

Evaluation of Cellular Networks in Underwater Acoustic Communication

Amirmansour Nabavinejad *, Samar Shahabi Ghahfarokhi **

* Department of Electrical Engineering, Najafabad Branch, Islamic Azad University , Isfahan ,Iran

** Department of Electrical Engineering and Information Technology, Ilmenau University of Technology, Ilmenau, Germany

dc.nabavinejad@gmail.com, samar.shahabi-ghahfarokhi@tu-ilmenau.de

Abstract—The characteristics of acoustic propagation through the underwater environment are the greatest challenges faced by Underwater acoustic communications systems. Limit bandwidth in these systems is of paramount obstacles. To overcome this problem the idea of frequency reuse pattern seems to be useful. The key characteristic of a cellular network is the ability to re-use frequencies to increase both coverage and capacity. One element that determines frequency reuse is the reuse distance depending on the cell radius and the number of cells per cluster. Analysis of frequency reuse between adjacent clusters and optimal cell-radius selection criteria has been carried out recently. In other recent works, the parameters of the cellular networks designing have been calculated based on a rough approximation of the attenuation and propagation model. In our work, after deriving the ratio of signal to interference for underwater acoustic channels with more accuracy, the constraints for the cell radius are determined. One of the most important results of this contribution is that, for special parameters like bandwidth, it may be impossible to provide the required signal to interference ratio and bandwidth for the network users. Furthermore, in this paper, the number of supportable users, per-user bandwidth, and the user capacity for a cellular underwater network are determined.

Keywords—Cell Radius, Frequency Reuse, Signal to Interference Ratio, Underwater Cellular Networks, User Capacity

I. INTRODUCTION

Underwater Acoustic Networks are very unique and can be deployed for commercial and industrial applications. Oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance are some of the applications of underwater networks. More and more research interest and efforts are shifting to this area in recent years. Underwater Acoustic Networks is a new research topic and there are many unsolved issues. The unique underwater environment is the root cause of these issues. An underwater acoustic channel is different from a ground-based radio channel from many aspects, including [1], [2].

1) Bandwidth is extremely limited. The attenuation of acoustic signal increases with frequency and range. Consequently, the available bandwidth of underwater acoustic channels is

limited and dramatically depends on both transmission range and frequency.

2) Propagation delay is long, the signal propagation speed in underwater acoustic channel is about 1500 m/sec, which is five orders of magnitude lower than the radio propagation speed (3×10^8 m/sec). Correspondently, propagation delay in an underwater channel becomes significant.

3) The channel impulse response is not only spatially varied but also temporarily varied. The channel characteristics vary with time and highly depend on the location of the transmitter and receiver. The fluctuation nature of the channel causes the received signals easily distorted.

4) Probability of bit error is much higher and temporary loss of connectivity (shadow zone) sometimes occurs, due to the extreme characteristics of the channel. Underwater acoustic communication channels are affected by many Factors such as path loss, noise, multi-path, and Doppler spread. All these factors cause high bit-error and delay variance.

Since the available bandwidth in underwater is severely limited, frequency reuse and cellular networks concepts are very important. The key characteristic of a cellular network is the ability to re-use frequencies to increase both coverage and capacity. Adjacent cells must utilize different frequencies; however there is no problem with two cells sufficiently far apart operating on the same frequency. Since bandwidth is at premium in an acoustic channel, the concept of Frequency reuse is an appealing one and, given the immense Success and practicality of terrestrial cellular systems, the question naturally arises as to how the cellular concept applies to an underwater acoustic environment. The first task in the design of a cellular network is the Selection of network topology, i.e. determination of the cell size (radius) and the reuse pattern. In other words, the practical questions that one wants to answer are the following: For a given distribution of users and the desired information throughput, what should the coverage area of one base station be? How far should another base station operating in the same frequency band be? According to what pattern should the frequency bands be reused?

