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Hybrid Space-Frequency Access for Underwater Acoustic Networks

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ABSTRACT Underwater acoustic networks have recently risen as an effective support to several marine and oceanic applications. However, the potential presence of a large number of nodes simultaneously connected has pushed the scientific community to address the matter of communication resources management, hence to provide the best possible performance for each link. Since underwater acoustic communications (UWACs) suffer from limited bandwidth and long propagation delays, medium access control results really challenging. The best known schemes, that are time division, frequency division and code division multiple access have been considered to handle this problem in underwater scenarios, even though they suffer from some weaknesses. Furthermore, spatial division multiple access achievable in Multiple-Input Multiple-Output (MIMO) systems has emerged as a promising technique able to fit with the multipath propagation typically characterizing UWACs. Dealing with underwater medium access control, we investigate the feasibility of a novel hybrid multiple access technique that works in a bi-dimensional resources domain, namely space and frequency. This solution is aimed to mitigate the multi-user interference by exploiting spatial diversity and, whenever necessary, by applying frequency reuse. Finally, we discuss the feasibility and potential of massive MIMO paradigm, conveniently recast into the underwater context.

INDEX TERMS Underwater acoustics, access protocols, massive MIMO.

I. INTRODUCTION

The last decades have been characterized by the increase of researchers interest towards the investigation of the underwater environment. In the field of wireless communications, acoustic technology has been recognized as a powerful and efficient instrument in supporting several applications, both military and civilian, requiring the development of broad sensor networks [1], [2]. Coastal surveillance [3], seismic events monitoring [4], Autonomous Underwater Vehicles (AUVs) remote control [5], scientific data collection and transmission [6] are some of the most attractive activities where underwater acoustic communications find use. The matching between sound propagation properties and physical characteristics of the medium makes the acoustic technology better suited to the underwater environment than solutions exploiting electromagnetic signals, which instead suffer from strong attenuation. However, the low speed of sound in water (about 1500 m/s, that is five order of magnitude lower than the speed of light) causes large signal propagation delay [7]. Besides, by taking into account the poor available bandwidth characterizing acoustic systems, it follows that the achievable data rate with UWACs is limited (especially if compared with RF systems performance). Hence, the paradigm of UWACs results particularly tailored to long range links scenarios where high reliability is required.

Due to the limited bandwidth characterizing underwater acoustic networks (UWANs), the efficient management of broadcast channel resources results to be fundamental in order to guarantee the best quality of service to users requesting for access [8]. In fact, medium access control (MAC)

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is considered as a very timely issue for UWACs, especially for networks intended to serve a large number of sensors, modems and AUVs.

A. RELATED WORKS ABOUT UNDERWATER MAC

The strategies for MAC can be organized in two main categories, oriented to random access and channelization, respectively. Overall, with random access based mechanisms (also referred as contention based access) it is possible to maximize the channel occupancy [9], since users transmit data immediately whenever needed, without any latency caused by scheduling or queueing. So they may be potentially fitting for delay-sensitive communication scenarios like the underwater acoustic one. However, the management of collisions due to the unscheduled users transmission becomes problematic [10]. In fact, the occurrence of a collision entails all the transmitting nodes to be informed about such event and proceed with retransmission. Such mechanism, together with channel sensing, unavoidably introduces delays and back-off times that further penalize the communication, already known to be slow due to the nature of acoustic waves propagation.

On the other hand, larger attention has been dedicated to channelization techniques, where the network resources are assigned to users following specific policies. The oldest and best known reference techniques are time division multiple access (TDMA) and frequency division multiple access (FDMA), but also code division multiple access (CDMA) and orthogonal frequency division multiple access (OFDMA) have been considered as potential strategies in UWACs [11], [12]. The work in [11] describes a TDMA mechanism that, exploiting spatial reuse and direct sequence spread spectrum at physical layer, provides an efficient traffic management in broadcast ad hoc UWANs. However, the nature of underwater acoustic propagation makes TDMA-based mechanisms unavoidably suffering from long and variable propagation delays, that negatively impact on the network synchronization as well. In general, the application of the sole FDMA principle is recognized as unsuitable for multiple access in UWACs. The main reason is that acoustic systems are characterized by a limited bandwidth that, whatever sliced to serve concurrent communications, may not provide sufficient performance to users. Furthermore, problems of inter-channel interference occur due to Doppler shift caused by transmitter and receiver relative movement [13]. A more convenient approach relies instead on OFDMA to handle independent downlink transmissions. Best performance for OFDMA are achieved when perfect channel state information (CSI) is available at the network central node. Such scenario is only ideal since, due to the long signal propagation delay, the procedure for channel estimation can be performed only with low cadence, hence it is not possible to have always updated CSI. Dealing with channel estimation, the authors in [14] propose a novel CSI selection method to drive the power allocation in OFDMA, resulting in users bit error rate improvement. In general, the performance of OFDMA is penalized by the fast time variability of the channel and high Peak-to-Average Power Ratio (PAPR). An alternative is represented by Single-Carrier (SC)-FDMA that provides a lower PAPR, even though it is less robust to intersymbol interference than OFDMA. By referring to the underwater case, the work in [15] describes the combination of SC-FDMA and interleave division multiple access, resulting in a hybrid access strategy particularly efficient in those channel scenarios characterized by large delay spread. The authors in [12] propose instead a distributed medium access control based on CDMA, where chaotic codes are employed for users separation and hybrid Automatic Repeat reQuest is implemented for error control issues. It is worth noting that CDMA requires the orthogonality of spreading codes in order to guarantee the orthogonality among users as well. Such condition is achieved only with perfect network nodes synchronization, making the spreading sequences aligned (from the temporal point of view) at the central node. However, achieving perfect synchronization becomes very hard due to the large propagation delays characterizing UWACs, and multiple access interference (MAI) unavoidably rises. Finally, the benefits brought by the use of MIMO architectures to improve the performance of point-to-point links [16] have suggested the researchers to exploit the spatial diversity for MAC issues as well. By referring to the work in [17], the authors propose a position-based probabilistic space division multiple access (SDMA) to optimize the transmitter beam direction and width, so to mitigate multi-user interference. However, the use of spatial diversity becomes fruitful if the number of the transmitting/receiving acoustic antennas is sufficiently large to achieve channels spatial uncorrelation. So, realizing SDMA would request large scale antenna arrays, especially at the network central node responsible for access management.

Interestingly, the benefits deriving from the use of spatial diversity have been also discussed in the context of 5G cellular technology, since the increasing demand for higher throughput is planned to be supported through the use of very large scale antenna systems [18]. Following this paradigm, also referred as massive Multiple-Input Multiple-Output (M-MIMO), the more antennas the transmitter/receiver is equipped with, the better performance in terms of data rate and link reliability can be achieved. Furthermore, the implementation of large-scale antenna systems demonstrates to be convenient for network coverage area optimization, scalability and multiple access management as well [19]. Some attempts to recast the principles of M-MIMO in the underwater context were recently done and focused on the uplink. In fact, a multi-user scenario is considered in [20], [21] where a central node equipped with a large hydrophone array receives data simultaneously from 4 AUVs. In those works, modified filter bank multi-carrier modulation schemes are proposed to counterbalance the time-frequency dispersion introduced by the channel. Moreover, equalization applied to the large array equipping the receiver allows multi-user

TABLE 1. Features of the best known access mechanisms.

Random Access	TDMA
✓ Better channel occupancy than channelization approaches ✘ Channel sensing and back-off times introduce delays ✘ Performance lowered by collisions and re-transmissions	✓ Full bandwidth available for each user ✘ Accurate synchronization is required ✘ A long time may be necessary to serve all the users
FDMA	**CDMA**
✓ Users transmit on separated bands ideally avoiding MAI ✘ Inter-channel interference may raise from Doppler shift ✘ If resources are statically allocated, having users not transmitting causes network efficiency reduction	✓ Users transmit simultaneously at full bandwidth ✓ Idle users make the interference reduced without network efficiency reduction ✘ Signal spread is not effective in underwater systems characterized by limited bandwidth ✘ Interference depends on users synchronization and codes uncorrelation ✘ Power control is necessary to solve the near-far problem
SDMA ✓ Users transmit simultaneously at full bandwidth ✓ Spatial diversity is exploited to mitigate MAI ✘ Performance limited by channels spatial correlation ✘ Spatial diversity not effective with few, close transmitters	

interference to be mitigated. However, some doubts rise about the feasibility and practicability of such network architecture, since simulation results shown in [20], [21] suggest that the receiving node should be equipped with an array of at least 40 hydrophones to provide good communication performance for all the transmitting nodes.

Summarizing, the analysis of the literature reveals how the study and design of very large MIMO systems for underwater communications are at a very early stage. In fact, to the best of our knowledge, the works mentioned above are the only ones dealing with multi-user interference in a underwater M-MIMO scenario. Moreover, in [20], [21] interference is addressed at the physical layer, while no straight reference to MAC issues is reported. The potential adoption of M-MIMO for access management in the underwater context may be suggested by the similarity between the structure of UWANs, very often characterized by a centralized node and multiple secondary ones as in [20]–[22], and cellular networks, with a base station usually serving different users. However hardware capabilities and signal processing techniques supporting cellular communications are significantly different from those characterizing UWACs. So, careful attention must be paid to the concept of *massive*, especially when dealing with underwater scenarios. In this direction, some fundamental and straightforward criticisms unavoidably arise. Specifically, the achievement of high performance in RF systems is tied to the capability of spatially resolving MAI. Such task is typically accomplished through the use of precoding techniques (for instance beamforming operating spatial filtering) that, basing on the frequently updated CSI, achieves an accurate real time adaptation of the transmission parameters, so to guarantee the highest quality of service possible. Dealing instead with UWACs, due to the low speed of sound, the use of frequent overhead signaling for channel estimation and adaptive signal processing may cause high latency, thus dramatically penalizing the throughput. So, solutions tailored to the RF communications can not be straight deployed in the underwater acoustic context, but they must necessarily pass through a careful recasting.

