COPPER: Increasing Underwater Sensor Network Performance Through Nodes Cooperation

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***Abstract*—Monitoring underwater environments is still a hard and costly task. Indeed, electromagnetic and optical waves suffer high attenuation, being absorbed in a few meters and even acoustic communication presents low throughput and high bit error rate. Most of the existing approaches to enhance underwater communication performance relies on developing acoustic modems, multiple access to the communication channel and, data routing. In this paper, we present COPPER: a COoperative Protocol for PERvasive Underwater Acoustic Networks. COPPER synchronously/asynchronously works on top of TDMA method combined with an ARQ scheme based on selective repeat technique. It uses idle sensor nodes as relay nodes, enhancing communication space diversity. Our simulations show that, when compared to a non-cooperative protocol, COPPER enhances overall network performance metrics. For instance, it reduces packet error rate by 28.32% and increases goodput by 16.87% while spending less than 1% more energy.**

***Index Terms*—Underwater Sensor networks, IoT, Cooperation**

I. Introduction

Underwater sensor network (UWSN) is an important research area that attracts an increasing interest from the research community and from the industry. Oceans, rivers, and lakes are critical to life on our planet and a number of society segments demand online underwater monitoring. For example, oil industry uses UWSNs to monitor and explore natural resources such as oil and gas. Governments monitor oceans to alert population about natural disasters as tsunamis.

Despite its importance, monitoring underwater environments is still a hard and costly task. The conditions of the aquatic environment impose great difficulties to communication. Below the water surface, electromagnetic and optical waves suffer high attenuation, being absorbed in a few meters. Even acoustic communication is challenging, and presents three major issues: (i) the limited and distance-dependent bandwidth, (ii) the multi-path fading varied by time, and (iii) the low speed of sound in water when compared to RF. Moreover, as with almost all sensor networks, UWSNs present several energy constraints.

To improve communication quality and overcome UWSN challenges, many techniques have been studied from the physical to the network layer. In fact, we are aware of a number of studies involving the development of acoustic modems and effective use of communication channels [1]–[3], multiple access of the communication channel (detailed in Section II) and routing data among sensors [4]–[11].

In such scenario, the use of Automatic Repeat reQuest (ARQ) protocols [12] is mandatory to achieve error-free communication. Although, for all well known ARQ based protocols as Stop & Wait and Selective Repeat, the long propagation delay combined with high Bit Error Rate (BER) of the underwater acoustic channel turns high throughput efficiency hard to be achieved [13]. Moreover, ARQ protocols also increase the use of energy and transmission latency, which is not desirable in UWSNs.

In this sense, we present COPPER: a COoperative Protocol for PERvasive Underwater Acoustic Networks. COPPER takes advantage of the broadcast nature of wireless transmissions where each network node overhears other nodes transmissions and may act as relays, concurrently transmitting the data it receives from the source to a sink node in the network. This increases the path diversity [14], and as a consequence, it also increases the chance of a successful transmission. Additionally, by means of cooperation, it is possible to achieve time diversity by transmitting the same data (or signal), that was overheard through a broadcast transmission, at a different time instant. In this case, the source node may transmit a new data packet, while the relay tries to recover the previously lost data transmission, enhancing system throughput.

In more detail, COPPER takes into account both sub-layers of the data link layer: the media access control and the logical link control. COPPER synchronously/asynchronously works on top of the time division multiple access (TDMA) method combined with an ARQ scheme based on selective repeat. It explores nodes idleness to enhance space diversity, or more specifically, cooperative diversity. Different from existing approaches [13], [15]–[18], our protocol is designed to efficiently integrate cooperative transmission and an ARQ scheme in a collision-free medium access control protocol.

We have evaluated COPPER through ns-3 simulations, in a scenario where various underwater sensor nodes attempt to communicate to a sink node. When compared to a non-cooperative protocol, COPPER enhances overall network performance metrics. For example, in the best-case scenario, the packet error rate is reduced by 28.32% and goodput increases by 16.87% while spending less than 1% more energy.