In a terrestrial radio environment, this problem has a very Simple solution, but in an underwater acoustic environment, the solution is complicated by the fact that the path loss does not consist only of the spreading loss (which grows with

distances r^k , where k is usually a number between 1 and 2), But the absorption loss as well (which grows with distance as a^r , And depends on the frequency through the factor a) [3]. Simple principles of cellular radio system design do not apply to an underwater acoustic environment. Instead, complex relationships between the system parameters are involved, which lead to a set of constrained solutions. Analysis of frequency reuse between adjacent clusters and optimal cell-radius selection criteria has been carried out recently[3]. In other recent works, the parameters of the cellular networks designing have been calculated based on a rough approximation of the attenuation and propagation model. In Section II, after driving the ratio of signal to interference for underwater acoustic channels with more accuracy, the constraints for the cell radius are determined. In section III, we determine the cell size and the frequency reuse pattern needed to support a desired number of users operating over a given area within a given system bandwidth. In section IV we define the capacity of an underwater acoustic cellular networks and the maximal user density that can be supported within a given bandwidth. Conclusions are summarized in Section V.

II. UNDERWATER CELLULAR NETWORKS PARAMETERS

Recently, there has been a growing interest in wireless sensor networks for underwater applications[7]. However, an underwater acoustic cellular network is an extension of centralized topology. Analysis of frequency reuse between adjacent clusters and optimal cell-radius selection criteria has been carried out recently[3]. In this section, we try to obtain underwater cellular network parameters with attention to limitations of underwater acoustic communication.

A. Design Constraints

In underwater cellular network design, a design constraint refers to some limitation on the conditions under which a cellular network is developed, or on the requirements of the network. The available bandwidth for an acoustic network typically is not more than 15 KHz [6]. This bandwidth must be shared among all users. In this section, the design of a cellular network begins with selection of the Frequency reuse pattern and the cell radius. The total bandwidth B is divided among N adjacent cells, which forms a cluster. The clusters are then replicated over an arbitrarily large area. In doing so, it is required that the co-channel signal-to-interference ratio be greater than some minimum, $SIR \geq SIR_0$ and that the bandwidth per user be $W \geq W_0$

B. Underwater Acoustic Propagation

An important difference between the design of underwater acoustic cellular systems and the RF terrestrial cellular systems is the fact that underwater propagation shows a frequency dependent absorption, in addition to distance-dependent path loss. Attenuation, or path loss that occurs in an underwater

acoustic channel over a distance r for a signal of frequency f is given by [4].

$$A(r, f) = r^k a(f)^r \quad (1)$$

Where k is the spreading factor, and $a(f)$ is the absorption coefficient. The acoustic attenuation, expressed in dB, is given by

$$10 \log A(r, f) = k \cdot 10 \log r + r \cdot 10 \log a(f) \quad (2)$$

The first term in the above equation indicates the spreading loss and the second term shows the absorption loss. Without the loss of generality, we will assume in the numerical examples a practical spreading factor $k=1.5$, and absorption according to Thorp, which is given in dB/km as [4].

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f} + 2.75 \cdot 10^{-4} f^2 + 0.003 \quad (3)$$

Where f is the signal frequency in kHz. Using the acoustic path loss (2), the power of the signal received at a distance d from the transmitter is given by

$$P(r) = \int_{f_{\min}}^{f_{\min}+W} s_t A^{-1}(r, f) df = s_t \int_{f_{\min}}^{f_{\min}+W} r^{-k} a(f)^{-r} df \quad (4)$$

Where s_t is the power spectral density of the transmitted signal which we assume to be constant and the integration is carried out over the frequency band occupied by the signal, starting at some $f_{\min}$ and extending over a bandwidth w .

