User Density in a Cluster Underwater Acoustic Network

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Abstract - It is well known that a Code Division Multiple Access (CDMA) scheme achieves higher user density in a cellular network with radio frequency signal in a terrestrial environment than either Time Division Multiple Access (TDMA) or (Frequency Division Multiple Access) FDMA could. The concept of a cellular (cluster) network has been introduced for underwater acoustic communications. However, its performance has not been investigated thoroughly. Due to the significant differences between the two propagation environments, the conclusions derived in terrestrial channel could not be extended to an underwater one. This paper investigates the user density difference among CDMA, TDMA and FDMA schemes in a cluster type acoustic network applied to an underwater environment. Close-form formulae are given for both ideal and realistic environments. We find that the user density of CDMA is primarily affected by intra-cluster and inter-cluster interference while that of TDMA/FDMA is determined by the total available bandwidth. We also find that when spreading factor is 2, CDMA achieves higher user density than TDMA/FDMA if the required receiving signal quality is below a certain level and guarding time/frequency has to be added into TDMA/FDMA in real underwater environment. This research gives one theoretical direction to design future topology and protocols for underwater acoustic networks. This work is supported by the Office of Naval Research.

Index Terms: Underwater Acoustic Network (UAN), Code Division Multiplexing Division (CDMA), Time Division Multiplexing Division (TDMA), Frequency Division Multiplexing Division (FDMA), Cluster, User Density

1 INTRODUCTION

There are many research efforts to compare the performance of CDMA scheme with that of TDMA/FDMA in a Radio Frequency Network (RFN) [1][2][3][4][5][6][7][8]. CDMA can achieve higher user density than either TDMA or FDMA does in a cellular (cluster) RFN [9]. It is because the performance of TDMA or FDMA is resource (time & bandwidth) restricted, while that of CDMA is interference restricted. The resource is limited; contrastingly, the interference level can be reduced by controlling transmission power. Consequently, the user density of CDMA increases.

There are significant differences between the propagation environments of underwater acoustic signal and terrestrial radio frequency one [10][11][12][13][14][15][16][17]. From a network’s aspect, the significant one is as follows [18]:

1) Long propagation delay, due to the slow acoustic signal propagation speed in water medium, which affects link/network protocol design;
2) Very limited bandwidth;
3) Very limited energy;
4) Unstable link condition; and
5) Transmission loss is frequency/environment dependent.

Due to aforementioned difference, this conclusion drawn from RFN cannot simply be extended to an underwater acoustic network. For example, instant power control becomes impossible; transmission power loss is frequency/environment dependent; and, significant guarding time and frequency should be included in TDMA and FDMA due to the long propagation time and Doppler shift/spread, respectively, in the underwater environment. Will CDMA still perform better than TDMA or FDMA in realistic underwater environment? If not, what is its root cause? Such questions remain unanswered. It motivates us to study how CDMA/TDMA/FDMA work in a UAN in the sea environment.

Topologies can be classified into two categories, i.e., centralized and distributed types. In the former, a data packet from a leaf node goes through an infrastructure node (central node, for example) to arrive at other nodes. The infrastructure node plays a central role in the network, e.g., resource allocation and traffic control, etc.; while in the latter, also called an ad hoc topology, an infrastructure node is not needed and all nodes are peer-to-peer related; multi-hop is used among peer nodes to transport messages from a source to a destination. It is shown that cluster networks have revolutionized terrestrial mobile communications by bringing into the concept of spatial frequency reuse [19]. By re-using the same frequency band in several clusters that are sufficiently far enough to bring in inter-cluster interference, a large area can be covered with the constraints of finite bandwidth. The concept of cellular type underwater network is also introduced in [19] and system capacity is analyzed by cell radius and frequency reuse. Since bandwidth is extremely limited in underwater acoustic communications, reusing bandwidth is not only appealing but also necessary in the underwater environment. Consequently, the questions naturally arise: 1) how to apply the concept of clusters to a UAN? and, 2) how a cluster UAN performs in the underwater environment? These two questions are related and the answer of the latter one is the foundation of the first one.

