SPACE-TIME CODING SOLUTION TO THE TWO-ANTENNA INTERFERENCE PROBLEM

Mark Geoghegan
Quasonix, West Chester, OH

Louis Boucher
Bombardier Flight Test Center (BFTC)-Mirabel, (Québec), Canada

ABSTRACT

In order to provide reliable line-of-sight communications, test aircraft typically use two transmit antennas to create top and bottom hemispherical patterns that cover the full range of possible aircraft orientations. The two transmit signals are normally generated by a single transmitter with the power being split between the two antennas. Although this configuration is straightforward and easy to implement, problems can arise due to the two signals constructively and destructively interfering with each other. This can result in the composite antenna pattern having periodic nulls with a depth and geometric spacing dependent upon the amplitude and phase differences of the two transmitted signals. This problem is usually addressed by either unevenly splitting the transmit power between the two antennas, or by using two separate transmitters at different frequencies. Unfortunately, these methods have drawbacks that require either system performance or cost trade-offs.

This paper discusses the use of Space-Time Coding to eliminate this antenna interaction by transmitting modified waveforms that simultaneously allow for both full power transmission and single-channel operation. This approach effectively restores the nominal antenna performance, thereby resulting in better overall coverage and less pattern-induced dropouts. Telemetry performance results from recent flight testing are presented to validate the benefits of this approach.

KEY WORDS

Space-Time Coding, Two-Antenna Problem, SOQPSK, 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. 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 tests, require test point repetition, or force testing to be cancelled. This wastes valuable personnel and equipment resources, costing a company time and money.

At the end of 2013, Cseries testing began to experience disrupting telemetry dropouts. Unexpected outages occurred at various distances (close and far), and the condition seemed to be worse in certain aircraft orientations. In some instances, both the top and bottom antennas were in line-of-sight from the ground station receiving dish. Shadowing from the airframe and interference between the top and bottom antennas were suspected. Attempts to adjust operating procedures and power-splitting levels had limited success and proved to be sensitive and hard to manage. Before making changes to the airframe or moving the antennas (both of which are very expensive options), it was decided to try a new type of telemetry system that uses Space-Time Coding in conjunction with SOQPSK modulation. The basic idea is to transmit different signals out the top and bottom antennas that do not interfere with one another, simultaneously occupy a single SOQPSK channel, and can be combined to efficiently recover the energy from both transmissions. This technique was published in [1], and subsequently commercialized by Quasonix in 2013. This paper describes performance results from some of the flight testing.

BACKGROUND

Two-Antenna Problem

Aircraft testing requires the telemetry system to maintain a reliable real-time data connection with the vehicle under test. As the plane maneuvers around the test range and changes orientation, it generally requires two hemispherical antennas to produce a composite pattern that can overcome airframe shadowing of the individual antennas. Typically, the power from a single transmitter is split and applied to the top and bottom antennas. Although this installation is straightforward, interference issues can arise due to the signals from the antennas adding either constructively or destructively, creating variations in the composite antenna pattern.

Figure 1 illustrates this concept using two point sources. Either one of the sources by itself produces a uniform pattern, while the two together create areas that either are “in-phase” and add, or “out-of-phase” and cancel. Signals with similar strength and opposite phase produce the worst-case fading (nulls), while signals with similar amplitude and phase produce the maximum enhancement (peaks).

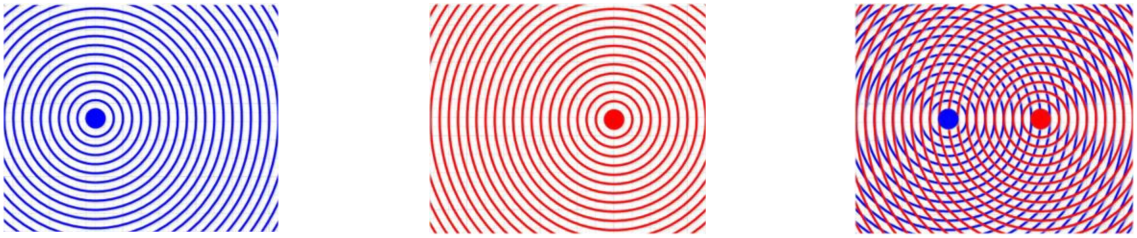


Figure 1: Source 1 (Left), Source 2 (Middle), Source 1 and 2 (Right)

