

Improving Coverage and Capacity in Underwater Acoustic Cellular Networks

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Abstract— Underwater acoustic communications systems are challenged by the characteristics of acoustic propagation through the underwater environment. There are a wide range of physical processes that impact underwater acoustic communications and the relative importance of these processes are different in different environments. Acoustic propagation is characterized by three major factors: time-varying multipath propagation, low speed of sound and attenuation that increases with signal frequency. Limited 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 driving 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.

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

I. INTRODUCTION

THE surface of the earth covered 70% by ocean and most of which are unexplored. There is a lot of potential applications in underwater environment such as oceanographic monitoring, scientific exploration, disaster monitoring and also especially for oil/gas field exploration. The underwater channel

remains one of the most challenging communication environments. Designing a reliable communication system remains an active area of research. The underwater is a time and spatially varying propagation environment whose characteristics pose significant challenges to the development of effective underwater wireless communications systems. For several decades, electromagnetic waves, especially radio waves, have seen extensive use in long range communications. When the propagating medium is water, however, electromagnetic waves find limited use. The high rate of absorption of electromagnetic signals in underwater has limited the development of electromagnetic communications systems. Similarly, optical signals are also rapidly absorbed in underwater and have the added disadvantage of scattering by suspended particles and high levels of ambient light in the upper part of the water column. As a result, the development of underwater optical communications systems has also been limited to few applications. Thus, acoustic signalling is primary form of wireless underwater communication. Despite its favourable characteristics relative to electromagnetic and optical propagation in the underwater environment, the physics of acoustic propagation pose significant challenge to underwater acoustic communications systems [1]. Acoustic propagation is best supported at low frequencies, and the bandwidth available for communication is extremely limited. An underwater acoustic channel is different from a ground-based radio channel from many aspects, including [2]-[7].

1) Bandwidth is extremely limited. Lack of available bandwidth is the biggest issue for underwater acoustic communication /network. 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. Sound propagates through water much more slowly than electromagnetic waves through air. Sound speed underwater depends on several factors, such as pressure, salinity, and temperature, but has a nominal value around 1500m/s [4]. The slower acoustic propagation speed, five orders of magnitude below the speed of light, greatly impacts communication protocols. Low sound speed combined

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with the large distances common in underwater networks makes propagation delays on the order of several seconds common. Long propagation delays in validate or decrease the usefulness of many techniques used in RF networks, such as carrier sensing and handshaking protocols.

3) The channel impulse response is not only spatially varied but also temporarily varied. In fact, the ocean is a dynamic and complex environment. Water movements are never-ceasing, and conditions are always changing with the time of day and weather. It is generally very difficult to predict. The fluctuation nature of the channel causes the received signals easily distorted. Acoustic signals travelling through it are distorted by a variety of factors. The major contributors are absorption, refraction and reflection (reverberation). Through these three factors, the signals picked up by receivers are duplicated forms of the original, of varying levels of strength and distorted by a certain degree of spreading or compression.

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.

5) In RF networks, the capacity of a channel depends primarily on the bandwidth utilized and the SNR at the receiver. The familiar equation from Shannon describes this relationship as $C = B \log_2(1 + \text{SNR})$ where C equals the channel capacity and

B equals the channel bandwidth. Acoustic channels, however, involve a more complicated relationship between capacity and device distance, as we will discuss in more detail later. 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) [8]. 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

The concept of frequency reuse is employed often in wireless communication technologies, cellular systems are widely used today and cellular technology needs to offer very efficient use of the available frequency spectrum. The basic principle of frequency reuse establishes its foundations over the idea of utilizing a limited number of available (or assigned) frequency channels in different and distant geographical locations. Actually, a cellular network is usually divided into small geographical segments or "cells" contained within a larger set called "cluster," and each cell has its own set of uplink and downlink carrier frequencies. In this manner, all the neighboring cells have different sets of carrier frequencies, and this difference is kept in order to avoid interference between their transmission and reception. This is in accord with a basic law of wireless communication, which states that similar frequencies cannot be used repetitively in a limited geographical area, as doing so results in their cancellation or creation of interference, which results in interrupting the process of communication. Analysis of frequency reuse between adjacent clusters and optimal cell-radius selection criteria has been carried out recently [8]. 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 [9]. 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, and that the bandwidth per user be $W \geq W_0$.

