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THE APPLICATION OF SPREAD-SPECTRUM
COMMUNICATIONS TO REA TACTICAL
NETWORKS AND DEPLOYABLE
UNDERWATER SURVEILLANCE SYSTEMS

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**The application of Spread-Spectrum
communications to REA Tactical
Networks and Deployable
Underwater Surveillance Systems.**

Berni, A. and Mozzone, L.

The content of this document pertains to work performed under Projects 01-A, 01-B and 04-B of the SACLANTCEN Programme of Work. The document has been approved for release by The Director, SACLANTCEN.



Jan L. Spoelstra
Director

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The application of Spread-Spectrum communications to REA Tactical Networks and Deployable Underwater Surveillance Systems.

Berni, A. and Mozzone, L.

Executive Summary:

Emerging concepts for Anti-Submarine Warfare (ASW) and Rapid Environmental Assessment (REA) increasingly rely on communication technology, in order to implement distributed information networks and to exchange information between naval units and military commands ashore. An operational advantage is expected from the efficient networking of a geographically dispersed force thus shifting the focus from single autonomous platforms to an integrated network approach.

This study examines the main features of spread-spectrum radio communications, such as gain against noise, interference rejection, anti-jam capability and reduced power spectral density for covert operations. Performance is evaluated in comparison with classical systems. The advantages are quantified by the Processing Gain, proportional to the used bandwidth, and by the bandwidth expansion factor that characterizes the spread spectrum techniques. Bandwidth / power trade-off is also addressed. (good for operation on a battery-powered platform).

The applicability of such new techniques to REA and ASW activities is evaluated and assessed, in comparison with traditional methods. Both application-specific requirements (such as transmission ranges / data rates) and common requirements (such as reliability, availability and security) are discussed. The impact of state-of-the-art LAN protocols (integrated in COTS SS products) is also discussed.

Field tests and accurate analysis of results are recommended for further work. Two different objectives should be pursued: the implementation of a reliable and efficient infrastructure for scientific data acquisition at SACLANTCEN and, at the same time, the demonstration of this concept for future operational applications.

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The application of Spread-Spectrum communications to REA Tactical Networks and Deployable Underwater Surveillance Systems.

Berni, A. and Mozzone, L.

Abstract:

The present document is a part of an ongoing study on advanced communication techniques in support of Rapid Environmental Assessment (REA) and Deployable Undersea Surveillance Systems (DUSS). It aims at the definition of data transmission architectures for both scientific data acquisition at SACLANTCEN and for operational concept demonstration.

Emerging methodologies for Anti-Submarine Warfare (ASW) and Rapid Environmental Assessment (REA) increasingly rely on communication technology, in order to exchange information with other naval units or military commands ashore.

The specific requirements (such as ranges and transmission data rates) are addressed. They vary from 2.4 kbps to 2 Mbps and from 10 to 20 n.mi. In addition to that, all military applications have common requirements in terms of reliability, availability and security. The eligibility of classical and spread-spectrum radio communication techniques to the fulfillment of such requirements is discussed and shown. Performance is estimated and compared.

Spread-spectrum techniques offer such features as interference rejection, anti-jam capability and low-density power spectra for covert operations: field tests of spread-spectrum equipment have successfully been conducted in 1998 during SACLANTCEN experiments GOATS 98 and DUSS 98. The availability of commercial off-the-shelf (COTS) products including sophisticated communication protocols also represents a relevant issue for scientific applications. Such features as the creation of a multi-point, error-free, packet switching Local Area Network (LAN) deserve to be carefully investigated in their impact on DUSS and REA applications.

Keywords: Radio - Communications - Spread spectrum - Tactical computer networks - Wireless communications - DUSS - REA - Sonar - Surveillance - Multistatic - Active.

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1

Introduction

Emerging concepts for Anti-Submarine Warfare (ASW) and Rapid Environmental Assessment (REA) increasingly rely on communication technology, in order to implement distributed information networks and to exchange information between naval units and military commands ashore. The necessary communication links could be accomplished using a variety of solutions: the main focus is on radio frequency (RF) links, which offer easy deployment and flexible operations.

Requirements (such as transmission data rate and ranges) change from one specific application to another. There are however a number of prerequisites that are shared by all applications and users: they include, but are not limited to, reliability, availability and security.

The biggest challenge derives from the fact that those requirements are countered by either natural factors, such as thermal noise and multipath interference, or by hostile activity aimed at disrupting the integrity of the lines of communication.

The present study examines the main features of spread-spectrum techniques, such as interference rejection, anti-jam capability and low-density power spectra for covert operations. An overview of real applications in ASW and REA is presented.

The specific requirements of wireless ad-hoc networks in support of ASW and REA include issues such as frequency re-use and multiple access to the same channel, dynamic reconfiguration of network topology, complex variable network structure (including support for moving platforms, such as ships), scalability and quality of service, communications and information security. A further study is recommended to discuss thoroughly this vast and complex subject.

This document illustrates how spread-spectrum techniques can be adopted to substitute and enhance existing communications systems, to permit the deployment of distributed, scalable networks of ships and sensors, characterized by reliable performance (resistance to hostile jamming and environmental interference) and low probability of interception.

After a general introduction (Section 1), spread-spectrum techniques are described in detail (Section 2), their performance is estimated (Section 3) and their applicability to DUSS and REA is shown (Section 4).

1.1 Wireless communications at sea

This section introduces the main issues of radio communications at sea.

Sophisticated sensors and information technology require the transfer of large flows of data. Current communication systems are limited in their throughput capability not only by technical limits, but above all by regulations about frequency assignment and by interference inherent to the frequency bands in use. For example, frequencies ranging from 2 MHz to 2 GHz, where the majority of naval communication systems are located, are crowded with signals generated by commercial users and radar emissions. In addition to that, the bandwidth that is made available to a single user is limited by practical reasons and by international regulations.

Frequencies above 2 GHz are less densely populated, and wider bandwidths are available. Operating at those high frequencies solves the problem of bandwidth availability and limits the adverse effects of thermal noise: it is a well known fact that sky noise temperature is minimum at frequencies between 1 and 10 GHz, in the so-called *microwave window* [1], as shown in figure 1.1. Moreover, stronger atmospheric absorption reduces interference from other users of the same channels. On the other hand, a large number of issues are still to be considered: for example, resistance to multipath interference and hostile jamming. Efficient use of radio communication resources is also important, to allow scalable and efficient operations with dynamic deployment topologies for ships and sensor platforms.

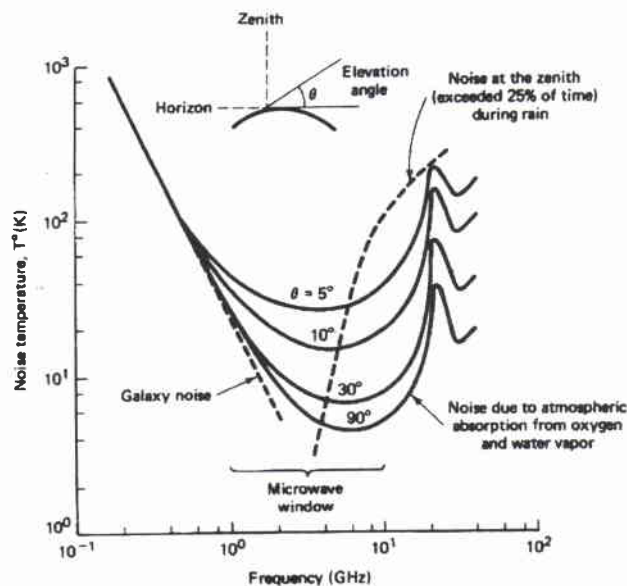


Figure 1.1 – Sky Noise temperature versus frequency.

Line of sight communications take place with low grazing angles; they correspond to the flattest curve of the above plot ($\theta = 5$ degrees). The most interesting frequency band

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appears to be in the 2 GHz – 10 GHz range. Further system parameters (e.g. antenna size) need to be considered in the final choice of the operating frequencies.

1.2 Benefits of Spread-Spectrum communications

In the study of digital communications systems, spectral power efficiency is very important to exploit effectively the available radio frequency bandwidth and transmission power, particularly in deployable buoys, where technical constraints are tight.

Spectral efficiency is defined as

$$n_s = \frac{R}{B_w} = \frac{\text{transmission_rate}}{\text{required_bandwidth}} \quad (1.1)$$

where

n_s = Spectral efficiency or bandwidth efficiency defined in b/s/Hz
 R = Transmission rate in b/s
 B_w = Bandwidth in Hz

Traditional modulation schemes, aim at *maximizing* spectral efficiency. However, interesting advantages can be obtained using a very large radio frequency bandwidth.

Such a transmission technique is called *spread-spectrum* (SS) and has been developed since the mid-1950's in support of military applications, including secure tactical communications. In SS systems, the bandwidth spreading is achieved using a code independent of the data: subsequent de-spreading and data recovery at the receiver is performed by correlation with the original code, in association with synchronization techniques.

The appropriate spreading of the spectrum leads to several benefits. Some of these are:

- Improved interference rejection
- Anti - jam capability
- Code division multiplexing for multiple access applications
- Low-density power spectra for covert transmission
- High-resolution ranging and timing
- Secure communications

In the following sections a summary of Direct-Sequence (DS) and Frequency-Hopping (FH) spread-spectrum techniques is presented. Most modern spread-spectrum systems are implemented using the above techniques, either alone or as a combination of the two.

2

Spreading techniques

Various signal spreading techniques exist: the most common and interesting ones are termed *direct-sequence* and *frequency hopping*.

In *direct-sequence spread-spectrum* (DSSS) a wide-band pseudo-random sequence, termed *pseudo-noise* (PN) *sequence*, is applied to the signal that needs to be transmitted, causing phase transitions in the data carrier. In *frequency-hopping spread-spectrum* (FHSS) the PN sequence forces the signal to rapidly hop its carrier frequency throughout the spread band-width for brief time slices in a pseudo-random way.