The remainder of this paper is organized as follows: in Section II, we overview the state of the art. In Section III, we present the COPPER protocol. In Section IV, we detail the evaluation scenario and also show our evaluation results. Finally, in Section V, we draw our conclusions.

II. Related Work

Previous works, in most cases, focus on showing that cooperative transmission can be effectively applied to underwater networks. Almost all these works have emerged as extensions of cooperation work on terrestrial wireless networks [19]–[24]. For example, Carbonelli et al. [19] address energy efficiency in an underwater multi-hop cooperation scenario. Vajapeyam et al. [20] also present a relay aided protocol, where relays use amplify-and-forward messages (mostly based on physical layer). Han et al. [21] also propose an amplify-and-forward cooperation scheme and showed that, even with the presence of noise on the physical layer (and its amplification), the quality of transmissions is improved with cooperation.

Han et al. [22] evaluated the effects of existing amplify-and-forward, decode-and-forward, and estimate-and-forward schemes. Moreover, authors presented Wave Cooperative, a protocol based on amplify-and-forward scheme. Their result shows that cooperative techniques present better performance than protocols without any cooperation. Moreover, their new approach presents superior channel capacity performance. Wang et al. [24], also propose an asynchronous cooperation scheme, applicable in scenarios with large and variable propagation delay. The authors have compared amplify-and-forward, decode-and-forward, and direct transmission schemes. Authors show that each technique improvement depends on the signal-to-noise ratio (SNR) conditions. For example, direct transmission has a better result for optimum SNR conditions, whereas amplify-and-forward scheme presents a better performance for scenarios with bad SNR conditions.

Some works [25], [26] have explored cooperation in a system based on MIMO and OFDM. But, they focused on the physical layer. Moreover, they do not explore ARQ schemes.

A number of works jointly use ARQ schemes and cooperative transmissions [13], [15], [16]. For example, Lee et al. [15] propose a cooperative S&W ARQ scheme in a single-hop acoustic channel. When the destination node receives an erroneous packet, it requests a retransmission for the cooperative node. Protocol recruits closest nodes first as relays and, in this case, authors assume each node knows the inter-node distance for its neighbor nodes. Lee et al. [16] also have proposed the use of the cooperative protocol in a multi-hop scenario, which in this case, enhances communication spatial diversity. Ghosh et al. [13] also propose a cooperative protocol, but in this case, authors propose the use of cooperative ARQ and Hybrid ARQ, where data are encoded with an FEC code, and redundant FEC bits are transmitted along with the data or requested by destination when errors are detected. Despite their importance, these three works only consider simple scenarios, where only one node originates messages. Moreover, MAC issues either assumed as resolved or ignored.

Kim et al. [27] consider a handshake-based MAC protocol with a cooperative ARQ scheme. The handshaking process is based on the request-to-send and clear-to-send mechanism, and the cooperation information is shared during the handshaking process. Despite their performance improvement, their approach presents a large number of control messages, which may cause more collisions and also extend the duration of the handshaking process, decreasing the overall throughput.

In sum, different from previous works which mostly relay their solution on physical layer schemes and amplify and forward, we take into account the MAC layer and its issues. Our approach effectively coordinates the retransmission of erroneous messages when more than one node shares the medium, using time division multiple access. Moreover, we dynamically explore system nodes as a relay in a synchronous or asynchronous way.

III. Cooperative Communication

In this work, we consider a single-hop sensor network where N nodes try to send data to a sink node. We also consider a time-division based medium access scheme (TDMA) where each node is assigned to a time period –called time slot– in which it exclusively accesses the communication medium.

Note that, wireless underwater communication follows a broadcast pattern. When a node tries to send data to the sink, all other nodes may receive these data. In this sense, idle nodes may act as a relay, increasing spatial or time diversity. For example, let n be the source node, s the sink and r any idle node located between n and s. When n tries to send data to s, r is more suitable to receive it correctly than s (due to spatial data channel fading). In this case, when s does not receive data correctly, but r does, the relay node may offer its time slot to send the aforementioned data to s. Then, retransmission will occur in a shorter link, with a higher success probability.

