OPTIMAL HYBRID FREQUENCY HOP COMMUNICATION SYSTEM USING NONLINEAR ADAPTIVE JAMMER COUNTERMEASURES AND ACTIVE FADING MITIGATION

Chad S. Bergstrom and J. Scott Chuprun

Motorola Space and Systems Technology Group
8201 E. McDowell Road, MD H1175
Scottsdale, Arizona , USA 85257-1417
602-441-3278, 602-441-2584 (fax), p21191@email.mot.com

ABSTRACT

Digital mobile battlefield environments impose challenging obstacles to battle group communications and data management. As future communication capabilities cascade from tactical commanders to individual soldiers, increased spectral clutter will complicate the task of preserving data throughput. Applied within a programmable radio architecture, frequency hop (FH) and direct sequence (DS) waveforms have inherent strengths that may be exploited to overcome battlefield communication obstacles. In this paper, we present a methodology that combines FH waveforms with pulse concealment and transform domain signal processing in order to overcome interference, hostile detection, and jamming. Rejection algorithms are demonstrated which significantly improve system performance in the presence of high-power partial-band jammers, co-site communication signals, and fading.

INTRODUCTION

Recent studies have shown that co-site and co-channel interference pose especially formidable obstacles to effective battlefield communications[1]. Even relatively low levels of interference have been found to interfere with mission critical parameters, such as GPS.

In order to combat ambient and hostile interference, time and frequency domain signal processing methods may be applied within a spread spectrum communications architecture. In this manner, software configurable radios use nonlinear signal processing methods in concert with FH and DS waveforms to mitigate interference while preserving high data throughput, even in the absence of coding.

The properties of DS waveforms inherently provide for interference rejection, low probability of intercept (LPI) and low probability of detection (LPD). However, practical power control limitations are well known to restrict channel capacity [2,3]. In contrast, FH systems are less dependent on power control, yet can be easier to detect, locate, and jam under certain conditions. Higher hop rates on the order of 1-2 Khops/sec enhance FH performance relative to jammer and detection threats [4,5]. However, DoD requirements for future communication systems include provisions for detection and direction of arrival (DOA) capability [6]. Hence, any communication methodology used by U.S. and allied forces must be able to defeat similar detection challenges posed by enemy battle units. In order to meet the challenges posed by the future digital battlefield, we present a hybrid FH/DS approach that preserves LPI/LPD characteristics and tolerates severe interference environments.

APPROACH

Figure 1 illustrates an example FH/DS hybrid spectrum, including typical interference sources. In this paper, we focus on adaptive mitigation of partial band interference and jammers, in contrast to

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*Prepared through collaborative participation in the Advanced Telecommunications & Information Distribution Research Program (ATIRP) Consortium sponsored by the U.S. Army Research Laboratory under the Federated Laboratory Program, Cooperative Agreement DAAL01-96-2-0002. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

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research which concentrates primarily on the narrow band case [7].

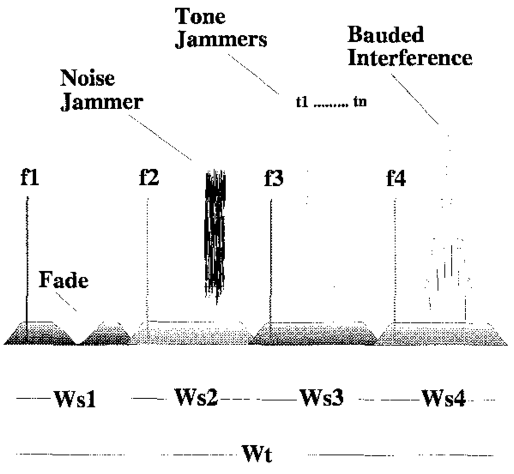

Fig. 1 - Frequency Hop / DS spectrum and interference sources, including Noise Jammers, Tone Jammers, Bauded Interference, and Fading.

Both time domain and frequency domain techniques are effective for state estimation and interference mitigation. Such methods include spectrum estimation and inverse filter countermeasures, and transform domain adaptive inverse weight countermeasures. Prior-art methods, such as frequency domain magnitude normalization, can improve system performance in interference conditions, but impose BER degradation when interference power is low. In contrast, the methods considered in this paper closely follow the theoretical system performance in the absence of jammers. Hence, the methods presented here meet a "do no harm" prerequisite, while providing orders-of-magnitude BER performance improvement over prior art normalization techniques. Referring again to Figure 1, each hop frequency fn is spread over a corresponding channel consisting of bandwidth Wsn, for a total spreading bandwidth of Wt. When operating near or below the ambient noise floor, spreading the hop impulse in this manner results in a spectral distribution that is less susceptible to follower-jammer and detection threats, while allowing for the application of anti-jam algorithms. Note that when the DS processing gain is low, the hybrid waveform will approach the pure FH system. Since spreading serves to conceal the hop impulse, slower hop rates may be implemented which are less than the current state-of-the-art. These lower hop rates will provide improved battery life for man-pack or hand-held radios. Furthermore, since DSPN is applied primarily for the purposes of impulse concealment and anti-jam functionality, power control issues are less problematic. Hence, in distributed mobile architectures, a small number of spreading sequences may be used primarily to prevent the damaging effects of hop collisions between sub-nets.

