HYPERBOLIC FREQUENCY MODULATION FOR MULTIPLE USERS IN UNDERWATER ACOUSTIC COMMUNICATIONS

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ABSTRACT

Nonlinear frequency-modulated signals have been effectively applied in multiple-user communication schemes. In this paper, we propose to implement a multiple-user communication scheme using hyperbolic frequency-modulated (HFM) signals for underwater acoustic communications. We derive constraints on the HFM parameters to optimally reduce multiple access interference (MAI) at the transmission side. Additional constraints on the frequency-modulation (FM) rate reduce the underwater channel effects of multipath and scaling. The proposed signaling scheme is compared to an HFM-based code-division multiple-access (HFM-CDMA) scheme to demonstrate improved error performance.

1. MOTIVATION AND RELATION TO PRIOR WORK

Underwater acoustic (UWA) communications methods, such as orthogonal frequency-division multiplexing (OFDM) and code-division multiple access (CDMA), have been widely-used for multiple users [1–4]. As the UWA communications channel is highly time-varying, it can cause undesirable distortions, such as multipath and Doppler scaling, under certain conditions [5–7]. Existing UWA communications schemes do not fully exploit matching the UWA channel characteristics to signaling schemes and often have to compensate for that at the receiver. In [1], the distorted OFDM signal due to Doppler is compensated at the receiver using resampling, and any remaining Doppler is removed using inter-carrier interference reduction techniques. A multiple resampling OFDM receiver front-end is designed in [2] such that each resampling branch deals with a different Doppler factor. Adaptive multi-user detection techniques are applied in [3], but their assumed UWA channel model does not include multiple Doppler paths at the receiver. A spread spectrum hyperbolic frequency modulation scheme in [8] can potentially match the UWA channel but only assumes one Doppler scale path and does not compensate for multiple time delay paths that can distort any potential scale diversity. In [9], we design an HFM scheme to match the UWA communications channel. The HFM scheme is integrated with the use of a discrete time-scale canonical model, which represents the received signal from a wideband channel as a linear superposition of discrete time shifts and Doppler scalings of the transmitted signal, weighted by the wideband spreading function (WSF) [10]. We demonstrate an inherent joint multipath-scale diversity using this scheme, and we combine it with direct sequence CDMA for use in multi-user UWA communications. The different users are distinguished by a unique pseudo-noise (PN) sequence [9]. As we demonstrate, the scheme can successfully resolve information bits at the receiver side, but the performance degrades as the number of users increases.

A nonlinear frequency-modulated signaling scheme is developed in [11] by deriving constraints on the nonlinear phase function of the transmit signal to achieve orthogonality; the scheme, combined with frequency-hopping CDMA, is used in a multi-user communication scheme in [11, 12]. In [13], chirp modulation, with a zero cross-correlation condition, is combined with CDMA for frequency-nonselective and frequency-selective fading channels. Similar chirp modulation is applied to an ultra-wideband scheme in [14] and a multiple-input multiple-output multi-user scheme in [15].

In this paper, we design a multiple user scheme for the wideband UWA communications channel using the discrete canonical channel model. Different from [9], we minimize multiple access interference (MAI) by assigning a unique HFM signal to each user at the transmission side. We design orthogonal HFM signaling by appropriately constraining the signal's FM rate. We also take into consideration that HFM signals are scale-invariant and thus potentially suitable for wideband channel transmission.

The paper is organized as follows. In Section 2, we provide the time-scale canonical model for wideband systems and the HFM signaling scheme for binary UWA communications. In Section 3, we derive a constraint on the HFM rate to allow for multiple users and extend the HFM signaling to multi-user UWA communications. In Section 4, we demonstrate the performance improvement of the proposed multi-user signaling scheme by comparing it to CDMA.

