Design of a Multichannel Transceiver System for Underwater Communication

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Abstract—*In this paper, we propose and design a multichannel uncoordinated code hopping direct sequence spread spectrum (UCH-DSSS) signaling scheme for underwater communication. Use of uncoordinated code hopping scheme in multiuser DSSS signaling scheme provides critical safeties in underwater communication without having any shared keys. To reduce the signal distortion which arose due to multipath fading, Doppler spread etc., multipath fading compensator (MFC) has been proposed and introduced in the receiver. The proposed circuit is designed using P-Spice circuit simulator and the bit error rate performance is evaluated using both circuit simulation model and analytical model. Further, the proposed circuit is also analyzed experimentally by generating shallow water wave (considering the wave characteristics of Arabian Sea (West coast of India)) in the laboratory.*

1. INTRODUCTION

Long multipath delay spread and severe frequency dependent attenuations are the main characteristics of underwater acoustic communication (UAC). Because of these, it is considered as one of the most challenging communications among the others [1]. Again one of the most important one regarding UAC is the presence of excessive multipath propagation and Doppler spread, causing inter-symbol interference (ISI). It degrades the quality of signal. From the previous studies it is observed that, to track the potentially time-varying Doppler shifts and to reduce the ISI, equalizers have been used adaptively by most of the researchers [2]. Code-hopping technique is also employed in ultra wideband wireless communication system for reduction of ISI [3]. But it is observed that although previous authors have employed various techniques to mitigate the effect of ISI as well as Doppler shift, but it is very much crucial to design a receiver which can mitigate both these effects as well as can accommodate multiuser in UAC [4]. DSSS signaling has been already reported in previous reports [5, 6] to enable multiuser communication. But it has some limitation of low BER for multiuser data communication. Although, frequency hopping spread spectrum (FHSS) is less sensitive to intentional interference or jamming, but previous studies [7-9] shows that the bandwidth required for FHSS is higher than that of DSSS. Also, the raw BER of FHSS is higher and is less sensitive to Doppler shift. Security and privacy of a signal are other issues in UAC as, without this it is very difficult to hide the transmitted information from malicious receivers. So, it is required to send the secret spreading of sequences in a jamming resistant manner. In this direction, uncoordinated DSSS system has been reported for anti-jamming broadcast communication [10].

Due to having more Additive white Gaussian Noise (AWGN), multipath propagation and Doppler spread, improvement of BER is a critical problem in UAC. Sparse partial response equalizer is used by the previous authors to improve the BER [2] but with this system, the obtained BER is 10^{-3} which is not suitable for high speed data transmission. To increase the bandwidth by enhancing bit rate transmission, two Focused Acoustic Field (FAF) experiments FAF-05 (2.5-4.5 kHz [11]) and FAF-06 (11-19 kHz [12]) have been performed by the previous researchers. In this paper, we have designed our proposed DSSS scheme with the experimental data collected from FAF-06 for UAC.

2. MULTICHANNEL UCH-DSSS SIGNALING TECHNIQUE

The block diagram of proposed UCH-DSSS transceiver system using MFC is shown in Fig. 1. The Fig. depicts that, in UCH-DSSS transmitter, K-bit symbol is generated from the K number of channels. These channels are used as an address line for multiplexer. In this uncoordinated transmission of signal, four different sets of PN sequences having length of 15 bits are used to spread the signal. From the four sets 16:1 multiplexer selects an independent PN sequence. Corresponding to four PN sets, four sets of tri-state buffers are also used to select a particular set of sequences as per a symbol. The tri-state buffers are made enable selectively by using randomizer at different times. Thus, for every symbol PN sequence is changed and we received an uncoordinated coded signal at the multiplexer output. The signal is then modulated with a carrier frequency of 15 kHz using binary phase shift keying (BPSK) modulator which is transmitted through wireless channel. The transmitted signal for n^{th} symbol can now be represented as,

$$x_n(t) = Ab_n PN_n(t - rT_b)c_n(t) \qquad (1)$$

where, n=1,2,3,.. M; M=2^K-1, K is the number of channels. A is the amplitude of the signal, PN_n is the n^{th} PN sequence, r is the r^{th} information bit. We have taken, $T_b=n_cT_c$; T_c=chip duration and T_b =data symbol period, n_c=n(L+1)/M; L=length of PN sequence.