The use of a larger portion of Radio Frequency (RF) bandwidth is compensated for by the advantages anticipated above. Signal energy becomes so diluted that the amount of power density present in any point within the spread signal is very limited. The dilution may result in the signal falling below the noise floor, and thus becoming invisible to receivers which are not sharing an appropriate despreading code.

Details on the generation of PN sequences go beyond the scope of this document. A clear illustration of pseudo-noise sequence characteristics is offered by Sklar in [1].

The following sections describe in detail SS algorithms. Chapter 3 analyzes their characteristics.

2.1 DSSS spreading

In classical non-spread systems a carrier wave is initially modulated with a data signal $x(t)$, obtaining a constant-envelope data-modulated carrier having power P , radian frequency ω_0 and data phase modulation $\theta_x(t)$, as follows:

$$s_x(t) = \sqrt{2P} \cos[\omega_0 t + \theta_x(t)] \quad (2.1)$$

In direct-sequence (DS) systems the data-modulated signal $s_x(t)$ is modulated one more time with a wideband spreading signal $g(t)$, so that the transmitted waveform can be expressed as

$$s(t) = \sqrt{2P} \cos[\omega_0 t + \theta_x(t) + \theta_g(t)] \quad (2.2)$$

where the phase of the carrier is the sum of two components, $\theta_x(t)$ which is function of the data, the other, $\theta_g(t)$, which depends on the spreading sequence that has been applied.

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In a binary phase shift keying (BPSK) modulation scheme, assuming the data signal $x(t)$ as an antipodal pulse stream with pulse values of +1 and -1, instantaneous changes of π radians of the phase of the carrier, depending on input data can be observed, as shown in the following equation:

$$s_x(t) = \sqrt{2P}x(t)\cos(\omega_0t) \quad (2.3)$$

In case not only the data, but also the spreading sequence modulation is BPSK, $g(t)$ is the spreading antipodal sequence. Its auto-correlation is 1 at the peak, close to 0 for shifts of one symbol (+1,-1) or more. Equation (2.2) can be written as

$$s_x(t) = \sqrt{2P}x(t)g(t)\cos(\omega_0t) \quad (2.4)$$

Demodulation is accomplished correlating the received signal with a synchronized copy of the spreading signal $g(t-T')$, where T' is the receiver estimate of the propagation delay T between transmitter and receiver.

Disregarding the effect of noise, interference and attenuation, the output of the correlator is written as

$$A\sqrt{2P}x(t-T)g(t-T)g(t-T')\cos[\omega_0(t-T)+\phi] \quad (2.5)$$

where A is a *system gain* parameter and ϕ is a random phase angle in the range $(0, 2\pi)$. As mentioned above, $g(t)$ is assumed to be a sequence of antipodal signals: this implies that the product $g(t-T)g(t-T')$ is equivalent to unity only when the transmitter and the received are properly synchronized, otherwise it is a sequence of +1s and -1s that after low pass filtering vanishes to 0. If transmitter and receiver are synchronized, the output of the correlator is an ordinary BPSK-modulated signal, which can be passed directly to a demodulator, in order to recover the data.

A simplified scheme of the spreading-despreading architecture is shown in Fig. 1.

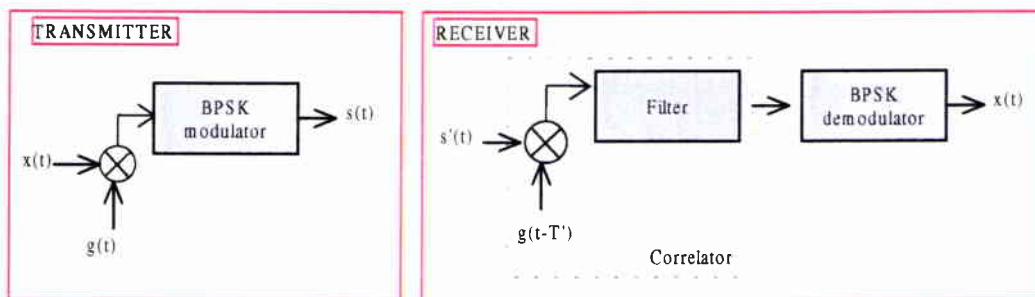


Figure 2.1 - Block diagram of DSSS spreading-despreading architecture

2.2 FHSS spreading

In frequency-hopping (FH) systems, the frequency synthesizer is driven by a pseudo-random sequence to *hop* from one frequency to another, within a pre-determined frequency range. Most commonly, FH is used in association to an M-ary frequency shift keying (MFSK) modulation. Instead of modulating a fixed frequency carrier, the data symbol modulates a carrier whose frequency is determined by a pseudo-random code. For a given hop, the bandwidth that is occupied during the transmission is identical to the bandwidth of conventional MFSK: however, averaging over several hops, the spectrum spreads to use all the available bandwidth. Current technology permits a spreading over a bandwidth of several GHz, allowing larger processing gains in comparison to DS systems.

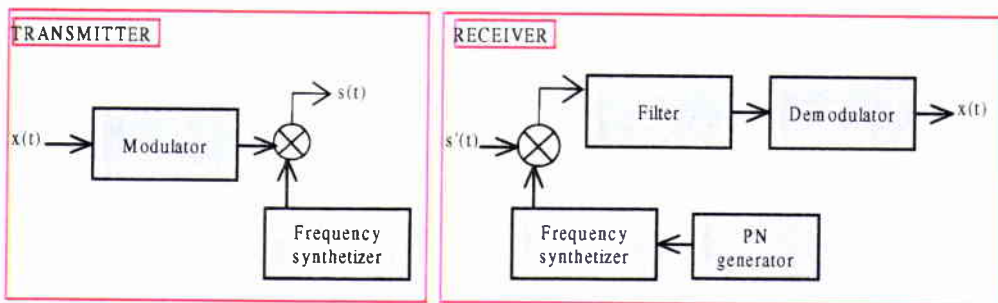


Figure 2.2 - Block diagram of FHSS spreading-despreading architecture

Frequency-hopping spread-spectrum systems can be further classified in two sub-categories, *slow frequency-hopping* (SFH) and *fast frequency hopping* (FFH), if the hopping rate f_h is less or more than the baseband message bit rate f_b , respectively.

2.3 US DoD and Commercial-off-the-shelf implementations

This section contains an overview of existing military or commercial systems.

The U.S. Department of Defense is in the process of specifying and developing a new wireless networking radio capable of transmitting voice, video, and data between its mobile vehicles, aircrafts, and ships. Among the most promising systems that are being evaluated are the Department of Defense Near Term Digital Radio (NTDR), GEC Marconi Hazeltine VRC-99, as well as Commercial-Off-The-Shelf CSMA/CA systems, such as those defined by standard IEEE 802.11. Specific research projects are being conducted at the Naval Research Laboratory and at SPAWAR Systems Center, San Diego [8].

The NTDR is a tactical radio developed by ITT for mobile networked Internet protocol data applications. The NTDR handles data packet information at a burst rate of 375 kbps. The resulting coded signal is modulated onto a Direct Sequence Spread Spectrum (DSSS) waveform at 500 kbps and transmitted at up to 20 Watts (+43 dBm) in the 225-

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450 MHz band. For a simple point-to-point connection the maximum throughput is about 250 kbps.

The VRC-99 is a direct sequence spread spectrum radio manufactured by GEC-Marconi Hazeltine guaranteeing reliable, simultaneous, multichannel voice, data, imagery, and video transmission. Data rate is 625 kbps with options of adaptive data rate operation from 157 kbps to 10 Mbps. Low probability of intercept and jamming resistance is achieved through specialized direct-sequence and frequency-hopping spread-spectrum techniques. Operation is conducted in the 1.2-2 GHz frequency band. The VRC-99 supports IP data from a standard Ethernet local area network (LAN) and up to four simultaneous voice telephone links.

In addition to the above systems, which are specifically conceived for military use, Commercial-Off-The-Shelf systems are being studied to assess their effectiveness. COTS systems are usually based on open standards, which implies availability of products from multiple suppliers on a shorter time scale, at a lower cost. It is possible either to purchase a complete turnkey system or to build up a custom made one to match specific requirement, using available chipsets and RF components.

COTS equipment is typically configured to operate in the ISM (Industrial, Scientific and Medical) frequency band (2.4 GHz and 5.7 GHz). License-free operation is granted for transmission in the ISM band using spread-spectrum equipment, provided limits on transmit power are respected (typically 0.1 W). Operation at higher transmit power is usually subject to approval by the national authorities.

“802.11” is the first true industry standard for Wireless Local Area Networks, or “WLANs”. Developed by the Institute of Electrical and Electronics Engineers (IEEE), 802.11 can be compared to the 802.3 standard for Ethernet wired LANs. The goal of 802.11 is to provide a standard set of operational rules so that WLAN products from different manufacturers interoperate in the same way that Ethernet equipment does today.

The physical layer of IEEE 802.11 includes three alternatives: DFIR (Diffuse Infra-Red), DSSS, and FHSS. Both the DS and FH spread spectrum specifications utilize the 2.4 GHz radio frequency band. The 2.4 GHz band was chosen because it is available for unlicensed operation worldwide and because it is possible to build low cost, low power radios in this frequency range that operate at LAN speeds.

The shared access of several users to a single frequency band is implemented by ad-hoc protocols.

IEEE 802.11 and other relevant WLAN products, such as P-Com Datametro II, use the CSMA/CA (Carrier Sense Multiple Access/Collision *Avoidance*) access method, which is, in turn, derived from the Ethernet standard, CSMA/CD (Carrier Sense Multiple Access/Collision *Detection*). In a nutshell, CSMA/CA applies a “listen before talk” approach that can minimize collisions by using request to send (RTS), clear-to-send (CTS), data and acknowledge (ACK) transmission frames, in a sequential fashion. This results in higher system throughput and better frequency utilization.

