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A Novel Optimized Approach for Underwater Acoustic (UWA) Cooperative Communication Systems to Achieve Delay Diversity

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Abstract

The communication through water is different scenario from the communication on the land, while transmission through the water the delays are frequently happens when the signals received from geographically separated nodes. Moreover, UWA communications enable high motion agility and flexibility of the nodes, and allow interactive system query and instantaneous system response. The UWA environment is commonly viewed as one of the most challenging environments for wireless communications and networking. It differs from the terrestrial radio environment in many different aspects. Although tremendous progress has been made in the past literature but still the synchronism issues is concerned area in the field of UWA communications. To resolve the issue of the synchronism issues usage of the OFDM communication system is employed and transmissions at the source node by preceding every OFDM block with an extremely long cyclic prefix (CP) which reduces the transmission rates dramatically. One may increase the OFDM block length accordingly to compensate for the rate loss which also degrades the performance due to the significantly time-varying nature of UWA channels. In this paper, we develop a new OFDM-based scheme to combat the asynchronism problem in cooperative UWA systems without adding a long CP (in the order of the long relative delays) at the transmitter. By adding a much more manageable (short) CP at the source, we obtain a delay diversity structure at the destination for effective processing and exploitation of spatial diversity by utilizing a low complexity Viterbi decoder at the destination, e.g., for a binary phase shift keying (BPSK) modulated system, we need a two-state Viterbi decoder. We provide pair wise error probability (PEP) analysis of the system for both time-invariant and block fading channels showing that the system achieves full spatial diversity. Finally the simulation results shows that performance of the proposed method is good over the conventional state of the art methods and extensive simulations that the proposed scheme offers a significantly improved error rate performance for time-varying channels (typical in UWA communications) compared to the existing approaches.

KEYWORDS: UWA system, synchronous communication, cooperative systems, underwater acoustics, OFDM

1. INTRODUCTION

The Earth is mostly a water planet, with two thirds of its surface covered by water. Exploration of the mysterious water world has never ceased in human history, yet at the time being, less than one percent of this environment has been explored, since it cannot be probed through satellites nor visited by humans for a long time. Driven by the unprecedented development of wireless communications and networking in terrestrial radio applications, underwater wireless networked systems, especially underwater acoustic (UWA) networked systems, are envisioned to revolutionize underwater exploration through providing long-term, continuous and real-time unmanned data acquisition.

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Nevertheless, a plethora of research issues associated with the UWA networked system have to be identified and addressed before meeting its great potential. Out of a myriad of challenges, UWA communications and networking are the most important components that underpin the system architecture.

Communication techniques for UWA channels with widely separated multipath clusters: This type of channel exists in many scenarios, such as the deep-sea horizontal communications and underwater broadcasting networks. Due to the extremely large delay spread and time variation of UWA channels, both interblock and intercarrier interferences are present in the received signal. Advanced receiver processing algorithms are investigated to address the above interferences and recover the transmitted information.

Our focus in this paper is on asynchronous cooperative UWA communications where only the destination node is aware of the relative delays among the nodes. Existing signaling solutions for asynchronous radio terrestrial cooperative communications rely on quasi-static fading channels with limited delays among signals received from different relays at the destination, e.g., see and references therein, in which every transmitted block is preceded by a time guard not less than the maximum possible delay among the relays. Therefore, we cannot directly apply them for cooperative UWA communications. Our main objective is to develop new OFDM based signaling solutions to combat the asynchronism issues arising from excessively large relative delays without preceding each OFDM block by a large CP (in the order of the maximum possible relative delay).

In systems employing OFDM, e.g.,, the existing solutions are effective when the maximum length of the relative delays among signals received from various nodes are less than the length of an OFDM block which is not a practical assumption for the case of UWA communications. In a space-frequency coding approach is proposed which is proved to achieve both full spatial and full multipath diversities. In OFDM transmission is implemented at the source node and relays only perform time reversal and complex conjugation. A trivial generalization of existing OFDM-based results to compensate for large relative delays may be to increase the OFDM block lengths. The main drawback in this case is that inter carrier interference (ICI) is increased due to the time variations of the UWA channels. Another trivial solution is to increase the length of the CP. This is not an efficient solution either, since it dramatically decreases the spectral efficiency of the system.

In this paper, we focus on OFDM based cooperative UWA communication systems with full-duplex AF relays where all the nodes employ the same frequency band to communicate with the destination. We assume an asynchronous operation and potentially very large delays among different nodes (known only at the destination). We present a new scheme which can compensate for the effects of the long delays among the signals received from different nodes without adding an excessively long CP. We demonstrate that we can extract delay diversity out of the asynchronism among the cooperating nodes. The main idea is to add an appropriate CP (much shorter than the long relative delays among the relays) to each OFDM block at the transmitter side to combat multipath effects of the channels and obtain a delay diversity structure at the destination.

