SPECTRUM-AWARE UNDERWATER NETWORKS

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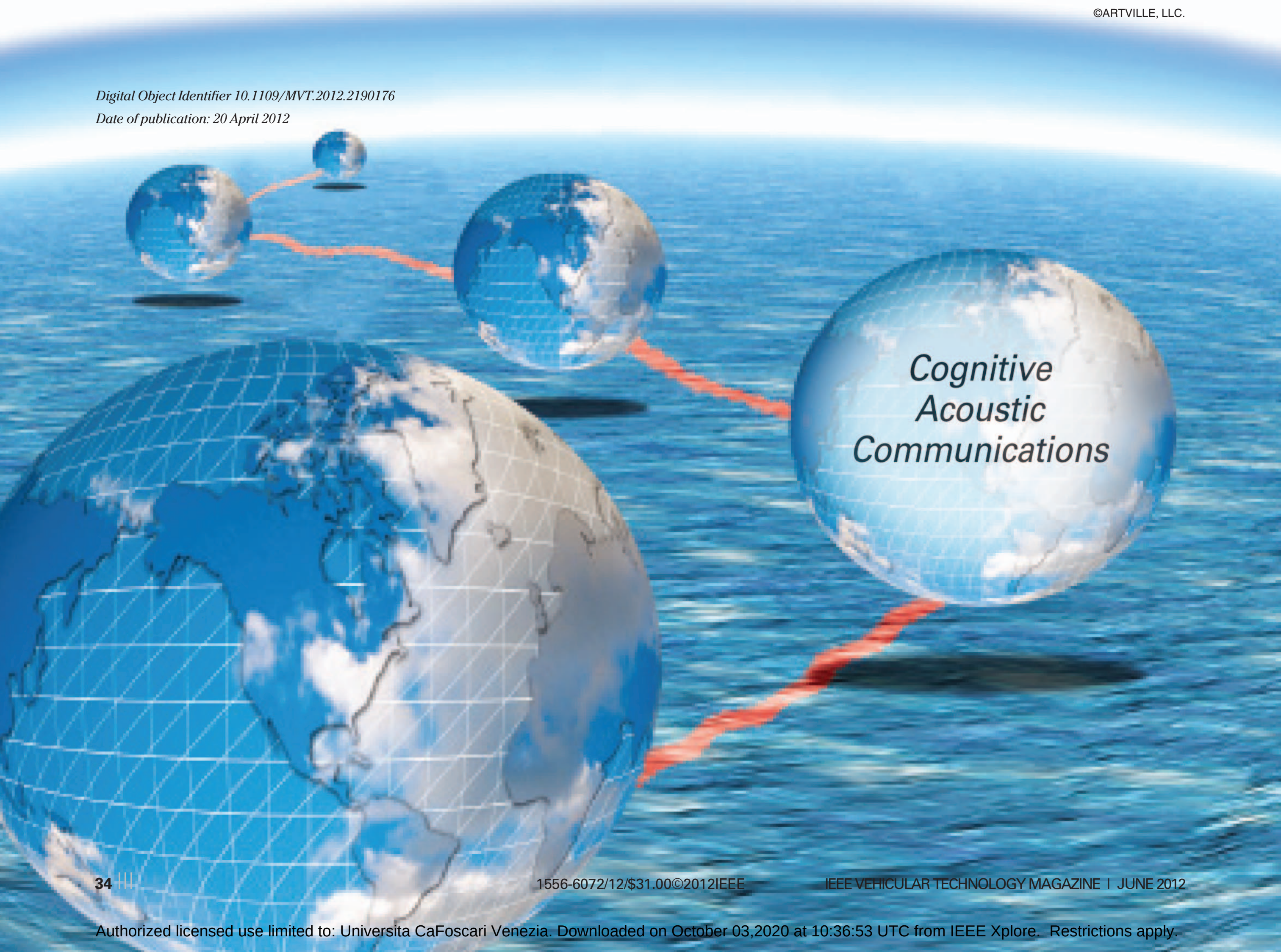
Communication capacity in underwater acoustic networks is severely limited by the uniquely challenging characteristics of underwater acoustic communications (UACs). In this article, dynamic spectrum sharing inspired from cognitive radio (CR) is applied to UAC networks, and spectrum-aware underwater networks (SUNs), i.e., cognitive acoustic communications (CACs), are proposed. First, the problem of spectrum scarcity in SUN is elaborately discussed by investigating the variation in acoustic channel capacity with respect to communication frequency and bandwidth. Then, the analysis of capacity gain via spectrum sharing in SUN is presented. To uncover the capacity gain via CAC, simulation experiments are performed, considering the effects of depth, distance, shipping, waves, spectrum management delay, and spectrum accessibility. The results of simulation experiments revealed a tradeoff between capacity gain and spectrum management delay.



