Cooperative Communication Techniques for Future-Generation HF Radios

Murat Uysal, Özyegin University and University of Waterloo
Mohammad R. Heidarpour, University of Waterloo

ABSTRACT

When Hurricane Katrina hit the Gulf Coast of the United States in 2005, it severely damaged the telecommunications infrastructure, isolating the area from the outside world. With all the high-end emergency communication gear in its path being knocked out by the hurricane, high-frequency (HF) amateur radio systems played a critical role in rescue and recovery operations. Such tragic incidents have resulted in re-appreciation of the "good old" HF technology that has been an essential part of worldwide information transmission since the advent of radio. HF systems traditionally have been associated with analog voice and very-low-rate data transmission. With the shift from analog to digital in voice communication and increasing demands for high-rate data transmission (e.g., email, Internet, FTP), HF communication has been going through a renaissance. Innovative techniques are required to push the capacity limits of the HF band. Our tutorial provides a contemporary overview of HF communication and discusses cooperative diversity as an enabler to support the challenging expectations of future-generation HF communication systems.

INTRODUCTION

For decades, the high-frequency (HF) band has been recognized as the primary means of long-range wireless communications. The HF band lies within 2–30 MHz of the electromagnetic spectrum. In this part of the spectrum, propagation via *direct wave*, *surface wave*, *near-vertical-incidence skywave* (NVIS), and *skywave* provides a means of communication, from line-of-sight (LOS) to beyond-line-of-sight (BLOS) and over-the-horizon (OTH) ranges [1]. Direct wave propagation supports LOS communication, whereas the surface wave mechanism (i.e., the propagation along the surface of the Earth) provides BLOS communication, typically in the range of 100–150 km or more based on the terrain conditions. On the other hand, the ionosphere, which is composed of a number of ionized regions above the Earth's surface, provides a natural mirror for HF electromagnetic waves. In NVIS, HF signals are transmitted in a near vertical direction toward the ionosphere, which, upon refraction, gives omnidirectional umbrella-like coverage as far as 300 km. This method of communication becomes particularly useful in mountain and forest areas. Furthermore, in skywave propagation, the oblique transmission toward the ionosphere lets HF radio achieve OTH communications with nearly worldwide coverage.

As a worldwide communication medium, spectrum utilization and allocation of the HF band is regulated by the International Telecommunication Union (ITU). Allocations are made on the basis of service type, which includes a wide range of applications, some of which are explained in the following.

Fixed radio communication: HF communication between specified land stations provides service to isolated or remote areas where alternative services (e.g., satellite) are not available or too expensive to use.

Mobile radio communication: HF communication between portable stations or between such stations and fixed land stations is particularly useful in establishing redundant links for disaster recovery, rescue operations, emergency responses, and battlefield scenarios.

Broadcasting: With its long range, the HF band makes international broadcasting possible. Numerous broadcast stations (e.g., the BBC World Service and Voice of America) exist in the HF band and are known as world band radios. Analog modulation techniques have been traditionally employed for broadcasting in the HF band. The digital HF broadcasting standard, known as Digital Radio Mondiale (DRM), was introduced only in 2003.

Amateur (ham) radio: A portion of the HF band is allocated for the use of people interested in radio technology as a hobby. An estimated six million people worldwide are regularly involved with amateur radio.

In this high-tech information age, HF communication continues to be used for a wide range of civilian, government, and military applications as a powerful alternative to a myriad of more sophisticated communication systems. Unfortunately, the data rates offered in conventional 3 kHz HF channel allocations rarely exceed 9.6 kb/s, and 128 kb/s for 24 kHz aggregated channels. These rates will not address wireless access needs of "high-tech information age" users. Our tutorial provides a contemporary

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overview of HF communications and discusses cooperative diversity as an enabling technique to meet the challenging expectations of future-generation HF communication systems.

Overview of HF Communications Milestones

Since Marconi demonstrated the first trans-Atlantic radio transmission in 1901, HF communication has been widely used for long-range transmission and worldwide coverage during most of the 20th century. When satellite communications first emerged in the 1960s, HF technology was considered obsolete. However, later in the satellite area, it became clear that satellites were not the panacea they first appeared to be in various deployment scenarios for various reasons, including vulnerability of ground stations in disaster situations, problems with indoor reception, the requirement for an unobstructed view of the satellite, high investment and maintenance costs, among others. Also, in northern latitudes, access to geosynchronous satellites and the majority of commercial services is limited by the low horizon angles. With its enduring qualities, HF communication has survived through this competition and positioned itself as a powerful complementary and/or alternative technology to satellite communications.

