Data Quality Estimation (DQE)
The Two Main Techniques
Their Strengths and Weaknesses

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Abstract

The estimation of data quality by a receiver has become a major talking point in the telemetry community over the past few years driven by the recently acknowledged need for correlating Best Source Selectors to improve link availability and reduce the environmental impact of rerunning missions. There are two main techniques for Data Quality Estimation (DQE), a bit-by-bit technique based on signal quality developed in conjunction with Patuxent River Naval Air Station in the early 2000s, and a frame-by-frame technique based on bit error probability developed by the Range Commanders Council and incorporated in the IRIG 106 standard in the late 2010s. This paper contrasts the two techniques and discusses their strengths and weaknesses for use with Best Source Selectors as well as other applications such as diversity combining and antenna tracking.

Key words: receiver, link availability, Data Quality Estimation (DQE), Best Source Selectors, diversity combining, antenna tracking.

Introduction

In this paper we contrast the two main techniques for Data Quality Estimation (DQE) used as the metric for Best Source Selection. First, the background of the Correlating Best Source Selector (BSS) is reviewed, and the two DQE methods are described. Next, the measures of BSS performance are described, and the performance improvements provided by the two DQE methods are discussed. Both static and dynamic performance improvements are considered. Then we examine the benefits of using the DQE for Diversity Combining and Antenna Control. In conclusion, the resulting strengths and weaknesses of the two DQE methods are summarized.

Background

Once upon a time, when a flight test was conducted, the telemetry signal would break up or be lost during the most important parts of the test; when the vehicle under test performed a maneuver. The signal loss was due to many factors such as aircraft antenna pattern lobing, airframe obstructions, multipath fading, and jet plume distortion, that commonly occur during the dynamics of a maneuver. Because the telemetry data from the maneuver was lost, the entire flight test, or at least some of the maneuvers, would need to be rerun. This was costly in terms of time, finances, and environmental impact.

All that changed in the early 2000s when GDP Space Systems, in collaboration with Patuxent River Naval Air Station, introduced the Correlating Best Source Selector (BSS) [1]. The Correlating BSS time aligns the signals from multiple antennas, weights the signals based on their Data Quality Estimate (DQE) and sums the signals to provide both combining gain and availability gain. Time alignment is key, without it a BSS could not provide combining gain, and when the best source changed from the signal from one antenna to the signal from another, the BSS output would suffer a forward or backward time jump.

This original correlating BSS used a DQE generated in the receiver, to take advantage of multiple antennas and spatial diversity, to dramatically reduce outages during maneuvers along the entire flight test path. Similar improvements in data reception by using a BSS and spatial diversity occur in other telemetry applications such as munition testing and rocket launches. Extensive testing [2] has proven that a BSS can maintain link availability and eliminate the need to rerun the maneuver or refly the mission. As a result of comparisons between the cost of reflying missions to the cost of a BSS, the use of the BSS on telemetry ranges is rapidly growing.

In the late 2010s, recognizing the benefits of spatial diversity, the Range Commanders Council (RCC) developed a distinct DQE and incorporated it in the IRIG 106 standard.

The DQE developed in collaboration with PAX River is a Bit-By-Bit (BBB) technique where a data quality bit is generated for each data bit and is sent along with the data bit for processing by a BSS. In this manner the DQE is similar to a soft bit that is used with forward error correction codes like LDPC. In this implementation a true direct measure of the DQ, similar to an EbNo, is sent to the BSS. Because a DQ bit is sent along with each data bit the resulting interconnect overhead rate between the receiver and BSS is 100%. As discussed later the BBB technique provides superior combining gain and more responsive availability gain compared to lower overhead techniques.

