Low-Cost Ground Station Antenna Arrays for Microspacecraft Mission Support

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ABSTRACT: Employing microspacecraft on interplanetary missions entails meeting numerous unresolved technical challenges. One such problem is how to maintain a reliable communications link with the microspacecraft over long distances. When considering the feasibility and costs of several alternatives, it has been shown that a ground station array is an ideal solution to the problem. Simulations and experiments performed at the Space Flight Laboratory of the University of Toronto Institute for Aerospace Studies have demonstrated that it is possible to create such an array using a group of amateur radio ground stations. When enhanced through the use of several digital signal processing techniques, these commercial-grade ground stations represent a low-cost, robust alternative to the Deep Space Network for terrestrial ground support of future microspacecraft missions or high data rate low-Earth orbit microsatellite missions. These ground stations can also be used to increase the array size of currently existing large dish arrays, such as those used in the DSN, by linking them to groups of small aperture ground stations. Such an increase in array size would yield an array that is better able tolerate antenna outages, equipped to decode noisier spacecraft transmissions, and has a longer baseline to facilitate the determination of spacecraft ranging information.

INTRODUCTION

The increasing capabilities and low cost of microsatellite missions make them an attractive means of broadening the scope and number of space science and exploration missions. However, despite these advances, microsatellites are presently limited to missions in low Earth orbit (LEO). One of the reasons for this limitation is that current microsatellites do not have sufficient available power to run a transceiver capable of communicating with a low-cost Earth ground station (e.g. a ground station with a two meter or three meter parabolic antenna), either from interplanetary distances or at data rates greater than a few tens of kilobits per second from LEO.

To gain an adequate perspective of the challenge this presents, one should note that communicating with a microspacecraft at interplanetary ranges using small aperture ground stations is very difficult as compared to how NASA communicates with its deep space probes. The significant difference in gain-to-noise temperature ratio (G/T) of the Deep Space Network (DSN) 70 m Goldstone ground station[1,2], as compared to a typical 3 m and 6.1 m ground station, is demonstrated in Table 1. A comparison of transmitter effective isotropic radiated power (EIRP) between Galileo[1,2], Mars Global Surveyor[3], and a microsatellite-class radio is presented in Table 2.

Table 1: Ground Station Gain-to-Noise Temperature Ratio (G/T) Comparison.

	70m Goldstone	3m Antenna	6.1m Antenna
Frequency (MHz)	2290	2232	2232
Ground Station G/T (dB/K)	59.02	10.71	16.80

Table 2: Spacecraft Transmitter-Antenna System Comparison.

	Galileo	Mars Global Surveyor	Microsatellite-class Radio
Frequency (MHz)	2290	8400	2232
Spacecraft Transmit Power (mW)	15000	10000	4000
Spacecaft Antenna Gain (dBi)	7	42	0
EIRP (dBm)	47.8	82.0	36.0

Ground Station Arrays

As previously determined[4], the best solution to overcome the communications problem for a microspacecraft is to significantly improve the ground station, rather than the microspacrcaft transceiver system, since limitations in mass and volume on the microspacecraft make it difficult to effect any major enhancements. The most effective way to improve the ground station solution that avoids dramatic price increases while still allowing for large aperture areas, and hence gains, is to array several smaller low-cost antenna dishes together and combine their signals. A plot of ground station cost vs. SNR improvement comparing an ideal 3-m parabolic antenna array to a single dish ground station (with the size of the dish increasing with the cost) is shown in Figure 1. The downlink frequency is 2.2 GHz, and a central array site estimated cost of CDN$70,000 is included in the array plot (hence the larger jump in price from the first point to the second). Using a larger array is more cost effective than using a larger single dish for dish diameters in excess of 4.9 m. This is when the "single ground station" plot in Figure 1 crosses over the "array ground station" plot. Similar results can be found even when using higher downlink frequencies. From the plot of Figure 1, it is apparent that arraying presents a more viable option for developing low-cost microspacecraft ground stations.

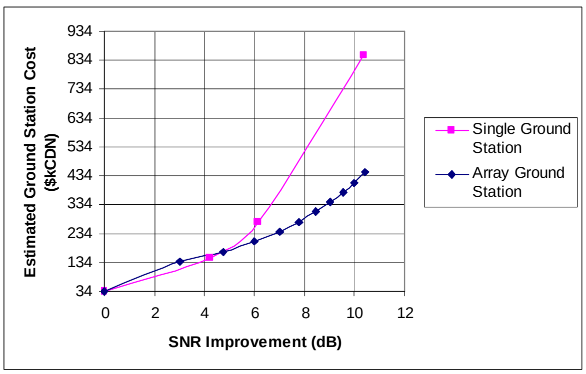

Figure 1: Estimated Cost vs. SNR Improvement Comparison Between Array and Single-Dish Ground Station.