In the receiver, the received signal is demodulated using BPSK demodulator which is then fed to MFC of each block (BLOCK-1, BLOCK-2, BLOCK-3 and BLOCK-4) for reduction of multipath fading originated from the mobile and immobile objects in under water. As shown in Fig. 1(c), in MFC, before correlation with the demodulated coded sequence, the locally generated PN sequence is advanced and the same is delayed by $\delta(\delta \leq T_C/2)$. The correlated signal is then detected through envelope detector, band pass filter and charge pump phase detector. The phase detector will detect the phase change between two correlated outputs. The output from phase detector will be a difference of the two correlated signal which is now fed to loop filter and voltage variable delay line (VVDL). The VVDL will generate a syn. clock which serves as a clock for the local PN generator. The output signal obtained from MFC is now exactly synchronized with the received signal [13]. The coded PN signal is now again cross correlated with the received PN sequence which will give a high or low output depending on the fully correlated or not correlated with the sequence and it is then integrated. Corresponding to the matched PN sequence, a particular integrator of all blocks will give the maximum output. For a particular time period T_b, the corresponding decision device will give a high output. Finally, the channels are separated by using decoder [14].

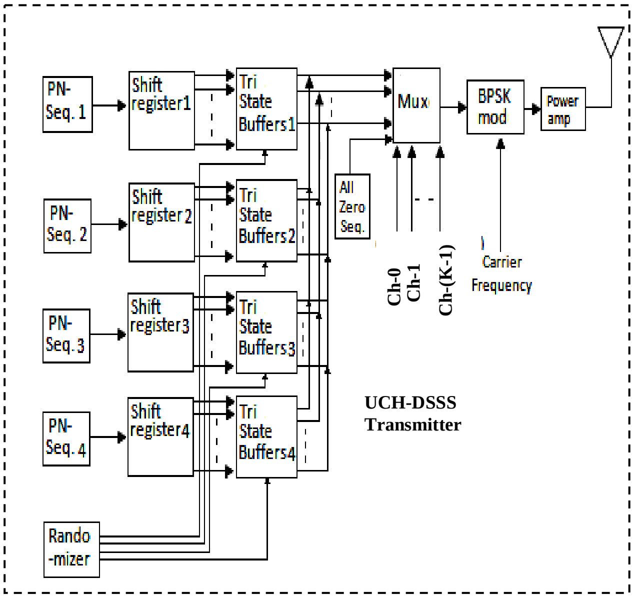
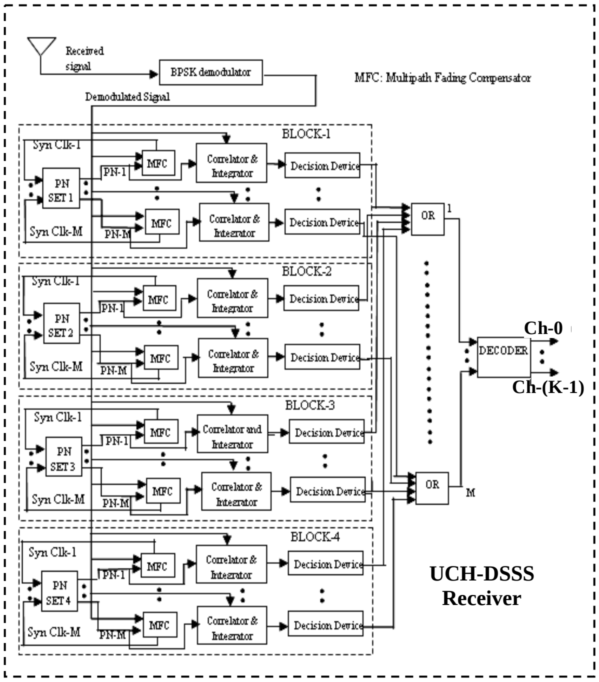


Fig. 1: (a) Block diagram of UCH-DSSS transmitter and receiver



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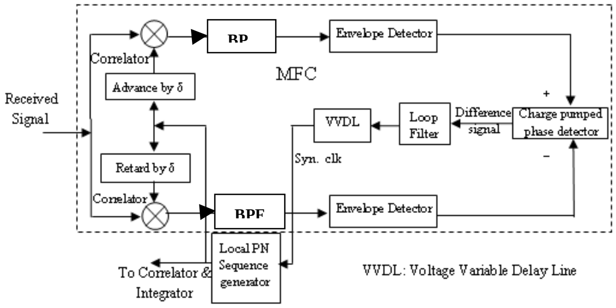

