# A Comparison of Multiple Access Techniques in Clustered Underwater Acoustic Networks

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***Abstract*— In this paper, we carry out an extensive performance evaluation of multiple access schemes applied to clustered UnderWater Acoustic Sensor Networks (UWASN). Networking underwater sensors poses new and interesting issues with respect to radio environments, as they require to account for unusual channel behaviors, such as large propagation delays, higher energy consumption during transmission as compared to reception, distance-varying available acoustic bandwidth, strong fading phenomena, and so on. In particular, managing channel access in converge-casting scenarios is difficult, as many nodes have to share the same medium under the previously cited contraints, in order to report to the same data collecting station. To this aim, we organize the network in clusters and give details on which access scheme (both for the clusterheads and for the children nodes) gives better results under a number of performance metrics, highlighting the different protocol behaviors in the scenarios of interest and translating the relevant tradeoffs into design criteria.**

***Index Terms*— Acoustic telemetry and communication (2.8); Access, custody, and retrieval of data (5.1); Information management (5.5).**

## I. Introduction

Remote monitoring, telemetry and data gathering are very attractive perspectives in many disciplines. Wireless communications are an important technology for allowing seamless data delivery to processing stations, easy access to distributed sensing points, and a deep level of interaction with the researchers commanding the infrastructure that gathers the data. This is especially important when the event to sample is harsh or difficult to reach, making human expeditions expensive or dangerous. Underwater environments represent a good example of such difficult scenarios, where a sensor network could greatly help in the effort of understanding and studying natural phenomena with even complex dynamics.

Distributed sensor networks are a quite well studied topic, as far as radio communications are involved. Nonetheless, the amount of knowledge currently found in the literature for radio sensor networks is not directly applicable to underwater communications. A number of effects are to be taken into account, such as the fact that high frequency radio waves tend to scatter and be absorbed in water within a very short distance from the transmitter. Optical communications may prove useful underwater, but they typically require the transmitter and receiver to be aligned in order to form a link, and tend to be effective on very short ranges, compared to the desired communication distances.

On the other hand, acoustic communications are deemed to be the enabling technology for underwater networking, allowing signals to propagate and be received at long distances from the transmitter (even on the order of $100\ \mathrm{km}$). UnderWater Acoustic Sensor Networks (UWASN) are currently at a very early stage of development, but the interest on them is rapidly increasing, due to the large number of applications where they would prove to be very helpful. Such applications include environmental monitoring, possibly with the aim of forecasting extreme weather conditions or natural disasters (such as a *tsunami*) in time, thus organizing the evacuation of civilians from endangered territories. UWASNs may also be very useful as a support to navigation. They would allow for a finer sampling of the water column characteristics, thus giving surface vessels a means of effectively identifying dangers, correcting the route, or following phenomena under study (such as fish movements). With the support of Autonomous Underwater Vehicles (AUVs), UWASNs may also offer a completely automated solution for water monitoring, whereby sensors offer a coarse grained view of the environment and AUVs are sent in to explore whenever some event is deemed to deserve further investigation. The AUVs themselves may then rely on the UWASN to decide where to move or where it is more interesting to gather data. UWASNs and AUVs may prove to be useful in military scenarios as well, as a support to underwater and surface units detection, especially since these devices do not require special skills to be operated.

Due to the high cost of deploying underwater devices, it would be desirable to reduce maintenance and similar human interventions to a minimum. Therefore, the sensors and AUVs have to be designed to operate unattended for the longest possible time. The communication protocols used for networking are of paramount importance in this context. Underwater transmissions are quite expensive in terms of consumed energy, calling for solutions that avoid collisions between communications or limit them to a reasonable and controllable level. However, it is not trivial to translate the large amount of knowledge gained for radio networks into acoustic networks, *e.g.*, by simply accounting for the different propagation speed and bit rate achievable. As the environment and the propagation conditions are quite different with respect to radio, new tradeoffs and new approaches need to be explored in order to design more effective protocols. For example, the power needed to receive an acoustic signal is small with respect to the transmit power. It may thus turn out to be worth leaving nodes in an idle state and aware of the signals being transmitted in the neighborhood, rather than sending them to sleep for some time, since the increased savings in this second case may not be significant. Moreover, UWASNs are typically much sparser than terrestrial wireless sensor networks, and turning nodes off may occasionally partition the network, hence requiring some redesign of sleep/awake policies.