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Furthermore, the tradeoff for capacity gain and spectrum accessibility period is also discussed. Here, our goal is to envision the potentials of CAC for mitigating spectrum scarcity in UAC.

Acoustic Spectrum

Frequency-dependent severe path loss and noise should be confined to frequencies less than a hundred kilohertz [1], [2]. Thus, UAC capacity is inherently limited by scarce underwater acoustic spectrum. This spectrum exhibits spatiotemporally varying characteristics, e.g., path loss may change based on the depth and season of the year, whereas noise can be further amplified by human activities and waves. Moreover, sharing the available scarce acoustic spectrum with other existing UAC systems, such as autonomous underwater vehicles (AUVs), underwater fleet, and underwater acoustic sensor networks (UASNs) deployed for underwater exploration tasks, can further decrease communication capacity. Also, nearby active sonars pose a significant challenge for UAC. In particular, frequencies used by low-frequency ultrasonic sonars fall in the range of frequencies that are used for underwater communications, and this can cause interference to UAC systems. These highly challenging and unique characteristics of underwater acoustic spectrum point out the need for spectrum-aware communications in underwater networks.

CR is an emerging technology to overcome spectrum scarcity by enabling unlicensed users to access licensed bands via dynamic and opportunistic spectrum access (DSA and OSA) and to improve overall spectrum utilization in terrestrial wireless communications [3]. Similarly, UAC networks can exploit CACs. UAC capacity can be increased, and spectrum scarcity can be mitigated via DSA and OSA, i.e., dynamic spectrum sharing. CAC can be employed to overcome the effects of spatiotemporally changing path loss and noise on underwater acoustic channel capacity. Furthermore, the capacity limitation due to interference caused by coexisting low-frequency ultrasonic sonars and other existing UAC systems can be mitigated as well. CAC unifies DSA and OSA to empower spectrum-aware acoustic communications in underwater networks. A UAC network with CAC capability can benefit from the following potential advantages.

- DSA can help to alleviate extreme path loss and noise by tuning to suitable unused frequency band in the spectrum. Nodes can tune higher-capacity spectrum bands and adapt spatiotemporally changing characteristics to achieve adequate capacity. Active UAC systems and noise sources, such as shipping, waves, and low-frequency ultrasonic sonars, can be detected by sensing of underwater acoustic spectrum, i.e., spectrum sensing, and decision can be made for appropriate band to be tuned in, i.e., spectrum decision. Then, the nodes can adapt their hydrophones to the selected band, i.e., spectrum handoff. This operational sequence is called *cognitive cycle* [3], and it is inherited from CR to increase achievable capacity in UAC networks.

OSA ENABLES UAC NETWORK NODES TO BENEFIT FROM INSTANTANEOUS COMMUNICATION OPPORTUNITIES IN UNDERWATER ACOUSTIC SPECTRUM.

- OSA enables UAC network nodes to benefit from instantaneous communication opportunities in underwater acoustic spectrum. OSA-capable nodes can identify suitable portions of the underwater acoustic spectrum for communication and capture their vacant periods via spectrum sensing. Then, nodes can adapt their transmission schedule to minimize effects of noise sources and path loss on communication capacity and not interfere with other existing UAC systems and active sonars. Specifically, mobile underwater nodes such as AUV can benefit from OSA to adapt spatiotemporally varying spectrum characteristics.

These advantages of CAC lead to a new networking paradigm, SUN. This paradigm can access any portion of the spectrum and adjust its transmission schedule via CAC to ease the effects of spatiotemporally varying path loss, noise, coexisting UAC systems, and ultrasonic sonars. To illustrate a mixture of different UAC systems, an arbitrary topology is presented in Figure 1. Although UASN is deployed for acquiring samples from ocean, submarines and AUVs travel around in the communication range, and a nearby ship runs its sonar as well.