2. RELATED WORK

We consider a full-duplex AF relay system with two relays, shown in Fig. 1, in which there is no direct link between source (S) and destination (D), and the relays help the source deliver its data to the destination by using the AF method. No power allocation strategy is employed at the relay nodes and they use fixed power amplification factors. Note that the model can be generalized to a system with an arbitrary number of relays and a direct link between source and the destination, and optimal power allocation can be used in a straightforward manner. We assume that the channels from the source to the relays and the relays to the destination are time-varying multipath channels where $h_i(t, \tau)$ and $g_i(t, \tau)$ represent the source to the i-th relay and the i-th relay to the destination channel responses at time t to an impulse applied at time $t - \tau$, respectively.

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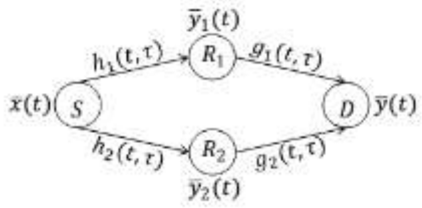

Figure 1: Relay channel with two relays

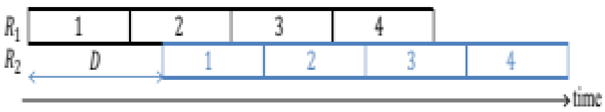

Figure 2: The structure of the received OFDM blocks from two different relays of the proposed delay diversity scheme for a relative delay of D seconds.

The system model of the new relaying scheme, we would like to give an example to demonstrate how a delay diversity structure is obtained. For illustration, Fig. 2 shows the received OFDM block structure of the proposed delay diversity scheme from two different relays with a relative delay of D seconds. In Fig. 2, D is in a range that each block relayed through the relay R1 is overlapped with its preceding block relayed through the relay R2.

2.1 Signaling Scheme

At the transmitter, we employ a conventional OFDM transmission technique with N subcarriers over a total bandwidth of B Hz. We consider successive transmission of M data blocks of length N symbols. We obtain the continuous time signal with time duration of T Seconds which can be written as

$$\bar{x}^m(t) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_k^m e^{j\frac{2\pi k}{NT_s}t\,R(t)} \quad (1)$$

The received signal corresponding to the respective each block of the transmitter can be written as

$$\bar{y}_i^m(t) = \int_{-\infty}^{\infty}\bar{x}^m(t-\tau)h_i^m(t,\tau)d\tau + z_{1,i}^m(t) + \sum_{m'\neq m}\int_{-\infty}^{\infty}\bar{x}^{m'}(t-(m'-m)T-\tau)(t,\tau)\,d\tau, \quad (2)$$

Assuming the length of the CP overhead is greater than the delay spread of the channel can be written as

$$\bar{y}_i^m(t) = \sum_{l=1}^{L_{h_i}} h_{i,l}^m(t)\,\bar{x}^m(t-\tau_{h_{i,l}}) + I_{1,i}^m(t) + z_{1,i}^m(t) \quad (3)$$

Therefore, by denoting the amplification factor of the i-th relay, for the received signal at the destination, we have

$$\bar{y}(t) = \int_{-\infty}^{\infty}\sqrt{P_1}\bar{y}_1(t-\tau)g_1(t,\tau)d\tau + \int_{-\infty}^{\infty}\sqrt{P_2}\bar{y}_2(t-D-\tau)g_2(t,\tau)d\tau + z_2(t) \quad (4)$$

The Gaussian random processes with zero mean and PSD is written as

$$\bar{y}(t) = \sum_{l=1}^{L_{g_1}}\sqrt{P_1}g_{1,l}(t)\bar{y}_1(t-\tau_{g1,l}) + \sum_{l=1}^{L_{g2}}\sqrt{P_2}g_{2,l}(t)\bar{y}_2(t-\tau_{g2,l}-D) + z_2(t) \quad (5)$$

Finally the Gaussian distribution signal can be Witten as

$$\bar{y}(t) = \sum_{l=1}^{L_{g_1}}\sqrt{P_1}g_{1,l}(t)\sum_{q=1}^{L_{h_1}}h_{1,q}(t-\tau_{g_{1,}}l)\bar{x}\left(t-\tau_{g_{1,}}l-\tau_{h_{1,q}}\right) + z(t) + \sum_{l=1}^{L_{g_2}}\sqrt{P_2}\,g_{2,l}(t)\sum_{q=1}^{L_{h_2}}h_{2,q}(t-D-\tau_{g_{2,}}l)\bar{x}\left(t-D-\tau_{g_{2,}}l-\tau_{h_{2,q}}\right) \quad (6)$$