Very Long Baseline Interferometry

A flexible array design, allowing the users to locate the individual antennas, each with its own local oscillator, wherever preferable, can be constructed using Very Long Baseline Interferometry (VLBI) techniques developed for radio astronomy in the 1960's[5,6]. The flexibility of this array would allow for the construction of a ground station array using existing ground stations located across a large surface area, increasing the sky coverage of the ground station. As well, by combining the signals at baseband, the array is made functional for a wide variety of RF bands. This array must be capable of compensating for errors such as:

- Phase offsets due to the fact that each antenna receives the signal at a different time due to their different geographic locations.
- Phase offsets introduced when downconverting the signal from RF to baseband.
- Frequency and phase offsets between the various local oscillators of each antenna in the array and the spacecraft.

By applying VLBI with today's technology, any data collected by the array can be sent directly to the central correlation site in real-time over an ADSL or other high-speed data link, rather than collected on magnetic tape for later correlation. As well, low-cost commercial GPS receivers can be used to determine the position of each antenna within a few centimetres, thus allowing the central site to correct phase errors arising from the reception, at different times, of the signal at each antenna.

At the central site, there are different ways in which the array signals can be processed before correlation. Many of these techniques were developed by JPL and have been used on the DSN[7] for communicating with spacecraft such as Galileo. With one method, Full Spectrum Combining (FSC, ref. Figure 2), the entire observed spectrum is downconverted in an open-loop manner, and performs symbol demodulation after the correlation stage. Any time and frequency errors introduced by the open-loop downconversion to baseband must be captured and corrected in the cross-correlation stage. However, since no carrier lock is required at each antenna, an array employing FSC can recover signals that are buried much deeper into the noise. Due to the low power signals that a microspacecraft will be transmitting, FSC is the best method to use for a microspacecraft ground station array.

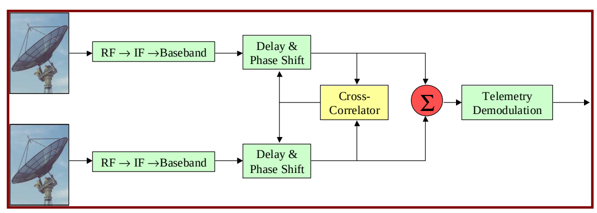

Figure 2: Full Spectrum Combining Block Diagram.

Data Resolution & Oscillator Frequency Drift

With FSC, the central site can correct for phase errors due to downconversion to baseband as well as any residual time offsets remaining that the GPS receivers did not properly correct. VLBI using FSC would allow for the creation of an arraying system that could theoretically array new and/or existing low-cost amateur ground stations from all over the world, each with its own independent local oscillator. However, the resolution of these corrections is limited by the quality of the equipment used at each antenna and at the central site. This places a limit on the maximum data rate that can be received due to the limited accuracy of commercial radio equipment. For example, a 10 µs accuracy is required for a 10 kHz signal if the baseband carriers must be aligned within 10% of a symbol period. This implies that for a 10 kHz signal with a wavelength of 30 km, the positions of the antennas must be known to within 3 km, which is achievable with commercial GPS receivers. Conversely, if a commercial GPS receiver is capable of 1 μs timing accuracy and 10 m position accuracy, then the maximum baseband bandwidth tolerable is the lesser of 100 kHz and 30 MHz. Thus, a limitation is imposed on the achievable data rate.

In addition to this, one source of error previously mentioned which has yet to be corrected in this system is local oscillator (LO) frequency drift between all of the antennas in the array. For radio astronomy and DSN arraying, this problem is circumvented by using very expensive, cryogenically cooled, ultra-stable oscillators with frequency stabilities of better than 10^{-10} for short averaging times[8]. Thus, frequency-domain errors are kept to a minimum. However, such equipment is not generally available or affordable for low-cost microspacecraft missions. These missions must use commercial radio equipment with accuracies of no better than 10^{-5}-10^{-9} times the received frequency for short averaging times. For S-Band, this would lead to a frequency offset errors ranging up to 20 kHz. If not corrected, this LO frequency drift error will lead to signal decorrelation at the central site.

Orthogonal Frequency Division Multiplexing

Improving the equipment to overcome these problems is prohibitively expensive. However, the signal can be divided into numerous, narrow bandwidth channels in order to increase the maximum possible data rate that the array can detect. As well, this will provide a wide-bandwidth signal suitable for correlation in the frequency-domain.

One way of doing this is through the application of Orthogonal Frequency Division Multiplexing (OFDM). The idea behind OFDM is to provide spectrally efficient frequency division multiplexing. In typical frequency division multiplexing systems, the narrow bandwidth channels are separated by large guard bands (ref. Figure 3). For OFDM, the separation between each channel is equal to the bandwidth of each channel, which is the minimum distance by which the channels can be separated (ref. Figure 4)[9]. Therefore, the channels occupy a similar bandwidth as the equivalent single-channel transmission, giving high spectral efficiency. OFDM is also useful for mitigating the effects of multipath interference, flat fading, and frequency selective fading. The technology is currently being used in wireless LANs and is under consideration for cellular networks and digital radio broadcasts.

