BEST SOURCE SELECTOR VERSUS DIVERSITY COMBINER

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ABSTRACT

Correlating Best Source Selectors and Diversity Combiners perform similar functions. We are often asked which technique should be used. For example, should the combined signal or the uncombined signals, or both, be sent to the best source selector. Or which technique will provide a higher link availability. This paper attempts to answer these questions and others. The strengths and weaknesses of both techniques are presented and compared. Examples are provided. Suggestions are made for a variety of scenarios based on the pros and cons of the Best Source Selector versus the Diversity Combiner.

INTRODUCTION

In this paper we take a deep dive into the practical aspects of diversity combining. We consider three general methods: the PreD Diversity Combiner, the PostD Diversity Combiner, and the Correlating Best Source Selector (BSS), as well as some implementation variations within these methods. We start with a review of signal diversity, then review the combining methods, followed by discussions of combiner performance for fades, multipath, disparate signals, differential delays, and signal dynamics. As a conclusion, the best combining methods for the various conditions are summarized.

DIVERSITY

The key to signal combining is to have multiple diverse signals available. The signals should be selected to have independent noise, multipath, fades, interference, etc. The 4 main types of diversity in use today for telemetry (in order of usage) are: Polarization, Spatial, Frequency and Code. Polarization diversity typically uses right and left hand circularly polarized antenna feeds to receive a signal from a linearly polarized or single circularly polarized transmit antenna regardless of source roll, yaw, or pitch.

Spatial diversity uses spatially separated antennas to provide independent signal perturbations, cover a total flight path, and fill in reception gaps due to obstructions and transmit antenna pattern nulls. It provides the best signal diversity but most often results in path delays that (as we cover later) are longer than can be compensated for by a Diversity Combiner and require a BSS to process. Some spatial diversity advantage can be achieved using vertically stacked antennas with shorter delays that are compatible with Diversity Combiner capabilities. Both Polarization and Spatial diversity are SIMO (Single-Input Multiple-Output) techniques (where Input is transmit antennas and Output is receive antennas).

Frequency diversity uses two transmit frequencies, and each frequency can be received with polarization diversity, so Frequency diversity is a MIMO (Multiple-Input Multiple-Output) technique. Frequency diversity is used to attempt to fill in nulls in the transmit antenna pattern and overcome airframe obstructions.

Code Diversity is a category that includes Space-Time-Coding, STC, where a group of bits are time shifted and polarity inverted to create two (somewhat) orthogonal signals that are transmitted from separate antennas, as with frequency diversity. Code diversity signals can't be combined with a Diversity Combiner, so in that sense Code diversity is a MISO (Multiple-Input Single-Output) technique but becomes MO by using a BSS to combine the outputs of multiple STC receivers. Both Frequency and Code diversity use two transmitters and two antennas for transmission.

COMBINING

This section provides a brief overview of the three main combining methods: the PreD Diversity Combiner, the PostD Diversity Combiner, and the Correlating Best Source Selector. Table 1 summarizes the features of the three methods. A main distinction between the methods is where in the signal flow the combining occurs. The PreD Combiner combines 2+ modulated signals in the receiver before the signal is demodulated, bit sync'd and error corrected. The PostD typically combines 2+ signals in the receiver after demodulation and bit synchronization but before trellis processing and error correction. A BSS can combine 16 or more signals downstream from the receiver after demodulation, bit synchronization, trellis processing, and error correction.

Method	PreD	PostD	BSS
Location	Modulated Signal, in receiver	Detected Signal, in receiver	Detected Signal, out of receiver
# of Signals	2 +	2 +	16+
Signal Adjustments			
Phase Alignment	Yes	-	-
Amplitude Weighting	Yes	Yes	Yes
Delay Alignment	Limited	Limited	Yes
Weighting Metric			
AGC/SNR	Yes	Yes	-
DQ	Yes	Yes	Yes
Combining Mode			
Optimal	Yes	Yes	Yes (WMV)
BS	Yes	Yes	Yes

Table 1 – Key Features of Combining Methods

Because PreD combines modulated signals, it must phase align the signals, the other methods don't require this step. A major advantage of the BSS, because it processes digital bit sync'd signals, is that it can align signals with significant delay differences. Historically the PreD and PostD don't provide delay compensation, but modern versions are starting to include some moderate delay compensation.

