) and the receiver's internal maximal ratio combiner was used to select the best signal.

Table 10 - SOQPSK Frequency Diversity LA

SOQPSK-TG F1/F2 Combined		
Site 1	Site 2	Site 3
97.0%	**95.1%**	**92.4%**

PCM/FM with Frequency, Spatial Diversity

Building upon the results for single site frequency diversity, spatial diversity was then added in an attempt to further increase LA. For this test, each channel (channel 1 for F1, channel 2 for F2) of each receiver at each site, totaling 6 telemetry streams, was assigned a DQM value at the receiver and sent using the DQE message structure to the Best Source Selector. Due to infrastructure constraints the combiner output for each receiver was not used. The BSS correlated the sources then made bit-by-bit source selection based upon the DQM value of each input stream. This combined stream was then sent to the BERT where bit error statistics were measured and logged. Link Availability of this configuration is shown in Table 11.

Table 11 - PCMFM Frequency/Spatial Diversity

LINK AVAILABILITY	
Flight	Frequency/Spatial Diversity BSS
PCMFM	**99.4%**

SOQPSK-TG with Frequency, Spatial Diversity

This test configuration is the same as the previous section with 6 sources being sent to the BSS but using SOQPSK-TG modulation. Link Availability of this configuration using both frequency and spatial diversity is shown in Table 12.

Table 12 – SOQPSK Freq/Spatial Diversity

LINK AVAILABILITY	
Flight	Freq/Spatial Diversity BSS
SOQPSK-TG	**96.7%**

SOQPSK-TG with STC and LDPC

This test combined SOQPSK-TG modulation with Space-Time Coding and Low Density Parity Check forward error correction. Because frequency diversity was no longer used, the single frequency transmitted was 2240.5MHz with one RF output (STC signal S0) of the transmitter connected to the upper antenna and the other RF output (STC signal S1) connected to the lower antenna. STC is being used to mitigate the self-imposed “two antenna problem” (previously mitigated with frequency diversity) and LDPC is being used to correct errors caused by the transmission channel. Since individual channels in the receivers were no longer tuning to individual frequencies, the receivers were configured to receive and decode the STC-LDPC signal and were reconnected to the antenna multicoupler, channel 1 to right hand circular polarization (RHCP) and channel 2 to left hand circular polarization (LHCP). LA numbers for this configuration at each site for each receive polarization are presented in Tables 13-15.

Table 13 - Site 1

SOQPSK STC/LDPC Link Availability		
Flight	LHCP	RHCP
SOQPSK STC/LDPC	**96.3%**	**97.5%**

Table 14 - Site 2

SOQPSK STC/LDPC Link Availability		
Flight	LHCP	RHCP
SOQPSK STC/LDPC	**95.9%**	**96.7%**

Table 15 - Site 3

SOQPSK STC/LDPC Link Availability		
Flight	LHCP	RHCP
SOQPSK STC/LDPC	**97.7%**	**96.2%**

SOQPSK-TG with STC/LDPC, Spatial Diversity

The final configuration built upon the previous results and combined STC/LDPC with spatial diversity utilizing best source selection. This configuration used all of the technologies currently standardized within IRIG 106 with the goal of providing the most robust telemetry link given the available mitigation technologies.

Each polarization (RHCP/LHCP) from each receiver at each receive site, totaling 6 telemetry streams, was assigned a DQM value at each receiver and sent with the DQE message structure to the Best Source Selector. The BSS performed its function on these 6 sources and sent the selected output to a BERT. Link Availability of the output of the BSS was calculated and is shown in Table 16.

Table 16 - SOQPSK STC/LDPC

LINK AVAILABILITY	
Flight	Spatial Diversity BSS
SOQPSK STC/LDPC	**100.0%**

ANALYSIS OF RESULTS

There are multiple ways to analyze the volume of data that was collected during the flight testing. The point of this paper is to highlight the systematic gains assessed in terms of Link Availability that are possible given the various mitigation techniques available today and standardized within IRIG 106. In addition to this, and perhaps more importantly, the analysis should emphasize the importance of assessing link quality at the telemetry receiver, i.e., the Data Quality Metric, and providing that information via Data Quality Encapsulation to a Best Source Selector to intelligently select the best data and provide that to the end user.