First, we propose a synchronized COoperative Protocol for PERvasive Underwater Acoustic Networks, or synchronous COPPER, where each TDMA frame presents a signaling period (SP) followed by a data period (DP). System nodes use the signaling period to exchange cooperation control messages, showing their interest to cooperate.

More precisely, in our scheme, a node is only able to transmit a single packet at a single frame, in its time slot. Then, when a node successfully receives a data packet, which by definition is addressed to the sink node, it stores this message in a cooperation buffer. By the end of the frame, the sink node transmits a single NACK to signal which packets of the current frame have failed. Upon receiving this message, each node knows which packets have failed and then, they can try to cooperate during the next frame, retransmitting this packet.

During the signaling period, idle nodes can cooperate by sending a Want To Cooperate (WTC) message. The WTC message indicates which packets a node may retransmit. In addition, it allows the node that originated the packet to continue to its transmission. By the end of the signaling period, each node already knows which packet it will transmit in the current frame and then, nodes can manage their cooperation

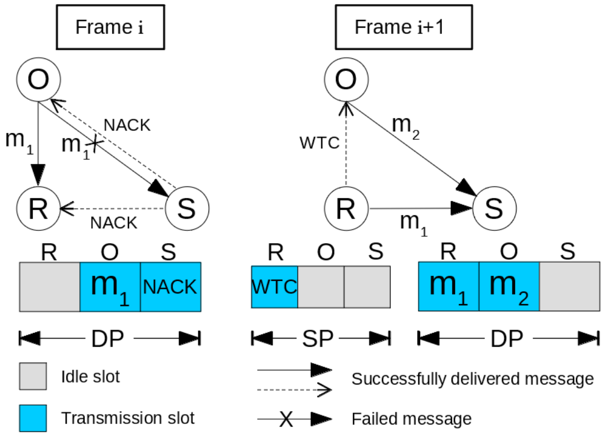

Fig. 1: Synchronous COPPER in a 3-node scenario.

buffer. As we consider only one time window cooperation period, each node just allocates $n - 1$ packet size to its cooperative buffer, where n is the number of network nodes.

For example, Figure 1 depicts a scenario containing 3 nodes. During the frame i, source node O transmits a message m_1, which is successfully received by relay node R, but fails to reach sink node S. By the end of the frame, S signals the failed message by transmitting a NACK packet, which is received by all nodes. As R is idle, it signals that it will cooperate during its next data slot. Thus, O can transmit its next message m_2 in the same frame as R retransmits m_1.

Figure 2 shows a more realistic scenario with four sensor nodes and a sink. During the first data period, all four nodes are not idle and try to transmit data. According to this figure, messages from nodes 3 and 4 fails, while the remaining messages are successfully delivered. Sink then sends a NACK, signaling it did not correctly receive messages from nodes 3 and 4. All nodes, upon receiving the NACK, check if they have any missing message. Case positive, they signal their intention to cooperate during the next signaling period.

We assume a priority order to avoid retransmission duplication. Node 1 is the first to signal its WTC message. When node 2 receives the WTC message from node 1, it perceives that node 1 will cooperate retransmitting the original data from node 3. Node 2 then signals its intention to cooperate with node 4. We let as future work the investigation of other deduplication policies. Upon receiving the cooperation message, nodes 3 and 4 know they can transmit their next enqueued messages. In the next data period, cooperative messages from nodes 1 and 2 are sent and received correctly. Likewise, the messages from nodes 3 and 4 are also delivered successfully.

The relay selection is crucial to the success of the cooperation. Intuitively, the closer the relay is to the sink, the better will be the chances of successful retransmission. Indeed, the closest nodes to the sink node will present a lower packet error rate than the more distant nodes as the packet error rate is proportional to the distance. For a given failed message, the relay is selected as the first node to transmit a WTC with the failed message identification. To prioritize nodes with lower packet error rate we order the nodes time slots in relation to their distance from the sink node, similar to [28]. In other words, the first slot of each frame will belong to the closest node to the sink. This way, in the synchronous COPPER, this node will present a greater opportunity to act as a relay . The major shortcoming of this approach is related to energy consumption balancing. Nodes closer to the sink may transmit more cooperative messages than other nodes, causing unequal power consumption. We highlight that different relay selection policies may be used. For example, policies may consider node energy level.