Recently, some research efforts have been presented in literature to adopt CR-oriented approaches to UAC networks. Channel allocation methods are proposed to improve the achieved capacity in the UAC network and provide fairness among users [4], [5]. Techniques for bandwidth management in underwater networks are also investigated using CR approach [6]. Learning from experiential interactions and tuning communication algorithms accordingly is addressed to overcome the obstacles of underwater spectrum [7]. An algorithm for acoustic channel parameter estimation and mapping is developed based on the concept of CR [8]. Incorporating the spectrum-sensing facility of CR networks, distributed spectrum coordination protocol is designed for channel allocation in one-hop UAC networks [9]. Furthermore, applications of software-defined radio technology for UAC are discussed in [10]. On the other hand, development efforts for software-defined underwater acoustic modem are presented in [11]–[13] However, although these software-based solutions ease reconfiguration of physical layer parameters, they do not aim to provide dynamic and autonomous adaptation of communication parameters,

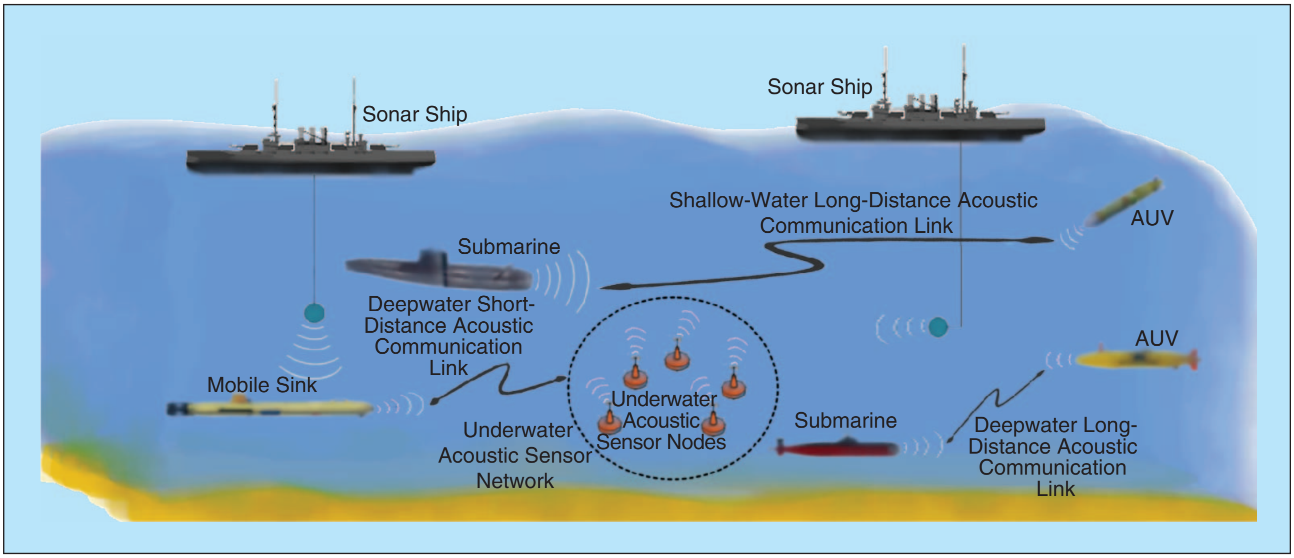

FIGURE 1 An example of a UAC system consisting of sonar ships, AUVs, submarines, UASN, and a mobile sink.

i.e., these software-based solutions are not specifically designed to enable DSA and OSA in UAC.