3

Performance of Spread-Spectrum systems

In this section the fundamental performance improvements of spread-spectrum are analyzed and compared to traditional modulations.

3.1 Relationship between SNR and bandwidth expansion

The underlying principle of SS is the spreading of relatively low bandwidth data signals in a broad frequency band. This means that a jammer with a fixed amount of transmitting power is forced to either spread the available power over a wide range of frequencies, or concentrate all power in a limited frequency range, leaving the remainder of the frequency space free of interference. So it is clear that, by using spread-spectrum, a jammer with a *finite* amount of power is effectively countered. This situation is the most common encountered in field operations, where man-made interference in very crowded frequency bands is the main constraint.

On the other hand, the use of signal spreading alone to counter white gaussian noise brings no improvements. The larger noise power falling in the wide receiver bandwidth is rejected by correlation of the received signal with the de-spreading sequence.

The performance of spread-spectrum can be expressed by means of the Hartley-Shannon theorem, which relates maximum channel capacity to transmit bandwidth and signal to noise ratio (SNR). Hartley-Shannon's equation is written as:

$$C = W \log_2 \left(1 + \frac{S}{N} \right) \quad (3.1)$$

where C is maximum channel capacity, W is the RF bandwidth, S is signal power and N is noise power. When a jammer / interferer with finite power and a fixed data rate R ($R < C$) are considered, the trade-off between transmit bandwidth and SNR can be derived. Yavuz [6] uses the following relation to quantify the extremely large possible improvements of receiver SNR as the transmit bandwidth is expanded for the same input SNR:

$$SNR_o = [1 + SNR_i]^{\gamma} - 1 \quad (3.2)$$

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SNR_o is the output signal-to-noise ratio, SNR_i is the input signal-to-noise ratio, and γ is the bandwidth expansion factor W/W_s . W_s is the spread-spectrum bandwidth, W_i is the information signal bandwidth.

The important result is that extremely large improvements of output SNR (of exponential order) are possible by increasing the bandwidth expansion factor γ for the same input SNR. In other words, using a low transmit power (compatible with battery operation) and expanding the transmit bandwidth (using spread-spectrum) it is possible to obtain the same performance of a conventional narrowband system, which requires a higher transmit power. A limit exists to this trade off, beyond which further increase of bandwidth does not permit transmit power reductions [1]. The same principle is illustrated in section 3.3 for the case of man-made interference.

The trade off between SNR and bandwidth discussed above corresponds in information theory to the encoding of a limited alphabet with a very large set of redundant symbols. The same advantages in terms of robustness to errors (i.e. noise) can be found.

Let us assume an information space of 8 bits, as in the ASCII character set: it can be represented using $2^8 = 256$ symbols. The data signal is transmitted using a DSSS system, in which, as an example, each symbol of the original signal is spread to 16 signal blocks (bits in the actual, spread-spectrum, transmission), corresponding to as many as $2^{16} = 65536$ code words of length 16. Of those words, only 256 are necessary, in order to represent the 8 bit information set: this means that only 256 out of 65536 words will be used, corresponding to 0.4 % of the spread-spectrum symbol space. With so many code words to choose from, it will be possible to select those separated by the maximum possible Hamming distance, defined as the number of elements in which two code vectors differ. As an example, the following 16-bit vectors, $U=[1001110000111011]$ and $V=[0010011000000011]$, have a Hamming distance $d(U,V)$ of 8.

Hamming distance has a direct influence of the code error detection and error correction capabilities. Generally speaking, a code is capable of detecting up to l errors per word if $d(U,V) \geq l+1$. At the same time, it will be able to correct up to t errors per word if $d(U,V) \geq 2t+1$. In our example, a code with maximum Hamming distance equal to 8 is capable to detect up to 7 errors per word, or correct up to 3 errors per word.

The availability of such a large symbol alphabet forms also the basis for Code Division Multiple Access (CDMA). Operational systems such as the Joint Tactical Information Distribution System (JTIDS), in use with all NATO AWACS/NAEW aircraft and associated ground segments, use DSSS expansion from 5 bits to 32 bits/blocks. The system also provides up to $2^7 = 128$ different CDMA nets, which correspond to $2^{(5+7)} = 2^{11} = 2048$ symbols. This figure represents a usage of less than 0.00005 % of the overall symbol space, leading to an increased robustness of the communication system. The Global Positioning System (GPS) uses such a wideband DS spreading that its signals are actually usable even at 30 dB below noise level.

3.2 Robustness to multipath

Multipath interference takes place when two or more wave trains meet at the receiver input, after travelling through different paths, e.g. as a consequence of reflections at the sea surface. When the travel time difference is very limited, if the waves arrive in phase, interference has a *positive* effect, so that the strength of the resulting electric field is higher, in comparison with the primary wave. With carrier phase reversal, multipath interference has a *destructive* effect, and the strength of the received signal is substantially decreased. When travel time difference of the two paths is large with respect to carrier period, the two data flows just interfere against each other. This happens at short and intermediate ranges, where the difference between reflected and direct path is more pronounced. In this case, the wide band / narrow auto-correlation of the spreading sequence better helps interference rejection.

The amount of multipath scattering in the marine environment is mainly a function of sea state: calm seas reflect better, so that multipath effects reach their maximum. Multipath structure and arrival time depend on antenna height at transmitter and receiver ends, and on reflection conditions [11].

The following sections describe how SS techniques achieve a good degree of protection against multipath effects.

3.2.1 FHSS

Let us consider two rays: the first one travels from the transmitter to the receiver directly, in line-of-sight conditions, while the other is reflected by the sea surface. The direct ray reaches the receiver with a delay τ_0 , while the reflected ray arrives after a propagation time τ_1 . Obviously, $\tau_0 < \tau_1$. The delayed signal causes considerable in-band interference, unless the receiver *hops* to a new frequency *before* the reflected ray reaches it. Let us assume that the hopping rate f_c is larger than the inverse of the delay difference between the reflected path and the direct path, that is

$$f_c > \frac{1}{(\tau_1 - \tau_0)} \quad (3.3)$$

The result is that the FHSS system has switched to another frequency before the arrival of the delayed signal. For this reason FHSS is capable of presenting excellent performance against multipath interference, provided the hopping rate is sufficiently high and that receiver synchronization is not disturbed by the interference. For this reason, fast frequency-hopping systems perform better than slow frequency-hopping systems.

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3.2.2 DSSS

Let's consider again an environment where multipath transmission takes place. Let us consider a DSSS receiver, which is synchronized to the time delay and RF phase of the direct line-of-sight path. The received signal $r(t)$ can be imagined as the sum of three components: the direct ray, the reflected ray, and noise.

$$r(t) = Ax(t)g(t)\cos(\omega_0 t) + \alpha Ax(t-\tau)g(t-\tau)\cos(\omega_0 t + \theta) + n(t) \quad (3.4)$$

The usual symbol conventions are kept: $x(t)$ is the data signal, $g(t)$ is the code signal used for spreading-despreading, $n(t)$ is noise, τ is the differential time delay between the direct and reflected path, α is the attenuation of the reflected signal, θ is a random phase, assumed to be uniformly distributed in the $(0, 2\pi)$ range.

At the receiver, the output of the correlator can be written as

$$\begin{aligned} z(t=T) &= \\ &= \int_0^T [Ax(t)g^2(t)\cos(\omega_0 t) + \alpha Ax(t-\tau)g(t)g(t-\tau)\cos(\omega_0 t + \theta) + n(t)g(t)]2\cos(\omega_0 t)dt \end{aligned} \quad (3.5)$$

where $g^2(t)=1$, in accordance to the properties of $g(t)$ exposed in section 2.1.

Let us define T_c as the duration of a symbol in the $g(t)$ PN sequence. Note that such duration is very short, compared to the duration of a symbol in the actual signal. For a delay $\tau > T_c$:

$$|g(t)g(t-\tau)| \ll 1 \quad (3.6)$$

This means that, for a differential time delay between the direct and the reflected ray that is higher than T_c :

$$z(t=T) = \int_0^T 2Ax(t)\cos^2(\omega_0 t) + 2n(t)g(t)\cos(\omega_0 t)dt = Ax(T) + n_0(T) \quad (3.7)$$

where $n_0(t)$ is zero-mean AWGN. This clarifies that SS systems effectively eliminate multipath interference by means of the code-correlating receiver.

3.3 Jamming

In order to estimate system resistance to hostile jamming, an expression of the SNR for digital systems is defined, including the jamming component.

Let us define *bit energy* as

$$E_b = ST_b = \frac{S}{R} \quad (3.8)$$

where S is the received signal power, T_b the bit duration and R the data rate, expressed in bit/s.

SNR can be also expressed in the following form:

$$\frac{E_b}{(N_0 + J_0)} \quad (3.9)$$

where J_0 is the noise spectral density induced by jamming and N_0 is, as usual, the thermal noise spectral density. It is assumed that the jammer operates over a very wide frequency band, equivalent to the spread-spectrum bandwidth. At the same time, it is assumed that jammer noise is considerably stronger than thermal noise. Under these assumptions it is possible to consider SNR through the following expression:

$$\frac{E_b}{J_0} \quad (3.10)$$

It is clear that a threshold in this ratio exists, that determines whether the system is capable of delivering the desired bit error probability, or not.

As mentioned above, the jammer power is spread all over the frequency range W_x , so

$$J_0 = \frac{J}{W_x}. \quad (3.11)$$

The threshold for the E_b/J_0 ratio can be defined as follows:

$$\left(\frac{E_b}{J_0} \right)_{thres} = \left(\frac{\frac{S}{R}}{\frac{J}{W_x}} \right)_{thres} = \frac{\frac{W_x}{R}}{\left(\frac{J}{S} \right)_{thres}} = \frac{G_p}{\left(\frac{J}{S} \right)_{thres}} \quad (3.12)$$

where $G_p = W_x/R$ is called *processing gain*, and $(J/S)_{thres}$ can be written as

$$\left(\frac{J}{S} \right)_{thres} = \frac{G_p}{\left(\frac{E_b}{J_0} \right)_{thres}} \quad (3.13)$$

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The ratio $(J/S)_{thres}$ is a figure of merit that measures the resistance to interference. The larger it is, the better the system resists to noise.