By substituting $a(f)$ from (2) we have:

$$\begin{aligned} p(r) &= s_t \cdot r^{-k} \int_{f_{\min}}^{f_{\min}+W} \exp\left(-\left(0.011 \frac{f^2}{1+f^2} + 4.4 \frac{f^2}{4100+f} + 2.75 \cdot 10^{-4} f^2 + 0.0003\right) \cdot r\right) \ln 10 df \\ &= s_t \cdot r^{-k} \int_{f_{\min}}^{f_{\min}+W} \exp\left(-\left(A \frac{f^2}{1+f^2} + B \frac{f^2}{4100+f} + C f^2 + D\right)\right) df \end{aligned}$$

Where A, B, C, D coefficients are:

$$\begin{aligned} A &= 0.01 \ln 10 & B &= 4.4 r \ln 10 \\ C &= 2.75 \times 10^{-5} r \ln 10 & D &= 3 \times 10^{-4} r \ln 10 \end{aligned}$$

Because the calculation of this integral is too hard, we use the below estimations:

$$\frac{f^2}{1+f^2} \approx 1, \quad \frac{f^2}{4100+f} \approx \frac{f^2}{4100} \quad (5)$$

Since frequency in underwater acoustic communication is about several KHz therefore this estimation can be proper estimation. Then $P(r)$ can be calculated from below:

$$\begin{aligned} p(r) &= s_t \cdot r^{-k} \cdot \int_{f_{\min}}^{f_{\min}+W} \exp\left(-\left(A \frac{f^2}{1+f^2} + B \frac{f^2}{4100+f^2} + Cf^2 + D\right)\right) df \\ &\approx s_t \cdot r^{-k} \cdot \int_{f_{\min}}^{f_{\min}+W} \exp\left(-\left(A + B \frac{f^2}{4100} + Cf^2 + D\right)\right) df \\ &= s_t \cdot r^{-k} \cdot K \cdot \int_{f_{\min}}^{f_{\min}+W} \exp(-Ef^2) df \end{aligned}$$

Where

$$E = \frac{B}{4100} + C \quad K = \exp(-(A + D))$$

Now using the error function ($\text{erf}(x)$) we have:

$$\begin{aligned} \text{erf}(X) &= \frac{2}{\sqrt{\pi}} \int_0^X \exp(-\lambda^2) d\lambda \\ p(r) &= s_t \cdot r^{-k} \cdot K \cdot \int_{f_{\min}}^{f_{\min}+W} \exp(-Ef^2) df \\ &= s_t \cdot r^{-k} \cdot \frac{K}{\sqrt{E}} \cdot \frac{\sqrt{\pi}}{2} [\text{erf}(f_{\min} + W) - \text{erf}(f_{\min})] \end{aligned} \quad (6)$$

With substituting E and K and introducing γ parameter as

$$\gamma = 17.6 \exp(-0.974r) \cdot r^{-(k+\frac{1}{2})} \quad (7)$$

Then, the power of the signal received at a distance r from the transmitter is given by

$$p(r) = s_t \cdot \gamma \cdot \exp(-0.974r) \cdot r^{-(k+\frac{1}{2})} \quad (8)$$

Now using $P(r)$ and the assumption that all of transmitters transmit the same power spectral density S_t , we can calculate the Signal to interference ratio (SIR) from below:

$$\begin{aligned} \text{SIR} &= \frac{p(r)}{\sum_i I_i} = \frac{\int_{f_{\min}}^{f_{\min}+W} s_t A^{-1}(r, f) df}{\sum_i \int_{f_{\min}}^{f_{\min}+W} s_t A^{-1}(X_i, f) df} \\ &= \frac{s_t \gamma \cdot \exp(-0.974r) \cdot r^{-(k+\frac{1}{2})}}{\sum_i s_t \cdot \gamma \cdot \exp(-0.974|X_i|) \cdot |X_i|^{-(k+\frac{1}{2})}} \end{aligned}$$

Where X_i is the interference user distance to the desired receiver. Therefore signal to interference ratio for underwater acoustic channel is equal to:

$$\text{SIR} = \frac{\exp(-0.974r) \cdot r^{-(k+\frac{1}{2})}}{\sum_i \exp(-0.974|X_i|) \cdot |X_i|^{-(k+\frac{1}{2})}} \quad (9)$$

As this equation shows, with acceptance of estimation (5), signal to interference ratio is independent from frequency therefore, this ratio is usable for different cellules that use different frequency. In the next sections we use this equation to obtain underwater cellular network designing parameters

III. CELL RADIUS AND THE REUSE NUMBER

The design of a cellular underwater network is addressed from the view point of determining the cell size and the frequency reuse pattern needed to support a desired number of users operating over a given area within a given system bandwidth.