The DQE developed by the RCC is a Frame-By-Frame (FBF) technique. It sends a 16 bit DQ word every frame (with the same quality bits being used for all the data bits in the frame). The RCC frame size is selectable from 1k to 16k bits. In the RCC implementation an estimate of the bit error rate, referred to as the Bit Error Probability, BEP, is sent to the BSS. In this case a signal with forward error correction will deliver a better BEP than one without error correction even if it has a worse EbNo. Using the shortest RCC frame length, one DQ word is sent for every 1k data bits (with the same quality word being used for all 1k data bits), for an overhead of only around 5%.

In the late 2010s the infrastructure used to connect receivers to a BSS was typically coaxial cable that struggled to support bit rates greater than 20Mbps. So, in the 2010s, a BBB DQ was a concern because of its 100% overhead. Now that the legacy cabled infrastructure is being replaced with Ethernet infrastructure, the significance of interconnect overhead is no longer a major concern, and a modern BSS could conceivably process multiple DQ bits on a BBB basis.

BSS Performance

The goal of a BSS is to use multiple independent signals to improve data quality and to combat fading. In the following these two classes of performance improvements are referred to as: Combining Gain and Availability Gain.

Combining Gain is straight forward, the signals add coherently (because they're the same signal) and the noise adds noncoherently (because the noise sources are independent). Every time you double the number of signals you pick up 3dB in Combining Gain. Remember that a 6dB improvement in Signal-to-Noise Ratio (SNR) has the same effect as doubling the antenna diameter or increasing the transmit power from 5W to 20W; it effectively doubles the signal range. The general expression for theoretical Combining Gain for four signals of different power levels is eg. (1):

$$\frac{S}{N}dB = 10LOG\left(\frac{S1}{N1}+\frac{S2}{N2}+\frac{S3}{N3}+\frac{S4}{N4}\right) \quad (1)$$

(Where S/N is in dB and the Si/Ni are linear).

Combining implementation loss depends on the matching of the signals, and the quantization and frequency of DQ bits (soft bits or properly scaled log likelihood ratios). The benefits of combining gain are most clearly illustrated by examining a diversity combiner. A diversity combiner operates in a similar manner to a BSS in that the input signals are aligned (in phase not time), weighted, and the weighted signals are summed. The diversity combiner uses multiple quality samples per bit and multiple bits per quality sample and, as a result, provides near ideal combining gain. The measured Combining Gain for a quad RF combiner is shown in Fig. 1. The figure clearly illustrates the benefit of Combining Gain and the minimal implementation loss of a diversity combiner that uses a multibit DQE for combining. The combining gain of a BSS with BBB and FBF DQE is discussed in detail in the next section.

Availability Gain is a bit more nebulous because it depends on the statistics of the signal outages and the correlation between outages at the diverse signal collection sites. Think of a scenario where an aircraft is following its flight path, transitioning from one antenna to another and doing maneuvers. Fig. 2 shows the improvement in mission Bit-Error-Rate (BER) as the number of signals is increased (it uses a Rayleigh fade distribution but that's not significant to the concept). What this illustrates is that, as a simple example, if a signal is received error free for 99.9% of the time and is lost (or makes continuous errors) 0.1% of the time, the average BER for the mission is eg. (2):

$$(0.999*0 + 0.001*1) = 10^{-3} \quad (2)$$

If you add a 2nd source with the same outage of 0.1%, but uncorrelated with the 1st signal outage, the average BER for the mission goes to ($10^{-3}*10^{-3}$) = 10^{-6}, and with a 3rd source to 10^{-9}.

Actuality a signal is most of the time somewhere between error free and lost, so the average BER depends on the SNR.