Space-Time Coding (STC)

Typical solutions to reduce this interaction and the resulting variations in the antenna pattern are to unevenly split the power between the two antennas so that one dominates the other under most circumstances, or to use two different frequencies. If the signal amplitudes are substantially different, then the smaller one cannot significantly cancel the larger even if they have opposite phases. The drawback to this approach is that there may not be a power split ratio that simultaneously reduces the worst-case fading, maintains reasonable gain in both paths, and performs well for arbitrary aircraft orientations at both short and long range. Another approach is to use two frequencies for the top and bottom transmissions. This eliminates the antenna interference problem, but doubles the utilized bandwidth and requires two separate frequency allocations, which may not be available.

Recently, the idea of using Space-Time Coding to address this problem has been presented [1]. The details of STC are presented in the reference and will not be repeated here. The key points are that the data is encoded into two separate SOQPSK modulated streams that do not interfere with one another. They are transmitted on the same center frequency, occupy approximately the same single-channel spectrum (4% bandwidth increase), and are able to be combined back into the original data stream efficiently from one or both sources. The main advantage of this scheme is that the composite antenna pattern is no longer a function of the amplitude and phase relationships between the two signals. This allows the pattern to consistently provide the original anticipated coverage without spatial nulls and variations due to antenna interactions. Figure 2 shows a simple example to help illustrate the concept of 'orthogonal' signals. Again, either one of the sources by themselves produces a uniform pattern, but this time the two signals do not interact. Also note that a 'Blue' vertical detector plus a 'Red' horizontal detector recovers all the energy in all three cases. Although the graphic looks like polarization diversity, the STC signals use waveform coding to achieve similar properties between the signals. This example is overly-simplified, but it helps illustrate the basic concept.

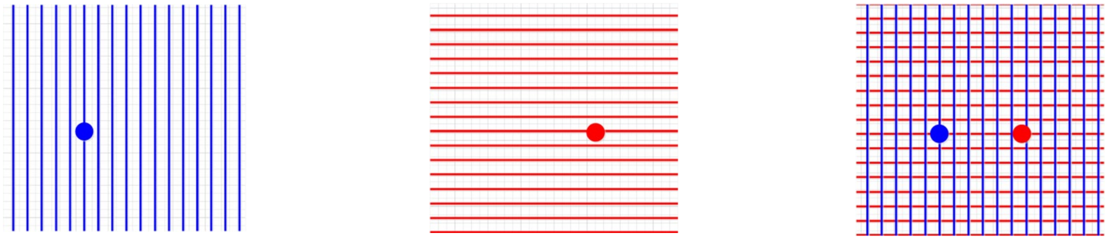


Figure 2: Source 1 (Left), Source 2 (Middle), Source 1 and 2 (Right)

SYSTEM DESCRIPTION

Figure 3 illustrates a typical telemetry application consisting of an aircraft downlinking data to a ground station. The source data is combined into a single digital stream that is converted into RF by the telemetry transmitter, split, and sent to a top and bottom antenna. The received signals are captured by the receive antenna, processed by a telemetry receiver, and demultiplexed to recover the transmitted data. Note that S_T and S_B are subjected to different channel responses, h_T and h_B, that are aircraft orientation dependent.

As discussed above, RF cancellation can occur when the two signals are of similar amplitude and opposite phase. In order to minimize this effect, an uneven power split between the top and bottom is often used. Unfortunately, this forces a trade between maximizing radiated power and coverage while minimizing self-interference. To make matters worse, the received levels from each antenna can vary significantly as the aircraft changes orientation, allowing cancellation to occur even with an uneven power split. This phenomenon was seen during Cseries initial flight testing.

