Evaluation of Antenna Diversity for BGAN Maritime and Land Mobile Environments

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A propagation measurement campaign has been conducted to gain an understanding of the feasibility and potential benefits of using a set of omni-directional antennas with spatial diversity to provide Inmarsat BGAN and BGAN-variant services at low elevation angles under the I4 and Alphasat footprints. The campaign involved recording BGAN and CW carriers from multiple satellites over extended periods, in both maritime and land-mobile environments, and analyzing the recorded signals to determine the propagation characteristics and the achievable communications performance in terms of packet error rate for various antenna configurations and diversity combining methods. The paper describes the recording equipment and processing tools developed, the field campaigns carried out, and the results obtained. Good performance was achieved with a small number of antennas in the maritime environment, while antenna diversity provided less benefit in the land-mobile case.

I. Introduction

THE objective of the work was to gain better understanding of the feasibility and potential benefits of using multiple low-cost omni-directional antennas in place of a stabilised high-gain antenna to provide Inmarsat BGAN and BGAN-variant services, particularly at low elevation angles where multipath fading can be severe. The work involved:

- developing a measurement system capable of receiving signals from a set of antennas and recording the signals over an extended period of time;
- installing the measurement system on board an ocean-going vessel and recording signals from satellites at various elevation angles and under various sea states;
- installing the measurement system on a land vehicle and recording signals from satellites at various elevation angles and under various terrain conditions;
- analyzing the recorded data to determine the fading characteristics of the signals from individual antennas and the correlation between signals received from different antennas, as affected by spatial and polarization diversity;
- evaluating the performance of diversity receiver architectures on the recorded signals and on synthetic signals with similar characteristics.

II. Recording Equipment

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Figure 1 shows the equipment used to record the signals from the satellites. It consists of an 8-channel L-band downconverter, four two-input IF digitizer units, a GPS receiver, a marine Motion Reference Unit (MRU), and a standard PC server, housed in a transportable shock-isolated rack case. The antenna RF cables connect to a transition panel at the top rear of the rack. LNA power is provided to the antennas via the RF cables.

The equipment can record two independently-tuned channels from each of 8 inputs at a sampling rate of 134.4 kHz (16-bit complex), or one channel from each input at 302.4 kHz. It can store approximately 16 TB of data on eight hot-swappable drives, equivalent to three weeks of continuous recording of 16 channels at 134.4 kHz.

Figure 1. Recording equipment.

The software of the recording system configures the digitizers and records the signal samples, along with information from the GPS and MRU and operator-entered annotation. The recording system provides a Microsoft Windows-based operator interface, allowing the operator to monitor the spectrum and the amplitude profile of the signals in real time or as previously recorded. The system is typically operated remotely using Windows Remote Desktop over a LAN connection.

Figure 2 shows the spectrum of the signal from one digitizer channel, covering 125 kHz. It includes two carriers of 40 kHz bandwidth (BGAN T1 rate), a CW carrier, and some narrowband carriers.

III. Measurement Campaigns

A. Maritime Campaign

The maritime measurement campaign was hosted by the Atlantic Container Line vessel Atlantic Concert, shown in Fig. 3. Six right-hand circular polarized (RHCP) omni antennas and one RHCP steerable directional antenna (Inmarsat class FB150) were used. One of the omni antennas also had a left-hand circular polarized (LHCP) feed. Figure 4 shows the antennas mounted on the upper deck of the vessel. The mounting fixture allows the omni antennas to be positioned independently in height, azimuth, and distance from the mast. The GPS antenna is also visible at the top of the mast. The omni antennas were arranged to provide various horizontal and vertical spacings between pairs of antennas. The FB150 permits comparison with the performance of a directional antenna.
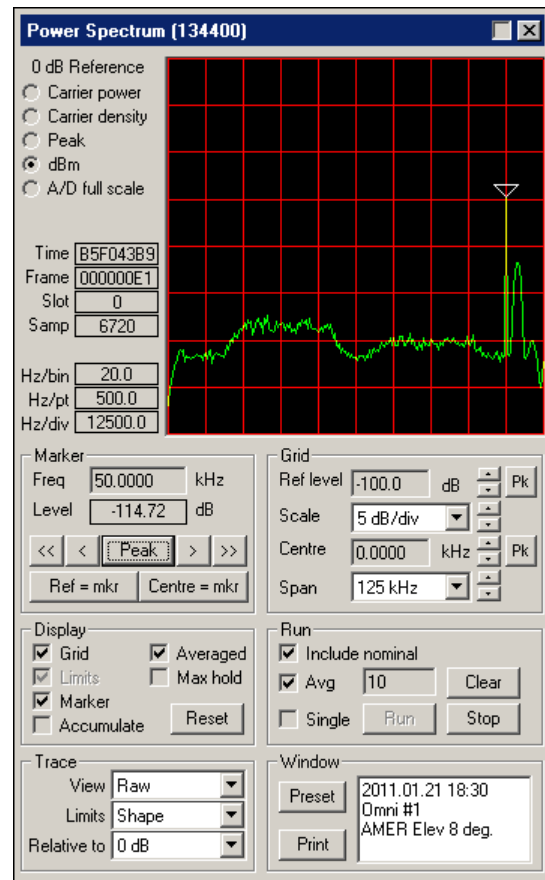

