Frequency Reuse Underwater: Capacity of an Acoustic Cellular Network

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ABSTRACT

Spatial frequency reuse is considered for large area coverage in bandwidth-limited underwater acoustic networks. The acoustic propagation laws – namely, the dependence of the path loss on both the distance and the frequency – lead to a set of constraints that the frequency reuse number N and the cell radius R must satisfy in order to constitute a valid solution for the network topology. For a required signal-to-interference ratio SIR_0, and per-user bandwidth W_0, the region of admissible solutions (R, N) depends on the desired user density ρ and the available bandwidth B. User capacity is defined as the maximal density ρ_{max} that can be supported within a given bandwidth, and it is derived analytically. Numerical results illustrate the fact that capacity-achieving architectures are characterized by N that grows with ρ_{max}. In a practical system, the bandwidth may be traded off for a smaller reuse number. The capacity is also shown to increase as the operational bandwidth is moved to higher frequencies. Although higher frequencies demand greater transmission power to span the same distance, they also imply a reduction in the cell size, which in turn provides an overall reduction in the transmission power. While complex relationships are involved in system optimization, the analysis presented offers a relatively simple tool for the design of autonomous underwater systems based on cellular network architectures.

Categories and Subject Descriptors

A.1 [**General**]: Introductory and survey; H.1.1 [**Information systems**]: Systems and information theory

General Terms

Theory

Keywords

Underwater acoustic networks, cellular systems, user capacity, spatial frequency reuse, power allocation.

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1. INTRODUCTION

Spatial frequency reuse is a key concept that has enabled wide area coverage in wireless communication systems with finite bandwidth, such as terrestrial radio (mobile cellular) systems. Since acoustic bandwidth is severely limited – not (yet) by frequency regulations, but by the nature of acoustic propagation [1] – the concept of frequency reuse appears as a natural candidate for underwater networks in which large coverage will be demanded.

In contrast to the land-based wireless networks, underwater acoustic networks today are in the early stages of development. Advances in acoustic modem technology have only recently enabled the first experimental network deployments [2, 3], that involve no more than a few tens of nodes. Nonetheless, these deployments demonstrate the feasibility of underwater acoustic networking, which serves as an incentive for a growing number of applications, and a motivation for further research.

Given today's state of technology, it is conceivable that future systems will demand much larger coverage, and support for an increasing number of users. To accommodate such demands, recent research has focused on the design of channel access protocols (for a recent overview, see [4]). The questions of network architecture selection, topology optimization, and associated capacity analysis remain open.

In this paper, we investigate spatial frequency reuse for a hypothetical underwater network based on cellular architecture. The fundamental question that we address is the impact of acoustic propagation on the system design and user capacity.

The design of a cellular network begins with selection of the frequency reuse pattern and the cell radius. For simplicity, we restrict our attention to a two-dimensional scenario in which the base stations are mounted either on the surface or on the bottom, with users (e.g., autonomous underwater vehicles) distributed horizontally within the coverage area. The total bandwidth B is divided among N adjacent cells, which form 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, $\text{SIR} \geq \text{SIR}_0$, and that the bandwidth per user be $W \geq W_0$.

In a radio system, where the signal power attenuates with distance as $P(d) \sim 1/d^n$,[1] the SIR condition has a very simple solution that leads to the well-known reuse number of 7. Namely, for a hexagonal cell geometry, the SIR is dominated by the six nearest co-channel cells, and the worst case SIR, which occurs at the cell edge, is given by [5]

$$\text{SIR} = \frac{P(R)}{6P(D)} = \frac{1}{6}\left(\frac{D}{R}\right)^n \tag{1}$$

[1] The path loss exponent n is usually a number between 2 and 4.

where R is the cell radius and D the distance to the nearest co-channel cell. For hexagonal geometry, the reuse distance is $D = \sqrt{3N}R$, and, hence, the SIR condition immediately yields the solution for N. In particular, N=7 ensures more than 17 dB of SIR for a path loss exponent of 4.