A. Calculating Cell Radius

The signal bandwidth B_0 depends on the multiple-access Technique used. If TDMA is used, it equals the bandwidth allocated to one cell, $B_0 = \frac{B}{N}$ where N is the reuse number. N is given In the form $N = i^2 + ij + j^2$, with i, j integers. If FDMA is used, it equals the width of a frequency channel allocated to one of U users sharing a cell, $B_0 = \frac{B}{NU}$ [5]. Let us assume (without the loss of generality) that time-division multiple-access (TDMA) is used. Assuming hexagonal cell geometry, the SIR is dominated by the six nearest co-channel cells, and the worst SIR, which occurs at the cell edge, is given by

$$\text{SIR} \approx \frac{P(R)}{6P(D)} \quad (10)$$

Where R is the cell radius and D the distance to the nearest co-channel cell. In a two-dimensional system geometry, the two distances are related by $D=QR$, where $Q=\sqrt{3N}$ and N is the reuse number [3].

Since SIR is more than one minimum, according to the signal to interference ratio which is obtained in pervious for underwater channel, we have:

$$\text{SIR} \geq \text{SIR}_0$$

$$\text{SIR} \approx \frac{P(R)}{6P(D)} = \frac{\exp(-0.974R) \cdot R^{-(k+\frac{1}{2})}}{6 \exp(-0.974D) \cdot D^{-(k+\frac{1}{2})}} \geq \text{SIR}_0$$

And therefore

$$\frac{1}{6} \exp(-0.974(R-D)) \cdot \left(\frac{R}{D}\right)^{-(k+\frac{1}{2})} \geq \text{SIR}_0$$

$$\Rightarrow \frac{1}{6} \exp(-0.974R(1-Q)) Q^{\left(k+\frac{1}{2}\right)} \geq \text{SIR}_0$$

$$\Rightarrow -0.974R(1-Q) \geq \ln(6\text{SIR}_0 Q^{\left(k+\frac{1}{2}\right)})$$

Then to satisfy condition ($\text{SIR} > \text{SIR}_0$) we obtain below inequality:

$$R \geq \frac{\ln(6\text{SIR}_0 Q^{\left(k+\frac{1}{2}\right)})}{-0.974R(1-Q)} = R_0(N) \quad (11)$$

The second system requirement is that the per user bandwidth be $W \geq W_0$. For a given density of users ρ , the number of users per cell is $\rho \alpha R^2$, where $\alpha = \frac{3\sqrt{3}}{2}$ for the hexagonal cell geometry ($\alpha = \pi$ if the cells are modeled as circular). The bandwidth allocated to one cell is B/N , therefore, the bandwidth per user must satisfy

$$W = \frac{B/N}{\rho \alpha R^2} \geq W_0 \quad (12)$$

In order for this condition to hold, the cell radius has to be less than some maximum,

$$R \leq R_1(N) = \frac{1}{\sqrt{\alpha \rho}} \sqrt{\frac{B}{N W_0}} \quad (13)$$

Finally, the number of users in a cell should be greater than 1, as the cellular concept is other wise meaningless. This fact yields an additional condition

$$R \geq \frac{1}{\sqrt{\alpha \rho}} \quad (14)$$

Combining the conditions (11), (13) and (14), we find that the cell radius must satisfy

$$\bar{R}_0(N) = \max \left\{ R_0(N), \frac{1}{\sqrt{\alpha \rho}} \right\} \leq R \leq R_1(N) \quad (15)$$

Only those values of (R, N) that belong to this region constitute a valid design of underwater cellular network.