UAC Channel Model

SUN nodes can tune their transmission parameters without replacing any hardware via CAC capability. If the noise is Gaussian and the channel is time invariant for some duration, then the channel response function is found to be flat. Therefore, noise $N(f_i)$ can be approximated as white for a narrow bandwidth Δf centered at f_i. Then, capacity $C(d)$ in bits per second can be obtained as

$$C(d) = \sum_i \Delta f \cdot \log_2 \left[\frac{S(f_i, d)}{\text{PL}(f_i, d) \cdot N(f_i)} \right], \tag{1}$$

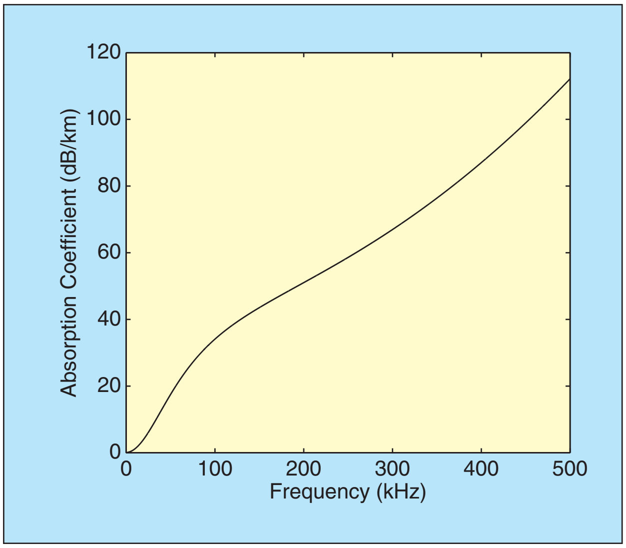

FIGURE 2 Variation of absorption coefficient with respect to frequency.

where $S(f_i, d)$ is the power spectral density (p.s.d.) of the transmitted acoustic signal in watts/hertz, and $\text{PL}(f_i, d)$ is the path loss in decibels. $\text{PL}(f_i, d)$ for acoustic signals in underwater environments is obtained by the Urick propagation model [14]:

$$\text{PL}(f, d) = k \cdot 10\log_{10}(d) + \frac{d}{1{,}000} \cdot \alpha(f), \tag{2}$$

where k is the geometric spreading factor, f is the frequency in kilohertz, d is the distance in meters, and α is the absorption coefficient in decibels/kilometer. The value of k is taken as one for shallow underwater because of its cylindrical (horizontal)-spreading property and two for deep underwater because of its spherical (omnidirectional)-spreading property [1]. Calculation of $\alpha(f)$ is given in [14], and $\alpha(f)$ versus frequency is plotted in Figure 2. Particularly, after 100 kHz, the absorption coefficient increases sharply and confines the UAC spectrum to a few hundred kilohertz. In evaluations, transmission power is set to 250 $\text{dB}_{\text{re }\mu\text{Pa/Hz}}$. Depth is assumed to be 10 m for shallow water and 1,000 m for deep water.

Noise in underwater acoustic channel is classified into four sources, namely, turbulence (n_t), human activity (shipping) (n_s), wind (waves) (n_w), and thermal noise (n_{th}). These four noise components are formulated in $\text{dB}_{\text{re }\mu\text{Pa/Hz}}$, incorporating the effects of shipping activity factor (s) that varies between zero and one, and wind speed (w) in meters per second [15].

Spectrum Scarcity in UACs

Here, we investigate and elaborate the spectrum confinement in UAC. In Figure 2, absorption coefficient $\alpha(f)$ is plotted with respect to carrier frequency f_0. As the carrier frequency increases, $\alpha(f)$ increases enormously. Since path loss is proportional to loss due to medium absorption being determined by $\alpha(f)$, a sharp increase in $\alpha(f)$ makes communication over a few hundred kilohertz hard to realize as a result of excessive path loss. Additionally, ambient noise for underwater communications relies upon frequency and environmental factors, i.e., shipping and wind. Ambient noise has a p.s.d. that resembles a V-shaped curve that reaches its minimum value around a few tens of kilohertz based on shipping and wind factors [2]. When ambient noise is combined with the extreme absorption loss proportional to distance and frequency, underwater acoustic nodes are confined to operate with f_0 below a few hundred kilohertz.