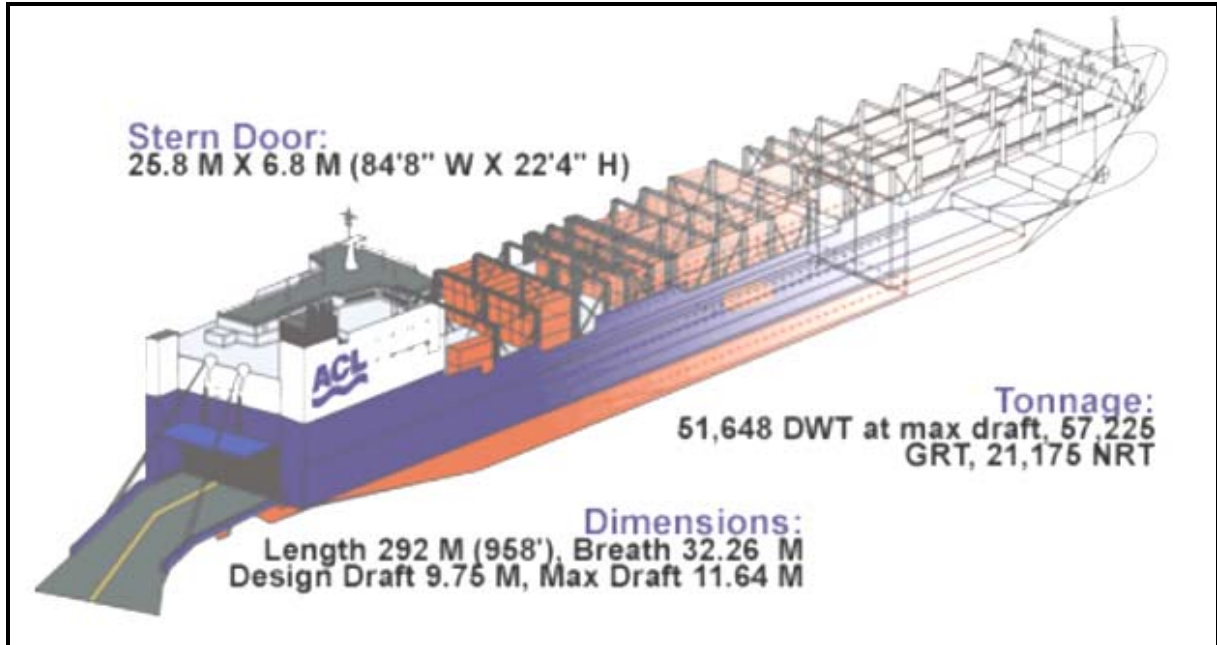**Figure 2. Channel power spectrum.**

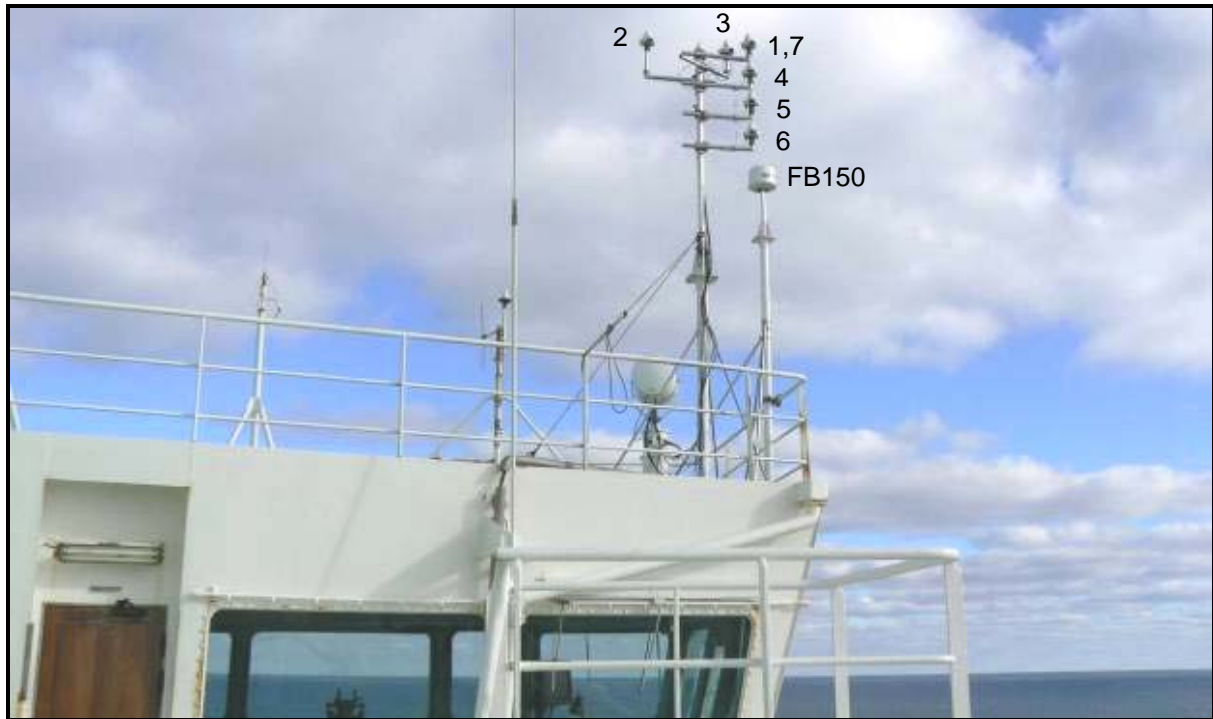**Figure 3. Atlantic Concert.**

Figure 4. Antenna installation on Atlantic Concert.

Signals were recorded continuously from Jan. 18 to Jan. 24, 2011 on a North Atlantic crossing from Halifax to Liverpool, and from Feb. 7 to Feb. 17, 2011 on the return crossing. One CW carrier and one QPSK carrier (BGAN F80T1Q) were recorded as received by each antenna from each of the AMER (98° W) and EMEA (25° E) satellites. The signals from each satellite were sufficiently close in frequency to fall within the recording bandwidth of a channel at a sampling rate of 134.4 kHz. The elevation angle to each satellite varied from below zero degrees to about 25 degrees. The sea state was predominantly Moderate to Rough, corresponding to wave heights of from 1.5 m to greater than 3 m.

B. Land Mobile Campaign

For the land mobile measurement campaign, the recording equipment was installed in a small van provided by the Communications Research Centre Canada. Four RHCP omni-directional antennas designed for vehicular applications were used. As shown in Fig. 5, the antennas were carried on a steel plate mounted on the roof of the host vehicle. Three antennas were mounted at 120° intervals on a circle centred on the plate, and the fourth on a non-conductive post at the centre of the plate. A GPS antenna was mounted at the rear of the plate.

Figure 5. Antenna installation on vehicle.

Since only four antennas were used, the signal from each antenna was applied to two digitizer inputs, allowing up to four channels to be recorded from each antenna. Three channels per antenna were actually used, corresponding to the AMER (98° W), AORW (54° W), and AORE (15.5° W) satellites. A CW carrier was recorded from each satellite, as well as a BGAN F80T1Q carrier from AMER.

Signals were recorded for approximately 8 hours per day on round trips between Ottawa and Toronto (Oct. 17 and Oct. 18, 2011) and between Ottawa and Charlottetown (Oct. 31 to Nov. 4, 2011). Figure 6 shows the overall route covered. The satellite elevation angle varied from 27° to 36° for AMER, 33° to 36° for AORW, and 10° to 20° for AORE. Forested, open rural, suburban, and urban terrain types were encountered.
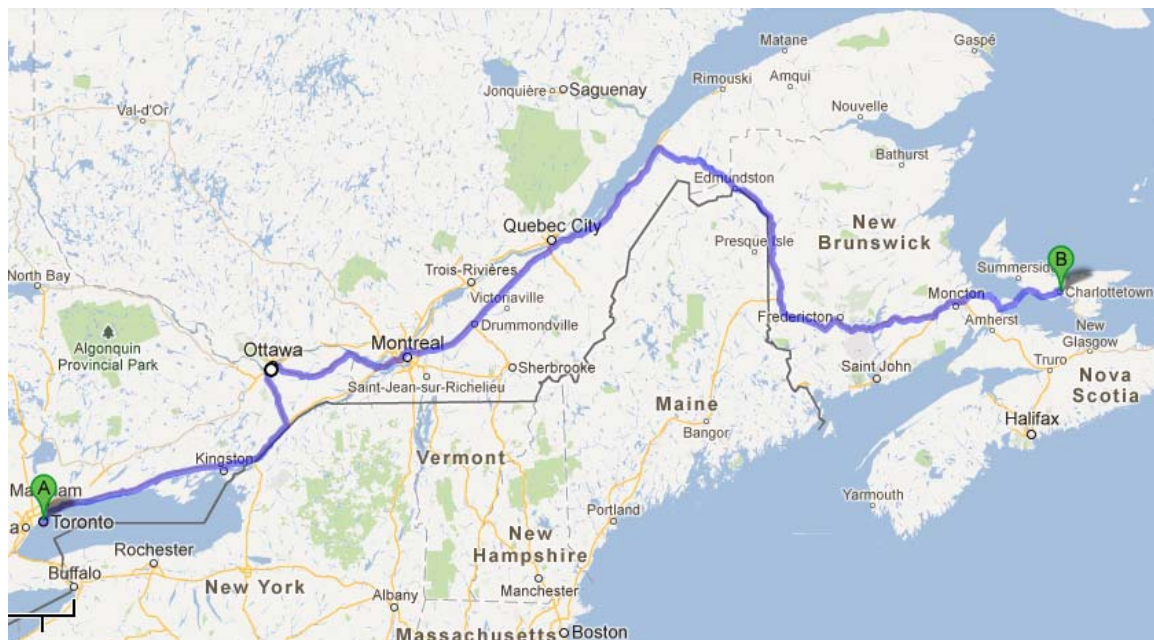

Figure 6. Land mobile measurement campaign route.

IV. Channel Characterization

A. Channel Parameters

The recorded signals were analyzed to derive the time-varying channel states and to determine the following parameters as functions of time:

- average signal power
- signal-to-noise-density ratio (C/N_0)
- carrier-to-multipath ratio (C/M)
- fading power spectral density shape and bandwidth
- cross-correlation of signal power between antennas

The power spectral density is derived from the magnitude of the signal rather than from the complex signal, to avoid a spreading effect caused by the presence of frequency jumps in the received carriers. These are presumably applied by the transmitting earth station to compensate for varying satellite Doppler. It was verified on synthetic signals that using the magnitude does not significantly distort the shape of the resulting PSD.