Early Period

The first HF modems typically used continuous wave (CW[1]), frequency shift keying (FSK), and single sideband (SSB) modulation to convey Morse, teletype, and voice signals, respectively [1]. The earliest multicarrier HF modem was the Kineplex system introduced by the Collins Radio Company in 1957 and was based on orthogonal frequency-division multiplexing (OFDM). This system used 16 parallel tones with differential quadrature phase shift keying (DQPSK) modulation at a symbol rate of 75 bauds to achieve a data rate of 2400 b/s. In the 1960–1970s, other OFDM-based HF modems were introduced such as Kathryn (by General Atronics in 1961), Andeft (by General Dynamics in 1967), and Codem (by General Atronics in 1971). Since the severe frequency-selective nature of HF channels requires relatively high complexity for single-carrier receivers, a multicarrier architecture with differential modulation was preferred in these modems. Following the advances in digital signal processing (DSP) and very large-scale integration (VLSI) technologies, practical implementation barriers to advanced communication signal processing (e.g., adaptive channel estimation and equalization) were removed, resulting in the dominance of single-tone modems. Progress in the areas of channel coding, modulation (e.g., coherent M-ary PSK/quadrature amplitude modulation [QAM]), and adaptive channel estimation/equalization have further contributed to the evolution of HF radio.

Second Generation

A major problem in the early HF radios was the need for manual operation to identify suitable transmission frequencies and maintain transmission in the presence of ionospheric changes. The introduction of automatic link establishment (ALE) in the 1980s was a major milestone for HF systems. The ALE system is used to continually monitor the available channels, rank them according to their quality and ensure the high quality of the transmissions. Such automated frequency management systems removed the need for the highly trained and experienced crews used in the past. In this context, manually controlled HF modems (before the introduction of the ALE technology) are typically referred to as the first generation (1G). The HF standards based on asynchronous ALE and synchronous ALE are, respectively, known as the second generation (2G) and third generation (3G) [2].

In 1988, MIL-STD[2] 188-141A was introduced as a standard for asynchronous ALE systems that can scan the spectrum at a rate of 2 or 5 channels/s. These ALE systems are used in conjunction with a physical layer (PHY) standard (e.g., MIL-STD 188-110A/B/C, STANAG[3] 4285/4539) and a data link standard (e.g., STANAG 5066). The PHY standard MIL-STD 188-110A (released in 1991) uses a half-rate convolutional code, QPSK modulation, and 50 percent frame pattern efficiency (i.e., the fraction of data symbols) to achieve a data rate of 1200 b/s. Different coding rates, interleavers, constellation sizes (e.g., binary PSK [BPSK], QPSK, 8-PSK, 16/32/64 QAM), and frame pattern efficiencies determine the overall data rate as well as the robustness of different waveforms. MIL-STD 188-110A supports data rates of 75, 150, 300, 600, 1200, and 2400 b/s in different configurations.

In MIL-STD 188-110B (released in 2000), data rates as high as 9600 b/s are supported. Furthermore, this standard describes an optional mode of HF data modem operation over multiple discrete channels (including independent sidebands of a single carrier), and specifies a waveform that supports data rates of 9600 to 19,200 b/s over two independent sideband (2-ISB) radios. In addition to the mandatory serial-tone waveforms, MIL-STD 188-110B considers an optional operation based on the 16- or 39-tone waveforms for data rates from 75 to 2400 b/s.

In 2011, MIL-STD 188-110C was released and involves a family of wideband high-frequency radio (WBHF) modem waveforms and coding specifications. The WBHF family of waveforms use single contiguous bandwidths greater than 3 kHz up to 24 kHz, supporting data rates in the range of 75–120,000 b/s. Although it suppresses the 16-tone mode, this standard still retains the optional 39-tone parallel waveform.

Third Generation

While 2G HF standards are based on asynchronous ALE, 3G HF standards, such as MIL-STD 188-141B and STANAG 4538, employ synchronous ALE as a result of the employed global positioning system (GPS) time reference, and therefore provide shorter call times than the earlier asynchronous ALEs. It should be noted that 2G technology has not been made obsolete by 3G systems, but rather coexists with them as a result of backward compatibility.

In 1999, MIL-STD 188-141B was released by the U.S. DoD. This standard supports backward

Current HF communication systems are not used only for traditional voice transmission, but also for data communication (including file transfer, facsimile, email, Internet access), still-image transmission, and even real-time videoconferencing.

[1] The CW technique is transmitting Morse code by on-off keying a sinusoid waveform with constant frequency and amplitude. It is the same as binary amplitude shift keying. However, CW is historically used to refer to Morse code transmission.

[2] MIL-STD stands for "Military Standard" and is a set of standards defined by the U.S. Department of Defence (DoD).

[3] STANAG stands for "Standardization Agreement" and is a set of standards defined by the North Atlantic Treaty Organization (NATO).

