PERFORMANCE RESULTS USING DATA QUALITY ENCAPSULATION (DQE) AND BEST SOURCE SELECTION (BSS) IN AERONAUTICAL TELEMETRY ENVIRONMENTS

Mark Geoghegan
Robert Schumacher
Quasonix, West Chester, OH

ABSTRACT

Flight test telemetry environments can be particularly challenging due to RF shadowing, interference, multipath propagation, antenna pattern variations, and large operating ranges. In cases where the link quality is unacceptable, applying multiple receiving assets to a single test article can significantly improve the overall link reliability. The process of combining multiple received streams into a single consolidated stream is called Best Source Selection (BSS). Recent developments in BSS technology include a description of the maximum likelihood detection approach for combining multiple bit sources, and an efficient protocol for providing the real-time data quality metrics necessary for optimal BSS performance. This approach is being standardized and will be included in Appendix 2G of IRIG-106-17. This paper describes the application of this technology and presents performance results obtained during flight testing.

KEY WORDS

Best Source Selection (BSS), Data Quality Metric (DQM), Data Quality Encapsulation (DQE), Aeronautical Flight Testing

INTRODUCTION

Aircraft testing uses real-time RF telemetry for safety-of-flight and performance monitoring. This data allows the Test Conductor and engineering team to monitor the status of various aircraft systems and analyze critical performance metrics during flight. Decisions on whether or not to proceed with testing, modify or skip particular tests, or to change mission goals during a flight rely heavily on having accurate, up-to-date downlink telemetry data. Further, for "single-shot" tests where the test article is lost or destroyed, repeating the test is costly, or impossible. Therefore, it is mandatory that the telemetry system provides a reliable communications link with the aircraft under test. Unpredictable outages in connectivity or having to overly restrict the operating range can disrupt testing, require test point repetition, or force testing to be cancelled. This wastes valuable personnel and equipment resources costing a company time and money.

In cases where the link quality is unacceptable, a common solution is to use receive diversity techniques to obtain multiple recovered data streams with different (hopefully independent) error characteristics. These individual outputs can be processed to produce a single 'best source' result. Significant performance improvements can be obtained relative to the individual signals. Examples include polarization diversity, frequency diversity, and spatial diversity.

This paper presents recent technology developments and discusses the new IRIG-106-17 Appendix 2G standard [1] that describes a BSS system based on maximum likelihood 'bit detection' and an efficient encapsulation protocol for providing the real-time data quality metrics necessary for optimal BSS performance. This paper also describes the application of this technology and presents performance results obtained during flight testing.

BACKGROUND

There is a long history of successfully improving the performance of a communication link through the use of multiple receive channels. By time aligning and comparing received copies of each transmitted bit, a composite stream can be produced whose likelihood of error is statistically as good or better than that of the individual channels. A block diagram of a simple BSS system is shown in Figure 1. The simplest example is a majority vote scheme where three received data streams are compared and the 'majority' decision is used to produce the combined output. One drawback to this approach is that majority voting is only possible with an odd number of observations. Furthermore, two weak 'ones' may actually be inferior to a single strong 'zero' for certain types of channels. Although the concept of combining multiple noisy copies of a transmission to produce a better output is straightforward, achieving the full potential of this type of system presents several challenges.