The relationship between spread-spectrum processing gain and resistance to interference is now clear: the higher is the processing gain, the better the system delivers the expected performance. For this reason, when adopting a spread-spectrum system, it is advantageous to have a processing gain as high as possible.

In order to provide further evidence of the above conclusion, the jamming signal is modeled as a zero-mean AWGN. Assuming that the jamming is conducted on the entire spread-spectrum bandwidth W_s , the jammer power spectral density is expressed by (3.11).

Sklar [1] demonstrates that the bit error probability P_b for a coherently demodulated BPSK system (without channel coding) is

$$P_b = \text{erfc} \left(\sqrt{\frac{2E_b}{N_0}} \right) \quad (3.14)$$

where $\text{erfc}(x)$ is the *complementary error function* or *co-error function*.

The presence of the jammer increases the noise power spectral density from N_0 to $(N_0 + J)$, so that the average bit error probability becomes

$$P_b = \text{erfc} \left(\sqrt{\frac{2E_b}{N_0 + J}} \right) = \text{erfc} \left[\sqrt{\frac{2E_b/N_0}{1 + (E_b/N_0)(J/S)/G_p}} \right] \quad (3.15)$$

When P_b is plotted versus E_b/N_0 , for a given J/S (see also eq. 3.13) the curves look like the following figure:

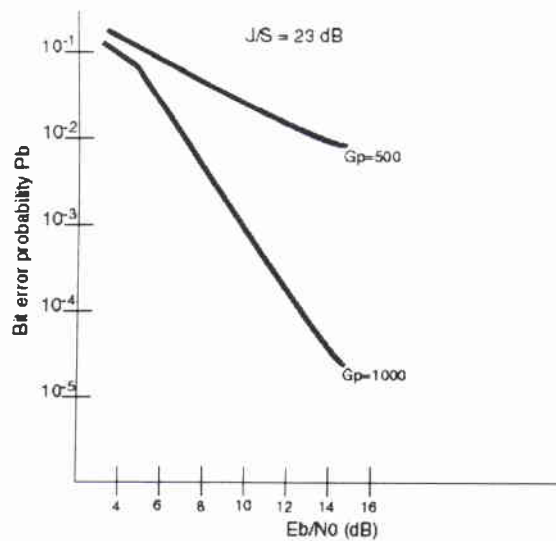


Figure 3.1 - Bit Error Probability versus E_b/N_0 for a given J/S ratio

For low E_b/N_0 ratios, the curves tend to group together, and the beneficial effects of large processing gains G_p are reduced. Anyway, a wide range of operational E_b/N_0 ratios exists, where spread-spectrum system counter jamming effectively.

Pickholtz gives a further discussion of this topic in [3].

In addition to that, Feher [4] gives an expression for the error rate of a frequency-hopping system in case of narrowband jamming.

The average error rate P_e is simply given by

$$P_e = \frac{J_n}{M} \quad (3.16)$$

where J_n is the number of interferers with large power compared to the signal power and M is the number of available frequencies. Associating to FHSS a code capable of correcting n errors, where $n \geq J_n$, the receiver is enabled to reject n jamming signals.

One consideration is necessary, in order to clarify the differences in jamming rejection between FHSS and DSSS. In FHSS, increasing jamming power beyond a certain limit, without increasing the number of channels on which jamming is conducted, brings no substantial advantage to the attacker. In DSSS, jamming energy is spread over the total bandwidth, so an increase in jamming power has a direct impact on the probability of error.

The following figure gives us a view of the qualitative result of the DSSS interference rejection property. In (a) is shown the spectrum of data signal and of interference at the

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input of the receiver correlator (see Fig. 1 for the basic structure of the SS receiver); (b) shows the output of the correlator, which is subsequently demodulated. The signal bandwidth is reduced to R , while the jamming energy is spread over a bandwidth in excess of W_p . The great part of the interference spectrum that does not overlap the signal spectrum is filtered out. The result is that the effect of hostile interference is minimized.

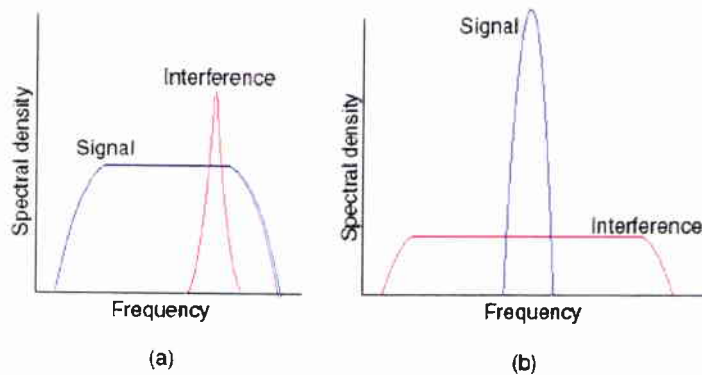


Figure 3.2 - Spectra of data signal and hostile interference

3.4 Low probability of detection and interception

The output of the spread-spectrum transmitter is a wideband noise-like signal, which is hard to distinguish from background noise. This characteristic results in low probabilities on interception and detection, which form the basis of secure communications.

Dillard discusses the detectability of spread-spectrum systems in [5], with specific reference to frequency hopping. The result is that detection of spread-spectrum signals is theoretically feasible, either using a wideband directional radiometer to integrate signal energy over the entire transmission and compare directional levels, or using a bank of filters to detect individual pulses. However, both approaches need to be exactly tailored to the specific target: the interceptor needs to know in advance the complete signal structure. The only exception is the spreading code of the day, which is assumed to be secret. This is a serious limit to the effectiveness of detection.

In addition to that, complete reconstruction of the spread signal from unauthorized receivers proves to be very difficult and is a function of the length of the PN code that is used for spreading. A long and well designed spreading code attains a low probability of intercept. Additional security can be achieved through encryption schemes at the application level.

3.5 Summary and comparison with conventional modulations

As discussed above, spread-spectrum techniques reduce transmit power consumption by means of wider frequency band usage. The frequency spreading factor γ in eq. 3.2 quantifies this trade off.

Performance against Gaussian Noise is equivalent to classical systems in terms of SNR. Smart digital error correcting techniques permit to implement this equivalence optimally. With increased signal payload, error rate may be controlled further.

Important advantages exist against man-made interference and jamming. They are quantified by processing gain G_p in Eq. 3.15 for DSSS and by the number of interferers for FHSS in Eq. 3.16.

Robustness to multipath is achieved in several ways: operation in a wide frequency band counters destructive interference from phase-reversed signals reflected by the sea surface. The short time auto-correlation of DSSS or short time duration of FHSS signal blocks counter symbol interference from delayed paths.

Multipath robustness, can be achieved also by narrowband modulation using "multicarrier modulations" (such as Orthogonal Frequency Division Multiplexing, OFDM, Ref. [7], that is currently being studied by the US Navy) and adaptive equalization techniques. Those non spread-spectrum techniques are not readily available, as a consequence of their greater complexity: prototypes are currently being defined, which may lead to product availability in the next years.

Spread spectrum also delivers low probability of interception (LPI) and detection (LPD). LPI and LPD are specific characteristics of spread-spectrum. Signals transmitted using non spread-spectrum techniques can be easily detected using RF spectrum analyzers. Narrowband filtering centered on the carrier frequency, followed by demodulation, leads to reconstruction of the original signal.

The specific requirements of wireless ad-hoc networks include also issues such as multiple access to the same channel, frequency re-use, dynamic reconfiguration of network topology, complex variable network structure (including support for moving platforms, such as ships), scalability and quality of service, communications and information security. The study of each of these topics is fundamental to come to the definition of an effective, scalable, reliable.

A further study of access and routing protocols (with special emphasis on resource reservation and quality of service) and of authentication and encryption mechanisms is recommended, to discuss thoroughly this vast and complex subject.

4

Applications

Both Rapid Environmental Assessment (REA) and Deployable Underwater Surveillance Systems (DUSS) present a common basis of communication requirements, whether field experiments or proof of operational concept is involved.

The following table lists some key services that are of interest to all users, together with the associated data rates.

<i>Service</i>	<i>Data rate (kbps)</i>
Automated real-time decision aides	>64
Concurrent, distributed data bases	>64
Data fusion	>64
Data transfer (vertical arrays, sonobuoys, DUSS)	Up to 10 Mbps
Distributed computing	Up to 10 Mbps
Distributed white board	>64
High-resolution imagery	>64
High-resolution maps	>64
Voice	>2.4
Web browsing	>64

Important requirements relative to availability, reliability and security can be summarized in the following list:

1. Guarantee of data integrity
2. Protection from denial of service
3. Low battery power requirements
4. Low probability of intercept
5. Source authentication
6. Secure encoding
7. Long ranges
8. Flexible multi-point architecture
9. Fault tolerant operation, graceful degradation

Low battery power requirements and low probability of intercept are strongly correlated: spread-spectrum transmission is stealth by its own nature. In addition to that, effective data transmission is accomplished with limited transmission power. Hostile interference is not fought by brute force (increasing the transmission power), but more advanced techniques are adopted, as explained by the Hartley-Shannon Theorem, presented in chapter 3.

The result is that spread spectrum equipment can be easily operated from a battery: Commercial-Off-The-Shelf spread-spectrum radios are capable of delivering data rates

in the order of several Megabits per second up to the distance of 20 NM, with transmission power lower than 1 W.