CDMA, TDMA and FDMA are three essential multi-access schemes and have been widely deployed in RFN. Their performance is well known. However, their performance as multi-access technologies in UANs is not well known yet and systematic investigation is needed.

The main purpose of this paper is to investigate the performance (user density) of different multi-access schemes, e.g., CDMA, TDMA, and FDMA, in a cluster type network applied to an underwater environment, such that we know their pros and cons accurately with quantitative information, which is needed to design a network system. In the remaining of the paper, Section 2 gives some concepts of cluster UANs; Section 3 analyzes the user density of CDMA scheme. The performance of TDMA/FDMA schemes is compared with that
of CDMA in Section 4. Section 5 gives the numerical results. Finally, the conclusions are drawn in Section 6.

## 2 USE DENSITY ANALYSIS OF DIFFERENT MULTI-ACCESS SCHEMES

In this paper, a cluster type UAN is defined as a network with one gateway node and a few distributed nodes inside a cluster. We assume that the cluster shape is hexagonal in this paper. The message from distributed nodes is sent to the gateway node.

Without loss of generality, we assume that each cluster has the same coverage area $S$, and its radius is $r$. Node density is $\rho$ in each cluster, i.e., each cluster has the same number of nodes. We further assume that nodes are uniform distributed inside a cluster, and there are near infinity clusters in the whole network system.

To simplify the analysis, we do not consider the effect of sectors as that in RF cluster networks. We further assume that power control strategy is not implemented and each node transmits with the same power density.

To simplify the analysis, we use a simple channel model in the following sectors in which the path loss is a function of travel distance and frequency, and it is given as [12]:

$$A(d, f) = A_0 d^k [a(f)]^{1/\alpha}$$

where $A_0$ is a normalized constant, $k$ is the spreading factor, $d$ is the distance, and $a(f)$ is a frequency dependent absorption coefficient. There is an empirical equation for $a(f)$ in dB per kilometer as shown in Fig. 1:

$$10 \log_{10} a(f) = 0.11 f^{-2} / (1 + f^{-2}) + 44 f^{-2} / (4100 + f^{-2}) + 2.75 \cdot 10^{-4} f^2 + 0.003$$

(1)

![Fig. 1 The absorption coefficient vs. frequency [11]](image)

### 2.1 User density of CDMA scheme in a cluster type UAN

Without loss of generality, we pick up a cluster randomly and name it cluster 0, which is shown in Fig. 2. Interfering neighboring nodes can be classified into four categories:

i. Boundary clusters that ranges from clusters 1 to 6; they are clusters that bound cluster 0.

ii. Clusters next to the boundary clusters, whose centers are $4r$ away from the center of cluster 0, ranging from clusters 7-12.

iii. Clusters next to clusters 7-12, whose centers are $\sqrt{12}r$ away from the one of cluster 0, ranging from clusters 13-18.

iv. Other clusters do not belong to categories i-iii.

In a CDMA scheme, a node is assigned with a unique code to pre-spread a data message before sending. The intended receiver knows the code beforehand, so it can despread the “spreaded” message properly. Since the codes allocated to each sending node are orthogonal to each other, the “spreaded” message becomes wideband noise, instead of narrow band interfering signal, at other receiving nodes.

Assume a central node is located at the center of their clusters. At cluster 0, assume that node 0 is talking with the central node. The interference comes from the following sources:

1) Intra-cluster interference, caused by the transmission of other nodes inside cluster 0.

2) Inter-cluster interference 1, caused by the transmission of other nodes in boundary clusters 1-6.

3) Inter-cluster interference 2, caused by the transmission power of other nodes in clusters 7-12.

4) Inter-cluster interference 3, caused by transmission from other nodes in clusters 13-18.

5) Inter-cluster interference 4, caused by transmission from other nodes in all clusters other than inter-cluster interference 1 - 3.