Fig. 1: (b)Block diagram of Multipath Fading Compensator

Now considering a linear time varying channel model, the received signal can be expressed as,

$$r(t) = x_n(t) * S(t,\tau) + N(t) \qquad (2)$$

where, $S(t,\tau) = \sum_{l=0}^{L-1} h_l(t,\tau)\delta(t - lT_b - \tau_l).\exp[j2\pi k\Delta\nu t]$ is the channel impulse response and N(t) is the additive white Gaussian noise (AWGN). Here, τ_l is the propagation delay for lth multipath and $h_l(t,\tau)$ is the complex channel gain. The received signal can now expressed as,

$$r(t) = \left\{ \sum_{l=0}^{L-1} \sum_{n=-\alpha}^{\alpha} \begin{matrix} Ab_n PN_n(t - nT_b - \tau_l)c_n(t - lT_b - \tau_l) \\ \times \exp[\Psi] + j\varphi_l(t,\tau)] \end{matrix} \right\} + N(t) \qquad (3)$$

Here, $\Psi = j2\pi[(K\Delta\nu + f_0 + F_c)(t-\tau_l)$. $\Delta\nu$ is the Doppler spacing, f_0 is the average Doppler shift across all the paths and F_c is the carrier frequency. The Doppler spread function is considered for estimation of Doppler shift effect, so the exponential part of 1st term of the equation (3) is arisen due to the Doppler shift which is expressed as,

$$S_{DS} = \sum_{l=0}^{L-1} \exp(j2\pi(k\Delta\nu + f_0 + F_c)(t-\tau_l) + j\varphi) \qquad (4)$$

For reduction of Doppler shift, MFC is used in the receiver. By analyzing the MFC signal, we have obtained a condition, in which the maximum likelihood (ML) estimator must have to follow a condition which is given below as,

$$\sum_i \frac{d\bar{r}^2}{d\tau_l}(\hat{\tau}_{ML} + iT_b) = 0 \qquad (5)$$

In MFC, the derivative in Eq. (5) is expressed as, $\frac{d\bar{r}^2}{d\tau_l}(\tau_l) \approx \frac{\bar{r}^2(\tau_l+\delta) - \bar{r}^2(\tau_l-\delta)}{2\delta}$, where δ is a small deviation of phase introduced in MFC for reduction of signal distortion.

To analyze the other effects such as self interference, multipath propagation, AWGN etc, we have taken the other terms of Eq. (3). For this we have consider a multipath channel model consisting of 4M number of MFC, according to which the total signal at the output of i^{th} MFC is written as,

$$\begin{aligned} Y_i &= \int_{\mu T_b+\tau_i}^{(\mu+1)T_b+\tau_i} r(t).h_i^* c_\mu(t - iT_b - \tau_i)dt \\ &= Y_{S_i} + Y_{N_i} \end{aligned} \qquad (6)$$

Where, h_i^* = conjugate of the complex channel gain

Y_{S_i} =Signal term with SI and MP

Y_{N_i} =AWGN noise term.

Now, summing up all the signals coming from the compensator, the final expression is written as,

$$Y_S = T_b A\{b_\mu PN_\mu(S_s + S_{SI}(\mu))\} + AT_b S_{MP}(\mu) \qquad (7)$$

where, S_S, S_{SI}, S_{MP} are the terms related to the desired signal, self interference and multipath propagation respectively.

Similarly, the total noise term is expressed as,

$$Y_N = \{\sum_{i=0}^{M-1} Y_{N_i}\} \qquad (8)$$

From the above equations, for K number of channels, the BER is written as,

$$BER = P_e\left(\frac{2^{K-1}}{2^K - 1}\right) \quad (9)$$

where ,
$$P_e = Q\left(Y_S \big/ \sigma_N\right) = \frac{1}{N_H}\sum_{\mu=0}^{N_H-1} E_s\left[Q\left(\sqrt{\frac{2}{\frac{1}{SNR} + JSR}}(S_A)\right)\right]$$

Here, $S_A = \frac{S_S + S_{SI}(\mu) + S_{MP}(\mu) + S_{DS}(\mu)}{\sqrt{S_S + S_{cn}(\mu)}}$

Here, SNR=signal to noise ratio, JSR=jamming to signal ratio, N_H=length of hopping sequence, S_{cn}=correlated noise term.