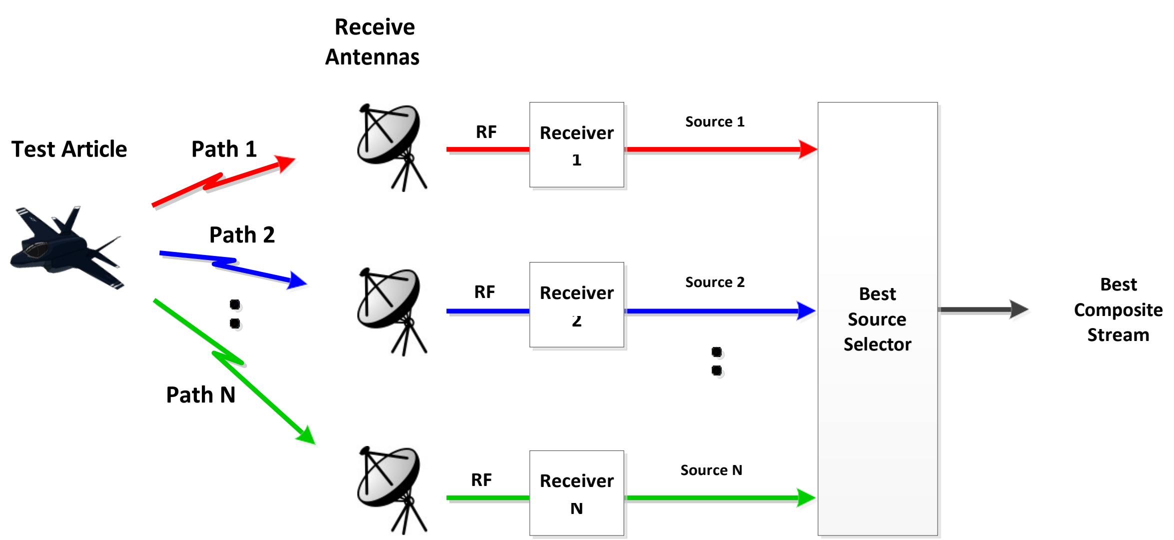

Figure 1: Best Source Selector System Diagram

The majority vote example illustrates the need for some type of confidence information to be supplied along with the binary data decisions. Developing a suitable confidence metric is challenging in itself as there are many possible indicators of bit quality including signal-to-noise ratio (SNR), error vector magnitude (EVM), measured errors in known segments of the transmission, and the number of errors corrected by forward-error-correction (FEC) schemes.

Unfortunately, it is unclear which metric, or combination of these metrics, provides the best performance, in all range environments. For example, SNR provides an excellent estimate of error rate in Additive White Gaussian Noise (AWGN), but performs poorly in multipath environments. Even worse is the fact that many of these measurements are typically unavailable due to the absence of coding, known framing patterns, or encryption. Even if a good confidence metric is generated, there is still the problem of transporting it independently across the test range along with the data, or encapsulating it into the data stream itself. Although proprietary schemes and equipment have tried to address these issues, the lack of performance standards and vendor interoperability have hindered the adoption of this powerful capability.

Multiple Bit Source Detection and a Standardized Encapsulation Protocol

The first question of the 'optimum' confidence metric was answered by Rice and Perrins [2], who concluded that the bit decision ($\mathcal{N}_0$, $\mathcal{N}_1$), along with its bit error probability (p_n), is sufficient to achieve maximum-likelihood bit detection (MLBD) performance. The calculation compares the sums of the log-likelihood ratios for channels with a 'zero' versus a 'one' to make its decision as shown in Figure 2. The detector behaves like a majority voter when all channels have the same probability of error, and a best source selector when there is a dominant channel.

$$\sum_{n\in\mathcal{N}_0} \log\left(\frac{1-p_n}{p_n}\right) > \sum_{n\in\mathcal{N}_1} \log\left(\frac{1-p_n}{p_n}\right) \rightarrow \mathbf{0}$$

MLBD Output

$$\sum_{n\in\mathcal{N}_1} \log\left(\frac{1-p_n}{p_n}\right) > \sum_{n\in\mathcal{N}_0} \log\left(\frac{1-p_n}{p_n}\right) \rightarrow \mathbf{1}$$

Figure 2: Maximum-Likelihood Bit Detection calculation from [2]

To illustrate the potential enhancement in link performance, a plot for the special case of equal channel probabilities is reproduced from [2] which shows dramatic improvements in link quality even with a relatively small number of low quality channels. Note that this plot assumes a binary symmetric channel and that the channels are statistically independent. Based on this mathematical result, the optimal approach is to accurately calculate and provide the probability of bit error along with each bit.

The second issue involves transportation of the confidence information. Many installations use receivers in remote locations and have limited connectivity (simple clock and data streams) to a central processing site, where multiple data streams converge and are processed by a BSS. Therefore, a natural solution is to encapsulate the additional BEP information directly into the data stream on the wired side of the range infrastructure. This approach doesn't require any changes or increase to the over-the-air transmission rate, as it adds the confidence information on the ground side only to provide the MLBD with the means to achieve optimal performance. An encapsulation protocol for efficiently realizing this capability is described in Appendix 2G, 'Standards for Data Quality Metrics and Data Quality Encapsulation', of IRIG 106-17.