B. Maritime Channel Characterization

Figure 7 shows the signal power from each omni antenna for the CW carrier from EMEA, averaged over intervals of 10 minutes on the eastbound crossing. The overall duration is approximately 6 days. The lower scale on the horizontal axis shows the nominal elevation angle to the satellite, ignoring satellite inclination and propagation effects. The antennas are RHCP except for antenna 7, which is LHCP. The LHCP power is about 6 dB below the RHCP, except at low elevations where it is within a few dB.
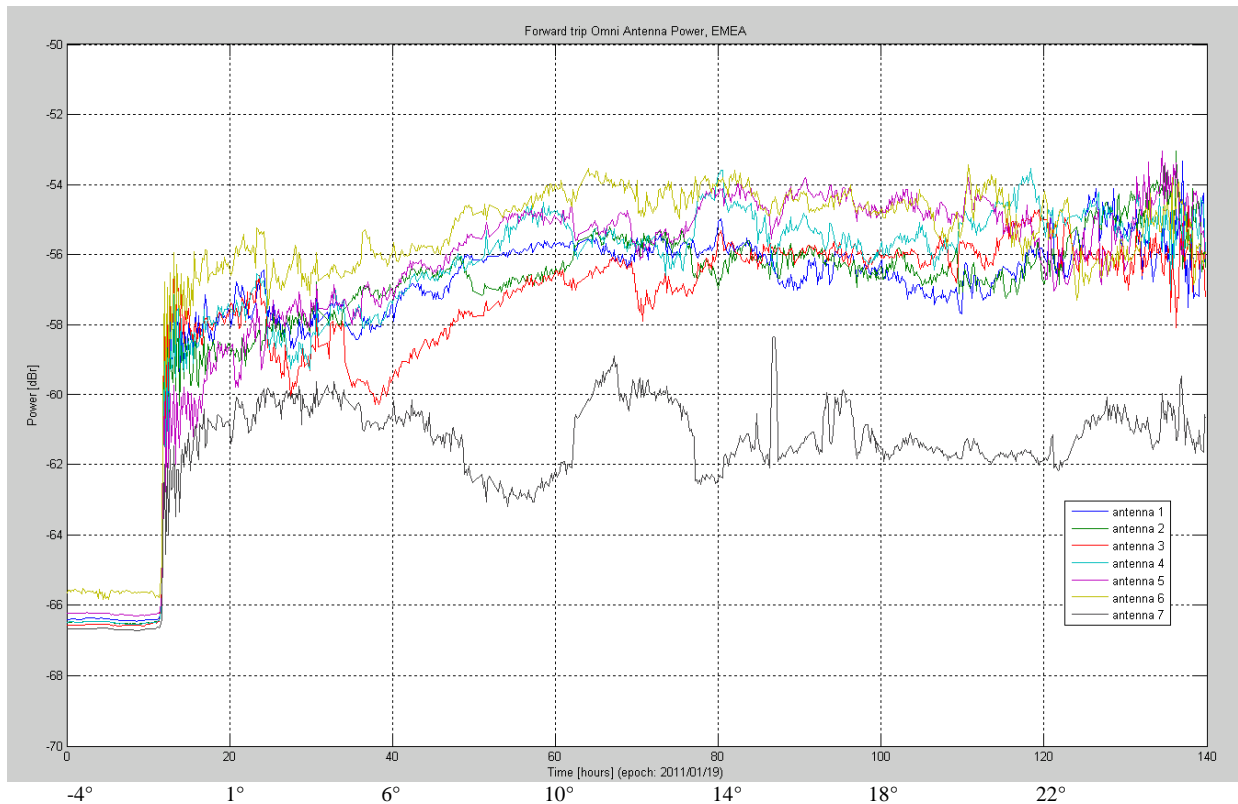

Figure 7. Signal power from omni antennas (EMEA CW, eastbound crossing).

The probability density function of the signal power closely matches a Rician characteristic. Figure 8 shows the C/M ratio for the same period as Fig. 7, calculated using the "moment" method[1]. The mean C/M ranges from about 6 dB at low elevation to about 12 dB at high elevation. The C/M from the LHCP antenna is off-scale at less than 0 dB. Antenna location can have a significant effect, as shown by the generally lower values from antenna 4 between about 6° and 20° elevation. The gap between about 35 and 40 hours is an artefact of the processing.
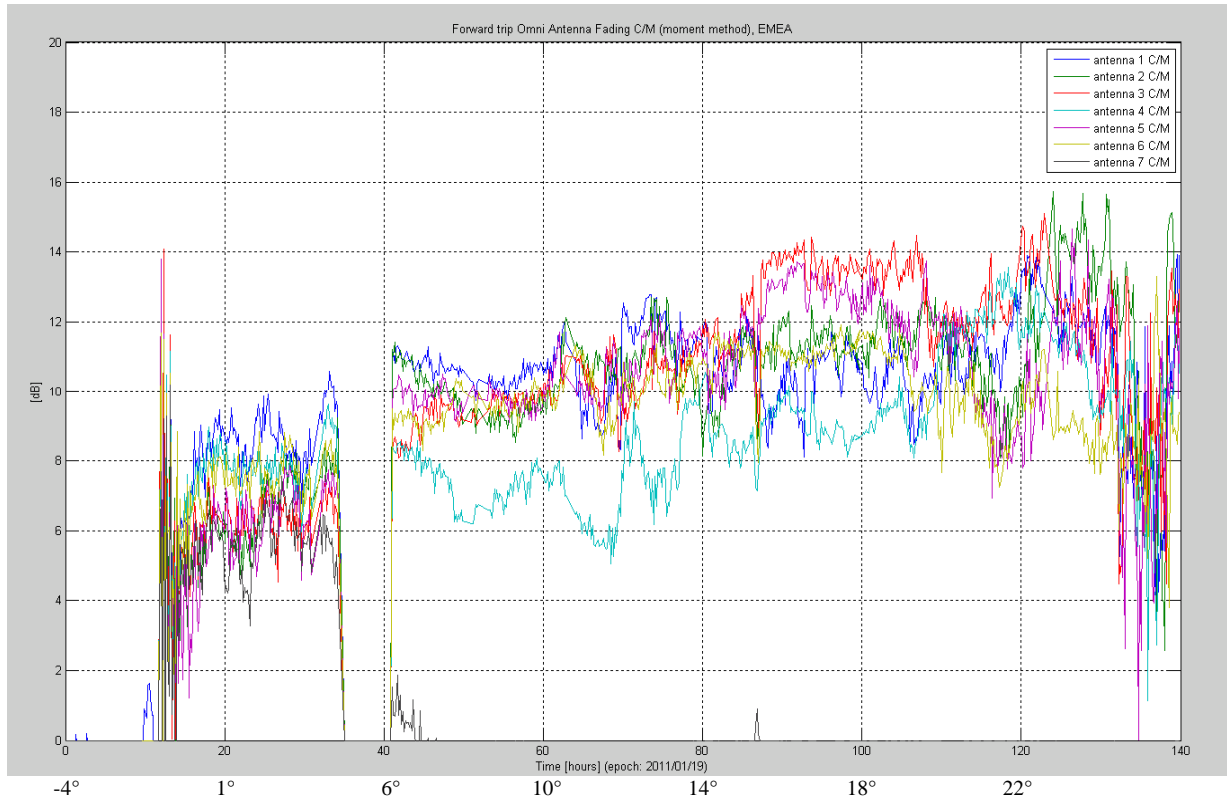
Figure 8. C/M from omni antennas (EMEA CW, eastbound crossing).

Figure 9 shows a typical signal magnitude power spectral density function, in this case at an elevation angle of 17°. A fit is shown to the sum of a second-order Butterworth characteristic with a corner frequency of 0.4 Hz and a
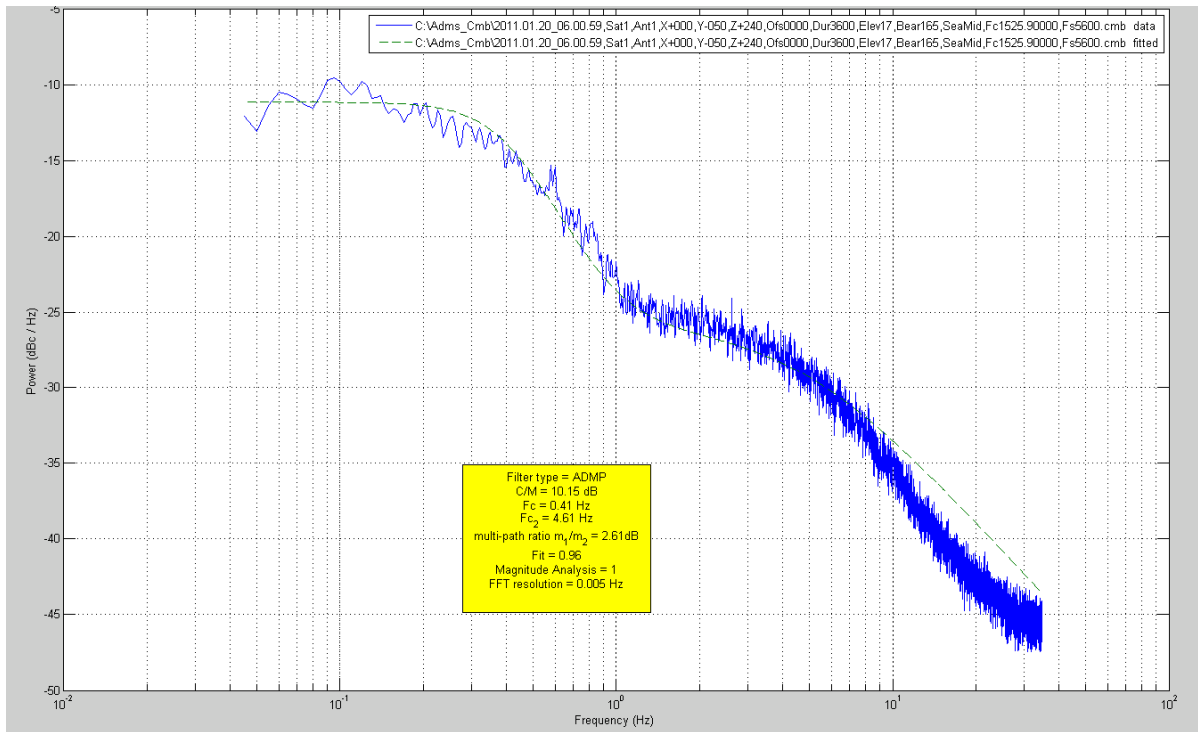

Figure 9. Power spectral density of fading (EMEA CW, eastbound crossing).

first-order Butterworth with a corner frequency of 4.6 Hz. The lower-frequency component contributes about 3 dB more multipath power than the higher-frequency component. This general shape was found to give a good fit at the higher elevation angles. At elevations of less than about 10° the two regions tend to merge, giving a corner frequency on the order of 1 Hz and a rolloff slope that is intermediate between first- and second-order.

