An OFDM based Channel Aware Access Protocol for Underwater Acoustic Networks of Submarine Pipeline Monitoring

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***Abstract*—Focused on underwater wireless acoustic communication and networks for data collection, this paper proposes a channel aware multichannel protocol for deep water pipeline monitoring system, where multiple sensor nodes report monitoring information to the drilling platform in the dynamically selected channel with subcarrier adaptive modulation. A two-stage channel selection and adaptive modulation protocol with both statistic and instantaneous channel information is proposed to optimize system performance. This scheme can be used in both vertical and horizontal pipeline monitoring system, and can be easily expanded to a common data collection network. Simulation results have shown its improvement compared to traditional FDMA scheme with random channel access.**

***Index Terms*—Channel aware, multichannel access, OFDM, FDM, underwater acoustic, submarine pipeline**

I. Introduction

Underwater acoustic (UWA) communication and networking has gain more and more popularity ranging from military to industry, and one of the most important application is monitoring underwater oil-gas drilling system. As the submarine oil-gas exploration has moved to deeper and deeper water, the pipelines suffer from harsh deep sea environments, whose fatigue status needs to be monitored to guarantee continuous safe production. As shown in Fig. 1, the pipelines are located in vast sea area to transport oil or gas from drilling wells to the surface platform, and a series of sensors nodes are distributed to collect information including water motions, riser fatigue etc. for realtime monitoring. For single user wireless UWA communication of submarine pipeline monitoring, experiments have been successfully taken in Chinese 981 oil drilling platform, and an efficient multi-user access scheme is crucial for the multiple nodes monitoring system.

There are several research focuses lie in underwater pipeline monitoring, including discussion of wired and wireless methods [1], failure area coverage with automatic vehicle (AUV) [2], and parallel data transmission in OFDMA [3]. This paper focuses on underwater monitoring data collocation by acoustic networks, with sufficient consideration on the unique characteristics of UWA channel. In [4], the attenuation loss which related to both transmission distance and carrier frequency is used for channel selection. But the consideration of channel condition only includes the attenuation loss, ignoring the channel fading varying. A TFO-MAC protocol [5] is proposed

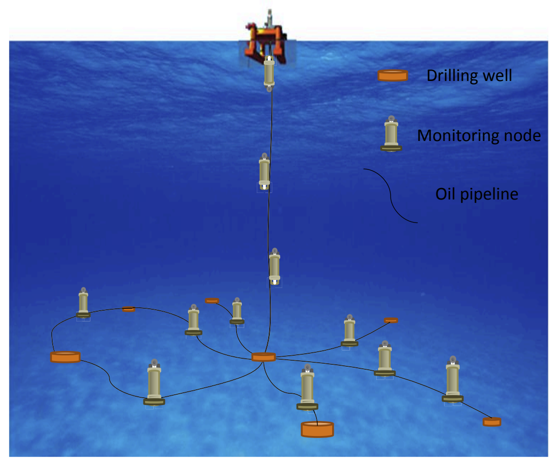

Fig. 1. Deepwater oil-gas pipelines monitoring system.

to jointly optimize the channel assignment, transmission mode and power. But it did not well address practical application issues, such as the number of channels, acquisition of channel information, delay of handshake, and so on. Our previous work [6] has shown the benefit of dynamic resources allocation with feedback channel state information (CSI), and both channel statistics and delayed CSI feedback were investigated with field tests.

In this paper, we proposed an orthogonal frequency division multiplexing based frequency division multichannel media access (OFDM-FDMMA) protocol for sensing data collection, where the multiuser channel selection based on long term CSI statistics is used to explore multiuser frequency diversity. Further, carrier adaptive modulation OFDM based on handshaking feedback is employed in each sub-channel to optimize channel capacity and network throughput. Compared to previous works, this paper considers both frequency dependant path loss and frequency selective fading, both statistics CSI and delayed feedback CSI, and all assumptions are reasonable which depends our previous tests.

The remainder of this paper is organized as follows. Section II introduces the channel model. Section III shows the multichannel access protocol. Section IV presents channel selection and further inner channel adaptive modulation algorithms.

