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Abstract

To mitigate the inter-symbol interference (ISI), multiple access interference (MAI) and the effect of different Doppler shifts within a data package incurred in variably mobile asynchronous underwater multiuser communications (VMAUMC), a Kalman filter-based chip differential blind adaptive multiuser detection (D-KF-BAMUD) algorithm is proposed in this paper. The Kalman filter-based blind adaptive multiuser detection (KF-BAMUD) algorithm has been adopted to combat ISI and MAI in the scenario of static users, and underwater and under-ice multiuser communication experiments have been carried out to verify the effectiveness of the KF-BAMUD algorithm. To tackle the more challenging VMAUMC, a differential modulation and demodulation technique operating at the chip level is proposed to reduce the impact of Doppler shift residues after the Doppler compensation with an average Doppler frequency offset within each data package. The technique is combined with KF-BAMUD algorithm, leading to D-KF-BAMUD algorithm, which is able to effectively handle ISI, MAI and the effect of Doppler shift residues simultaneously in VMAUMC. This paper reports our experiments on VMAUMC carried out in Songhua River in April 2016 (7 users, data rate 7.87bit/s, up to 2m/s variably relative velocity in each data package, and horizontal distance 200m shallow-water channel between transducer and hydrophone), and the encouraging experimental results demonstrate the effectiveness of the proposed system and the D-KF-BAMUD algorithm.

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Kalman Filter-Based Chip Differential Blind Adaptive Multiuser Detection for Variably Mobile Asynchronous Underwater Multiuser Communications

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ABSTRACT To mitigate the inter-symbol interference (ISI), multiple access interference (MAI), and the effect of different Doppler shifts within a data package incurred in variably mobile asynchronous underwater multiuser communications (VMAUMC), a Kalman filter-based chip differential blind adaptive multiuser detection (D-KF-BAMUD) algorithm is proposed in this paper. The Kalman filter-based blind adaptive multiuser detection (KF-BAMUD) algorithm has been adopted to combat ISI and MAI in the scenario of static users, and underwater and under-ice multiuser communication experiments have been carried out to verify the effectiveness of the KF-BAMUD algorithm. To tackle the more challenging VMAUMC, a differential modulation and demodulation technique operating at the chip level is proposed to reduce the impact of Doppler shift residues after the Doppler compensation with an average Doppler frequency offset within each data package. The technique is combined with the KF-BAMUD algorithm, leading to the D-KF-BAMUD algorithm, which is able to effectively handle ISI, MAI, and the effect of Doppler shift residues simultaneously in VMAUMC. This paper reports our experiments on VMAUMC carried out in Songhua River in April 2016 (seven users, data rate 7.87 bit/s, up to 2 m/s variably relative velocity in each data package, and horizontal distance 200-m shallow-water channel between transducer and hydrophone), and the encouraging experimental results demonstrate the effectiveness of the proposed system and the D-KF-BAMUD algorithm.

INDEX TERMS Inter-symbol interference, multiple access interference, Doppler shift residues, variably mobile underwater multiuser communications.

I. INTRODUCTION

Underwater acoustic channels are hostile, which are characterized by low carrier frequency, narrow bandwidth, severe multipath delay, and large Doppler shift [1]. Research and experiments in the literature have been mainly focused on static underwater multiuser communications, i.e., both the transducers and the hydrophones of the users are assumed to be static [2]–[17]. A typical application example is shown in Fig.1 (a), where a fixed underwater network communicates to a static autonomous underwater vehicle (AUV). In this scenario, two sensors transmit data to the AUV simultaneously, and there is no Doppler shift because both sensors and