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2. WIDEBAND UWA CHANNEL HFM DESIGN

2.1. Discrete Time-Scale Wideband Model

The output of a wideband linear time-varying (LTV) system can be characterized by a superposition of time shifts and scale changes, weighted by the WSF of the system. The wideband system is thus assumed to include fast moving scatterers, continuously distributed in range and velocity and with reflection strength represented by the WSF [10, 16]. Under certain conditions (signal frequency content, ocean depth, etc), the UWA channel can be shown to be wideband due to the movement of the scatterers causing Doppler scale on the transmitted signal. We consider UWA signals that are characterized by time-shift and Doppler-scale changes after transmission; the signals have spectral components within 300 to 20,000 Hz and bandwidths comparable to their central frequencies.

The received signal of a wideband LTV channel, without the additive noise component, is given by [7, 10]

$$y(t) = \int_0^{T_s} \int_{A_0}^{A_1} \chi(\tau, a)\, \sqrt{a}\, s(a\,(t-\tau))\; da\, d\tau \qquad (1)$$

where τ and a are continuous time-delay and Doppler-scale parameters, respectively, and $s(t)$ is the transmitted signal. The WSF, $\chi(\tau, a)$, represents the random phase change and attenuation of underwater scatterers corresponding to different values of τ and a. Due to path loss or velocity limit restrictions of realistic UWA channels, we assume that the WSF time shift and scale support regions are $\tau \in [0, T_d]$ and $a \in [A_0, A_1]$, respectively, where T_d and $A_d = A_1 - A_0$ are the channel time-delay and Doppler scale spreads, respectively.

Efficient wideband system processing can be achieved using a discrete time-scale system model [10]. Using this model for a wideband UWA communications channel, we can represent the system output as [7, 10]

$$y(t) = \sum_{m=M_0}^{M_1} \sum_{n=0}^{N(m)} \chi_{n,m}\, a_d^{m/2}\, s\Big(a_d^m\, t - \frac{n}{W}\Big)\,, \qquad (2)$$

where the transmitted acoustic signal $s(t)$ has bandwidth W and duration $T \gg T_d$ to ensure no intersymbol interference. In (2), $a_d = \exp\,(1/\beta_d)$, β_d is the Mellin support of $s(t)$, the lower and upper Doppler scale indices are given by $M_0 = \lfloor \ln A_0 / \ln a_d \rfloor$ and $M_1 = \lceil \ln A_1 / \ln a_d \rceil$, respectively, $N(m) = \lceil a_d^m W T_d \rceil$ for integer m, and $\chi_{n,m}$ are the WSF coefficients. Assuming independence between the scatterers contributing to the nth time delay and the mth scale path, then (2) decomposes the UWA communications channel into a total of

$$M = \sum_{m=M_0}^{M_1} (N(m) + 1)$$

independent, flat-fading channels. Using (2) at the receiver can potentially achieve a joint multipath-scale diversity of order M [10].

2.2. HFM Signaling Scheme Design for Single User

In [9], we used the discrete time-scale canonical model for UWA communication channels in (2) to design a channel-matched signaling scheme for single-user binary communications. The scheme uses HFM signals, with a different FM rate to transmit symbol 0 or 1. The ith HFM signal, corresponding to the ith symbol, $i = 0, 1$, is given by

$$s^{(i)}(t) = e^{j2\pi c^{(i)} \ln((t+t_c)/t_r)}\,, \quad t \in [0,\, T]\,, \qquad (3)$$

where $c^{(i)}$ is the FM rate, T is the signal duration, $(1/t_c)$ is a reference frequency (that can be used to modulate the signal), and t_r is a normalization time constant.