B. GOALS

The previous discussion has clearly highlighted how the efficient management of the system resources represents a very challenging issue in underwater communications. With a view to the future, it is expected that wider and busier networks must be build up and it is therefore crucial to optimally handle the problem of multiple access. As briefly summarized in Table 1, the best known access techniques show strengths but also weaknesses, mainly due to the impairments on underwater signal propagation and to the limited bandwidth characterizing acoustic systems. In this contribution, we present a novel access mechanism that:

- relies on a two-dimensional domain, described by space and frequency, allowing the realization of a space-frequency division multiple access (SFDMA);
- uses spatial diversity to overcome the limitations characterizing access in the frequency domain and, viceversa, resorts to users separation in the frequency domain to mitigate spatial interference;
- handles the channel resources assignment through a reverse-greedy-like algorithm so as to guarantee access for the highest number of nodes possible, meeting the communication requirements.

Furthermore, we investigate the access performance as a function of ratio between the number of transmitting acoustic antennas at the central node and the number of users to be served. In this regard, we present a critical discussion about the feasibility and limits of M-MIMO in the underwater acoustic scenario.

The paper is organized as follows. In Sec. II we introduce the network model, providing an overview of the best known underwater access mechanisms. The proposed SFDMA scheme is presented in Sec. III, with the algorithm for network resources assignment and the discussion about the feasibility of underwater M-MIMO being described in Sec. IV. Simulation analysis and discussions are reported in Sec. V. Finally, conclusion is drawn in Sec. VI.

II. NETWORK MODEL AND OVERVIEW OF UNDERWATER MAC STRATEGIES

Let us refer to a broadcast UWAN with a central node acting as acoustic base station and N nodes/users. Channel resources are handled by the central node that is also responsible for downlink medium access control (Figure 1). The central node is assumed to be equipped with M transmitting elements to serve multiple concurrent communications, while the N

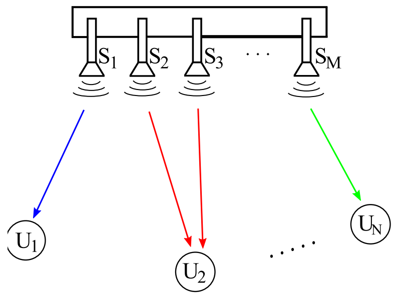


FIGURE 1. **Massive MIMO scenario where a central node, equipped with *M* sources, serves *N* users.**

nodes, without loss of generality, perform signal reception by means of a single hydrophone. For those schemes not relying on spatial diversity, namely TDMA, FDMA and CDMA, we have $M = 1$ [23], [24]. On the other hand, for SDMA the parameter M is set to be larger than 1. Furthermore, we consider the transmit acoustic antennas at the central node as working according to an ON-OFF operation mode. That is, sources can be either idle or active and transmitting at fixed power P_{t}. It is worth recalling that, in the field of acoustic communications, P_{t} is typically referred as the source level defined as the intensity of the radiated sound at a distance of 1 meter from the source, measured in dB re 1 μPa @1 m. The assumption about transmitters ON-OFF behavior does not oversimplify the network model, on the contrary its motivation will be thoroughly discussed further. In addition, note that commercial devices for UWACs typically work with fixed source levels that cannot be tuned on-the-fly [25]. The total available system bandwidth is B_{tot}.

Signal propagation from the central node to the other ones (and viceversa) is characterized by reflection and scattering phenomena off the water surface and bottom, giving rise to multipath fading and shadowing. In this regard, the channel impulse response related to the link between the m-th acoustic transmitter and the n-th user can be modeled as [26]:

$$h_{m,n}(t) = \sum_{\ell=1}^{L^{(m,n)}} a_\ell^{(m,n)} \delta(t - \tau_\ell^{(m,n)}) \tag{1}$$

that is the sum of $L^{(m,n)}$ paths arriving with amplitude a_ℓ and delay τ_ℓ. For the ℓ-th path, the amplitude $a_\ell^{(m,n)}$ is the result of the path, spreading and absorption loss experienced by the signal. Such effects are function of the distance $d_\ell^{(m,n)}$ and the frequency f, with the most known reference models given by Urick and Rodgers [27]. The delay $\tau_\ell^{(m,n)}$ instead refers to the time of arrival of the signal component passing through the ℓ-th path, so it essentially depends on the propagation distance. When dealing with multiple access, link capacity and signal-to-noise ratio (SNR) issues (that is, the main topics of this work), $h_{m,n}(t)$ is reliably described as a single-tap impulse response [28]–[30], hence a coefficient $h_{m,n}$. Such assumption has been widely accepted in the literature for two main reasons. First, even though the underwater acoustic channel is known to be long in time, causing large delay spread, channel energy is in general carried by the very first path [31]. In fact, SNR is essentially considered to be function of the attenuation on the first signal component arrival [32]. Second, a single-tap impulse response is typically the result of channel equalization performed at the receiver [33]–[35]. In this direction, communication performance can be reliably evaluated as a function of the SNR rather than the channel impulse response [36], [37]. Finally, acoustic signal propagation is also corrupted by ambient noise, modeled as a combination of turbulence, shipping, waves and thermal noise. Noise sources are typically characterized as Gaussian with continuous power spectral density [38].

The network model depicted in Figure 1 can be taken as a suitable reference scenario to describe the essentials of conventional underwater multiple access techniques, namely TDMA, FDMA, CDMA (with $M = 1$) and SDMA (with $M > 1$). The considered schemes are presented and discussed as a function of the user channel capacity, so to emphasize the dependency of performance on the signal-to-interference-plus-noise ratio (SINR), that is on the channels condition. Dealing with TDMA, FDMA and CDMA we have the channel capacity for the n-th user defined as:

$$C_{n,\text{x-DMA}} = \frac{B_{\text{tot}}}{N} \log_2(1 + \Gamma^{-1}\gamma_{n,\text{x-DMA}}) \text{ with } x = \text{T,F,C} \tag{2}$$

which is formally the same expression for the considered schemes ($x = \mathrm{T}$ refers to TDMA, $x = \mathrm{F}$ to FDMA and $x = \mathrm{C}$ to CDMA, respectively), but on the other hand it shows some conceptual differences. The term Γ indicates a gap introduced to measure the increase (margin) of SINR $\gamma_{n,\text{x-DMA}}$, requested to achieve a certain target error probability [39]. Let us give a numerical example to highlight the meaning of Γ. Given $N = 1$, if no gap was introduced, that is $\Gamma = 1$, we have that a SNR equal to 0 dB would be sufficient achieve a spectral efficiency of 1 bit/s/Hz. This means that we can use a binary modulation (for instance On-Off Keying). However, for SNR around 0 dB, binary modulations are characterized by low performance in terms of bit error rate [40]. So, the SINR gap $\Gamma > 1$ is introduced to let the system provide a sufficiently reliable link. As further discussed in the next sections, Γ is used as a countermeasure to potential SINR fluctuations causing the channel capacity to be under a certain target level, so assuring a certain degree of robustness.
Specifically, $\gamma_{n,\text{x-DMA}}$ is given by:

$$\gamma_{n,\text{x-DMA}} = \frac{P_r}{P_n + P_{\text{int}}} = \frac{P_t|h_{1,n}|^2}{N_0 B^{(n)} + P_{\text{int}}} \tag{3}$$

where each term has a specific meaning to be detailed. Being P_t the transmitted power and $h_{1,n}$ the channel gain modeling the link from the single acoustic source of the broadcast node to the n-th user, respectively, the received signal power results to be $P_r = P_t|h_{1,n}|^2$. The noise power is represented by $P_n = N_0 B^{(n)}$, with N_0 being the overall acoustic noise spectral density and $B^{(n)}$ the corresponding bandwidth ($B^{(n)} = B_{\text{tot}}$ in TDMA while $B^{(n)} = B_{\text{tot}}/N$ in

FDMA and CDMA). Finally, P_{int} is the power of potential interference rising from non-orthogonal access. For ideal x-DMA (x = T, F, C) we have $P_{\text{int}} = 0$, while such condition is not verified in real cases [24]. Specifically, in TDMA the network access is scheduled along the time, thus meaning that each of the N users is allowed to transmit exploiting the full bandwidth B_{tot}, but only during specific time slots. So, in TDMA P_{int} represents the interference caused by imperfect synchronization and giving rise to the partial overlap of different communications. Concerning FDMA, the system bandwidth B_{tot} is partitioned in N sub-bandwidths, thus allowing the simultaneous transmission of N users over separated sub-channels. In this case, P_{int} describes the inter-carrier interference occurring when, due to Doppler shift, simultaneous communications overlap as sub-channel separation is not perfect. By referring to CDMA, we have different users exploiting the full time-frequency channel resources simultaneously, being separated thanks to the use of particular coding schemes. The term P_{int} in CDMA refers essentially to MAI occurring when the misalignment of signals referring to different communications makes the spreading codes loose their uncorrelation property.