All three methods weight the signals for combining, the distinction is how often, with how many bits, and with what metric. The weighting and combining of signals in a Diversity Combiner is traditionally referred to as Optimal Ratio Combining (ORC). PreD historically uses analog weights but now days weights digitally on a sample-by-sample basis with more than a hand full of bits per sample. PostD, since it's after bit syncing, weights on a Bit-By-Bit (BBB) basis with a handful of (or at least 3) bits per sample. The BSS is somewhat different, primarily due to concerns over the cabled infrastructure originally used to connect signals from multiple receivers to the BSS. GDP developed two BSS techniques in the mid-2000s [1]. One technique weights each data bit with one Data Quality (DQ) bit for the data bit and provids true BBB weighting. The other technique uses one DQ bit for every 4 data bits (with the same quality bit for all 4 data bits). The resulting interconnect overhead rates for the two GDP techniques are 100% and 25% respectively.

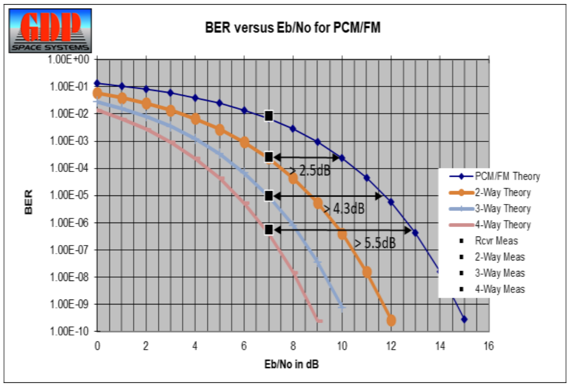
The RCC IRIG technique weights on a Frame-By-Frame (FBF) basis and sends a 16-bit DQ word every frame (with the same quality bits being used for all the data bits in the frame). The IRIG frame size is selectable from 1k to 16k bits. Using the shortest frame length, one DQ word is sent for every 1k data bits (with the same quality word being used for all 1k data bits), for an overhead of only around 5%. Now that the legacy cabled infrastructure is being replaced with ethernet infrastructure, the significance of signal overhead is no longer a major concern, and a modern BSS could conceivably process multiple DQ bits on a BBB basis.

BENIFITS

The goal of the Diversity Combiner is to improve data quality and to combat fading. Let's refer to these two classes of performance improvements as: Combining Gain, and Availability Gain respectively.

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), so 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 signals of different power levels is $S/N_{dB} = 10LOG(S1/N1 + S2/N2 + S3/N3 + S4/N4)$. 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 measured Combining Gain for a quad RF combiner is shown inFigure 1. The figure clearly illustrates the benefit of Combining Gain and the minimal implementation loss of a PreD Combiner.

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. Figure 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



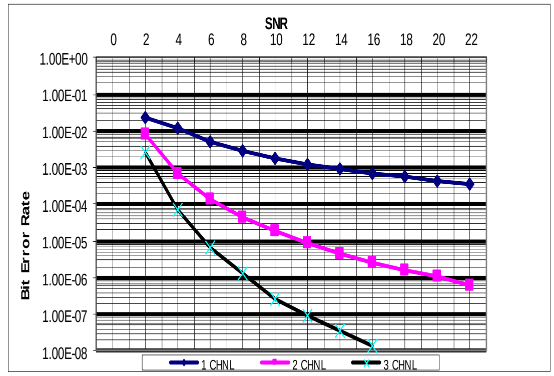
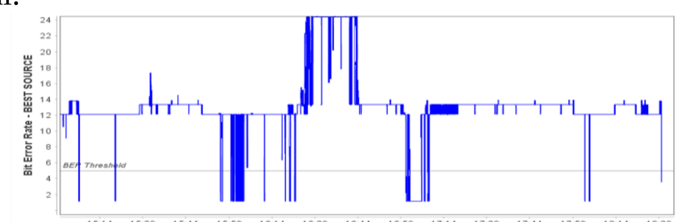


Figure 1 - Combining Gain of a Quad PreD Combiner

Figure 2 - Availability Gain vs Number of Signals

the time and is lost (or makes continuous errors) 0.1% of the time, the average BER for the mission is 10-3 (0.999*0 + 0.001*1 = 10-3). 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 10-6, 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. Looking again at Figure 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 Figure 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 signal.



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%

Figure 3 - BSS Link Availability Report

COMBINING GAIN

The key to Combining Gain is weighting every bit with an accurate measure of the data quality for that 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'. WMV is the term used for ORC in a BSS, 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.