The cross-correlation among the signal powers as received by multiple antennas determines the benefit that can be obtained from diversity, since low correlation corresponds to high probability that when one antenna's signal is faded another's will be strong. Figure 10 shows the cross-correlation of the signal power from pairs of horizontally separated antennas as a function of time, with the correlations averaged over 10 minute intervals. A value of 1 indicates that the signal powers are proportional, whereas independent complex Gaussian signals would give a value of 0.5 . The observed correlations are quite high, with the mean of the three pairs ranging from about 0.87 to 0.97. The lowest correlation is generally seen from pair 1/2, which has the largest separation (100 cm).

Figure 10.   Power cross-correlation, horizontal separation (EMEA CW, eastbound crossing).

Figure 11 shows the cross-correlation between pairs of antennas separated by 32 cm vertically. For elevation angles below about 15°, the correlation is significantly lower than with horizontal separation. The correlation was also evaluated for antenna pairs separated by 64 cm and 96 cm vertically. Somewhat surprisingly, the correlation was lowest at the smallest vertical separation.

C. Land Mobile Channel Characterization

The recorded signals were analyzed as for the maritime case, using 10-minute averaging intervals. In addition, two 30-minute periods were processed using 100 ms averaging intervals to reduce the effect of long-term amplitude variation on the statistical results and to capture more rapid fluctuations in the channel characteristics:

- 17:10 to 17:40 Nov 4, 2011 (Suburban)
- 18:30 to 19:00 Oct 18, 2011 (Forested)

For these periods the CW test signals from AMER and AORE were analyzed. For both periods the elevation to AMER was between 32° and 33°, and to AORE was between 12° and 13°.

Figure 12 shows the power received from each antenna and as derived by equal-gain combining of all four antennas, for the Suburban case for AMER. For display, the combined signal power is scaled by a factor of -6 dB to reflect the effect on the C/N_0 of the summed noise from the four antennas, to avoid giving a misleading impression
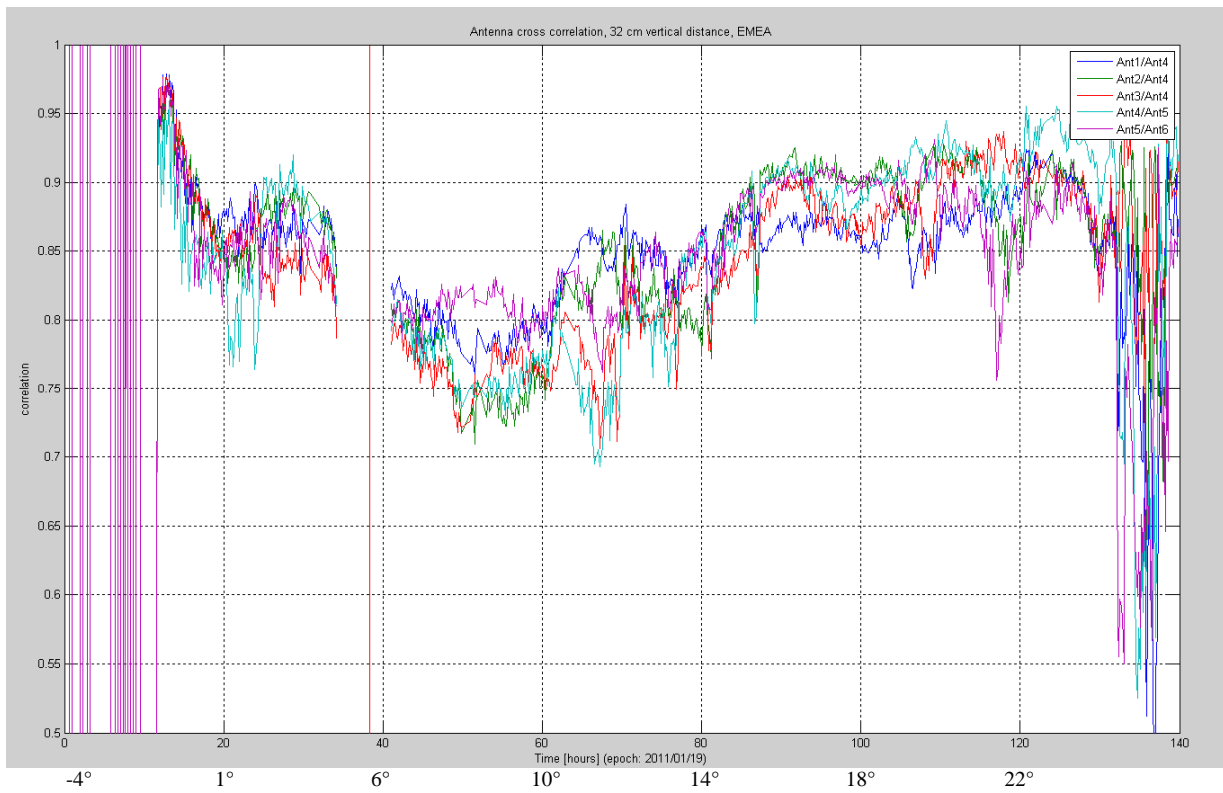
Figure 11.   Power cross-correlation, 32 cm vertical separation (EMEA CW, eastbound crossing).
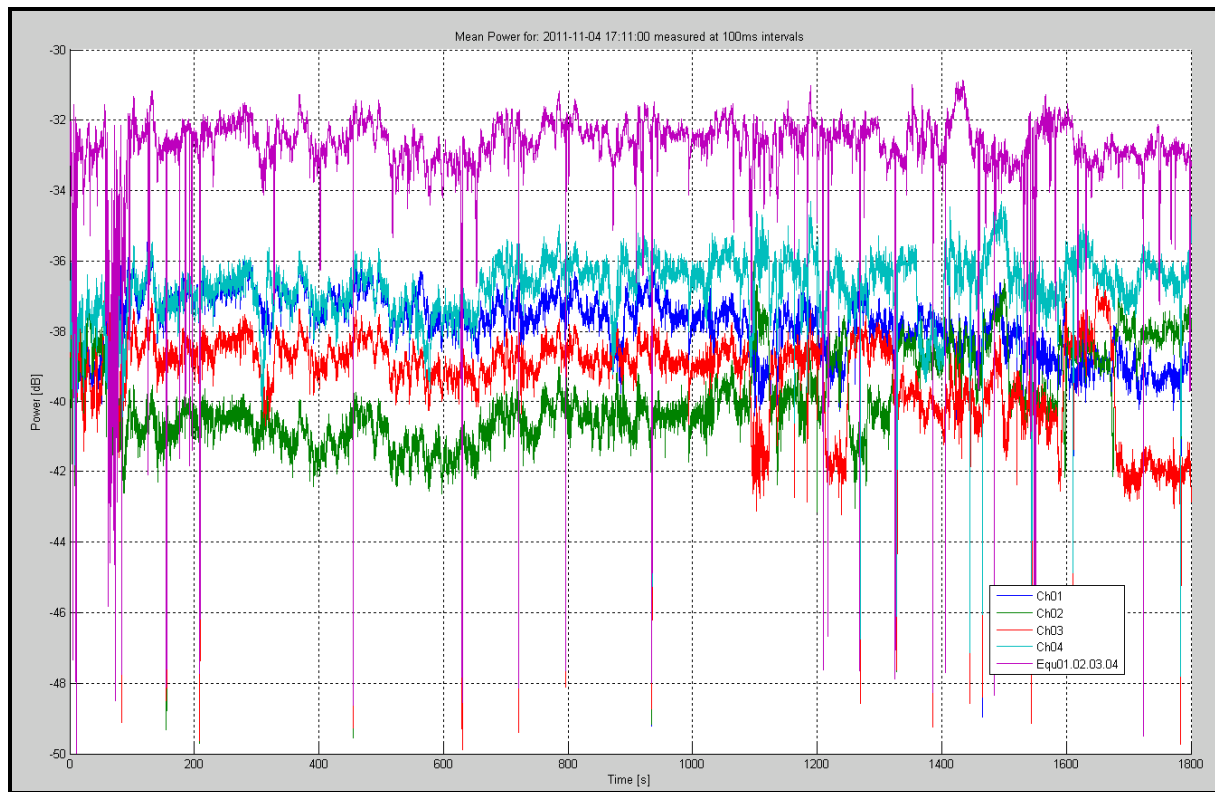