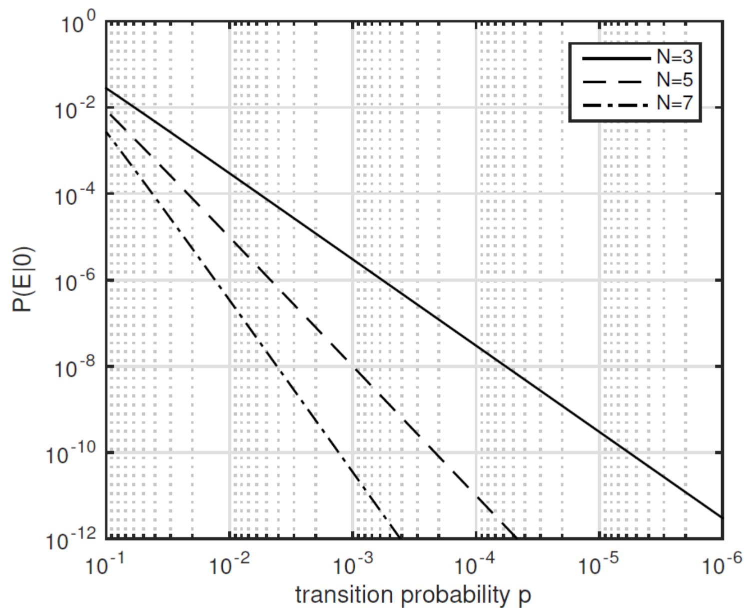

Figure 3: MLBD performance with equal channels ($p_n = p$) from [2]

The appendix consists of two separate parts, a standard for Data Quality Metric (DQM) and a standard for Data Quality Encapsulation (DQE). The DQM standard describes how to map the estimated Bit Error Probability (BEP) into a 16 bit word, but it does not define how the telemetry receiver performs its BEP estimation. Note that this approach does not depend on any particular modulation scheme, coding selection, transmission rate, or a priori knowledge of the data being transmitted. It is up to the receiver to accurately estimate the real-time BEP under the current channel conditions. Given the candidate decisions and their associated BEP, the BSS calculation is straightforward.

The DQE standard describes how to format the received telemetry data with the associated DQM for transport. A summary of the DQM and DQE protocol is illustrated in Figure 4 and Figure 5. The result is the definition and format of an optimal metric and an encapsulation protocol for a high-performance, interoperable, BSS system. Note that the BSS overhead on the ground side is at most (48+1024)/1024 = 4.7% and as low as (48 + 16384)/16384 = 0.3%. Again, there is no change or expansion of the over-the-air transmission format or rate.

The estimated BEP is first converted to a Likelihood Ratio (LR) between 0 and 1, converted to the log domain and quantized to 16 bits. The table below shows how the BEP, LR, and DQM are related. The DQE protocol consists of 48 bits that are periodically inserted into the data stream to convey the estimated quality for use by the BSS. For detailed information consult the standard [1].

k is the exponent for lowest estimated bit error probability
n number of bits in the DQM field
LR is the Likelihood Ratio

For this standard ***k*=12, *n*=16**.

$$DQM = \frac{-log_{10}(LR)}{k} * 2^n$$

$$LR = \frac{BEP}{(1 - BEP)}$$

BEP	LR	DQM
0.5	1.00	0
1e-01	1.11111e-01	5211
1e-02	1.01010e-02	10899
1e-03	1.00100e-03	16382
1e-04	1.00010e-04	21845
1e-05	1.00001e-05	27307
1e-06	1.00000e-06	32768
1e-07	1.00000e-07	38229
1e-08	1.00000e-08	43691
1e-09	1.00000e-09	49152
1e-10	1.00000e-10	54613
1e-11	1.00000e-11	60075
1e-12	1.00000e-12	65535

Figure 4: Summary of the IRIG 106-17 Data Quality Metric (DQM)

16 Bits	12 Bits	4 Bits	16 Bits	1024 – 16384 Bits
SW	RSV	VER	DQM	PAYLOAD

a. SW = Sync Word (16 bits). The Sync word is a fixed value of 0xFAC4.
b. RSV = Reserved (12 bits). Reserved for future use. These bits shall be set to zero (0) until used.
c. VER = IRIG 106 Version number (4 bits). Version number shall start with Version 0 (0000) for IRIG 106-17.
d. DQM = Data Quality Metric (16 bits). This field will contain the DQM value as defined in Paragraph 3.0.
e. PAYLOAD = Telemetry data payload to which the DQM value applies. The DQM and the Data Payload are contained in the same block. The minimum payload size shall be 1024 bits and the maximum size shall be 16384 bits. Payload size can be any multiple of 32 bits between the minimum size and maximum size.