PreD provides the best performance for identical signals using sample-by-sample weighting with more than enough resolution. PostD provides BBB weighting with adequate resolution if classic 3 bit soft decisions are available as long as combining is done before trellis processing or before a hard bit decision out of an error correction decoder. If PostD is done after trellis processing and decoding both must be of a Soft-In-Soft-Out (SISO) type.

Historically combining in receivers (both PreD and PostD) has used the signal level (AGC) or SNR as the weighting metric. This essentially uses the signal amplitude as the weighting metric 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.

Consider a test where a distorted signal was input to receiver 1 and a clean signal was input to receiver 2 with the power of the distorted signal 10dB higher than the undistorted signal. Because receiver 1 signal was distorted the receiver 1 signal had a BER of 4*10-2 with an EbNo of about 4dB, while the undistorted signal in receiver 2 was error free with an EbNo of > 15dB. When the combiner used the AGC/SNR metric it weighted the bad signal at 100%, resulting in a 4*10-2 BER for the combiner. When the combiner was switched to the DQ metric it weighted the good signal at 100%, resulting in an error free combiner. In some cases, the PreD Combiner can't make a good signal better by combining it with a poorer quality signal even with the DQ metric. This is visually obvious in the case of FM analog video, where the visual quality of the combined signal is worse than the quality of the better signal. A similar situation sometimes occurs when combining a reflected circularly polarized signal (the reflected signal has the opposite rotation from the source). This may be due to the differential delay of the reflected signal as discussed below. For cases like this a PreD combiner typically has a Best Source (BS) mode where the best of the input signals, based on the selected metric, is provided as the output.

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 GDP 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 PreD 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 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.

Figures 4 compare Combining Gain for the PreD ORC, GDP (BBB) WMV, IRIG (FBF) WMV and MV to the Best Source (BS) signal. For 2 signals, one signal with a 3dB worse EbNo than the other, Figure 4a, PreD ORC provides over 1.5dB of Combining Gain, GDP WMV provides nearly 1.5dB and IRIG WMV is equal to the BS. For 3 signals with equal power, Figure 4b,

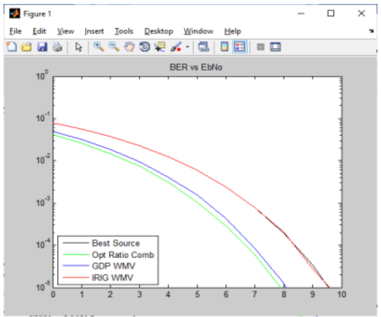


Figure 4a- BER for 2 Signals
***$E_bN_0$1- $E_bN_0$2* = 3dB**

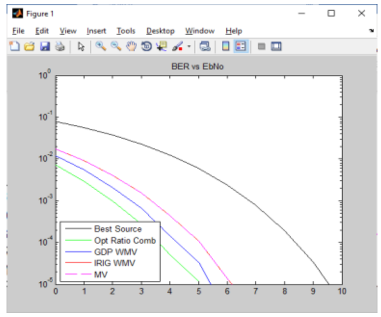


Figure 4b- BER for 3 Signals
$E_bN_0$1 = $E_bN_0$2 = $E_bN_0$3

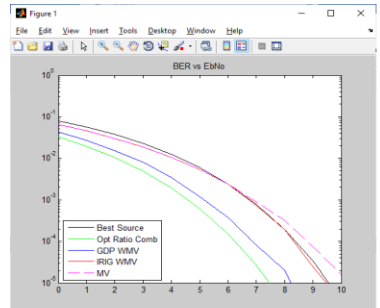


Figure 4c - BER for 3 Signals
***$E_bN_0$1- $E_bN_0$2 = $E_bN_0$1- $E_bN_0$3* = 4.5dB**

ORC provides over 4.5dB of Combining Gain, as expected. GDP WMV provides 4dB and IRIG 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, Figure 4c, ORC provides around 2dB of Combining Gain and GDP WMV provides around 1dB. IRIG WMV is equal to and provides no gain over the BS. MV is worse than the BS because the majority is often wrong.

Measured BSS performance is verified in Figure 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.