In addition, we have developed an asynchronous COPPER, where nodes do not need to signalize to cooperate during a signaling period. An asynchronous protocol may simplify the original COPPER and turn transmission faster (as we do not need a signaling period). On the other hand, nodes are not aware of which messages each node will cooperate, which may lead to duplicated messages.

The asynchronous COPPER assumes that nodes overhear NACK messages and simply randomly draw one of the failed messages it has in its cooperative buffer. In this approach, the same failed message can be retransmitted by multiple nodes, which may lead to a waste of energy. On the other hand, it may increase the number of transmission paths, and consequently, reduces the packet error rate.

Figure 3 shows the asynchronous protocol in the same scenario of Figure 2: 4 nodes transmitting messages to the sink node over two frames. Note that each frame contains only the data period, and no longer both the signaling period and data period. In the first frame, each node has a message to transmit. However, messages from nodes 3 and 4 are not delivered correctly. At the end of the frame, the sink signals with a NACK that messages from nodes 3 and 4 have failed. In the next frame, nodes 1 and 2 have no messages to transmit, being available to cooperate. Since both received the NACK and the failed messages correctly, they randomly draw one of them to cooperate. In this example, both end up selecting the same message. Node 3 also retransmits its own failed message, totaling three possible diverse paths.

The COPPER protocol considers that all nodes transmit directly to sink, that is, a single-hop network. For cases where the coverage area is larger, a multi-hop network may be more suitable. To modify the synchronous COPPER to allow multi-hop transmissions, nodes must also transmit NACK confirmation messages. One possible solution would be to decrease the payload size of the data messages so that the common nodes can transmit a confirmation message after the data message. Due to space constraints, we leave as future work the evaluation of a multi-hop scenario.

IV. Evaluating COPPER

A. Evaluation Methodology

We have evaluated COPPER through simulations, using the ns-3 discrete event network simulator. We have implemented both, synchronous and asynchronous COPPER, and a TDMA base protocol.

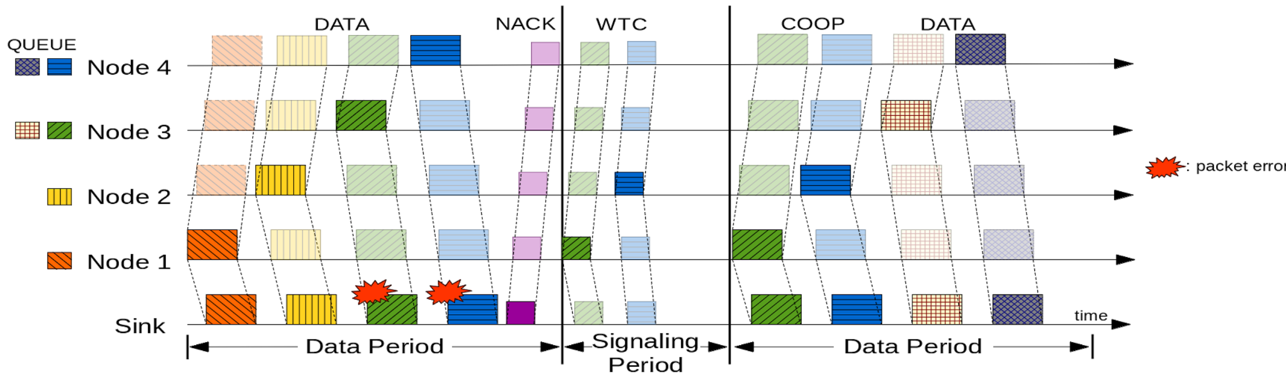

Fig. 2: Synchronous COPPER in a 5-node scenario.