Requirements 5 and 6 cannot be satisfied totally by simply adopting spread-spectrum techniques: better results would probably be obtained operating at the application level, using appropriate authentication schemes which should be supplemented by strong encryption. Nevertheless, since a spread-spectrum wireless network node can communicate with the other nodes only by using the appropriate PN code, it can be said that SS plays a non marginal role in satisfying source authentication requirements.

Spread-spectrum with no doubt fulfils requirements 2, 3 and 4.

The following sections show how spread-spectrum could be adopted to support ongoing and future research activities in Rapid Environmental Assessment and Anti-Submarine Warfare.

4.1 Rapid Environmental Assessment

To accomplish their mission, naval forces rely on all kinds of environmental data. Weather and climatology information, tide atlases, satellite images of cloud cover, and oceanographic databases are regularly generated and distributed: this activity of preparation, collection and delivery of standard environmental products represents the standard level of service offered to navy customers. A situation may however arise, when oceanographic support centres are not able to supply the environmental information that is needed by naval commanders and planners. In such a case, a request is issued to the NATO military oceanography (MILOC) group, to conduct specific surveys in the area of interest to acquire the necessary data.

In the past, the whole process of data collection, processing and distribution of a final environmental report always took several years. Such a long delivery time was not deemed satisfactory by the end users, which formulated a requirement to obtain operationally relevant products within a tactically relevant time frame after the identification of a particular area. The definition of "tactically relevant time frame" ranges from several months, during the operational planning phase, to few days, during navy operations.

Acceleration of traditional methodologies (e.g. re-assignment of priorities in data collection and processing) can reduce the delivery times from several years to few months, which is not even close to meeting the most stringent requirements.

Rapid Environmental Assessment (REA) is a set of state of the art methodologies and techniques that enable the collection, processing and distribution of environmental data and products within a compressed time frame, in the order of days, if not hours.

The REA concept requires the collection of in-situ data by one or more survey vessels, as illustrated in figure 4.1. Survey vessels perform the necessary environmental measurements and relay the information to a data fusion centre afloat (e.g. a command

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ship), which can be positioned several miles away. Fused data are then transferred to a fusion centre ashore, where they are made available to the REA community (data providers, product developers, and customers) using wide-area computer networks. An objective range of 20 n.mi can be assumed as a reference specification.

In the recent past, during SACLANTCEN **Rapid Response** surveys (1996-1998), transmission of data from the individual vessels to the data fusion centre was accomplished using point-to-point links (based on cellular telephone). Ship-to-ship data communications was attempted using conventional VHF radio links, but the results were not convincing. Satellite communications between the data fusion centre afloat and its counterpart ashore were extensively tested and proved to be a major success.

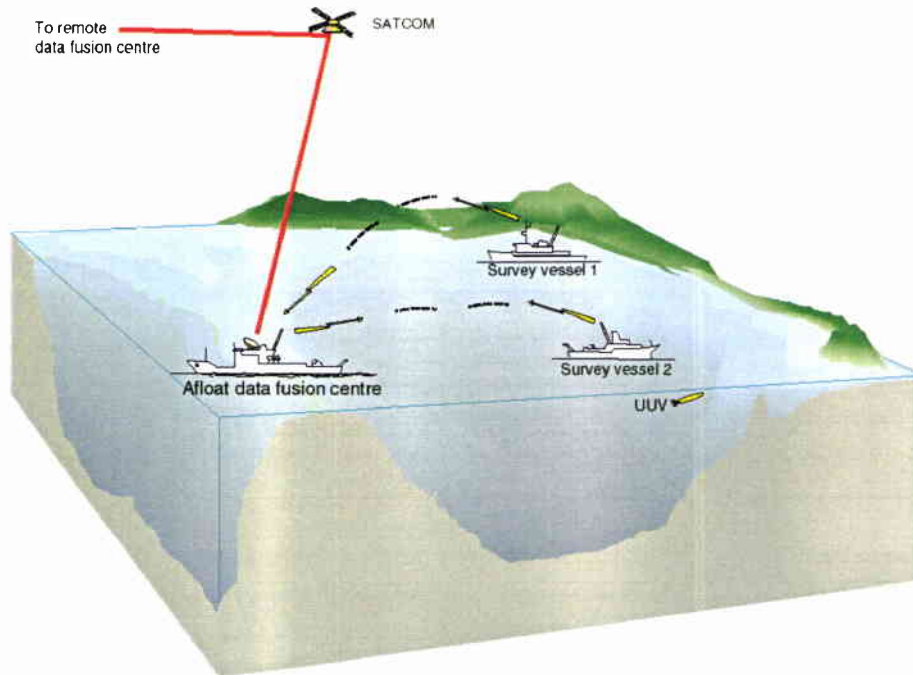


Figure 4.1 - Transmission of REA information from survey vessels to a data fusion centre

REA experiments conducted so far constitute proof of the effectiveness of the REA concept: however, additional efforts are still necessary to define a communication architecture suitable for use in operational conditions. There is no doubt that the availability of reliable and scalable ship-to-ship data links is of paramount importance to the effectiveness of REA surveys.

During a crisis the access to commercial land-based communication infrastructures (such as cellular phone networks) will be easily denied. It is very important that the communication architecture that is defined is independent from local infrastructures. On the basis of the above consideration, the deployment of a wireless LAN connecting the survey vessels is a practical solution.

The WLAN, implemented using medium or high data rate RF links with a high resistance to multipath interference and hostile jamming, is the first level of the REA tactical network. The second level is the long range communication link, typically implemented using SATCOM, that connects the survey group to the commands ashore.

Spread-spectrum makes an excellent candidate to implement the REA tactical network. When operating near the shore, a major challenge comes from the multipath interference that is caused by reflections of RF waves by the sea surface and by the land. The characteristics of robustness to multipath interference of spread-spectrum enable the delivery of reliable wireless data communication at the required high data rate. The LPI and LPD properties of spread-spectrum, together with resistance to hostile jamming, may prove extremely useful for adoption in an operational situation.

Computer simulations using the AREPS model [10] show that ship-to-ship communications can achieve a maximum range of 18 n.mi. (21 n.mi. when directive antennae are used) with only 1 W of transmit power, operating in the 2 GHz frequency range with antenna masts 33 m high, as summarized in the following table.

Transmit power	Antenna type	Range (n.mi.)
1 W	Omnidirectional	18
1 W	Directive (*)	21

(*) requires tracking system to ensure antenna alignment

Tests have been conducted during SACLANTCEN experiment **Advent 99** in May 1999, to demonstrate the effectiveness of the concept. Italian Navy ship Ciclope towed a CTD chain and transferred data in quasi-real time to NRV Alliance, using a DSSS link with a data rate of 128 kbps and a transmit power of 0.6 W. NRV Alliance was positioned at a maximum distance of 10 n.mi.

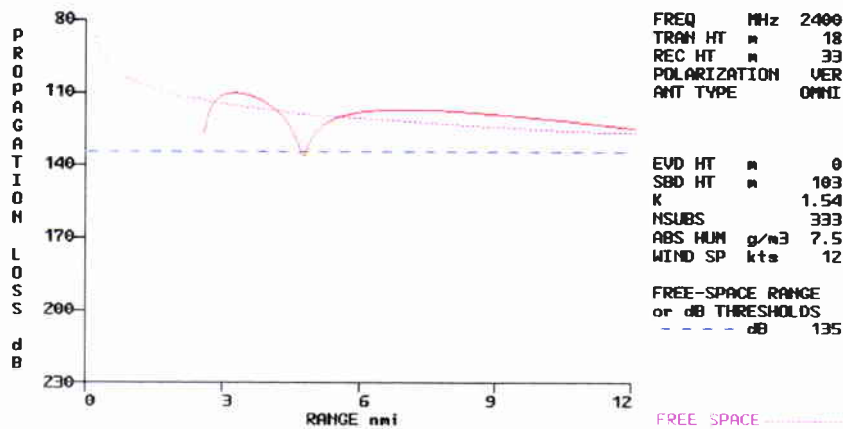


Figure 4.2 – Theoretical propagation loss (red) for the Advent 99 DSSS radio link. The blue dashed line represents the communication threshold

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The spread-spectrum communication system was judged extremely reliable and contributed to the success of the experiment.

A brief interruption of the link has been observed, as a consequence of the multipath effects due to reflections from sea surface. This is in accordance with RF propagation loss predictions computed using the EREPS model and the methodologies described in [11]. The result is summarized in figure 4.2: multipath induced propagation loss brings the system below communication threshold at the range of 4.7 n.mi. Loss of signal is observed for an additional 0.1 n.mi, where communications is resumed. From the range of 4.8 n.mi onwards, communication is stable and reliable, up to a range exceeding 12 n.mi.

4.2 Deployable Underwater Surveillance Systems

ASW nowadays places very demanding requirements on sonar capabilities, in an era of shrinking budgets. Protection of worldwide commercial flows on sea routes from the attacks or mining operations of hostile submarines have become the highest priority. The areas of interest have now moved to shallow littoral waters and choke points, characterized by heavy (and noisy) shipping traffic, poor and complex sound propagation, strong reverberation. The submarines that need to be countered are now small, diesel electric vessels, already too silent for easy passive detection, and now undergoing major technological improvements like sound absorbing cladding, air independent propulsion, modern passive sonars (towed and flank arrays) and navigation systems. Finally, operational requirements have become very strict in terms of probability of detection, completeness and accuracy of coverage, risk for naval units and personnel, discretion, interoperability.

SACLANTCEN is conducting theoretical and experimental investigations on Deployed Undersea Surveillance systems to meet these requirements. The new concept consists of multiple acoustic sources and receivers: small, inexpensive, expendable elements easily deployed from any air or sea platform (Figure 4.3).

Sonar units can be drifting, moored to the bottom at chosen depths or laid directly on the seabed. Battery powered, they are autonomous and transmit data in compressed form via radio, satellite link, optic fiber or other. The moderate gain receivers, which may be used also in passive mode, have the advantage of no own ship noise and can be laid to form a large network extended over wide areas. The covertness of receivers suits operations in critical areas and improves chances of detection of unaware submarines (that optimize their course only with respect to the transmitter position) with either a favorable aspect angle or Doppler shift.