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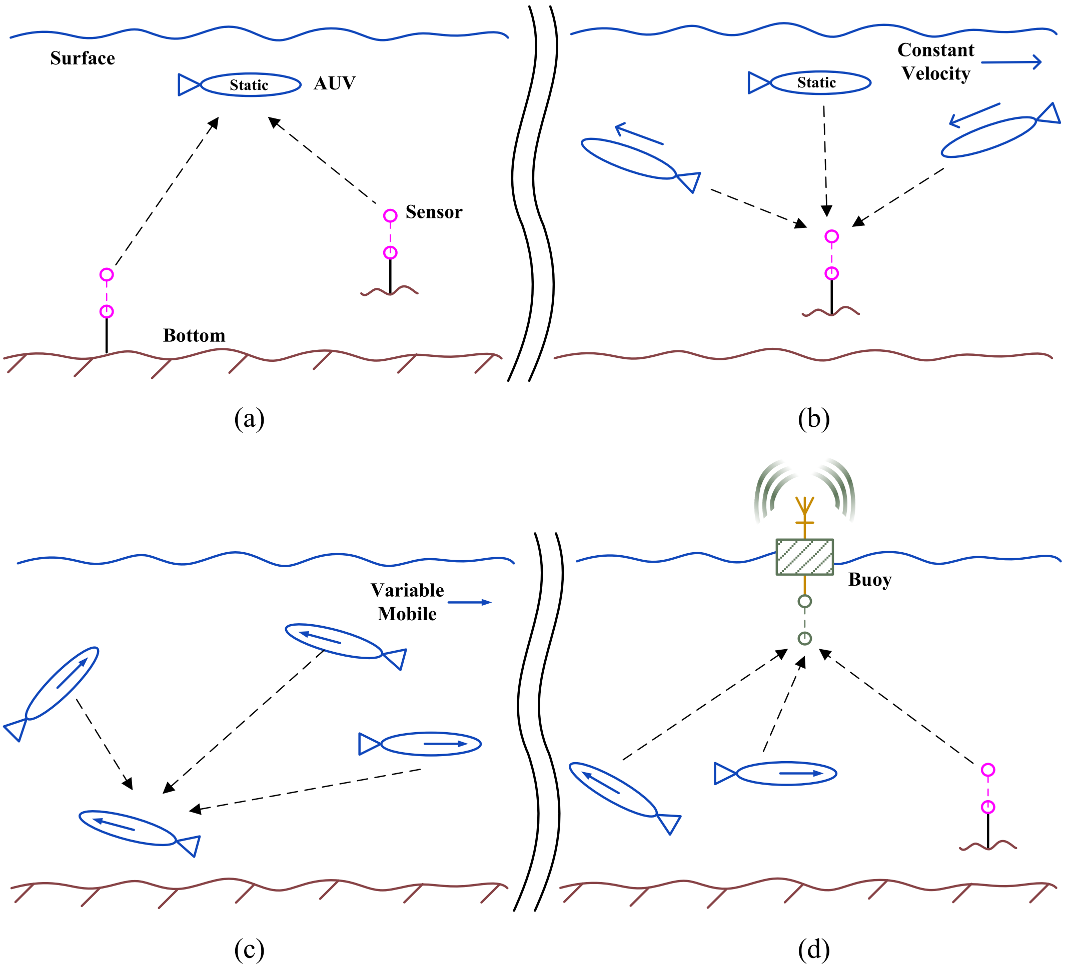


FIGURE 1. **(Color online) Comparison between application examples of this paper and some references (a) Communication scenario in [2]–[10] (b) Communication scenario in [11]–[14] (c) Communication scenario 1 in this paper (d) Communication scenario 2 in this paper.**

AUV are static. Another important scenario of underwater multiuser communications is variably mobile asynchronous underwater multiuser communications (VMAUMC) where the relative movement between transducers and hydrophones has to be considered. The communication environment of VMAUMC is more hostile due to the variable Doppler shifts within each data package incurred by the variably relative velocity of the transducer and the hydrophone.

To the best of our knowledge, only three organizations have carried out research and experiments on mobile underwater multiuser communications with approximately constant velocities (the relative movement between the transducer and the hydrophone has constant velocities), which include Massachusetts Institute of Technology (MIT), Scripps Institution of Oceanography, and University of Connecticut. An application example is shown in Fig.1 (b), where three AUVs communicate with a fixed sensor simultaneously. In this case, one AUV is static, the second is moving away from the sensor at a constant velocity and the third moves towards the sensor at another constant velocity. In 2013, Stojanovic in MIT carried out research on underwater 2-user mobile communication experiments in Kauai and the coast of Massachusetts in USA. In the first experiment, the relative velocity between the transducer and hydrophone of the expected user is 1.5m/s with a horizontal distance of 2km. In the second experiment, the relative velocity between the transducer and hydrophone of the expected user is 1m/s with a horizontal distance ranging from 0.5km to 4.5km [18]. In 2013, Zhou at the University of Connecticut conducted research on underwater 2-user mobile experiments in the coast of Massachusetts in USA. The relative velocities between the transducer and hydrophone of the expected user are 1.2m/s and 1m/s with a horizontal distance between 0.5km and 4.5km, respectively [19], [20]. In the same year, Song in Scripps Institution of Oceanography carried out research on underwater 2-user mobile communication experiments in Kauai in USA. The relative velocity between transducer and hydrophone of the expected user is 1.3m/s with a horizontal distance of 1.3km [21]. We can see that the maximum relative velocity of all the experiments mentioned above is 1.5m/s. In addition, the orthogonal frequency division multiplexing (OFDM) is adopted for the communication systems in the experiments. It is noted that, in the above works, the channel state information is acquired by using a separate channel estimator at the hydrophone side. However, when the transducer and (or) hydrophone of the expected user move with variable velocities, e.g., in VMAUMC, it is very difficult to obtain an accurate channel estimate, which may thereby result in performance degradation. Hence non-coherent detection without channel estimation may be desirable.