Modulation Comparison

Before mitigation techniques are analyzed, a quick comparison of modulation schemes shows PCMFM as the clear winner for a helicopter operating in this transmission channel. This should be of no surprise as historically PCMFM is known as a very robust waveform with the receiver/demodulators exhibiting excellent detection efficiency and extremely fast receiver resynchronization properties. There is a reason it was used for over 40 years to telemeter data. Conversely, it is not nearly as spectrally efficient as SOQPSK-TG. As was stated above, historically the trade when determining modulation schemes is spectral efficiency versus detection efficiency, perhaps Link Availability should be added to this trade-off.

Another conclusion from the consolidated data presented in Table 17 is that the bottom antenna, regardless of the modulation scheme, always provided better LA. This was due in part to the flight profile and to the proximity of the rotary wing to the top transmit antenna. The flight profile led to portions of the flight where the upper antenna was shadowed from the receive site antenna due to the helicopter airframe. Also, the proximity to the rotary wing amplitude modulated the telemetry signal that at times caused the receiver to lose synchronization. Both conditions adversely affected overall Link Availability of the signal from the upper antenna.

Mitigation Technique Comparison with PCMFM Modulation

Systematic gains based on the mitigation technique for PCMFM are analyzed next. As IRIG 106 does not address PCMFM coupled with Space-Time Coding or LDPC forward error correction, these mitigation techniques were not implemented. Even so, frequency and spatial diversity techniques were tested and analyzed. Consider each one of the “Baseline” LA numbers in Table 18 to stand alone. In other words, during a “normal” flight test mission the data would be sent using one antenna at one center frequency and would be received using any one of the three receive sites.

Frequency diversity was the first mitigation technique explored. Each receive site configured the telemetry receiver to IF combine the two input signals, F1 and F2, and output the combined demodulated baseband signal to the BERT where LA was calculated using the captured statistics. IF combining, typically polarization combining and not frequency combing, is done every day on nearly every test range. In this case, significant gains in LA were achieved using frequency diversity with IF combining. At Site 1, LA increased from 93.6% to 99.3%, Site 2 increased from 87.0% to 96.2%, and at Site 3 an increase from 90.1% to 97.0% occurred.

The last of mitigation techniques for PCMFM used a combination of frequency and spatial diversity. For this test, the IF combiner in the receivers at each site was not used, instead each channel in the telemetry receiver (channel 1 for F1, channel 2 for F2) from each receive site was assigned a data quality metric and then sent via the range IP infrastructure using data quality encapsulation to the BSS resulting in 6 sources, each with a data quality estimate, to choose between. In this configuration resulting LA was 99.4%. In comparison, the telemetry link implemented in a fashion very similar to standard range practices today using a single frequency, a bottom-only antenna, and receiving at one ground station resulted in a best LA of 93.6%.

Coupling diversity techniques led to a very impressive gain in LA. Realizing this gain was achieved without the use of advanced techniques like Space-Time Coding, LDPC forward error correction, or even equalization. Rather, tried and true methods of frequency and spatial diversity were used and optimized by a link quality assessment made at the receive site and sent to a BSS using DQM/DQE for source selection.

Mitigation Technique Comparison for SOQPSK Modulation

A systematic approach in the application of mitigation techniques available for SOQPSK-TG modulation was applied to the telemetry link with the goal of clearly illustrating increasing LA with the results shown in Table 19. Baseline LA numbers from Table 17 are used for comparison. These baseline numbers can be considered as typical SOQPSK-TG link performance numbers, the configuration is representative of how a flight test mission would transmit and receive data. Best LA achieved under this baseline configuration was 86.2% using the bottom transmit antenna and receiving that signal at Site 1.