Being cautious on the concept of MIMO HF is understandable because the separation between antennas to extract diversity is on the order of several hundred meters because HF band wavelengths are in the range of 10–150 m.

compatibility for 2G systems. Furthermore, unlike 2G standards, it is a standalone standard and includes the specifications for PHY and data link layers. Specifically, MIL-STD 188-141B includes two data link protocols: the high-rate data link protocol (HDL), for large messages and/or good channel conditions, and the low-rate data link protocol (LDL), for short messages and/or poor channel conditions. At the PHY layer, different burst waveforms (BWs) are defined for the various kinds of signalling required in the system, such as 3G-ALE (BW0), traffic management and HDL acknowledgment (BW1), HDL traffic data (BW2), LDL traffic data (BW3), and LDL acknowledgment (BW4). All BWs use the basic 8-PSK modulation at 2400 bauds (also used in the MIL-STD 188-110A serial tone modem waveform). On the other hand, different code rates, interleaving lengths, and payload volumes are deployed in different BWs. For instance, BW2 uses a 1/4-rate convolutional code and 66 percent frame pattern efficiency, and contains $1881 \times n$ bits ($n = 3, 6, 12, 24$). In 2011, the U.S. DoD released another revision of the 3G standard, referred to as MIL-STD 188-141C, which also contains WBHF specifications to support high-speed HF data communication.

The Future

Current HF communication systems are not used only for traditional voice transmission, but also for data communication (including file transfer, facsimile, email, Internet access), still-image transmission, and even real-time video conferencing [3, 4]. Traditional analog voice transmission has recently been replaced by digital techniques, as seen in the recent introduction of DRM broadcasting. However, demands for high-speed data communication are still imposing new requirements on HF system design, and innovative approaches are required.

Within the last decade, we have witnessed exciting developments in the area of wireless communication theory, most notably multiple-input multiple-output (MIMO) and cooperative communication techniques. MIMO systems involve the deployment of multiple antennas at the transmitter and/or receiver side and achieve significant improvements in transmission reliability and throughput. Multiple-antenna systems have been studied extensively in the context of transmission in the UHF (300 MHz–3 GHz) and SHF (3–30 GHz) bands assigned for cellular phones, cordless phones, Wi-Fi, and WiMAX systems.

The deployment of multiple antennas is, however, not possible for some wireless applications due to size and power constraints (especially in mobile environments). This limitation motivates the concept of cooperative communication (also known as user cooperation or cooperative diversity) between different nodes, in which a node attempts to use others' antennas to relay its message [5]. In fact, cooperative diversity exploits the broadcast nature of wireless transmission and relies on the cooperation of users relaying information to one another. When a source node transmits its signal, this is received by the destination node and also overheard by other nodes in the vicinity. If these nodes are willing to share their resources, they can forward the overheard information to the destination as a second replica of the original signal and act as relays for the source node. Since the fading paths over source-to-destination and source-to-relay-to-destination links are statistically independent, this generates spatial diversity on the order of relay numbers. It should be emphasized that relay-assisted cooperative communication differs from the conventional deployment of relays (repeaters) in current HF systems. The conventional purpose of relay deployment is to mitigate the path loss effects and effectively increase the link range. In contrast, cooperative communication aims to extract spatial diversity advantages, thus mitigating the degrading effects of fading, via the use of relays.

With a few recent exceptions (e.g., [6–8]), neither MIMO nor cooperative communication techniques have been extensively investigated for HF band. Being cautious on the concept of MIMO HF is understandable because the separation between antennas to extract diversity is on the order of several hundred meters because HF band wavelengths are in the range of 10–150 m. This fact limits the potential use of MIMO HF to certain fixed applications for which the deployment area of an HF station permits such wide uses of space. On the other hand, cooperative communication is an effective means to exploit the spatial dimension of the wireless channel in the HF band. An initial performance study of a cooperative HF system has already demonstrated the potential of this emerging concept [7, 8].

In the following, we first provide an overview of the HF channel model that is later used in the performance evaluation. Then we present the concept of an OFDM-based cooperative HF system and demonstrate error rate performance results.

HF Channel Model

Path Loss

Path loss models for the HF band significantly differ from those developed for higher frequency bands (i.e., UHF, SHF). Under the assumption that transmit and receive antennas are elevated less than a few wavelengths (which is easily justifiable in the HF band for most applications except aircraft-to-aircraft links), the surface wave becomes the dominant component in the ground wave since its other two components (i.e., direct and reflected waves) cancel each other out. For distances smaller than $10\lambda^{1/3}$ km (λ is the wavelength in meters), the path loss of the surface wave is proportional to d^{δ}, where d is the link distance, and δ is the path loss coefficient. At small distances from the transmitter, δ takes the value of 2. As the distance increases, it tends to 4. For distances larger than $10\lambda^{1/3}$ km, the curvature of the earth begins to become more important, and the path loss becomes exponential [1]. Besides the dependence on the propagation distance, the path loss of the surface wave is also affected by terrain type (e.g., sea/fresh water, wet/dry ground) due to different electrical parameters (i.e., conductivity and relative permittivity). As a result, surface wave propagation can provide coverage of 100 km or more depending on the terrain conditions and transmission power. GRWAVE software [1], freely available at the ITU website, provides a convenient tool to predict the path loss of the surface wave.