In Figure 3, capacity with respect to f_0 is presented for different bandwidths, and distance is taken to be 5 km, shipping factor s is set to one, and wind speed w is assumed to be 10 m/s. From the viewpoint of basic application, frequencies above 180 kHz became infeasible for UAC. Furthermore, because of increasing path loss with f_0, the capacity decreases dramatically with increasing f_0 for the same bandwidth. For example, from f_0 =50–110 kHz, one third of the capacity diminishes for $B = 20$ kHz, while for $B = 50$ kHz, one half of the capacity diminishes in the same f_0 range. Therefore, nodes that are operating at higher f_0 than others, i.e., if they are closer to the higher end of available spectrum, are likely to suffer from fixed channel-allocation scheme because of the capacity variation illustrated in Figure 3.

Heterogeneity in underwater acoustic spectrum points out the necessity of spectrum awareness, and hence, it is promising to adopt DSA and OSA approaches for CR-oriented UAC. SUN nodes must have the capability of CAC, i.e., sharing acoustic spectrum adaptively via tuning their acoustic transducers to a dynamically changing environment based on the application needs, such as UASN event reporting, AUV coordination, intersubmarine video conferencing, and distributed sonar imaging. Hence, SUN is essential to improve communication capacity via CAC. In the following sections, we investigate the performance of DSA and OSA with respect to various environmental conditions, spectrum management delay, and spectrum accessibility duration in SUN.

DSA for Underwater Acoustic Networks

In this section, we analyze the effect of DSA on communication capacity in SUN. The band in the range of 0–160 kHz is divided into C equal bandwidth channels, e.g., there are eight channels with 20-kHz bandwidth for $C = 8$. The duration spent for spectrum management functionalities, i.e., spectrum management delay, is expressed by τ_s. To analyze the effect of different τ_s values, we alter the instantaneous throughput r_s, i.e., ratio of the communication duration (τ_c) to total spent duration, including spectrum management delay ($\tau_c + \tau_s$), which equals $r_s = \tau_c/(\tau_c + \tau_s)$.

DSA CAN HELP TO ALLEVIATE EXTREME PATH LOSS AND NOISE VIA TUNING TO SUITABLE UNUSED FREQUENCY BAND IN THE SPECTRUM.

DSA scheme is compared with the capacity of fixed spectrum assignment at the highest available f_0 with the same B, e.g., fixed access to 140–160-kHz band for $C = 8$. For the DSA scheme, nodes sequentially change their f_0 and access each channel in the spectrum with equal probability. Here, we calculate the achieved capacity for a DSA scheme by multiplying the average capacity of these heterogeneous C channels with instantaneous throughput r_s. In Figures 4 and 5, comparison of achievable capacities via non-DSA and DSA schemes with equal and nonequal channel access probabilities is presented for different depths, d, s, w, C, and r_s values.

Deep Water

The evaluations for deepwater environment are presented in Figure 4. DSA provides access to lower f_0 channels with B. For a 5 km distance, achievable capacity for $r_s = 0.7$ stays above the one for non-DSA scheme while the capacity of non-DSA scheme reaches a higher value than the one for $r_s = 0.7$ when the communication range is decreased from 5 to 0.5 km. The effect of spectrum management delay becomes dominant as the communication range decreases; thus, communication capacity gain decreases for lower r_s. For $d = 5$ km, $s = 0$, and no wind ($w = 0$), non-DSA scheme stays behind DSA scheme (Figure 4). Furthermore, non-DSA scheme for that environmental setting achieves less capacity than did the DSA scheme for $d = 5$ km, $s = 1$,

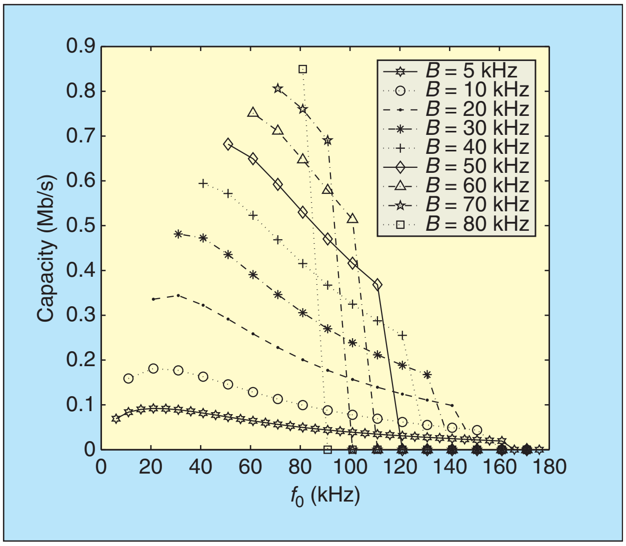

FIGURE 3 Variation of capacity with respect to center frequency for $d = 5$ km, $s = 1$, and $w = 10$ m/s.