Instead of sending data modulated on a single carrier with a given bandwidth, the usable spectrum is divided into multiple carriers, each modulated with a portion of the data at a lower data rate. A high data rate signal that previously could not be decoded by the correlator due to timing inaccuracies can now be decoded due to the longer baseband symbol time corresponding to the individual channel data rates. The multiple channels in the wide-bandwidth OFDM signal also make it possible to perform accurate frequency spectrum correlation of the signals, allowing the correlator to correct for local oscillator frequency drift. This mitigates the need to maintain frequency coherence between the local oscillators of each individual antenna.

With new IEEE standards available for OFDM and widespread terrestrial use, equipment costs can be kept to an absolute minimum. This means that spacecraft and ground station transceivers can be developed at relatively low cost. The hardware and algorithms involved in OFDM are also relatively simple, involving the application of the Fast Fourier Transform (FFT) and Inverse-FFT (IFFT) algorithms, making it possible to develop custom OFDM transceivers for a specific data rate.

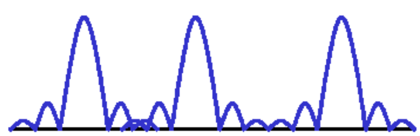

Figure 3: Frequency Division Multiplexing.

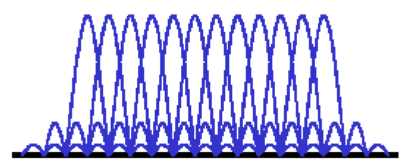

Figure 4: Orthogonal Frequency Division Multiplexing.

LOW-COST, FLEXIBLE SOLUTION: ARTEMIS

Arraying Technique for Enhanced Multiplexing of Interferometric Signals (ARTEMIS) incorporates the techniques used for VLBI-FSC, and OFDM to establish an alternative to DSN in terms of providing terrestrial ground capability for communicating with low–power spacecraft at distant ranges or at high data rates. This configuration also has direct application in supplying low-cost, reconfigurable, and rapidly installable communication stations on Earth and other planetary bodies in support of space exploration missions. It is also flexible enough to be used for any RF transmission frequency (e.g., S, C, and Ka bands), provided that the baseband bandwidth is sufficiently broad to capture any frequency drift introduced by the local oscillator used at each ground station. ARTEMIS can also be used to improve current large dish antennas, such as those in the DSN, by reducing the requirement of frequency coherence between the local oscillators of the antennas in the array and the oscillator on the spacecraft, and allow for the correlation of noisier signals. Typically, the DSN works on signals with SNRs in the range of -3 dB to 3 dB. ARTEMIS can substantially improve upon this, potentially facilitating correlation on signals with SNRs of -20 dB or lower. It would also allow the arraying of DSN antennas to groups of smaller antennas, such as the proposed Allen Array radio astronomy observatory in California, comprised of over 300 6.1m parabolic antennas. In addition to communications, ARTEMIS can provide a low-cost method for accurately ranging interplanetary probes. If the ground stations are spread along a very long baseline, then accurate tracking using interferometry is possible.

The University of Toronto Institute for Aerospace Studies' Space Flight Laboratory (UTIAS/SFL) is developing ARTEMIS as a VLBI-FSC-OFDM array solution to the problem of enhancing communications with low-power spacecraft based on low-cost commercial components.

TECHNICAL DESCRIPTION OF ARTEMIS

Ground Station Configuration

As illustrated in the architecture diagram of Figure 5, the ARTEMIS system is comprised of a number of remote ground station sites connected to a central processing facility. At each remote site is located an element of the antenna array, which receives the downlink transmission from the microspacecraft. The received RF signal is downconverted to a sufficiently low IF as to facilitate digitization, and the digital data are prepared for transmission to the central site. The software modules implementing the ARTEMIS OFDM/VLBI operations (i.e., FFT, correlation, frequency correction, summation, demodulation) are executed at the central processing site. The nature of the communication problem and the amount of data being transferred necessitate that each remote site be linked to the central site by means of a real-time, high bandwidth data communications link (e.g., ADSL).

The downlink correlation approach is summarized in the following series of steps:

At Each Antenna (each array element):

- Use an open-loop receiver to downconvert the incoming signal spectrum to baseband.
- Perform analog to digital conversion – oversample to reduce quantization noise.

Correct for delays due to array geometry to bring signals into alignment.

- Send digitized, delay-corrected, baseband signal to central processing site with timing information determined by commercial GPS.

At VLBI Array Correlator/Combiner (central processing site):

- Perform Fast Fourier Transform to convert to frequency-domain.
- Correct for frequency shifts due to Doppler.
- Perform baseband carrier interferometry (i.e., correlation) in the frequency domain on signals received from all array elements to obtain carrier and time phase alignment. This will correct for local oscillator frequency drift between stations. For an OFDM signal, this is done with several carriers.
- Perform time-domain correlation to correct for any remaining time offsets
- Combine the baseband carriers to form an enhanced baseband carrier.
- Demodulate OFDM carriers into a collection of soft symbol streams.
- Feed soft symbol streams into decoders.
- Re-integrate resulting data streams into single data stream.