B. Underwater Acoustic Transmission

The ocean is a dynamic and complex environment. Water movement is never-ceasing and conditions are always changing with the time of day and weather. It is generally very difficult to

predict. Acoustic signals travelling through it are distorted by a variety of factors. The major contributors are absorption, refraction and reflection. Through these three factors, the signals picked up by receivers are duplicated forms of the original, of varying levels of strength and distorted by a certain degree of spreading or compression.

C. Propagation Loss

Propagation loss causes a sound wave's amplitude to gradually diminish as it travels. There are two main contributors to this loss. The first is spreading loss and the second cause of transmission loss is due to attenuation loss includes losses due to absorption, leakage out of ducts, scattering and diffraction from the actual water medium. Absorption describes those effects in the ocean in which a portion of the sound intensity is lost through conversion of heat [10]. Spreading loss does not represent a loss of energy, but refers to fact that the propagation of the acoustic pulse is such that the energy is simply spread over a progressively larger surface area, thus reducing its density. Spreading loss is not frequency dependent. Underwater communications are currently characterized by low data rates and long propagation delays. The long propagation delays are a result of the speed of sound being slow, and the low data rates are primarily a result of utilizing low-frequency acoustic signals to minimize absorption, which can be very high as shown in Fig. 1. If shorter range of communication is used then higher operating frequencies can be used.

As mentioned before, 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 [11].

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

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. Spreading loss consists of cylindrical spreading and spherical spreading. Fig. 2 and Fig. 3 illustrate these two types of spreading loss. Cylindrical spreading usually occurs in shallow water and spherical spreading in deep water environment. In low frequency (100-3KHz), the absorption coefficient is given by [12].

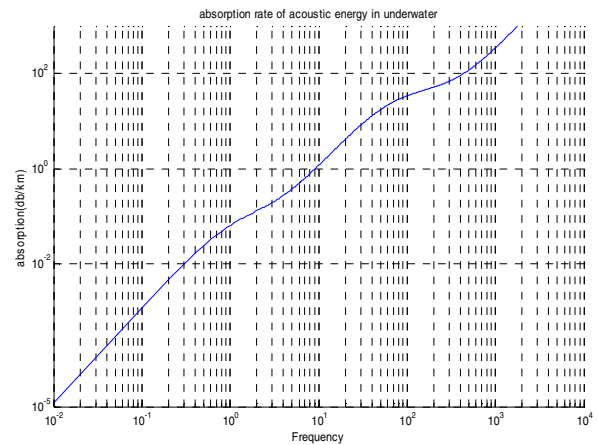


Fig.1. Absorption of underwater acoustic signal

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

where the quantity $10 \log a(f)$ has unit of dB/km and f has unit of kHz. Without loss of generality, we will assume in the numerical examples a practical spreading factor $k=1.5$.

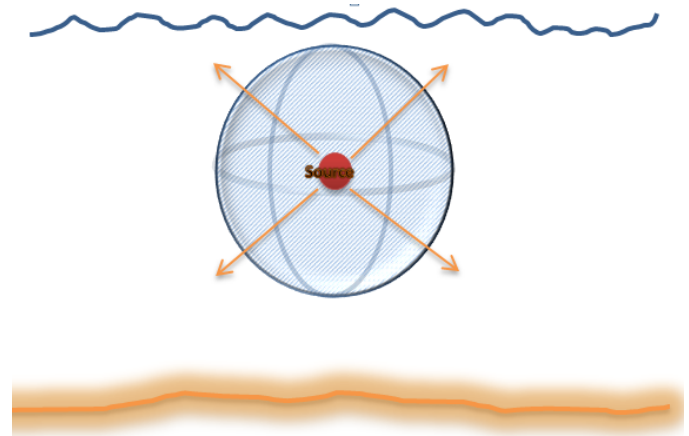


Fig. 2. Spherically spreading of sound wave

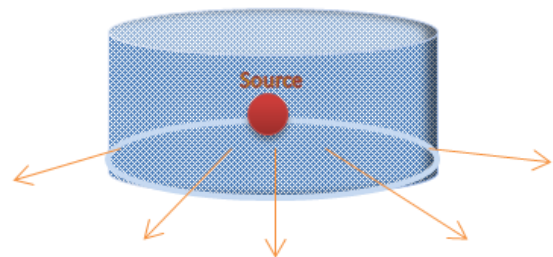


Fig. 3. Cylindrically spreading of sound wave

Using the acoustic path loss (2), the power of the signal received at a distance d from the transmitter is given by

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

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) into (4), we have:

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

where the coefficients A , B , C and D are given by

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

In order to evaluate the integrals, we make the following approximations,

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

Since the signal frequency in underwater acoustic communication is about several KHz, the above approximation is valid. Then $P(r)$ can be calculated as follows

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

where

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

Now by using the definition of the error function,

$$\operatorname{erf}(X) = \frac{2}{\sqrt{\pi}} \int_0^X \exp(-\lambda^2) d\lambda \quad (6)$$

we obtain

$$\begin{aligned} P(r) &= s_t r^{-k} K \int_{f_{\min}}^{f_{\min}+W} \exp(-E f^2) df \\ &= s_t r^{-k} \cdot \frac{K}{\sqrt{E}} \cdot \frac{\sqrt{\pi}}{2} [\operatorname{erf}(f_{\min} + W) - \operatorname{erf}(f_{\min})] \end{aligned} \quad (7)$$

By substituting E and K into (7) and introducing the parameter γ

$$\gamma = 17.6 \exp(-0.974 r) r^{-(k+\frac{1}{2})} \quad (8)$$

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

$$P(r) = s_t \gamma \exp(-0.974 r) r^{-(k+\frac{1}{2})} \quad (9)$$

Now by using (9) and the assumption that all transmitters transmit the same power spectral density s_t , we can calculate the signal to interference ratio (SIR) by the following expression

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

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

$$\text{SIR} = \frac{\exp(-0.974 r) r^{-(k+\frac{1}{2})}}{\sum_i \exp(-0.974 |X_i|) |X_i|^{-(k+\frac{1}{2})}} \quad (10)$$

As this equation shows, under the approximations given by (5), the signal to interference ratio is independent from frequency and thus, this ratio is usable for cells with different frequencies. In the next sections we may apply (10) 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. Calculation of Cell Radius

The signal bandwidth depends on the multiple-access technique used. If time-division multiple-access (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 by form $N = i^2 + ij + j^2$ in which i and j are integers. If frequency-division multiple-access (FDMA) is used, it equals the width of a frequency channel allocated to one of U users sharing a cell, $B_0 = \frac{B}{NU}$ [13]. Let us assume (without loss of generality) TDMA is used. Assuming hexagonal cell geometry, as illustrated in Fig. 4, the SIR is dominated by the six nearest co-channel cells, and the worst SIR, which occurs at the cell edge, is given by

$$SIR \approx \frac{P(R)}{6P(D)} \quad (11)$$

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 [8]. By using (9), the SIR condition can be written in terms of the cell radius R and the reuse factor Q as

$$\begin{aligned} SIR &\approx \frac{P(R)}{6P(D)} = \frac{\exp(-0.974R).R^{-\left(k+\frac{1}{2}\right)}}{6\exp(-0.974D).D^{-\left(k+\frac{1}{2}\right)}} \\ &\approx \frac{1}{6} \exp(-0.974(R-D)) \cdot \left(\frac{R}{D}\right)^{-\left(k+\frac{1}{2}\right)} \\ &\approx \frac{1}{6} \exp(-0.974R(1-Q)) \cdot Q^{\left(k+\frac{1}{2}\right)} \quad (12) \end{aligned}$$

Fig. 5 shows the SIR as a function of cell radius for different values of the reuse number. As is seen, the SIR increases with increasing both R and N .

Since SIR has more than one minimum value, according to the signal to interference ratio which was obtained before for underwater channel, we have,

$$\begin{aligned} SIR &\geq SIR_0 \\ \Rightarrow -0.974R(1-Q) &\geq \ln(6SIR_0Q^{-\left(k+\frac{1}{2}\right)}) \end{aligned}$$

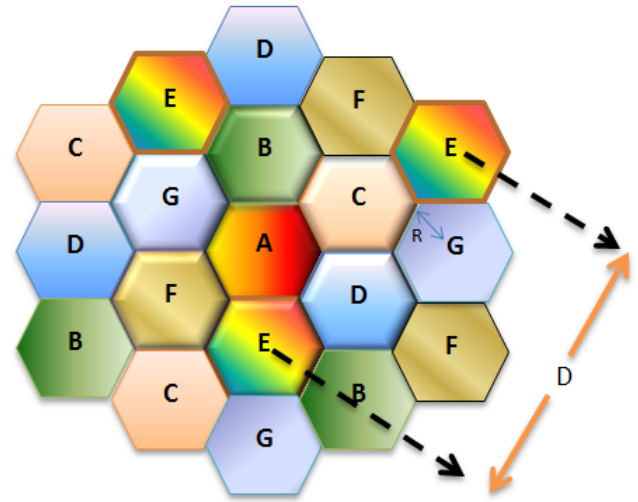


Fig. 4. Concept of cellular networks

Thus to satisfy the condition $SIR \geq SIR_0$ we should have

$$R \geq \frac{\ln(6SIR_0Q^{-\left(k+\frac{1}{2}\right)})}{-0.974R(1-Q)} = R_0(N) \quad (13)$$