In an acoustic channel, the simple path loss model does not hold. Instead, the attenuation depends on the signal frequency as well as on the transmission distance. In addition to the spreading loss which is of the form d^k,[2] a frequency-dependent absorption loss is present. The overall acoustic path loss is given by

$$A(d, f) = (d/d_0)^k a^{d/d_0}(f) \tag{2}$$

where d_0 is a reference distance, and $a(f)$ is the absorption coefficient which increases with frequency approximately as f^2 (a more accurate empirical formula can be found in [6], also in [1]).

The frequency-distance dependence of the acoustic path loss complicates the system design, as the cell radius no longer vanishes from the SIR calculation. Instead, the SIR condition implies a set of constraints that the reuse number *and* the cell radius have to satisfy in order to constitute an admissible solution. These constraints were analyzed in [7], where it was shown that the region of admissible (R, N) – if it exists – depends on the system requirements (SIR_0, W_0), but also on the available bandwidth B and the desired density of users ρ.

The findings of [7] motivate the ultimate question of system capacity: What is the maximal user density ρ_{max} [users/km^2] that can be supported by a cellular architecture based on the spatial frequency reuse of a given bandwidth B? In this paper, we attempt to answer this question.

The paper is organized as follows. Sec.2 summarizes the results of [7] which serve as the background for the capacity analysis. The capacity analysis is presented in Sec.3, along with numerical illustrations and discussion of results. Sec.4 is devoted to the issues of power and bandwidth allocation. Finally, conclusions are summarized in Sec.5.

2. DESIGN CONSTRAINTS

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

$$P(d) = \int_{f_n}^{f_n+B_0} S(f)A^{-1}(R, f)df \tag{3}$$

where $S(f) = P_T/B_0$ is the power spectral density of the transmitted signal, which we assume to be flat, and the integration is carried out over the frequency band occupied by the signal, starting at some f_n and extending over a bandwidth B_0.

The signal bandwidth B_0 depends on the multiple-access technique used. Let us assume (without the loss of generality) that time-division multiple-access (TDMA) is used. The signal bandwidth is then equal to the bandwidth allocated to one cell, $B_0 = B/N$. The frequency f_n differs among the N cells, and, due to the frequency-dependence of the acoustic path loss, different cells experience different attenuation. In particular, higher bands experience greater attenuation. However, this is true both for the desired signal and for the interfering signals, with the overall effect that the SIR improves with an increase in frequency. Hence, to ensure that the worst-case conditions are met, the system design should be carried out for the lowest frequency band, which is the one at the band-edge, $f_1 = f_{min}$.

[2] The spreading factor k is usually a number between 1 and 2.

The SIR requirement can now be expressed in terms of the cell radius R and the reuse factor $Q = \sqrt{3N}$ as

$$\text{SIR} = \frac{1}{6} Q^k \frac{I(R)}{I(QR)} \geq \text{SIR}_0 \tag{4}$$

where

$$I(x) = \int_{f_{min}}^{f_{min}+B/N} a^{-x}(f)df \tag{5}$$

For a fixed N, the SIR (4) increases with the cell radius. Hence, in order for the SIR to be greater than the design value SIR_0, the cell radius has to be greater than some minimum which depends on N,

$$R \geq R_0(N) \tag{6}$$

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 $\alpha = 3\sqrt{3}/2$ for the hexagonal cell geometry ($\alpha = \pi$ if the cells are modeled as circular). The bandwidth allocated to one cell is B/N, and, hence, the bandwidth per user must satisfy

$$W = \frac{B/N}{\rho\alpha R^2} \geq W_0 \tag{7}$$

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

$$R \leq R_1(N) = \frac{1}{\sqrt{\alpha\rho}} \sqrt{\frac{B}{NW_0}} \tag{8}$$

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

$$R \geq \frac{1}{\sqrt{\alpha\rho}} \tag{9}$$

Combining the conditions (6), (8) and (9), we find that the cell radius must satisfy

$$\max\{R_0(N), \frac{1}{\sqrt{\alpha\rho}}\} = \overline{R}_0(N) \leq R \leq R_1(N) \tag{10}$$

This expression defines the admissible region of (R, N). Only those values of (R, N) that belong to this region constitute a valid design.