and $w = 10$ m/s case. Although there is noise due to shipping and wind, DSA scheme performs better than non-DSA scheme with no shipping and wind. Capacity gain provided by DSA is smaller for $d = 5$ km, $s = 1$, and $w = 10$ m/s case with respect to the one for $d = 5$ km, $s = 0$, and $w = 0$ m/s case; hence, s and w affect capacity gain via DSA adversely.

In SUN, accessed spectrum channels can be dynamically altered based on the communication range to increase capacity, since noise is not the same for each spectrum band. Therefore, communication capacity gain can be achieved by accessing better-conditioned spectrum bands dynamically in underwater acoustic spectrum. Furthermore, dividing spectrum into higher number of channels (C) is also depicted in Figure 4. Increasing the number of channels causes degradation of B per channel. However, the higher number of channels allows to operate higher number of communication systems concurrently. Therefore, underwater acoustic spectrum must be fine grained to allow different underwater acoustic systems with heterogeneous capacity requirements.

Shallow Water

In Figure 5, the performance of DSA scheme with $r_s = 0.7$ is given for different distances, s, and w values in shallow water. As in deepwater case, the capacity decreases monotonically while spectrum is further divided into smaller channels. Although the achieved capacity is higher than the deepwater case, overall, for $r_s = 0.7$, DSA does not provide capacity gain in shallow water, i.e., a higher r_s value is required to achieve an increase in capacity. For $r_s = 0.7$, DSA schemes stay behind the non-DSA scheme in each environment setting. This reveals the fact that capacity gain via CAC reduces with decreasing depth as well as decreasing distance for the same value of r_s.

In shallow water, communication capacity exhibits less variation with respect to altering distance, shipping, and wind than in deep water. However, the obtained gain via CAC is lower with respect to deepwater case. A higher r_s value is needed to benefit from CAC and reach higher capacity values in shallow water when compared with the deepwater case.

OSA for Underwater Acoustic Networks

CAC is formed by the unification of OSA and DSA. Apart from DSA, OSA can provide access to higher-capacity portions of underwater acoustic spectrum in an opportunistic manner so that the effects of spatiotemporally varying noise and path loss on communication are minimized. Here, we analyze the relation between bandwidth, center frequency, and underwater communication parameters, i.e., distance, shipping, and wind. For OSA, the spectrum accessibility ratio r_a is defined as the probability of having access to that channel at any time during communication. The value of r_a is taken as half for accessed channels in evaluation.

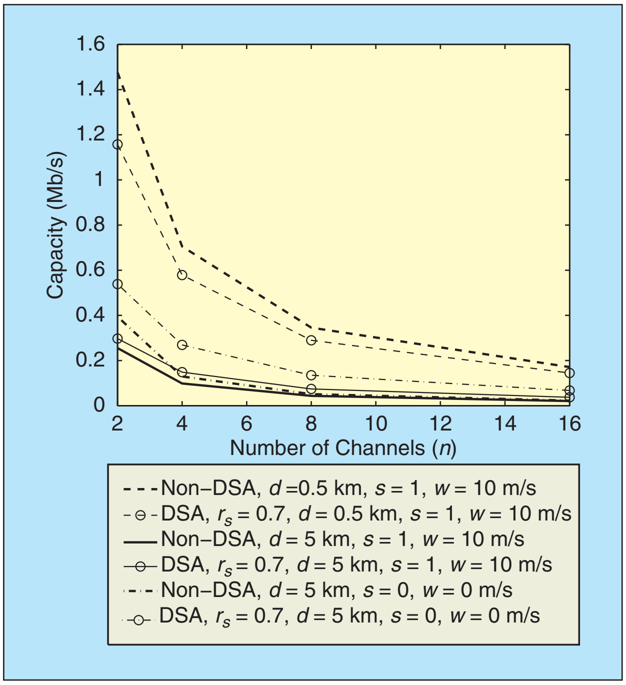

FIGURE 4 The capacity of DSA-enabled SUN with respect to the number of channels in deep water (1 km).