In other words, in order that the SIR to be greater than the design value SIR_0 , the cell radius should be greater than the minimum value of $R_0(N)$. The minimal cell radius depends on the reuse number N , and also on the required SIR and the system bandwidth.

The second system requirement is that W is greater than or equal to W_0 ($W \geq W_0$). 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 modelled as circular). The bandwidth allocated to one cell is B/N , therefore, the bandwidth per user should satisfy

$$W = \frac{B/N}{\rho\alpha R^2} \geq W_0 \quad (14)$$

The above inequality shows that the cell radius should be less than some maximum value,

$$R \leq R_1(N) = \frac{1}{\sqrt{\alpha\rho}} \sqrt{\frac{B}{NW_0}} \quad (15)$$

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

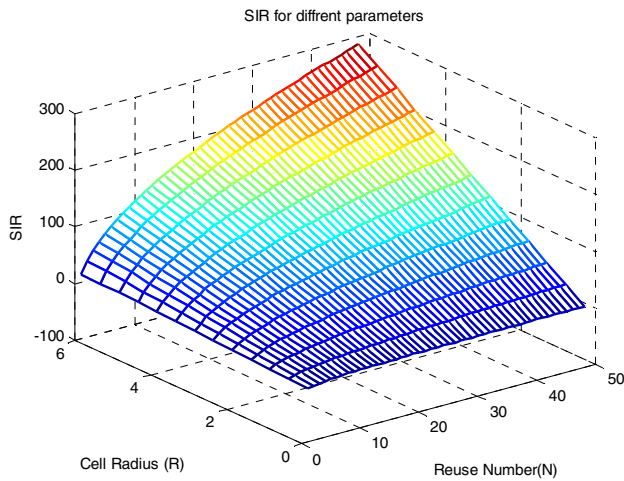


Fig. 5. Acoustic SIR for different Values of N and R

$$R \geq \frac{1}{\sqrt{\alpha\rho}} \quad (16)$$

Combining the conditions (13), (15) and (16), we find that the cell radius should satisfy

$$\bar{R}_0(N) = \max \left\{ R_0(N), \frac{1}{\sqrt{\alpha\rho}} \right\} \leq R \leq R_1(N) \quad (17)$$

This expression defines the admissible region of R and N . Only those values of R and N that belong to this region constitute a valid design of underwater cellular network. Fig. 6 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 $W_0=0.14\text{kHz}$. This region is bounded by $R_0(N)$, $R_1(N)$ and the straight line $\frac{1}{\sqrt{\alpha\rho}}$.

We observe that $R_1(N)$ decays faster than $R_0(N)$. The point at which $R_0(N)$ falls below $\frac{1}{\sqrt{\alpha\rho}}$, determines the maximal

reuse number. For each admissible value of N , there is a range of cell radii that can be chosen to design the system. In practice, it is desirable to use a small value of N , because it facilitates the frequency allocation process and minimizes the loss incurred by insertion of necessary guard bands. However, we may want to choose somewhat greater than minimum to ensure a margin for the selection of the cell radius.

A slight change in the system requirement (SIR_0 , W_0) may lead to a situation in which the range of solution becomes narrow, and also to situation in which there is no solution. These situations are illustrated in Fig. 7 for a system with $\rho=0.35\text{user/km}^2$, $B=60\text{kHz}$, $\text{SIR}_0=23\text{dB}$, and $W_0=3\text{kHz}$. Stricter performance requirements cause the admissible region becomes more narrow. Increasing

SIR_0 causes R_0 to increase, and increasing W_0 causes R_1 to decrease.