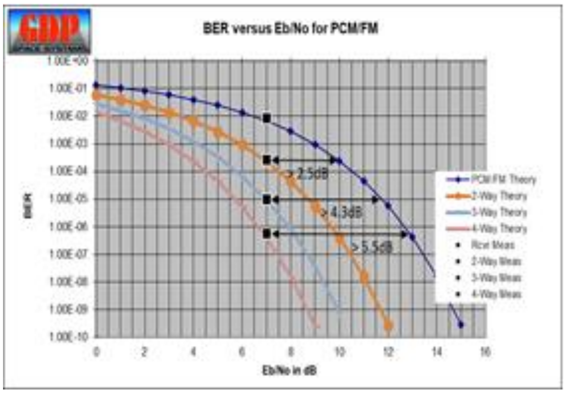


Fig. 1 - Combining Gain of a Quad Combiner

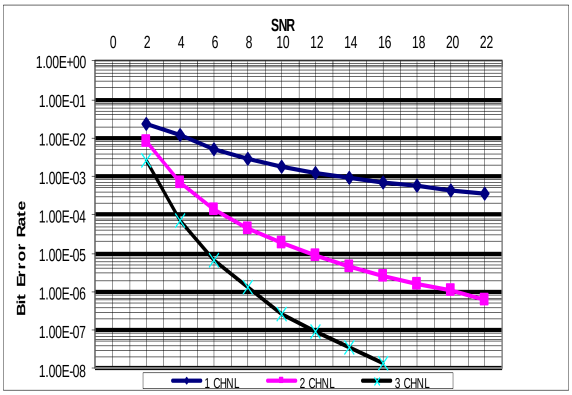
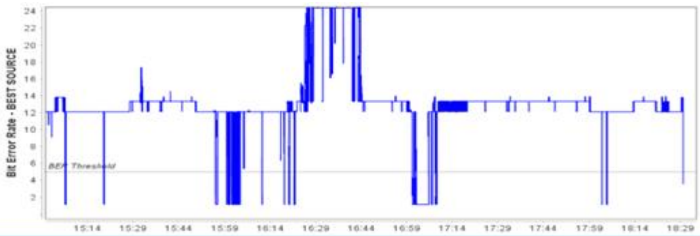


Fig. 2 - Availability Gain vs Number of Signals

Looking again at Fig. 2, if we define link availability as a BER greater than 10-5, a single received signal has a link availability of zero regardless of the received SNR. For two signals the composite link is available for high SNRs, and with three signals it's available for all reasonable SNRs.

An actual automated report generated from a BSS illustrates the Availability Gain in *Fig. **3***. It shows, on the right side of the chart, that the link availability increases from 84% for the best individual signal to 97% for the composite of four signals.



Group Summary / GRP1				
Input	**Best Source**	**Correlated**	**On-Deck**	**Link Availability**
CH01	3.01%	6.01%	100.00%	3.34%
CH02	49.27%	82.22%	99.16%	83.65%
CH03	16.54%	35.11%	97.86%	38.09%
CH04	31.18%	46.04%	100.00%	45.00%
Best Source	--	--	--	96.53%

Fig. 3 - BSS Link Availability Report

Both Combining Gain and Availability Gain depend on the signal dynamics and the ability of the DQE and BSS to track the signal dynamics. A BSS that performs well tracking the flight of a Cessna Skyhawk may not perform well against a hypersonic target.

Combining Gain

The key to Combining Gain is weighting data bits with an accurate measure of the data quality for the bit. If more than two signals are being combined, Combining Gain can also be achieved through simple Majority Vote (MV) or Weighted Majority Vote (WMV). As an example of MV for 3 signals, if two of signals say a data bit is a '0' and the third signal says the data bit is a '1', the majority decides that the data bit is a '0'. For WMV the signals are weighted by their DQ so the votes from low DQ signals don't count, are eliminated, and performance is improved over straight MV.

To get Combining Gain using a BSS with only two signals (the most common scenario), DQ must be sent for each data decision bit. The BBB algorithm sends one soft (DQ) bit per data decision bit to provide Combining Gain. Because only one DQ bit is sent for weighting each data decision bit the BSS Combining Gain is degraded by about 1dB from Optimal Combining which uses multiple bits for both weighting and data decisions. Since a BSS operates on detected and decoded data, the detector and decoder must produce soft bit outputs for use as DQ bits and not just hard bit decision outputs. For example, for SOQPSK with LDPC, both the trellis processor and LDPC decoder must be of a Soft-In-Soft-Out (SISO) type.