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Section V compares the performance of different schemes by simulation. Section VI concludes this paper.

II. Channel model

There are some specific features of underwater channel, such as water absorption, low sound speed and various noise sources. The underwater acoustic wave transmission is affected by these characteristics and resulting in large scale fading e.g. path loss, small scale fading e.g. multipath fading, and complicated ambience noise.

Distinguish from electromagnetic channel, the underwater acoustic channel exhibits frequency dependant attenuation. The transmission loss $A(d, f)$ depends on both carrier frequency f and distance d, and mainly includes spreading loss of signal and absorption loss from water. In UWA communication, define $Q^2(d, f)$ as the attenuation gain, which can be written as [5]

$$Q^2(d, f) = A^{-1}(d, f) = A_0^{-1} d^{-sf} (a^2(f))^{-d}, \quad (1)$$

where A_0 is the normalizing constant, sf is the spreading factor whose value is empirically 1.5, and $a^2(f)$ represents the absorption coefficient at the frequency f which can be approximated by Thorps formula as

$$10\log a^2(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \cdot 10^{-4} f^2 + 0.003. \quad (2)$$

where f is in kHz and $a^2(f)$ is in dB/km.

The UWA channel impulse response (CIR) with multipath effect can be modeled as

$$h(\tau) = \sum_{p=1}^{P} h_p(\tau)\delta(\tau - \tau_p), \quad (3)$$

where P is the total number of paths, h_p and τ_p is the amplitude and delay of pth path, respectively. Its corresponding channel transfer function is

$$H(\tau, f) = \sum_{p=1}^{P} h_p(\tau) e^{-j2\pi f \tau_p}, \quad (4)$$

where f is the carrier frequency. Due to the low sound propagation speed, the multipath delay in the water is very large, and typically in dozens of milliseconds. The severe multipath effect usually causes frequency selective fading.

For multicarrier modulation system with wide bandwidth, on one hand, attenuation across the signal bandwidth is not flat, and depends on the carrier frequency. On the other hand, instantaneous channel transfer function is also frequency dependant, which comes from different arrival time of the delay paths. Considering these two effects, the frequency dependant UWA fading channel transfer function can be given by [6]

$$G(d, t, f) = Q(d, f)H(t, f). \quad (5)$$

In this paper, the channel model is used for wide band UWA system. For a narrow band system, $Q(d, f)$ can be seen as a constant.

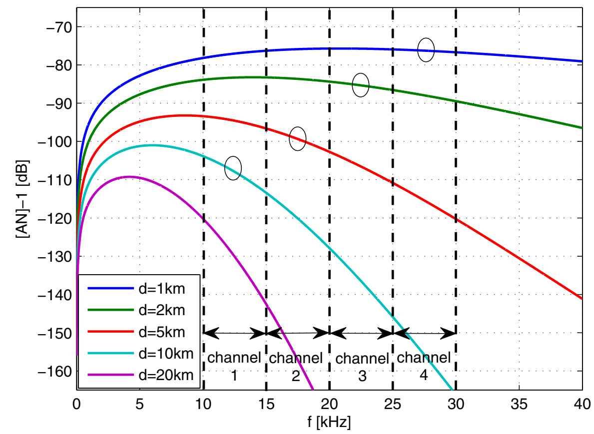

Fig. 2. AN factor.

The UWA noise power spectral density (PSD) is frequency dependant, and can be expressed by Wenz model as

$$N(f) = Nt(f) + Ns(f) + Nw(f) + Nth(f), \quad (6)$$

where the right hand side denotes the superposition of four contributions: turbulence (Nt), shipping and other human activities (Ns), wind and waves (Nw), and thermal noise in the receiver circuitry (Nth). An empirical expression is approximated by

$$10\log N(f) = 50 - 18\log f. \quad (7)$$

OFDM is an efficient multicarrier technique for UWA networks [7], the channel input output relationship for carrier k in block n at a certain communication distance is