Fig.1 illustrates the admissible region for a system with $\rho = 1 \text{ user/km}^2$, $B = 15 \text{ kHz}$, $\text{SIR}_0 = 20 \text{ dB}$, and $W_0 = 0.14 \text{ kHz}$.

B. Number of Users and Bandwidth per User

A natural criterion to consider is maximization of the number of users supported per Hz of occupied bandwidth,

$$C = \frac{\rho \alpha R^2}{B/N} \quad (16)$$

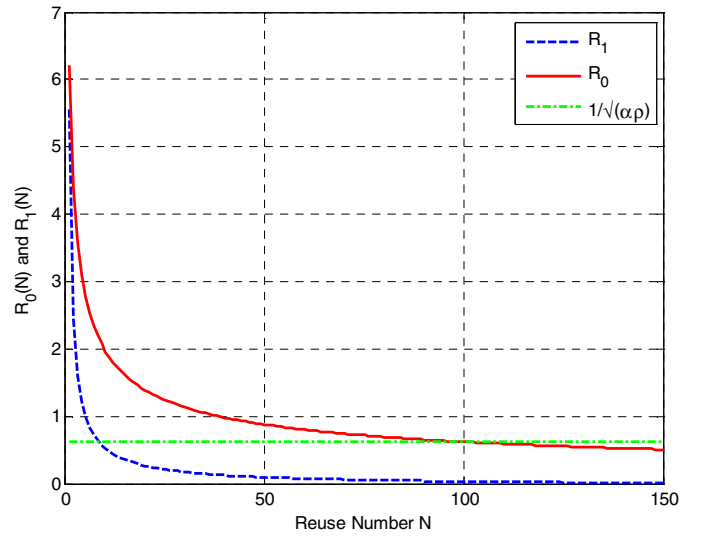


Figure1. Region of acceptable values (R, N) lies between

To maximize this quantity for a given N , while respecting the constraints $\text{SIR} \geq \text{SIR}_0$ and $W \geq W_0$, the maximum value of the cell radius should be chosen, $R = R_1(N)$. This selection results in the maximum $C_{\max} = 1/W_0$. Alternatively, it may be desired that the per user bandwidth W be maximized. In that case, the smallest cell radius should be chosen, $R = \bar{R}_0(N)$. This selection yields the maximum

$$W_{\max}(N) = \frac{B/N}{\rho \alpha \bar{R}_0^2(N)} \quad (17)$$

IV. CAPACITY ANALYSIS

The fact that the range of admissible network topologies is determined by the desired user density (among other parameters) gives rise to the question of user capacity. We define the capacity of an underwater acoustic cellular network as the maximal user density that can be supported within a given bandwidth. To assess the user capacity, we turn to the design condition (15). This condition implies that in order for a valid design to exist, the following inequality must hold:

$$\bar{R}_0(N) \leq R_1(N) \quad (18)$$

Substituting for $R_0(N)$ and $R_1(N)$ this condition can be expressed in terms of the user density and the system bandwidth. To do so, we observe that for any given N , there are two possibilities: (a) $R_0(N) \leq R_1(N)$ or (b) $\frac{1}{\sqrt{\alpha \rho}} \leq R_1(N)$. If (a) is true, then in order for a solution to exist, condition (18) implies that the user density has to be $\rho \leq (B/W_0)/\alpha N R_0^2(N)$. If (b) is true, then in order for a solution to exist, the bandwidth