This paper is focused on VMAUMC. Two application scenarios of VMAUMC are shown in Fig.1 (c), where three variably mobile AUVs communicate with a variably mobile AUV simultaneously, and Fig.1 (d), where two variably mobile AUVs and a fixed sensor communicate to a floated buoy simultaneously. Fig.1 (c) shows three variably mobile transducers and one variably mobile hydrophone, where their velocities change freely. In Fig.1 (d), two variably mobile AUVs and a fixed sensor are transmitters, and the receiver is a floated buoy, where the AUVs' velocities change freely. We have designed a Kalman filter-based blind adaptive multiuser detection (KF-BAMUD) algorithm to deal with the inter-symbol interference (ISI) and multiple access interference (MAI) incurred in asynchronous underwater multiuser communications [14]. In 2017, the KF-BAMUD algorithm was successfully employed for under-ice multiuser communications with rising and diving interfering users [15]. We made attempts to apply the KF-BAMUD algorithm to VMAUMC and conducted experiments in Bohai Sea in 2015 and 2016 and compared the effectiveness of the KF-BAMUD algorithm for underwater and under-ice communications. Our experiments showed that the KF-BAMUD algorithm does not work well when the transducer and the hydrophone of the expected user are variably relatively mobile due to the variable Doppler shifts within each data package, which is induced by the relative variable movement between the transducer and hydrophone of the expected user.

In this work, we propose to use a differential modulation and demodulation technique at the chip level for the underwater communication system to mitigate the impact of the different Doppler shift residues in each data package after the Doppler compensation with an average Doppler frequency offset. For VMAUMC, although Doppler shifts of two adjacent chips are not exactly the same, but they are very close because the time duration of the adjacent chips is very short. Therefore, Doppler shifts of two adjacent chips can be considered approximately the same when using differential modulation and demodulation at the chip level, which facilitates the use of the KF-BAMUD algorithm for VMAUMC and leads to a Kalman filter-based chip differential blind adaptive multiuser detection (D-KF-BAMUD) algorithm. In April 2016, we carried out VMAUMC experiments with a horizontal distance of 200m shallow-water channel between the transducer and hydrophone in the Songhua River, where the number of users is 7, the data rate is 7.87bit/s, and the variably relative velocity is up to 2m/s. The encouraging experimental results are reported in this paper, which verify the effectiveness of the proposed system and the D-KF-BAMUD algorithm.

The paper is organized as follows. The system and algorithm designs are presented in Section II. Field experiments are reported in Section III. Finally, conclusions are drawn in Section IV.

II. MULTIUSER DETECTION FOR VMAUMC

The chip-level differential modulation and detection based spread spectrum underwater multiuser communication system for VMAUMC is shown in Fig.2, where the system includes L users, and each user is assigned a unique Gold sequence for spreading. Without loss of generality, we take User1 as the expected user.

A. TRANSMITTERS WITH CHIP-LEVEL DIFFERENTIAL MODULATION

The transmitters are shown in Fig.2 (a), The information bits to be transmitted by User1 are denoted by $\{b_1(n), \ n \geq 1\}$, which take $+1$ or 1 with equal probability independently. The spreading sequence for User1 is denoted by $\boldsymbol{s}_1 = [s_1(1), s_1(2), \ldots, s_1(N_s)]^T$, where N_s is the spreading gain. After spreading, the chip sequence corresponding to the n-th information bit of User1 can be represented as

$$\boldsymbol{b}_{1n} = b_1(n)\,\boldsymbol{s}_1, \quad n \geq 1 \tag{1}$$

where $\boldsymbol{b}_{1n} = [b_{1n}(1), \ldots, b_{1n}(N_s)]^T$. Then, the chip differential operation is performed, yielding the differentially coded bit

$$d_{1n}(i) = b_{1n}(i) \oplus d_{1n}(i-1), \quad 2 \leq i \leq N_s \tag{2}$$

where $\oplus$ denotes the xor operation and $d_{1n}(1) = b_{1n}(1)$. The signal is then modulated with a carrier, i.e., the transmitted signal can be represented as