Fig.1 illustrates the admissible region for a system with ρ=1 user/km^2, B=20 kHz, SIR_0=15 dB, and W_0=1 kHz. Markers are placed on the curves to indicate possible values of N (3, 4, 7, etc.).[3]

Examples of admissible regions obtained with varying system requirements (SIR_0, W_0) and design parameters (B, ρ), including those situations in which there is no solution for (R, N), can be found in [7].

3. CAPACITY ANALYSIS

Our discussion so far indicates that there are complex relationships that govern the design of a cellular system for the underwater acoustic environment. 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.

[3] The reuse number N is of the form $i^2 + ij + j^2$ with i, j non-negative integers [5].

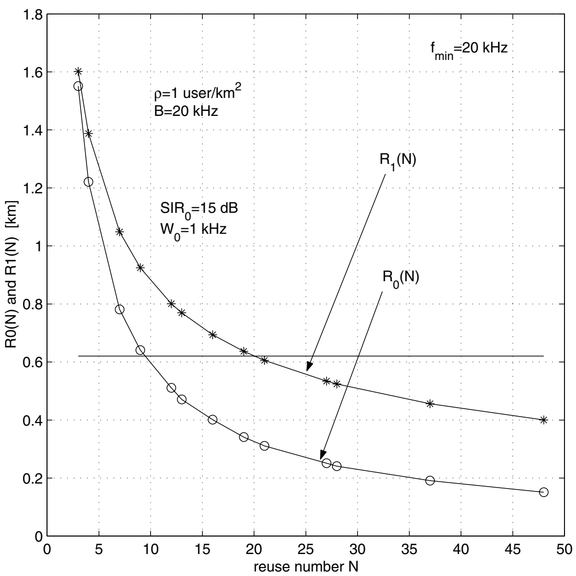

Figure 1: Region of acceptable values (R, N) lies between $R_0(N)$, $R_1(N)$, and the straight line $1/\sqrt{\alpha\rho}$.

To assess the user capacity, we turn to the design condition (10). This condition implies that in order for a valid design to exist, the following inequality must hold:

$$\overline{R}_0(N) \leq R_1(N) \tag{11}$$

Substituting for $\overline{R}_0(N)$ 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) $\rho \geq 1/\alpha R_0^2(N)$ or (b) $\rho < 1/\alpha R_0^2(N)$. Note that $R_0(N)$ depends on the bandwidth B, and, hence, the possibilities (a) and (b) correspond to some regions in the (ρ, B) space.

If (a) is true, then in order for a solution to exist, condition (11) implies that the user density has to be $\rho \leq (B/W_0)/\alpha N R_0^2(N)$. Thus, the maximal density for a given N is $(B/W_0)/\alpha N R_0^2(N)$ in case (a). The maximal density depends on the bandwidth explicitly, and also through $R_0(N)$.

If (b) is true, then in order for a solution to exist, the bandwidth has to be $B \geq NW_0$. Conversely, if $B < NW_0$, there is no solution, i.e. $\rho_{max}(N) = 0$.

Combining the two cases (a) and (b), we obtain the maximal user density that can be supported for a given N:

$$\rho_{max}(N) = \begin{cases} (B/W_0)/\alpha N R_0^2(N), & B/W_0 \geq N \\ 0, & B/W_0 < N \end{cases} \tag{12}$$

We now define the system capacity as the supremum of maximal user densities, taken over the reuse number N:

$$\rho_{max} = \sup_N \rho_{max}(N) \tag{13}$$

The capacity is a function of the system bandwidth B, and it also depends on the system requirements (SIR_0, W_0), as well as on the band-edge frequency f_{min}.

Fig.2 illustrates an example of the system capacity. Shown in dashed line is the set of maximal user densities conditioned on N, $\rho_{max}(N)$, for N varying from 3 to 37. The overall system capacity (13) is shown in solid line. Below this curve lies the region of points (ρ, B) for which a cellular system can be designed.