The calculation of path loss for ionospheric propagations (NVIS and skywave) is more complicated than that of surface waves and is even dependent on weather conditions and particular time of transmission (i.e., time of day, day of year). Several software packages such as the IONCAP family (REC533, VOACAP, ICEPAC) are available for ionospheric propagation predictions. A simplified path loss formula (valid up to a total path length of 7000 km) is given by [9]

$$L_b = 32.45 + 20\log f_c + 20\log p' + 2(n-1) + L_w, \quad (1)$$

where f_c is the carrier frequency in MHz, p' is the virtual slant range in kilometers (a function of total path length and elevation angle), and L_w is the loss term that includes ionospheric absorption loss, maximum usable frequency (MUF) loss, and auroral signal losses. In Eq. 1, n is also the number of reflections (hops) from the ionospheric layers. The total path length, D_p, can readily be approximated from the geometrical relation between the Earth's radius R_0 and the equivalent plane-mirror reflection height, h_r. Among the three ionized layers of the ionosphere (i.e., the D, E, and F layers), electromagnetic waves are mainly reflected from either the E or F layer. The D layer, with its lower electron density, is principally responsible for the attenuation of the cross-passing waves. For the reflection from the E layer, h_r = 110 km, and for the reflection from the F layer, h_r is a function of time, location, and hop length, and up to 800 km [9]. A depiction of skywave propagation with a single hop is illustrated in Fig. 1.

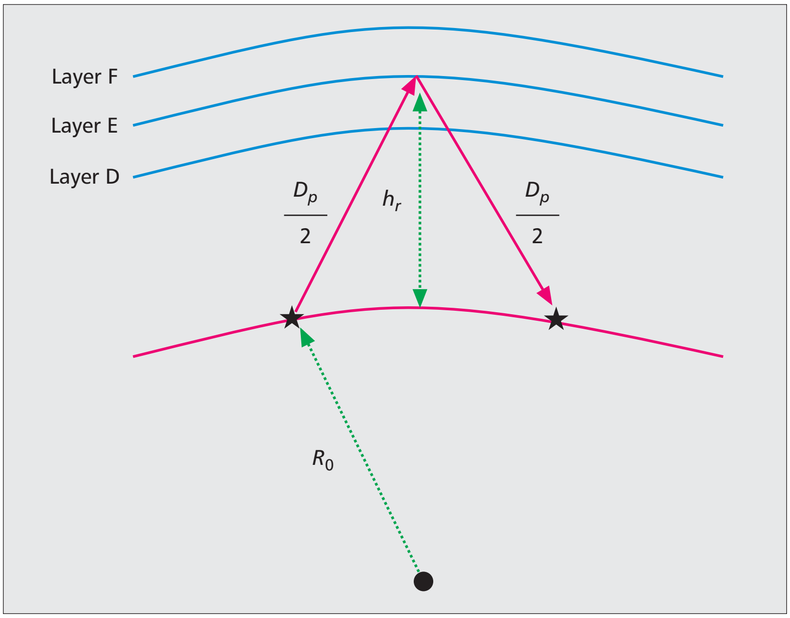

Figure 1. *A simplified geometry of skywave propagation with a single hop.*

Fading

In skywave propagation, path loss determines the average received signal-to-noise ratio (SNR), while small-scale fading causes fluctuations around the average value. Typically, a Doppler spread in the range of 0.1–1 Hz, 0.5–10 Hz, and 0.5–30 Hz is observed for mid, low, and high altitudes, respectively [10]. Further Doppler shifts are also possible due to the speed of the mobile units in mobile HF applications. Besides the frequency dispersion that occurs independently for each path (mode), another source of fading is the interference between two or more propagation modes. Because different modes can have different numbers of hops and can be refracted from different ionospheric layers (the E and F layers), large delay spreads on the order of several milliseconds are typically observed. All these effects result in a doubly-selective (i.e., time-selective and frequency-selective) fading channel.

The widely adopted fading channel model for HF transmission (up to 12 kHz) is the Watterson model [10]. In this model, the ith mode of the ionospheric propagation with delay τ_i is considered to have a Rayleigh faded amplitude, $G_i(t)$, $i = 1, 2, \ldots, N_p$. It also has a bi-Gaussian Doppler power spectral density $S_{G_i}(\nu)$, which consists of two Gaussian components with a frequency shift relative to each other as follows:

$$S_{G_i}(\nu) = \frac{1}{A_{ia}\sigma_{ia}\sqrt{2\pi}}\exp\left(\frac{-(\nu-\nu_{ia})^2}{2\sigma_{ia}^2}\right) + \frac{1}{A_{ib}\sigma_{ib}\sqrt{2\pi}}\exp\left(\frac{-(\nu-\nu_{ib})^2}{2\sigma_{ib}^2}\right) \quad (2)$$

where A_{ia}, A_{ib} are the component attenuations and ν_{ia}, ν_{ib} are the Doppler shifts. The frequency spread of each component is determined by $2\sigma_{ia}$ and $2\sigma_{ib}$. Each Gaussian component in $S_{G_i}(\nu)$ corresponds to either the so-called O or X component of the ith mode. When the O/X components are not distinguishable, $S_{G_i}(\nu)$ simplifies to a (single) Gaussian function. For HF modem performance evaluation, ITU recommends a two-path Watterson model (i.e., N_p = 2) with a centered (single) Gaussian Doppler power spectral density function.