$$S_{1n}(i) = d_{1n}(i)e^{j\omega_c t}, \quad 1 \leq i \leq N_s \tag{3}$$

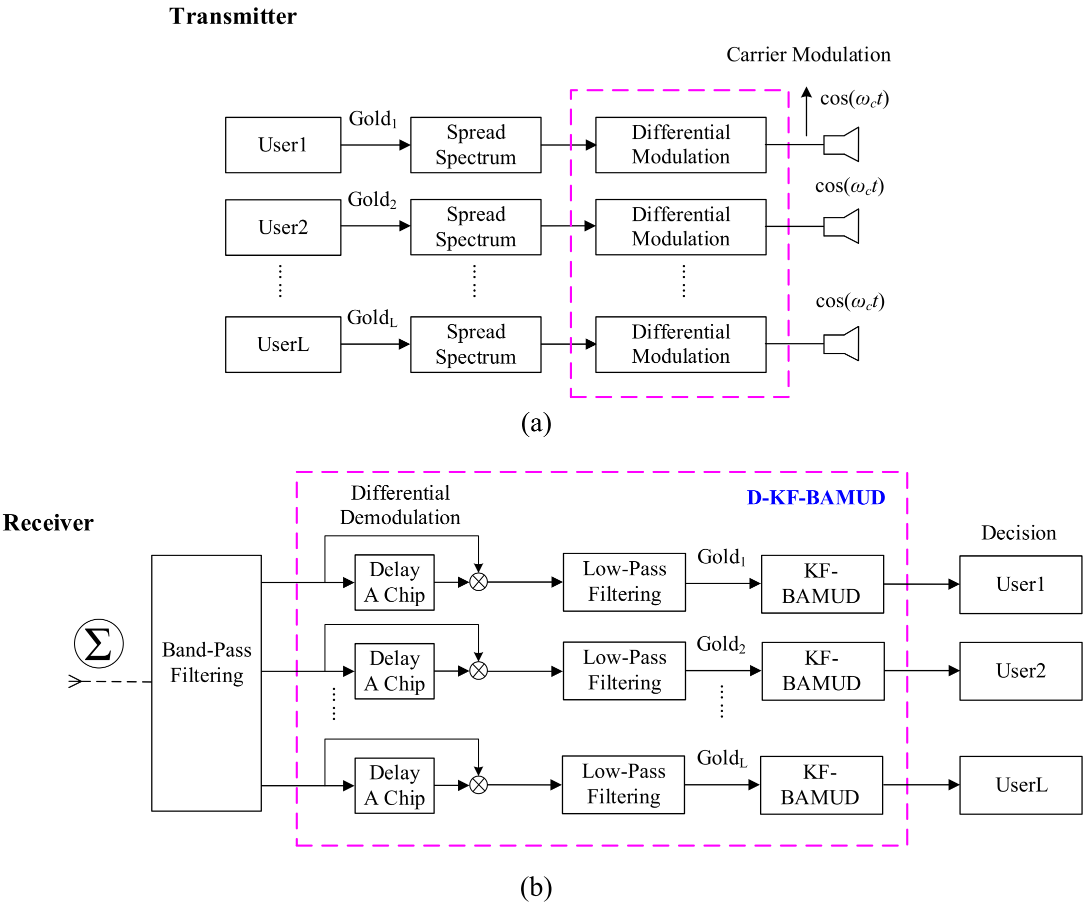
where $\omega_c = 2\pi f_c$ and f_c is carrier frequency.

B. MULTIUSER DETECTION AT RECEIVER

It is known that underwater acoustic communication suffers from multipath propagation, especially in shallow water, which induces severe ISI. We adopt a simple strategy, where the signals from distinct paths of a user are treated as signals transmitted by some virtual users. That is, the receiver treats the ISI and MAI in the same way. We use K to represent the total number of virtual users.

Let the Doppler shift for virtual Userk be Δf_k, i.e., $\Delta\omega_k = 2\pi\Delta f_k$, and the corresponding path gain be A_k, then the received signal in underwater variably mobile multiuser communications can be represented as [21]

$$r(i) = A_1 d_{1n}(i)e^{j(\omega_c+\Delta\omega_1)t} + \sum_{k=2}^{K} A_k d_{kn}(i)e^{j(\omega_c+\Delta\omega_k)t} + v(i) \tag{4}$$



(a)

(b)

FIGURE 2. **(Color online) Chip-level differential modulation and detection multiuser communication system for VMAUMC (a) Transmitters in a multiuser communication system (b) Receiver in a multiuser communication system.**

where $v(i)$ denotes the white Gaussian noise, and we deliberately separate the signal from User1 from the sum as we assume User1 is the expected user (the same way can be used to treat other users). As shown in Fig.2 (b), the differential demodulation is performed firstly, and the received chips are delayed by one chip duration T_c and then multiplied with the original chip sequence, i.e. (5), where $I' = A_1 d_{1n}(i-1)e^{j(\omega_c+\Delta\omega_1)(t-T_c)}I(i)+A_1 d_{1n}(i)e^{j(\omega_c+\Delta\omega_1)t}I(i-1)+I(i-1)I(i)$ and $I(i) = \sum_{k=2}^{K} A_k d_{kn}(i)e^{j(\omega_c+\Delta\omega_k)t} + v(i)$. Taking the real part of (5), as shown at the bottom of this page, we have (6), as shown at the bottom of this page. Then the signal is low pass filtered, which yields (7), as shown at the bottom of this page, where I'' represents the interference plus noise after low pass filtering. As the Doppler shifts of two adjacent chips are approximately the same, $\Delta\omega_1$ and $\cos\left[(\omega_c+\Delta\omega_1)T_c\right]$ can be