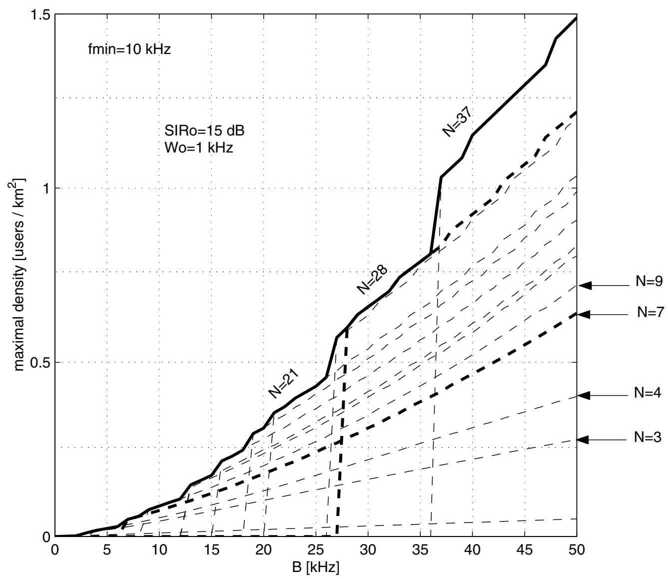

Figure 2: Capacity of a cellular system: maximal user density ρ_{max} that can be supported for a given bandwidth B, while meeting the system requirements (SIR_0, W_0). Dashed curves represent the conditional capacities $\rho_{max}(N)$. The band-edge frequency f_{min} is indicated in the figure.

The capacity increases with bandwidth, following a double trend: a sharp increase occurs at points $B/W_0 = N$ which correspond to the valid reuse numbers 3, 4, 7, etc., while between these points, the capacity curve follows the function $\rho_{max}(N)$. For example, between B/W_0=28 and 37, the capacity equals $\rho_{max}(28)$ (highlighted dashed curve). The number $N = 28$ is indicated on the capacity curve in this region, where it represents the reuse number needed to achieve the capacity, i.e. to support the associated density ρ_{max}. The capacity increases abruptly to $\rho_{max}(37)$ at B/W_0=37.

A key observation to be made from Fig.2 is that the capacity-achieving architectures are characterized by the reuse number N that grows with ρ_{max}. Depending on the system constraints and the desired performance, this fact may imply the need for a large N. To be specific, if we want to support a user density of 0.25 users/km^2, Fig.2 indicates that a bandwidth of at least 19 kHz is needed to meet the given system requirements. Using the minimal bandwidth will require N=19, which is a large, impractical number to use. However, this is not to say that N has to be as large as 19 to support this density. If a greater bandwidth is available, the same density can be supported at a lower N. For example, allocating 30 kHz of bandwidth allows the system to be designed with N as low as 7. This system may not be very efficient in terms of bandwidth utilization, since N=7 is the capacity-achieving architecture for much lower bandwidths. Nonetheless, it may provide an acceptable practical solution. If the system is constrained to a reuse number no greater than 7, the user density will be limited by the conditional capacity $\rho_{max}(7)$ (highlighted dashed curve). At B=50 kHz, the capacity curves show that N=3 is the lowest N for which $\rho_{max}(N) >$ 0.25 users/km^2; hence, the system can be designed with N as low as 3. If the desired user density increases to 0.5 users/km^2, the lowest N that can support it within the same 50 kHz of bandwidth is 7.

The capacity shown in Fig.2 corresponds to a pre-determined set of system requirements (SIR$_0$, W_0). For a different set of system requirements, this picture will change. Not surprisingly, imposing stricter requirements causes the capacity to decrease. For example, the capacity drops to less than half of that shown Fig.2 for SIR$_0$=17 dB and W_0=1.5 kHz.

In addition to being sensitive to (SIR$_0$, W_0), the capacity depends on the band-edge frequency f_{min} through $R_0(N)$. Since the SIR improves with an increase in f_{min}, so does the system capacity. Fig.3 shows the capacity region for the same system requirements (SIR$_0$, W_0) as those of Fig.2, but a different f_{min}. The total capacity is obviously much greater in this case. In the light of the previous example, ρ=0.25 users/km^2 can now be supported with B=5 kHz and N=4 (which happens to be the capacity-achieving architecture for the requirements specified). The same density can also be supported with B=7 kHz and a reuse number of 3, 4 or 7. For a greater density ρ=1 user/km^2, the design choices at B=20 kHz range between N=3 and 19, which agrees with the situation analyzed in Fig.1. Note that with a band-edge frequency f_{min}=10 kHz, it is not possible to support 1 user/km^2 within 20 kHz of bandwidth – this (ρ, B) point lies above the capacity limit shown in Fig.2.