Our work is meant to shed some light on communication schemes for UWASNs, by studying simple channel access techniques and studying their performance in an underwater environment, from different points of view. We also wish to indentify which solution offers the best efficiency and effectiveness and what is the price to pay (if any) in terms or flexibility to provide such advantages.

## II. Related Work

Underwater acoustics is currently being used for different purposes, such as sonar and telemetry [1]. On the other hand, the idea of using sound for general-purpose data communications is rather new. While the problem of setting up efficient acousting links in the harsh underwater environment has received a lot of interest [2]–[4], underwater networking still presents many open challenges [5].

From the point of view of channel access techniques, some previous works highlighted the pros and cons of classical schemes such as Time Division, Frequency Division and Code Division Multiple Access (TDMA, FDMA and CDMA) [6], with the main focus on the feasibility and effectiveness of a clustering solution. Recently, [7] has also explored a comparison between ALOHA and a collision avoidance protocol.

The design of Medium Access Control (MAC) protocols has also received some attention. Slotted FAMA [8] was designed with energy saving in mind, in that it tries to avoid collisions as much as possible. This objective is pursued through the use of handshake messages (Request-To-Send, RTS and Clear-To-Send, CTS) and of carrier sensing. Time is divided in slots, each long enough to accommodate a whole propagation time, so that even the farthest node in the network can receive signaling messages and refrain from transmission if needed. Similarly to Slotted FAMA, PCAP [9] pre-determines the length of any handshake by setting up a waiting time for the recipient before it sends a CTS packet, such that the transmitter hears the CTS exactly after one round-trip time.

A recently proposed MAC protocol [10] takes a different approach, thereby removing the need for synchronization. The protocol is based on an RTS/CTS exchange, with a further delay before transmission, which is used to listen for other potentially interfering handshakes and delay the transmission if any is detected. Furthermore, if a node replies to an RTS with a CTS, and then receives a second RTS (possibly meant for another node) within a short time, it sends a warning message. If the first sender is reached by this message in time, it refrains from transmitting, thus avoiding the collision between the data packets. Even if collisions are not completely avoided, the performance of this protocol turns out to be better than Slotted FAMA, without the need to maintain node synchronization.

The issue of how to manage idle sensor time and how to exploit the low power required for listening was addressed in [11]. The authors there argue that near-optimal energy performance can be reached by implementing ultra-low power transducer wakeup modes. Tone-Lohi [12] also exploits the low idle listening power and proposes to avoid collisions by sending very short busy tones.

In this paper we perform an in-depth performance evaluation of different channel acces schemes, considering also a form of random channel access, *i.e.*, ALOHA. We believe that clustering may be a good solution to enhance the network throughput performance, and that it deserves deeper investigation to understand which scheme best exploits a hierarchical structure. To the best of our knowledge, there is currently no contribution of this kind in the literature.

## III. Channel Access Schemes

In this Section, we provide an overview of the channel access schemes we are going to compare in this paper. All schemes assume the existence of a cluster hierarchy, whereby some nodes elected as clusterheads (CH) collect the data passed on by the other nodes, and convey it to the sink. The clustering scheme we employ is the well-known Lowest ID Clustering Algorithm (LIDCA) [13]. After an initial neighbor discovery phase, LIDCA lets the node with the lowest identifier among its own neighbors elect itself as the CH. The other nodes wait for a joining message to be broadcast by the CH, and join the cluster accordingly. If a node does not receive messages from any neighbor with lower ID, it assumes that all of them belong to other clusters. Thus, it declares itself a CH and broadcasts a new joining message for its higher ID neighbors. The hierarchy created this way is single-level, *i.e.*, the CHs are allowed to communicate only with the sink. For greater efficiency, CHs and children [1] may use different access and communications schemes. In the following description, such techniques will be addressed using a notation such as `X—Y`, where `X` is the scheme used by the children to communicate with the CH, whereas `Y` is used by the CHs and the sink.