Due to the much longer propagation time of acoustic signal in water, real time power control is hard to achieve in the underwater environment, which is different from RF networks. Correspondently, we assume that each node transmits with the same power density and we further assume that each node has the same activity factor. Without losing generality, we also assume that the transmission power of each node is 1 and activity factor is 1; i.e., propagation loss is the only factor to affect the receiving power. Consequently, the receiving $\text{SNIR}$ at the central node of cluster 0 from node 0 is:
in which, $G$ is the processing gain achieved by dispreading signal. $P_s$ is the received transmission power of node 0 at the central node of cluster 0. $P_{0i}$ is the interference introduced by other nodes’ transmission inside cluster 0. $P_i$ is caused by nodes’ transmission in clusters 1-6 (boundary clusters). $P_2$ is the receiving signal power from nodes in clusters 7-12 at cluster 0’s central node. $P_3$ is introduced by the receiving signal power of nodes in cluster 13-18 at the central node of cluster 0. $P_4$ is produced by nodes in other clusters that are more than two “rings” away from cluster 0. $P_N$ is the ambient noise power in the underwater environment.

$P_s$ can be expressed as:

$$P_s = \int_{f_{\text{max}}}^{f_{\text{min}}} \frac{1}{A_i d_i^k a^d (f)} df$$

where $f_{\text{min}}$ is the lower bound of the frequency band, $f_{\text{max}}$ is the upper bound of the frequency band, and $d$ is the distance from node 0 to central node of cluster 0. Note that, the bandwidth $B = f_{\text{max}} - f_{\text{min}}$. $P_{0i}$ is expressed as:

$$P_{0i} = \int_{f_{\text{max}}}^{f_{\text{min}}} \frac{1}{A_i d_i^k a^d (f)} dfdfA \approx \int_{f_{\text{max}}}^{f_{\text{min}}} \frac{1}{A_i d_i^k a^d (f)} dfdfA$$

where $\rho$ is the node density of cluster 0 excluding of node 0, $d_i$ is the distance from node $i$ in cluster 0 to the central node at cluster 0, $0 \leq i \leq N-1$. $N = \rho \cdot S + 1 = \rho \cdot S$, $S$ is the area of the cluster inside which nodes are located. When $N$ is big enough, we have: $\rho^* \approx \rho$, in which $\rho$ is real the node density (including node 0) of cluster 0. $P_{\text{in cluster } 1}$ is expressed as:

$$P_1 = \sum_{j=1}^{6} \int_{f_{\text{min}}}^{f_{\text{max}}} \frac{1}{A_i d_j^k a^d (f)} dfdfA$$

in which, $d_j$ is the distance from node $i$ in cluster $j$ to the central node at cluster 0, $0 \leq i \leq N-1$, $P_2$ is:

$$P_2 = \sum_{j=7}^{18} \int_{f_{\text{min}}}^{f_{\text{max}}} \frac{1}{A_i d_j^k a^d (f)} dfdfA$$

$P_3$ is expressed as:

$$P_3 = \sum_{j=13}^{18} \int_{f_{\text{min}}}^{f_{\text{max}}} \frac{1}{A_i d_j^k a^d (f)} dfdfA$$

and, $P_4$ as:

$$P_4 = \sum_{j=18}^{\infty} \int_{f_{\text{min}}}^{f_{\text{max}}} \frac{1}{A_i d_j^k a^d (f)} dfdfA$$

Combining equations (2) - (8), we have:

$$SNIR = \frac{PGQ}{P_s + P_{0i} + 5P_i + 6P_2 + 7P_3 + 4P_4}$$

To get a close form formula, some approximation approaches are used. Compared with interference from 1)-4), the power of noise is much smaller and interference from 5) is also much smaller due to the much longer distance. Approximately, we have:

$$\alpha(f) \approx \alpha(f_{\text{min}}) = \alpha$$

Hence, we get:

$$SNIR = \frac{PGQ}{P_s + \rho \cdot S \cdot B + \rho \cdot S \cdot 1 + \rho \cdot S \cdot 1 + \rho \cdot S \cdot 1 + \rho \cdot S \cdot 1}$$

$$\rho \cdot S \cdot B \approx 0$$

Since $dA = 3\sqrt{3}rdA$, and assuming nodes are uniformly distributed between rings $r_1 \leq d_i \leq r_2$ in cluster 0 (nodes in other clusters are distributed with the same pattern), we have:

$$SNIR = \frac{PGQ}{P_s + P_{0i} + 5P_i + 6P_2 + 7P_3 + 4P_4}$$

$$\rho \cdot S \cdot B \approx 0$$

$$\rho \cdot S \cdot B \approx 0$$

$$\rho \cdot S \cdot B \approx 0$$
Fig. 3 The coverage area of a cluster (shadow area)

$$SIR \approx \frac{PG}{d_0^2 r^2} \int_0^{r_2} \rho \frac{1}{r^4} 3\sqrt{3} dr + \sum_{i=1}^{n-1} \rho \frac{1}{A_{ij}^2 r_i^4} dA + \sum_{i=1}^{n} \rho \frac{1}{A_{i0}^2 r_0^4} dA + \sum_{i=1}^{n} \rho \frac{1}{A_{i0}^2 r_0^4} dA$$

(14)

There is no closed-form solution for the above equation. However, since nodes are uniformly distributed inside the range of a cluster, and more importantly, inter-cluster interference from neighboring clusters is much weaker in the underwater environment, due to the much longer distance; approximately, we can use the “average” distance represents neighboring clusters’ nodes range. In the following analysis, the distance from nodes in other clusters is the range between the centers of the clusters to that of cluster 0, which are $2r_2$ for clusters 1-6, $\sqrt{12}r_2$ for clusters 7-12, $4r_2$ for clusters 13-18, respectively. Consequently, we have:

$$SIR \approx \frac{PG}{d_0^2 r^2} \int_0^{r_2} \rho \frac{1}{r^4} 3\sqrt{3} dr + \frac{6\rho S}{2^k \cdot a^2 r^2} + \frac{6\rho S}{(\sqrt{12})^k a^{12/2}}$$

(15)

Where $S$ is the coverage area of a cluster. When $k = 1$,

$$\int_0^{r_2} \rho \frac{1}{r^4} 3\sqrt{3} dr = \frac{3\sqrt{3}\rho}{ln a} (a^2 - a^4); \text{ when } k = 2,$$

$$\int_0^{r_2} \rho \frac{1}{r^4} 3\sqrt{3} dr = 3\sqrt{3}\rho (E_i(-r_2 \ln a) - E_i(-r_1 \ln a))$$

in which,

$$E_i(x) = C + \ln(-x) + \sum_{i=1}^{\infty} \frac{x^j}{j-i!} \quad [x < 0]$$

[20]. Consider the worst scenario. The intended node is located at the boundary of cluster 0. Since $SNIR \geq T$, where $T$ is the required quality threshold, we then have:

$$SNIR \approx SIR = \frac{G}{r_k^2 a^2} \rho M + \frac{6\rho S}{2^k \cdot a^2 r^2} + \frac{6\rho S}{(\sqrt{12})^k a^{12/2}} \geq T$$

(16)

Where

$$\frac{3\sqrt{3}}{ln a} (a^2 - a^4), \quad k = 1$$

$$3\sqrt{3}(E_i(-r_2 \ln a) - E_i(-r_1 \ln a)) \quad k = 2$$

Finally, we have:

$$\rho \leq \frac{PG}{r_k^2 a^2} \int_{T_{\text{shield}}} (M + \frac{6\rho S}{2^k \cdot a^2 r^2} + \frac{6\rho S}{(\sqrt{12})^k a^{12/2}} + \frac{6\rho S}{4^k a^{4r^2}})$$

(18)

Completely, the node density of a cluster UAN with a CDMA scheme is limited by the Processing Gain $G$, the received signal quality threshold $T$, the radius of the cluster, the location of nodes, and the spread coefficient in the water medium. Assuming that each node transmits with at least rate $R_0$, we have:

$$R \geq R_0 = \frac{\mu B}{G},$$

in which $\mu$ is the spectrum coefficient. Thus we have:

$$G = \frac{\mu B}{R_0}$$

(19)

