Decentralized space-propagation-aware channel access for wireless underwater swarm of AUVs

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***Abstract*—Long propagation delay of acoustic signal has long been considered the nemesis of wireless underwater communication. This paper proposes a novel space-propagation-aware Medium Access Control (MAC) protocol for swarm of Autonomous Underwater Vehicles (AUV). We show that, with proper design, we can take advantage of propagation delay, and improve underwater channel utilization in a way that is not possible in terrestrial wireless networks. The proposed MAC protocol leverages a unique spatial-temporal property of acoustic medium, enabling a fully decentralized channel access for multiple underwater nodes, while maintaining zero packet collisions at high traffic. The results from simulations and real experiments show that the protocol outperforms contention-based, and contention-free channel access schemes in terms of scalability, and energy consumption, achieving up to 50% gain in network throughput. In addition, the proposed scheme does not require prior knowledge about network topology, and it can successfully operate in highly dynamic networks without synchronization overhead. This makes the protocol a practical, and efficient solution for densely deployed underwater networks, such as swarm of AUVs.**

***Index Terms*—UWSN, TDMA, ALOHA, token ring, AUV swarm, TSP, MAC, spatial-temporal effect**

I. Introduction

Underwater wireless sensor networks (UWSNs) are currently receiving significant attention and are rapidly emerging as a prominent field within wireless communications. This growing interest is primarily attributed to the unique opportunities they offer for marine industrial and environmental applications, including oceanographic research, environmental monitoring, marine pipeline inspection, tsunami early warning, underwater exploration, and much more.

As the underwater robotics industry continues to evolve, the concept of an underwater swarm, comprising tens or hundreds of mobile autonomous robots, is gaining traction. This technology holds great promise for ocean exploration. To ensure its success, it is vital to develop robust protocols that can adapt to the unique conditions of the underwater wireless channel and facilitate efficient underwater communications.

In this paper, we present a Medium Access Control (MAC) scheme designed for the dense and dynamic UWSN, with a goal to maximize the efficiency of the underwater acoustic channel. Instead of viewing the long propagation delay - a significant research challenge in UWSN [1] - as a hindrance, we have leveraged it to enhance network throughput. Our proposed MAC protocol exploits the *spatial-temporal* property of the underwater channel, enabling fully decentralized collision-free communication in a token-ring fashion.

The content of the paper is structured as follows: Section II describes current state-of-the-art MAC protocols for wireless underwater networks, and for the underwater swarms in particular; in Section III we concentrate on a spatial-temporal property of underwater channel, and describe how this property can be used for efficient medium access; Section IV presents system design of the proposed protocol, as well as a formal description of the problem presented as a special case of Traveling Salesman Problem (TSP); in Section V and VI we evaluate the algorithm using NS-3 simulations and real experiments. Section VII presents conclusion and future work.

II. Related Work

There are two types of MAC protocols. The first is *Contention-based* protocols. The examples are [2], [3]. This class of protocols has two main advantages: 1) no control messages and synchronization are required; 2) data packets are sent immediately with minimum delay. These two factors reduce energy consumption (the nodes may remain in a sleep or standby mode when there is no traffic), improve network scalability without careful network planning, and achieve good performance under bursty traffic. This makes contention-based protocols suitable for UWSNs with low channel capacities and energy constraints. Since contention-based protocols send data packets arbitrarily to the channel, they do not guarantee collision-free transmission. Therefore, a major downside of this type of access is poor performance under high and persistent traffic.

The other type, *Contention-free* methods, focuses on proactive resource allocation of a channel. That is, every node is assigned a portion of guaranteed *collision-free* access opportunity. Common allocation strategy uses a *time domain*, represented by TDMA types of protocols [4]. Other approaches include FDMA, OFDMA and CDMA [5], [6]. Contention-free methods usually require prior knowledge about a network to achieve fair resource allocation. It typically involves the transmission of control messages that take up a certain portion of channel resources. In scope of UWSNs and underwater swarms, the relevant contention-free protocols have

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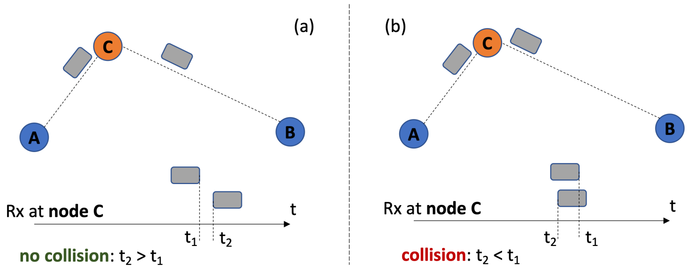

Fig. 1. Spatial-temporal effect in: a) underwater; b) RF channel

been studied in [7]. Some of these protocols rely on cluster-based algorithms to establish reliable transmission slots, while the others use handshaking-based mechanisms [8] to obtain collision-free transmission opportunities.