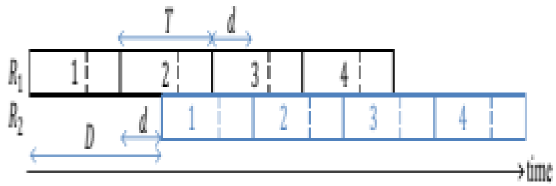

Figure 3: The structure of the received signal

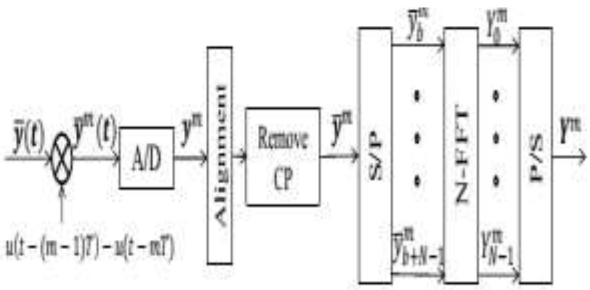

Figure 4: The structure of the receiver.

3. PROPOSED METHOD

3.1 Delay Diversity Structure

To achieve a delay diversity structure and overcome ISI at the destination, we need to add an appropriate CP at the source and perform CP removal at the destination

3.1.1 Appropriate CP Length

In a conventional OFDM system, if we have a window of length (N+L)Ts seconds corresponding to one OFDM block, then by removing the first L samples of the considered window and feeding the remaining N samples to the FFT block, the ISI is completely removed. Therefore, in our scheme, to guarantee robustness of the system against ISI, we need to have an overlap of length (N+L)Ts seconds between two blocks received from two different relays at the destination. Fig. 3 shows the structure of the received signal at the destination for the case that the blocks relayed by R2 are received D seconds later than the blocks relayed by R1

3.1.2 Received Signal at the Destination

The sampled vector of the received signal in the m-th signaling interval and b is the starting point of the m-th FFT window which is decided by the destination based on the delay value D is written as follows, the following notation represents the ISI, and BD and dr

$$I_1^m(t) = \sum_{l=1}^{L_{g_1}} \sqrt{P_1}\, g_{1,l}^m(t) \sum_{g=1}^{L_{h_1}} h_{1,q}^m(t-\tau_{g_1,}l) \times \bar{x}^{m-1}(t+T-\tau_{g1,}l - \tau_{h_1,q}) \quad \text{and}$$

$$I_2^{m+BD}(t) = \sqrt{P_2}\sum_{l=1}^{L_{g_2}} g_{2,l}^{m+BD}(t) \sum_{q=1}^{L_{h_2}} h_{2,q}^m\left(t-d_r-\tau_{g2,l}\right) \times \left[\bar{x}^{m-1}\left(t+T-d_r-\tau_{g2,l}-\tau_{h_{2,q}}\right) + \bar{x}^{m+1}\left(t-T-d_r-\tau_{g2,l}-\tau_{h_{2,q}}\right)\right] \quad (7)$$

3.1.3 Appropriate CP Removal at the Destination

To take FFT at the destination, we need to choose the FFT window by appropriate CP removal. Since the received OFDM blocks are not synchronized, we align the receiver FFT window with one of the relays. By precise alignment, an overlap of length (N+L)Ts seconds between the OFDM blocks received through R1 and R2 can be achieved which is determined with the value of d. Note that an overlap of at least N+L samples is necessary to guarantee robustness of the transmission against ISI.

3.1.4 Detection by Viterbi Algorithm

The time-invariant channel scenario the noise samples $Z_m k$ are independent complex Gaussian random variables for all m and k and i.i.d. for any specific k. Therefore, for time invariant channel conditions, N parallel Viterbi detectors with M BD states (assuming M-PSK modulation) can be employed for ML detection of the transmitted symbols, where the kth Viterbi detector gets Y k as input to detect the transmitted symbols over the k-th subcarrier. On the other hand, for the time-varying channel scenarios, the received noise samples at each OFDM block are dependent complex Gaussian random variables conditioned on known channel state information. Note also that the noise samples corresponding to different FFT windows at the destination are independent but not necessarily identically distributed.