Central Correlator Site Hardware & Software

The implementation of VLBI over an OFDM communications link requires high-performance computing capabilities in the baseband signal processing hardware. In particular, an onerous computational load is placed on the central-site processor, as it is required to perform, in real time, pair-wise correlations of the incoming signals from each node of the array, corrections for errors in phase and frequency, and OFDM de-channelization, as well as demodulation and detection. The FFT and IFFT are the most prevalent functions used by the ground correlator software for both correlation calculations and OFDM de-channelization. Because of the frequent use of the FFT, this processing is best performed in the digital domain, by an FFT-optimized digital signal processor (DSP). The FFT has an operations order of $n\log(n)$, assuming that n is a power of two. All other

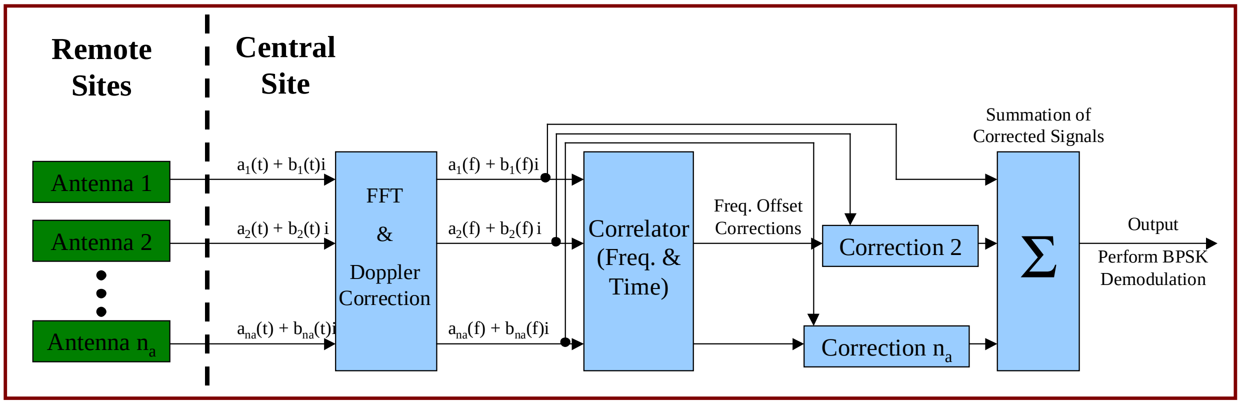

Figure 5: ARTEMIS System Architecture.

software functions used by the central site correlator software, such as any multiplications, will be of order *n*.

Spacecraft Hardware & Software

The one change to the microspacecraft hardware that is needed is the addition of the DSP used to generate the OFDM signal. The OFDM signal will be generated in real-time as data is being transmitted to Earth, and its power and bandwidth characteristics must be compatible with the transmitter equipment typically employed on microsatellites.

OFDM Signal Generation

To create an OFDM symbol with N channels, an N-point IFFT applied to N data symbols. This signal can then be digitally upconverted to a higher IF before being converted to an analog signal via a DAC, and upconverted to RF. The IFFT is applied contiguously for every N data symbols, in each instance generating an OFDM symbol for transmission. In the case of the OFDM receiver on the ground, the software continuously performs an N-point FFT to the received signal after it has been correlated and combined at the array central site, retrieving the data symbols for each of the N streams. A block diagram of this process is illustrated in Figure 6.

The time domain representation of a four-channel OFDM symbol, and its constituent carriers, are illustrated in Figure 7 and Figure 8, respectively. In practice, generation of an N-channel OFDM symbol requires an FFT/IFFT of at minimum 2N points in order to avoid aliasing. Any greater number of points (e.g., 4N, 8N, etc.) will result in an oversampled OFDM symbol, which provides a wider bandwidth in which to detect any frequency offsets between the signals received by the ground station array.

The practical limit to the number of OFDM channels into which the available bandwidth can be divided depends upon the clock frequency of, and amount of memory available to the processors performing the modulation and demodulation of the OFDM signal. Further, increasing the number of channels results in a greater peak-to-average power (PAP) ratio in the transmitted signal. A high PAP ratio imposes more stringent design requirements (e.g., greater linearity) upon the power amplifier of the transmitter. Therefore, the maximum number of channels considered in this work is 4096, which corresponds to the maximum number currently investigated by researchers in the field of OFDM communications.

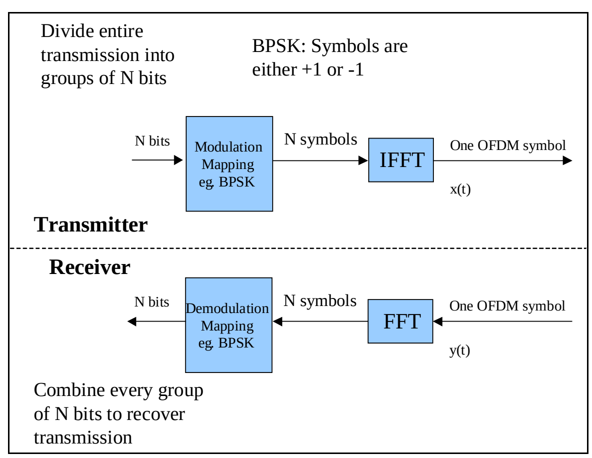

Figure 6: OFDM Communications System Block Diagram.