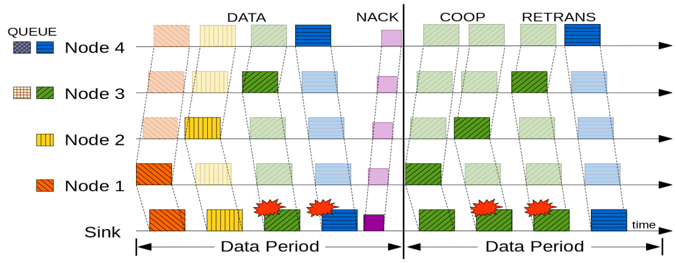

Fig. 3: Two frames of asynchronous COPPER in a 5-node scenario.

The simulation scenario contains 50 nodes, including the sink node. Regular nodes are responsible for generating data packets and transmitting them to the sink node. Each regular node can act as a relay when idle. The sink node does not generate data and only receives the packets and transmits NACK messages. In this work, nodes are static and are randomly distributed in a star topology inside a 200 m side square area and 70 m depth. Nodes are repositioned at each simulation execution, except the sink node which is always positioned in the center of the square.

We model channel error rate through the use of widely adopted model as follows: for each pair of communication nodes, distant by d meters, we calculate the attenuation of the acoustic signal using [29]: $10\,log\,A(d,f) = k \cdot 10\,log\,d + d \cdot 10\,log\;a(f)$, where the first term is the scatter loss of the signal and f is the transmission frequency. The second term is the absorption loss given by Thorp's approximation [30]: $0{,}11\,\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f} + 2{,}75 \cdot 10^{-4} f^2 + 0{,}003$ for frequencies $f \geq 0{,}4$ Hz. Then we calculate the signal-to-noise ratio $\gamma(d) = SL - A(d,f) - NL + DI$ where SL is the power of the transmission signal, NL is the ambient noise approximation given by the Wenz equation in [31], and DI is the directing factor that for omnidirectional hydrophones (e.g. acoustic modems) is $DI = 0$ [32]. Finally, we can describe the bit error probability, for the BPSK modulation [33], as: $p_e(d) = \frac{1}{2}\left(1 - \sqrt{\frac{\Gamma(d)}{1+\Gamma(d)}}\right)$, where $\Gamma(d)$ is given by $\Gamma(d) = 10^{\gamma(d)/10}$.

To generate random values, ns-3 implements an algorithm based on streams and substreams. Each stream generates a set of substreams that do not overlap. Thus, to produce multiple independent runs, we fix the stream by choosing a value for the seed and change only the substream for each run. In this work, we use 138 as seed and i as substream for the i-th execution ($i \in \mathbb{N}^*$).

We generated data traffic randomly according to a uniform random variable. A node may generate a packet according to a probability L at each frame beginning. We call this probability L network load. In other words, when network load $L = 0$, no packet is generated in the whole simulation, and when $L = 1$, all nodes will always have a packet to transmit, at every frame. We have varied L to evaluate the performance of the protocol with different network loads, from 10% to 100%.

Moreover, we setup the number of retransmission attempts to 1. In other words, when a node fails to deliver a message, this message will be retransmitted by the original node, or by some cooperative node (if available). In the case of retransmission failure, we consider as a packet loss. Such low number of retransmission attempts is a conservative approach, which gives us an upper bound of packet loss rate.

For each protocol, we have varied network load from 0.1 to 1. Each simulation regards to 50 executions and, unless we tell otherwise, results we present are mean values and confidence interval, for a confidence level of 95%. We also conducted additional executions of the synchronous COPPER varying the number of nodes for four different network loads.

Each execution simulates the operation of the network during 3,600 seconds. The size of data packets is set to 540 bytes, WTC packets to 3 bytes and NACK packets to 5 bytes, which are in the same order of magnitude as [13], [18]. The transducer settings are based on the UNET-2 [34] acoustic modem: data rate of 2,400 bps, center frequency of 4,000 Hz and BPSK modulation, bandwidth of 2,000 Hz, transmitting power of 138 dB, power consumption for packet transmission of 50 W, power consumption for reception of packets of 158 mW and power consumption in idle mode of 158 mW. Data slots present 2 s duration, with 1.8 s for data transmission and 0.2 s as guard time to avoid packet collision. In the signaling period, the control slots last 0.2 s, which represents only 10% of the data slot time.