$$Y_{n,k} = \sqrt{\gamma}\, G_{n,k} X_{n,k} + N_{n,k}, \quad (8)$$

where $\sqrt{\gamma}$ is the transmission power scaling factor, and $X_{n,k}$ and $Y_{n,k}$ is transmitted and received symbol, respectively. And the corresponding signal to noise ratio (SNR) can be expressed as

$$\eta = \frac{\gamma \cdot Q^2(d, f_k)\,|H(n, f_k)|^2}{N(f_k)\Delta f} = \frac{\gamma \cdot |H(n, f_k)|^2}{A(d, f_k)N(f_k)\Delta f}. \quad (9)$$

where f_k is the frequency of carrier k. Without considering of multipath effect, the channel state is determined by $Q^2(d, f_k)/N(f_k)$, and that equals to $[A(d, f)N(f)]^{-1}$ which is named attenuation-noise (AN) factor. As the attenuation $A(d, f)$ increases with frequency while $N(f)$ decreases, the inverse of the product of the two factors has a maximum on some frequency f_0. This maximum represents the best frequency to employ to transmit the tone. In a multiuser system, the users usually transmit in different distances, and the corresponding best frequency with minimum loss for each user varies. Furthermore, in a wide band system, each user has its own better frequencies or sub-bands for reliable communication. This specific feature is the motivation of dynamically channel selection in distributed underwater multiuser networks.

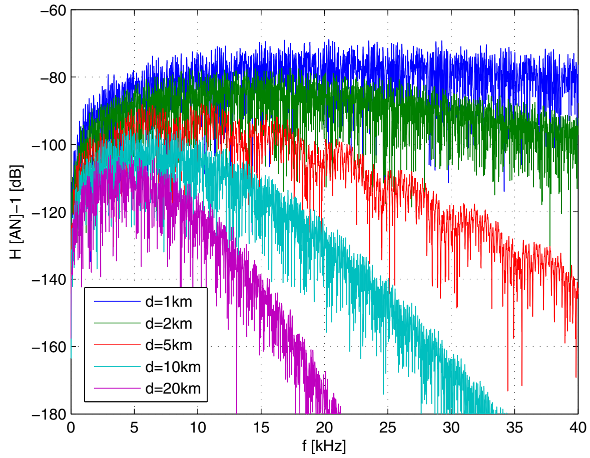

Fig. 3. Channel factor F.

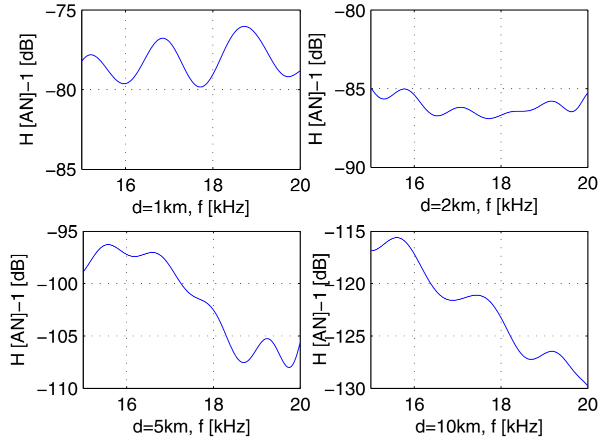

Fig. 4. F in a sub-channel.

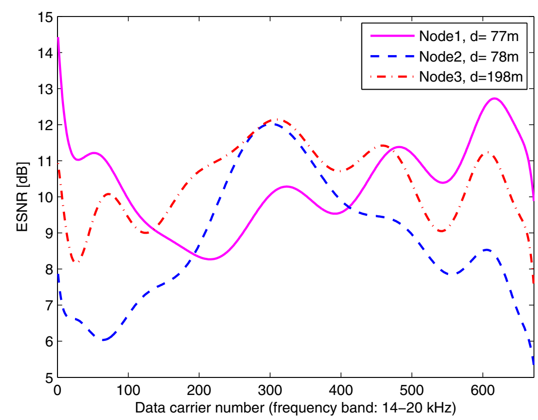

Fig. 5. Average SNR, @ Mansfield Hollow Lake, CT, USA.