Finally, another solution to reach an efficient resource management in multiple access is given by SDMA. In fact, the use of spatial diversity allows not only to improve the communication robustness with respect to multipath propagation, but also to reduce the interference among users accessing the network. In such scenario, differently from TDMA, FDMA and CDMA, the network central node is now considered as equipped with an array of transmitting acoustic antennas to serve multiple communications. The quality of the n-th link is tied to the possibility of serving the user by exploiting more than a single source. On the other hand, since there is no time or frequency separation between communications, the n-th user may also suffer from interference caused by transmitters active on other links. Therefore, the expression of SINR characterizing the access for the n-th is the following:

$$\gamma_{n,\text{SDMA}} = \frac{P_r}{P_n + P_{\text{int}}} = \frac{P_t \sum_{u \in \mathcal{U}_n} |h_{u,n}|^2}{N_0 B_{\text{tot}} + P_t \sum_{i \in \mathcal{D}_n} |h_{i,n}|^2} \tag{4}$$

where the useful signal components come from the acoustic sources, gathered in the set $\mathcal{U}_n$, serving the n-th user, while the interference is generated from those (disturbing) transmitters, so belonging to the set $\mathcal{D}_n$, serving other communications and acting as disturb. Eq. (4), together with the expression of channel capacity for the n-th user given as:

$$C_{n,\text{SDMA}} = B_{\text{tot}} \log_2(1 + \Gamma^{-1} \gamma_{n,\text{SDMA}}) \tag{5}$$

allows to appreciate that in SDMA multiple communications occur simultaneously (as in FDMA) and exploiting the whole channel spectral resources (as in TDMA), making interference arising in the spatial domain. In fact, a convenient assignment of central node transmitters to different users would result in the term $h_{i,n}$ to be sufficiently small, thus providing high SINR. For the sake of completeness, we highlight that each acoustic source can serve only a single user, therefore $\mathcal{U}_n \cap \mathcal{D}_n = \emptyset$.

III. HYBRID SPACE-FREQUENCY MULTIPLE ACCESS

The expression of the SINR in eq. (4) shows that the performance of SDMA depends on the spatial resources (that is, the transmitters) assignment, defining P_r and P_{int} for each link. Since we assume all the acoustic sources at the central node as provided of the same transmit power P_t when in active mode, it follows that P_r and P_{int} depend on the channel gains $h_{u,n}$ and $h_{i,n}$. In this regard, when the first taps of the channel impulse response $h_{u,n}$ and $h_{i,n}$ are comparable in amplitude (*e.g.* $h_{u,n} = 0.011$ and $h_{i,n} = 0.013$), the u-th and i-th channels are meant to be highly spatially correlated [41], [42]. Such occurrence may be penalizing for the n-th user since, if the number of serving antennas is equal to the number of interfering sources, it may result $P_r \approx P_{\text{int}}$. So, according to eq. (4), the resulting SINR may be too low to provide good performance. The problem of channels correlation is typical of those scenarios where users are not uniformly distributed in the whole network coverage area, but they are concentrated in a smaller space.

By recalling that pure underwater TDMA, FDMA and CDMA show some weaknesses as detailed in Tab. 1, it results that channel access performed on a *single domain* may not always provide good performance. Open challenges about medium access control are orienting the attention of researchers towards new paradigms [43]. To this aim, we propose a particular access scheme, previously introduced as SFDMA, where space and frequency diversity are jointly exploited to make network resources management more efficient and to increase the user channel capacity. The rationale behind SFDMA is basically to exploit the spatial diversity so as to serve users with different sources, and separating them over different sub-bandwidths when the mutual spatial interference is too strong. Given the whole system bandwidth B_{tot} as divided in Q portions, we have that the SINR for the n-th user measured over the q-th sub-bandwidth, with $q = 1, 2, \ldots, Q$, is given by:

$$\gamma_{n,\text{SFDMA}}^{(q)} = \frac{P_r}{P_n + P_{\text{int}}} = \frac{P_t \sum_{u \in \mathcal{U}_n} |h_{u,n}^{(q)}|^2}{N_0 \frac{B}{Q} + P_t \sum_{i \in \mathcal{D}_n} |h_{i,n}^{(q)}|^2} \tag{6}$$

representing the same expression of SINR in the case of SDMA, but applied on a single sub-bandwidth. The fundamental difference is that, while the term P_{int} in eq. (4) accounts for the interference generated by all the transmitters not serving the n-th user, in SFDMA the interference is related only to those concurrent communications active in the same q-th sub-bandwidth. The received power P_r is measured only on the single sub-bandwidth as well. Furthermore, it is worth distinguishing two different cases related to the way of assigning the space-frequency resources. If the n-th user is served by multiple sources but transmitting on the same sub-carrier, then it means that the access is essentially granted in form of pure SDMA. In fact, since the SINR is measured on a unique sub-bandwidth returning eq. (6) as equal to eq. (4), the corresponding channel capacity is measured as in eq. (5). On the other hand, it may happen that a user is served by multiple sources working on different sub-carriers. In that case, the channels assigned to the user are *parallel* since spectrally separated, so the overall channel capacity is given by the sum of the capacities related to the Q_n frequency channels where the n-th user is served on. Specifically, we have:

$$\begin{aligned} C_{n,\mathrm{SFDMA}} &= \sum_{q=1}^{Q_n} C_{n,\mathrm{SFDMA}}^{(q)} \\ &= \frac{B_{\mathrm{tot}}}{Q} \sum_{q=1}^{Q_n} \log_2(1 + \Gamma^{-1} \gamma_{n,\mathrm{SFDMA}}^{(q)}) \end{aligned} \tag{7}$$

where the SINR is defined as a function of the considered q-th sub-bandwidth occupied by the n-th user, with $Q_n \leq Q$. So, from eq. (7), the overall capacity results from the sum of the space-frequency channel resources assigned to the user. The joint use of spatial and frequency diversity allows two or more users to transmit over the same sub-bandwidth and, differently from SDMA, to be potentially served by the same transmitting acoustic antenna (but on different sub-bandwidths). So, by performing a suitable assignment of the network space-frequency resources among users, it would be possible to achieve better access performance than in pure SDMA and FDMA.

A. PROBLEM FORMULATION

Let us depict the overall network space-frequency resources schedule as a grid composed of Q rows equal to the number of available sub-bandwidths and M columns representing the transmitters of the broadcast node. By resorting to the matrix notation, the grid can be described as:

$$\mathbf{G} = \begin{bmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,M} \\ g_{2,1} & g_{2,2} & \cdots & g_{2,M} \\ \vdots & \vdots & g_{q,m} & \vdots \\ g_{Q,1} & \cdots & \cdots & g_{Q,M}^{(Q)} \end{bmatrix} \tag{8}$$

with $\mathbf{G}$ being a $[Q \times M]$ matrix where the generic element $g_{q,m}$ represents a space-frequency slot (SFS), identified by the pair (q,m) referred to the indexes of the sub-bandwidth where the communication takes place over ($q = 1, 2, \ldots, Q$) and of the transmitter serving the user ($m = 1, 2, \ldots, M$), respectively. Therefore, $Q \cdot M$ SFSs are available. Specifically, we have $g_{q,m} = 0$ when the SFS is free, otherwise $g_{q,m} = n$ when it is assigned to the n-th user. The proposed SFDMA technique aims to provide network access to as many users as possible, operating the channel resources assignment allowing the achievement of potentially requested communication requirements. In this regard, the problem formulation can be presented in a binary fashion [44], [45]. Specifically, we represent the n-th user requesting the access by means of a binary variable z_n that describes the access status, that is, $z_n = 1$ if the access is granted, otherwise $z_n = 0$. Stemming from this notation, the problem of SFDMA can be formulated as follows:

$$\max \sum_{n \in N} z_n \tag{9}$$

$$\text{s.t.} \quad C_n \geq C^*, \quad \forall n \in N \tag{10a}$$

$$P_t \in \{0, P_{\max}\} \tag{10b}$$

with the solution to eq. (9) achieved by finding that SFSs assignment maximizing the number users for whose access is granted with channel capacity greater than a target threshold C^* (eq. (10a)). Furthermore, from eq. (9) we can also evaluate the access percentage provided by SFDMA, given as $\eta = (1/N) \sum_{n \in N} z_n$. Finally, eq. (10b) specifies the acoustic sources to work in ON-OFF mode. Such choice meets the typical hardware capabilities of the acoustic modem commercially available and, as further discussed, it is suited to the proposed channel resources allocation mechanism. As shown in eq. (7), the quality of the link strictly depends on the SINR and, more specifically by referring to eq. (6), on the relationship between the power of the received signal P_r and power of interfering components measured at the receiver P_{int}. The substitution of eq. (6) in eq. (10a) allows the condition on channel capacity for SFDMA to be rephrased as a function of the SINR, so that after some analytical manipulations we obtain:

$$\begin{aligned} &\frac{B_{\mathrm{tot}}}{Q_n} \sum_{q=1}^{Q_n} \log_2(1 + \Gamma^{-1} \gamma_{n,\mathrm{SFDMA}}^{(q)}) \geq C^* \\ &\prod_{q=1}^{Q} (1 + \Gamma^{-1} \gamma_{n,\mathrm{SFDMA}}^{(q)}) \geq 2^{\frac{QC^*}{B_{\mathrm{tot}}}}, \quad \forall n \in \{1, 2, \ldots, \mathrm{N}\} \end{aligned} \tag{11}$$

that represents the constraint to be simultaneously met for all the users served by the broadcast node. Therefore, the core of SFDMA relies on the smart assignment of resources SFSs among users so as to achieve a sufficiently high SINR to meet eq. (11) for the largest possible number of users. In this regard, users with granted access must meet eq. (10a), and this *implicitly* guarantees that the level of MAI is under control.