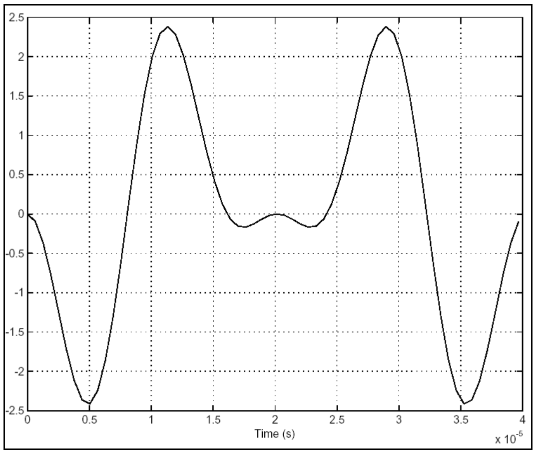

Figure 7: Time Domain Representation of a Four-Channel OFDM Symbol.

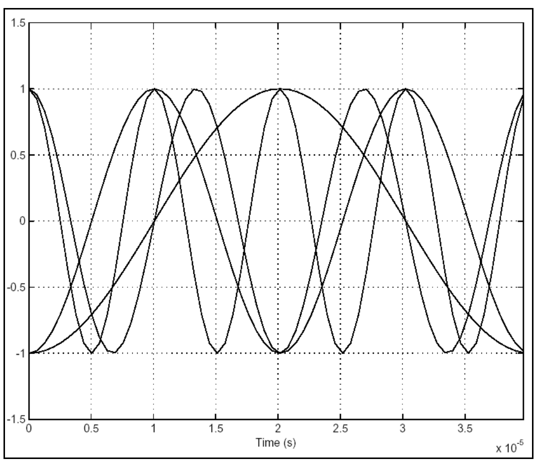

Figure 8: Time Domain Carriers of a Four-Channel OFDM Symbol.

ARTEMIS ARRAY PERFORMANCE REQUIREMENTS

The software at the central site of the array must be capable of correlating – in both the time and frequency domain – the signals received by the antennas in the array. Five communications link scenarios, illustrating typical E_b/N_0 (bit energy to noise density ratio – essentially the signal-to-noise ratio (SNR) of a digital signal) conditions under which the software will be required to perform the correlations, are illustrated in Table 3. These scenarios include a past NASA mission utilizing the DSN, a mission involving a high data rate Earth-orbiting microsatellite communicating with a small-aperture ground station antenna, and two interplanetary microspacecraft missions, at the Moon and Mars, also communicating with small-aperture ground station antennas.

Table 3: Communications Link Scenarios.

Scenario	Galileo	Microsatellite (LEO)	Microspacecraft (Moon)	Microspacecraft (Mars)
Frequency (MHz)	2290	2232	2232	2232
Spacecraft Transmit Power (mW)	15000	400	4000	4000
Spacecaft Antenna Gain (dBi)	7	0	0	0
EIRP (dBm)	47.76	26.02	36.02	36.02
Path Loss (dBm)	-280.00	-172.94	-212.25	-265.04
Diameter of Antennas on Ground (m)	70	3	3	6.1
Individual Ground Station G/T (dB/K)	59.02	10.29	10.71	16.80
Data Rate (bps)	400	4000000	14400	1
Individual Receiver Eb/No (dB)	-0.64	-4.06	-8.50	-13.62

The gain-to-system noise ratios (G/Ts) for the amateur ground stations usable in a system employing ARTEMIS are significantly lower than then those of the ground stations comprising the DSN. The software must be able to perform frequency domain and time domain correlation on these very noisy signals. The correlation and decoding of the signal should be performed in "real-time," to eliminate the need for large memory buffers in the system. Furthermore, the time required to perform one correlation must be minimized in order to guarantee that any frequency offsets present remain constant over the duration of the correlation period. The maximum correlation time will depend upon the frequency stability of the transceivers employed.

Receiver & Array Signal-to-Noise Ratio

Two values that are very important when it comes to judging the performance of the array are the E_b/N_0 of each individual receiver in the array (see the last row of Table 3) and the combined E_b/N_0 of the entire array. The former must be high enough so that correlation can be done, and the latter must be high enough – assuming correlation was done properly – so that the output data stream has a low bit-error rate (BER).

In terms of bit-error rate (BER) vs. E_b/N_0 characteristic of the array output signal, the performance of a BPSK-modulated OFDM signal differs only negligibly from that of a BPSK modulated single-channel signal (ref. See Figure 9)[9]. Furthermore, as evidenced by the curves of Figure 9, this performance similarity applies equally for different numbers of channels, as well as various oversampling ratios. Consequently, a desired BER of, for example, 10^{-5} would require an array output E_b/N_0, after signal combination, of 9 dB, as it would for single-channel BPSK.