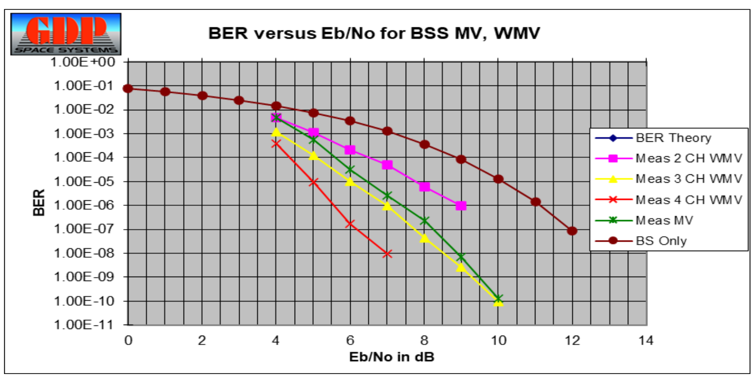


Figure 5 - BSS Performance for Equal EbNo Signals

From the standpoint of Combining Gain the PreD combiner is the best, followed by the PostD, BBB BSS and last the FBF BSS. In addition to providing a higher SNR for bit detection PreD combining also provides higher SNR for demodulation, clock recovery, trellis processing and frame synchronization. This is important because it results in an improved lock threshold with fewer drop locks as needed for the modern powerful FECs like LDPC. The PostD combiner, depending on its placement in the signal flow, will likely provide a better SNR for the frame sync, trellis processing and FEC. Because a BSS operates with data and DQ bits after trellis processing and FEC, there is no improvement in signal threshold, only in the signal BER.

So far, we've looked at combing uncorrupted signals, but the objective of the combiner is to make a poor signal better, by combining multiple signals, or in some cases selecting the best signal.

CORRUPTED SIGNALS

Signal Fades – Fades, where a signal disappears or drops to a very low SNR, often occur during a mission. They occur for many reasons including airframe obstructions, signal path obstructions, transmit antenna pattern nulls, and multipath nulls. Although Polarity and Frequency diversity can help combat fades, Spatial diversity using a BSS, is far and away the best solution for combatting fades because it provides maximum Availability Gain. Consider that during a flight test, fades usually occur when the aircraft does a maneuver, at the exact time the telemetry data is most important to be reliably received. 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.

Multipath - One of the most common signal degradations is multipath, where the signal from a primary line-of-site path is summed with reflected signals at the receive antenna to create a distorted signal into the receiver. As a result of the intended signal diversity into a combiner, the signals being combined by the combiner have different multipath conditions. Since multipath creates both phase and amplitude signal distortion and since the PreD combiner aligns signals in phase and weights the signals by amplitude or DQ, there are cases of severe multipath where the PreD combiner cannot reliably combine the signals. However, the PostD combiner and BSS can still combine the signals as long as the individual receivers can receive and process the signals. As a result, for modest multipath PreD DQ Optimal Combining is recommended. For severe multipath PostD DQ or a BSS should be used.

Signal Disparities - Combiner performance is affected by signal source variations. An example of this is the deviation of a PCM/FM signal. When the deviation of the signals being combined is significantly different, the spectral content of the signals is different and the optimal PreD combiner struggles to maintain phase lock resulting in poor, intermittent performance. In this case some Combining Gain can be achieved using PostD DQ combining or with BBB BSS.

Another example of disparate signals is STC, where the same data is transmitted using two signals from two transmitters with differing bit delays and polarities. Because the two signals at the receiver are different, they can't be PreD combined. If soft output bits are available, the signals can be combined with some Combining Gain using PostD or BBB BSS. Link Availability Gain for STC, as with any signal, can be achieved using a BBB or FBF BSS.

In the extreme, if the signals are the same bit rate but use different modulations, for example one signal PCM/FM modulated and the other SOQPSK modulated, a BBB BSS can still be used to provide Coding Gain.

Differential Delays - As mentioned earlier PreD and PostD combiners typically provide no, or at best limited, delay compensation while a BSS can align signals with 100k+ bit differential delays. For perspective, Table 2 lists some typical delays encountered in a telemetry system.