Figure 4.4 illustrates the advantages of aspect diversity.

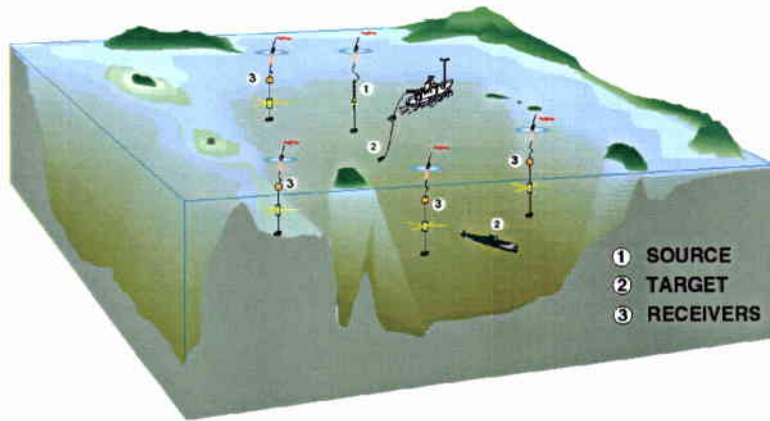


Figure 4.3 - Pictorial view of the DUSS concept.

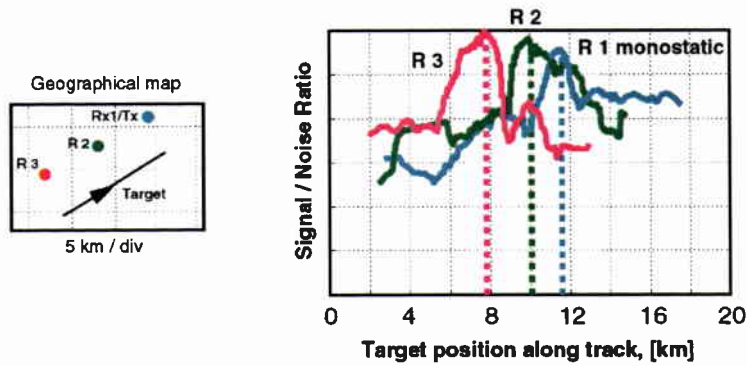


Figure 4.4 - Target detection opportunities are multiplied by the deployment of additional multistatic receivers.

Elementary detection volumes can be overlapped: each node has an independent opportunity to detect the target, while inter-sensor data fusion reduces false alarms and exploits deployment geometry to enhance localization and tracking. Figure 4.5 illustrates this concept.

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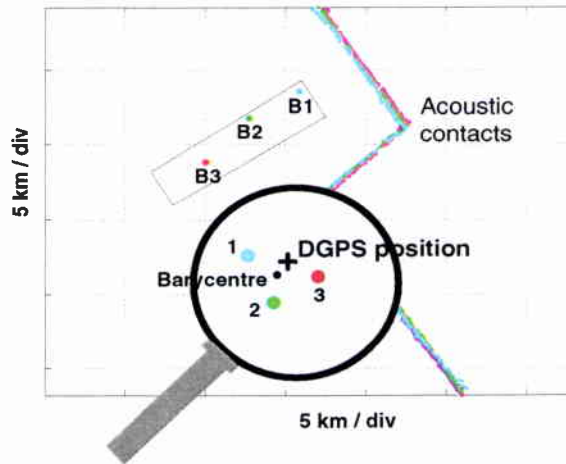


Figure 4.5 - Consistency of contacts localized from different receivers.

A field of moored elements facilitates detection of any moving object, as the background remains relatively stationary. Towed sources, on the other hand, are not subject to the same critical constraints in power and endurance, while the towing ship does not need to be the master operation center. Figure 4.6 shows raw sonar displays for three separate receivers.

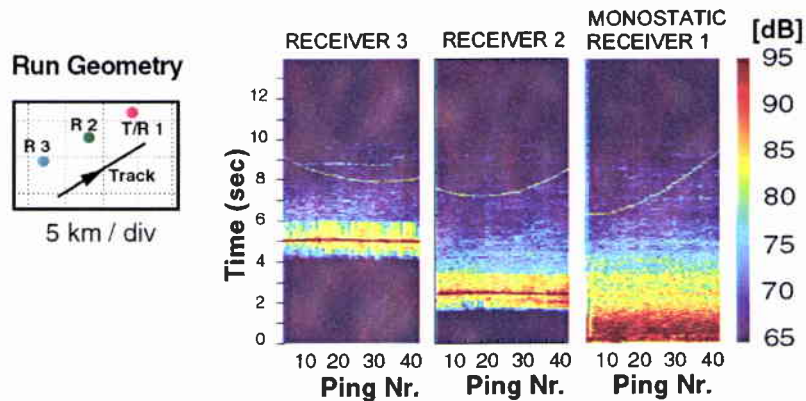


Figure 4.6 - Raw data on sonar displays for three DUSS receivers.

Such raw data need to be faithfully copied and archived in the central lab during experiments. One way transmission is the priority. On the contrary, operational systems rely on cheap in-buoy processors to reduce data flows by several orders of magnitude. They benefit from two-way, multi-point communications, exchanging and processing information about contacts through neighboring buoys in a distributed way.

The feasibility of the whole concept largely relies on the recent advances of communication, geographical localization and digital processing techniques, which permit distributed sonar processing on small autonomous nodes and transmission of the data collected in compressed form. Different degrees of data reduction before

transmission are possible, according to the tasks to be executed. The following sections address the two cases of scientific experiments and of demonstrators approaching operational conditions.

4.2.1 DUSS radio link specifications

Accurate collection of scientific data requires hydrophone data to be stored with a large dynamic range. The whole bunch of information collected by the sensors is transmitted to the laboratory on NRV Alliance and maintained for successive off-line processing and analyses that can not be anticipated during the experiments. Data reduction is limited, in this case, to base-band filtering and shifting. The follow on estimates requirements for DUSS.

- Raw data: recordings of raw data on board Alliance are mandatory for scientific work. Therefore they will always be required as a first – priority output for all experiments. In - buoy recordings are also being considered, and represent a safe backup resource. Expected rates are $24 \text{ bits} * 64 \text{ Hydr.} * 1365 \text{ Hz} = \mathbf{2 \text{ Mbps}}$
- Compressed data: an operational DUSS may resorts to in-buoy processing and implement a distributed – knowledge, distributed – processing network. Pre-processed contact information is passed through the net in a packet switching fashion. Data rates are reduced. This section tries to produce an estimate of expected reduction ratios by considering very simple approaches.
- Geographical map of cells: range resolution reduced to 50 m via pre-processing. Max range: 30 km. 600 cells. 8 bits per cell (e.g. level coded in dB of SNR after normalization and thresholding between 0 and 32 dB in 0.5 dB steps). 64 beams. Total: **5 kbps**.
- Markov Random Field processing: this method transforms the raw sonar display into a list of OBJECTS. Each of them is described by time, bearing, size, level (i.e. 16 bytes). Analyses of experimental data (DUSS and SWAC data) estimated an average reduction between 1 % and 0.1 % of the number of raw sonar cells to objects. Assuming 2 bytes / cell and 16 bytes / object, 1 % data rate reductions represent a reasonable conservative guess for reverberating environments after full development of this method. Total: **20 kbps**.
- Thresholding: the analysis of DUSS data produced the false contact distribution shown in Fig. 4.7. The experimental probability of false alarm is plotted versus level in dB with respect to normalized background. Contacts above 6 dB represent 1 % of the total. Their range needs to be stored in sparse files. Their level can be recorded with just 1 byte. The result is a 1 % compression ratio. Total **20 kbps**.

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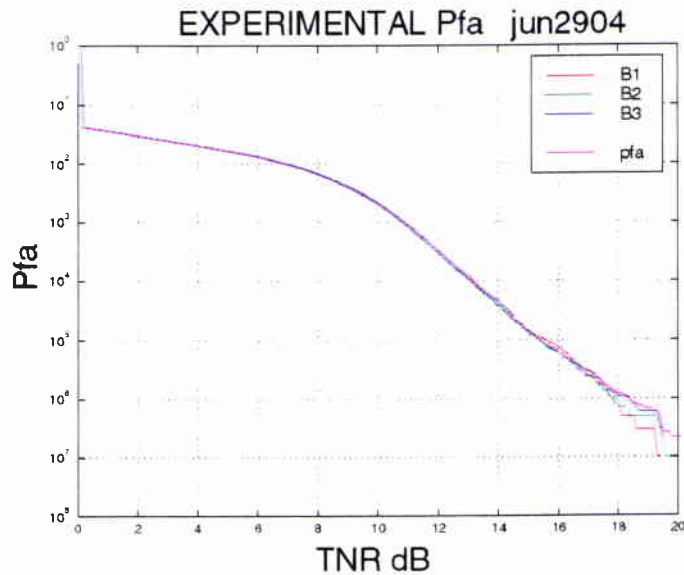


Fig. 4.7 DUSS 97 data. False alarm rates vs normalized level.

- Estimated rates sum up together when a Local Area Network (LAN) structure is used, with nodes that forward data through the network together further to broadcasting their own contacts.
- Bit error rate (BER) requirements for raw data acquisition range from 10^{-3} to 10^{-5} . In fact, as shown by field experiments, the isolated error bursts that occur on radio data links can easily be detected, and do not affect the measurements.
- On the contrary, compressed data require lower BER, around 10^{-8} , thus partially losing the advantage of a lower data rate.
- Typical working ranges, necessary for significant multistatic sonar tests, are of 10 n.mi.