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$$\begin{aligned}
r(i)r(i-1) &= A_1 d_{1n}(i)e^{j(\omega_c+\Delta\omega_1)t}A_1 d_{1n}(i-1)e^{j(\omega_c+\Delta\omega_1)(t-T_c)}\\
&\quad + A_1 d_{1n}(i-1)e^{j(\omega_c+\Delta\omega_1)(t-T_c)}I(i)A_1 d_{1n}(i)e^{j(\omega_c+\Delta\omega_1)t}I(i-1)+I(i-1)I(i)\\
&= A_1 d_{1n}(i)e^{j(\omega_c+\Delta\omega_1)t}A_1 d_{1n}(i-1)e^{j(\omega_c+\Delta\omega_1)(t-T_c)}+I' \qquad (5)
\end{aligned}$$

$$\begin{aligned}
Re\left\{r(i)\,r(i-1)\right\} &= A_1^2 d_{1n}(i)d_{1n}(i-1)\cos\left\{(\omega_c+\Delta\omega_1)t\right\}\cos\left\{(\omega_c+\Delta\omega_1)(t-T_c)\right\}+I'\\
&= A_1^2\left[b_{1n}(i)\oplus d_{1n}(i-1)\right]d_{1n}(i-1)\\
&\quad \cdot\frac{1}{2}\left\{\cos\left[(\omega_c+\Delta\omega_1)T_c\right]+\cos\left[2(\omega_c+\Delta\omega_1)t-(\omega_c+\Delta\omega_1)T_c\right]\right\}+I' \qquad (6)
\end{aligned}$$

$$r'(i) = A_1^2\left[b_{1n}(i)\oplus d_{1n}(i-1)\right]d_{1n}(i-1)\frac{1}{2}\cos\left[(\omega_c+\Delta\omega_1)T_c\right]+I'' \qquad (7)$$

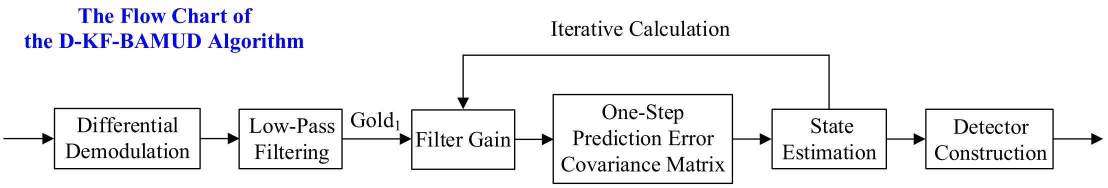


FIGURE 3. (Color online) Flow chart of the D-KF-BAMUD algorithm.

regarded as constants. Let $k_d = \cos[(\omega_c + \Delta\omega_1)T_c]$, then we have

$$\begin{aligned} r'(i) &= A_1^2\left[b_{1n}(i) \oplus d_{1n}(i-1)d_{1n}(i-1)\right]\frac{k_d}{2} + I'' \\ &= A_1^2\left[b_{1n}(i)\oplus 1\right]\frac{k_d}{2} + I'' \\ &= \frac{-k_d A_1^2}{2} b_{1n}(i) + I'' \end{aligned} \tag{8}$$

Define $\boldsymbol{y}'(n) = [r'(1), r'(2), \ldots, r'(N_s)]^T$ and $\boldsymbol{I}'' = [I''(1), I''(2), \ldots, I''(N_s)]^T$. We may use the spreading sequence $\boldsymbol{s}_1$ to extract the transmitted bits of User1 from (8) by the following correlation

$$\begin{aligned} \langle \boldsymbol{y}'(n), \boldsymbol{s}_1\rangle &= \boldsymbol{s}_1^T \frac{-k_d A_1^2}{2}\boldsymbol{b}_{1n} + \boldsymbol{s}_1^T \boldsymbol{I}'' \\ &= \boldsymbol{s}_1^T \frac{-k_d A_1^2}{2} b_1(n)\,\boldsymbol{s}_1 + \boldsymbol{s}_1^T\boldsymbol{I}'' \end{aligned} \tag{9}$$

However, it is noted that, the interference $\boldsymbol{s}_1^T\boldsymbol{I}''$ may be very significant because the orthogonality between $\boldsymbol{s}_1^T$ and $\boldsymbol{I}''$ cannot be guaranteed, and the performance can be degraded with the increase of the number of users and their amplitudes. Hence, we propose to apply the blind adaptive multiuser detection technique [22]. The detector can be represented as

$$\hat{b}_1(n) = sgn\left(\langle \boldsymbol{c}_1(n), \boldsymbol{y}'(n)\rangle\right) = sgn\left(\boldsymbol{c}_1^T(n)\boldsymbol{y}'(n)\right) \tag{10}$$

with

$$\boldsymbol{c}_1(n) = \boldsymbol{s}_1 - \boldsymbol{C}_{1,null}\boldsymbol{x}_1(n) \tag{11}$$

where, the columns of matrix $\boldsymbol{C}_{1,null}$ span the null space of $\boldsymbol{s}_1$, i.e. $\langle \boldsymbol{s}_1, \boldsymbol{C}_{1,null}\rangle = \boldsymbol{0}$, and $\boldsymbol{x}_1(n)$ is the adaptive part of $\boldsymbol{c}_1(n)$. This is inspired by the generalized side-lobe canceller to minimize the impact of the interference. It is worth mentioning that, as $\boldsymbol{s}_1$ is known, $\boldsymbol{C}_{1,null}$ can be obtained through off-line computation. The problem here is how to update $\boldsymbol{c}_1(n)$ or $\boldsymbol{x}_1(n)$, adaptively, which can be achieved using the Kalman filtering [22] by building a state equation and measurement equation. The VMAUMC system with chip level differential modulation can be treated as a slow time-varying system, and the optimal weight vector $\boldsymbol{c}_{opt1}(n+1) \approx \boldsymbol{c}_{opt1}(n)$. So, the state equation for the optimal adaptive weight vector $\boldsymbol{x}_{opt1}(n)$ can be approximately written as:

$$\boldsymbol{x}_{opt1}(n+1) = \boldsymbol{x}_{opt1}(n) \tag{12}$$

Define

$$e(n) = \langle \boldsymbol{c}_1, \boldsymbol{y}'(n)\rangle = \boldsymbol{c}_1^T(n)\boldsymbol{y}'(n) \tag{13}$$

Substituting (11) into (13), we get:

$$e(n) = \boldsymbol{s}_1^T\boldsymbol{y}'(n) - \boldsymbol{y}'^{\boldsymbol{T}}(n)\boldsymbol{C}_{1,null}\boldsymbol{x}_1(n) \tag{14}$$

Define $z(n) = \boldsymbol{s}_1^T\boldsymbol{y}'(n)$ and $\boldsymbol{H}(n) = \boldsymbol{y}'^{\boldsymbol{T}}(n)\boldsymbol{C}_{1,null}$. When $\boldsymbol{x}_1(n)$ is equal to $\boldsymbol{x}_{opt1}(n)$, we get the measurement equation

$$z(n) = \boldsymbol{H}(n)\boldsymbol{x}_{opt1}(n) + e_{opt}(n) \tag{15}$$

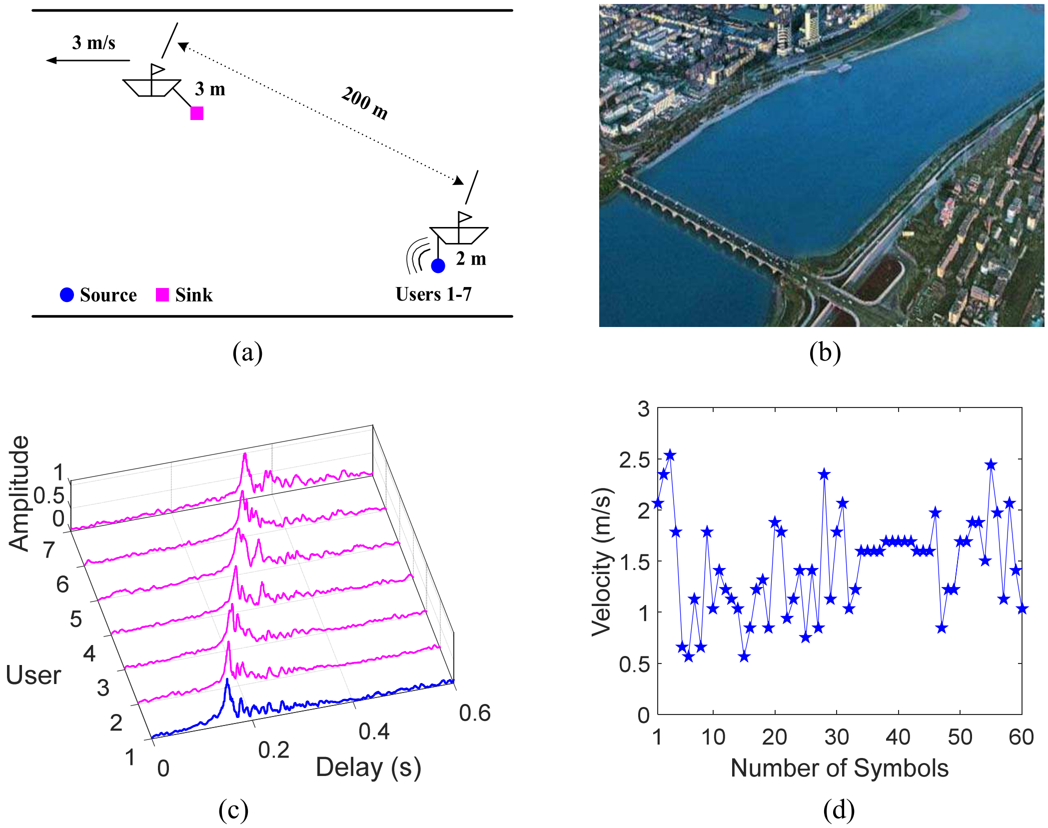
Let variance of $e(n)$ be $\xi(n)$, and $\xi_{\min}=E\left\{e_{opt}^2(n)\right\}$. From (14), the mean of $e_{opt}(n)$ is 0, and $e_{opt}(n)$ is a white Gaussian noise with mean value 0 and variance $\xi_{\min}$. Now, the multiuser detection for the VMAUMC system is transformed to the Kalman filtering problem with (12) as the state equation and (15) as the measurement equation. $\hat{\boldsymbol{x}}_{opt1}(n)$ can be found with the standard Kalman algorithm in (16), as shown at the bottom of this page, where we initialize $\hat{\boldsymbol{x}}_{opt1}(0) = \boldsymbol{0}$, $\boldsymbol{P}(1/0) = \boldsymbol{I}$ and $\boldsymbol{H}(1) = \boldsymbol{y}'^{\boldsymbol{T}}(1)\boldsymbol{C}_{1,null}$.