3. RESULTS AND DISCUSSION

The UCH-DSSS transceiver system is designed and simulated using P-spice circuit simulator with consideration of multipath propagation, AWGN, jamming signal etc. using carrier frequency of 15 kHz. The simulated waveforms are shown in Fig. 2 which depicts that the signal of four transmitted channels is almost close to that of signal of received channels.

To analyze the performance of the system, we have estimated the BER under multipath fading, AWGN and jamming signal. A circuit simulation model was developed consisting of data generator, UCH-DSSS modulator, AWGN generator, multipath signal generator, jamming signal generator, UCH-DSSS demodulator, XOR gate and counter. Fig. 3(a) shows the BER vs. SNR plot obtained by circuit simulation model using the carrier frequency of 15 kHz and analytically from the Eq. (9) and (10). It is observed that the variation of BER with SNR plot obtained by circuit simulator is almost close to that obtained analytically. The BER range of our proposed circuit obtained with the SNR range ~ (5dB to 19dB) is ~$1.4\text{x}10^{-1}$ to $2\text{x}10^{-6}$ (using FAF-06 data). We have also estimated the variation of BER with JSR as shown in Fig. 3(b), which evident that BER increases with JSR.

Noise margin and distortion due to ISI has also been estimated from eye pattern of the proposed circuit using P-Spice circuit simulation. Fig. 4 shows the variation of noise margin and distortion with SNR for frequency f= 15 kHz. The Fig. 4 depicts that, noise margin increases and distortion due to ISI decreases with SNR. Inset of this Fig. also shows an eye pattern at SNR value of 10 dB providing the noise margin and distortion of ~ 1.1V and ~0.7V respectively which are tolerable for high speed data communication.

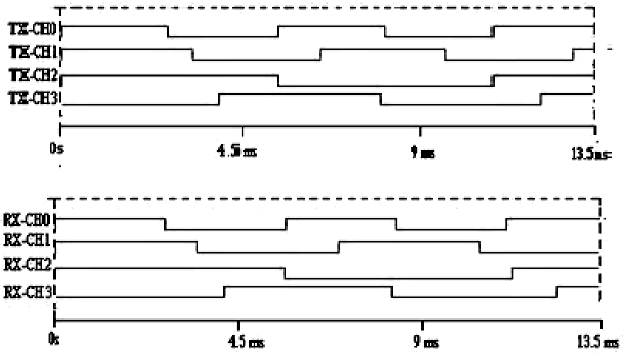

Fig. 2: Waveform of UCH –DSSS transmitter and receiver with f= 15 kHz

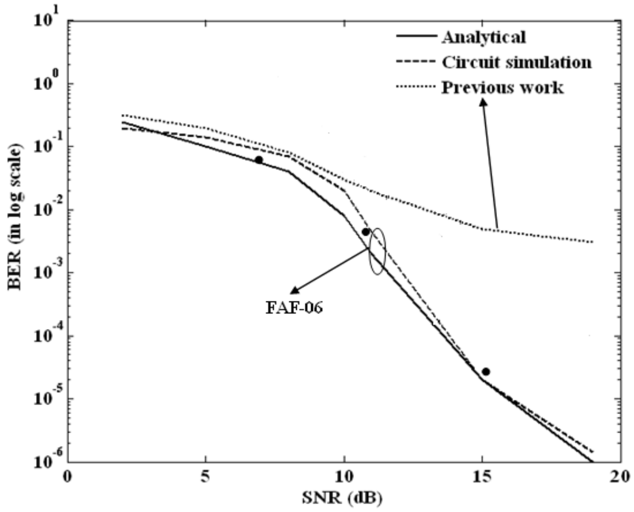

Fig. 3: (a) Variation of BER vs. SNR (dB) for proposed UCH-DSSS transceiver using MFC by taking the carrier frequency of 15 kHz (used in FAF-06)