If we substitute the HFM $s^{(i)}(t)$ in (3) for $s(t)$ in (2), and we let $t_r = 1$ s, $a_{m,i} = a_d^m$ and $\tau_{n,i} = n/W$, the time-scaled signal for the ith symbol in (2) is $s^{(i)}(a_d^m\, t - n/W) = \mathtt{s}_{i,n,m}(t) = e^{j2\pi c^{(i)} \ln(a_{m,i}t - \tau_{n,i} + t_c)}$. As demonstrated in [9], the correlation between $\mathtt{s}_{i,n,m}(t)$ and $\mathtt{s}_{l,n',m}(t)$ for $i \neq l$ (different symbols), and for $n = n'$ or $n \neq n'$ (different time shifts) can be significantly reduced provided the difference between the FM rates $c^{(i)}$ and $c^{(l)}$ for symbols i and l, respectively, is as large as possible. As the largest frequency of the HFM signal is proportional to $c^{(i)}/t_c$, the range of $c^{(i)}$ values that can be selected are limited by the signal's time-bandwidth product. Thus, the HFM rates $c^{(i)}$ and $c^{(l)}$ for a single user to transmit symbols i and l, $i \neq l$, over an UWA communications channel, with reduced interference, must satisfy the condition:

$$\text{select } D^{(i,l)} = |c^{(i)} - c^{(l)}|,\ i \neq l,\ \text{to be large}\,, \qquad (4)$$

based on a maximum $B_{\max}T$ time-bandwidth signal constraint.

3. MULTI-USER UWA COMMUNICATIONS SCHEME

3.1. HFM Signaling for Multiple Users

In order to accommodate multiple users using HFM signaling, we consider an amplitude-modulated version of the signal in (3), as in [17]. The amplitude modulation leads to signal orthogonality for infinite duration signals; for finite duration signals, it leads to high correlation when signals match in FM rate. Making use of this property in a communications system with K users, each user is assigned one of K sub-channels by equally dividing the available bandwidth. For a K-user system, the HFM signal for the kth user, $k = 1, \ldots, K$, is

$$s_k(t) = \frac{1}{\sqrt{t+t_c}}\, e^{j2\pi c_k \ln((t+t_c)/t_r)}\,. \qquad (5)$$

We assign an FM rate to each user in such a way as to minimize the cross correlation between the signals of any two users and thus reduce multiple access interference (MAI) among users. In order to determine the FM rates for approximate orthogonal signaling, we consider the signals for the kth and mth users, respectively, as

$$s_k(t) = \frac{1}{\sqrt{t+t_c}}\, e^{j2\pi c_k \ln((t+t_c)/t_r)}$$
$$s_m(t) = \frac{1}{\sqrt{t+t_c}}\, e^{j2\pi c_m \ln((t+t_c)/t_r)} \,. \quad (6)$$

The correlation between the signals in (6), setting $t_r = 1$, can be calculated as [11]

$$q_{k,m} = \int s_k(t) s_m^*(t) dt = \int_0^T \frac{1}{t+t_c} e^{j2\pi(c_k - c_m)\ln(t+t_c)} dt.$$

The closed form of the correlation magnitude is given by

$$|q_{k,m}| = \eta_T \,\mathrm{sinc}((c_k - c_m)\,\eta_T)$$

where $\eta_T = \ln(T+t_c) - \ln(t_c)$ and $\mathrm{sinc}(x) = \sin(\pi x)/(\pi x)$. In order to minimize the correlation, we can select the FM rates c_k and c_m such that $(c_k - c_m)\,\eta_T$ is any integer. Based on this, we select the FM rate for the kth user, $k = 1, \ldots, K$, to satisfy the condition

$$c_k = \frac{K+1-k}{\eta_T} = \frac{K+1-k}{\ln(T+t_c) - \ln(t_c)} \quad (7)$$

based on a maximum $B_{\max}T$ time-bandwidth signal constraint. Using the FM rate in (5), we ensure that the correlation in (7) is zero. A less restrictive condition that still reduces correlation is obtained by selecting the FM rates of the kth and mth users such that

$$(c_k - c_m)\Big[\ln(T+t_c) - \ln(t_c)\Big] \gg 1 \,. \quad (8)$$

Using the maximum HFM signal time-bandwidth constraint for all users, the maximum number of possible users is [11]

$$K_{\max} = \left\lceil \left(\frac{1}{2}(B_{\max}\, t_c\, \eta_T - 1\right) \right\rceil . \quad (9)$$

3.2. Multi-User UWA HFM Signaling

We now consider the combined case of multiple users in an UWA communications channel. In order to use the HFM signaling scheme, we combine the two conditions we derived in Equations (4) and (7) (or for a less restrictive case, the two conditions in Equations (4) and (8)). The sub-channel for each user is further divided in two bands so that each user can transmit two binary symbols.