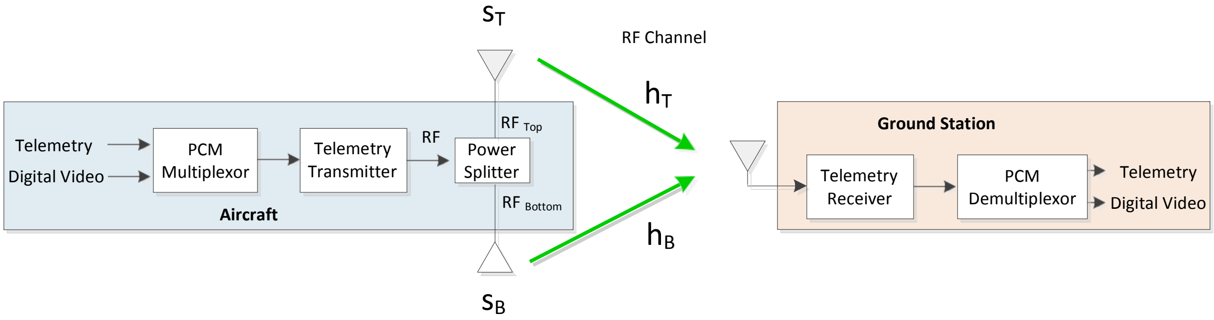


Figure 3: Typical Telemetry System

To help illustrate these effects, Figure 4 shows a mathematical representation of the horizontal and vertical slices of an idealized antenna pattern at L band. For this example, the radiation pattern was modelled as two ideal dipoles separated by several meters in the vertical direction and slightly offset in the horizontal plane as might be expected in an aircraft installation. A cardioid function was also used to weight the response of each dipole towards the top or bottom as one might see with a typical blade antenna.

Although this example is highly idealized, it helps illustrate the trade-off facing a test engineer. The blue trace in both the horizontal (left) and vertical (right) slices represents an even power split ($P_B/P_T = 1$). Although the power output and coverage are maximized, extremely deep nulls are observed, which can result in a significant loss of signal at the receiver. In the other extreme, turning off the bottom antenna (magenta trace with $P_B = 0$) eliminates the nulls but also degrades coverage when only the bottom of the plane is visible or the top is shadowed by the airframe. In practice, fixed coupler values of 6 or 10 dB are commonly used and represent a compromise between coverage and interference. To summarize, equal weighting produces the best spatial coverage but has significant nulls, while an uneven split reduces the nulling at the cost of coverage.

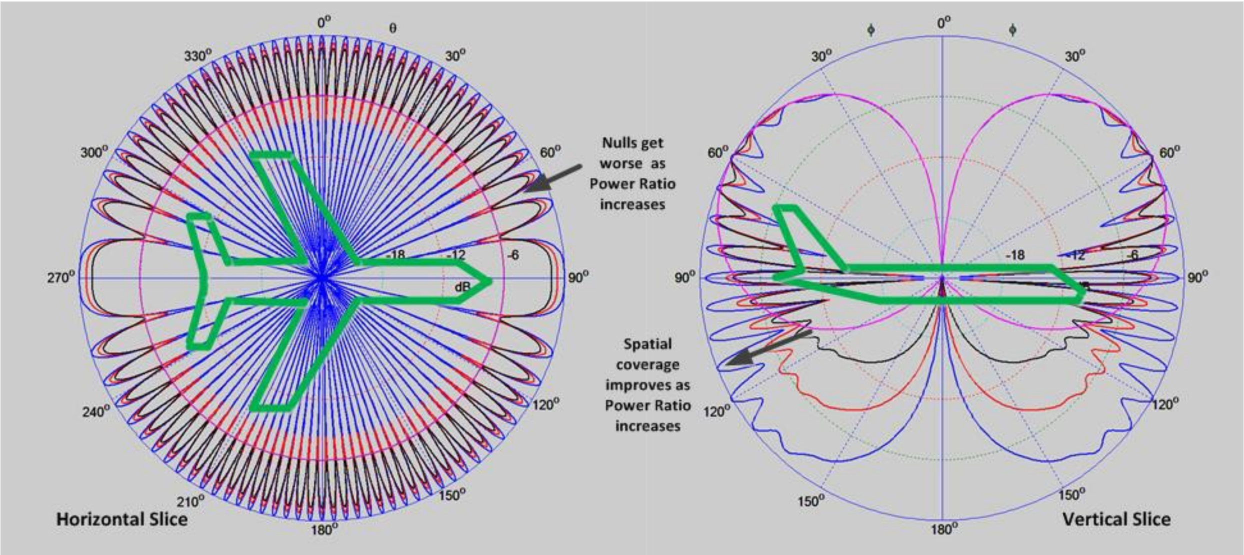


Figure 4: Idealized Antenna Pattern (Power Split Approach)