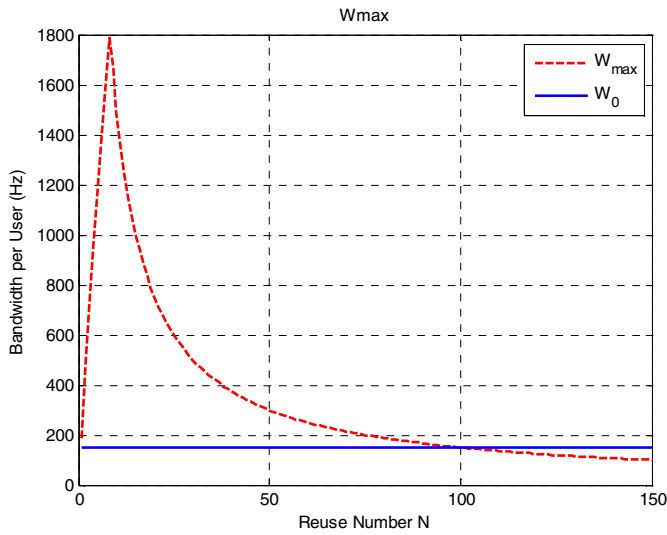


Figure 2. Maximum of bandwidth per user with the reuse number

has to be $B \geq NW_0$. Combining the two cases (a) and (b), we obtain the maximal user density that can be supported for a given N:

$$\rho_{\max}(N) = \begin{cases} (B/W_0)/\alpha NR_0^2(N) & B/W_0 \geq N \\ 0 & B/W_0 < N \end{cases} \quad (19)$$

Therefore the maximal user density depends on the bandwidth explicitly overall system and it also depends on the system requirements (SIR_0, W_0).

Fig.2 illustrates maximum value of bandwidth per user.

V. CONCLUSION

Since the available bandwidth in underwater is severely limited, frequency reuse and cellular networks concepts are very important. The fact that the acoustic path loss depends both on the transmission distance and the signal frequency imposes a bound on the range of admissible cell radius and

frequency reuse numbers N that can be used to meet the system requirements specified by the co-channel SIR and per-user bandwidth (SIR_0, W_0). This constraint in turn implies a limitation on the overall user capacity, which we define as the maximal density of users $\rho_{\max}$ that can be supported within a given bandwidth B. The basic acoustic propagation loss was shown to lead to a set of constraints that the cell radius and the reuse pattern (R,N) must satisfy in order to constitute an admissible solution for the cellular system topology. In this paper, after deriving the ratio of signal to interference for underwater acoustic channels, the constraints for the cell radius are determined. The constraints that acoustic propagation imposes on the System design, and consequently on its capacity, serve as a motivation for further research into the spatial reuse methods that will enable effective interference mitigation while remaining efficient in terms of both bandwidth and power usage [8].

REFERENCES

- [1] Z. Jiang, "Underwater Acoustic Networks – Issues and Solutions," in *proc. IEEE International Conference on Systems, Man and Cybernetics*, 2003.
- [2] J. H. Cui, J. Kong, M. Gerla, and S. Zhou, "Challenges: Building scalable mobile underwater wireless sensor networks for aquatic applications," *IEEE Network, Special Issue on Wireless Sensor Networking*, pp. 12-18, 2006.
- [3] M. Stojanovic, "On the Design of Underwater Acoustic Cellular Systems," *IEEE oceans conf.*, pp. 1-6, 2007.
- [4] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic channel," in *Proc. first ACM international workshop on Underwater Networks*, 2007.
- [5] T. S. Rappaport, *Wireless communications principles an practice*, Englewood Cliffs, NJ: Prentice-Hall, 1996.
- [6] M. Cardei, "Energy-efficient scheduling and hybrid communication architecture for underwater littoral surveillance," *Computer communication*, vol. 29, no. 17, pp. 3354-3365, Jan. 2006.
- [7] J. H. Cui, J. Kong, M. Gerla, and S. Zhou, "Challenges: Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications," *IEEE Network, Special Issue on Wireless Sensor Networking*, vol. 20, pp. 12-18, June 2006.
- [8] B. Srinivasan, V. Rodoplu, "Capacity of Underwater Acoustic OFDM cellular Networks," *IEEE Oceans Conf.*, pp. 1-10, 2010.