We assume that User k transmits Symbol i and User m transmits Symbol l. Using the symbol FM condition in (4) ensures that the following FM rate differences are large: $D_{k,k}^{(i,l)} = |c_k^{(i)} - c_k^{(l)}|$ and $D_{m,m}^{(i,l)} = |c_m^{(i)} - c_m^{(l)}|$, $i \neq l$. Using (8) ensures that $(c_k^{(i)} - c_m^{(l)})\eta_T \gg 1$, $i, l = 0, 1$, $k \neq m$. Combining (4) and (8) then ensures that $D_{k,m}^{(i,l)}$ is also large for $i \neq l$ and $k \neq m$. Thus, although the FM rate condition in (7) is derived using the amplitude modulated HFM in (5), we combine it with the condition in (4) to represent any pair of two FM rates. The transmitted signal model in this paper can be seen as below:

$$s_k^{(i)}(t) = \frac{1}{\sqrt{t+t_c}}\, e^{j2\pi c_k^{(i)} \ln((t+t_c)/t_r)} \,. \quad (10)$$

After propagating through the wideband UWA channel, the observed signal of User k transmitting Symbol i at the receiver can be written as

$$r(t) = \sum_{k=1}^{K} y_k^{(i)}(t) + w(t),$$

where

$$y_k^{(i)}(t) = \sum_{m=M_0}^{M_1} \sum_{n=0}^{N(m)} \chi_{n,m}\, a_d^{m/2}\, s_k^{(i)}(a_d^m t - n/W)\,,$$

and $w(t)$ is assumed to be an additive white Gaussian noise. The correlation between the received signal and the expected signal is given by

$$\Lambda(y_k^{(i)}) = \int_{-\infty}^{\infty} r(t)\, y_k^{*(i)}(t)\, dt$$
$$= \sum_{m=M_0}^{M_1} \sum_{n=0}^{N(m)} \chi_{n,m}\, a_d^{m/2} \int_{-\infty}^{\infty} r(t)\, s_k^{(i)}\left(a_d^m t - \frac{n}{W}\right)\, dt$$

The information symbol of the kth user can then be estimated using

$$\hat{i} = \arg\max_{i=0,1} \Lambda(y_k^{(i)}) \,.$$

Note that we assume that the UWA channel WSF coefficients are estimated *a priori*; methods for estimating the WSF coefficients can be found in [6, 7].

4. SIMULATION RESULTS

We demonstrate next the improved bit-error-rate (BER) performance of the HFM signaling scheme in multi-user UWA communications. We consider all possible HFM signals with duration $T = 0.1$ s and 5 kHz maximum bandwidth. Using the channel model in (2), we assume an UWA channel with $T_d = 10$ ms multipath spread, $\beta_d = 90$ Mellin spread resulting in $a_d = 1.011$, and $M_0 = 0$, $M_1 = 1$. Note that we

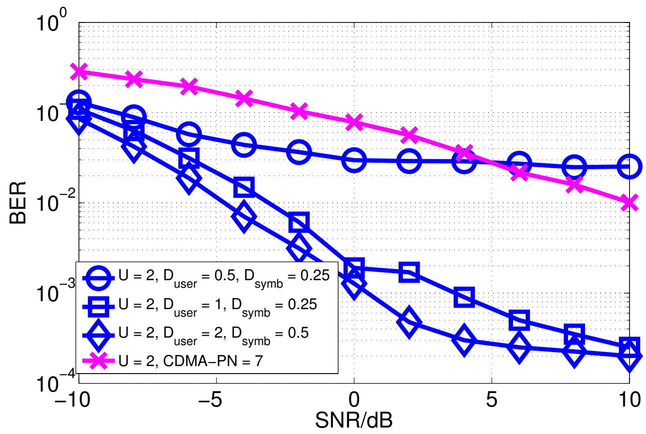

Fig. 1. Comparison between HFM-CDMA and new signaling scheme for varying D_{symb} and D_{user} for $K = 2$ users.