Figure 5 illustrates the same setup using an STC approach. The source data is multiplexed and converted into two separate RF signals by the STC transmitter and directly applied to the top and bottom antennas (no split). A helpful comparison is the case where transmit frequency diversity is used and F_T and F_B are different frequencies. The signals are not split and they do not interfere with each other. In contrast, STC uses separate coding on the two outputs to accomplish this with only a single frequency. Since the STC receiver estimates h_T and h_B as part of its normal demodulation process, the amplitude and phase of each received signal can be directly observed and recorded. With the exception of transmitting on two separate frequencies or using sophisticated channel sounding methods, STC provides valuable information that is not typically available about how each antenna path is performing. Having independent channel measurements on an operational link significantly simplifies debugging of transmission and reception issues.

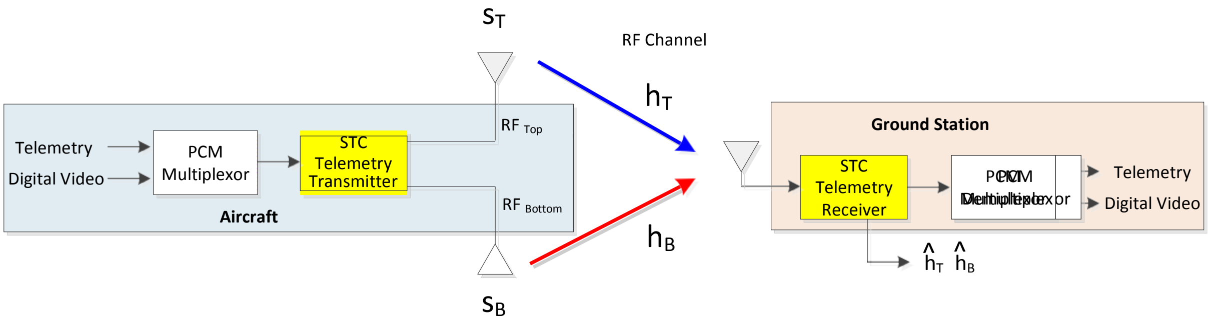


Figure 5: STC Telemetry System

Figure 6 shows the resulting idealized patterns for an STC setup. Notice that there is no trade to be made, as full power is simply applied to both top and bottom antennas. Since the signals do not interfere with each other, there is no constructive or destructive interaction. This results in having both full power and full coverage without the nulls.