Path	100' Tx Ant Separation	1 Mile Rx Ant Separation	TMoIP Delay, <10msec	LEO Relay, 15msec	TDRSS Relay 300msec
Delay @ 10Mbps	1 bit	60 bits	100k bits	150k bits	3M bits

Table 2 - Typical Delays Encountered in a Telemetry System

To combine signals with differential delays the combiner must be able to adjust and or align the signals to compensate for the delay. At 10Mbps, transmit and receive antenna separations of up to 100 feet result in less than one-bit period delay between antennas. Receive antenna separations of up to one mile require delay compensation of at least +/- 60-bit periods. Electronics in the signal path also create delays that must be accounted for. Most commonly, the use of TMoIP gateways and switches adds delays on the order of 100k bit periods. If all signals are passed through gateways with the same bulk delay, then it is only the differential delay that must be considered. Some telemetry signals are received through relay systems. For rocket launch telemetry, the signals are sometimes relayed through LEO or GEO satellites. The delay through a GEO, such as TDRSS, is on the order of 3M bit periods at 10Mbps. So, to combine a signal relayed through TDRSS with a directly received signal, the combiner must compensate for 3M bit periods.

A PreD combiner (without delay compensation) can process a differential delay of around +/-1 bit period. This is adequate to combine two frequency diversity transmit antennas on an airframe, and the spatial diversity of vertically stacked antennas. Because the signals are aligned in phase the alignment effectively creates a multipath signal for the combiner to process. As the signal differential delay increases the effective bandwidth of the combined signal decreases to the point where the signal can no longer be processed. This is shown in Figure 6. The figure shows the wideband spectrums for PCM/FM and SOQPSK signals, the multipath spectrum created by a one-bit and two-bit period delay, and the resulting spectrum of the combined signals with the one-bit and two-bit period differential delays. Note how the combiner induced multipath reduces the effective bandwidth of the signals. For the two-bit delay case the combiner induced multipath has reduced the effective signal bandwidth beyond the point where the combiner can process the combined signal.

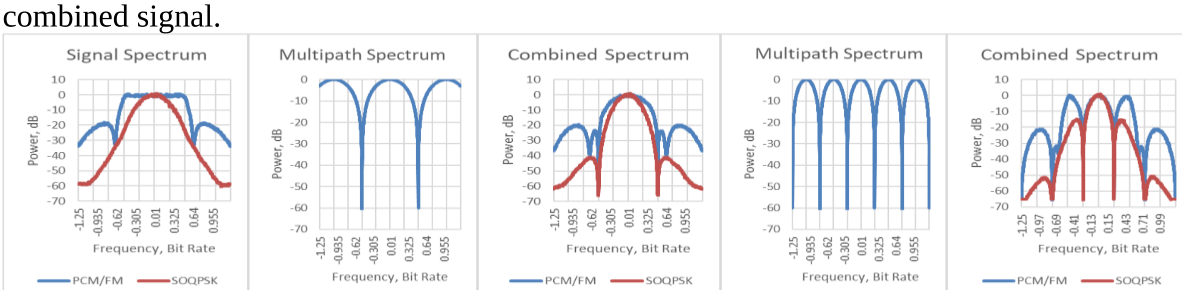


Figure 6 - Multipath Created by PreD Combiner for 1- and 2-Bit Differential Delays

Similarly, for the PostD combiner without delay compensation, the combining limit is less than 1 bit period. This is because a detected bit can't be combined with an adjacent bit due to the random nature of the data. A BSS, because of a large memory and signal correlation alignment algorithms, can provide the maximum Availability Gain and with BBB processing also provide Combining Gain for signals with large differential delays. As a result, for signals with less that a bit period differential delay, PreD Optimal Combining is preferred because of the maximum Combining Gain. For longer delays the BSS must be used and will provide maximum Availability Gain.

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 combiner to process dynamic signals can be defined as a break frequency, the frequency at which the combiner no longer tracks the signal variations and the combiner's performance degrades or it fails to combine. To test a combiner's performance in a dynamic environment its fade tracking ability was tested. Two signals with alternating (linear in dB) 30dB fades were input to the combiner. The fades were set up so that when one signal was at the minimum level the other signal was at the maximum. 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 combiner remained error free. So, the break frequency of the combiner was higher than 33kHz and the combiner can track signal variations and provide Combining Gain up to and beyond 33kHz.