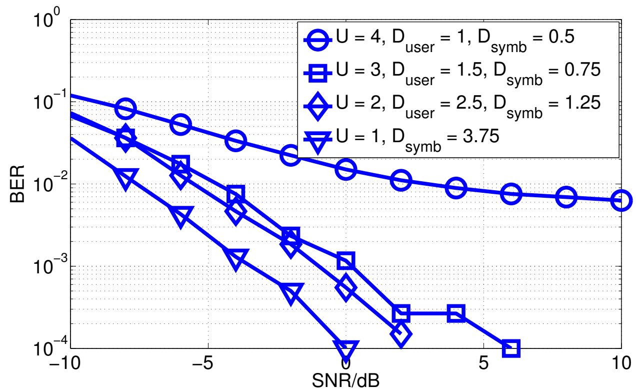

Fig. 2. Comparison between new signaling scheme for different number of users, where $K = 1, 2, 3, 4$ users with the best D_{symb} and D_{user} are chosen.

assume that the channel WSF coefficients are estimated at every iteration [7]. All users are assumed to transmit symbol 0 or 1 with equal probability.

Using the HFM signal orthogonality condition in (8) to select FM rates for the two users to reduce MAI, we denote by $D_{\text{user}} = D_{k,m}^{(i,i)} = |c_k^{(i)} - c_m^{(i)}|$ the difference in the FM rates between the two users. Similarly, $D_{\text{symb}} = D_{k,k}^{(i,l)} = |c_k^{(i)} - c_k^{(l)}|$ denotes the difference in the FM rates between the two symbols of the kth user to reduce the UWA channel effects (following the condition in (4)). Using this notation, for the 2 user case, we use HFM signals with FM rate difference $D_{\text{symb}} = c_k^{(1)} - c_k^{(0)} = 0.25,\ 0.5$ for $k = 1, 2$ and $D_{\text{user}} = c_1^{(i)} - c_2^{(i)} = 0.5,\ 1,\ 2,$ for $i = 0, 1$. The BER simulation results for different signal-to-noise ratio (SNR) values (in dB) are shown in Figure 1. Also shown superimposed in the figure are the corresponding BER results obtained using the HFM-CDMA scheme from [9]. The HFM-CDMA simulations used PN sequences of length 7 from the sequence generator [18]. As expected, as proposed HFM method performs better than the HFM-CDMA. This is because two different types of conditions are imposed when selecting the FM rates of the HFM signals. Note that the BER performance increases as the symbol FM rate difference D_{symb} and the user FM rate difference D_{user} increase.

In Figure 2, we extend our simulations to $K = 1,\ 2,\ 3,\ 4$ users, demonstrating simulated BERs for different SNR values. The UWA channel parameters and the HFM signal parameters remain the same as in the first figure. For these cases, for each value of K, we selected D_{symb} and D_{user} to satisfy both conditions (4) and (8) are satisfied for the given time-bandwidth product of $T = 0.1$ and 5 kHz maximum bandwidth. It can be observed that the BER performance decreases as the number of users increases.

5. CONCLUSION

In this paper, we proposed a multiple user underwater acoustics communications scheme using HFM signals. We derived constraints on the FM rates of the HFM signals in order to reduce both multiple access interference and the distortion effects of the UWA channel. Our simulations demonstrated the improved BER performance of this scheme when compared to the corresponding one of our previously published scheme that combined CDMA with the selection of the HFM rates to reduce the channel distortion effects.