The flow chart of the D-KF-BAMUD algorithm is shown in Fig.3. The iterative calculation is realized by the Kalman filter algorithm in (16).

III. 7-USER UNDERWATER VARIABLY MOBILE ASYNCHRONOUS COMMUNICATION EXPERIMENTS IN SONGHUA RIVER IN APRIL 2016

Due to the limited experimental resources, only one transducer and one hydrophone were used for the field measurement. Similar to [18]–[21], the received signal for the multiuser communications is generated by superimposing the

$$\begin{aligned} \boldsymbol{H}(n) &= \boldsymbol{y}'^{\boldsymbol{T}}(n)\boldsymbol{C}_{1,null} \\ \boldsymbol{K}(n) &= \boldsymbol{P}(n/n-1)\boldsymbol{H}^{\boldsymbol{T}}(n)\left[\boldsymbol{H}(n)\boldsymbol{P}(n/n-1)\boldsymbol{H}^{\boldsymbol{T}}(n) + \xi_{\min}\right]^{-1} \\ \boldsymbol{P}(n+1/n) &= \left[\boldsymbol{I} - \boldsymbol{K}(n)\boldsymbol{H}(n)\right]\boldsymbol{P}(n/n-1) \\ \hat{\boldsymbol{x}}_{opt1}(n) &= \hat{\boldsymbol{x}}_{opt1}(n-1) + \boldsymbol{K}(n)\left[z(n) - \boldsymbol{H}(n)\hat{\boldsymbol{x}}_{opt1}(n-1)\right] \\ \boldsymbol{c}_1(n) &= \boldsymbol{s}_1 - \boldsymbol{C}_{1,null}\hat{\boldsymbol{x}}_{opt1}(n) \end{aligned} \tag{16}$$



(a) (b)

(c) (d)

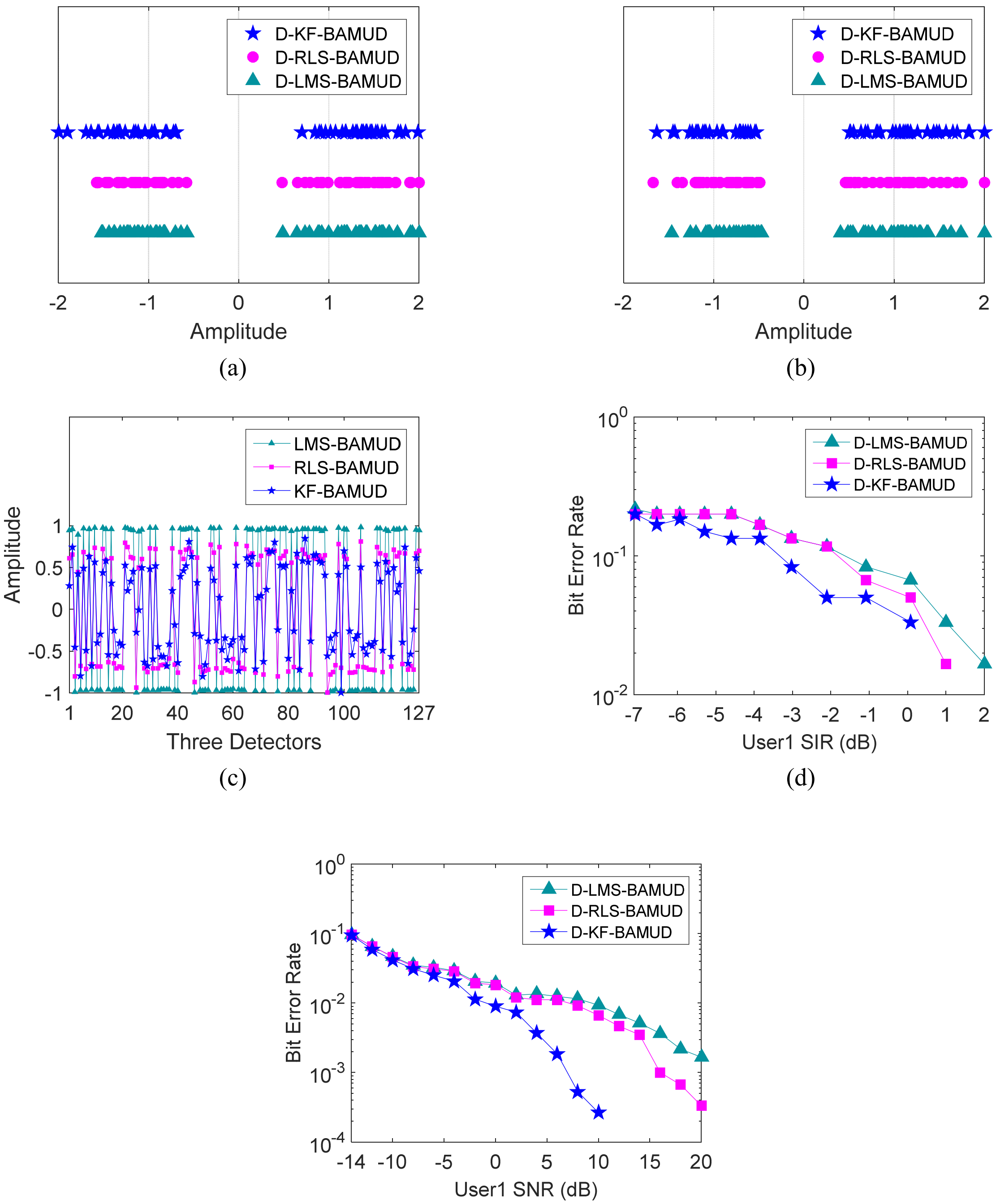
FIGURE 4. **(Color online) Deployment, testing scene, channels and variably relative velocities of the VMAUMC experiments in Songhua River (a) Field deployment (b) Testing scene (c) Channel impulse responses (d) Variably relative velocities of the estimated transmitted symbols.**