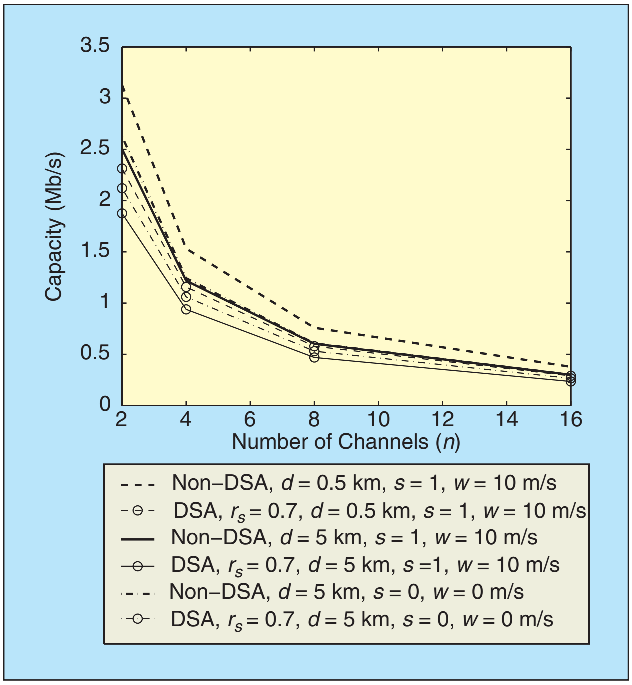

FIGURE 5 The capacity of DSA-enabled SUN with respect to number of channels in shallow water (0.01 km).

Deep Water

In Figure 6, the capacity available to OSA users increases linearly as the opportunistically accessed bandwidth increases. For $d = 5$ km, regardless of shipping activity and wind, the achieved capacity is favorable for $f_0 = 40$-kHz case against $f_0 = 120$-kHz case. This result points out the fact that the achieved capacity in OSA is higher while accessing lower f_0 channels than the higher f_0 channels with the same bandwidth. Nodes operating at higher f_0 portions of the spectrum can be moved opportunistically to increase communication capacity. While moving from $f_0 = 120$-kHz to $f_0 = 40$-kHz channels with the same bandwidth, achieved capacity increases at 5-km distance for $s = 0$ and $w = 0$ m/s case is higher when compared with $s = 1$ and $w = 10$ m/s case.

Adverse effects of frequency-dependent noise and path loss on communication capacity can be mitigated by opportunistically accessing higher-capacity portions of acoustic spectrum. Limitations on capacity due to small r_a can be mitigated as well by dynamically moving to higher-capacity portions of the spectrum, i.e., lower f_0 channels of spectrum. Small r_a cases with lower f_0 can achieve higher-capacity levels than higher r_a cases with higher f_0 for the same B because of acute path loss and ambient noise proportional to frequency.

Shallow Water

Achieved capacity evaluations regarding shallow water are presented in Figure 7. In shallow water, achieved

SUN CAN REACH HIGHER CAPACITIES THAN TRADITIONAL FIXED SPECTRUM APPROACHES WITH THE HELP OF CAC CAPABILITY.

capacity via OSA for different settings becomes closer with respect to the deepwater case. Because path loss decreases when compared with deep water, the received signal power for the same distance is higher for shallow water. Therefore, communication capacity becomes less vulnerable to noise for the same frequency range, i.e., f_0 and B, in shallow water compared with the deepwater case. For example, only a small difference in achievable capacities via OSA is observed for $f_0 = 120$ kHz with the removal of shipping and wind when $d = 5$ km. However, when the achieved capacity difference between $f_0 = 40$ and $f_0 = 120$ kHz is considered, it is greater for $d = 5$ km, $s = 0$, and $w = 0$ m/s than the one for $d = 5$ km, $s = 1$, and $w = 10$ m/s although the significant path loss decreases in the latter one. This result once again reveals the importance of the accessed spectrum band in accordance with the environmental settings in SUN.