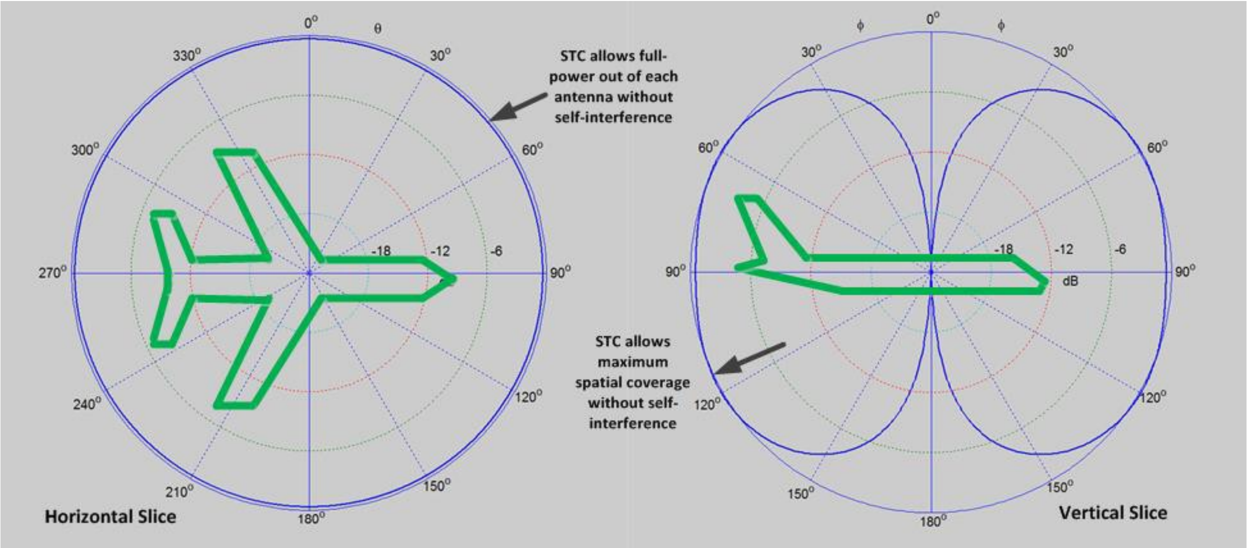
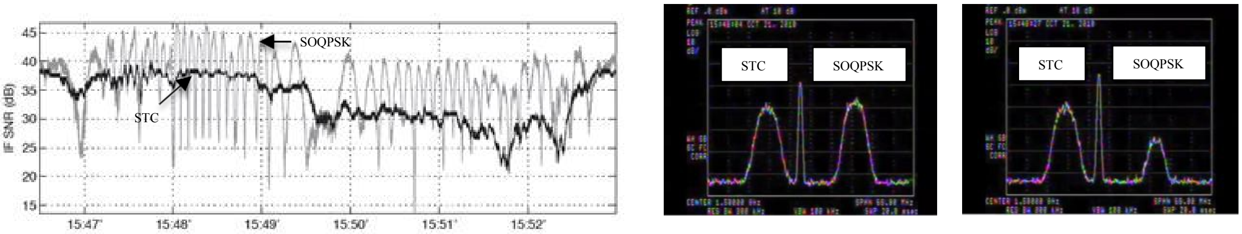


Figure 6: Idealized Antenna Pattern (STC Approach)

The calculated patterns shown above are simple examples to help illustrate the differences between the two systems and highlight general trends and trades. Figure 7 shows measured data from [2] and further corroborates the significance of the two-antenna problem by showing the received signal SNR versus time along with snapshots of the IF for both a traditional system with power splitting and a STC system. Notice how the STC signal level remains consistent and does not experience the rapid fluctuations as does the traditional shared signal arrangement. The peak levels are limited by the signal addition (approximately 6 dB) while the nulls due to signal cancellation can be infinite.



Data from STC and SOQPSK flight test. Recorded IF SNR versus Time.

STC IF stable, SOQPSK IF constructive interference

STC IF stable, SOQPSK IF destructive cancellation

Figure 7: Published STC flight data showing the two-antenna interference phenomenon

FLIGHT TEST RESULTS

This section describes flight test results that took place during the winter of 2013 and the spring of 2014 at Bombardier's Mirabel facility, Québec, Canada. As mentioned above, an STC telemetry system was installed after experiencing issues with a conventional SOQPSK power-split system. With the exception of limited hangar and runway testing, all STC flight test results were taken during operational aircraft testing. As such, the most convenient observables were the live video, data displays, and a running PCM subframe ID ramp signal recovered from the downlink. In addition to these outputs, specific information from the STC receiver was recorded, including the IF signal strengths and the reported levels of the top and bottom channels. Observing the behavior of the individual channels provides insight in how a two-antenna system in the real-world performs during a typical mission.