Frequency diversity was tried next with bit error statistics captured and analyzed for each receive Site 1, 2, and 3. Frequency diversity was achieved by configuring the telemetry transmitter to transmit the same information on two frequencies, F1 and F2. Each receiver at each site was configured to IF combine the two frequencies and output the demodulated combined signal. LA was calculated for each of the combined outputs shown in the row labeled “Frequency Diversity” in Table 19. Highest LA was 97.0% achieved at Site 1. Note: Most test ranges implement polarization diversity by IF combining left-hand and right-hand receive antenna polarizations, this test differed from that by combined two separate signals containing the same information centered at F1 and F2.

Spatial diversity was then added to this configuration using each received signal from each receive site (F1 and F2 with no IF combining) resulting in 6 frequency AND spatially diverse signals being sent to the BSS. Combining frequency and spatial diversity resulted in a LA of 97.0%, shown in the row labeled "Freq/Spatial w/BSS" of Table 19. It is interesting to note this is the exact same LA achieved at Site 1 using frequency diversity suggesting Site 1 was selected most of the time by the BSS.

Applying advanced mitigation techniques as specified in IRIG 106 was the final step towards trying to achieve error-free telemetry. The first step towards this goal was to determine single site link performance by coupling together Space-Time Coding and Low Density Parity Check forward error correction to the telemetry link. Reiterating. STC is used with SOQPSK-TG due to the tight coupling between modulation and the code. Each site used RHCP and LHCP as channel 1 and channel 2 inputs to the telemetry receiver and LA was calculated for each of these signal paths and shown on row "STC/LDPC in Table 19. Best LA that was achieved for this configuration was 97.1% receiving LHCP at Site 3. Note, this single site LA is greater than what was achieved using frequency and spatial diversity with uncoded SOQPSK-TG.

The last configuration again used a combination of STC/LDPC but this time coupled with best source selection. The received signals (STC/LDPC RHCP, STC/LDPC LHCP) had a data quality metric assigned to each signal accomplished at each of the three receive sites then encapsulated for transfer to the best source selector located at Site 1. This gave the BSS 6 coded, spatially diverse sources in which to make a bit by bit link selection based upon the assigned DQM for each source.

It is important to understand this last configuration for both the airborne platform and ground stations prior to taking an in-depth look at the results. Recapping, the STC-enabled transmitter had one RF output (S0) connected to the top antenna, the other RF output (S1) connected to the lower antenna and both STC and LDPC were enabled in the transmitter. In this specific case, the information block size for the LDPC code was 4096 and the code rate was 2/3. Data was PRBS23 at a rate of 5Mbps (uncoded), over-the-air rate after applying LDPC and STC was 7.8125Mbps transmitted at a center frequency of 2240.5MHz. At each receive site the telemetry receiver had channel 1 connected to the RHCP RF multicoupler, channel 2 was connected to the LHCP RF multicoupler, and STC and LDPC decoding for SOQPSK-TG was selected for each channel. The receiver then applied a DQM value to each demodulated signal and encapsulated that information for transport via TMoIP to the best source selector located at Site 1. A total of 6 coded, diverse sources were applied to the BSS which first time correlated the sources then made bit by bit best source selection based upon the DQM value for each. The output of the BSS was connected to a bit error rate tester where bit error statics were logged and displayed real-time.

The flight path shown in Figure 2 was flown and bit error statistics were captured at each site per Figure 1 throughout the flight. Referring to Table 19, LA for this flight and test configuration was **100%**. Equation 1 for Link Availability tells us this result means there were no severely errored seconds (SES) and no pattern loss seconds (PLS) throughout the flight. Because the BERT's used were able to log individual bit errors, a deeper look at the recorded bit error statistics revealed that the output of the BSS had zero bit errors throughout the flight.