Combined (19) with (18), finally we get:

$$\rho \leq \frac{\mu B}{R_0} \cdot \frac{R_0 \cdot r_k^2 a^2}{T \cdot (M + \frac{6\rho S}{2^k \cdot a^2 r^2} + \frac{6\rho S}{(\sqrt{12})^k a^{12/2}} + \frac{6\rho S}{4^k a^{4r^2}})}$$

$$= \frac{\mu B}{T \cdot R_0 \cdot r_k^2 a^2} \cdot \frac{6\rho S}{2^k \cdot a^2 r^2} + \frac{6\rho S}{(\sqrt{12})^k a^{12/2}} + \frac{6\rho S}{4^k a^{4r^2}}$$

(20)
2.2 User density analysis of a TDMA scheme in a cluster type UAN

In a TDMA scheme, a node can only transmit on allocated time slot; and the frequency has to be shared among clusters. Due to these differences, the user density that a TDMA scheme can achieve is significantly different from that of CDMA.

Assuming the frequency reuse factor is K, i.e., a cluster has to share the bandwidth with \((K-1)\) neighboring nodes, as shown in Fig. 3. Consequently, each cluster can only use \(B_0 = B/K\) frequency band.

Similarly, we assume cluster 0 is the cluster of concern. There is no intra-cluster interference in TDMA scheme in the ideal case (assumed in the following analysis), and the inter-cluster interference comes from clusters re-using the same frequency band as cluster 0 does. Hence, the SNIR at the gateway node of cluster 0 is:

\[
SNIR = \frac{P_s}{P_s + P_a + P_n} \tag{21}
\]

in which, \(P_s\) is introduced by six clusters using the same frequency that is closest to cluster 0, range from cluster 0_1 to cluster 0_6 in Fig. 2. \(P_a\) comes from other clusters that are further away using the same frequency band. Compared with \(P_s\), \(P_a\) is much smaller due to the significantly longer travel distance and thus can be omitted to simplify the analysis. We can also omit \(P_n\). Therefore, we have:

\[
P_s = \int_{f_{min}}^{f_{min}+B_0} \frac{1}{A_0 d^k a^d(f)} df \tag{23}
\]

\(P_{itcluster,1}\) can be expressed as:

\[
P_{itcluster,1} = \sum_{j=1}^{6} \int_{f_{min}}^{f_{min}+B_0} \frac{1}{A_0 d^j a^d(f)} df \tag{24}
\]

Similar to Section 3, we further simplify the equation by assuming \(f_{min}\) < \(B_0\), or, \(a(f) \approx a(f_{min}) = a\). Consequently, we have:

\[
SNIR \approx SIR \approx \frac{\int_{f_{min}}^{f_{min}+B_0} \frac{1}{A_0 d^k a^d(f)} df}{\sum_{j=1}^{6} \int_{f_{min}}^{f_{min}+B_0} \frac{1}{A_0 d^j a^d(f)} df} \tag{25}
\]

Similar to the previous section, we can use the “average” distance, which is \(\sqrt{3}K r_2\), as the range between the centers of the cluster to that of cluster 0, to represent \(d^k_{ij}\). Then we have:

\[
SNIR \approx SIR \approx \frac{\int_{f_{min}}^{f_{min}+B_0} \frac{1}{A_0 d^k a^d(f)} df}{\sum_{j=1}^{6} \int_{f_{min}}^{f_{min}+B_0} \frac{1}{A_0 d^j a^d(f)} df} = \frac{B_0}{6} \frac{d^k a^d}{\frac{1}{(\sqrt{3}K r_2)^k a^{\sqrt{3}K r_2}}} \tag{26}
\]

Notice that \(d\) is uniformly randomly distributed in \([r_1, r_2]\), at the worst scenario, \(d = r_2\). Assuming that the threshold is \(T\), we then have:

\[
SNIR \approx SIR \approx \frac{1}{6 \cdot \frac{1}{(\sqrt{3}K r_2)^k a^{\sqrt{3}K r_2}}} \geq T \tag{27}
\]