Figure 12.   Short-term mean power, individual antennas and combined (AMER suburban).

of the combining gain. The mean power averaged over 100ms generally shows fairly small variation, on the order of ± 1dB, except for brief dropouts. The combining gain is typically 4 to 6 dB, which is similar to the 6 dB that would be expected for identical signals. The corresponding results for AORE, at lower elevation, are similar. The results

for the Forested case for AMER are also similar, except that the dropouts are somewhat more frequent. However, for AORE the signal level is much lower and there are extended periods of signal loss, as shown in Fig. 13. This is expected, due to blockage of the low-elevation signal by the surrounding trees. In this case the combined signal shows little or no improvement, which suggests that the C/No is insufficient for accurate phase alignment of the signals.
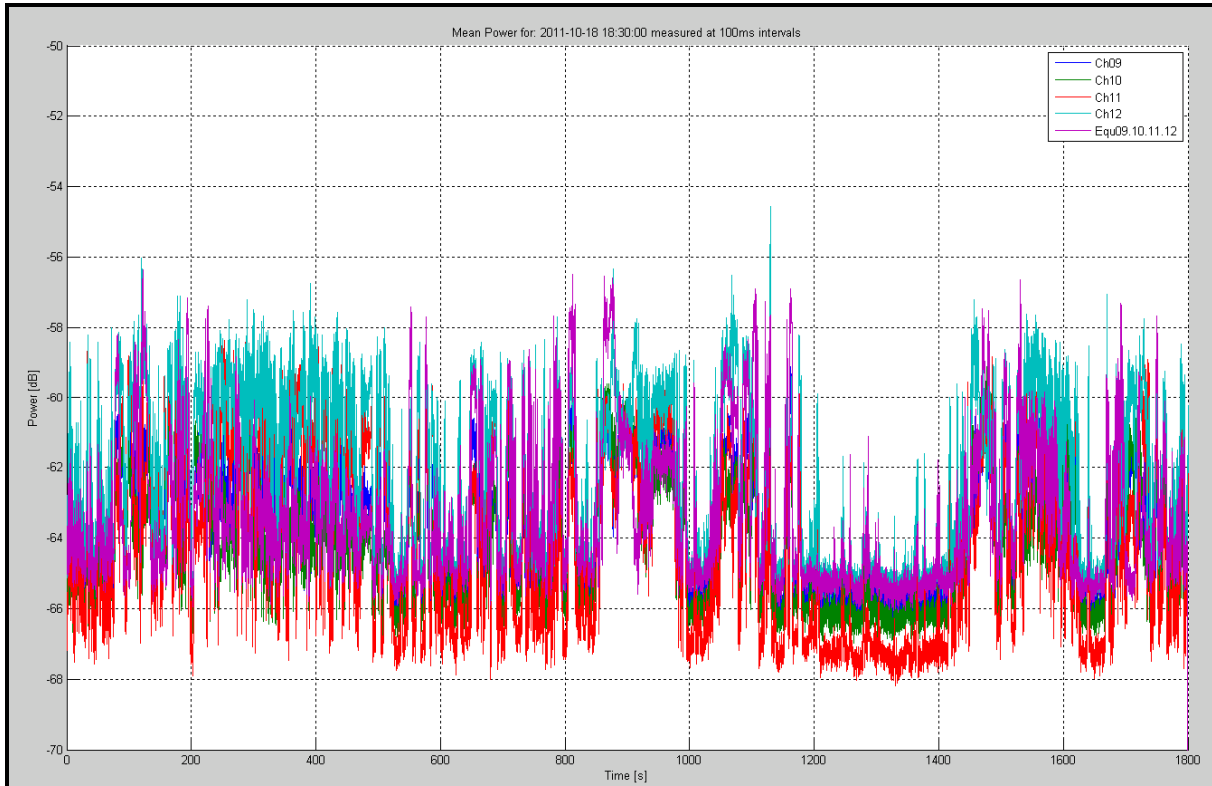

Figure 13.   Short-term mean power, individual antennas and combined (AORE forested).

The C/M showed combining gain similar to that for power, with the following mean C/M values for the combined signal:
- AMER Suburban: 17 dB
- AORE Suburban: 10 dB
- AMER Forested: 17 dB
- AORE Forested: 0 dB

The value of 17 dB at high elevation (AMER) is similar to that for the maritime case. The value of 10 dB for the low-elevation (AORE) Suburban case is somewhat worse than for the maritime case at the same elevation, presumably due to the more complex reflection environment. The value of 0 dB for the AORE Forested case corresponds to severe blockage.

The long-term power spectral density again resembles the sum of two Butterworth characteristics, with corner frequencies of roughly 0.1 Hz and 1 Hz.

The following mean power correlation values were obtained:
- AMER Suburban: 0.93
- AORE Suburban: 0.78
- AMER Forested: 0.93
- AORE Forested: 0.50, 0.70

The values of 0.93 at high elevation (AMER) and 0.78 and 0.70 at low elevation (AORE) are similar to those obtained for the maritime case. For the AORE forested case, the value of 0.50 is equal to that for independent complex Gaussians, which indicates that the signal was below the noise floor due to blockage.

V. Performance Evaluation

A. Performance Evaluation Tool

Receiver performance was evaluated on the recorded BGAN F80T1Q signals, and on synthetic signals generated using channel models derived from the channel characterization activity. A program referred to as the Antenna Diversity Receiver Design Tool or ADRDT was employed. It incorporates modulators and demodulators for all BGAN forward bearer types, as well as channel simulation, diversity processing, and packet error statistics functions. The ADRDT has the following capabilities:

- generation of a synthetic transmitted BGAN forward link signal of any bearer type and code rate, with PRBS user data.
- generation of multiple simulated received signals from the synthetic transmitted signal, with independent AWGN and correlated or uncorrelated multipath.
- selection of C/N_0, C/M, fading filter shape and bandwidth, and degree of multipath correlation between channels for synthetic signals.
- measurement of C/N_0 and C/M for recorded signals.
- demodulation and decoding of synthetic and recorded BGAN forward link signals. For recorded signals, the embedded code rate signaling is processed to handle multiple code rates within a frame.
- determination of Packet Error Rate (PER) from synthetically generated signals.
- determination of PER from recorded signals without knowledge of the transmitted data.
- selection-based diversity combining, using the following selection criteria:
  - frame UW errors
  - FEC block C/N_0
  - FEC block power
  - FEC block parity bit errors
  - ideal selection (uses the correct FEC block if available from any channel)
- signal-weighting diversity combining, using the following methods:
  - equal-gain combining or EGC (the signals are phase-aligned and summed with equal weighting)
  - maximal-ratio combining or MRC (the signals are phase-aligned and summed with weights proportional to the square roots of the estimated signal-to-noise power ratios)

B. Signal Combining Methods

The performance of the different combining methods was evaluated. Figure 14 shows PER vs C/N_0 for three-antenna diversity, using selection combining with various selection criteria. The performance of individual antennas and of maximal-ratio combining are also shown. Synthetic signals were used, with uncorrelated multipath and C/M = 7 dB.

The best selection criterion is estimated FEC block parity errors. In this case it coincides with the ideal selection combining bound. Selection based on FEC block power is very close to the bound. Selection based on FEC block C/N_0 or on unique word errors is significantly worse.

Maximal-ratio combining is approximately 2 dB better than ideal selection.

C. Maritime Performance Evaluation

PER performance was measured on the recorded F80T1Q signals with EGC, MRC, and ideal selection combining. Figure 15 shows the PER at the L8 (lowest) code rate for the individual antennas, for the AMER satellite on the eastbound crossing. As expected, the FB150 performs better than the omnis, and the LHCP omni is significantly worse than the RHCP. There is a general trend to higher PER with time, corresponding to decreasing elevation angle over about 25° to 8°. The FB150 gives approximately the nominal network design PER of $1x10^{-3}$.

Figure 16 shows the PER at L8 for pairs of omni antennas, using MRC combining. The performance is improved significantly over a single antenna. The benefit is least where the second antenna is LHCP (pair 17 in the figure).

Figure 17 shows the PER at L8 for three antennas spaced vertically, using EGC, MRC, and ideal selection combining. The PER of the FB150 is shown for comparison. All of the combining methods outperform the FB150 almost all of the time, and thus achieve nominal network performance. MRC is best, although EGC is very similar. Both are superior to ideal selection.

Further results indicate that vertical separation is superior to horizontal, and that vertical separation of 32 cm is superior to larger separations. The effect was strong enough that in some cases a two-antenna configuration with 32 cm vertical separation out-performed a three-antenna configuration with horizontal separation and larger vertical separation.