In underwater acoustic communication, a significant part of signal latency is contributed by a propagation delay, since the signal is carried out by acoustic waves. AST-TDMA protocol presented in [7] proposes a contention-free TDMA-based channel access for underwater swarm of nodes. Using topology information of a network, the authors propose a transmission algorithm for the nodes, that adjusts the duration of a TDMA slot, based on the distance between current and next sender. AST-TDMA outperforms a conventional TDMA scheme in terms of channel utilization.

Our protocol is inspired by AST-TDMA, and logically continues the work by introducing an algorithm for optimal transmission schedule, and proposing an enhanced channel access procedure under low traffic. The protocol name is TRUMAC - Token Ring based Underwater MAC, since it relies on data-token transmissions under high traffic.

III. MAC Protocols and Underwater Channel

Underwater acoustic communication is different from the terrestrial RF counterpart in two significant ways. First, the propagation delay of acoustic signals is *five orders of magnitude* higher than that of RF signals. The speed of sound underwater is around 1500 *m/s*, while the RF wave propagates at the speed of light, *i.e.* $3{\cdot}10^8$ *m/s*. Second, transmitting an acoustic signal takes substantially more power than the RF signal. For example, a conventional WHOI underwater modem consumes 60*W* of power in the transmission mode [9], while a RF transmitter takes only 48 *mW* of power [10].

These two factors must be considered when designing an efficient MAC scheme for UWSNs. The *energy-consumption* factor puts a limit on control overheads since it would have significant consequences on a network's lifetime. Thus, network controls, such as handshakes, synchronization, and negotiation for channel resource allocation, must be reduced to a minimal amount. The *long-propagation* factor has long been considered the nemesis of the UWSNs, since it makes CSMA-based and handshaking-based MACs highly inefficient. However, this work shows that the long-propagation factor can also present unique opportunities for collision-free access, which is not feasible in the terrestrial world. The next two subsections describe this effect in detail.

A. Spatial-temporal property

The *spatial-temporal* property can be described as the diversity in propagation delays, caused by the distance differences between pairs of nodes, and the fact that the propagation delay is often more significant than the transmission delay in the underwater channel.

Consider three nodes A, B and C sharing the same communication channel, with node C being closer to node A than to node B, as shown in Fig. 1. Nodes A and B each simultaneously send an equally sized packet to node C. Let's define t_1 to be the end of the reception time of a packet from A to C and t_2 to be the start of the reception time of a packet from B to C. Fig. 1 compares the outcomes of the same scenario in (a) an underwater wireless network, and (b) in a terrestrial RF network.

Due to high propagation delay in the acoustic channel, and the fact that Node A is closer to Node C, we observe the propagation delta that results in $t_1 < t_2$ at Node C for Fig. 1(a). This phenomenon also results in *collision-free* reception of the two packets, even though both packets had been sent exactly at the same time. In contrast, Fig. 1(b) shows the same scenario with the RF link, where a negligible propagation delay results in almost zero propagation diversity. This causes the expected collision at Node C.

The *spatial-temporal* property reveals certain research opportunities in designing MAC protocols for UWSNs, making many terrestrial-based MACs not efficient underwater. For example, under the scenario in Fig. 1, a CSMA-based protocol would be inefficient, because the fact that the channel is overheard busy at some location in a network does not indicate that an immediate transmission would cause a collision at another part of the network.

B. Token-based collision-free access

In this subsection, we show how token-ring-based access can provide higher utilization of an underwater channel, which is not achievable by state-of-the-art TDMA.

Imagine five nodes, A, B, C, D, and E, sharing an underwater channel. Each node transmits exactly 1 packet, following a pre-defined transmission sequence: A $\rightarrow$ B $\rightarrow$ C $\rightarrow$ D $\rightarrow$ E $\rightarrow$ A, as depicted in Fig. 2. This sequence, where each node transmits a packet right after the reception of the previous one, has been proven to be successful.