Then:

\[
r_2 \geq \frac{10 \log(T) + 7.78 - 10 \log \sqrt{3}K}{10(\sqrt{3}K - 1) \log a} \tag{28}
\]

From (16), we know the coverage area of a cluster is:

\[
S = \frac{3}{2} \sqrt{3}(r_2^2 - r_1^2). \text{ Thus,}
\]

\[
N = \rho S = \rho \cdot \frac{3}{2} \sqrt{3}(r_2^2 - r_1^2) \tag{29}
\]

nodes in a cluster, i.e., there are \(N\) time slots. Each node should at least transmit with rate \(R_0\). Since there are total \(N\) time slot, hence, \(NR_0 \leq \mu B_0\), \(\mu\) is the spectrum coefficient.

In an ideal case, each symbol lasts \(T_s = \frac{1}{2B_0}\). However,
since the propagation time cannot be omitted in the underwater environment, a guarding time should be inserted with each time slot. The real duration time of each node

\[ T_s' = T_s + T_L, \]

where \( T_L = \frac{r_2 - \eta_1}{c} \), and \( c \) is the acoustic signal speed in an underwater environment. Correspondently, we have:

\[
\frac{\mu B_0}{N} \cdot \frac{T_s}{T_s + T_L} = \frac{\mu B_0}{\rho S} \cdot \frac{1}{2B_0 + \frac{r_2 - \eta_1}{c}} \geq R_0
\]

That is:

\[
\rho \leq \frac{3}{2} \sqrt[3]{(r_2^2 - \eta_1^2)(1 + \frac{r_2 - \eta_1}{2B_0 c})}R_0
\]

In realistic underwater environment, e.g., shallow water, the interference in an FDMA scheme is similar to that of TDMA. Each node should have at least \( W_0 \) Hz bandwidth, i.e., \( NW_0 \leq B_0 \). From (28)-(29), we have:

\[
\rho \leq \frac{3}{2} \sqrt[3]{(r_2^2 - \eta_1^2)W_0} \leq B_0 = \frac{B}{K}
\]

Hence, we have the node density for an FDMA scheme:

\[
\rho \leq \frac{B_0}{\frac{3}{2} \sqrt[3]{(r_2^2 - \eta_1^2)W_0}}\]

To make fair comparison, we assume CDMA/TDMA/FDMA have the same spectrum coefficient, and the each user transmits with same rate \( R_o \), i.e., \( \mu W_0 = R_0 \), i.e.,

\[ W_0 = R_0 / \mu \].

Correspondently, we rewrite equation (33) as:

\[
\rho \leq \frac{B_0}{\frac{3}{2} \sqrt[3]{(r_2^2 - \eta_1^2)W_0}} = \frac{\mu B / K}{\frac{3}{2} \sqrt[3]{3} R_0 (r_2^2 - \eta_1^2)W_0}
\]

3 USEER DENSITY ANALYSIS OF MULTI-ACCESS SCHEMES IN NON-IDEAL PROPAGATION ENVIRONMENT

In realistic underwater environment, e.g., shallow water horizontal channels are extremely hostile for communications. There are two significant obstacles: one is the excessive multipath spread. Another is the severe Doppler shift and Doppler spread. In a medium range shallow water channel, the multipath spread is usually on the order of 10 ~ 50 ms; the ratio of Doppler to carrier frequency in underwater channels is in the order of \( 10^{-3} \). Consequently, the user density becomes significantly different from that under an ideal channel condition one.

3.1 User density of a CDMA scheme with multipath fading channel

Multipath brings in inter-symbol interference (ISI) and fading. Correspondently, the received signal threshold needs to be increased. We assume that SNIR should increases \( l \) dB to decode the information bit properly. Correspondently, (14) becomes:

\[
\text{SNIR} \approx \text{SIR} \geq \frac{PG}{\rho M + \frac{6\rho S}{(\sqrt{12})^r} a^{\mu_0} + \frac{6\rho S}{4^r} a^{\frac{1}{2^r}} (T + l)}
\]