Knowing the contribution of each antenna allows the calculation of their combined interaction. Particular items of interest include the performance loss due to self-interference and the effect of varying the power ratio of the top and bottom transmissions as mitigation. The transmitted signals and complex channel gains can be represented as shown in Equations 1 and 2 assuming a power-split of $P_B / P_T = \alpha^2$.

$$s_T(t) = e^{j\theta_T(t)} \; and \; s_B(t) = \alpha e^{j\theta_B(t)}. \tag{1}$$

$$h_T = |h_T| e^{j\theta_T} \; and \; h_B = |h_B| e^{j\theta_B}. \tag{2}$$

The resulting received signal is shown in Equation 3 with τ_T and τ_B being the respective time delays for each channel, ω_0 the frequency offset, and $w(t)$ representing additive noise. For most applications, the time delay between channels is usually small compared to a symbol period ($\tau_T \cong \tau_B$). Therefore, if S_T and S_B are simply scaled versions of each other, as in the case of a traditional power-split system, a single loss factor can be produced that is solely a function of the channel gains and attenuation value α. An expression for the worst case self-interference loss, which occurs when the channels have opposite phase, is shown in Equation 4. Similarly, the reduction in radiated power which occurs when one of the channels is attenuated is described by Equation 5.

$$r(t) = [h_T s_T(t - \tau_T) + \alpha h_B s_B(t - \tau_B)] e^{j\omega_0 t} + w(t) \tag{3}$$

$$L_{WC\ INT}\ (\text{dB}) = 20 \log_{10} \left(\big| |h_T| - \alpha |h_B| \big| / \left(|h_T| + \alpha |h_B| \right) \right) \tag{4}$$

$$L_{RAD\ PWR}\ (\text{dB}) = 20 \log_{10} \left(\left(|h_T| + \alpha |h_B| \right) / \left(|h_T| + |h_B| \right) \right) \tag{5}$$

Since the aircraft is electrically large and in motion, the phase difference between channels is constantly changing and therefore guarantees the worst-case loss will occur for portions of the flight. Equations 4 and 5 provide a convenient means to compare the performance loss of a power-split system relative to an STC system.

Flight Test Data

Flight testing occurs most days at the Mirabel facility depending upon the weather conditions and the testing schedule. Most flights last for a couple of hours and consist of basic maneuvers at a variety of altitudes. Testing is typically conducted to the north with terrain largely being a mixture of mountainous forested areas and water. Figure 8 shows the general area used during testing. At typical ranges and moderate altitudes, the antenna elevation angle is usually quite small (< 5 degrees).

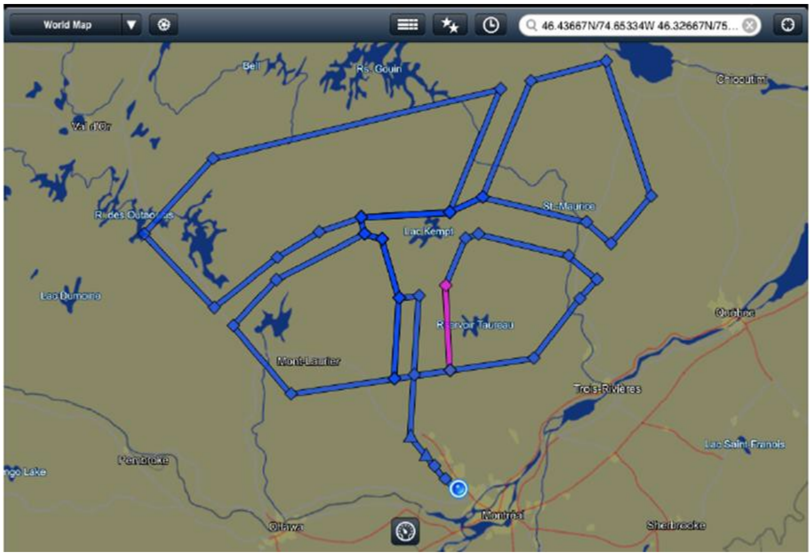


Figure 8: Test Flight Area North of Montreal

Switching to the STC system from a traditional SOQPSK power-split system significantly reduced the data outages seen during testing. Furthermore, there was a significant increase in the range at which testing could be successfully conducted. This can be attributed to two factors: the STC system reduced the variations in the antenna pattern, and it also provided 3 dB more radiated power (dual 10W instead of a split 10W output). The positive results led to the decision to equip all of the test aircraft with STC capability.