B. Number of Users and Bandwidth per User

Once the reuse number is fixed, the cell radius R can be chosen as any value between the minimum and the maximum. The choice depends on the system optimization criterion. A natural criterion is maximization of the number of users supported per Hz of occupied bandwidth [8].

$$C = \frac{\rho\alpha R^2}{B/N} \quad (18)$$

To maximize this quantity for a given value of N , under the constraints $\text{SIR} \geq \text{SIR}_0$ and $W \geq W_0$, the maximum value of the cell radius should be chosen, $R = R_1(N)$. With this choice we have,

$$\begin{aligned} C_{\max} &= \frac{\rho\alpha R_1^2(N)}{B/N} \\ &= \frac{\rho\alpha \left(\frac{1}{\sqrt{\alpha\rho}} \sqrt{\frac{B}{NW_0}} \right)^2}{B/N} = \frac{1}{W_0} \end{aligned} \quad (19)$$

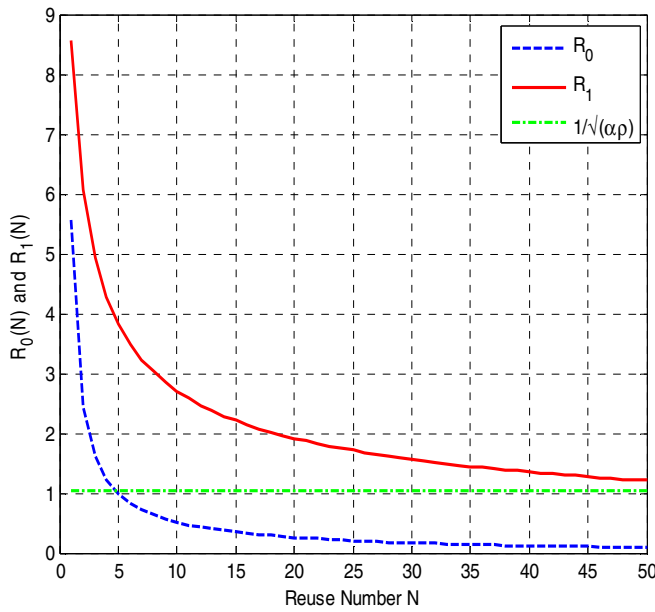
Whenever the cell radius is chosen greater than $R_0(N)$, the SIR will be greater than the design value SIR_0 ; when $R = R_1(N)$, the SIR will equal some $\text{SIR}_{\max}(N)$. Alternatively, it may be desired that the per user bandwidth W be maximized. In that case, the smallest cell radius should be chosen, $R = \bar{R}_0(N)$. This selection results in the maximum value of W which is given by

$$\begin{aligned} W_{\max}(N) &= \frac{B/N}{\rho\alpha_0 \bar{R}_0^2(N)} \\ &= \frac{B/N}{\rho\alpha_0 \left(\max \left\{ R_0(N), \frac{1}{\sqrt{\alpha\rho}} \right\} \right)^2} \end{aligned} \quad (20)$$

Hence, depending upon the chosen value of N , the associated number of users per cell $U = \rho\alpha R^2$, depends on the cell radius. Fig. 8 illustrates the bounds on the quantity U for a system with $\rho=0.35\text{user/km}^2$, $B=60\text{kHz}$, $\text{SIR}_0=20\text{dB}$, and $W_0=900\text{Hz}$

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. Acoustic communication channel capacity determines the maximum data rate that can be supported (theoretically) by an


 Fig. 6. Region of acceptable values (R, N)

acoustic channel for a given source power and source/receiver configuration. 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 (17). This condition implies that in order for a valid design to exist, the following inequality must hold

$$\bar{R}_0(N) \leq R_1(N) \quad (21)$$

Substituting for $\bar{R}_0(N)$ and $R_1(N)$ this condition can be expressed in terms of the user density and the system bandwidth. In this manner, we observe that for any given, 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 should be $B \geq N W_0$. Combining the two cases (a) and (b), we obtain the maximal user density that can be supported for a given N ,

$$\rho_{\max}(N) = \begin{cases} (B/W_0)/\alpha N R_0^2(N) & B/W_0 \geq N \\ 0 & B/W_0 < N \end{cases} \quad (22)$$