In a frequency division media access (FDMA) scenario, all the sub-channels can be allocated to users according the the sensed channel status for improving system performances. One example illustration is shown in Fig. 2. We can observe that the user at different distance has its best carrier frequency, and path losses of large distance users on higher frequencies are extremely heavy. In a 4-user 4-sub-channel network, assume the distances of users to a common destination are 1 km, 2 km, 5 km, 10 km, respectively. The optimal channel allocation is marked by circles as shown in Fig. 2, which presents that the users with large distance should choose channels with lower frequency to reduce transmission loss. For users with small distance, the loss on each channel does not varies much.

For further consideration of combination of $H(f)$, which indicates frequency selective fading, define a channel factor as $F(n, d, f_k) = |H(n, f_k)|^2 / [A(d, f_k)N(f_k)]$. To generate $H(f)$, in real field application the multipath can be calculated by BELLHOP model if the topography and water parameters are available. In this paper, without loss of generality, the simulated multipath channel has 10 randomly discrete paths, whose amplitudes follow Rayleigh distribution and maximum path delay is 15 ms. No Doppler effect is considered as so far. Fig. 3 presents the channel factor in d and f. It can be seen that channel factor varies with both carrier frequency and communication distance, and multipath fading keeps varying among the neighboring carriers. There are two observations can be made. Firstly, for two users with likely distances from destination, the channel condition in the same sub-channel still could be quiet different which depends on the multipath fading situation. Even for users with likely distance and similar path loss, the channel selection is necessary. Secondly, the frequency selective fading is obvious. To validate the inner sub-channel fading property, we plot an enlarged figure of F in one sub-channel as shown in Fig. 4. The data was polynomial fitted for a smoothing point of view. Compared to the average SNR of a lake test in similar bandwidth shown in Fig. 5, the variation of channel appears coincident. With this observation of sub-channel, the subcarrier adaptive modulation can be adopted to improve sub-channel capacity.

III. A TWO-STAGE CHANNEL AWARE ACCESS SCHEME

In a channel aware network, how to acquire CSI is one of the most critical issues. Handshaking among users is a natural approach to exchange control information and gather channel information. For obtaining channel information, it is unrealistic to carry out handshakes in all sub-channels with all the monitoring nodes for each data burst, as it takes too much time. In the previous sea and lake tests with our wide-band OFDM modems [6], the long term average SNR is stable as shown in Fig. 2, and the PDF distribution in [8] also approved this observation. So it is reasonable to use statistic channel information for sub-channel allocation. As the average value will drift [8] in the long monitoring period with sea environment varying, it is necessary to set up a maximum time T_s for collecting latest statistic information, and all the outdated SNRs will be discarded.

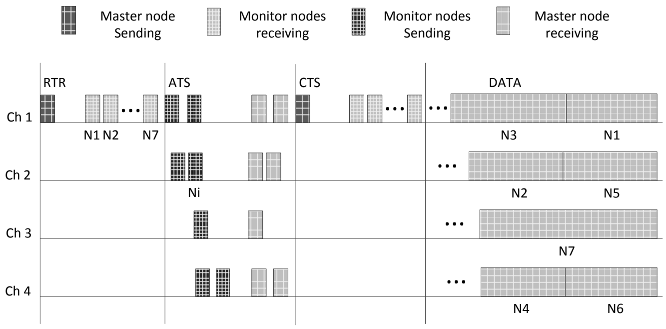

Fig. 6. The example of handshake on 4 channels with 7 users.

We consider a single-hop UWA network with one master node in charge of data collection and several monitoring nodes for data reporting. The monitoring nodes can tune to any one of the channels at a time, and the master node can simultaneously overhear all the sub-channels which have multiple hydrophones installed. Taken the cost and implementation complexity into account, assume there are a few OFDM sub-channels, e. g. 4-6, and suppose there are 7-15 monitoring nodes in a 10km×10km oilfield without loss of generality [3]. As the underwater acoustic attenuation is proportional to the carrier frequency, we choose the lowest frequency band as control channel, and the others are data channels.