When more than two signals are present some Combining Gain can be achieved without BBB DQ using straight MV or FBF WMV. FBF WMV operates the same as BBB WMV except the average DQ for the frame is used instead of the

DQ of each data bit. In FBF WMV the signals are scaled by the average DQ over the entire frame so the votes from low DQ signals for the frame don't count and are eliminated, and performance is somewhat improved over straight MV.

Fig. 4a, 4b, and 4c compare Combining Gain for Optimal Combining (OC), BBB WMV, FBF WMV and MV to the Best Source (BS) signal. For 2 signals, one signal with a 3dB worse EbNo than the other, Fig. 4a, OC provides over 1.5dB of Combining Gain, BBB WMV provides nearly 1.5dB and FBF WMV is equal to the BS. For 3 signals with equal power, Fig. 4b, OC provides over 4.5dB of Combining Gain, as expected. BBB WMV provides 4dB and FBF WMV is equal to MV providing about 3.5dB gain over the BS. For 3 signals, two of the signals with 4.5dB worse EbNo than the first signal, Fig. 4c, OC provides around 2dB of Combining Gain and BBB WMV provides around 1dB. FBF WMV is equal to and provides no gain over the BS. MV is worse than the BS because the majority is often wrong.

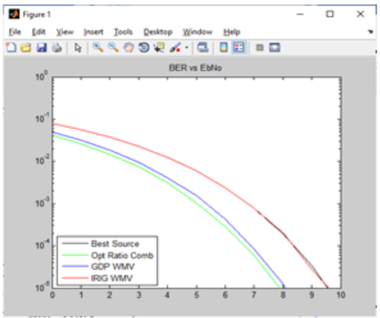


Figure 4a- BER for 2 Signals
$E_bN_01 - E_bN_02 = 3$dB

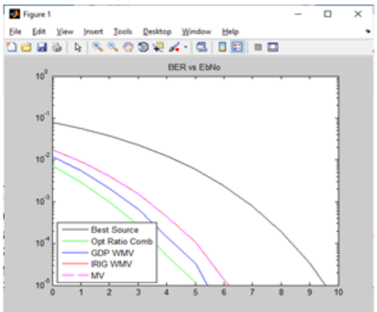


Figure 4b- BER for 3 Signals
$E_bN_01 = E_bN_02 = E_bN_03$

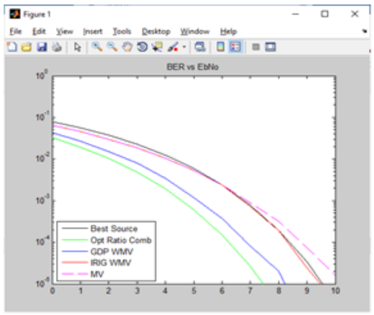


Figure 4c - BER for 3 Signals
$E_bN_01 - E_bN_02 = E_bN_01 - E_bN_03 = 4.5$dB

Fig. 4 - Figures 4a, Figure 4b, and Figure 4c Combining Gain Comparison Charts

Measured BSS performance is verified in Fig. 5. From the figure it is seen that BBB WMV provides the expected gain of about 5+dB for 4 signals, 4dB for 3 signals and 2+dB for 2 signals while straight MV provides 3.5dB for 3 signals. Although not shown in the figure MV provides no gain for 2 signals and the no improvement for 4 signals over 3 signals because there is no majority.