For a BSS, things are a bit more complex. Because a BSS aligns signals with differential delays, when a signal is added or dropped, relative delays are recalculated and readjusted as needed. Depending on the number of signals present, this realignment process negatively affects the BSS response time. To compare the response time of a BSS to that of a Diversity Combiner the BSS test should be set up to not require signal realignment. For testing the BSS, the fade depth was reduced to 9dB to avoid the effects of realignment. The signal levels were set so that the minimum signal level resulted in a BER of around 1x10-4 for each receiver and for the maximum signal level the receivers were error free. The average BER for each receiver while the receivers were experiencing fades was between 6x10-6 to 1.5x10-5. From Table 3 it is seen that the BBB BSS Combining Gain degrades as the fade rate increases, until at a rate of 5kHz the performance is about the same as the FBF IRIG algorithm with a 1k block size.

BSS Fade Performance					
Test Number	**Fades Per Second**	**CH1 Average BER**	**CH2 Average BER**	**BSS WMV, IRIG 1k Frame**	**BSS WMV, BBB**
1	100	6.6x10^-6	1.5x10^-5	6.0x10^-6	3x10^-8
2	500	6.6x10^-6	1.5x10^-5	6.6x10^-6	1.0x10^-7
3	1000	6.6x10^-6	1.5x10^-5	6.8x10^-6	5.0x10^-7
4	5000	6.6x10^-6	1.5x10^-5	6.8x10^-6	2.2x10^-6

Table 3 - BSS Fade Performance

Based on these results, for a dynamic signal, PreD combining provides the best performance followed by BBB BSS and then FBF BSS.

Good, but not perfect - For a dynamic signal the combined signal sometimes, for a short transient, is not as good as one of the input signals. This is due to processing delays and algorithm imperfections. Also, separate equalizers in the receivers and combiner can create conditions where a receiver output is better than the combined output because typically the combiner does not process equalized signals from the receivers. It is always recommended, if the resources are available, that a BSS be used with signals from multiple combiners. However, it is generally not recommended to send signals from individual receivers along with the combiner signal to a BSS because the combined signal is dependent on the receiver signals. Errors in the signal from the combiner are a result of errors in the signals from the receivers. With multiple combiner signals and WMV the BSS will always provide additional performance improvements.

SUMMARY

Table 4 summarizes the results for combiner selection. PreD combing is the best method for Combining Gain. BSS is the best method for Availability Gain.

For Combining Gain, PreD is the best choice followed by PostD and BBB BSS due to their decrease in signal and DQ processing bits, and the need for soft bits from trellis and error correction decoders. FBF BSS provides the least Combining Gain and is limited to majority vote or best source performance due to the DQ information on a FBF basis.

Method	PreD	PostD	BBB BSS	FBF BSS
Combining Gain	1	2	3	4
Availability Gain	Limited	Limited	Excellent	Excellent
Polarity	Yes	Yes	Yes	Yes
Frequency	Yes	Yes	Yes	Yes
Spatial	Limited	Limited	Yes	Yes
Code (STC)	No	Yes	Yes	Yes
Deviation	Limited	Yes	Yes	Yes
Multipath	Limited	Yes	Yes	Yes
Threshold	Yes	No	No	No
Dynamics	1	2	3	4

Table 4 - Combining Ability for Combining Methods

For Availability Gain the BSS is far superior in that it can process truly diverse signals with large physical separations. Spatial diversity is limited to less than a bit period for PreD and PostD without some delay compensation ability, while the BSS can take advantage of signals with large time separations. PreD combining cannot be used for Code diversity signals such as STC. PostD and BBB BSS can provide Combining Gain if soft bits are available out of the STC processor, and a BSS can always provide Availity Gain for signals from multiple sources.

For signals with modest deviation disparity, multipath, or other signal perturbations as long as the signal variations can be constructively combined, PreD provides the best results because of its superior Combining Gain. If the signal variations are so severe that the signals can't be PreD combined, Combining Gain can be provided by PostD and BBB BSS if soft bits are available and, as always, Availability Gain can be provided by a BSS.

PreD combining is the only method that can improve the signal threshold because the SNR gain occurs in front of the signal processing. This presents the possibility of increased signal range for existing transmitters and antennas. Regarding dynamics, Pred is superior followed by PostD, BBB BSS and lastly FBF BSS due to the FBF mature of the DQ decision metric.

Finally, it is recommended that Best Source Selectors be used with Diversity Combiners whenever possible, and generally that only the combined signals, not both the combined and the uncombined signals, be sent to the BSS. Doing so will maximize both the Combining Gain and the Availability Gain. For more details, please visit the GDP website.

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[1] S. Nicolo, "History and Advantages of Best Source Selection", in *Proceedings ettc2018*, pp. 48 – 54, June 2018

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