As with single-channel signals, forward-error correction (FEC) techniques can be employed to reduce the minimum array output E_b/N_0 required for successful demodulation of the OFDM signal. Simulations performed using convolutional encoding, and Reed-Solomon encoding have both demonstrated that achievable BER performance improvements with OFDM signals are similar to, or greater than those achievable with single-channel signals. The performance of FEC with OFDM signals is further improved in the case of burst errors due to frequency fading, since the FEC can interleave the frequency channels, thus whitening the noise. Such frequency fading-induced errors will be present in the array-combined signal if any time offset errors remain after correlation. Initial simulations have demonstrated that a FEC scheme composed of a ½-rate convolutional code combined with a (255,239) Reed-Solomon code can reduce the required E_b/N_0 for a BER of 10^{-5} to less than 2 dB (ref. Figure 10), approaching Shannon's limit of 0 dB for a ½-rate FEC. Such a coding scheme would be easy to implement in software on the spacecraft. However, decoding this FEC at the central correlator site of the ground station could potentially be very complex, and require a processor either with built-in FEC capabilities or with a very high clock speed. The use of Turbo codes to reduce the computational load on the central site processor is a promising option that remains to be investigated.

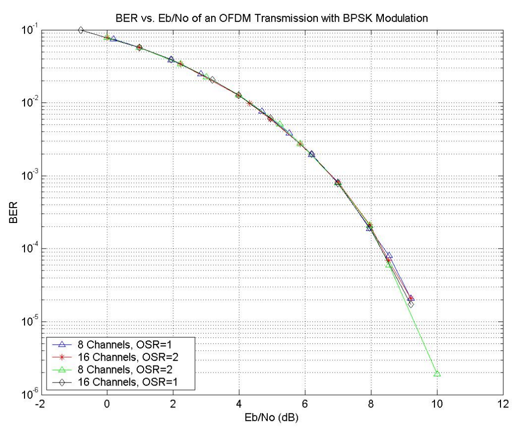

Figure 9: BER Characteristic for OFDM Signals.

In all the cases shown in Table 3, the receiver E_b/N_0 is much lower than 2 dB, so even if FEC is used, arraying will be required to extract the signal from the noise if a BER of 10^{-5} is desired. Assuming perfect correlation and that all the antennas in the array are of the same size, the required size of the array is:

$$n_a = 10^{\left[\frac{(E_b/N_0)_{Required} - (E_b/N_0)_{Receiver}}{10}\right]}$$

where both E_b/N_0 values are in dB. Essentially, for every 3 dB that must be made up from the receiver E_b/N_0, the array size must double. The array size can be reduced if some larger antennas are included in the array.

However, the above equation assumes that the individual receiver E_b/N_0 values are high enough to properly perform correlation to correct for time and frequency offsets between the various signals received the array. When arraying is done using the DSN, the correlation of very noisy signals is accomplished by collecting the signal over a very long time period and correlating over the entire period. However, such a technique will not aid in the frequency-domain correlation of a typical narrow bandwidth spacecraft transmission.

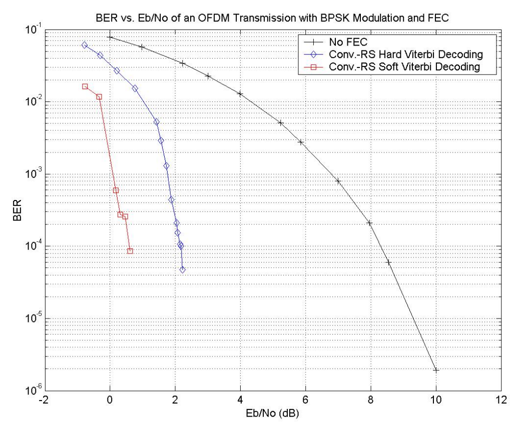

Figure 10: BER Characteristic for OFDM Signals with ½ Convolutional & (255,239) Reed Solomon Forward Error Correction.

For ARTEMIS, OFDM enables frequency-domain correlation of noisier signals. An OFDM signal has many digital data points defining its spectrum (one per channel), in contrast to a single-channel signal, which has only one. With an increased number of digital data points defining the signal spectrum, correlation of the OFDM symbol is made easier. Therefore, if the noise level associated with the signal is elevated, then correlation of the signal can be facilitated by merely increasing the number of OFDM channels. The multiple channels in the OFDM signal make it possible to easily perform frequency-domain correlation since the same equations used to perform time-domain correlation can be used, with only an additional FFT operation required. The system requirement for successful frequency drift compensation is that the rate at which the OFDM signal is sampled must be great enough to accommodate the maximum frequency drift, without inducing aliasing. Furthermore, the frequency drift rate must also be sufficiently low that the frequency offset may be considered constant over the duration of the correlation window.