6. REFERENCES

[1] B. Li, S. Zhou, M. Stojanovic, L. Freitag, and P. Willett, "Non-uniform Doppler compensation for zero-padded OFDM over fast-varying underwater acoustic channels," in *OCEANS Europe*, 2007, pp. 1–6.

[2] K. Tu, T. M. Duman, M. Stojanovic, and J. G. Proakis, "Multiple-resampling receiver design for OFDM over Doppler-distorted underwater acoustic channels," *IEEE Journal of Oceanic Engineering*, vol. 38, no. 2, pp. 333–346, 2013.

[3] E. Calvo and M. Stojanovic, "Efficient channel-estimation-based multiuser detection for underwater CDMA systems," *IEEE Journal of Oceanic Engineering*, vol. 33, no. 4, pp. 502–512, 2008.

[4] S. A. Aliesawi, C. C. Tsimenidis, B. S. Sharif, and M. Johnston, "Iterative multiuser detection for underwater acoustic channels," *IEEE Journal of Oceanic Engineering*, vol. 36, no. 4, pp. 728–744, 2011.

[5] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 84–89, 2009.

[6] N. F. Josso, J. J. Zhang, D. Fertonani, A. Papandreou-Suppappola, and T. M. Duman, "Time-varying wideband underwater acoustic channel estimation for OFDM communications," in *IEEE International Conference on Acoustics Speech and Signal Processing*, 2010, pp. 5626–5629.

[7] N. F. Josso, J. J. Zhang, A. Papandreou-Suppappola, C. Ioana, and T. M. Duman, "Nonstationary system analysis methods for underwater communications," *EURASIP Journal on Advances in Signal Processsing*, vol. 11, pp. 14, 2011.

[8] L. Zhang, X. Xu, W. Feng, and Y. Chen, "HFM spread spectrum modulation scheme in shallow water acoustic channels," in *MTS/IEEE OCEANS Conference*, 2012, pp. 1–6.

[9] M. Zhou, J. Zhang, A. Papandreou-Suppappola, and T. Duman, "An underwater acoustic communications scheme with inherent scale diversity for multiple users," in *MTS/IEEE OCEANS Conference*, September 2013.

[10] Y. Jiang and A. Papandreou-Suppappola, "Discrete time-scale characterization of wideband time-varying systems," *IEEE Transactions on Signal Processing*, vol. 54, no. 4, pp. 1364–1375, 2006.

[11] S. Machineni, S. Hao, and A. Papandreou-Suppappola, "Multi-user schemes using nonlinear time-varying modulation," *IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, vol. 4, pp. 941–944, 2004.

[12] C. Gupta, T. Mumtaz, M. Zaman, and A. Papandreou-Suppappola, "Wideband chirp modulation for FH-CDMA wireless systems: coherent and non-coherent receiver structures," *IEEE International Conference on Communications, ICC '03.*, vol. 4, pp. 2455–2459, 2003.

[13] A. Kocian and D. Dahlhaus, "Downlink performance analysis of a COMA mobile radio system with chirp modulation," *IEEE Vehicular Technology Conference*, vol. 1, pp. 238–242, 1999.

[14] H. Liu, "Multicode ultra-wideband scheme using chirp waveforms," *IEEE Journal on Selected Areas in Communications*, vol. 24, pp. 885–891, 2006.

[15] M. A. Khan, R. K. Rao, and X. Wang, "Performance of multiuser MIMO communication system using chirp modulation," in *Int. Symposium on Performance Evaluation of Computer and Telecommunication Systems*, 2013, pp. 115–119.

[16] L. G. Weiss, "Time-varying system characterization for wideband input signals," *Signal Processing*, vol. 55, pp. 295–304, 1996.

[17] A. Papandreou-Suppappola, "Time-varying processing: Tutorial on principles and practice," in *Applications in Time-Frequency Signal Processing*, A. Papandreou-Suppappola, Ed., p. 184. CRC Press, 2002.

[18] S. W. Golomb, *Shift register sequences*, Holden-Day, Inc., 1967.