Correspondently, we have:

\[
\rho \leq \frac{\mu B}{(T + l) \cdot R_0 \cdot (c/2) \cdot (M + \frac{3}{2} \sqrt[3]{(c_2^2 - c_1^2)} + \frac{3}{2} \sqrt[3]{(c_3^2 - c_1^2)} + \frac{3}{2} \sqrt[3]{(c_4^2 - c_1^2)})}
\]

hence,

\[
\rho \leq \frac{\mu B}{(T + l) \cdot R_0 \cdot (c/2) \cdot (M + \frac{3}{2} \sqrt[3]{(c_2^2 - c_1^2)} + \frac{3}{2} \sqrt[3]{(c_3^2 - c_1^2)} + \frac{3}{2} \sqrt[3]{(c_4^2 - c_1^2)}} / 4^r a^{\frac{1}{2^r}} (T + l)}
\]

3.2 User density of a TDMA scheme with a multipath channel

Due to the severe multipath spread in the underwater environment, the user density of TDMA scheme will be impacted significantly. The design of time slot length should consider the worst multipath spread, which we assume is \( T_{mp} \). Correspondently, we have:

\[
\frac{\mu B_0}{N} \cdot \frac{T_s}{T_s + T_L + T_{mp}} = \frac{\mu B_0}{\rho S} \cdot \frac{1}{2B_0 + \frac{2 - \eta_1}{c} + T_{mp}} \geq R_0
\]
3.3 User density of an FDMA scheme with Doppler spread

In an underwater environment, due to the relative motion between a source and a destination and the dynamic motion of water medium, and the environment-based varying sound speed profile, Doppler shift and spread can significantly impact the fading channel response and signal waveforms. It is shown that the ratio of Doppler to carrier frequency in underwater channel is in the order of $10^{-3}$ to $10^{-4}$ [21]. As a rational solution, the frequency planning in FDMA should take the Doppler effect into consideration.

Since each node should have at least $W_0$ Hz bandwidth to guarantee the transmission rate of $R_0$, i.e., $NW_0 \leq B_0$. Due to the Doppler, each frequency band should include a guarding band, which is $10^{-3}$ of the carrier frequency, which we assume is $f_0$, such that we have: $W_0 = W_0 + 0.001f_0$. From (28)-(29), we have:

$$\rho \geq \frac{3}{2} \sqrt{3(r_2^2 - \eta^2)}W_0 \leq B_0 = \frac{B}{K}$$

Finally, we have the node density for an FDMA scheme with Doppler shift and spread:

$$\rho \leq \frac{3}{2} \sqrt{3(r_2^2 - \eta^2)}W_0' = \frac{\mu B}{K}$$

(39)

4 NUMERICAL ANALYSIS

To compare CDMA with TDMA/FDMA in an underwater environment with different parameters, we have used Matlab to obtain the numerical results. This section presents some of them.

Fig. 5 (a) Threshold vs. the user density (ideal case, $k = 2$)

Fig. 5(b) Threshold vs. the user density (ideal case, $k = 1$)

Fig. 5 demonstrates the relationship between threshold and user density in ideal case with spreading factor equals 1 and 2. The user density of TDMA/FDMA is not affected by the threshold; meanwhile, the one of CDMA decreases with the threshold. When $k=2$, CDMA achieves higher user density when the threshold is less than 1.8 dB and lower user density, otherwise.

Compared with that, Fig. 6 gives the more realistic case in which guarding time and frequency have to be added in TDMA and FDMA, respectively. We find that the user density of FDMA drops significantly when the guarding frequency is inserted while the one of TDMA drops almost to zero when guarding time is added.