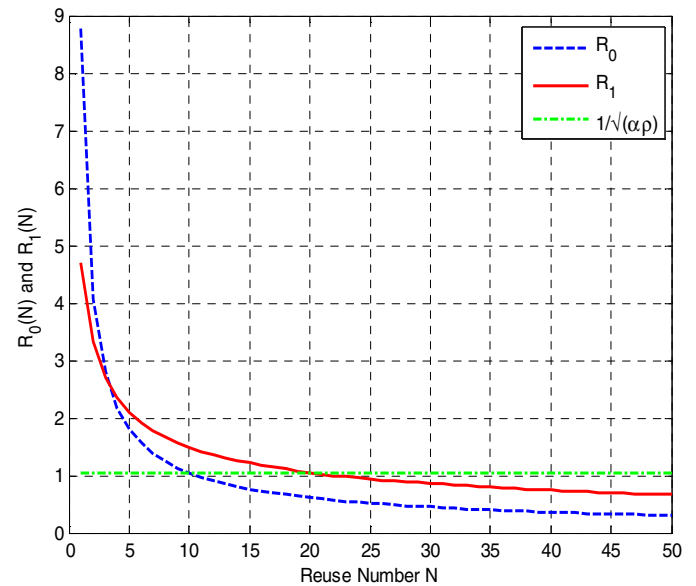
We now define the system capacity as the maximum of conditional capacities $\rho_{\max}(N)$ taken over the reuse number N

$$\rho_{\max}(N) = \rho_{\max}(N) \quad (23)$$

Therefore the maximal user density depends explicitly on the bandwidth of the system and it also depends on the system requirements (SIR_0, W_0). Fig. 9 illustrates the 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. Simple rules of cellular radio system design do not apply. The acoustic path loss depends both on the transmission distance and the signal frequency and thus it 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). Reuse number N and cell radius R must satisfy a set of constraints in order to constitute an admissible solution for a cellular network topology. The range of solutions depends on performance requirements and system parameters ρ and B . Relationships between various system parameters are complicate, but design rules are (relatively) simple. This constraint in turn implies a limitation on the overall user capacity, which is defined as the maximal density of users that can be supported within a given bandwidth B . Capacity increases as the operational bandwidth moves toward higher frequencies. We showed that there exists a set of constraints that the cell radius and the reuse pattern R and N must satisfy in order to constitute an admissible solution for the cellular system topology. 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 [14].


 Fig. 7. Region of acceptable values (R, N) by changing the design parameters (SIR_0, W_0)

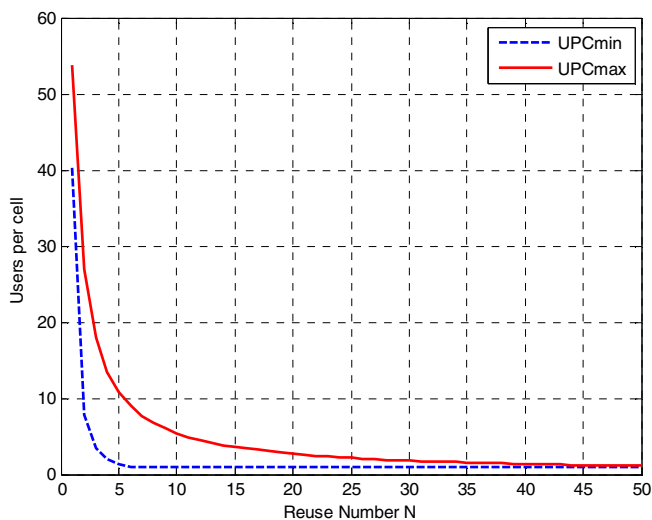


Fig. 8. Bounds on the number of users per cell U as a function of the reuse number N

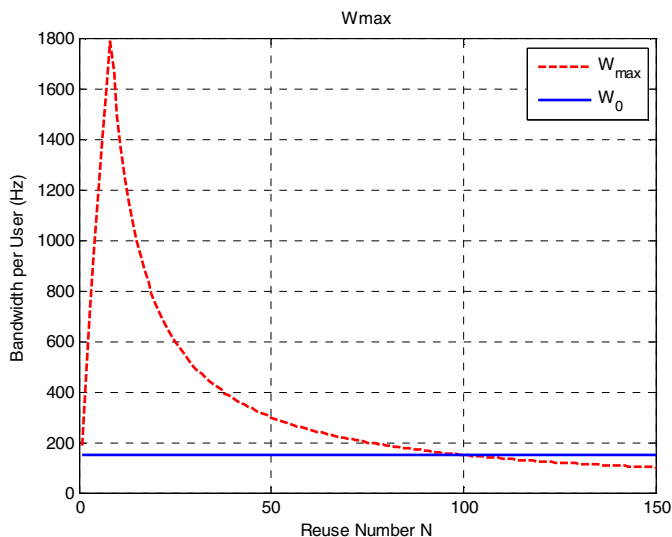


Fig. 9. Maximum of bandwidth per user with the reuse number

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