To investigate the benefits of this approach, a QPSK source is used for the I,Q data stream with a DS processing gain of 24 dB. Channel interference sources include a frequency selective fading component, H(s), occurring over the symbol duration. For wideband interference sources and shadowing fades, channel coding can provide sufficient gain to close the link, albeit at a reduction in data throughput. In order to evaluate the effectiveness of interference mitigation functions for the hybrid FH/DS system, we consider such functions in the absence of channel coding.

In one embodiment of this approach, each Wsn channel is tuned corresponding to the hop sequence, with timing given by t_{ref}. Advances in accurate, stable oscillators make near-synchronous FH systems possible for near term communication systems [8]. Following tuning, corrupted channel data is passed to an adaptation processor, which performs periodic state estimation, stores the state information to interference state memory I, and, in parallel, performs interference countermeasures corresponding to the prior interference state. In contrast to interference mitigation approaches that require feedback (e.g., adaptive rate methods), it is desirable that state estimation and interference mitigation be performed solely at the receiver to simplify the transceiver architecture. In order to perform these estimation and countermeasure tasks, emerging device technologies may be applied which enable advanced signal processing functions within a programmable radio architecture[9,10,11].

COUNTERMEASURES

Spectrum Estimate Countermeasure For the hybrid FH/DS system, the individual channel characteristics for each Wsn are similar to white noise. As such, perturbations in the channel serve to color or distort the spectral characteristic from this ideal. Hence, by obtaining an estimate of the spectral envelope, and by using this estimate to inverse filter the corresponding data, a whitened, or "restored" spectrum may be obtained in moderate interference conditions or severe fading conditions. In order to ensure that the underlying phase information is undisturbed, an all-pole spectral envelope estimate is required. Equation 1 illustrates an all-pole spectral model, where a_k represents the prediction coefficients for an Nth order model that is obtained using classic autocorrelation and durbin recursion [12].

$$H(z) = \frac{1}{1 + \sum_{k=1}^{N} a_k z^{-k}} \qquad \text{Eq. 1}$$

Once the a_k prediction coefficients are computed, the inverse whitening filter is given by Equation 2, which provides the residual waveform. Hence, Eq. 2 represents the countermeasure that is applied to the received data x(n) by the adaptation processor in order to whiten the corrupted spectrum.

$$y(n) = x(n) + \sum_{k=1}^{N} a(k)x(n-k) \qquad \text{Eq. 2}$$

Using the inverse filter approach, a partial band noise jammer having bandwidth B = (0.25)Wsn is applied to the hybrid FH/DS signal within the hop bandwidth. Using a reasonable number of prediction coefficients, for example N = 24, the inverse filter is applied using Eq. 2. Without reduction in data throughput, the resulting spectral content is whitened, restoring data that had been lost to jamming. To graphically illustrate the effect of the inverse filter countermeasure, Figure 2 shows the effect of the partial band noise jammer on the data QPSK constellation before and after the inverse filter mitigation. Note that the I,Q state information is obliterated by the damaging effects of the partial band jammer. Following application of the inverse filter countermeasure, the I,Q state information is restored.

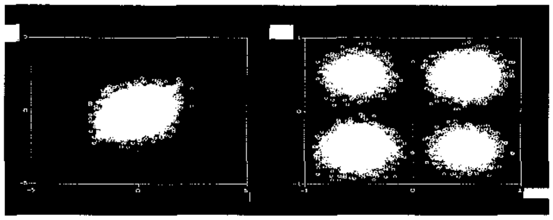

Fig. 2 - QPSK Constellation in presence of partial band noise jammer, showing destruction of I,Q state information, and restored QPSK constellation after application of inverse filter countermeasure.

In addition to the damaging effects of jammers and cosite signal interference, communication link integrity can suffer from shadowing and frequency selective fading. Figure 3 illustrates the BER improvement that is obtained using the inverse filter countermeasure in the presence of frequency selective fading having deep excursions, circa 40 dB. Note that the damaging effects of the fade are largely removed by the inverse filter countermeasure over a range of channel noise levels. Resulting performance is restored to near fade-free levels.