One may wonder whether the improvement in capacity that results from allocating the operational bandwidth to higher frequencies comes at some price, such as increased transmission power. We address this question in the following section.

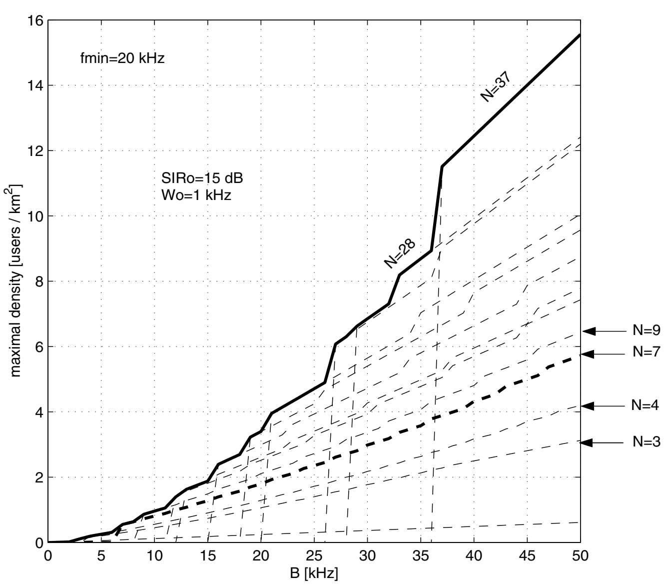

Figure 3: Capacity of a cellular system increases as the operational bandwidth is moved to higher frequencies.

4. POWER AND BANDWIDTH ALLOCATION

Power and bandwidth allocation, which are already made difficult for a single, interference-free link due to the very nature of frequency-dependent path loss and the ensuing distance-dependent acoustic bandwidth [1], are further complicated in the presence of interference. Selection of the band-edge frequency f_{min} is obviously influenced by many factors, including the physical constraints of the transducers and the power budget.

Using a higher frequency band ensures a greater SIR (and, consequently, a greater user capacity); however, it results in higher attenuation, making the signal more vulnerable to noise. A practical system is normally designed such that the noise is negligible with respect to interference, i.e. SNR >> SIR, or, equivalently, the signal-to-noise-plus-interference ratio is SINR $\approx$ SIR. When this approximation holds, the SIR can be used as a figure of merit for the system design.

To illustrate the design choices in power allocation, let us consider an example. Let us assume that the system requirements are specified by SIR$_0$=15 dB and W_0=1 kHz, and that the available bandwidth is B=20 kHz. To keep the system practical, we want to use no more than N=7. Given a desired user density, say ρ of about 1 users/km^2, the capacity curves $\rho_{max}(7)$ can be used to find f_{min} that will meet our requirements. For the example considered, let us use f_{min}=20.

Once the frequency f_{min} has been chosen, we can determine the cell radius R that meets the SIR requirement (4). Using the expression (10), let us settle for R=1 km.

Up to this point, our design is based on the SIR criterion which implicitly assumes that noise is negligible with respect to the signal. This assumption must now be justified through proper selection of the transmission power.

To be precise, let us denote by SINR$_n(f_{min}, P_{Tn})$ the SINR for the n-th cell, which operates using transmission power P_{Tn}, in the frequency band $[f_n, f_n{+}B/N]$, where $f_n = f_{min}{+}(n{-}1)B/N$, and $n = 1, \ldots N$. Using the power spectral density $N(f)$ of the ambient noise as in [1], the noise power in the n-th frequency band is evaluated as

$$Z_n(f_{min}) = \int_{f_n}^{f_n+B/N} N(f)df \qquad (14)$$

The corresponding SINR is given by

$$\text{SINR}_n(f_{min}, P_{Tn}) = \frac{S_n R^{-k} I_n(R)}{Z_n + 6S_n(QR)^{-k} I_n(QR)} \qquad (15)$$

where $S_n = P_{Tn}/(B/N)$, and $I_n(x)$ is computed using the expression (5) with the integration bounds adjusted for the n-th frequency band.