Figure 5: Summary of the IRIG 106-17 Data Quality Encapsulation (DQE)

FLIGHT TEST RESULTS

In order to determine the potential performance improvement achievable in an actual flight test environment, a BSS system was tested in a military setting. The equipment consisted of three Quasonix RDMS receivers and a NetAcquire Advanced Correlating Source Selector (A-CSS). A standard PN test pattern was used as the transmission source and the recovered data and estimated BEP were encapsulated into the DQE stream and provided to the BSS. The resulting 'best' output was monitored by a BERT and the error statistics were logged. In addition to the BSS result, the embedded BERT capability within each receiver was used to log the error statistics of each receiver channel. This allows direct comparison of the performance of each site and the improvement achieved by processing all sites. The error statistics were converted to a Link Availability score which indicates the percentage of time the link conditions were better than the 10^{-5} BER threshold.

A simplified diagram of the BSS setup is depicted below in Figure 6. Although not shown in the diagram, the receivers are typically located at remote antenna sites with their clock and data signals being transported to a central location via range infrastructure. Several combinations of modulation format and rate were used over a variety of channel conditions. These included runway testing, up and away, and flight paths through challenging areas of the range. The focus of this test is on the improvement achievable with the BSS under real-world operating conditions.

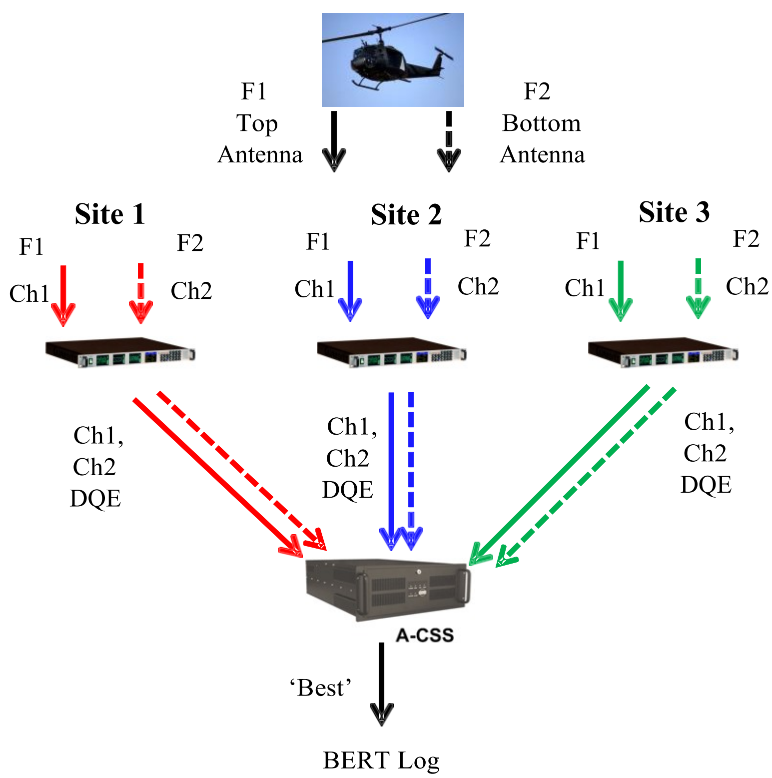

Figure 6: High Level BSS Test Setup

YUMA Proving Grounds (BSS with Multiple Receive Sites)

Flight testing at YPG used a flight profile that covered a variety of ranges and altitudes over diverse terrain, including open desert, mountains, and take-off and landing areas. Figure 7 shows the flight profile and relative positions of the receiving sites which are reproduced from [3]. During the four flights, several configurations of modulation, data rate, and coding were tested. Figure 8 shows the overall link availablility from the top (blue) and bottom (green) antennas for each of the individual sites as well the BSS (black) as measured by a known PN23 test pattern. Also included for comparison is the best performance achievable from a single site (brown). For this particular setup the bottom antenna outperformed the top, and using both antennas provided a substantial additional improvement. Finally, processing all the sites through the BSS yielded significantly better results and culminated with 34 minutes of error-free flight (0 bit errors over 1.02E10 bits at 5 Mbps) over this very challenging test course. This spectacular result illustrates the potential of the BSS system and associated technology to solve difficult telemetry links.