The vertically spaced four-antenna configuration performed extremely well, with no packet errors except at the highest code rate. The co-located RHCP/LHCP pair performed poorly, due to the low C/N$_0$ from the LHCP.
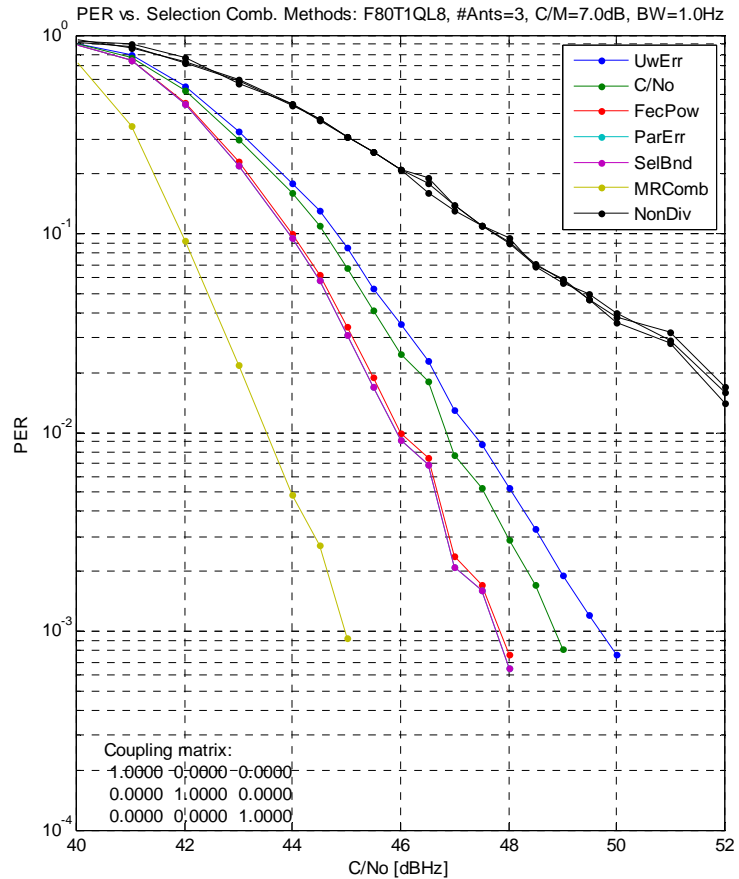

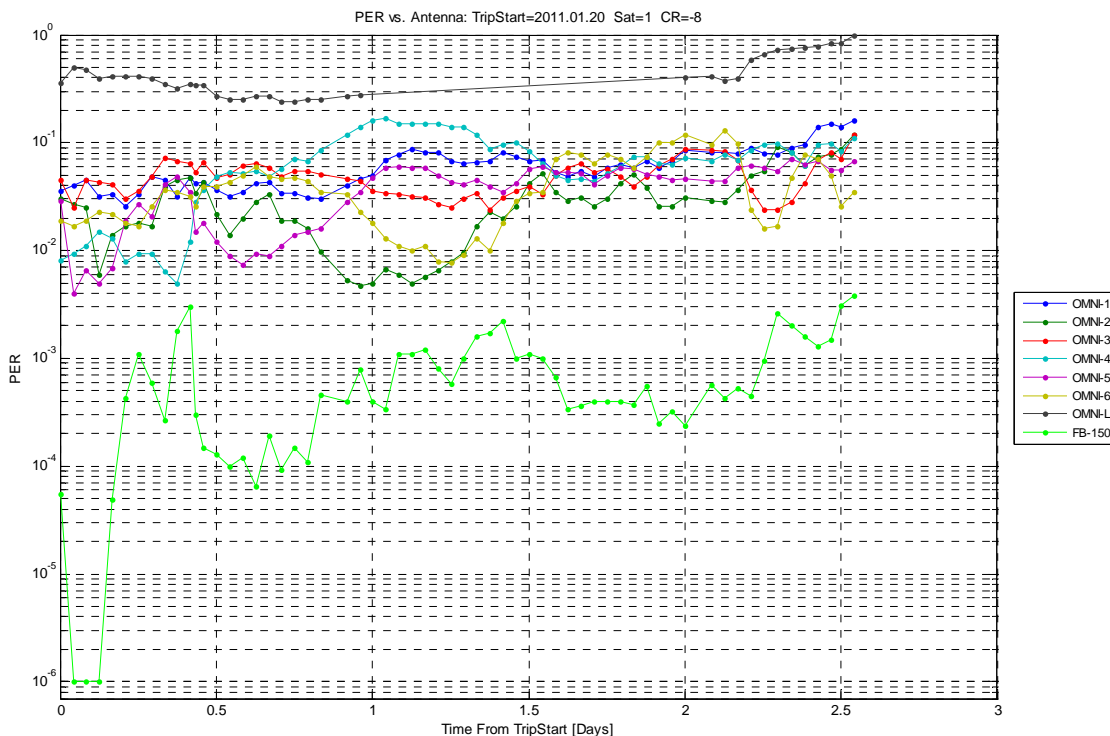**Figure 14.   Performance of signal combining methods.**

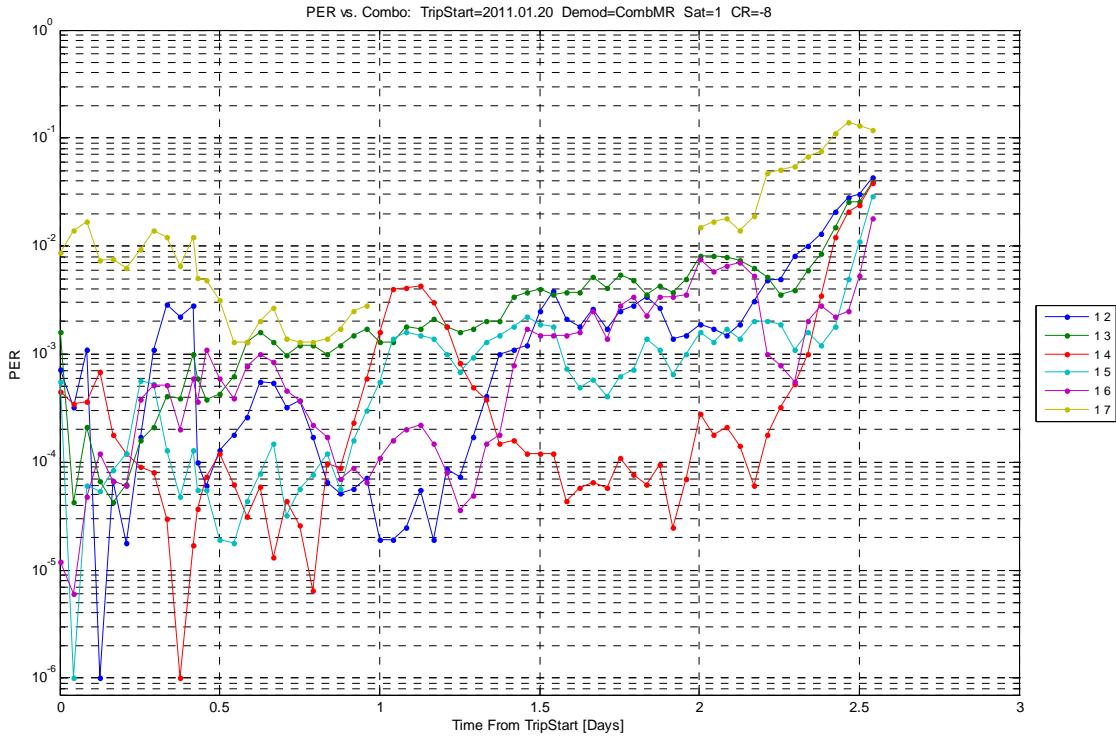**Figure 15.   PER for individual antennas at L8 (AMER, eastbound crossing).**