We now want to find the minimal transmission power, P_{Tnmin}, for which SINR$_n$ $\approx$SIR$_n$, $\forall n$. Specifically, let us say that the minimal power is that for which the SINR deviates no more than 1 dB (or some other level) from the SIR at the chosen frequency f_{min}. To illustrate the process, we will refer to Fig.4.

When the transmission power is equal for all cells, $P_{Tn} = P_T$, we have that SINR$_n(f_{min}, P_T)$ = SINR$_1(f_{min} + (n-1)B/N, P_T)$. In other words, the SINR curve for the nth cell is obtained simply by shifting the SINR curve for the lowest-band cell. The same is true for the SIR curves (regardless of the transmission power). The transmission power P_{Tmin} must be determined so as to ensure that at f_{min}=20 kHz, the 1 dB deviation is met for the highest band. The design assumption SINR$_n(f_{min}, P_{Tmin})$ $\approx$SIR$_n(f_{min})$ will then be justified for all the lower bands $n < N$ as well. This fact is illustrated by the curves labeled SINR$_N(f_{min}, P_{TNmin})$ and SINR$_1(f_{min}, P_{TNmin})$. Hence, the minimal power in this case is $P_{Tmin} = P_{TNmin}$ (which is evaluated to be 130 dB reμPa in this example).

Equal power allocation, however, may not be an efficient choice. In particular, a cell operating in a lower band requires less power to meet the 1 dB SINR deviation rule than does a cell operating in a higher band. Since minimal power is dictated by the highest band in the equal-power allocation policy, lower bands are using more power than necessary. The overall system resources are thus

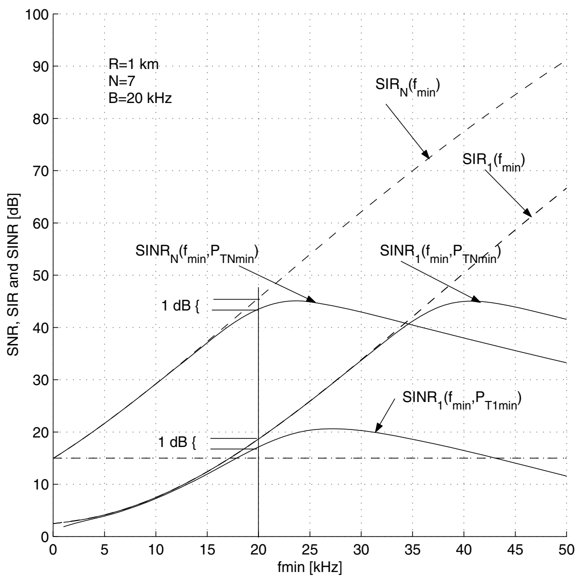

Figure 4: Determining the minimal transmission power needed to support the SIR-based design.

wasted. A more efficient power utilization can be achieved if different cells are allowed to use different transmission powers P_{Tn}. In this case, each cell's transmission power must be determined as the minimum needed to satisfy the 1 dB deviation rule at the chosen f_{min}. Power selection for the lowest frequency band is illustrated by the curve labeled $\text{SINR}_1(f_{min}, P_{T1min})$. The power P_{T1min} is 30 dB less than P_{TNmin}, the power that would have been consumed by the lowest-band cell under the equal-power allocation policy. The overall savings in power obtained through non-uniform allocation are thus considerable.

In summary, Fig.5 illustrates the minimal power as a function of the band-edge frequency f_{min}. The power is computed as

$$P_{Tnmin} = \xi \frac{B}{N} \frac{Z_n(f_{min})}{6(QR)^{-k} I_n(QR)} \tag{16}$$

where ξ is a scale factor corresponding to the 1 dB deviation.