Data was collected from several flights that occurred over the period of roughly one month. Signals from the receiver were sampled at a rate of 50 Hz and logged to a data recorder. Most flights exhibited similar behavior, and the general conclusions are evident by examining a typical flight. The following data was taken during routine testing in the surrounding areas north of Mirabel. The take-off and landing portions have been excluded since airframe shadowing during these periods are platform- and range-specific and are not necessarily representative of typical test conditions.

Figure 9 shows three plots: the receiver AGC voltage, the amplitude of the top and bottom channels as seen by the receiver, and the resulting worst-case cancellation loss assuming opposite phase angles. The equipment configuration was STC with no power split ($\alpha = 1$). The left and right hand polarized antenna feeds were combined and processed by the STC receiver.

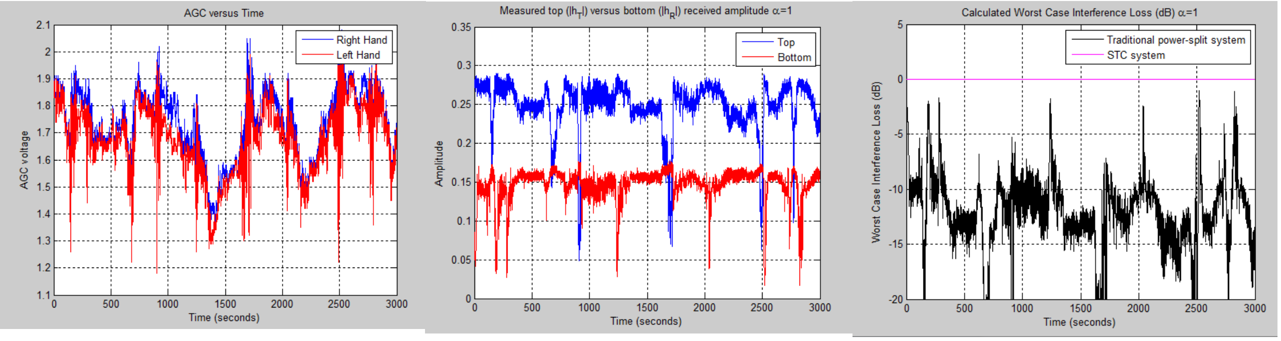


Figure 9: Flight Data from the spring of 2014

The receiver AGC voltage of the right-hand (blue) and left-hand (red) polarized signal feeds are virtually identical as expected. The middle plot shows that the average signal from the bottom antenna is weaker that the top by about half. However, there are many instances where the signal strength varies during turns or changes in orientation where that is not the case. When the received levels are similar, the signal cancellation can be severe as seen in the black trace in the graph on the right, calculated using Equation 4. This is in contrast to the magenta trace representing the STC approach that is not susceptible to two-antenna self-interference.

Figure 10 illustrates the fundamental trade-off in selecting the power ratio in a power-split system. The curves show how the performance varies as the attenuated antenna changes from having no power to having the same power as the other antenna. The red curve shows the potential 6 dB increase as both outputs are driven with the same power. The black curve illustrates how the spatial coverage also improves as both antennas are fully driven. The blue curve (based on the experimental data at a 90 percent confidence level) shows that the inter-antenna interference gets progressively worse as both antennas approach equal power. The light blue shaded area shows the theoretical performance envelope of a power-split system. Note that it experiences both perfect signal addition and cancellation when both antennas are driven equally. If only one antenna is used, both systems converge to the same moderate power performance with poor spatial coverage.

These relationships force a choice somewhere between turning off an antenna (lowest power output, lowest antenna-interference, worst spatial coverage) and using full power out of both (highest power output, worst antenna-interference, best spatial coverage). Typically, a split of 10 dB or so is used, yielding a compromise of power, self-interference, and spatial coverage. In contrast, only the red and black curves apply to the STC system. Therefore, the correct strategy is to simply apply full power to both antennas to simultaneously achieve the highest power performance and best spatial coverage with no interference penalty.

Although the exact losses are platform dependent, the trades presented in the analysis are applicable to all single-source power-split systems. It is very difficult to eliminate this effect altogether due to the large gain variability in antenna patterns and range of possible aircraft orientations. Options for making up these losses include increasing the transmit power, switching to a frequency diversity scheme (at the cost of two RF channels), or using a waveform coding scheme such as STC.