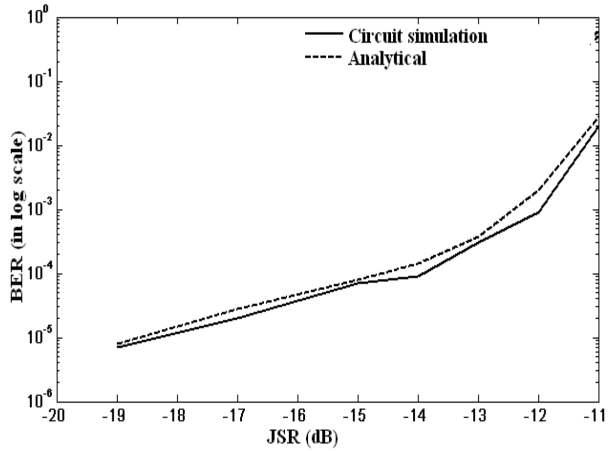

Fig. 3: (b) Variation of BER with JSR (dB) by using MFC with BPSK modulation scheme and carrier frequency of 15 kHz within the JSR range of -20dB to -11 dB.

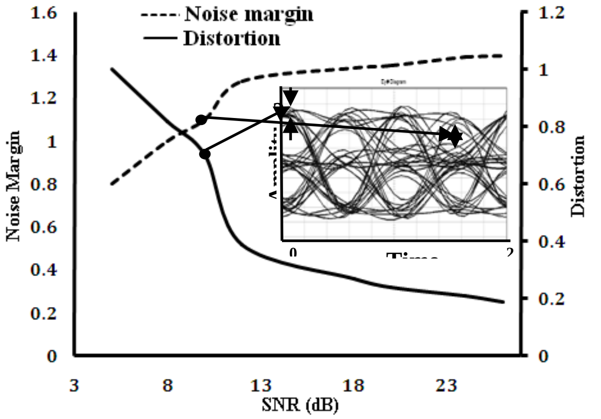

Fig. 4: Variation of Noise margin and Distortion with SNR (dB)

4. EXPERIMENTAL RESULTS

The proposed UCH-DSSS transceiver system is tested and analyzed in the laboratory with the generation of shallow water waves. By taking the wave characteristics of Arabian Sea and with carrier frequency of 15 kHz, the shallow water waves are generated in the laboratory. The experiment is performed by putting the transmitter and receiver at a depth of 5m. The channel impulse response experienced during the experiment is shown in Fig. 5. It is observed that, the channel exhibits a delay spread of approximately 30-40 ms for higher frequency range of 15 kHz. As shown in Fig. 6, scatter plot is also obtained at the output receiver which shows that BER of the proposed system at SNR of 10 dB with f= 15 kHz is obtained as $6.2\text{x}10^{-3}$.

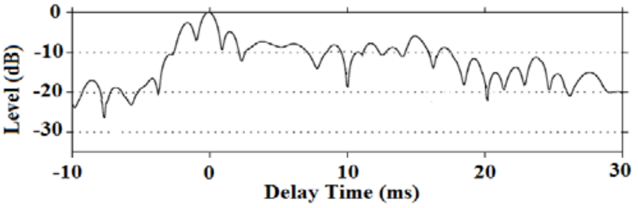

Fig. 5: Channel impulse response experienced during the experiment using BPSK modulation scheme having water depth of 5m for FAF-06 frequency

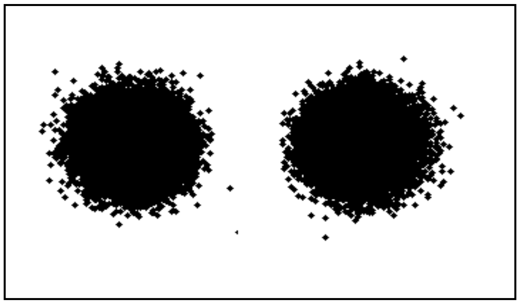

Fig. 6: Scatter plot at SNR of 10 dB experienced during FAF-06 experiment

5. CONCLUSION

In this paper a multichannel transceiver system using UCH-DSSS technique for underwater communication is proposed and designed. Using carrier frequency of 15 kHz, the circuit was simulated with p-spice circuit simulator. In the receiver, multipath fading compensator has been introduced to reduce the effect of multipath propagation and Doppler spread. For performance analysis of the system, BER was analyzed by using both analytically and using circuit simulation model under consideration of AWGN, multipath propagation. It is seen that, BER of the proposed system is less than that of the previous work. BER of the proposed system was also analyzed under presence of jamming signal. From the BER vs. JSR plot it is observed that BER increases with JSR. Eye pattern was also analyzed for the transceiver system which showing at at SNR of 10 dB, the noise margin and distortion is obtained as ~ 1.1V and ~0.7V respectively.

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