### A. Scheme 1: ALOHA—ALOHA+CDMA

With this scheme, children nodes communicate with the CH using ALOHA. Whenever a node has a packet ready, it begins a transmission and then waits for an acknowledgment message (ACK) to be received back from the CH. If the ACK is not received, a collision with another packet is assumed, and all following retransmission attempts are delayed by a backoff time, which is intially uniformly chosen in the interval $[0, 2T_d]$, where $T_d$ is the data packet transmission time. The length of the interval is doubled upon each subsequent failure. The CHs use ALOHA as well to communicate with the sink, but their transmissions are protected using CDMA waveforms with a certain spreading factor ($SF$). This is made necessary by the hierarchical structure, because the CHs convey the whole cluster traffic toward the sink, constituting a possible network bottleneck. The value of $SF$ is chosen so that some level of protection is ensured, without wasting too much bandwidth. Our simulations show that $SF = 32$ is a good value for this case. When the sink needs to reply back to the CHs, it uses its own unique spreading sequence, which we suppose to be known by all CHs. Note that the siblings *do not* employ CDMA to address their CH, otherwise they could interfere with the CH-to-sink transmissions due to the random access protocol. Instead, their *unspread* signal is confined within a band that is centered on the same carrier frequency used for the CDMA transmissions, but $SF$ times smaller. All sibling nodes in all clusters follow this rule, and thus use the same (smaller) band.

[1] In the following, we will use the terms *sibling* and *child* interchangeably, to indicate all nodes within a cluster, except the CH. We will also sometimes refer to children-to-CH communications ans *intra-cluster*.

### B. Scheme 2: TDMA—CDMA

In this case, we enforce a deterministic channel access within a cluster, by setting up a schedule among the CH and the children nodes. Specifically, a slot must be reserved for each of the children to send its data and receive an ACK packet from the CH. Moreover, a guard time must also be taken into account to separate subsequent slots. In a practical setting, this interval is necessary to ensure that the communications within the same cluster do not collide due to the long and variable propagation times experienced in an underwater acoustic channel. A TDMA slot must thus accommodate one data and ACK trasmission time ($T_d+T_a$), plus one round-trip time between the transmitter and the CH, plus the guard time. In the worst case this time span is $T_{slot} = T_d + \bar{\tau} + T_a + \bar{\tau} + 2\bar{\tau}$, where $\bar{\tau}$ is the maximum propagation time in the whole network and $2\bar{\tau}$ is therefore the maximum required guard time between subsequent TDMA transmissions. A TDMA frame is then composed of as many slots as there are nodes within the cluster, including the CH. During its own slot, the CH communicates with the sink using CDMA. As for ALOHA, we will consider here a very basic setting where the children's signals are constrained in a band $SF$ times smaller than the CHs, centered on the same frequency. However, we also consider a different configuration.

Indeed, the TDMA schedule with worst-case guard times prevents collisions between children's and CHs' transmissions within the same cluster. Therefore, we enable the nodes to use on the children-to-CH links the same spreading code used by their CH for transmitting to the sink. This way, the children's signals are separated through CDMA and generate a smaller amount of interference toward other clusters. A tradeoff arises here between the amount of protection endowed to the intra-cluster communications and the transmission bit rate. We will compare two different solutions, with a spreading factor of $16$ and $32$, respectively, to see if it is more convenient to have a higher bit rate and less protection ($SF = 16$) or vice-versa. We point out that such considerations apply only to intra-cluster communications: the CH-to-sink links are in fact crucial for the system, and thus they are always assigned a spreading factor of $32$ for better interference rejection. Notice that TDMA requires synchronization among nodes. Since we use LIDCA to create single level hierarchies, an easier way to maintain synchronization could be, *e.g.*, to have the cluster-heads broadcast very short sync beacons at periodic intervals.