Further investigation of this revolutionary result is justified. The underlying assumption of utilizing diversity for telemetry systems is that the channel distortion is uncorrelated with respect to the diversity method. For example, if diversity is used it is assumed that channel distortion including multipath, composite transmission antenna pattern nulling, ground station antenna pointing error, or threshold signal-to-noise ratio (SNR) do not occur at the same time at each receive station. Previous analysis has shown this can be illustrated by plotting the estimated bit error probability that each receiver assigned the signal throughout the duration of the test or during times of interest. This information can be captured at each receiver and then again at the BSS. If the distortion was time correlated these plots would show groupings of estimated BEP indicating that errors occurred at exactly the same time. If the plot was magnified, it would further show that there were groupings on a per site basis where degraded BEP was time correlated. If the receiving sites are truly diverse, there will be no correlation of multipath or channel distortion events. For this test we know this analysis to be true as the BSS always had an error-free source to select.

Table 17 – Comparison of Modulation Schemes

	BASELINE LINK AVAILABILITY					
	Site 1		Site 2		Site 3	
Flight	Upper Antenna (F1)	Lower Antenna (F2)	Upper Antenna (F1)	Lower Antenna (F2)	Upper Antenna (F1)	Lower Antenna (F2)
PCM/FM	**86.1%**	**93.6%**	**77.0%**	**87.0%**	**83.3%**	**90.1%**
SOQPSK-TG	**76.7%**	**86.2%**	**72.9%**	**80.5%**	**81.4%**	**81.5%**

Table 18 – Comparison of Mitigation Techniques, PCMFM

	PCM/FM LINK AVAILABILITY					
	Site 1		Site 2		Site 3	
Flight	Upper Antenna (F1)	Lower Antenna (F2)	Upper Antenna (F1)	Lower Antenna (F2)	Upper Antenna (F1)	Lower Antenna (F2)
Baseline	**86.1%**	**93.6%**	**77.0%**	**87.0%**	**83.3%**	**90.1%**
Frequency Diversity	**99.3%**		**96.2%**		**97.0%**	
Freq/Spatial w/BSS	**99.4%**					

Table 19 – Comparison of Mitigation Techniques, SOQPSK-TG

	SOQPSK-TG LINK AVAILABILITY					
	Site 1		Site 2		Site 3	
Flight	Upper Antenna (F1)	Lower Antenna (F2)	Upper Antenna (F1)	Lower Antenna (F2)	Upper Antenna (F1)	Lower Antenna (F2)
Baseline	**76.7%**	**86.2%**	**72.9%**	**80.5%**	**81.4%**	**81.5%**
Frequency Diversity	**97.0%**		**95.1%**		**92.4%**	
Freq/Spatial w/BSS	**97.0%**					
	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP
STC/LDPC	**96.3%**	**97.5%**	**95.9%**	**96.7%**	**97.1%**	**96.2%**
STC/LDPC w/Spatial BSS	**100.0%**					

CONCLUSIONS

There are few transmission channels as challenging as a helicopter flying at low altitudes. This combination coupled with rotary wing effects on the transmitted signal led to a multipath rich environment causing Link Availability for the baseline configuration of 76.7%. The baseline configuration mimicked traditional transmission and reception methods used today throughout the airborne telemetry community. By coupling various standardized techniques together for both PCMFM and SOQPSK-TG modulation schemes, significant increases in link availability were achieved when compared to the baseline configuration. These gains in LA were achieved using tried and true frequency and spatial diversity methods as well as methods standardized within IRIG 106, Space-Time Coding, Low Density Parity Check forward error correction coding, and Data Quality estimation. The key enabling technology was the ability of the telemetry receiver to accurately estimate signal quality without a priori knowledge of the signal. With this quality estimate in the form of an estimate of bit error probability, a best source selector with signal correlation capabilities could use the link quality estimates to intelligently select the best source on a bit-by-bit basis.