Interference

Another impairment in the HF band is the ambient interference. HF interference for a particular receiver can come from a wide range of sources, including motor ignitions and man-made noise within the environment. Since the energy generated in one location within the HF band can propagate through the ionosphere and might affect receiver antennas far away, other interference sources are lightning (with a worldwide average of 44 times/s), and the presence of other HF users operating all over the world in the same frequency band. As a result, the amount of HF interference depends on ionosphere conditions, and therefore, on solar activities. Let Q_k denote the probability that interference power (in dBm) in a channel located in the kth ITU allocation with the center frequency f_k (in MHz) exceeds a predefined power threshold x. According to the Laycock-Gott empirical model [11], Q_k is given by

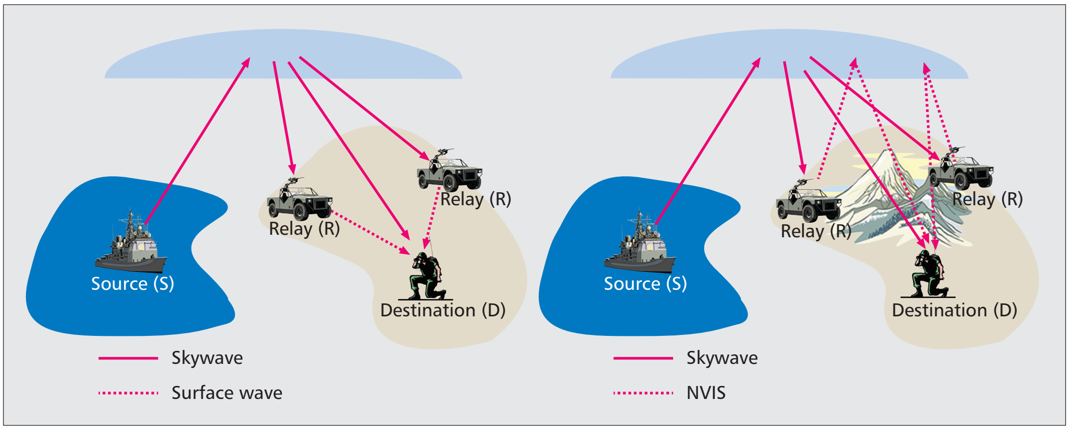

Figure 2. *Illustration of cooperative HF communication using either surface wave or NVIS R→D propagation.*

$$Q_k = \frac{1}{1+\exp\left(-\left(\frac{\beta x+\alpha_k+\left(b_0+b_1 f_k\right)\log_{10}}{\left(BW\right)+b_2\left[\log_{10}\left(BW\right)\right]^2}\right)\right)} \quad (3)$$

where BW (in kHz) is the bandwidth of the channel. In Eq. 3, β, α_k, b_0, b_1, and b_2 are also either fitting parameters or functions of the center frequency, the sunspot number (an indication of solar activity), and so on. The time between two interference power transitions can be modeled by an exponential distribution whose mean is on the order of a few minutes. In frequency, a separation of 1 kHz and more results in almost independent interference powers. On the other hand, in the spatial dimension, interference powers are highly correlated. Experimental results demonstrate that there is no significant difference between interference powers measured simultaneously at two sites separated by about 100 km.

Cooperative HF Communications

We consider a wireless communication scenario in which source and destination terminals separated far apart communicate via skywave propagation, a typical scenario for single-team ad hoc applications (law enforcement, first response, military, etc.) where a deployed field team establishes communication with its headquarters. We assume that the destination terminal has nearby neighbor terminals willing to share their resources via relaying their received signals to the destination.

It is assumed that all the terminals operate in half-duplex mode (i.e., a node can either transmit or receive but not both), which is motivated by the practical implementation problem resulting from the large difference between transmit and receive powers. In the considered time-division multiple access (TDMA)-based cooperation protocol, known as orthogonal cooperation [5], the source broadcasts to the destination and the relay terminals during the first phase (i.e., broadcasting phase). During the second phase (i.e., relaying phase), the source stops transmission and the relay terminals forward a processed version of their received signals to the destination. The type of processing depends on the relaying mode. In the amplify-and-forward (AaF) relaying under consideration, each relay, without any attempt to decode, only applies certain linear operations (e.g., matrix multiplication and scaling) to received signals, and forwards the result to the destination.

System Model

We assume that N AaF relay terminals are located around the destination terminal and provide communication to the destination through either surface wave or NVIS (Fig. 2). Transceivers are equipped with ALE modules and assumed to be perfectly snychronized. To exploit both available multipath and spatial diversities, we consider a bit interleaved coded modulation (BICM) cooperative OFDM system based on distributed space-time coding.