Concurrent Frequency & Time Domain Correlation

An ARTEMIS array must also be able to correlate noisy signals with *both* time offsets and frequency offsets present between the various signals. When simultaneous time and frequency offsets are present in two signals, the difficulty associated with determining the offset values through cross-correlation is exacerbated. A method for circumventing this limitation, developed for ARTEMIS, involves correlating the *magnitude* of the frequency spectrum of the signal received at each antenna with a noise-free version of the spectrum. This procedure entails first generating an estimate of the frequency offset, which is then used to discard the OFDM channels most adversely affected by the phase offset. An accurate determination of the frequency offset can then be made with the remaining channels. Once the frequency offset is corrected for, the time offset can be determined. The limitation of this technique is that the minimum E_b/N_0 required for correlation is increased since fewer frequency channels are included in the correlation step. The minimum number of channels required for correlation can be determined for a given communication scenario, which will lead to a maximum time offset that can be tolerated before frequency-domain correlation is performed.

Included in Figure 11 is the frequency correlation curve resulting when a 9600 bps, 4096-channel OFDM signal with a received E_b/N_0 of –10 dB is correlated with a noise-free version of itself that is not offset in time or frequency, with respect to the FFT window. A frequency offset of approximately 1 kHz, and a time offset of approximately 52 μs (both with respect to the FFT window) are present in the received signal, resulting in a frequency correlation curve that exhibits no well-defined peak. However, upon application of the algorithm described above, the frequency correlation curve of Figure 12 is obtained, with a peak clearly indicating the 1 kHz offset. Subsequent to correction of the indicated frequency offset, a time correlation curve is then easily generated, indicating a time offset of 52 μs.

ARTEMIS "PROOF-OF-CONCEPT" HARDWARE EXPERIMENT

Based on the results of the initial simulations, and case examples analyzed, an experimental plan was

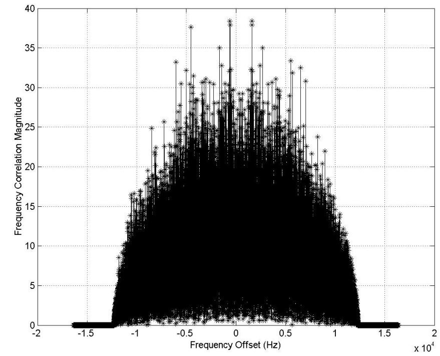

Figure 11: Frequency Correlation with Concurrent Errors, Before Filtering.

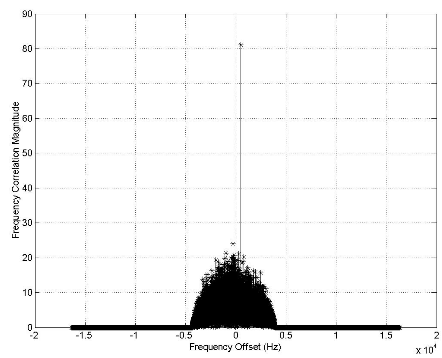

Figure 12: Frequency Correlation with Concurrent Errors, After Filtering.

developed for validation of the ARTEMIS principle. The test setup for the proof-of-concept experiment is illustrated in Figure 13. In order to maintain controlled experimental conditions, and to eliminate the complexities associated with development of an S-Band communications link in the initial stages of the experiment, a hardware test setup was devised in which the DSP implementing the spacecraft transmitter and the DSP implementing the ground station correlator communicate via a low-IF analog channel. In the absence of an actual antenna array, a software routine was developed to introduce representative frequency and phase offsets in the transmitted signal. All software modules integral to execution of the experiment have been successfully developed and tested; these include:

- "Spacecraft" transmitter, i.e., modulator and OFDM signal generator.
- DAC controller.
- Antenna array impairment emulator.
- ADC controller.
- Central site correlator, i.e., frequency and phase correction and demodulation.

An analog channel interface was implemented in hardware to provide anti-alias filtering at the input to the ADC, and to facilitate adjustment of the SNR of the received analog signal.

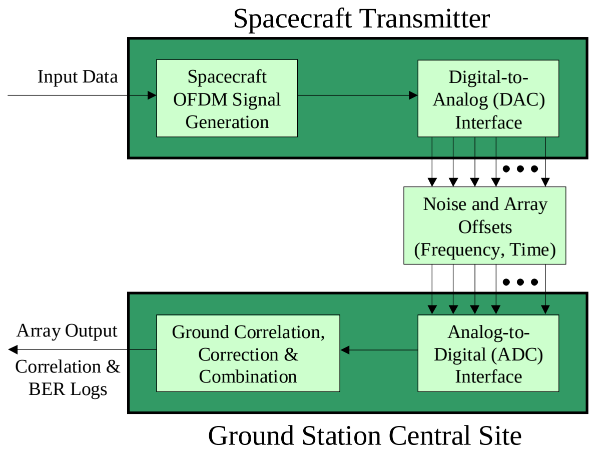

Figure 13: Baseband Experimental Test Setup.

The test scenario implemented in the hardware experiment is designed to closely emulate a 9600 bps downlink from LEO, received with a ground station array consisting of three parabolic antennas. OFDM signals from 8-channels wide to 512-channels wide can be generated. Data has been collected for transmissions impaired by LO frequency drift, under a range of E_b/N_0 conditions to simulate different antenna sizes and/or longer transmission distances. In all cases, these observations are in close agreement with theoretical predictions and simulation results.