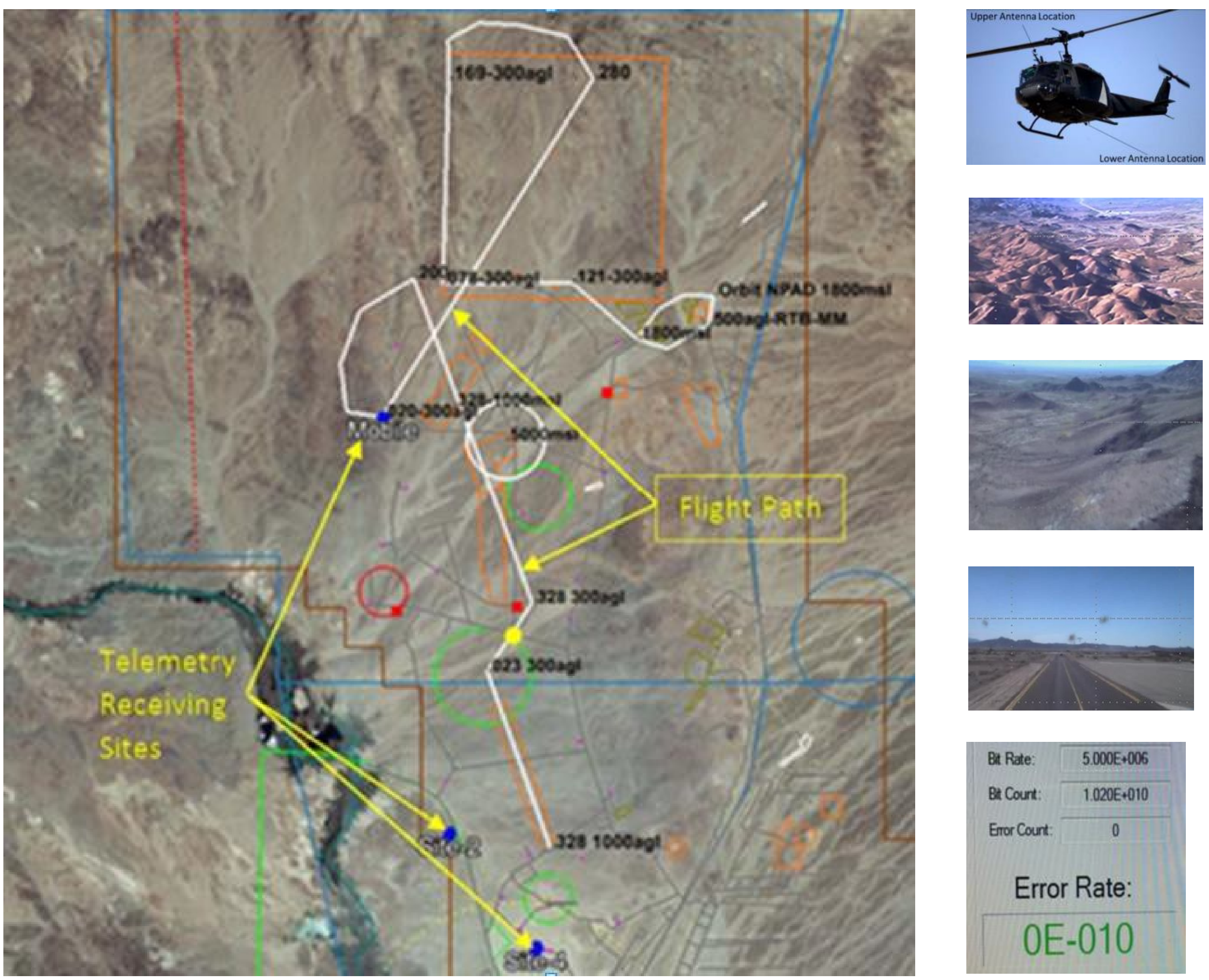

Figure 7: Flight profile from YPG flight testing [3]