At the source terminal, an input binary data sequence is first convolutionally encoded and then interleaved. The interleaving depth is confined to only one OFDM symbol, so extra decoding delay is avoided while full multipath diversity is still achievable. The consecutive groups of coded bits are linearly mapped to the constellation symbols (e.g., PSK, QAM). The serial stream of modulation symbols is then converted into parallel streams, which are applied to an inverse fast Fourier transform (IFFT) block. A cyclic prefix (longer than the delay spread of the channel) is inserted into the resulting OFDM symbol. In the broadcasting phase, the source terminal broadcasts N successive OFDM symbols through the skywave link. These symbols are received by N relay terminals and the destination.

The relay terminals remove the cyclic prefix, perform FFT on their received signals and apply distributed space-time coding among themselves (e.g., the distributed Alamouti scheme for a two-relay case). After performing OFDM modulation steps (i.e., taking IFFT and inserting cyclic prefix) and proper power scaling, the relays simultaneously transmit the resulting N distributed space-time coded OFDM symbols to the destination, via either surface wave or NVIS. Contrary to fading-free surface waves, NVIS links are subject to doubly-selective fading. However, these links have the advantage of providing umbrella-like BLOS coverage particularly useful in forest or mountain areas.

At the destination terminal, the log likelihood ratio (LLR) for each bit is calculated by taking into account all received OFDM symbols (i.e., N symbols from the source during the broadcasting phase and N space-time coded symbols from the relays during the relaying phase). The bit-level LLRs are fed to the Viterbi algorithm, and the survivor path with maximum codeword-level LLR is announced as the maximum likelihood (ML) decision.

Error Rate Performance

In this section, we present the error rate performance of the HF cooperative scheme through Monte Carlo simulations. We consider an HF communication link between a task force (including a destination terminal and a number of relay terminals) and its headquarters, separated by 700 km. We assume QPSK modulation, a bandwidth of 9 kHz and 192 subcarriers with a frequency spacing of Δf = 46.875Hz. A convolutional code with rate $R = 1/2$ and free distance $d_{free} = 7$ is employed. Unless otherwise noted, we consider interference-free transmission. For interference environments, we assume Gaussian distributed interference terms, and their powers are generated based on the Laycock- Gott congestion formula in Eq. 3.

Based on Eq. 1, path losses for skywave and NVIS links are, respectively, calculated as 114 dB and 103 dB, assuming f_c = 5MHz, $n = 1$, h_r = 110km, L_w = 10 dB and D_p = 740 km. Path loss in the surface wave link has been calculated through GRWAVE software, assuming electrical parameters for the medium dry ground (i.e., relative permittivity $\varepsilon = 15$ and conductivity σ = 0.001 siemens per meter [1]). For a range of 3.5 km (which denotes the distance between the destination and each relay), the path loss for the surface wave is found to be 84 dB. Following the common notation in cooperative communications literature [5], we normalize the path losses of the source-to-relay (S→R) and relay-to-destination (R→D) links with respect to the source-to-destination (S→D) link. Thus, for the aforementioned communication scenario, the path gains for S→R and S→D links with almost equal path losses are 0 dB (i.e., $G_{SD} = G_{SR} = 0$ dB), while the gain for the R→D link depends on the propagation method (G_{RD} = 10 dB and 30 dB, respectively, for NVIS and surface wave methods). For small-scale fading, we adopt the two-path Watterson ionospheric channel with 2 Hz Doppler spread and 2 ms delay, following the simulation scenario of MIL-STD 188–110B.

Figure 3 illustrates the bit error rate (BER) performance of the cooperative HF system under consideration, assuming N = 1, 2 relays. For the cooperative case, we assume that the relay terminals are communicating through surface wave. In our simulation, we assume that 90 percent of the total power budget is dedicated to the source for the broadcasting phase and the remaining portion is equally distributed among the relay terminals. Point-to-point direct link performance (i.e., no cooperation) is also provided as a benchmark. For a fair comparison, BPSK is employed

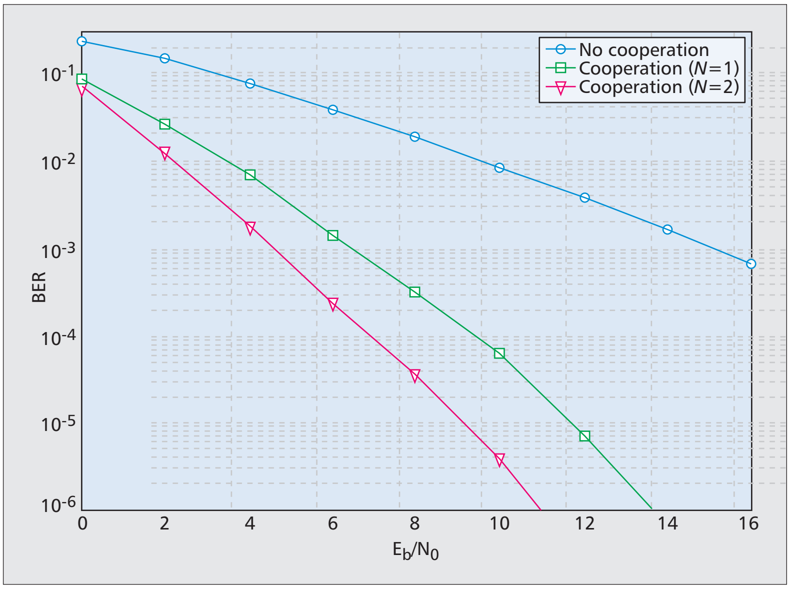

Figure 3. *BER performance of the proposed system with different number of relays when the link(s) between relay(s), and the destination is surface wave.*