The first scenario tested the accuracy of frequency correlation between every signal received by the array and determined the average error in the correlation vs. the E_b/N_0 of the signals (ref. Figure 14). As expected, the minimum E_b/N_0 of a received signal before errors are present in the frequency correlation decreases as the number of OFDM channels is increased. For a 512-channel OFDM signal, the minimum E_b/N_0 that an ARTEMIS array can tolerate is about -9 dB. Extrapolating for a 4096-channel OFDM signal, the minimum E_b/N_0 would be around –15 dB. The trade-off of increasing the number of OFDM channels is that a higher computational load is placed on the correlation DSP and the correlation time (ie. the period of each OFDM symbol) is increased. Therefore, any frequency offsets must be constant for a longer duration in order for the correlation algorithm to work properly.

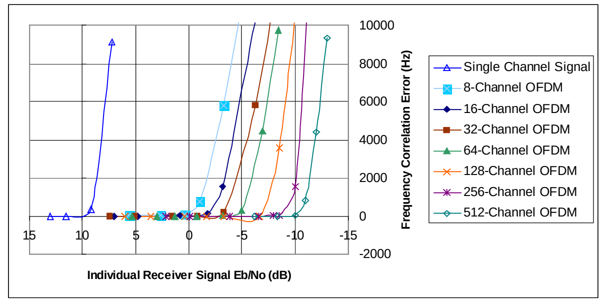

Figure 14: Frequency Correlation Error vs. Receiver E_b/N_0 for Signals Correlated With Each Other

For the second scenario, the signal sent by the spacecraft DSP periodically contains an OFDM symbol with a known structure (ie. a training symbol). It is only these training symbols that are correlated, with every signal in the array correlated with a noise-free version of the training symbol. The correction information generated by this correlation is then used for the next set of OFDM symbols, until the next training symbol is received, at which point the correlation information is then updated.

Again, the average frequency error in the correlation vs. the E_b/N_0 of the signals was determined (ref. Figure 15). The performance was much better than when the signals were correlated with each other, where for a 512-channel OFDM signal, that minimum array element E_b/N_0 that an ARTEMIS array can tolerate before errors are introduced is now -20 dB. The minimum E_b/N_0 for a 4096-channel OFDM signal is predicted to be approximately -26 to -29 dB at each array element. The trade-off for this improved performance is that any frequency offsets must be stable not only for the OFDM symbol time, but also for the period between appearances of the training symbol.

Future Experiments

In addition to the frequency drift and variable SNR tests noted above, further experiments proposed for the existing test setup include:

- Correction for concurrent frequency and phase offsets.
- Correction of residual time drift by the addition of a cyclic prefix (a copy of the end of each OFDM symbol appended its start).
- Correction of impairments that do not remain constant over the duration of a correlation period.

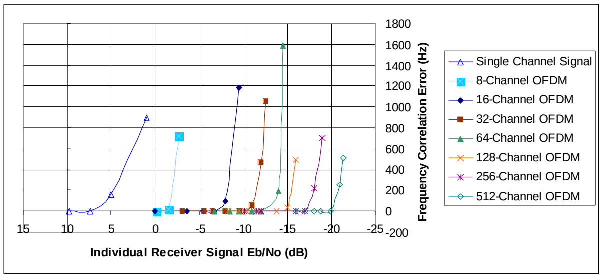

Figure 15: Frequency Correlation Error vs. Receiver E_b/N_0 for Signals Correlated With a Noise-free Training Sequence

Subsequent to completion of experiments on the current test set, further verification of the ARTEMIS concept would be obtained by replacing the low-IF communication channel with a full S-Band communications link. Finally, an in-flight test would be performed, with an ARTEMIS module aboard a future Space Flight Laboratory nanosatellite.

CONCLUSIONS

ARTEMIS combines the radio astronomy techniques of FSC and VLBI with OFDM to create a promising new technology for facilitating more advanced microspacecraft missions, while minimizing ground station costs. A thorough development of the theoretical principles underlying the ARTEMIS concept has been accomplished. As well, several case examples have been analyzed that indicate ARTEMIS could be employed to enhance ground stations, as a low-cost alternative to the DSN for spacecraft communications. ARTEMIS can also be used to increase the array size of currently existing large dish arrays, such as those used in the DSN, by linking them to groups of small aperture ground stations. Such an increase in array size would yield an array that is more flexible and powerful. A proof-of-concept experiment has been undertaken by SFL to validate the ARTEMIS principle. Preliminary observations are promising, and concur with results derived from theoretical models and simulations. More advanced experiments have been devised to further demonstrate the benefits of ARTEMIS.

From the data presented in this document, it is evident that ARTEMIS will be of particular benefit to future microspace missions, in that its application will facilitate higher data rates from microspacecraft in LEO, and extend the microspace concept to interplanetary distances. Also, ARTEMIS represents a promising technique for improved tracking and ranging of interplanetary spacecraft, in general, by increasing the baseline of existing large dish arrays.

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