IV. ACCESS RESOURCE MANAGEMENT FOR SFDMA

The maximization of network access percentage passes through a convenient assignment of SFSs among different communications, aided by CSI that must be necessarily available at the central node. In this regard, channel estimation must be performed by the central node before proceeding with users access management.

A. CHANNEL ESTIMATION

Channel knowledge is necessary to the central node to evaluate the users SINR impacting on the capacity performance. It is worth noting that the SINR is measured on the downlink channel, the estimation of which would consider a three-way communication between central node and user, that is *i)* the user sends an access request to the central node, *ii)* the central node sends some pilot signals to let the user perform channel estimation and *iii)* the user sends back to the central node the information about the estimated channel. Such procedure, due to the long propagation delay of the acoustic signal, is time consuming and lowers the communication throughput [46]. Furthermore, because of the time-variability of the channel, the central node may receive the estimates while the channel has already changed. So, even in this case, channel state information at the central node would be not reliable.

Alternatively, channel estimation may be conveniently performed as follows. Together with the access request message, users may send a known sequence of training symbols so that the central node is able to perform the estimation of $Q \cdot M$ channels. The resulting estimates refer to the uplink, but by assuming channel reciprocity, they can be considered for the downlink as well. However, it is worth highlighting that, differently from RF communications, the characteristics of the underwater channel make reciprocity property not always verified [47]. So, CSI may suffer from inaccuracy impacting also on the reliability of the measured SINR. Anyway, it is worth recalling that the use of the SINR margin Γ in the context of channel capacity evaluation makes the performance robust to such kind of SINR fluctuations as well.

In general, channel estimation is still considered a very challenging issue for UWACs [48], but discussing in detail the performance of different estimation techniques goes beyond the scope of this paper. Since dealing with multiple access, without loss of generality, we assume CSI available at the central node.

B. SFS ASSIGNMENT THROUGH EXHAUSTIVE SEARCH

By referring to the n-th user, the assignment of specific SFSs reveals which are the transmitters and sub-bandwidths reserved for the n-th link. So, basing on CSI and the distribution of SFSs among different communications, the SINR for each user can be calculated according to eq. (6) and, later, channel capacity can be evaluated to find how many users access the network meeting the constraint in eq. (10a). In principle, the solution to eq. (9) can be found by resorting to an exhaustive search approach, returning the most convenient resources assignment chosen after evaluating all the possible SFSs distributions among users. In this regard, given $K = Q \cdot M$ as the number of SFSs composing the resource grid $\mathbf{G}$, we can define a $[K \times 1]$ vector $\mathbf{v}_n$ describing the SFSs allocation for the n-th user. Specifically, the k-th element of $\mathbf{v}_n$ can assume binary values, namely 1 and 0, if the corresponding SFS is assigned to the user or not, respectively. The necessary but not sufficient condition potentially allowing the access for the n-th user entails the reservation of at least one of the K total SFSs. Such constraint must be met for all the N users, therefore we have that the number of SFSs assignable to the n-th user, that is the number of 1s in $\mathbf{v}_n$, is defined as $1 \leq x \leq (K - N + 1)$. As a consequence, the number of 0s in $\mathbf{v}_n$ is returned as $y = K - x$. Following the combinatorics principles, the number of potential resource allocations for the n-th user is given as $\xi = \sum_{x=1}^{K-N+1} \frac{K!}{x!y!}$, where $(\cdot)!$ denotes the factorial operator. So, ξ represents also the number of possible vectors $\mathbf{v}_n$. Given N users, we can introduce the $[K \times N]$ binary allocation matrix as:

$$\mathbf{S} = [\mathbf{v}_1 \mathbf{v}_2 \ldots \mathbf{v}_n \ldots \mathbf{v}_N] \tag{12}$$

that is formed by the combination of N different allocation vectors and describes the overall channel resources assignment. Since each column of $\mathbf{S}$ has ξ representations, an exhaustive search like algorithm proceeds by searching for all the possible allocation matrices, whose total number is:

$$\mathcal{O}_{\text{EX}} = \xi^N = \left[\sum_{x=1}^{K-N+1} \frac{K!}{x!y!} \right]^N \tag{13}$$

that can be also taken as a reference to measure the computational effort requested by such approach. Furthermore, since each SFSs can be occupied by at most one user, the allocation associated to a certain $\mathbf{S}$ is valid only if its column vectors are orthogonal, that is $\mathbf{S}^T \cdot \mathbf{S}$ is a diagonal matrix, with $(\cdot)^T$ referring to the transpose operation. The main advantage of exhaustive search is that, by evaluating all the $\mathcal{O}_{\text{EX}}$ potential SFSs assignment scenarios, it is possible to exactly identify the one providing the highest access percentage. Furthermore, if multiple solutions are available, different choice criteria can be followed. In the context of network energy saving, we may consider the solution that maximizes the number of idle transmitters at the broadcast node. Otherwise, in order to maximize the communication performance, the SFSs allocation may be chosen to provide the highest SINR (averaged on the number of user with access granted). Alternatively, the solution would be that one saving the larger number of SFSs, hence allowing the further access to other potential users. Unfortunately, the increase of K and N lead $\mathcal{O}_{\text{EX}}$ to growth as well, so the computational cost of an exhaustive search becomes unsustainable. However, exhaustive search is suitable for demonstrating the effectiveness of the proposed SFDMA technique.

C. REVERSE-GREEDY LIKE ALGORITHM FOR RESOURCE ALLOCATION

In order to provide a convenient trade-off between complexity and performance, we present a resource allocation mechanism for multiple access based on a reverse-greedy like approach, so that eq. (9) can be solved achieving an optimal solution with limited computational cost. While usually a greedy algorithm assigns resources to the *luckiest* user that requires less resources, here the reverse-greedy algorithm tries to allocate resources to the *less fortunate* node first.

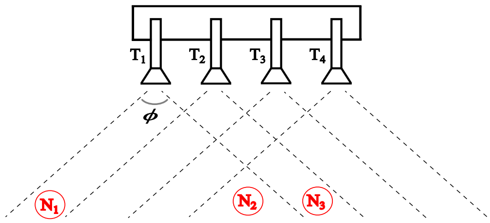


FIGURE 2. Example of coverage area of a central node with $M = 4$ transmitters.

Together with CSI, some considerations about the network coverage are exploited to simplify the SFSs assignment. In fact, we have that each of the M transmitters at the central node is characterized by a specific radiation pattern defining its horizontal beam aperture ϕ (without considering beam steering since different nodes may require tracking and this can easily lead to the problem feasibility). This means that the m-th acoustic source can serve only those users falling into its coverage cone. Figure 2 reports an example where a central node equipped with $M = 4$ sources is serving $N = 3$ users. The considered scenario highlights N_2 as the user with the potentially largest spatial resources since it can be served by all the transmitters. On the other hand, N_3 is able to capture the signals coming from T_2, T_3 and T_4. Finally, N_1 is recognized as the user with less available resources as it can be reached only by T_1. Such reference scenario highlights that, in general, due to particular nodes distribution, users may not be provided of the same spatial resources. In this direction, the proposed algorithm for multiple access management relies on the following principles:

- when performing the SFSs assignment, the priority is given to the users with *less* available spatial resources (by referring to the example in Figure 2, users are served in the following order: N_1, N_3 and finally N_2). This results in a sort of reverse-greedy approach, since in conventional algorithms the *best* users are served first. Such paradigm well fits for the underwater acoustic context, where the bandwidth resources are scarce while spatial diversity offers a greater degree of freedom.
- whenever possible, both frequency and space reuse is exploited in order to let sufficient resources be available for potential new incoming users.

The quality of the links for the n-th user is measured as a function of the corresponding channel estimates, conveniently gathered in a $[Q \times M]$ matrix:

$$\tilde{\mathbf{h}}^{(n)} = \begin{bmatrix} \tilde{h}^{(n)}_{1,1} & \tilde{h}^{(n)}_{1,2} & \dots & \tilde{h}^{(n)}_{1,M} \\ \tilde{h}^{(n)}_{2,1} & \tilde{h}^{(n)}_{2,2} & \dots & \tilde{h}^{(n)}_{2,M} \\ \vdots & \vdots & \tilde{h}^{(n)}_{q,m} & \vdots \\ \tilde{h}^{(n)}_{Q,1} & \dots & \dots & \tilde{h}^{(n)}_{Q,M} \end{bmatrix} \tag{14}$$

with the element $\tilde{h}^{(n)}_{q,m}$ representing the estimate of the channel between the m-th transmitter and the n-th user, measured in the q-th sub-bandwidth. If the user does not fall into the m-th source coverage area, we have $\tilde{h}^{(n)}_{q,m} = 0, \forall q$.