In this work, we assume the network can keep time synchronized among nodes, as it can be achieved in a practical scenario. Indeed, the slots synchronization of all nodes of the network is of extreme importance for the operation of the protocol [35]. If one node is not synchronized, it can lead to collisions in the sink node, negatively impacting network performance. To avoid this problem, time synchronization can be achieved using the modem's own functionality [36]. The modem's ranging feature is used to get the clock offset between the nodes and adjust it accordingly, so the time slots can also be synchronized. Nevertheless, the added guard time at the end of each slot reduces the impact of small-scale time desynchronization until a node is synchronized again.

Finally, we evaluate COPPER according to a set of three metrics: (i) the goodput which corresponds to the amount of data packets bytes which sink node receives, in relation to the total simulation period; (ii) packet error rate (PER) which represents the percentage of data packets that are not properly received by sink node; (iii) total energy spent in the simulation.

B. Numerical Results

Figure 4 presents UWSN performance metrics mean values (and confidence interval) while we vary the network load. According to Figure 4a, asynchronous COPPER presents lower PER when compared to the non-cooperative protocol. For example, at a 10% network load, the asynchronous COPPER is more than 87% better than the non-cooperative TDMA. In fact, while the first presents about 4% of mean PER, the former presents more than 37%.

Indeed, under low network load, there are numerous idle nodes. Without nodes synchronization and a large number of idle nodes, many nodes may retransmit a given packet and, as a consequence, the better will be the chance of a successful transmission. In this case, as there is a large number of idle nodes, all packets that need to be retransmitted may be covered by at least one relay. On the other hand, when the network load increases (e.g. > 0.4) the synchronous COPPER overcomes the asynchronous version. In this case, synchronization avoids that two or more nodes retransmit the same packet, covering a larger number of distinct packets that need to be retransmitted.

Despite the notable improvements in packet error rate, for lower network load scenarios, all three protocols tend to present similar PER in high loaded scenarios (e.g. > 0.8). In fact, in high loaded scenarios, all nodes are transmitting data practically all the time. In this case, nodes are not idle and do not have the opportunity to cooperate. Conversely, for lower network load, the cooperative protocol achieves better results. The lower the network load, the more nodes are idle, and, consequently, the greater the chance of some node cooperate.

Asynchronous COPPER also presents better goodput, when compared to synchronous and non-cooperative TDMA at lower network loads. As shown in Figure 4b, asynchronous COPPER is about 52% better than the non-cooperative TDMA at 10% network load. However, as occurs to PER (and for the same reasons), synchronous COPPER presents better goodput when network load increases.

Despite the gains in goodput and packet error rate, asynchronous COPPER protocol demands more energy to its proper functioning. Indeed, when multiple nodes try to cooperate, without any synchronism, they may waste energy, retransmitting the same data packet. According to our results, at a 10% network load, the asynchronous COPPER, consumes almost three times more energy, when compared to the non-cooperative TDMA. In this scenario –low network load–, synchronous COPPER presents a better goodput and PER while consuming about the same amount of energy of the non-cooperative TDMA.

Figure 5 evaluates COPPER scalability. Due to space constraints, we focus on synchronous COPPER as synchronization leads to protocol overhead, which may be impacted by the number of nodes. According to this figure, PER remains roughly stable –Figure 5a– while goodput and energy consumption –Figures 5b and 5c respectively– slightly increases with the number of network nodes. Indeed, increasing the network will also increase the path diversity between source nodes, relays, and sink. In turn, path diversity may reduce the error probability, which will lead to better network performance. As expected, energy consumption increases with the number of network nodes but, in this case, we clearly note that energy scales. Finally, as we previously stated, the higher the network load, the lower the performance (e.g. higher PER, lower goodput, and higher energy consumption).