4.2.2 DUSS radio link experiments

Accura A classical, narrow-band link has been developed and successfully tested at sea (Ref. [11]) at the rates and distances mentioned above. Antenna mast height above the water, transmit power, receive antenna gain represented the most critical issues. Two different working frequencies were tested, 0.4 and 2.3 GHz, with equivalent overall performance, but different features. Figs. 4.8 and 4.9 show the reconstruction of propagation conditions after model validation with experimental data. The objective of 10 NM ranges at 2 Mbps was accomplished by both frequencies with powers of 6 W and antenna gains of 22 dB (2 GHz) or 20 W with antenna gains of 7 dB (400 MHz).

As discussed above, spread-spectrum techniques and other signal modulation and coding schemes deserve serious attention. Their interaction with the peculiar environment of the present application (air-sea boundary) may result in remarkable improvements of system performance and reliability. In fact, as shown in [11], the most relevant limiting factor derives from multipath and destructive interference from the sea surface reflected signal.

Spread spectrum is expected to counter such effects, providing at the same time a better rejection of man made interference. Such a system also represents a test bed for the application of sophisticated protocols to multistatic sonar problems.

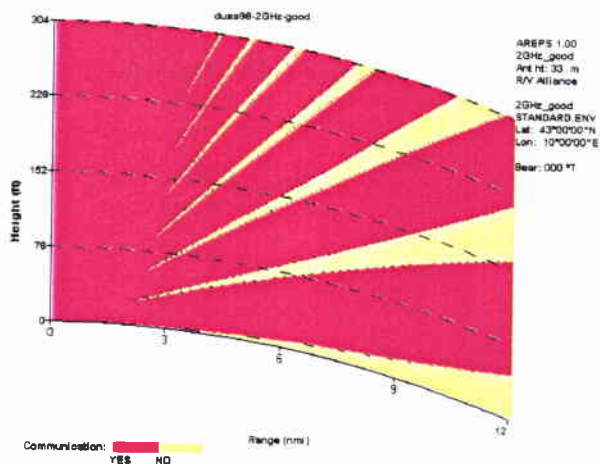


Figure 4.8 - AREPS output for 2.28 GHz link.

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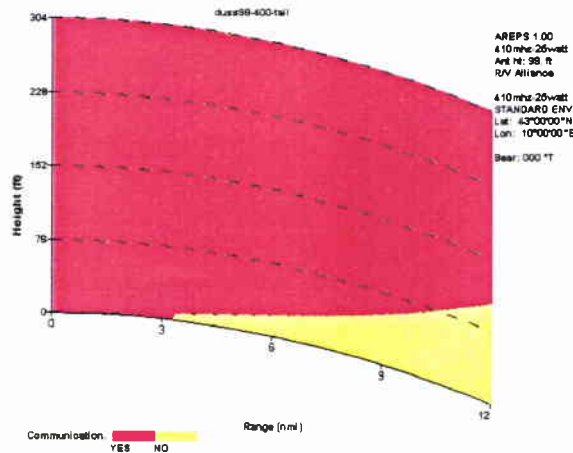


Figure 4.9 - AREPS output for 400 MHz link.

Computer simulations have been conducted with AREPS to determine the practical transmission range for DUSS with spread spectrum techniques, in three representative cases. Case A accounts for an elevated communications relay station (33 m above sea level), that could either be the mast of a support ship (e.g. NRV *Alliance*), a moored buoy with a communications payload connected to a tethered balloon, or an antenna installed ashore, in case of littoral surveillance (e.g. a harbor). Cases B and C are representative of Line-of-sight (LOS) buoy-to-buoy communications, with antennae 6 m and 9 m above sea level, respectively.

	Transmit power	Range (n.mi)
Case A (33 m)	0.1 W	6.1
Case A (33 m)	1 W	10
Case B (6 m)	0.1 W	3
Case B (6 m)	1 W	4.7
Case B (6 m)	6 W	6.8
Case C (9 m)	0.1 W	4
Case C (9 m)	1 W	6.6
Case C (9 m)	6 W	9

Validation to this estimation has been produced during engineering tests conducted with the following link:

Lucent WaveLAN IEEE Turbo at 0.5 Mbps.

2.4 GHz, 100 MHz passband, 1 Watt RF power.

- 9 dBi omni antenna at 33 m on Alliance, 11 dBi omni co-linear antenna at 30 m on Formica Grande island. Link up to 12 km range, with periodical signal loss.
- 9 dBi omni antenna at 33 m on Alliance, 15 / 24 dBi directive Yagi / parabolic antenna at 20 m on Formica Grande island. Link up to 25 km range, with periodical signal loss.
- 9 dBi omni antenna at 33 m on Alliance, 7 dBi omni co-linear antenna at 7 m on buoy. Link up to 6 km range, with periodical signal loss.

The result is that, adopting spread-spectrum transmission, it is possible to communicate at a range compatible with DUSS operations, using a limited transmit power (1 W). This result is extremely important when operating from a battery-powered platform, where a trade-off exists between transmit power and battery duration. The execution of further tests at sea is warmly recommended, due to the variability and uncertainty introduced by the environment, and is made easier by the reduced costs and efforts involved by COTS.

The concept of a "repeater" buoy is also promising, in a packet-switching context, in the attempt to align the limited radio ranges to acoustic ones. The following figure 4.10 illustrates a tactical network of DUSS nodes configured according to Case A, described above. A repeater buoy (or station on coast / island) is used to reach buoys positioned beyond line of sight (LOS) thanks to its very high antenna elevation on the sea surface.

The availability of cost-effective off-the-shelf systems also represents a very attractive issue for scientific applications. Such systems can be very easily interfaced to a computer-controlled buoy, thus providing additional advantages in terms of remote operation of the system. Finally, no special licenses are required for the access to existing channels, thus making easier the organization of tests at sea.

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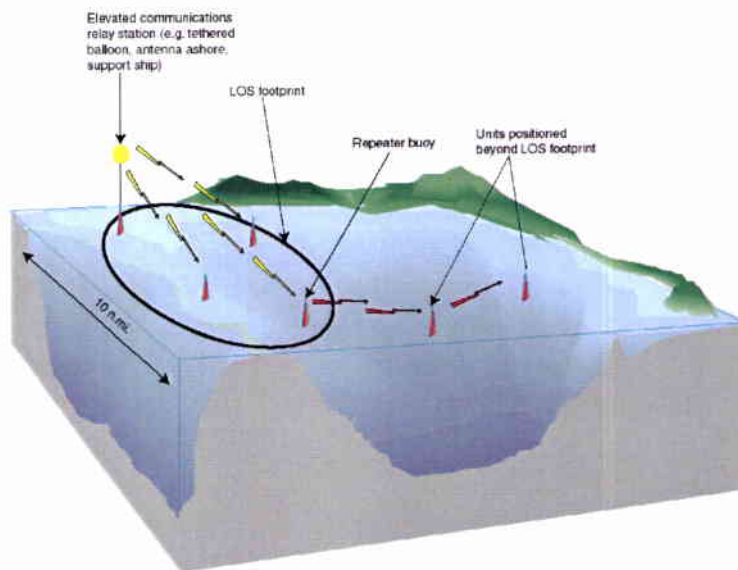


Figure 4.10 - Example of DUSS WLAN deployment pattern, using an elevated communications relay to extend LOS range and a repeater node to reach nodes beyond LOS (drawing not to scale)

4.2.3 DUSS radio link features for operational concept demonstration

This case presumes the capability to reduce the flow of data transmitted across the transmission channels by an in-buoy processor. At the same time, the physical radio link is required to set up a multi-point wireless LAN. Each buoy operates in a partial-knowledge / partial-connection configuration, exchanging the minimum necessary information with neighboring buoys in order to identify and track contacts in their progress through the sonobuoy field. An objective range of 10 n.m.i can be assumed as a reference specification.

The advantages of multistatics in terms of detection of the fluctuating and aspect-dependent contacts have been demonstrated in [13,14]. The feasibility of consistent contact localization and inter-buoy integration has also been demonstrated in [15,16].

The bi-directional exchange of contact information between neighboring buoys becomes therefore vital for the existence of DUSS as a system. This traffic overlaps to the flow of information packets towards the surveillance command site. DUSS becomes a true wireless network of independent, interacting sonar surveillance units.

Work on smart data reduction is going on, towards the definition of a minimum information size and structure for the identification and integration of contacts without performance loss. The performance and methodologies of data exchange therefore become a key factor for the determination of sonar surveillance performance.

All the typical features of packet switching networks can be inherited by DUSS, as resilience, scalability, fault tolerance, and diversity of communication paths through the network towards the final destination(s) of surveillance information. Techniques, protocols and commercial systems developed for the civilian communication market can be profitably applied to the present application. The limited traffic generated by each unit makes it possible to consider both satellite and classical radio links. Spread-spectrum radios provide the necessary sharing of bandwidth, as well as covert, robust transmission. Techniques and experience derived from the Internet and cellular phone applications are expected to provide valuable contributions both in terms of concept development and of implementation of a demonstrator.

The study of a network framework to be installed on top the new DUSS prototypes (being developed at the present time) is warmly recommended. It would be ready to support the studies and experiments on data reduction and fusion which are expected to make an integrated, unique surveillance system out of the prototype DUSS.

4.3 Is SATCOM a suitable alternative to a spread-spectrum tactical network?

One last word should be spent to discuss the role of satellite communications in the fulfillment of the requirements discussed so far. In particular, it is interesting to assess whether Low Earth Orbit (LEO) SATCOM systems can efficiently substitute ad-hoc wireless networks deployed on the field. The constraints associated to SATCOM are the narrow bandwidth that is presently made available for data communications and the high associated cost. As an example, providing 24 hours a day connectivity to 10 platforms (e.g. buoys, ships) would cost about \$100000 per day using Iridium, and between \$12000 and \$18000 using Globalstar. Those costs could be reduced activating the link on demand, instead of keeping it open 24 hours a day.