### C. Scheme 3: TDMA—FDMA

In this case, we suppose that clusters are separated in the frequency instead of the code domain. The available bandwidth is therefore split into a fixed number of sub-bands. Each cluster is assigned a different sub-band, that will be shared via TDMA for transmission both within the cluster and from the CH to the sink. We assume that the sink is able to simultaneously receive and detect signals coming from any sub-band. Each sub-band is separated from adjacent ones by a guard band, designed to be such that the different signals can be isolated, given the selectivity of the used receive filters. We chose to consider FDMA because it results in a different tradeoff between performance and flexibility. In fact, reliable CDMA detection requires a sufficiently high spreading factor, which may slow down the siblings' transmissions too much. On the other hand, accommodating a new cluster is just as easy as generating a new spreading sequence whose knowledge is shared among the CH, the siblings and the sink. FDMA reverses this paradigm, because the sub-bands can be designed to yield well separated signals in the frequency domain, but once they have been defined (something that can be done *a priori*) it is much harder to reorganize them, *e.g.*, to allow for a new cluster. In other words, the only way to introduce some flexibility is to design for more sub-bands than would be probably needed, so that some are free if a new cluster needs one. Clearly, this comes at the price of a decreased communication speed in all other bands, thus a lower throughput. This motivates us to consider also the following scheme.

### D. Scheme 4: TDMA—Optimal FDMA

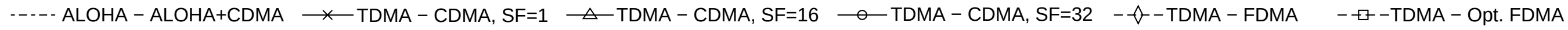
In order to assess the impact of the difference among FDMA and CDMA, we consider a version of FDMA which is less realistic, but "optimal," in the sense that it provides exacly the number of bands needed to accommodate all clusters for a given network topology, thus maximizing the allowed communication rate. We highlight that with this scheme, the number of sub-bands will depend on the hierarchical structure obtained with the clustering protocol (LIDCA in our case), more specifically on the number of clusters created.

## IV. Network Setting

We have developed an event-driven MATLAB simulator to study the effects of the aforementioned access schemes. Our network is formed of $20$ nodes randomly deployed over a $16\ \mathrm{km}^2$ square area. For each topology, we run the LIDCA clustering algorithm prior to the simulation. We set the maximum range of each cluster to be $1.5\ \mathrm{km}$, which allows for a reasonable number of clusters to be formed. The communication bandwidth is set so that the transmission between the two farthest nodes in the network (spaced $4\sqrt{2}\ \mathrm{km}$ apart) can be accommodated. We suppose that acoustic waves travel at a uniform speed of $1.5\ \mathrm{km/s}$, and explicitly model this propagation time, by keeping track of which signals have reached a certain node at any given time. This information is translated into the Signal to Interference plus Noise Ratio (SINR) whenever a node becomes a receiver. More specifically, the SINR at a generic receiver $x$ is defined as

$$SINR_x = \frac{P_u A_{ux} \gamma_{ux}}{N + \sum_{i \in \mathcal{I}} \frac{P_i A_{ix} \gamma_{ix}}{SF_{ix}}}, \quad (1)$$

where $P_u$ is the power transmitted by the wanted node, $P_i$ is the power from the interfering node $i$ and $\mathcal{I}$ is the set of all nodes emitting interfering signals. The factor $1/SF$ models the interference reduction achieved through CDMA. Note that the equation in (1) holds for FDMA communication as well, provided that we set $SF_{ix} = +\infty$ for all nodes $i$ transmitting in a different sub-band. $N$ represents the in-band noise power, and is obtained by integrating the power spectral density of the noise as reported in [14] over the communication band. In this specific case, we have assumed a wind speed of $3\ \mathrm{m/s}$ and a shipping factor of $0.5$ to represent some common noise parameters. The attenuation is calculated as a function of the distance between the communicating



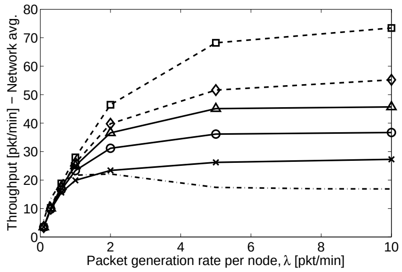




Fig. 1. Throughput (network average).