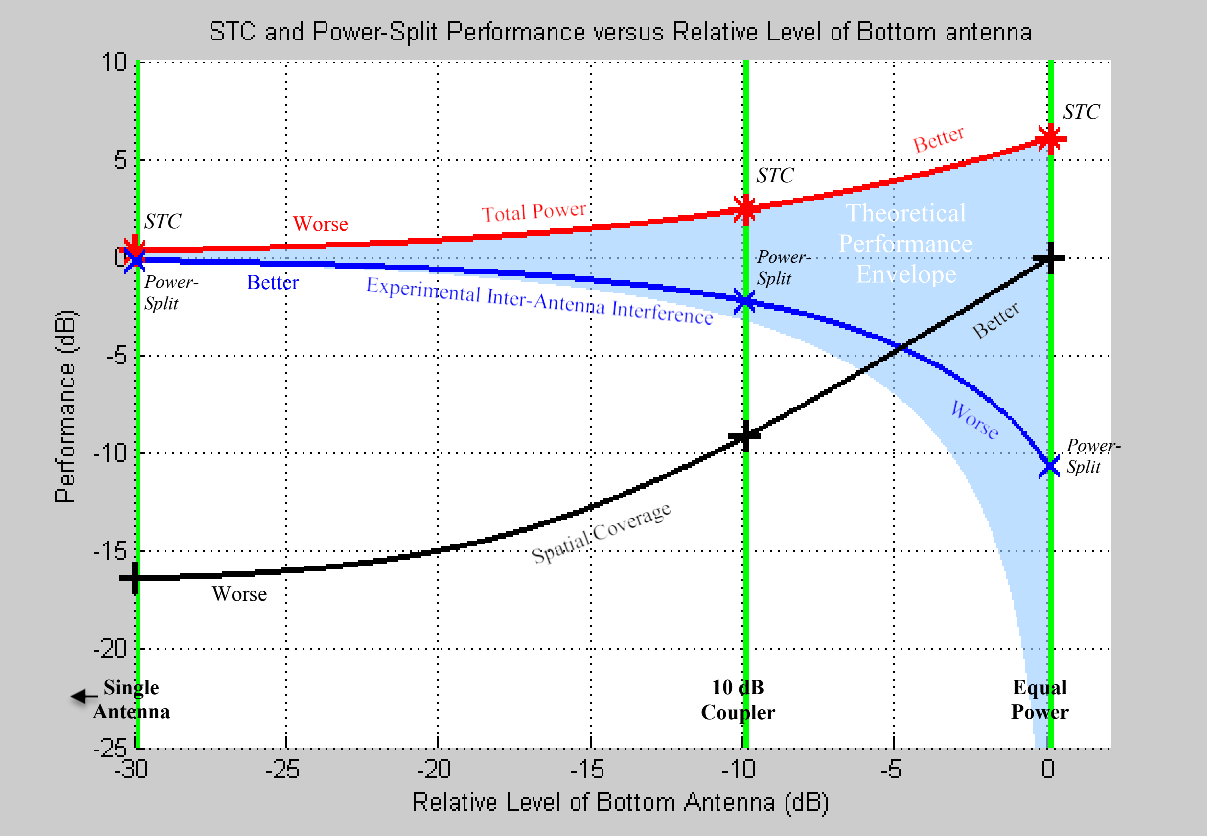


Figure 10: Link Margin Losses for Power-Split and STC System

CONCLUSION

It was shown that using two transmit antennas to address spatial coverage can lead to significant self-interference issues if the signals are derived from a single source. An alternate approach is to use STC, which allows full-power transmission with no inter-antenna interference on a single frequency. Examples were presented that showed the trade-offs between coverage and interference that traditional systems have to make in selecting the power-split ratio. No such trade-offs are required with the STC system as it simply applies full power to each antenna. Operational flight data was presented that confirmed the effectiveness of the STC system as having significantly less data dropouts and improved range over the previous traditional telemetry configuration.

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