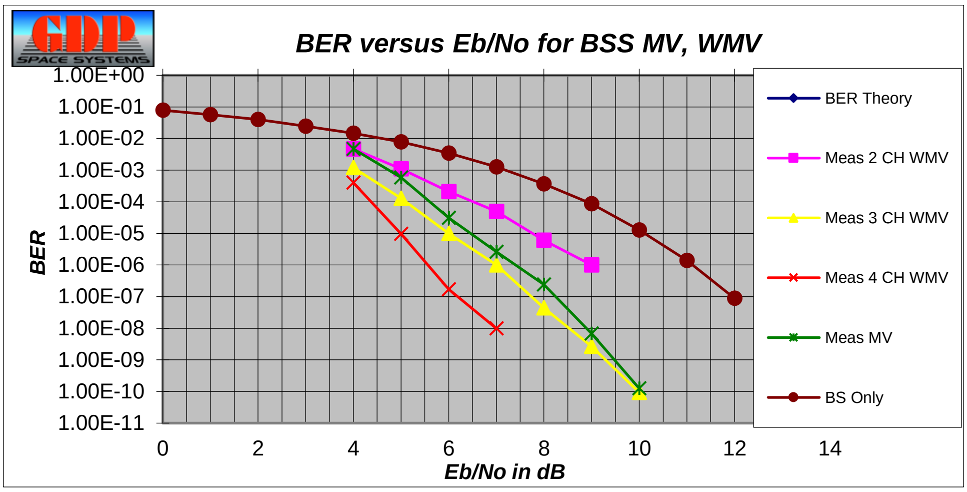


Fig. 5 - BSS Performance for Equal EbNo Signals

From the standpoint of Combining Gain BBB WMV provides the best performance followed by FBF WMV, MV and last BS.

Signal Dynamics

So far, we've considered combining in a static or slowly varying environment. But, in most cases outside of the lab, the signal conditions change dynamically at least during portions of a mission. The ability of a BSS to process dynamic signals can be defined as a break frequency, the frequency at which the BSS no longer tracks the signal variations, the combining gain degrades, or the BSS performance becomes worse than the best signal. To test combining gain in a dynamic environment, the fade tracking ability was tested using a BBB DQ. Two signals with alternating (linear in dB) 30dB fades, were tested. The fades were set up so that when one signal was at the minimum level the other signal was at maximum. Care was taken to avoid the signals completely dropping out of lock so that realignment was not a factor. The frequency of the fade, max to min to max, was increased to 33kHz, the maximum of the test set. At this rate the average BER of the individual receivers was around 1.2 x 10^{-2} yet the combined result remained error free. So, the break frequency for Combining Gain is higher than 33kHz and signal variations can be tracked and Combining Gain provided up to and beyond 33kHz. For a FBF DQ, the DQ is updated once per frame. Using the shortest RCC frame length of 1k bits, the break frequency for a 5Mbps signal is limited to less than 5kHz, and for a 4k bit frame, to less than 1.25kHz.

For a BSS, when a signal drops lock, things are a bit more complex. Because a BSS aligns signals with differential time delays, when a signal is added or dropped, relative delays are calculated and readjusted as needed. Depending on the number of signals present, this realignment process negatively affects the BSS response time and negatively impacts both combining gain and availability gain. The time required to align a signal is the gating item, until a signal is aligned the performance will track the performance of the surviving signal. The alignment time is dependent on the length (the number of bit periods) of the time correlator, the number of parallel correlators used, the time uncertainty (in bit periods) that must be searched by the correlators, and the minimum EbNo (of both signals) for which acquisition is desired. For simplicity, assume the use of ten 32-bit sliding correlators. At 5Mbps two antennas separated by 5 miles have a relative delay of approximately +/- 600-bit periods, so each correlator must search 120-bit periods. At 5Mbps this will take each 32-bit correlator 800 microseconds resulting in a best-case acquisition frequency for outages (starting with no knowledge of relative timing) of 1.25kHz. Reacquisition time can be shortened for temporary outages and slow moving targets by focusing the search around the signals relative time delay prior to the outage.

For a BBB DQ the reacquired signal is immediately available for WMV. The FBF DQ has to wait a frame period for a BEP update to make a decision or change a signals weighting. Acquisition can proceed between updates with the same results as BBB. When three or more signals are present the signal alignment time becomes less of a performance limitation.