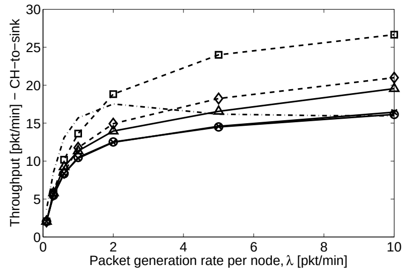



Fig. 2. Throughput (CH-to-sink).

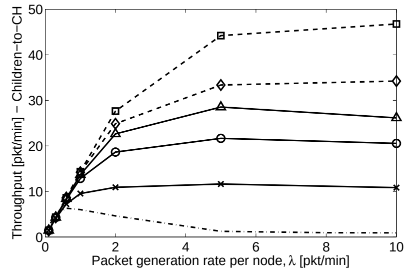



Fig. 3. Throughput (children-to-CH).

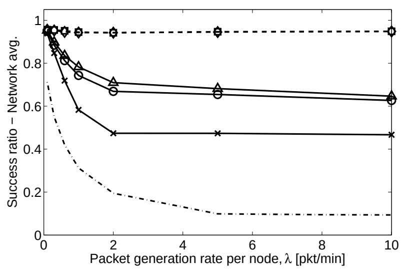



Fig. 4. Success ratio (network average).

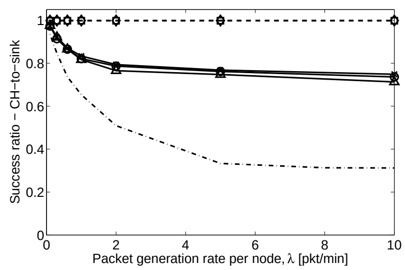



Fig. 5. Success ratio (CH-to-sink).

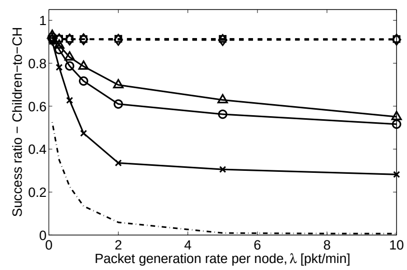



Fig. 6. Success ratio (children-to-CH).

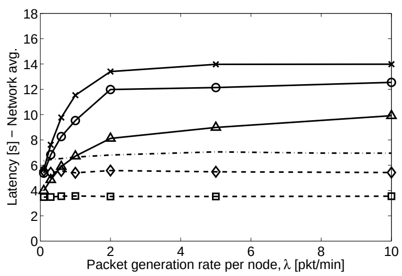



Fig. 7. Latency (network average).

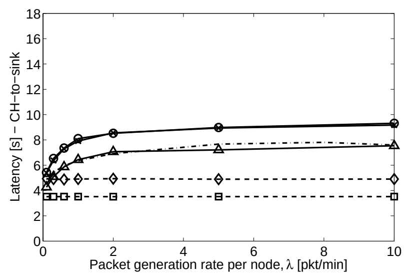



Fig. 8. Latency (CH-to-sink).

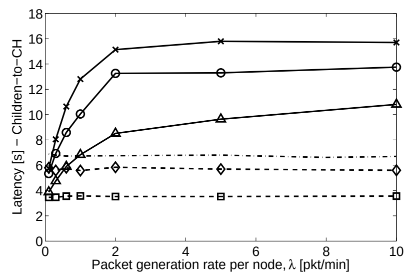



Fig. 9. Latency (children-to-CH).

nodes, using the well known formula $A_{ix} = d_{ix}^k a(f)^{d_{ix}}$, where $k$ is the wave spreading coefficient (set equal to $1.5$) and $a(f)$ is given by Thorp's formula for acoustic power absorption [6]. The value of $f$ depends on the acoustic carrier frequency, and the attenuation in a band is optimistically considered to be equal to the attenuation undergone at the center frequency. Furthermore, we suppose that acoustic links are operated in a shallow water environment, and thus undergo independent fading phenomena, which are modeled using a Rayleigh distribution. Fading is assumed to be constant over a single transmission and independent between subsequent transmissions. Such effects are conveyed in the SINR formula through the coefficients $\gamma$, whose net effect is thus to increase or decrease the power received over a certain link. Assuming independent bit errors and the use of a BPSK modulation, the SINR is translated into the probability of error for the packet being received, *i.e.*, $P_e = 1 - [1 - 0.5\,\mathrm{erfc}(\sqrt{SINR})]^L$, where $\mathrm{erfc}(\cdot)$ is the complementary Gaussian error function, and $L$ is the packet length.