The complexity of the Viterbi algorithm for the time varying case is prohibitive due to the ICI effects. Therefore, we implement a suboptimal detector is written as

$$y_k^m = \frac{1}{\sqrt{N}}\sum_{n=b}^{b+N-1}\Big[\sum_{l=1}^{L_{g1}}\sqrt{P_1}\, g_{1,l}^m(nT_s)\sum_{q=1}^{L_{h_1}} h_{1,q}^m\left(nT_s - \tau_{g1,l}\right)\bar{x}^m\left(nT_s-\tau_{h1,q}-\tau_{g1,l}\right) + z^m(nT_s) + \sum_{l=1}^{L_{g_2}}\sqrt{P_2}g_{2,l}^m(nT_s)\sum_{q=1}^{Lh_2} h_{2,q}^{m-BD}\left(nT_s-d_r-\tau_{h_{2,q}}-\tau_{g2,l}\right)\Big]e^{-j\frac{2\pi n}{N}k}$$
(8)

$$G\,H_1^m[k,k'] = \frac{\sqrt{P_1}}{N}\sum_{n=b}^{b+N-1}\sum_{l=1}^{L_{g_1}} g_{1,l}^m(nT_s)\sum_{q=1}^{L_{g_1}} h_{1,q}^m(nT_s - \tau_{g1,l})\, e^{j\frac{2\pi n}{N}(k'-k)} e^{-j\frac{2\pi k'}{NT_s}(\tau_{g1,}l+\tau_{h1,q})}$$

$$G\,H_1^m[k,k'] = \frac{\sqrt{P_2}}{N}\sum_{n=b}^{b+N-1}\sum_{l=1}^{L_{g_2}} g_{2,l}^m(nT_s)\sum_{q=1}^{L_{h_2}} h_{1,q}^{m-BD}(nT_s - d_r - \tau_{g2,l})\, e^{j\frac{2\pi n}{NT_s}[n(k'-k)T_s - k'(d_r+\tau_{g2,l}+\tau_{h2,q})}\quad (9)$$

4. A MODIFIED AMPLIFY AND FORWARD RELAYING SCHEME

However, for BD = 0, the scheme does not provide spatial diversity. To address this limitation, we present a slightly modified version of the proposed scheme in this section which achieves the delay diversity structure for large values of the relative delay D, i.e., BD ≥ 1, and also provides diversity for small values of D, i.e., BD = 0. We still employ full duplex amplify and forward relay nodes. Similar to the scheme described in Section III, the second relay simply amplifies and forwards its received signal. The only modification is at the first relay in which instead of forwarding the received signal unchanged, a complex conjugated version of the received signal is amplified and forwarded to the destination. At the receiver, if the signal from the second relay is received D seconds later than the signal from the first relay, by following the same steps

$$Y_m^k = GH_2^{m-BD}(k)X^{m-BD} + Z_k^m + \sqrt{\frac{P_1}{N}}\sum_{n=b}^{b+N-1} e^{-j\frac{2\pi n}{N}k} \times$$

$$\left[\sum_{l=1}^{L_{g_1}} g_{1,l}^{m}(nT_S)\sum_{q=1}^{L_{h_1}} h_{1,q}^{m}\left(nT_S - T_{g_1}, l\right)^{*}\overline{x}^{m}\left(nT_s - \tau_{h_1,q} - \tau_{g_1,l}\right)^{*}\right]$$

$$=\overline{GH_1}^{m}(k)\tilde{X}^{m} + GH_2^{m-BD}(k)X^{m-BD} + Z_k^{m}, \qquad (10)$$

$$Y_K^m = \overline{GH_{1,K}}^m X_{N-k}^{m\,*} + GH_{2,K}^{m-BD} X_K^{m-BD} + Z_k^m \quad (11)$$

$$\begin{bmatrix} Y_k^m \\ Y_{N-k}^{m\,*} \end{bmatrix} = C_k^m \begin{bmatrix} X_k^m \\ X_{N-k}^{m\,*} \end{bmatrix} + \begin{bmatrix} Z_k^m \\ Z_{N-k}^{m\,*} \end{bmatrix} \qquad (12)$$

However, in detection of the remaining sub carriers spatial diversity is extracted out of the proposed system. The worst case is to not occupy the subcarriers k = 0 and k = N 2 for data transmission which results in a very small loss in rates, e.g., in an OFDM transmission with N = 1024 subcarriers, the system experiences a rate loss of less than 0.2%.