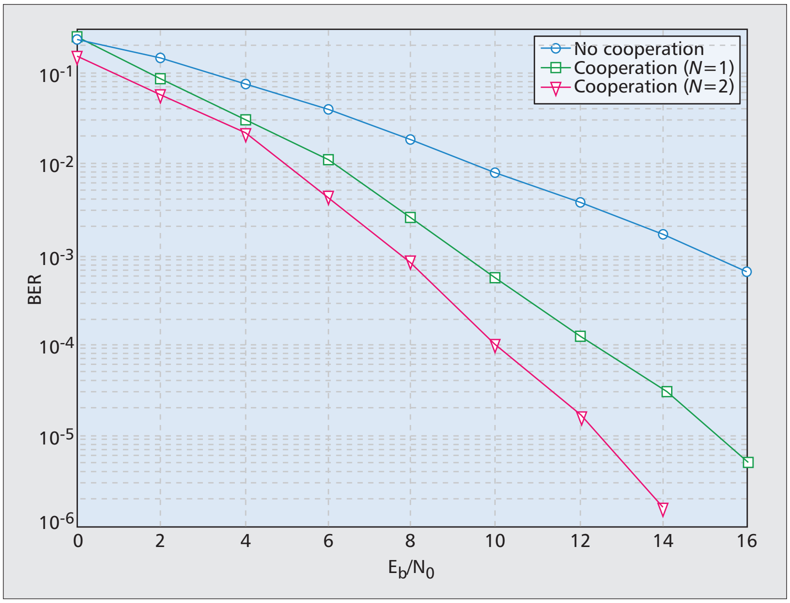

Figure 4. *BER performance of the proposed system with different number of relays when the link(s) between relay(s) and the destination is NVIS.*

in the non-cooperative scheme to achieve a throughput of 1 b/time slot as in the cooperative case. Our results clearly demonstrate that cooperation brings significant performance improvements through the extraction of available diversity. Specifically, at a target BER of 10^{-3}, a performance improvement of 9 dB with respect to direct communication is observed for a single relay scenario. This value climbs to 11 dB for two relays.

Figure 4 illustrates the BER performance under the assumption that relay terminals communicate through NVIS. The performance gains (with respect to direct communication) for N = 1, 2 are given by 6 and 7.5 dB at the target BER of 10^{-3}, respectively. The reduction in performance gains in comparison to those achieved