Supported data rates are also very limited, in the order of 2.4 kbps for both systems. This is acceptable for less demanding applications, such as transmission of positioning information, but is hardly adequate for REA or DUSS operations, unless radical data compression/data reduction schemes are adopted.

Until more performing and cost-effective alternatives are presented, the most practical solution is to deploy tactical wireless networks granting full coverage of the geographical area of interest, using SATCOM gateways to ensure interconnection with land-based infrastructures (e.g. wide area networks).

Conclusions and recommendations

This document presents an overview of spread-spectrum radio communications, including both direct-sequence and frequency-hopping techniques. Performance is compared to classical narrow band modulation schemes. Applications to REA and DUSS are investigated.

- Using spread-spectrum, transmit bandwidth can be traded for transmit power (good for battery operation) (Chapter 4). The frequency spreading factor γ in eq. 3.2 quantifies this trade off.
- A Processing Gain term G_p is computed, which expresses in terms of Signal to Noise Ratio the capability of Spread Spectrum to counter jammers and interferers: $G_p = W_x / R$ where W_x is the used bandwidth and R is the data rate. This is, in turn, related to the bandwidth expansion factor that characterizes the spread spectrum system.
- Resistance to multipath, derives from the narrow auto-correlation of the spreading function of Direct Sequence techniques or from the short time slice duration of Frequency Hopping techniques.
- Other features that are not offered by classical systems are low probability of detection and low probability of intercept.
- Spread-spectrum systems play a vital role in all modern telecommunication systems (both military and commercial). They also play a central role in current US DoD research projects on wireless networking in support of the *network-centric warfare* concept, in which operational advantage is achieved from the efficient networking of a geographically dispersed force. This means a focus shift from single autonomous platforms to an integrated network approach.
- The introduction of spread-spectrum communications in Rapid Environmental Assessment and Deployable Underwater Surveillance Systems permits the deployment of distributed and scalable wireless tactical networks of ships and sensors, characterized by reliable performance (survivability, resistance to hostile jamming and environmental interference) and low probability of interception. The high data rates that can be delivered by spread-spectrum systems (up to 10 Mbps) are sufficient to accommodate the most demanding applications that are presently supported.
- The specific requirements of wireless ad-hoc networks include issues such as frequency re-use and multiple access to the same channel, dynamic reconfiguration of network topology, complex variable network structure (including support for moving platforms, such as ships), scalability and quality of service, communications

and information security. A further study is recommended to discuss thoroughly this vast and complex subject. Particular emphasis should be put on the issues of resource reservation, quality of service, authentication, and encryption.

- An alternative to spread-spectrum techniques is represented by traditional narrow-band modulation schemes, enhanced by multi-carrier modulation and adaptive equalization techniques. However, implementation of such systems is still at the prototyping phase: additional studies and tests are required before systems become available to end-users.
- The characteristics and performance of SS and next generation multicarrier systems (such as OFDM, which is currently being studied at SPAWAR Systems Center, San Diego) are compared in the next Table.

	Spread - Spectrum	Next generation multicarrier systems (such as OFDM)
<i>Availability</i>	Wide availability of turnkey solutions	Unavailability of inexpensive, commercial-of-the-shelf hardware. OFDM LOS radios are still in prototype form.
<i>Power requirements</i>	Low power requirements, compatible with operation from battery-powered platforms (such as buoys)	High transmission power is usually required (acceptable for ship-borne installations, but causes problems with battery-operated systems)
<i>Implementation issues</i>	Readily available circuitry and components (COTS)	Implementation proves to be more complex (adoption of advanced DSP and adaptive equalization schemes)
<i>Licensing requirements</i>	No license is required when operating in the ISM band (2.4 GHz, 5.7 GHz), with limited transmit power (depending on national regulations)	A license is usually required
<i>Low probability of interception/detection</i>	Yes	No (depends on transmit power)
<i>Resistance to jamming</i>	Yes	(depends on transmit power and on waveforms adopted)
<i>Multiple access</i>	Yes	-
<i>Resistance to multipath</i>	Partial	Expected

Table 1 - Comparison of SS and Orthogonal Frequency Division Multiplexing (OFDM) systems.

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- Field tests and accurate analysis of results are recommended for further work. Two different objectives should be pursued: the implementation of a reliable and efficient infrastructure for scientific data acquisition at SACLANTCEN and, at the same time, concept demonstration for future operational applications.

References

- [1] Sklar, B., Digital Communications, Fundamentals and Applications, Prentice Hall, 1988 [ISBN 0-13-211939-0]
- [2] Carlson, A.B., Communication Systems, McGraw-Hill, 1986 [ISBN 0-07-100560-9]
- [3] Pickholtz, R.L., Schilling, D.L., Milstein, L.B., Theory of spread-spectrum communications-A tutorial, IEEE Trans. Commun. Vol. COM-30, pp. 855-884
- [4] Feher, K., Wireless Digital Communications, Modulation & Spread Spectrum Applications, Prentice Hall, 1995 [ISBN 0-13-098617-8]
- [5] Dillard, R.A., Detectability of spread-spectrum signals, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-15, pp. 526-537
- [6] Yavuz D., Spread spectrum and Mobile/Tactical Radio/Wireless communications, RTO-IST Panel symposium on Tactical Mobile Communications, Lillehammer, Norway, June 14-16, 1999
- [7] Moose, MH, North, R, Geile, R, Roderick, D, A COFDM-based Radio for HDR LOS Networked Communications, International Communications Conference, Vancouver, BC, 1999
- [8] North, R., Bryan D., Baker, D., Wireless Networked Radios: Comparison of Military, Commercial, and R&D protocols. 2nd Annual UCSD Conference on Wireless Communications, San Diego, CA, February 28-March 3, 1999
- [9] Trangeled A., Franchi P., Berni A., Data Communication and Data Fusion Architectures for Rapid Response 96-98, SACLANTCEN SR-296. La Spezia, Italy, NATO SACLANT Undersea Research Centre, 1999
- [10] Patterson, W.L., Advanced Refractive Effects Prediction system (AREPS). Version 1.0 User's Manual. TD-3028, Space and Naval Warfare systems Center, San Diego, CA, 1998
- [11] Mozzone L., Berni A., Guerrini P., Long range, large throughput radio data link for DUSS (Deployable Underwater Surveillance Systems). SACLANTCEN SM-360. La Spezia, Italy, NATO SACLANT Undersea Research Centre, 1999.
- [12] Sellschopp, J. "Rapid Environmental Assessment", Naval Forces 3/1999
- [13] Mozzone L., Bonghi S., Diversity in deployable underwater surveillance systems. SACLANTCEN SR-318. La Spezia, Italy, NATO SACLANT Undersea Research Centre, 1999.
- [14] Mozzone, L., Filocca, F., Bonghi, S., Diversity in DUSS (Deployable Underwater Surveillance Systems) with CW pulses. SACLANTCEN SR-308. La Spezia, Italy, NATO SACLANT Undersea Research Centre, 1999.
- [15] Mozzone, L., Bonghi, S., Deployable Underwater Surveillance Systems - Deployable Underwater Surveillance Systems. Localization and fusion of multistatic contacts. Evaluation of feasibility using experimental data. SACLANTCEN SR-291. La Spezia, Italy, NATO SACLANT Undersea Research Centre, 1998.
- [16] Mozzone, L., Lorenzelli, P., Target localization with multiple sonar receivers. SACLANTCEN SR-317. La Spezia, Italy, NATO SACLANT Undersea Research Centre, 1999.

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Summary of Acronyms

ASW	Anti-submarine warfare
AW	Amphibious warfare
AWGN	Additive White Gaussian Noise
CDMA	Code Division Multiple Access
COTS	Commercial-off-the-shelf
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTD	Conductivity, Temperature, and Depth
DSSS	Direct-sequence spread-spectrum
DUSS	Deployable Underwater Surveillance Systems
FHSS	Frequency-Hopping spread-spectrum
GSM	Groupe Speciale Mobile (Global Mobile System)
GPS	Global Positioning System
kbps	Kilobit per second
IP	Internet Protocol
LEO	Low Earth Orbit
LOS	Line-of-sight
LPD	Low probability of detection
LPI	Low probability of interception
Mbps	Megabit per second
MILOC	Military Oceanography
MW	Mine warfare
OFDM	Orthogonal Frequency Division Multiplexing
REA	Rapid Environmental Assessment
RF	Radio Frequency
SATCOM	Satellite communications
SS	Spread-spectrum

Document Data Sheet

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The application of Spread-Spectrum communications to REA Tactical Networks and Deployable Underwater Surveillance Systems		
<i>Abstract</i>		
<p>The present document is a part of an ongoing study on advanced communication techniques in support of Rapid Environmental Assessment (REA) and Deployable Undersea Surveillance Systems (DUSS). It aims at the definition of data transmission architectures for both scientific data acquisition at SACLANTCEN and for operational concept demonstration.</p> <p>Emerging methodologies for Anti-Submarine Warfare (ASW) and Rapid Environmental Assessment (REA) increasingly rely on communication technology, in order to exchange information with other naval units or military commands ashore.</p> <p>The specific requirements (such as ranges and transmission data rates) are addressed. They vary from 2.4 kbps to 2 Mbps and from 10 to 20 n.mi. In addition to that, all military applications have common requirements in terms of reliability, availability and security. The eligibility of classical and spread-spectrum radio communication techniques to the fulfillment of such requirements is discussed and shown. Performance is estimated and compared.</p> <p>Spread-spectrum techniques offer such features as interference rejection, anti-jam capability and low-density power spectra for covert operations: field tests of spread-spectrum equipment have successfully been conducted in 1998 during SACLANTCEN experiments GOATS 98 and DUSS 98. The availability of commercial off-the-shelf (COTS) products including sophisticated communication protocols also represents a relevant issue for scientific applications. Such features as the creation of a multi-point, error-free, packet switching Local Area Network (LAN) deserve to be carefully investigated in their impact on DUSS and REA applications.</p>		
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