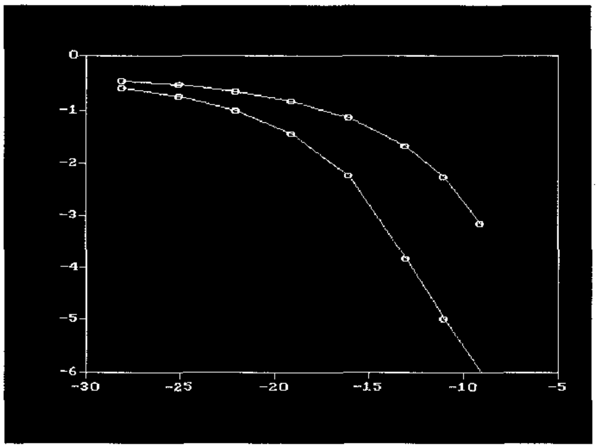

Fig. 3 - BER improvement in frequency selective fade environment after application of Inverse Filter Countermeasure.

The inverse filter countermeasure provides improvement in BER performance at moderate to high Jammer/Signal (J/S) levels, while approaching the asymptotic limit at low J/S levels. Hence, in contrast to other techniques which can induce significant errors in relatively clean conditions, application of this method at low or negligible jammer power does not induce undue BER performance distortion. In comparison, the adaptive inverse weight countermeasure described below has similar asymptotic behavior, yet provides superior BER improvement for high-power interference and jamming.

Adaptive Inverse Weight Countermeasure The second countermeasure method considered for this paper involves transform domain signal processing for interference mitigation. Selective spectral limiting has long proven effective for jammer and interference mitigation [13]. We improve upon such approaches by computing modal spectral statistic estimates μ_i , σ_i for each signal component i. These non-arithmetic statistics may be used to selectively target only those statistical outliers that exceed some value $\alpha = \mu + k\sigma$ of the fundamental transmission mode.

Figure 4 illustrates a typical multimode statistic for the FH/DS signal in the presence of a partial band noise jammer. Using the transform domain magnitude, an adaptive interference rejection function is applied that measures the modal statistics, determines the fundamental mode, and applies an interference rejection weight ω that is inversely proportional to the observed deviation δ relative to the dominant mode. In this approach, the statistical outliers are reduced by the weight given by Eq. 3, where m is an integer. In addition to minimizing the statistical extremes, application of Eq. 3 to $\pm$ n proximity samples provides further performance improvement by enhancing the attenuation of the interference envelope.

$$\omega = \alpha / \left[\alpha + [\delta - \alpha]^m\right] \qquad \text{Eq. 3}$$

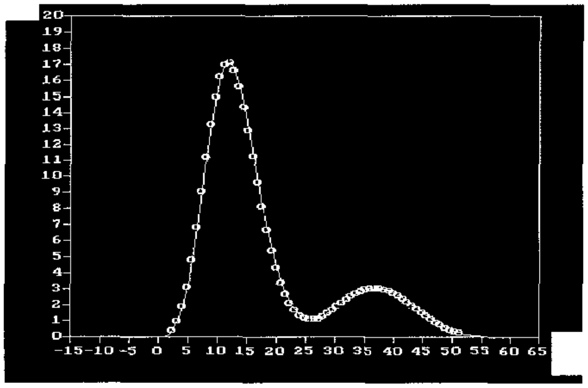

Fig. 4 - Modal statistic estimate for FH/DS signal corrupted by partial band noise jammer.

Figure 5 shows the significant BER improvement gained by the adaptive weight countermeasure in the presence of QPSK interference encompassing a quarter bandwidth, (0.25)Wsn, with a channel SNR of -15 dB. Given identical interference bandwidths, the BER performance shown in Figure 5 is similar for QPSK cosite and partial band jammer interference. As with the inverse filter countermeasure, the adaptive inverse weight method approaches the asymptotic limit at low J/S ratios. Note that the adaptive inverse weight dramatically improves BER at high jammer power levels, resulting in 3 orders of magnitude improvement in link quality.

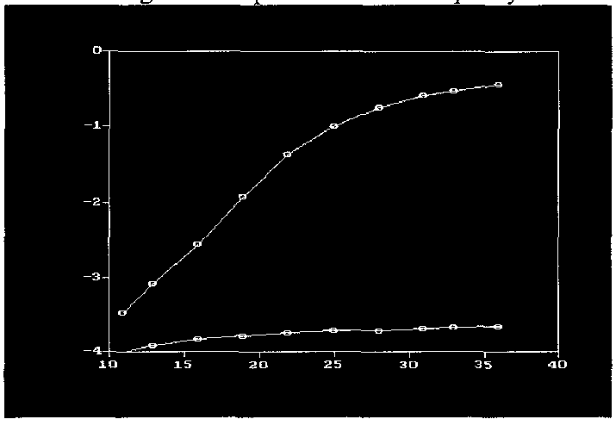

Fig. 5 - BER Improvement in presence of quarter band QPSK interference using Adaptive Inverse Weight countermeasure.