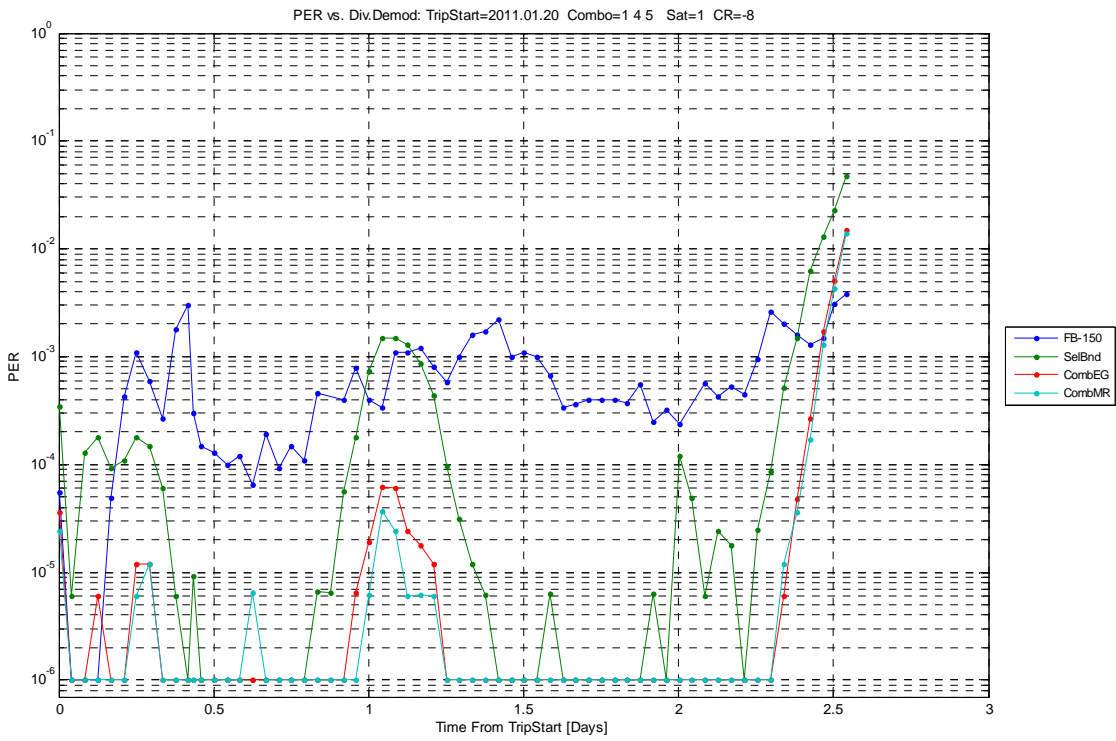**Figure 16.** PER for 2-antenna diversity at L8 (AMER, eastbound crossing).

Figure 17. PER for 3-antenna diversity at L8 (AMER, eastbound crossing).

Synthetically generated signals were used to evaluate the performance of diversity receivers on BGAN bearer types and under channel conditions that were not present in the recorded signals. The synthetic signals were verified to give similar performance to recorded signals with the same channel parameters (C/N_0, C/M, fading bandwidth, and power correlation between antennas).

In particular, synthetic signals allow the power correlation between antennas to be set as desired. Figure 18 shows the effect of correlation on PER performance for the case of two antennas, with C/M = 7 dB and maximal-ratio combining,. The degree of correlation of the multipath varies from fully correlated to fully anti-correlated.

As the figure shows, correlation has a dramatic effect on performance. With fully correlated multipath, the performance is 3 dB better than for a single antenna, as would be expected with coherent combining. With uncorrelated multipath, the performance at PER = 10^{-3} is about 12 dB better than for a single antenna. A further 6 dB of improvement is obtained with fully anti-correlated multipath. Fading bandwidth and spectral shape (e.g., single vs dual Butterworth characteristic) have little effect on performance.

Figure 18. **Effect of multipath correlation on PER performance for two-antenna maximal-ratio combining..**

The following observations can be made from the results of the performance evaluation on recorded and synthetic signals:

- Diversity combining can give large improvement relative to a non-diversity receiver in fading. This improvement is well above the basic increase in SNR that could be obtained by combining the same number of identical channels coherently.
- At least three omni antennas are required to match or exceed the performance of a standalone FB150 antenna in maritime fading. A larger number would be required to match the performance of an FB150 in the absence of fading, where only coherent combining gain is available.
- Vertical separation of the omni antennas gives better performance than horizontal separation. Three antennas in a horizontal plane gave the poorest performance of the possible three-antenna combinations.
- No direct relationship between antenna spacing and performance was identified. However, the minimum vertical spacing of 32 cm provided good performance, and appeared to be superior to larger spacings.
- Including an LHCP omni antenna is of less benefit in a multi-antenna configuration than an additional spatially separated RHCP. However, an LHCP co-located with an existing RHCP can provide some benefit without increasing the overall size of the antenna array.
- Maximal-ratio combining performs best. The improvement over equal-gain combining is roughly 0.5 dB at C/M = 7 dB, and less at higher C/M. This implies that PER performance is fairly insensitive to the accuracy of the weights used for MRC, and thus to the accuracy of the SNR estimates from which they are derived. Selection combining is significantly inferior to MRC and EGC, typically requiring 2 to 3 dB higher C/No for PER = 10^{-3}.
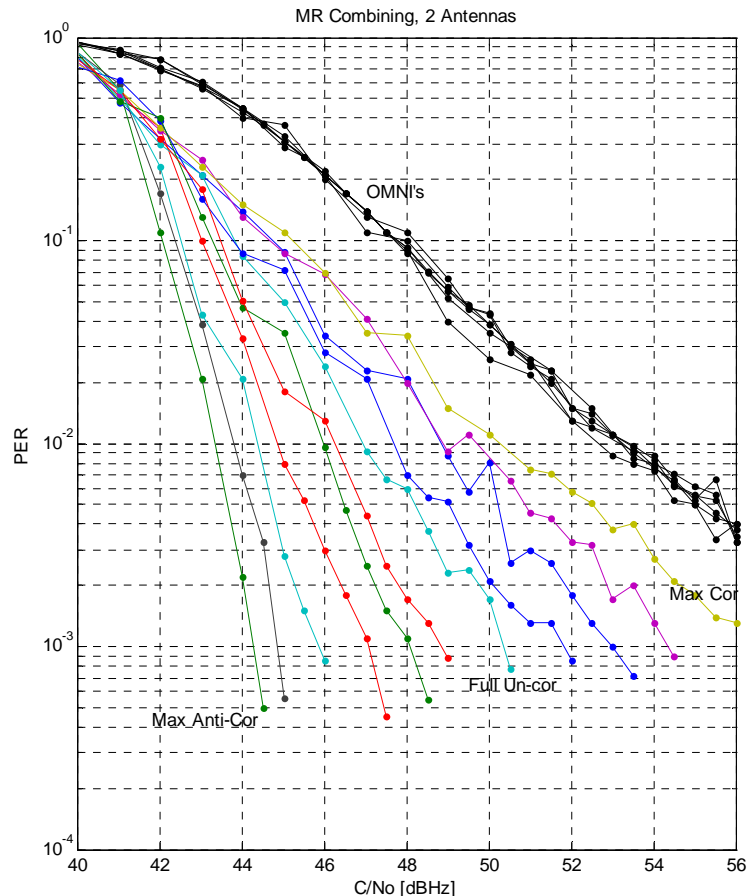
- The fading bandwidth does not significantly affect receiver performance over the range of bandwidths tested (0.7 to 2.0 Hz). Also, using the fading spectral shape derived from the recorded signals does not significantly affect the performance compared to a second-order Butterworth shape of similar bandwidth.
- Receiver performance is highly sensitive to the power correlation between channels, which reflects the correlation of the multipath components between antennas. The degree of correlation typically seen in the recorded signals requires up to 2 dB higher C/No than for fully uncorrelated multipath.
- The reflection environment for a vessel of the type used for the campaign is complex and includes large, strongly reflective surfaces. This is likely to make the detailed reception behaviour of a given antenna very dependent on the installation and the direction to the satellite.

D. Land Mobile Performance Evaluation

The land mobile propagation environment is much more dynamic than the maritime environment. The PER was therefore averaged over periods of minutes, as opposed to the 1 hr periods used for the maritime case. A useful overall performance measure is the percentage of 1-minute periods for which the PER is less 10^{-3}, as a function of the number of antennas used. Averaging this over the entire campaign and over various antenna combinations gave the following results for the F80T1Q bearer from AMER:

- Single antenna: 46%
- Two antennas: 66%
- Three antennas: 70%
- Four antennas: 72%

More detailed PER results indicate that:

- the benefit of diversity is modest except possibly in forested conditions.
- most of the benefit of diversity is obtained with two antennas.
- there is no appreciable benefit from including vertical separation between antennas.
- front-to-rear separation between antennas may be preferable to side-to-side, to reduce the likelihood of simultaneous blockage by roadside obstructions.

The benefit of diversity was most apparent in the forested environment. Cases were seen where individual antennas gave PER > 10% for extended periods of time, while diversity combinations were 10 to 100 times better. The other environments showed much less benefit. In urban environments, which are highly dominated by blockage, performance was generally poor both with and without diversity. In rural environments, with minimal fading, performance was generally good in both cases.

Rather than using an explicit channel model, the time-varying channel states were derived from the recorded CW signals and were applied to synthetically generated BGAN signals. This allows the performance to be evaluated under real-world conditions for signal types that were not recorded, and was used to investigate the following cases:

- F80T1Q at low elevation
- F80T1X (16-QAM)

The CW test signal was received from AORE at lower elevation angles (10° to 20°) than the F80T1Q signal from AMER (26° to 36°). Using synthetic signals thus allows the performance to be evaluated under the more severe fading associated with the lower elevation angles. Figure 19 shows the PER over a one-hour period for single antennas and for combinations of two and four antennas. The two- and four-antenna combinations perform about the same, and substantially better than the single antennas.