The traffic in the network is generated according to a Poisson process with rate $\lambda$ packets per minute per node. Each packet is $256$ $\mathrm{bits}$ long and is transmitted (unless otherwise stated) at a bit rate of $256$ $\mathrm{bit/s}$. Packets waiting for transmission are temporarily stored in a queue that can hold up to $20$ packets. As for FDMA, the sub-bands are $600$ $\mathrm{Hz}$ wide and are separated by a guard band of $400$ $\mathrm{Hz}$. The non-optimal version of FDMA always uses 8 sub-bands. All packets are convergecast toward the sink through the clustering infrastructure built using LIDCA.

The relevant metrics shown in the following Section are obtained by averaging over $15$–$20$ different topologies, each run for a simulated time of $1000$ minutes. This has proven to yield statistically meaningful results in our setting.

## V. Results

Figure 1 to 3, 4 to 6, and 7 to 9 respectively show an overview of average throughput, transmit success ratio and latency for all schemes reported in Section III, by explicitly addressing the different behavior of the CH-to-sink and the children-to-CH links. Here, throughput is defined as the number of packets that reach their destination correctly in a minute, and latency as the time elapsed from when a packet reaches the head of the queue and is considered for transmission, to when its *correct* reception starts at the receiver. Latency is thus a measure of the ability of a node to access the channel (and thus does *not* include any queueing delays). In the legend, the $SF$ used by the sibling nodes in TDMA—CDMA schemes is specified, with $SF = 1$ meaning that CDMA is used by the CHs only. The first insight gained is that using ALOHA as an intra-cluster communication pattern is not always the best choice. ALOHA offers the best performance only for very low traffic values, when the probability that two siblings' communications collide is sufficiently small. Notice that the global throughput curve for ALOHA reaches a floor at high traffic, as compared to a classic ALOHA network, whose throughput tends to $0$. The reason behind this behavior is twofold. On one hand, our network is composed of a finite number of nodes, thus its throughput reaches a stable value even at high traffic. On the other hand, a limited number of nodes (*i.e.*, the CHs) are less prone to interference and collisions due to the use of CDMA, and thus experience a better throughput. Instead, the amount of data that is correctly transmitted from the siblings to the CHs decreases rapidly with increasing data generation rate, as expected. Correspondingly, the success ratio of the transmissions within a cluster (Figure 6) drops to a very low value as well, whereas for CH-to-sink links it remains at $35\%$ thanks to CDMA (Figure 5). The latency (Figures 7 to 9) instead is almost constant for any traffic value, after a small increase at low traffic. In fact, since the number of nodes in the network is fixed, when the network is lightly loaded any traffic increase translates into increased contention for the channel and therefore the delay also increases. On the other hand, if the traffic is large enough, all nodes will have non-empty queues, and adding more traffic does not affect the contention performance (which determines the access latency) but only the queueing delays.

TDMA, on the other hand, offers slightly worse throughput than ALOHA at very low traffic, but is able to sustain a much larger number of transmissions as the network load increases. In fact, the scheduled transmission pattern is able to limit the interference coming from both within and outside the cluster, thereby improving the probability of success and the overall throughput. Nonetheless, insofar as different clusters are allowed parallel communication activity, some interference is expected to affect transmission with CDMA. In particular, the probability of success is not guaranteed to be high due to fading and channel reuse, but instead drops to a lower value depending on the used spreading factor. As expected, the latency reaches a stable value at high traffic for the same reasons explained for the ALOHA case. Notice that decreasing the spreading factor from $32$ to $16$ for intra-cluster communications has the effect of increasing the network throughput. In fact, halving the spreading factor halves the transmission time as well, allowing for more (shorter) TDMA frames, which in turn allows for more traffic to be delivered to the CH. This helps keep the network less loaded and the overall interference under control. As observed from Figures 1 and 4, both the throughput and the success ratio are therefore slightly increased for $SF=16$, with the main advantages on the children-to-sink links (Figure 3 and 6. In fact, a greater bit rate allows for more traffic to be delivered per unit time, and yielding emptier TDMA schedules at low to medium traffic, which in turn helps decreasing the average overall interference. As expected, the latency drops as well for a smaller spreading factor, as a consequence of the higher success ratio.