Two cases are considered in this figure. In the first case, the cell radius is fixed to R=1 km. The minimal transmission power in this case is shown by the dashed curves for P_{T1min} and P_{TNmin}. Although the SIR improves with increasing f_{min}, the absolute level of the signal at the distance R decreases, requiring more power to make up for the loss in the SNR. Hence, the power needed to ensure the desired SINR≈SIR increases with f_{min}. In the second case, the cell radius is computed as $R = R_0(N)$ for each f_{min}, and this value is used to determine the signal power. The minimal transmission power corresponding to this case is shown in solid curves. It may be somewhat surprising to see that the power now *decreases* with frequency. This behavior is explained by the simultaneous effect that f_{min} has on the signal power and on the transmission distance: an increase in frequency requires an increase in transmission power required to span the same distance; however, it also allows a reduction in the cell size. The radius $R_0(N)$ is shown in the upper plot as a function of f_{min} (along with $R_1(N)$ and $1/\sqrt{\alpha\rho}$ which are independent of f_{min}). The savings in power that result from transmission over a shorter distance outweigh the expenses required to transmit at higher frequencies, leading to the overall decrease of P_{Tnmin} with f_{min}. This fact further speaks in favor of using higher frequency bands.

There is, of course, a limit to increasing the band-edge frequency, not only in that the cell size cannot be shrunk indefinitely, but also from the practical viewpoint of transducer design and adjacent channel interference. However, moving the operational bandwidth to higher frequencies within the practical system limitations yields a greater user capacity, and reduces the overall power consumption provided that the cell radius is kept at a minimum.

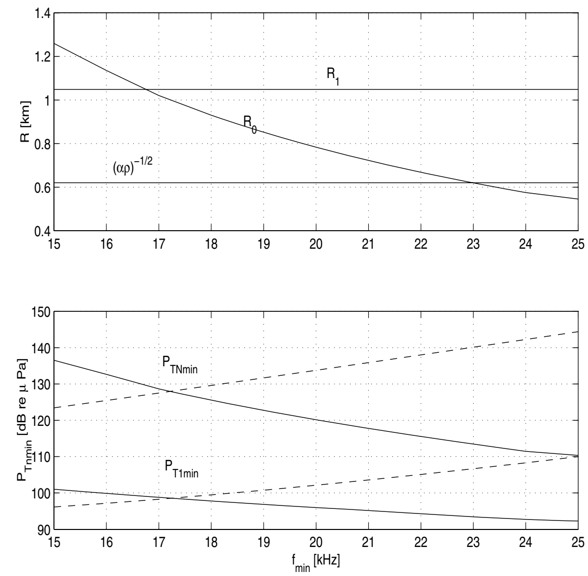

Figure 5: Cell radius, and minimal transmission power as functions of band-edge frequency f_{min}. Solid power curves correspond to cell radius $R = R_0$; dashed curves correspond to fixed cell radius R=1 km. SIR_0=15 dB, W_0=20 kHz, ρ=1 user/km^2, N=7.

5. CONCLUSION

The concept of a cellular network was considered for autonomous underwater systems, where spatial frequency reuse may enable large coverage within the constraints of limited acoustic bandwidth. Top-level system design was addressed in light of acoustic propagation. A simple depth-invariant scenario, and a nominal acoustic path loss model were used as a first approximation.

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 radii 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 limit on the overall user capacity, which we define as the maximal density of users ρ_{max} that can be supported within a given bandwidth B.

Analytical results show that capacity-achieving architectures are characterized by the reuse number that grows with ρ_{max}. The capacity region is determined by the system requirements (SIR_0, W_0), and also by the band-edge frequency f_{min}. When the operational frequency band is centered at lower frequencies, reuse numbers (much) greater than 7 may be needed to support a desired density of users without expanding the bandwidth beyond the minimum needed. Nonetheless, if bandwidth is available, it can be traded off for a lower, more practical reuse number. Alternatively, moving the operational frequency band to higher frequencies greatly improves the system capacity by virtue of increasing the SIR. It also requires less transmission power, provided that the cell radius is kept at a minimum. Total power consumption can further be reduced through non-uniform power allocation across the cells.

While acoustic propagation dictates complex relationships between the various system parameters, the analysis presented can easily be applied to any set of system constraints. It thus offers a simple tool that can be used to obtain basic guidelines for the design of future underwater networks based on the cellular types of architecture.

6. ACKNOWLEDGMENT

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