collected data from the field measurement asynchronously. In each experiment, for the carrier demodulation of each user, we used an average phase to compensate the phase deviation and the average phase was estimated using a pilot sequence. The arrival time of the expected User1 is used as the benchmark, and the power of interfering users is artificially changed by scaling their signals so that different signal to interference ratios (SIRs) of User1 can be obtained. BPSK (Binary Phase Shift Keying) was used for all the experiments and the spreading gain 127. The SIR is defined as

$$SIR(dB) = 10\log_{10}\left(\frac{P_{ExpectedUser1}}{P_{InterferenceUsers}}\right) \qquad (17)$$

where $P_{ExpectedUser1}$ and $P_{InterferenceUsers}$ are the power of the expected User1 and the total power of the other users, respectively. A 7-user experiment was carried out in Songhua River in April 2016. Deployment and testing scene of the VMAUMC experiments in Songhua River are shown in Fig.4 (a) and (b). The transducer was deployed at a fixed location, and it transmitted 7 packages of data to simulate 7 users, while the hydrophone moved away from the transducer with about 3m/s. The original distance between the transducer and hydrophone was about 200m and the river depth was about 6m. Carrier frequency was 2.5kHz, sampling frequency was 16kHz and the bandwidth was 1kHz. Each user transmitted 60bit within a duration of 7.62s, i.e., the data rate was 7.87bit/s. Channels of the experiments are shown in Fig.4 (c), where the blue stars represent the channel of the expected User1 and pink lines represent the channels of the interfering users. Variably relative velocities of the estimated symbols during one data packages (60 bit) are shown in Fig.4 (d), where the maximum velocity difference is about up to 2m/s.

The experimental results of the Songhua River multiuser communications are shown in Fig.5, where, besides D-KF-BAMUD, we also implement and test the performance of RLS-BAMUD and LMS-BAMUD with differential modulation (denoted by D-RLS-BAMUD and D-LMS-BAMUD). For the single user and multiuser cases, BERs are 0, and their constellation plots are shown in Fig.5 (a) and (b), where it can be seen that the performance of the D-KF-BAMUD algorithm is the best among the three algorithms for mitigating ISI and MAI. The output of the detectors with SIR = 2dB is shown in Fig.5 (c) and the BERs of the expected User1 versus SIR are shown in Fig.5 (d). We fixed SIR at 2dB and added random Gaussian white noise artificially to adjust the SNR of the expected User1 and tested 60 data packages. The BERs of the expected User1 versus SNR are shown in Fig.5 (e). It can be seen that the D-KF-BAMUD algorithm works well for VMAUMC, and it delivers the best performance for mitigating ISI, MAI and Doppler shift residues among the three kinds of algorithms.



(a) (b) (c) (d) (e)

FIGURE 5. (Color online) VMAUMC experimental results in Songhua River (7 users) (a) Constellation plot of single user communication (b) Constellation plot of multiuser communication with SIR = 2dB (c) Detector output with SIR = 2dB (d) BERs of the expected User1 versus SIR (e) BERs of the expected User1 versus SNR.

IV. CONCLUSION

In this paper, we have proposed an underwater multiuser communication system with chip level differential modulation and the corresponding D-KF-BAMUD algorithm for VMAUMC. In the proposed receiver, ISI is treated as MAI, so that ISI and MAI are handled simultaneously. The differential modulation at the chip level is used to reduce the effect of Doppler shift residues within the data package after the Doppler compensation, which facilitates the use of a Kalman-based blind adaptive multiuser detection without channel estimation. The VMAUMC experiments have been carried out in Songhua River and the good experimental results demonstrate the effectiveness of the proposed system and algorithm.

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