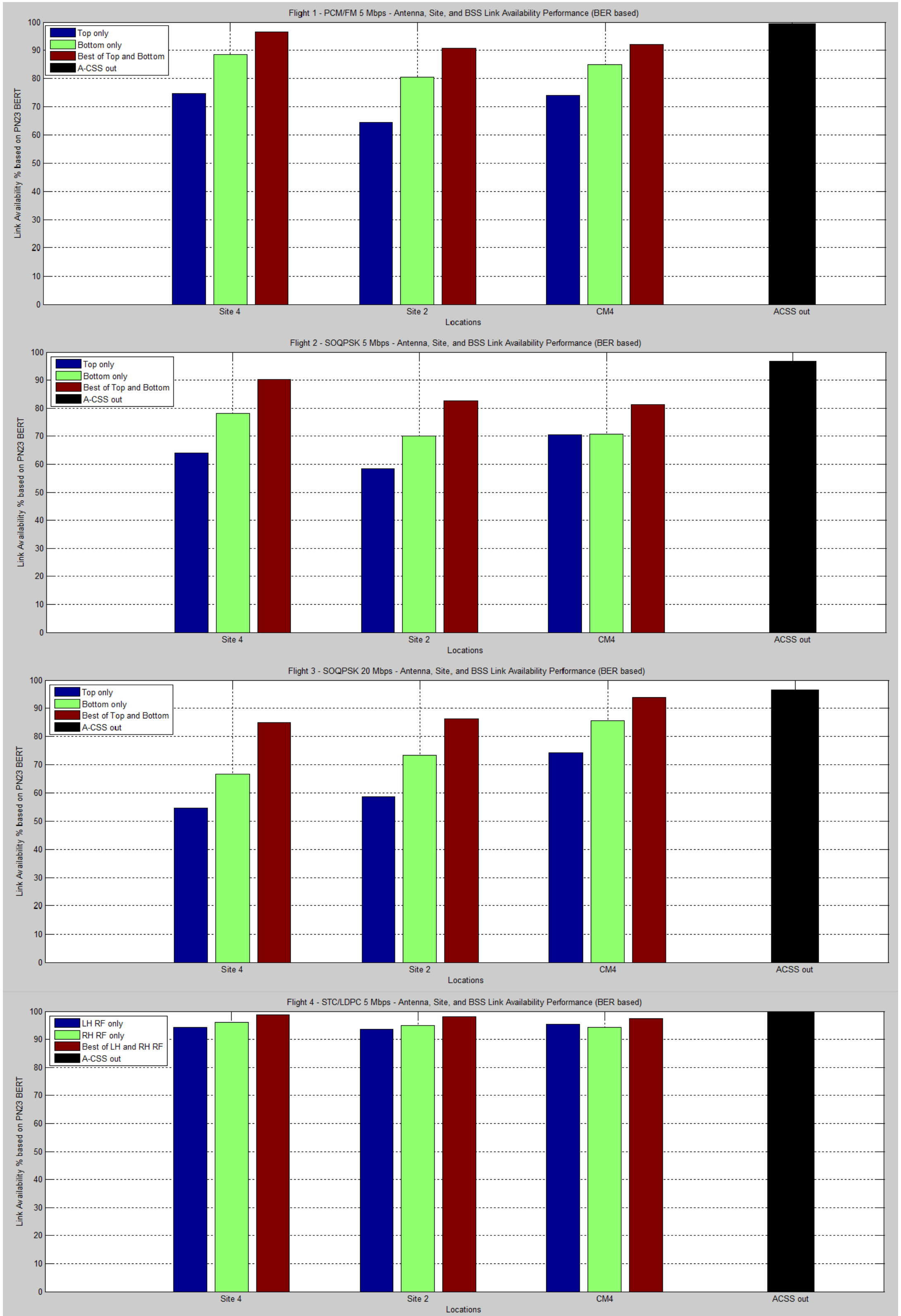

Figure 8: Link Availability of Individual Receiving Sites and BSS

BSS with a Single Receive Site

In addition to the testing performed at YPG, this BSS technology has also been field tested at a commercial avionics facility with similar results. While the most impressive performance gains were seen when multiple receiving sites were available, it was also shown that the performance with just a single site can be significantly improved if multiple received streams are available with different error characteristics. A common example includes frequency and polarization diversity as shown in Figure 9. Furthermore, specialty processing modes such as signal combining or adaptive equalization can also be included to yield additional improvement under certain types of RF channel conditions.