As a final note, decreasing the $SF$ further for intra-cluster communications yields significant disadvantages. In fact, our simulations show that the protection obtained with $SF = 8$ is not sufficient for simultaneous correct packet delivery. Figures 1 to 9 show that, in the limit case where no CDMA is used inside the cluster (or equivalently, $SF=1$), the children nodes cause very strong interference to one another.

Separating clusters through FDMA instead of CDMA brings significant benefits. As a general rule, the CHs are constrained to a smaller transmission sub-band, and thus have to reduce their transmission rate accordingly. On the other hand, the signal is unspread, *i.e.*, the available bandwidth is exploited only for conveying information. In particular, the children-to-CH nodes are not constrained any more within a fraction $1/SF$ of bandwidth of the CHs, and may end up with a larger bit rate. This is especially true if optimal FDMA is considered, *i.e.*, the sub-bands are designed such that the maximum possible bandwidth is assigned to every cluster, given the actual topology. This allows for a higher bit rate in general, which in turn improves both the throughput and the delay. Moreover, the probability of transmission success remains very high even in the presence of fading. A first conclusion we can draw from this study is that on one hand FDMA clustering allows for a generally better network performance, and on the other hand it forces to design the numer of sub-bands for the worst-case topology, thereby likely allotting more sub-carriers than necessary on average. In turn, each sub-band would be smaller, thus decreasing the global throughput.

Actually, how many sub-bands are really necessary depends on the clustering algorithm. For example, the clustering behavior of LIDCA is shown in Figure 16. Namely, as the number of nodes in the network increases, one can expect to deal with only about $6$ clusters on average. This allows to keep the number of sub-bands sufficiently low even with an increasing number of nodes. The price to pay for this advantage is a longer TDMA frame inside each cluster, thus a longer time between two transmissions of the same child node, due to the greater number of nodes present.

The throughput performance of FDMA with $10$, $20$ and $30$ nodes within the network area is given in Figures 10 to 12. The average throughput increases for an increasing number of nodes, with little difference between $20$ and $30$ nodes. A deeper inspection of the network behavior shows that the improvement is mostly due to the greater number of nodes per cluster, thus to the greater traffic channeled toward the CHs. Anyway, due to the longer TDMA frames, CHs have a smaller share of the channel for sending data to the sink, thus becoming more rapidly a traffic bottleneck. For the same reasons, the average latency (Figure 17) is increased for an increasing number of nodes, even if this change is limited thanks to the good transmission efficiency yielded by FDMA. Indeed, CDMA (we consider $SF=16$ here) achieves smaller throughput improvements for an increasing number of nodes with respect to FDMA (Figures 13 to 15). In particular, the interference caused to both intra-cluster and CH-to-sink communications gives rise to more errors, thus also a longer average latency (Figure 17).

## VI. Conclusions

In this paper, we have carried out a comparison of access techniques as applied to underwater acoustic network, considering a clustered network topology. The compared techniques include random access as well as deterministic access. We have discussed the flexibility limits of an FDMA solution in terms of allotted sub-bands and of the chance to accommodate more clusters than initially foreseen, and compared FDMA to CDMA in CH-to-sink links, which would yield more flexibility, by sacrificing performance. The final outcome of

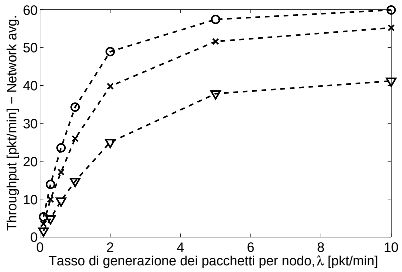




Fig. 10. Throughput of FDMA clustering for varying number of nodes (network average).