5. PAIRWISE ERROR PROBABILITY ANALYSIS

Design of the space-time codes is out of the scope of this work; however, we present the PEP performance analysis of the system under quasi-static and block fading frequency selective channel conditions which can be useful in a diversity order analysis of the proposed scheme and possible space-time code designs. In the following, we present the PEP analysis for the quasi-static and block fading frequency selective channels, respectively. we assume that the channels from the source to the relays have significantly higher SNRs than the channels from the relays to the destination. We first give the considered block fading channel model. We then provide a discussion on the discrete noise samples at the destination under the block fading channels and at the end provide the PEP analysis for which similar to the quasi-static channel conditions, we assume that no coding is employed over the subcarriers and focus on the spatial diversity analysis of the system.

6. SIMULATION RESULTS

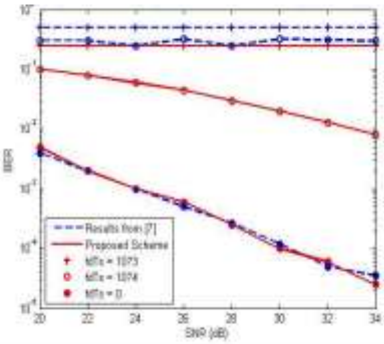

Figure 5: Comparison between the performances of the proposed scheme with the scheme proposed using Cyclic Prefix under the scenario S1.

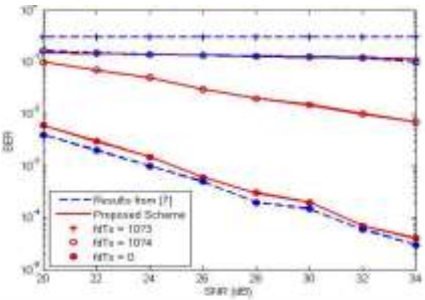

Figure: 6 Comparison between the performance of the proposed scheme with the scheme proposed in Cyclic Prefix under the scenario S2

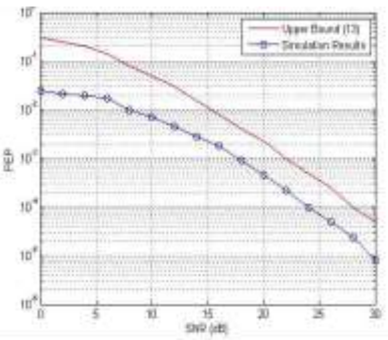

Figure 7: Comparison between the upper bound and actual PEP for under quasi-static frequency selective channels.

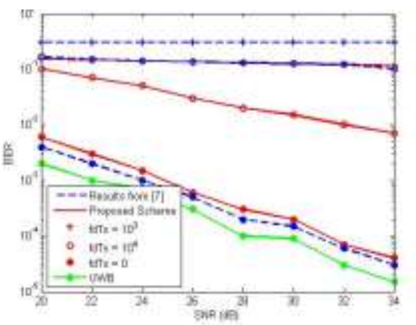

Figure 8: Comparison between the performances of the

proposed scheme with the scheme proposed using Cyclic Prefix under the scenario S1 Using Ultra Wide Band

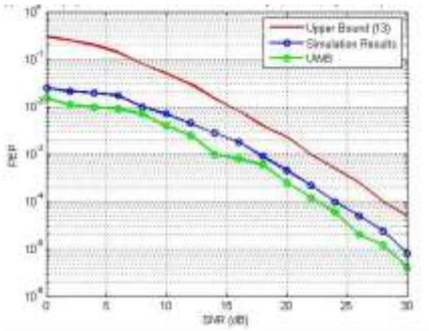

Figure 9: Comparison between the upper bound and actual PEP for under quasi-static frequency selective channels Using Ultra Wide Band

7. CONCLUSION

We developed a new OFDM transmission scheme for UWA cooperative communication systems suffering from a synchronism among the relays by considering possibly large relative delays among the relays (typical in UWA systems) and time varying frequency selective channels among the cooperating nodes. The main advantage of the proposed scheme is in managing the a synchronism issues arising from excessively large delays among the relays without adding time guards (or CP in OFDM-based transmissions) in the order of the maximum possible delay, which increases the spectral efficiency of the system and improves the performance in time-varying channel conditions compared with the existing solutions in the literature. In fact, we showed that independent of the maximum possible delay between the relays, by adding an appropriate CP at the transmitter and appropriate CP removal at the receiver, a delay diversity structure can be obtained at the receiver, where a full-duplex AF scheme is utilized at the relays. Through numerical examples, we evaluated the performance of the proposed scheme for time-varying multipath channels with Rayleigh fading channel taps, modeling UWA channels.

We compared our results with those of the existing schemes and found that while for time invariant channels, the performance is similar, for time varying cases (typical in UWA communications) the proposed scheme is significantly superior. By adopting UWB we are improving the performance in the bit error rate and pair wise probability error such that we can reach the destination with the low power and high accurate level.

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