V. Conclusions

In this paper, we discuss cooperative communication on medium access layer for underwater acoustic sensor networks. We also present COPPER, a novel cooperative MAC protocol for UWSNs. Our cooperation technique is based on a SR ARQ scheme and incorporates the error signaling and retransmission of messages into the medium access control. Nodes who would, otherwise, be idle are responsible for failed messages retransmission. Our simulation results show an improvement in the packet loss rate and goodput metrics, with small impact on energy consumption. More specifically, synchronous COPPER achieves a reduction of 28.32% in packet loss rate in the best-case scenario. The proposed protocol performs better at mid to lower network loads, which corresponds to most underwater sensor networks applications [37]. Nevertheless, it still retains gains at higher network loads.

Future work includes the study of different relay selection techniques as well as the cooperation using other MAC protocols, besides implementing them in a real environment.

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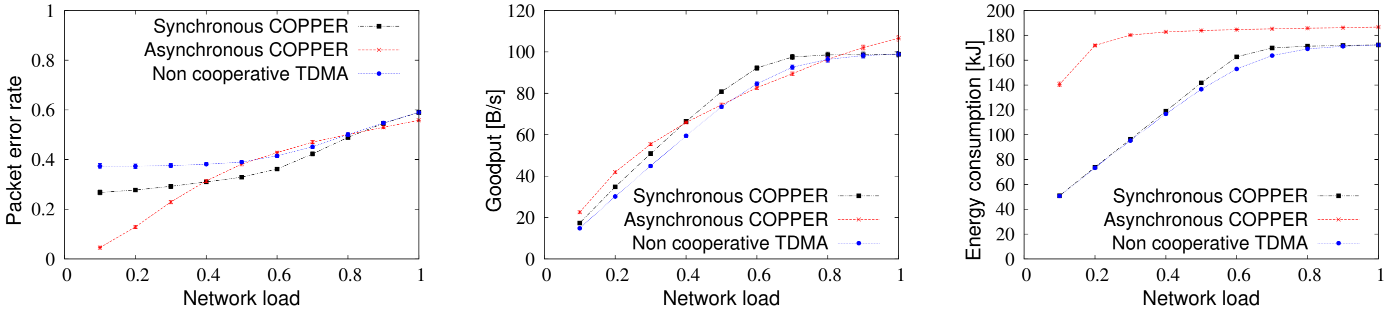
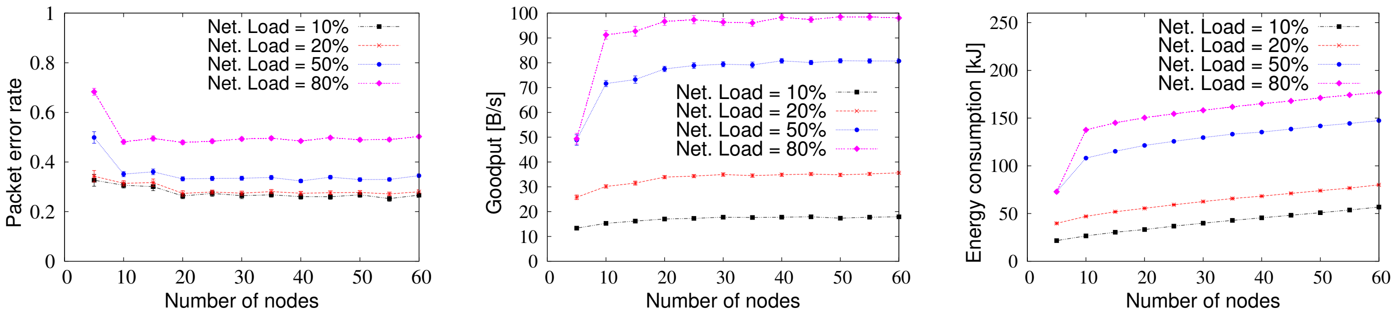


(a) Packet error rate. (b) Goodput. (c) Energy consumption.

Fig. 4: Evaluating UWSN performance for a 50 nodes network size.



(a) Synchronous COPPER PER. (b) Synchronous COPPER Goodput. (c) Synchronous COPPER energy.

Fig. 5: Synchronous COPPER scalability.

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