Assume the data bursts are delivered in frame. One frame is consisted of two sections, initialization section and data exchange section. The initialization section collects information for initial statistic sub-channel allocation. The data exchange section includes two stages, one is handshake on the allocated sub-channel to obtain instantaneous CSI, update long term statistic channel information and perform sub-channel allocation. and another is adaptive bit loading of subcarriers within each sub-channel based on the handshake feedback in the ongoing stage to optimize channel capacity to improve system throughput.

In the frame initialization section, the master node would exchange messages with every monitoring nodes at all sub-channels for a number of rounds to obtain the statistic channel status information and propagation delay information for channel and transmitting time arrangement. With the statistic sub-channel information, the objective of channel selection is to find the set of sub-channels to optimize the channel condition of overall system as

$$\mathcal{S}^* = \arg \max_{\mathcal{S}} \sum (\mathbf{H} \cdot \mathbf{I}). \tag{10}$$

where $\mathbf{H}$ is the SNR matrix of users on sub-channels, $\mathbf{I}$ is a matrix whose element is either 0 or 1 to indicate if a channel is chosen by a certain user. The initial channel allocation result will be employed in next section.

In the data exchange section as shown in Fig. 6, at the first stage, mater node broadcasts a request-to-receive (RTR) message with channel allocation information, and then each monitoring node would reply an available-to-send (ATS) in the predetermined sub-channel. Additionally, time control is employed to ensure all ATSs arrive without collision and within minimum access time, and the closer user has higher priority to access the destination. Especially, with time control mechanism, each node can access the master with minimum delay, which is important for obtaining delayed channel information. For example, a user at $d = 3km$ can access destination about at least 2 seconds, which can better guarantee the correlation between feedback and real CSI [6]; for a far away user, large delay is tolerable as the channel is more affected by path loss. The master node can obtain the instantaneous SNR with latest ATSs, update the statistic SNR, discarding outdated record, and perform the solution algorithm to update the optimal channel allocation result. In the second stage, the maser node generates an optimal bit loading schedule for each user according to the received instantaneous SNR, and then announce the schedule by a clear-to-send (CTS) message to all monitoring nodes. A typical single user bit loading can be adopted. At last the monitoring nodes receive allocation information from CTS and send bit loaded adaptive modulation data symbols in the corresponding channel. The data exchange section is repeated until one monitoring data burst has been transmitted, or the sensed channel varies so sharply that a channel statistical handshake will restart.

IV. Channel selection and optimization

We assume there are N_u data nodes and N_{ch} sub-channels in the monitoring network. Each node is assigned one sub-channel for data collection, and multiple users could share a channel in time division method. Recall that the user' sub-channel capacity depends on CSIs of data carriers, and the indicator SNRs depend on distance and multipath fading scale. All algorithms we describe are based on these concepts. Notice that due to the particular shape of the AN factor, it is not possible in general for each user to be assigned its optimal channel. Furthermore, the distance related effects enhance the channel performance for near users. A near user will achieve a fairly high capacity even when using a sub-optimal channel, whereas a far user may experience very low capacity unless it is assigned a sufficiently low frequency channel. Therefore, a general optimization algorithm should be addressed which ensures the capacity of far users (that may have very low capacities in some sub-channels), without sacrificing too much capacity of nearer users. The algorithm we describe explores the concept of greedy allocation so that the minimum performance experienced among all users is maximized at every optimization step.

In this paper, we present a sub-optimal algorithm for multiuser channel selection, where the sub-channel c for user u with the lowest capacity is removed at each step, and related checking is conducted to ensure the effectiveness. The algorithm works in loops, where in each loop all channels are greedily assigned once to N_{ch} users. After removed the users who have already got channels, it goes to another allocation loop until each user has been allocated a sub-channel. The algorithm works as follows:

1) Set initial available channel indicator matrix $\Delta = \text{ones}(N_u, N_{ch})$, set channel allocation matrix $\mathbf{I} = \text{ones}(N_u, N_{ch})$, and available channel SNR matrix as $\mathbf{H}a = \mathbf{H} \cdot \Delta$.
2) Find the minimum SNR $\eta_{u,c}$ in $\mathbf{H}a$ and its index, and set $i_{u,c} = \delta_{u,c} = 0$ to mark the channel c for user u is unavailable.
3) Check if the remaining matrix is a feasible solution and update the matrix for next round. Check if user u still has channel to choose, if $\sum_{c=1}^{N_{ch}} \delta_{u,c} \neq 0$, keep $i_{u,c} = 0$, and goto a); else, reverse $i_{u,c} = 1$, and goto b).
   a) Check if there is only one channel left for user u, if $\sum_{c=1}^{N_{ch}} \eta_{u,c} = 1$, the left channel is the only choice of user u, set the corresponding i_{u_j,ch_j} to be 1, and set all the other channel indicators of channel c to be 0. Check if there is only one user can choose channel c, if $\sum_{u=1}^{N_u} \eta_{u,c} = 1$, the channel should be chosen by the left user, set the corresponding i_{u_j,ch_j} to be 1, and set all the other channel indicators of user u to be 0. Update $\mathbf{H}a$.
   b) $i_{u,c}$ is included in the solution, set the other indicators except $i_{u,c}$ at column u row c to be 0, and update $\mathbf{H}a$.
4) If all the channels have been occupied, remove the user information which has already has assigned channel; else go back to step 2) until each user has its sub-channel be chosen .

In the inner channel subcarrier adaptive modulation, a typical single user greedy algorithm can be carried out directly by assigning one bit at a time to the subcarrier which requires the least additional power.

V. Simulation

We assume one specific geographical area with 10 km radius to conduct simulations, where there are at most $N_u = 10$ underwater sensor nodes and one destination in the center. The channels are generated as in Section II and the acoustic transmission power defined in dB as sound source level (SL) is set to be 120 dB. The user distances are randomly generated. The sub-channel bandwidth is the same as Fig. 2, the number of efficient data carrier (except null and pilot carriers) in a sub-channel is 512 and the payload is 1024 bits for each OFDM block. For the adaptive bit loading, BPSK, 4-QAM, 8-QAM, and 16-QAM are adopted as limited constellations, and 4-QAM is the reference for equal bit loading.

We compare three schemes: a). random channel access, b). adaptive channel access without OFDM subcarrier adaptive modulation c). adaptive channel access with OFDM subcarrier adaptive modulation. Fig. 7 has shown the throughput of network in different number of users in the monitoring area. The dynamic channel aware selection outperforms random access, and additional improvement has achieved by adaptive modulation of data carriers within inner sub-channel .

VI. Conclusion

This paper presented a multiuser channel aware adaptive OFDM-FDMMA system for underwater data collection in a pipeline monitoring network. A channel model which includes both path loss and multipath fading was used for evaluation, and a frame based two-stage allocation protocol was proposed with both statistic and instantaneous channel state information. A max-min channel allocation algorithm was proposed for sub-channel selection, and the bit loading algorithm was used for inner channel capacity optimization. Simulation results shown the advantages of adaptive channel allocation and channel allocation with subcarrier adaptive modulation for the OFDM-FDMMA system.

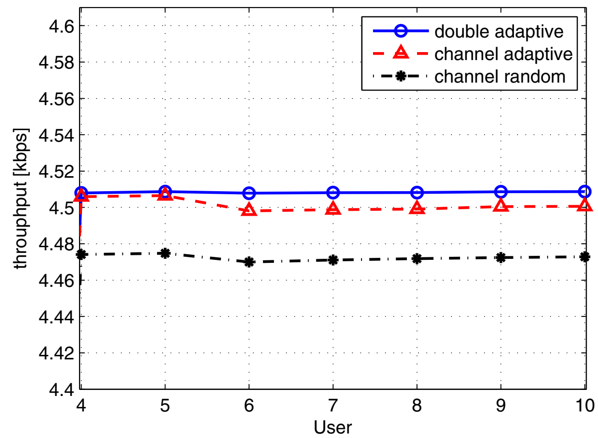

Fig. 7. System throughput.

Acknowledgment

The authors are supported by the National Science and Technology Major Project of China (2011ZX05026-001-06), and the Fundamental Research Funds for the Central Universities (3102015BJ015). They thank Prof. Shengli Zhou for his related discussion on this paper.

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