Once a baseline link performance was established, systematically stepping through frequency diversity, spatial diversity, STC, LDPC, and best source selection illustrated the gain associated with each method and ultimately showed how coupling these methods can significantly improve link availability.

Ultimately, the combination of SOQPSK-TG modulation with STC and LDPC with DQM/DQE assigned to the received signals allowed the use of a BSS to intelligently choose the best telemetry signal to output. This configuration achieved a LA of 100%. Further investigation into this result led to the realization that not one bit error occurred at the BSS output, realizing the goal of ***error-free telemetry****.*

The methods standardized in IRIG 106 have been shown to increase link availability either

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individually or when used in conjunction. These standardized methods should be considered when designing new telemeters if end user data quality is of ultimate importance.

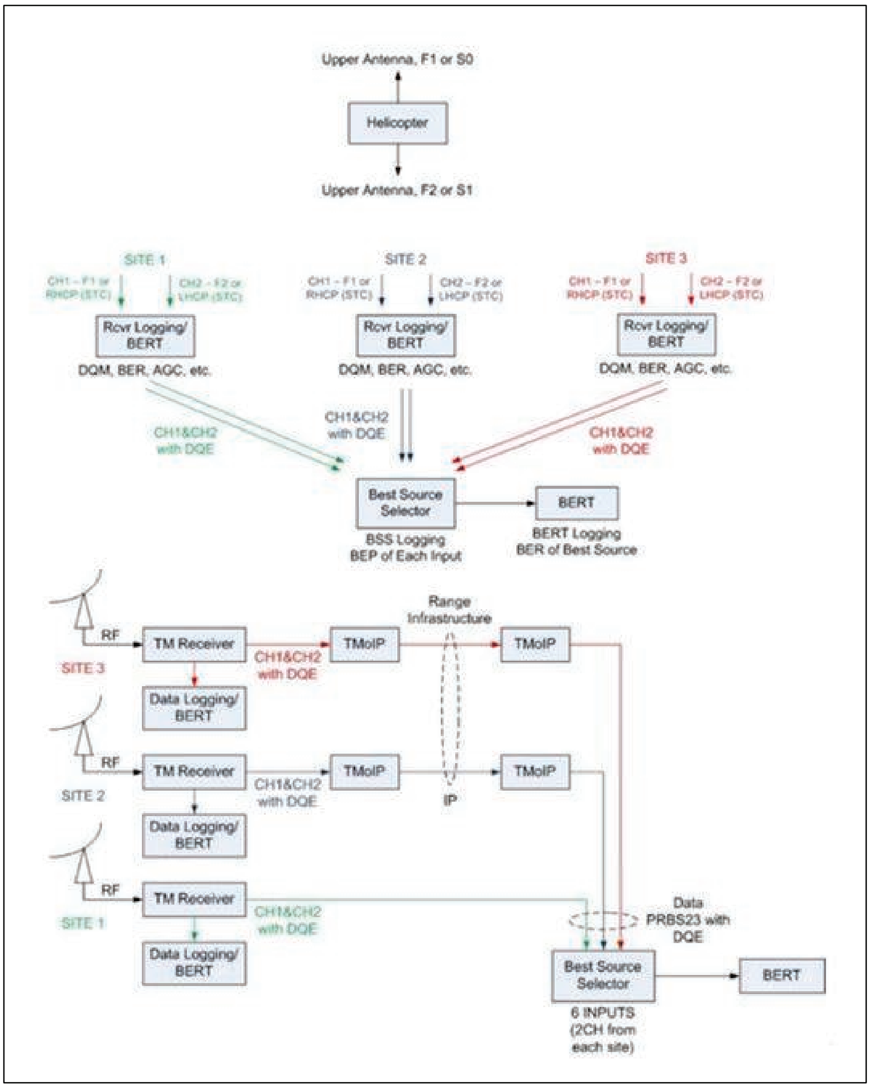

Figure 1 – Test Set-Up and Data Logging

Figure 2 – Flight Test Path

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