For signal dynamics, BBB DQ has a clear advantage over FBF DQ for both break frequency and acquisition.

Diversity Combining

A usefull DQE cannot be based on SNR alone. It must be truly based on the quality of the signal and include the effects on signal distortion and interference in addition to SNR. This applies in all applications, not just for a BSS, but also for a diversity combiner or for antenna tracking. As a clear example of the importance of using a proper DQE consider again the impact on the performance of a Diversity Combiner. Historically combining in receivers has used the signal level (AGC) or SNR as the weighting metric. This essentially uses a signal amplitude as the signal‘s weight and can be a problem because the **biggest signal is not always the best signal.** In a multipath environment a distorted signal is often the biggest signal. A solution to this problem is to use the signals DQ as the weighting metric. The DQ not only measures SNR but also factors in degradation due to signal distortion and interfering signals.

Fig. 6 and Fig. 7 illustrate the problem and the solution. In the figures a distorted signal (by multipath) is input to receiver 1 and a clean signal is input to receiver 2. The power of the distorted signal is 10dB higher than the undistorted signal. Because the receiver 1 signal is distorted, the receiver 1 signal has a BER of 4×10^{-2} with an EbNo of about 4dB, while the undistorted signal in receiver 2 is error free with an EbNo of >15dB. In Fig. 6 the combiner uses the AGC/SNR metric and weights the bad signal at 100%, resulting in a 4×10^{-2} BER for the combiner output.

Fig. 6 - Using the AGC/SNR metric the bad signal is weighted at 100%

Fig. 7 - Using the DQ metric the good signal is weighted at 100%

In Fig. 7 the combiner uses the DQ metric and weights the good signal at 100%, resulting in an error free combiner output. This clearly illustrates the need to use a proper DQE. Both the PAX BBB DQ and the RCC FBF DQ require the use of a DQE that includes not only SNR but also other factors such as phase noise, jitter, signal distortion and interference.

Antenna Tracking

In addition to the benefit of using a proper DQE for a BSS and diversity combiner, the DQE also provides a valuable benefit to antenna tracking. Historically an Antenna Control Unit, ACU, has used the AGC from a receiver to determine the best signal to track. Typically, a receiver provides the AGC from a single transmitted signal for both the right- and left-hand antenna feeds to the ACU and the ACU assumes that **the biggest signal is the best signal**. But as with a diversity combiner or BSS, the biggest signal is not always the best. As a result, a modern ACU is now using the DQE to select the best signal for tracking. By using the DQE, the antenna tracks the best quality signal and is not prone to tracking a multipath or interfering signal.

It is becoming increasingly common for a target vehicle to transmit more than one signal. To take advantage is this transmit diversity for antenna tracking, the ACU often accepts AGC signals from multiple receivers that process the multiple signals transmitted from the target. Again, this is historically done using the AGC, but now is starting to use DQE to improve performance. However, this is where caution must be used, not all DQEs are suited to the multiple signal scenario. The DQE used must be based directly on signal quality, the signal quality before any forward error correction, and not a derived parameter like BEP. Consider the scenario where one telemetry signal from the target is rate ½ LDPC encoded QPSK, and a 2nd signal is an unencoded QPSK signal. Fig. 8 shows the BER of both signals, and the RCC BEP for the encoded signal, versus EbNo. (In the figure a BEP of zero is shown at the bottom of the figure on the 1.0E-08 line for convenience). The RCC DQE is BEP based, so for the encoded signal the

BEP is zero when the signal's EbNo is greater than about 1.5dB. This is due to the FEC and not based directly on the quality of the signal itself. If the RCC BEP of the encoded signal at an EbNo of 3 dB, a BEP = 0, is compared to the BEP of the unencoded signal with a 7dB better EbNo of 10dB, a BEP = 4.0E-06, the encoded signal will be declared the better signal even though it has a much worse signal quality. Because the encoded signal has a much worse EbNo it is much closer to its loss threshold and much more prone to a signal loss than the unencoded signal. Based on the RCC BEP the ACU would track the signal with the worse EbNo, a signal much closer to its loss threshold, a signal that will provide a lower quality, noisier AM control signal and as a result tracking performance would be degraded.