The results across the 10° to 20° elevation range indicate that the benefit of diversity combining is less at low elevation angles, likely because blockage of all antennas simultaneously becomes more probable. As seen above, two antennas provide most of the benefit available from diversity.

A synthetic F80T1X signal was evaluated using the channel states derived from the CW signal from AMER. The higher elevation was used in this case because QAM is more sensitive to channel impairments than QPSK. Figure. 20 shows the PER over a one-hour period for single antennas and for combinations of two and four antennas. The two- and four-antenna combinations again perform about the same, and substantially better than the single antennas.
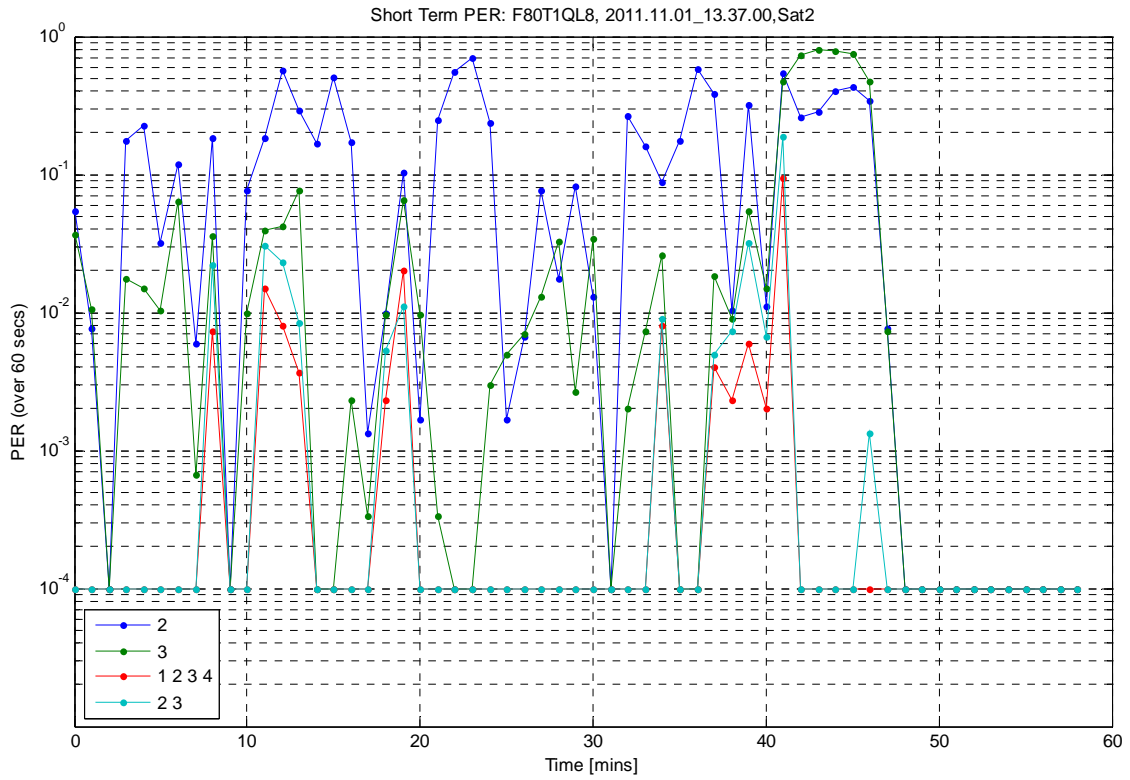
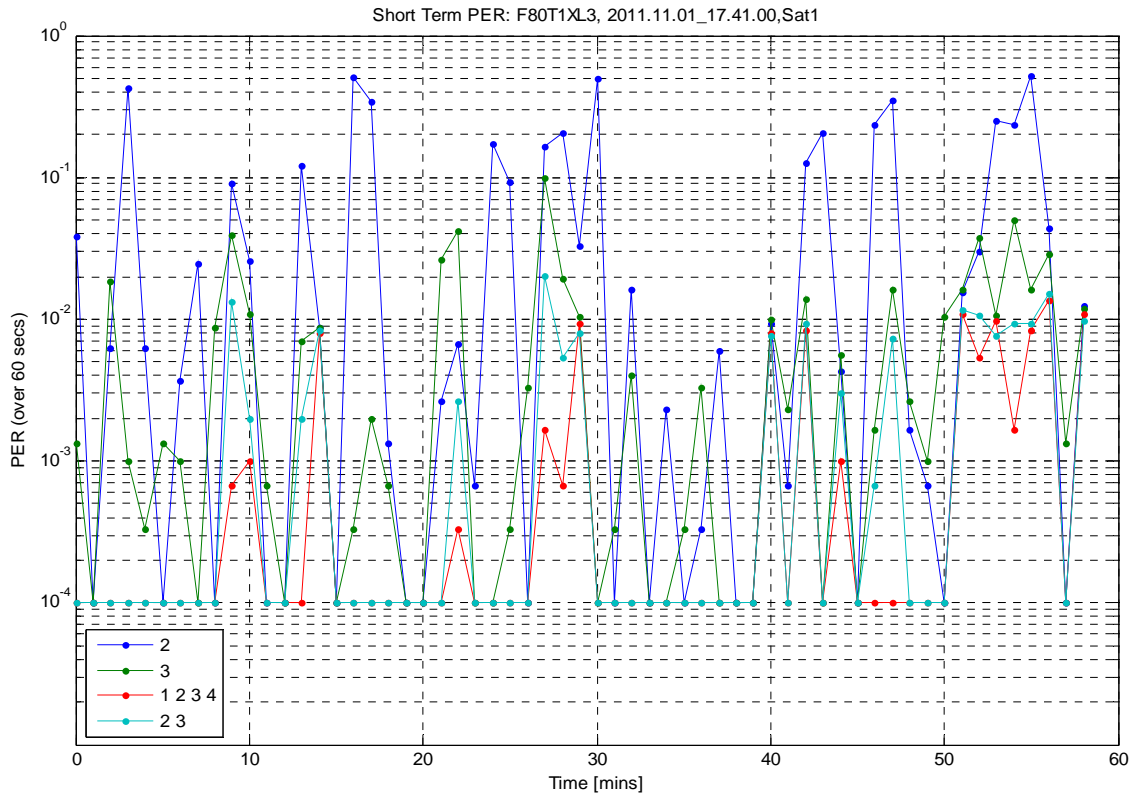**Figure 19.   PER for synthetic F80T1Q at low elevation.**

Figure 20.   PER for synthetic F80T1X.

The following observations can be made from the results of the performance evaluation on recorded and synthetic signals:

- Antenna diversity improves the PER performance over that achieved by a single omni antenna. However, the performance gain is modest compared to that seen in the maritime campaign.
- Two antennas achieve most of the benefit of diversity.
- Antennas mounted in-line with the direction of travel perform slightly better than antennas mounted perpendicular to it.
- Including vertical separation between antennas does not appear to improve performance.
- Diversity provides less benefit at low elevation angles, where blockage becomes the dominant factor.
- The benefit of diversity is most apparent in the forested environment, where multipath fading is the most significant.

VI. Conclusion

The following overall conclusions can be drawn from the work as applied to the maritime environment:

- The use of multiple omnidirectional antennas in place of a stabilized directional antenna appears to be feasible for the reception of BGAN signals at low elevation angles. Three omni antennas should be sufficient, or possibly two depending on the service requirements and the installation conditions.
- Vertical separation of antennas is superior to horizontal separation. Vertical separation of about 30 cm is sufficient, and more separation does not improve performance.
- Including an LHCP omni antenna is of less benefit in a multi-antenna configuration than an additional spatially separated RHCP. However, an LHCP co-located with an existing RHCP can provide some benefit without increasing the overall size of the antenna array.

The following overall conclusions can be drawn from the work as applied to the land mobile environment:

- The benefit of antenna diversity for the land mobile environment is less apparent than for the maritime case. The benefit obtained depends on the terrain, with forested conditions showing the most improvement.
- Contrary to the maritime case, the benefit of antenna diversity in the land mobile environment decreases at low elevation angles. This is likely due to increased blockage.
- A pair of antennas provides most of the benefit of antenna diversity. Additional antennas do not provide significant benefit beyond the expected C/N_0 improvement due to coherent combining.
- Vertical separation does not provide significant additional benefit over horizontal. The antennas should be positioned along the direction of travel rather than orthogonal to it.

Acknowledgments

References

[1]Greenstein, L. J., Michelson, D. G., and Erceg, V., "Moment-Method Estimation of the Ricean K-Factor," *IEEE Communications Letters*, Vol. 3, No. 6, June 1999.