Fig. 6 (a) Threshold vs. the user density (realistic case, $k = 2$)
Fig. 6 (b) Threshold vs. the user density (realistic case, k =1)

Fig. 7 and 8 give the relationship between cluster radius and node density in ideal and realistic case, respectively. The SNIR threshold is set as 2dB and the cluster radius ranges from 1 to 10 kilometers. Other parameters are the same as that in Fig. 5 and 6. It is clear that the cluster radius affects the node density of both CDMA and TDMA/FDMA schemes. The bigger the cluster radius is, the less the node density will be. This is because that although the intra-cluster and inter-cluster interference decrease with distance (the received signal decreases with distance, too), the number of total nodes increases with the cluster radius if the node density is the same. As a consequence, the interference increases in a CDMA scheme. To maintain the received signal quality, the node density needs to be decreased. On the other hand, the total available bandwidth is limited, and each node needs to transmit with at least the minimum rate, which means each node takes a constant bandwidth. Consequently, the increase of cluster radius will cause the decrease of node density in a TDMA/FDMA scheme. We also notice that the user density of FDMA/TDMA drops dramatically if guarding frequency/time has to be added in real underwater environment.

Fig. 7 (a) Radius vs. user density (ideal case, k =2)

Fig. 7 (b) Radius vs. user density (ideal case, k =1)

Fig. 9 and 10 demonstrate the effect of minimum transmission rate of each node (we assume they are the same for each node) on user density in ideal and realistic case. The parameters are the same as those in Fig. 7 and 8, except for the re-use factor is 7 and minimum rate varies from 50 to 500 bps. The spreading factor is set as 2 in the simulation. It shows that the higher the minimum transmission rate a node has, the less the node density is for both CDMA and TDMA/FDMA schemes. It is obvious because that higher transmission rate requires more bandwidth for each node. Hence, with limited total available bandwidth, this results in less node density. It also shows that the user density of FDMA/TDMA is much less in realistic case than in the ideal case.

Fig. 8 (a) Radius vs. user density (realistic case, k =2)

Fig. 8 (b) Radius vs. user density (realistic case, k =1)
In this paper, the node density of cluster type underwater acoustic networks is analyzed when CDMA and TDMA/FDMA schemes are adopted. To simplify the inference analysis, we use an ideal underwater channel condition, i.e., single path without fading effect. By using approximations, we obtain close-form formulae for the user density of CDMA, TDMA and FDMA schemes in cluster type UANs. We find that the user density of a CDMA scheme is primarily affected by intra-cluster and inter-cluster interference. If the interference level can be reduced, for example, power control or transmission activity factor reduction, the user density of a CDMA scheme can be further increased. By contrast, the user density of both TDMA and FDMA schemes are primarily determined by the total available bandwidth.

We also find that the CDMA scheme could achieve higher user density than TDMA/FDMA if the required signal quality is below a certain level when spreading factor equals 2. Our analysis indicates that the level is 1.6 dB in ideal case and 2.6 dB in realistic case (in which guarding time/frequency needs to be added in TDMA/FDMA). We also find that the insertion of guarding time/frequency affects the user density of TDMA/FDMA significantly, especially for the former scheme. Since the addition of guarding time/frequency is inevitable in underwater environment, CDMA/FDMA could be a better candidate than TDMA in realistic underwater environment.

We will consider more realistic channel conditions, i.e., with multi-path and fading, in our next step research. Intuitively, CDMA has some advantages in multi-path fading environment and TDMA/FDMA has some disadvantages. The underwater multi-path delay can be huge, such that TDMA/FDMA needs pretty significant “guarding time” or “guarding frequency” to reduce the interference caused by multi-path spread. CDMA does not require that.

If multi-hops are used to deliver messages from a source to a destination, the user density analysis can be much more complex due to the more degrees of freedom. Our further research will also analyze the network user density of CDMA, TDMA and FDMA schemes when multi-hops are used, e.g., ad hoc underwater networks.

6 REFERENCES

Zaihan Jiang received the BE degree from Xi’an Jiaotong University, Xi’an, China, the MS degree from New Jersey Institute of Technology, Newark, in 1999, and the PhD degree from the New Jersey Institute of Technology in 2006, all in electrical engineering. He has spent nine years with the telecommunication industry in the US, before he joined the US Naval Research Laboratory, Washington DC, in 2008. His research interests include capacity analysis, cross-layer design, system security, multimedia applications for Wireless networks, and underwater acoustic networks/communications. He serves as a program committee member for several IEEE international conferences and has more than 20 publications in referred conferences and journals. He has been a senior member of the IEEE since 2009.