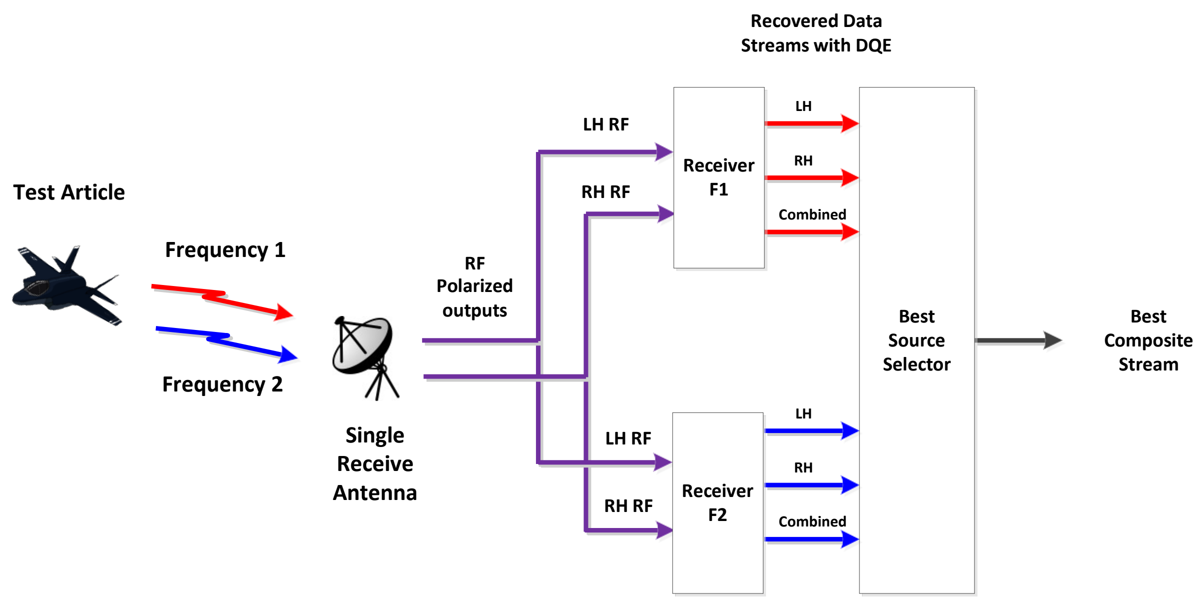

Figure 9: Single Site BSS example using both Frequency and Polarization Diversity

Another application of the BSS is to add simple fixed antennas around problem areas such as the runway or hangar areas. This is a cost-effective approach that can often solve stubborn connectivity issues. The BSS makes it easy to add in extra receive streams that occasionally outperform the primary TM equipment.

CONCLUSION

This paper has presented a BSS system based on the protocol described in 'Standards for Data Quality Metrics and Data Quality Encapsulation' in Appendix 2G of IRIG-106-17, along with mathematical and operational flight test results. The process involves recovering the data from RF signal, estimating the bit error probability, mapping it into a 16 bit DQM word, encapsulating it into a DQE telemetry data stream, and processing two or more streams with an optimal multiple bit detection algorithm. The resulting 'best' composite stream was shown to significantly outperform the individual streams, particularly when multiple receive sites were available. Configurations for a single site application were also discussed using the BSS to process streams from different polarizations, frequencies, or even simple fixed antennas to provide coverage in challenging locations.

During flight testing, one of the runs was completely error-free for 34 minutes over a variety of challenging link conditions. This level of performance illustrates the potential improvement attainable with this technology. In summary, the combination of the maximum likelihood bit detector algorithm and the development and standardization of the data quality metric and encapsulation protocol have led to an efficient BSS implementation that offers significant opportunities to improve wireless telemetry links.

REFERENCES

[1] Telemetry Group, Range Commanders Council, IRIG Standard 106-17 Appendix 2G, Telemetry Standards, Secretariat, Range Commanders Council, U.S. Army White Sands Missile Range, NM, 2017.

[2] M. Rice and E. Perrins, "Maximum Likelihood Detection from Multiple Bit Sources," in Proceedings of the International Telemetering Conference, Las Vegas, NV, October 2015.

[3] M. Diehl, J. Swain, and T. Wilcox, "Rotary-Wing Flight Tests to Determine the Benefits of Frequency and Spatial Diversity at the Yuma Proving Ground," in Proceedings of the International Telemetering Conference, Las Vegas, NV, October 2016.