As previously outlined, the proposed algorithm is oriented to frequency reuse, but first attempting to limit MAI in the spatial domain. In fact, the idea is to first try to allocate users on spectrally shared but spatially separated channels and, only if interference is too strong, to exploit separated frequency resources. In this regard, we define two vectors, namely $\mathbf{r}$ and $\mathbf{f}$, gathering the index of sub-bandwidths already occupied by any communication and the index of completely free sub-bandwidths, respectively. So, since the q-th sub-bandwidth can be either occupied or free, it follows that its corresponding index q can be either in $\mathbf{r}$ or in $\mathbf{f}$. In addition, since $\mathbf{r}$ and $\mathbf{f}$ have variable size, we have that $dim(\mathbf{r}) + dim(\mathbf{f}) = Q$. Moreover we refer to $\mathbf{t}_n$ as the vector collecting the indexes of the transmitters potentially serving the n-th user, so that $h^{(n)}_{q,m} \neq 0, \forall q, \forall m \in \mathbf{t}_n$. For the n-th user requesting the access, $\mathbf{r}$, $\mathbf{f}$ and $\mathbf{t}_n$ are read and updated to perform the SFSs allocation. The procedure is summarized in the flowchart of Figure 3 and proceeds as follows. As initial stage, an access check is made to verify the potential presence of a user attempting to access. If so, the mechanism for assigning SFSs to the user, referred as the n-th one, begins. Specifically, the steps to follow depend on the possibility to operate or not frequency reuse. If there is any sub-bandwidth already occupied by other users ($\mathbf{r}$ is not empty), frequency reuse is attempted, otherwise if $\mathbf{r}$ is empty, the n-th user will be assigned on a free sub-bandwidth. Let us focus on the first case, where frequency reuse is considered (stage 2 in the flowchart). First, all the SFSs potentially assignable to the n-th user are identified. In detail, the availability of a SFS, described by the element $g_{q,m}$ in the space-frequency resource matrix $\mathbf{G}$ (eq. (8)), is subject to the joint meeting of three conditions: *i)* the SFS must be not assigned yet, that is $g_{q,m} = 0$, *ii)* according to frequency reuse, the q-th sub-bandwidth associated to $g_{q,m}$ must be so that $q \in \mathbf{r}$ and *iii)* the transmitters coverage must guarantee that the m-th source associated to $g_{q,m}$ must be so that $m \in \mathbf{t}_n$. From another point of view, such conditions guarantee that the m-th source is not transmitting on the q-th sub-bandwidth (that is, $g_{q,m}$ is free). Once the available SFSs with such properties are found, the algorithm proceeds by searching for the best SFS for the n-th user, referred as $g_{q^{(n)},m^{(n)}}$, that is the one associated to the highest channel gain. In this regard, by taking into account the direct relation between the elements in $\tilde{\mathbf{h}}^{(n)}$ and the elements in $\mathbf{G}$ (note that $\tilde{\mathbf{h}}^{(n)}$ and $\mathbf{G}$ are both $[Q \times M]$), we have the space-frequency indexes of the best SFS given as:

$$(q^{(n)}, m^{(n)}) = \underset{q^{(n)} \in \mathbf{r}, m^{(n)} \in \mathbf{t}_n}{\arg\max} \ \tilde{\mathbf{h}}^{(n)} \tag{15}$$

that identify the best space-frequency channel $h_{q^{(n)},m^{(n)}}$ where to serve the n-th user and the corresponding SFS $g_{q^{(n)},m^{(n)}}$ to be potentially assigned. We recall that, since dealing with the case where frequency reuse is attempted (stage 2 in the flowchart), the sub-bandwidth index $q^{(n)}$ is searched in the subset $\mathbf{r}$, gathering the indexes of the frequency channels already use by other users, while $m^{(n)}$ is the transmitter index chosen in $\mathbf{t}_n$, that instead collects the

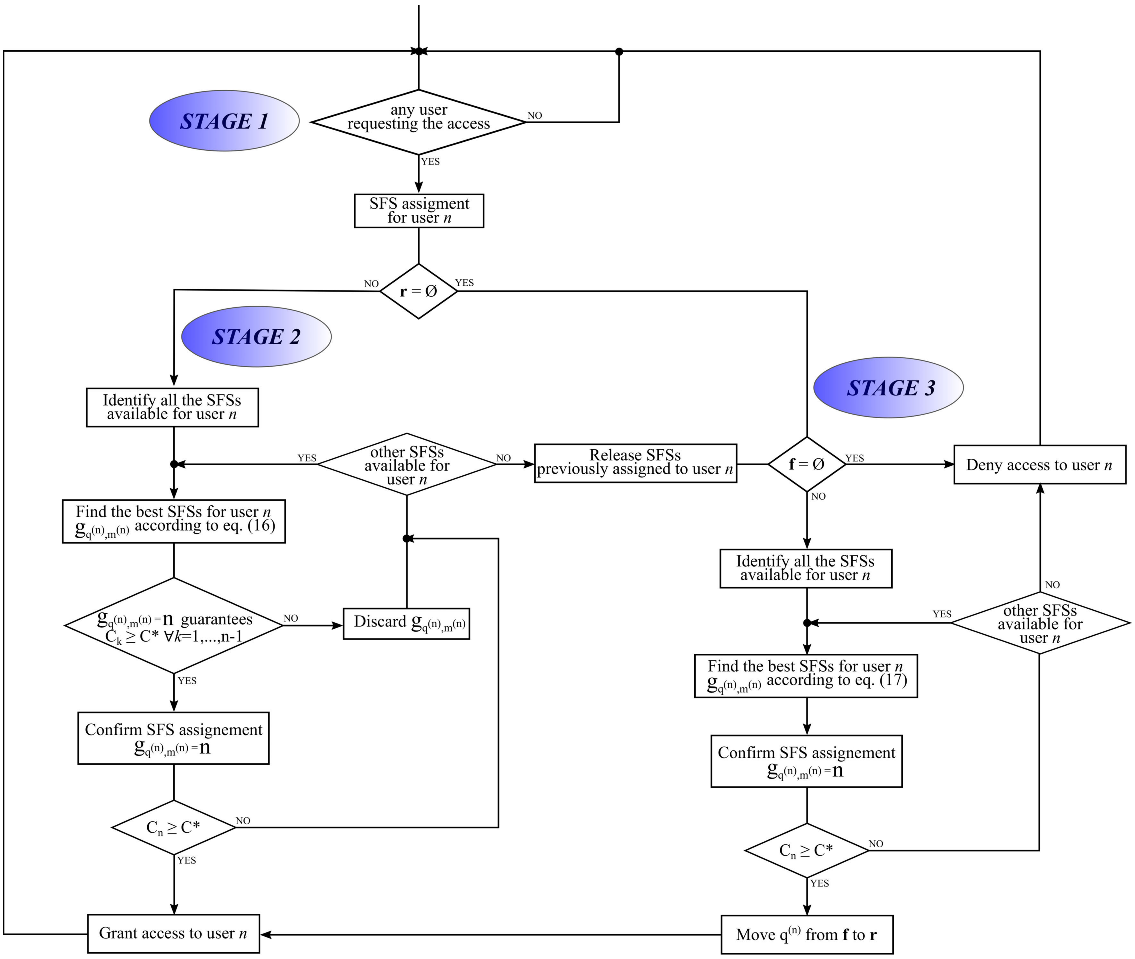


FIGURE 3. **Flowchart describing the proposed reverse-greedy like allocation mechanism.**

indexes of the transmitters potentially able to serve the n-th user. Before validating the SFS assignment to the n-th user, it must be checked whether such allocation causes excessive interference on the (n-1) users served ahead. That is, it must be $C_k \geq C^*$ for any $k = 1, 2, \ldots, n$-1. If this condition is verified, then the SFS assignment can be confirmed, making $g_{q^{(n)},m^{(n)}} = n$. Otherwise, the SFS corresponding to $g_{q^{(n)},m^{(n)}}$ is discarded and another attempt of allocation is performed by considering the remaining available SFSs. However, it is worth noting that the assignment of a single SFS may not be sufficient to the n-th user for the achievement of the requested channel capacity C^*. So, SFSs allocation for the n-th user continues until this target is reached, of course depending on the SFSs availability and on the meeting of the interference constraints with the other users. Finally, if there are no sufficient SFSs available to let the target capacity be achieved, it means that frequency reuse is not applicable and the n-th user access must necessarily pass through the use of any free sub-bandwidth gathered in $\mathbf{f}$ (stage 3 in the flowchart). In that case, the SFSs previously assigned to the n-th user are released, so that the interference caused on the other concurrent communications is removed. Then, the SFSs allocation is performed by following some constraints similar to that one introduced before. Specifically, conditions *i)* and *iii)* remain unchanged. On the other hand, the condition *ii)* now entails the q-th sub-bandwidth, associated to the potentially valid SFS $g_{q,m}$, to be so that $q \in \mathbf{f}$, meaning that the user will be served by exploiting a free sub-bandwidth. Following this direction, the best SFS assignable to the n-th user is given by:

$$(q^{(n)}, m^{(n)}) = \underset{q^{(n)} \in \mathbf{f}, m^{(n)} \in \mathbf{t}_n}{\arg\max} \; \tilde{\mathbf{h}}^{(n)} \tag{16}$$

with the corresponding $g_{q^{(n)},m^{(n)}}$ having space-frequency indexes $q^{(n)} \in \mathbf{f}$ and $m^{(n)} \in \mathbf{t}_n$. Since dealing now with free sub-bandwidths, no problem of multiuser interference occurs and SFSs can be allocated for the n-th user until the target capacity C^* is achieved.