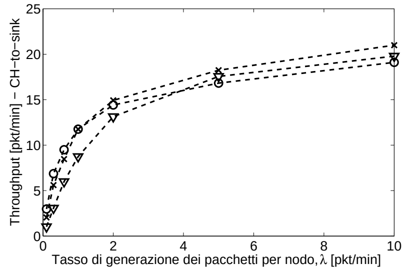



Fig. 11. Throughput of FDMA clustering for varying number of nodes (CH-to-sink).

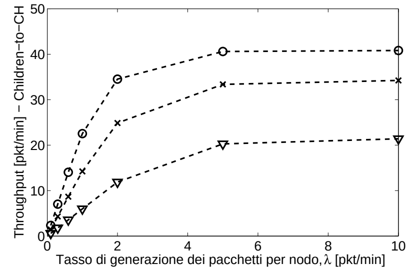



Fig. 12. Throughput of FDMA clustering for varying number of nodes (children-to-CH).

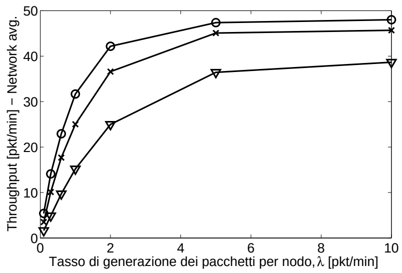



Fig. 13. Throughput of CDMA clustering for varying number of nodes (network average).

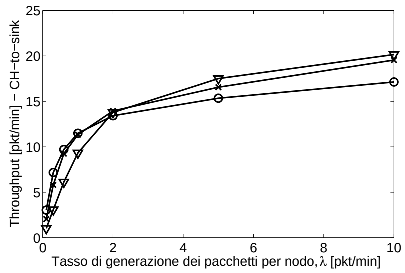



Fig. 14. Throughput of CDMA clustering for varying number of nodes (CH-to-sink).

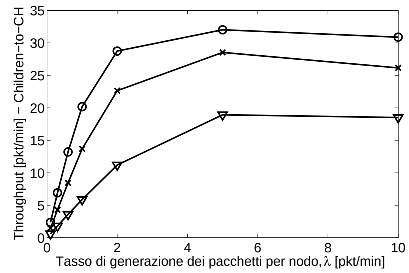



Fig. 15. Throughput of CDMA clustering for varying number of nodes (children-to-CH).

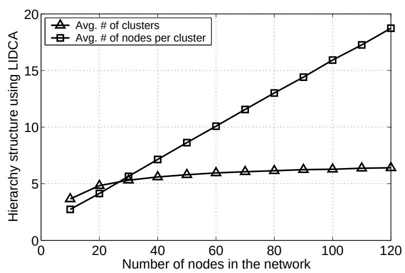



Fig. 16. Number of clusters and number of nodes per cluster using LIDCA.

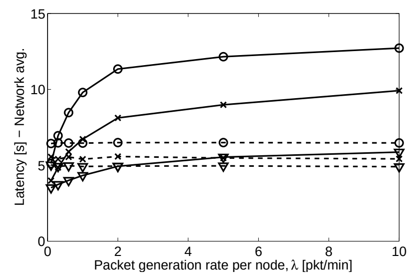



Fig. 17. Latency of FDMA and CDMA clustering with 10 to 30 nodes.

this study is that in an underwater network with a clustering hierarchy CDMA should be used for separating clusters only if their number can be affected by substantial variations and more flexibility is sought. ALOHA should also be resorted to only in the case of very low generated traffic. Instead, as a general rule, it is better to organize the hierarchy using FDMA for separating clusters and TDMA for intra-cluster communications, even if the final choice on the communication scheme should be made depending on the specific details of the scenario.

## ACKNOWLEDGMENT

This work was partially supported by NOAA's Sea Grant Project no. NA060AR4170019.

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