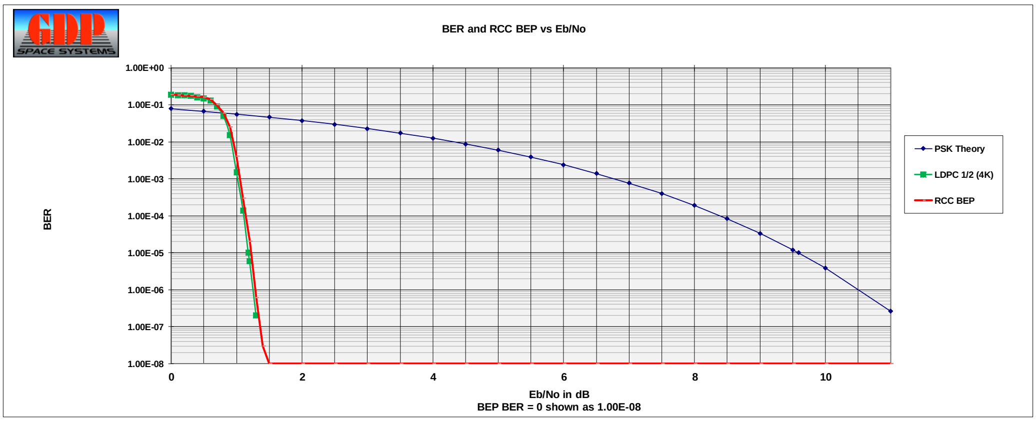


Fig. 8 – Encoded and Unencoded BER & BEP vs EbNo

For antenna tracking, using DQ provides superior performance over AGC but the DQ must be based directly on signal quality and not BEP.

Summary

Tab. 1 summarizes the performance of a DQE using a BBB DQ versus a FBF BEP. The FBF metric has a much lower overhead, this is an advantage when using legacy cabled infrastructure to connect a receiver to a BSS but is irrelevant for modern network centric Ethernet connectivity. Combining Gain for two signals is only available for BBB DQ. For more than 2 signals BBB DQ provides the best performance with true BBB WMV. FBF BEP provides some Combining Gain but is limited to majority vote or best source performance due to the DQ information arriving on a FBF basis. Both BBB DQ and FBF BEP provide Availability Gain from spatial diversity but for signal dynamics, BBB DQ is understandably superior. For a two signal diversity combiner BBB DQ is a much better metric than classic AGC providing full optimal combining performance, while FBF BEP can select a best source subject to FBF decisions. For antenna control with polarization diversity both BBB DQ and FBF BEP are superior to AGC but for a multi signal application the FBF BEP metric is misleading and only BBB DQ can provide a valid best source selection.

Tab. 1- Performance Summary

BBB DQ vs FBF BEP Performance		
PERFORMANCE MEASURE	***BBB DQ***	***FBF BEP***
Overhead	*100%*	*<5%*
BSS Static Performance		
Combining Gain	*Yes*	*Limited to BS or MV*
Availability Gain	*Yes*	*Yes*
BSS Dynamic Performance		
Combining Gain	*Fast*	*Limited By Frame Rate*
Availability Gain	*Limited by Acq. Time*	*Limited By Frame Rate*
Diversity Combiner	*Yes*	*Limited to BS*
Antenna Control		
Polarization	*Yes*	*Yes*
Multiple Signals	*Yes*	*No*

References

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[2] D. G. Normyle, "Implementing Telemetry Best Source Selection at ATR Patuxent River" presented at DATT Summit, June 2018.