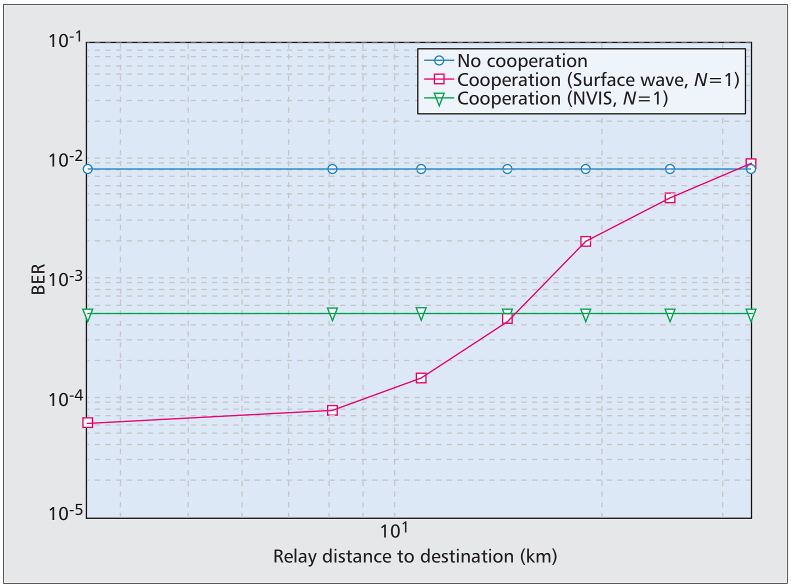

Figure 5. *BER performance as a function of relay-to-destination distance.*

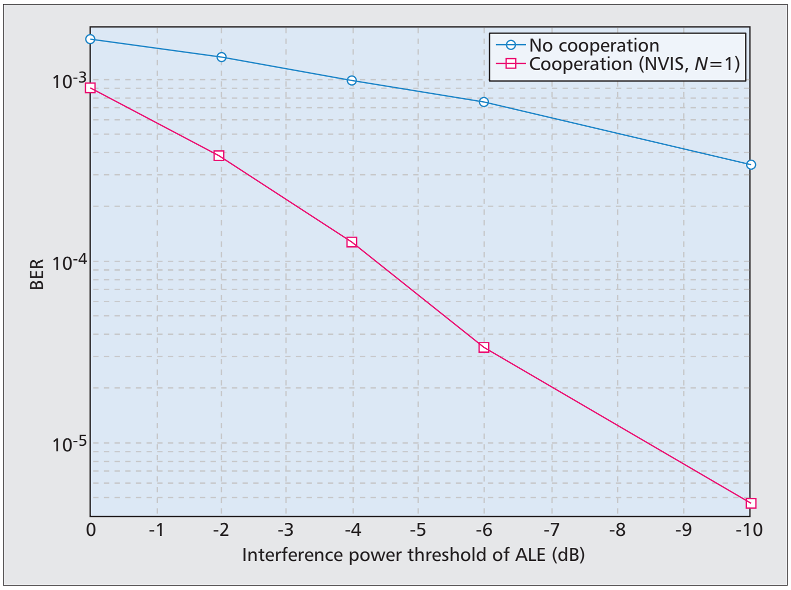

Figure 6. *BER performance as a function of ALE threshold.*

through surface wave are due to the fading nature of NVIS links and different path losses. It is worth emphasizing that path loss becomes the main differentiating factor between two different propagation mechanisms.

To further highlight the performance difference between surface wave and NVIS links, Fig. 5 illustrates the corresponding BER performances vs. the distance of the R→D link for a fixed SNR chosen to be equal to 10 dB. It is observed that increasing the distance increases the path loss of the surface wave, consequently worsening the associated performance. On the other hand, if NVIS is used, the path loss is almost fixed, so the corresponding performance remains unchanged. Thus, for small distances between the relay and the destination, having a surface wave link is better than NVIS. For larger distances, the situation is reversed.

In Fig. 6, we present the performance of the proposed system in an interference-limited environment. Due to interferers, if the signal-to-interference ratio (SIR) falls below a predetermined threshold, ALE transfers the communication link to another frequency. Here, we consider both direct and single-relay (with NVIS link to the destination) scenarios and present the achievable BER vs. ALE thresholds. In the simulations, we assume that the mean of SIR is equal to 20 dB, while its instantaneous value changes according to environmental conditions. As shown in the figure, a large performance improvement is obtained through cooperation, which justifies its deployment in interference-limited environments.

Conclusions and Future Directions

In this article, we have discussed the deployment of cooperative communications as a major performance-boosting technique for future-generation HF modems. Cooperative communication differs from the conventional relay-assisted HF systems and aims to achieve spatial diversity advantages via the use of relays. Specifically, we have considered a cooperative coded OFDM system assuming AaF relaying. Our error rate performance results have demonstrated significant performance gains in various deployment scenarios. It is hoped that promising simulation results will stimulate the HF community to experiment with this promising concept.

An important issue to consider in the practical implementation is synchronization among cooperating nodes. The cooperating nodes are geographically dispersed, and each relies on its local oscillator. Their signals may arrive at the destination with different timing and carrier frequency offsets. Therefore, cooperative schemes need to be implemented taking into account this asynchronous nature. It can be noted that in an OFDM implementation, timing offsets are absorbed into the channel frequency responses, and therefore, can be handled through proper channel equalization. On the other hand, the mitigation of multiple carrier frequency offsets (CFO) becomes more problematic and requires judiciously designed CFO correction algorithms.

Besides synchronization, open research topics in the context of cooperative HF communication include the investigation of different cooperation protocols (e.g., orthogonal and non-orthogonal cooperation), relaying techniques (e.g., decode-and-forward, estimate-and-forward, compress-and-forward), channel codes (e.g., turbo codes, low density parity check codes), and detection methods (e.g., non-coherent, differential), among others.

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Biographies

MURAT UYSAL (murat.uysal@ozyegin.edu.tr) is an associate professor at Ozyegin University, Istanbul, Turkey, where he leads the Communication Theory and Technologies (CT&T) Research Group. Prior to joining Ozyegin University, he was a tenured associate professor at the University of Waterloo, Canada, where he still holds an adjunct faculty position. His research interests are in the broad areas of communication theory and signal processing with a particular emphasis on the physical layer aspects of wireless communication systems in radio, acoustic, and optical frequency bands. He has authored more than 160 journal and conference papers on these topics.

MOHAMMAD REZA HEIDARPOUR (mrheidar@ece.uwaterloo.ca) received B.Sc. and M.Sc. degrees in electronics and communication engineering from Isfahan University of Technology, Iran, in 2006 and 2008, respectively. He is currently a Ph.D. student in electrical engineering at the University of Waterloo. His research interests include the design and analysis of wideband wireless systems, cooperative communication, and adaptive systems, among others.