Once the access to the n-th user is granted, the network central node moves to search for a further user requesting the access. Moreover, if n-th user has been served exploiting any free sub-bandwidth $q \in \mathbf{f}$, then the corresponding index is moved from $\mathbf{f}$ to $\mathbf{r}$. It is worth noting that the operations at stage 3 are performed only if there are free sub-bandwidths, that is $\mathbf{f}$ is not empty. This is always true for the very first user asking the access (the algorithm does not pass through stage 2 since all the frequency resources are free), while it is not guaranteed for further users. Moreover, especially when all the sub-bandwidths are occupied, the access may not be granted to some incoming users because of MAI. However, interference depends also on the mutual distance among users. Hence, for the same number of available SFSs, some users may be able to get the access while others may be not. If the resource allocation is successful for all the users, it means that $C_n \geq C^*$, $\forall n$ and the solution found to the problem in eq. (9) is the best one since returning the maximum network access percentage. Otherwise, the solution achieved is an optimal one. The mechanism shown Figure 3 has been introduced as referring to SFDMA where multiple sub-bandwidths are considered. However the procedure remains valid also for SDMA, in fact it is sufficient to consider the presence of a single sub-bandwidth ($Q = 1$) as available and shared with all the users. Finally, we would highlight that the knowledge about the transmitters coverage allows the search for a convenient SFSs allocation reduced in terms of complexity.

Interestingly, it is worth noting that the exhaustive search and reverse-greedy-like algorithms here discussed rely on very different approaches. In fact, exhaustive search considers a *static* environment where SFSs allocation is performed simultaneously on N users, thus providing $\mathcal{O}_{\text{EX}}$ potential possibilities, each one represented by a specific matrix $\mathbf{S}$ (eq. (12)). On the other hand, the reverse-greedy-like algorithm is aimed to deal with scenarios unknown a priori, with users potentially joining the network at different times. In this regard, the proposed mechanism proceeds with a sequential resources assignment, that is user by user, and depends on the network access conditions. The result is represented by a single allocation matrix built column by column, where the vector $\mathbf{v}_n$ describing the SFSs allocation for the n-th user depends on $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_{n-1}$, that is the SFSs assignment for the (n-1) users previously served. Specifically, we have that the number of SFSs assignable to the n-th user, namely x_n, can be at most equal to $X_n = K\text{-}\sum_{j=1}^{n-1} w_j$, where w_j is the number of SFSs given to the j-th user of the (n-1) served before the current one ($j = 1, \ldots, n-1$). So, the number of potential SFSs allocations for the n-th user is $\xi_n = \sum_{x_n=1}^{X_n} \frac{K!}{x_n!y_n!}$, with $y_n = K\text{-}x_n$ being the number of SFSs assigned to previous users or left empty. So, y_n corresponds also to the number of 0s in v_n. It follows that the computational cost characterizing the reverse-greedy-like algorithm can be calculated as:

$$\mathcal{O}_{\text{RG}} = \sum_{n=1}^{N} \sum_{x_n=1}^{X_n} \frac{K!}{x_n!y_n!} \tag{17}$$

that takes into account the resources allocation as performed user by user. It is worth highlighting that eq. (17) returns the measure of the computational cost assuming each user as covered by all the transmitters, providing the possibility to exploit all the K SFSs. So, such scenario represents the worst case since ξ_n is maximum for all the users, thus potentially maximizing $\mathcal{O}_{\text{RG}}$ as well. On the other hand, if the n-th user was out of the coverage of some sources (see N_1 in Figure 2), X_n would decrease reducing the number of possibilities returned from eq. (17), but also leaving smaller chances of access. Together with the variability of $X_1, X_2, \ldots X_n$, we have that the number of SFSs assigned to each user $w_1, w_2, \ldots, w_N$ are function of network geometry and channel conditions, so they can not be known a priori. Therefore, in general, given K and N, the algorithm cost $\mathcal{O}_{\text{RG}}$ varies from scenario to scenario. In terms of performance, in general exhaustive search outperforms the reverse-greedy-like algorithm, but at the expense of a very high computational cost, especially if the network scale grows. Moreover, every time a new user attempts for access, SFSs allocation must be performed again, requesting therefore additional effort and introducing significant latency lowering the communication performance. On the other hand, reduced complexity and delays are provided by the reverse-greedy approach since able to deal with users accessing the network in a sequential fashion, even though access performance may be potentially lower than that one achieved with exhaustive search.

D. ON MUTUAL SUPPORT BETWEEN M-MIMO AND SFDMA

The novelty introduced with SFDMA is the use of a bi-dimensional domain where to allocate channel resources for users. Such approach allows the weaknesses of underwater FDMA and SDMA, relying on a single resource domain, to be mutually compensated, finally achieving a more efficient access management. In fact, pure FDMA is not considered as a feasible and effective solution due to the poor bandwidth of underwater acoustic systems. On the other hand, SDMA is recognized to be a viable solution due to the rich multipath effect characterizing UWACs. However, despite sound undergoes a waveguide-like propagation, constrained by the water floor and surface, the spatial diversity achievable in such scenario is less pronounced than in a typical RF urban environment. Therefore, the effectiveness of underwater SDMA must pass necessarily through the use of large scale antenna arrays. At glance, the paradigm of M-MIMO (also known as very large-scale antenna systems) seems to be fitting for users spatial interference mitigation in UWACs as well. However, the benefits brought by M-MIMO mainly rely on the use of specific precoding techniques, such as beamforming, aimed to achieve the spatial selectivity necessary to support simultaneous and independent communications. Unfortunately, such kind of signal processing is conveniently tailored to RF systems, while several criticisms arise from its application in the underwater acoustic context. Specifically:

- beamforming consists in a spatial filtering, operated by adapting the sources transmit power to the channel conditions. In RF communications, very low latency is caused by overhead signaling for continuous CSI update, therefore beamforming tracks the channel variations with negligible delay. Differently, UWACs are penalized by the slow signal propagation, making frequent channel estimation be onerous in terms of delay and reducing the communication throughput [46]. On the other hand, in the proposed SFDMA, not much frequent channel estimation is affordable since the gap Γ introduced in eq. (7) acts as a margin, thus counterbalancing the potential SINR estimate fluctuations due to CSI inaccuracy. By recalling eq. (6), it is worth noting how the evaluation of the user SINR depends on channel gains, therefore CSI is necessary to implement SFDMA as well. However, even when sudden variations in the channel make the current CSI at the transmitter imperfect and no more updated, the use of Γ guarantees the user performance to be more robust;

- due to the long propagation delay and underwater channel time-variability, during the time spent to make CSI available at the transmit node, the propagation conditions may have already changed [46] (*e.g.* the channel coherence time is in the order of few tens of milliseconds, while the acoustics signal propagation on a 150 meters reference link lasts about a hundred of milliseconds). Therefore, power control operated through beamforming results very sensitive to the CSI accuracy, and having outdated channel estimates may cause performance degradation. Differently, with the transmitters working according to a ON-OFF policy, the proposed SFDMA returns essentially a channel assignment rather than power optimization, so the mechanism is more robust to the potential CSI inaccuracy;
- beamforming entails the capability of tuning the transmit power on-the-fly. In RF communication, this task is accomplished via software, while controlling the electro-acoustic conversion in devices for UWACs is in general not possible. Furthermore, power tuning (especially on-the-fly) is not allowed for acoustic modems commercially available [25], thus making beamforming unpractical. So, the assumption about the transmitters ON-OFF operation mode in SFDMA cannot be considered as penalizing since it essentially meets the current capabilities of the underwater acoustic modems.

Summarizing, because of the concerns highlighted above, the paradigm of M-MIMO can not be straight applied in the underwater context as well. Differently, the proposed SFDMA overcomes the signal processing limitations characterizing UWACs. In fact, frequency reuse can be seen as a more convenient support to spatial diversity than beamforming. Viceversa, spatial diversity counterbalances the problems arising from the scarce bandwidth availability. Furthermore, the use of SINR gap Γ, jointly combined with the ON-OFF policy characterizing the transmitters behavior, represents a simple but extremely fitting solutions for the UWAC scenario where the unfeasibility of conventional spatial precoding techniques penalizes the realization of M-MIMO architectures.

TABLE 2. Simulation parameters.

Number of users (N)	from 1 to 12
Source transmit power (P_t)	100 dB re μPa @1m
Beam aperture (ϕ)	120° (SDMA,SFDMA), 128° (FDMA)
Number of transmitters (M)	1 (FDMA), 15 (SDMA, SFDMA)
Number of sub-bandwidths (Q)	1 (SDMA), 3, 4 (FDMA, SFDMA)
Total bandwidth (B_{tot})	12 kHz
SINR gap (Γ)	5
Target capacity (C^*)	2, 4 kb/s

V. SIMULATION RESULTS

We discuss the performance of different multiple access schemes, namely FDMA, SDMA and SFDMA, by resorting to computer simulations based on MATLAB software. All the simulation parameters are listed in Tab. 2. Specifically, we develop a network scenario where a horizontal array of M acoustic sources serves N users randomly placed within a semicircular space with radius equal to 300 meters, representing the central node coverage area. The total system bandwidth is $B_{\text{tot}} = 12$ kHz and ranges from 15 kHz to 27 kHz [25]. For SDMA and SFDMA we consider the transmit array as composed of $M = 15$ elements, spaced by $d_{\text{TX}} = 1$m, with $P_t = 100$ dB re 1 μPa @1m and beam aperture $\phi = 120°$. For FDMA we have instead $M = 1$. In order to guarantee the fairness between the considered network scenarios, in FDMA we set the single transmitter beam aperture to $\phi = 128°$ so to provide the same network coverage achieved in SDMA and SFDMA with $M = 15$ sources.