The final interferer considered for the adaptive inverse weighting countermeasure is a four-tone hostile jammer. As with the partial band interferers, the adaptive inverse weight is effective for tone jammers even at very high J/S ratios. This approach is especially beneficial against narrow band interference, which is readily canceled without distortion of the underlying hybrid FH/DS data. Figure 6 shows the BER performance for this method in high-power tone interference. Note that the four tone jammer is mitigated using the adaptive method, resulting in a near-flat BER corresponding to the -15 dB SNR used for this example.

CONCLUSION

We have presented a hybrid Frequency Hop DSPN transceiver approach that preserves LPI/LPD characteristics and mitigates severe interference. This approach is especially applicable to communications for small unit operations (SUO), where both stealth and link integrity are essential [8]. In the digital mobile battlefield, the severity of interference and jamming necessitates countermeasures that supplement inherent spread spectrum processing gain without reducing data throughput. We have demonstrated BER improvement using receiver-based preprocessing functions, including an adaptive inverse weight countermeasure based upon spectral modal statistic estimates, and an inverse whitening filter countermeasure based on an all-pole spectral model. In contrast to adaptive processing gain methods, both countermeasures improve BER performance without sacrificing system bandwidth. Furthermore, each approach exhibits orders-of-magnitude performance improvement relative to prior-art full-band normalization methods. Of the two countermeasures, the inverse weight function provides superior BER improvement in the presence of high-power partial band jammers and communication signal interference. The adaptive inverse filter function further provides a mechanism for improving BER performance in the presence of frequency selective fades. Hence, a composite jam/fade scenario will significantly benefit from a cascaded mitigation approach that applies both methods to alleviate severe interference and frequency selective fading.

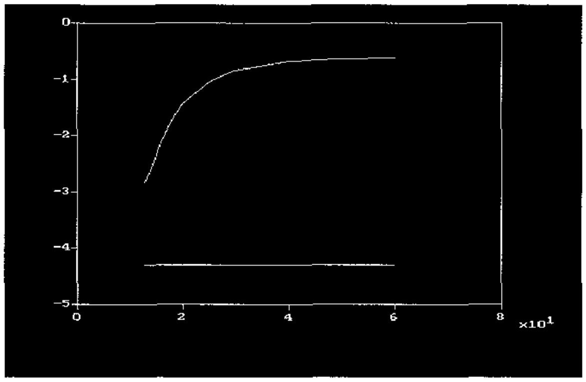

Fig. 6 - BER Improvement in presence of multitone jammers using Adaptive Inverse Weight countermeasure.

REFERENCES

[1] Joe C. Capps, US Army Signal Corps Communicator Magazine, Tactical Internet (EPLRS, SINCGARS SIP), TXFFI Lessons Learned Report, July 1, 1997.

[2] R. Cameron and B. Woerner, "Performance Analysis of CDMA with Imperfect Power Control", IEEE Transactions on Communications, Vol. 44, July 1996.

[3] D. Torrieri, "Frequency Hopping and Future Army Mobile Communications", Proceedings, ATIRP Annual Conference, University of Maryland, 1997.

[4] D. Torrieri, "Fundamental Limitations on Repeater Jamming of Frequency-Hopping Communications", IEEE Journal on Selected Areas in Communications, Vol. 7, No. 4, May, 1989.

[5] U.S. Government, "Contractor's Design Handbook for Protecting RF Transmissions", Revision 1, July 1994.

[6] Joseph Mitola III, "Spectrum Supremacy Program Concept", Mitre Technical Report, Jan. 7, 1997.

[7] Kumpumaki, Isohookana, Juntti, "Narrow-Band Interference Rejection Using Transform Domain Signal Processing in a Hybrid FH/DS Spread

Spectrum System", Proceedings, Milcom '97, Monterey CA, November 1997.

[8] B. Kaspar, LtCol, USAF, "SUO SAS Phase II Industry Brief", January 29, 1998.

[9] Analog Devices, "White Paper on the Texas Instruments TMS320C6x"

[10] Susan Gilfeather and Scott Chuprun, "Complex Arithmetic Processor Performance Metrics on LPI Waveforms", MILCOM '95 Classified Proceedings, November, 1995.

[11] Motorola, "SPEAKeasy II - An IPT Approach to Software Programmable Radio Development", Proceedings, Milcom '97, Monterey CA, November 1997.

[12] Deller, Proakis and Hansen, Discrete Time Processing of Speech Signals, p. 297, Macmillan Publishing Co., 1993.

[13] Simon, Omura, Scholtz, Levitt, Spread Spectrum Communications Handbook, p. 451, McGraw-Hill, 1994.

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