In shallow water, increasing bandwidth results in increased achieved capacity for the same f_0, while it decreases if f_0 is increased for the same B. Capacity difference between low and high f_0 is smaller compared with the deepwater case, and this difference grows as the bandwidth of the channel increases. This relatively small

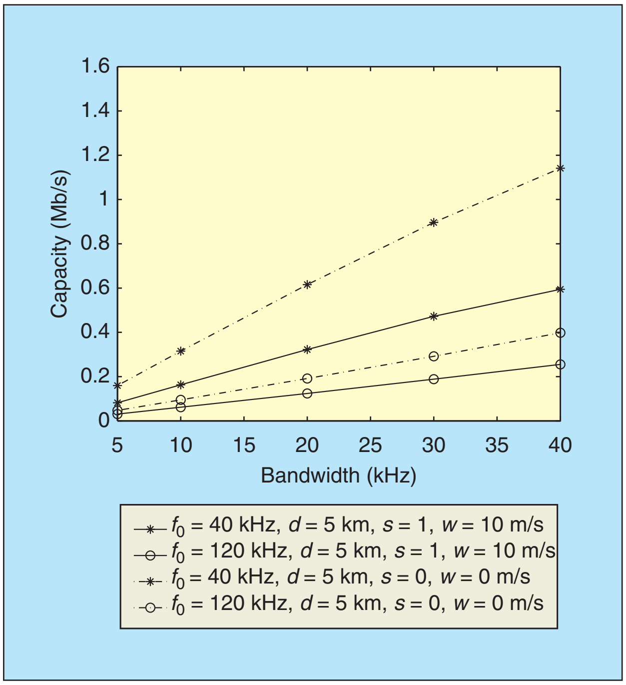

FIGURE 6 The capacity of OSA-enabled SUN with respect to bandwidth in deep water (1 km).

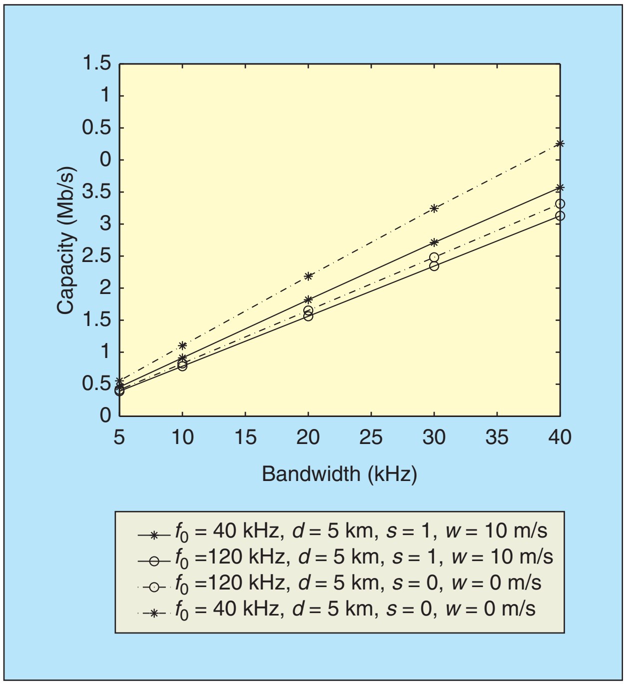

FIGURE 7 The capacity of OSA-enabled SUN with respect to bandwidth in shallow water (0.01 km).

RECENTLY, SOME RESEARCH EFFORTS HAVE BEEN PRESENTED IN LITERATURE TO ADOPT CR-ORIENTED APPROACHES TO UAC NETWORKS.

variation in capacity provides flexibility in f_0 selection while accessing with same bandwidth and r_a.

Conclusions

In this article, CAC to empower SUN inspiring from CR paradigm in wireless terrestrial communications is proposed. Spectrum scarcity in UAC due to the uniquely challenging underwater acoustic spectrum is discussed, and the need for spectrum-aware communication techniques is pointed out. We explore the capacity gain that can be achieved via CAC in SUN by simulation experiments and investigate the advantages and limitations of SUN along with its tradeoffs for DSA and OSA separately. Clearly, SUN can reach higher capacities than traditional fixed-spectrum approaches with the help of CAC capability. We expect that this article will provide better recognition for the capabilities of SUN and actuate further research efforts to explore this favorable area.

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