The performance of the considered schemes have been evaluated in terms of access percentage, that is how many users out of N can be simultaneously provided of sufficient resources so as to meet the constraint about the target channel capacity C^*. For simulations, we set the SINR gap equal to $\Gamma = 5$. Such value, by assuming quadrature amplitude modulation as transmission scheme, guarantees the symbol error rate to be below $5 \cdot 10^{-3}$ [39]. The simulations concerned FDMA implemented with B_{tot} divided into $Q = 3$ and $Q = 4$ sub-bandwidths, respectively, SDMA, and SFDMA with both $Q = 3$ and $Q = 4$. In SFDMA, having $Q = 3$ and $M = 15$ returns the channel resource grid $\mathbf{G}$ as composed of 45 SFSs. For $Q = 4$ and $M = 15$, $\mathbf{G}$ has instead 60 SFSs. In this latter case, the number of available SFSs is higher, even though each sub-bandwidth is narrower than in the case where $Q = 3$. It is worth recalling that in the context of FDMA we have $M = 1$ since spatial diversity is not considered, while for SDMA we have $Q = 1$ as users share the same spectral resources. The access performance have been measured as a function of the number of users to be served N, that ranges from 1 to 12. The choice of such scaled network scenario is tied to the possibility of showing the impact of spatial and frequency diversity on access performance. Furthermore, regarding SDMA and SFDMA, we show how the ratio between M and N significantly impacts on the access performance. Given a target capacity $C^* = 2$kb/s to be provided (such value is in line with typical data rates

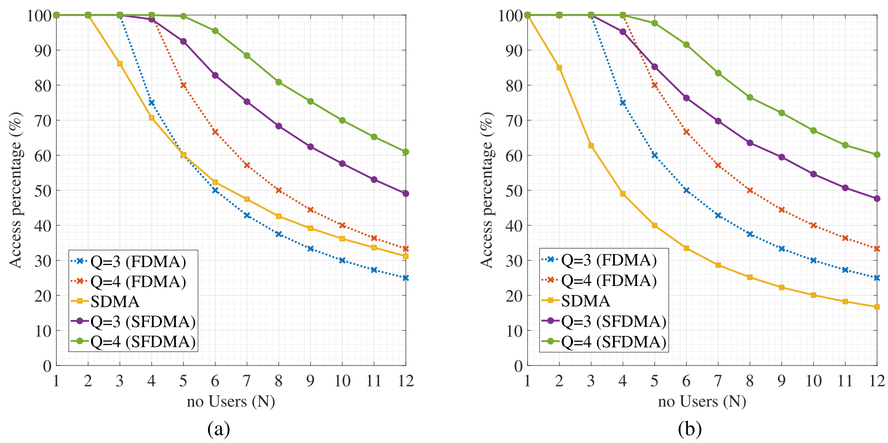
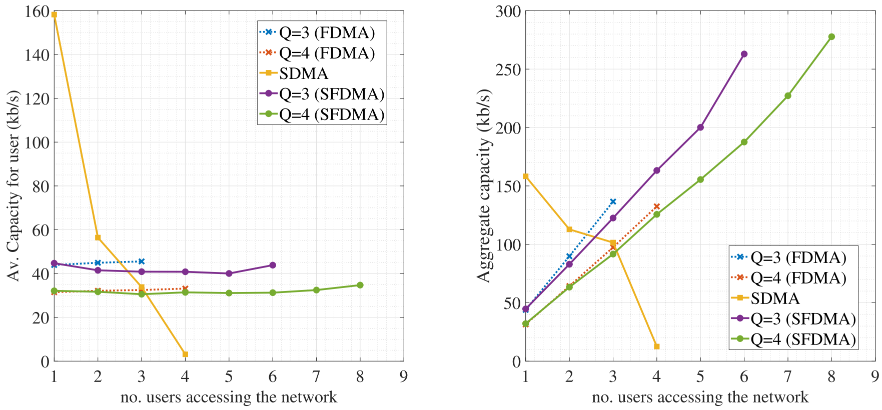


FIGURE 4. Network access performance considering $C^* = 2$kb/s (a) and $C^* = 4$kb/s (b).

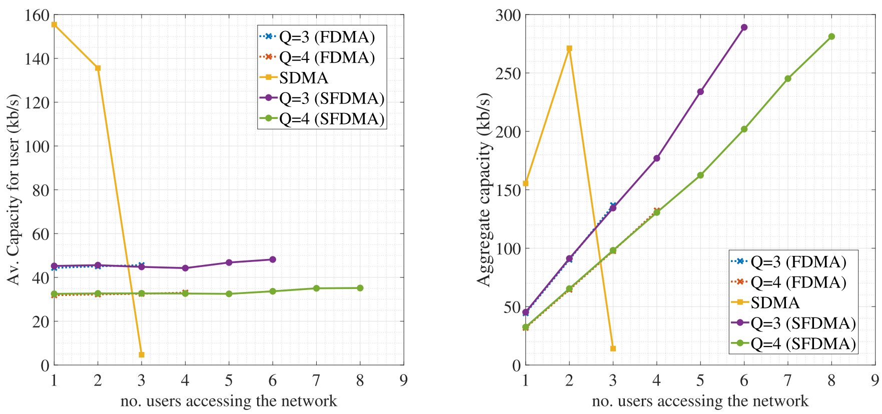
achievable with commercial underwater acoustic modems), the results averaged on 1000 simulations are reported in Figure 4(a). As expected, FDMA (dotted curves) provides full access until the number of users does not exceed the number of available sub-bandwidths Q. Otherwise, the access percentage unavoidably decreases as N grows. For what concerns SDMA (yellow squared line), performance are in line with FDMA. In particular, when N approaches M, separating users only in the spatial domain becomes no more effective, so low access percentage is provided. On the other hand, the exploitation of a bi-dimensional domain, namely space and frequency, allows SFDMA to significantly outperform both FDMA and SDMA. In fact, access percentage is improved by about 20%, guaranteeing good performance even when the number of users becomes comparable with the number of acoustic sources. By increasing the target capacity to $C^* =$ 4kb/s, the constraint becomes tighter, so performance may decrease. The curves in Figure 4(b) show that performance of FDMA are comparable with that ones shown in Figure 4(a). This is due to the fact that the sub-bandwidths are large enough to guarantee the channel capacity to be greater than C^*. Robust performance are still provided by SFDMA, where the joint use of space and frequency resources allows to mitigate MAI and achieve high values of access percentage. On the other hand, the effectiveness of SDMA significantly lowers since space diversity is not enough to mitigate MAI, so only few users out of N can be provided of the requested performance in terms of channel capacity.

From a different point of view, it is possible to evaluate the performance of the schemes under investigation by considering the average channel capacity for user and the aggregate network capacity. Specifically, Figure 5 shows the results referring to the scenario where $C^* = 2$kb/s. From Figure 5(a), we can appreciate that FDMA and SFDMA provide essentially the same average capacity for user. However, it is worth noting that in FDMA the number of users accessing the network is at most equal to the number of available sub-bandwidths Q, while SFDMA allows the access to be achieved for a larger number of users. This is the reason why the curves have a different length. Concerning SDMA, due to the channels spatial interference, the average capacity decreases as the number of users granting the access grows. Figure 5(b) reports instead the aggregate channel capacity, characterized by a linear increase in the case of FDMA and SFDMA and by a descending curve while dealing with SDMA. So, taking into account the average values in Figure 5(a), if follows that SFDMA outperforms FDMA as it allows a larger number of users to be simultaneously served. The same analysis has been performed considering $C^* = 4$kb/s, with the results being shown in Figure 6. For FDMA, as users access on separated sub-bandwidths without suffering from interference, the performance are essentially the same as in Figure 5. In SFDMA, interference may rise both in space and frequency. However, good performance are guaranteed thanks to the particular access developed in a two-dimensional domain. Furthermore, with the increase of C^*, average and aggregate capacity slightly grow with respect to Figure 5. Finally, as expected, SDMA confirms to be the worst performing scheme. Interestingly, we note in Figure 6(b) a fluctuating behavior of the aggregate capacity provided in SDMA, that can be explained as follows. Until the number of users accessing the network is less or equal to 2, the channel capacity for user and, as a consequence, the corresponding aggregate capacity is high since multiple access interference can be efficiently mitigated in the spatial domain. On the other hand, when 3 users access the network, the effect of interference increases, so in general the channel capacity lowers. Furthermore, due to the tighter constraint on C^*, the maximum number of users achieving the access is exactly 3, while it is 4 when considering $C^* = 2$kb/s (Figure 5(b)). So, the shortest length of the yellow curves with respect to the others reveals how SDMA is the scheme providing the access to the least



(a) (b)

FIGURE 5. Average channel capacity for user (a) and aggregate capacity (b), considering $C^* = 2$kb/s.



(a) (b)

FIGURE 6. Average channel capacity for user (a) and aggregate capacity (b), considering $C^* = 4$kb/s.

number of users. Finally, it is worth noting some interesting results achieved when a single user accessing the network is considered, that is the case where there is no multiple access interference. Specifically, it seems from both Figs. (5-6) that SDMA outperforms FDMA and SFDMA in terms of channel capacity. Such issue is explained as follows. In the absence of MAI, the assignment of a single transmitter is sufficient to the user to meet the constraint about the target capacity and obtain the access in SDMA, FDMA and SFDMA. However, by recalling eq. (5), we have that SDMA considers the exploitation of the the full system bandwidth, namely B_{tot}. So, this is the reason why the achievable channel capacity is very high. On the other hand, in both FDMA and SFDMA, the system bandwidth is divided in Q sub-bandwidths, so for the single user in the network is sufficient to exploit a single transmitter and a single sub-bandwidth (that is, only a portion of B_{tot}) to achieve the target capacity. In fact, in eq. (2) and eq. (7) the bandwidth is given by B_{tot}/Q. So, as the user in FDMA and SFDMA exploits a narrower bandwidth than in SDMA, at equal interference level conditions, the capacity performance considering a single user are higher in SDMA than in FDMA and SFDMA.

It is worth noting that the achievement of spatial separation among users in SDMA and SFDMA is function of the transmitters beam aperture ϕ. In this regard, by widening ϕ, a better network coverage would be provided since each user may be reachable by all the sources, but on the other hand spatial interference would increase as well. In order to investigate the impact of transmitters beam aperture on the access performance, we simulate SDMA and SFDMA for different values of ϕ, ranging from 60° to 180°. Figure 7(a) shows the results achieved considering $C^* = 2$kb/s and $N = 6{,}12$ users. Interestingly, it is possible to observe the access percentage as following a bell like behavior, where the peak is achieved with ϕ ranging from 110° to 120°. For beam apertures narrower or wider than 120° the access percentage rapidly decreases, finally assuming quite constant values. As expected, the cause of low performance achieved for large values of ϕ is that each transmitter is essentially able to cover all the users, so unavoidably acting as useful source for one user and as interference for the others. On the other hand, by reducing ϕ, the probability of having multiple users covered by the same transmitter is reduced, therefore diversity in the spatial domain may be successfully achieved. However, many network coverage holes may rise

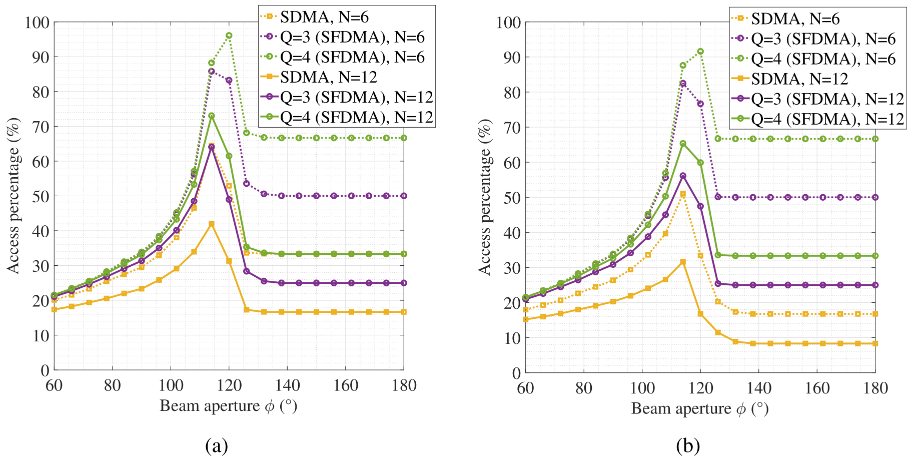


FIGURE 7. Access percentage as a function of beam aperture, considering $C^* = 2$kb/s (a) and $C^* = 4$kb/s (b).

TABLE 3. Performance comparison between exhaustive search and greedy algorithm applied to SFDMA, with $M = 4$, $Q = 2$, $C^* = 2$kb/s.

				Computational effort (no. of flops)				
N	1	2	3	4	5	6	7	8
$\mathcal{O}_{\text{EX}}$	255 (255)	$6.4 \cdot 10^4$ (6050)	$1.4 \cdot 10^7$ $(4.6 \cdot 10^4)$	$2.2 \cdot 10^9$ $(1.6 \cdot 10^5)$	$1.1 \cdot 10^{11}$ $(3.1 \cdot 10^5)$	$6.1 \cdot 10^{11}$ $(3.3 \cdot 10^5)$	$7.8 \cdot 10^{10}$ $(1.8 \cdot 10^5)$	$1.6 \cdot 10^7$ $(4.1 \cdot 10^4)$
$\mathcal{O}_{\text{RG}}$	255	508	738	872	810	552	252	64
				Access percentage (%)				
η_{EX}	100%	100%	81.8%	70.1%	57.9%	52.8%	45.3%	43.1%
η_{RG}	100%	100%	80.9%	69.2%	57.4%	52.6%	44.8%	42.2%
				Average capacity for user (kbit/s)				
$C_{\text{av,EX}}$	70.2	66.1	65.3	69.2	_	_	_	_
$C_{\text{av,RG}}$	66.9	64.6	63.9	68.9	_	_	_	_

from the narrowing of ϕ, so users in specific positions may not attempt to access since they can not be served by any of the available transmitters. The same trends can be appreciated in Figure 7(b). Of course, dealing with only 6 users allows the achievement of higher performance than in the case where 12 users are present. In general, the impact of transmitters beam aperture is relevant in SDMA where spatial diversity is the only way to mitigate MAI. In SFDMA, the frequency reuse makes the access performance less sensitive to ϕ. In fact, while the access percentage in SDMA lowers as C^* increases from 2 to 4 kb/s, the curves related to SFDMA (referring to both $Q = 3$ and $Q = 4$ cases) remain quite similar.

Finally, a further peculiarity of SFDMA to be discussed concerns the reverse-greedy-like algorithm driving the resource allocation in a computationally efficient fashion (actually, the mechanism works for FDMA and SDMA as well). In fact, the alternative would be given by an exhaustive search based approach, that may not be feasible when the network complexity grows. In the previous section, we defined the computational effort requested by the two methods, namely $\mathcal{O}_{\text{EX}}$ (eq. (13)) and $\mathcal{O}_{\text{RG}}$ (eq. (17)), as a function of the number of users N to be served and the number of SFSs K composing the network resource grid. In this regard, Tab. 3 shows some numerical results concerning the computational effort requested for network resources assignment in SFDMA, considering both exhaustive search and the proposed reverse-greedy-like algorithm. Specifically, we consider a reference network scenario with $M = 4$, $Q = 2$, resulting in a resource grid with $K = 8$ SFSs. Furthermore, we report also the performance in terms of users access percentage and average capacity (expressed in kb/s) evaluated as a function of the number of users $N = 8$, with a target capacity $C^* = 2$ kb/s to be achieved. By looking the values reported in the table, it is possible to appreciate how the exhaustive search requires a significantly high number of SFSs allocation possibilities to be calculated. Concerning $\mathcal{O}_{\text{EX}}$, we highlight two values. The first one is calculated from eq. (13) and represents exactly the number of potential allocation matrices $\mathbf{S}$ computed through exhaustive search. However, we recall that not all the solutions provided are feasible (for instance, some may return the same SFS as associated to multiple users), so we report in brackets the number of valid allocations. So, it can be seen from a different point of view how following the exhaustive search approach is not computationally convenient. In general, we observe that the requested computational effort grows with the number of users to be served, until N is sufficiently lower than K. On the other hand, when N approaches K, the number of potentially valid resource allocations decreases, so computing becomes less onerous as well. Concerning the access performance, exhaustive search and greedy algorithm provide essentially the same results. So, at equal users access percentage, the proposed mechanism demonstrates to be more convenient. Differently, the average capacity for users achieved with exhaustive search is in general higher than that one measured when resorting to the greedy algorithm (in the considered scenario, the maximum number of users accessing the network is 4, so values for $N > 4$ are missing). Such result was however expected since with exhaustive search it is possible to find the optimal SFSs assignment for users, while the proposed algorithm provides only a sub-optimal solution. Finally, it is worth noting that the values in Tab. 3 refer to network scenarios where K and N are quite small. By increasing such values, the cost of exhaustive search will dramatically increase, with the reverse-greedy-like algorithm instead providing a better trade-off between performance and complexity.

VI. CONCLUSION

This contribution has dealt with multiple access in UWANs. Since the use of the well known FDMA, TDMA, CDMA and SDMA techniques, performing the access in a single domain, presents both advantages and drawbacks, we presented a novel SFDMA scheme allowing multiple access to be handled in a bi-dimensional domain, namely space and frequency. In this context, a reverse-greedy like algorithm has been proposed in order to conveniently perform the network resources allocation. The analysis here reported shows that spatial and frequency diversity, jointly combined in SFDMA, allow the problem of bandwidth constraints and channels correlation, typically characterizing the underwater systems, to be partially mitigated, providing an efficient access strategy. Moreover, the proposed algorithm for channels resources allocation demonstrates to be significantly more computationally efficient than an exhaustive searched based approach. Therefore, its implementation results as feasible and convenient, especially when the network scale grows. Finally, we discussed about the feasibility and potential of M-MIMO approach, conveniently rethought for the underwater context.

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