The timing diagram in Fig. 2 illustrates five consecutive transmission events (green and numbered packets) starting from node A. The corresponding reception events are shown as orange packets. It's important to note that despite the overlap in transmission, there is no collision. This collision-free nature of the transmission is a key feature of our proposed solution, ensuring the reliability of the system.

It can be noted that node E keeps receiving packets from the other nodes back-to-back, with minimum delay between

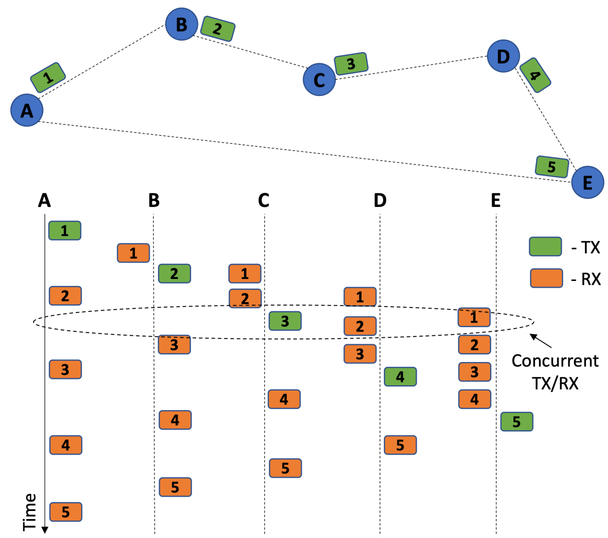

Fig. 2. Collision-free transmission in token-ring fashion: dashed ellipse shows concurrent RX/TX events in shared underwater channel

packet receptions. This becomes possible due to the spatial-temporal property described earlier. Given a topological formation of the nodes, we can arrange a token-ring schedule that would minimize the duration of a transmission round. Thus, more transmissions can be triggered per second. This increases the channel utilization, which is confirmed by network simulations and real experiments conducted in Sections V and VI.

To maximize channel utilization, it is crucial to develop an optimal transmission schedule for a particular network topology. In the scenario depicted in Fig. 2, it is obvious that the optimal transmission schedule is A → B → C → D → E → A, because this schedule minimizes *total propagation delay* of a transmission round of 5 packets. Any other transmission sequence (schedule) would only increase the delay. In the next section, we formalize this problem as a special case of TSP [11]. We show that maximum channel utilization can be achieved with a transmission schedule represented by a minimum Hamiltonian cycle in a graph $G(v)$, with edge weights defined as propagation delays of network links.

IV. System Design

In this section, we propose the design of a MAC protocol called TRUMAC (**T**oken-**R**ing **U**nderwater **MAC**), based on the token-ring transmission described earlier. The operation of TRUMAC can be split into two parts: 1) basic channel access operation, where packets are sent in a token-ring fashion according to a transmission schedule; 2) contention-based access, needed to handle low and bursty traffic efficiently.

A. TSP and token selection

Traveling Salesman Problem in graph theory focuses on finding a minimum Hamiltonian cycle in a graph [11]. In the context of token-ring transmission, a network can be represented as an undirected graph $G(v)$ with edge weights representing a propagation delay between the vertices. Thus,

TABLE I
TSP algorithms

	Brute-force	**Nearest neighbor**	**Random selection**
Complexity	O(n!)	O(n^2)	O(1)
Feasible # of nodes	<9	<200	unlimited
Optimality	100% optimal	sub-optimal	50% from optimal (improves over time)
Network information	global	global	local

TSP algorithms can be applied to find a schedule that outputs a transmission round with minimum total propagation delay. In this work, we consider a *1-hop* network (i.e., a swarm of AUVs), where all the nodes are located within a maximum transmission range from each other.

Since TSP is a well-known NP-hard problem, a brute-force algorithm is only applicable to a very limited number of nodes. Instead, in this paper we consider two sub-optimal solutions to run TSP, and output a sub-optimal transmission schedule: 1) *nearest-neighbor* algorithm [11]; 2) *random selection*. Random selection picks the next sender arbitrarily among neighbors. Thus, it does not require global topological information, which makes it more practical. The nearest-neighbor method requires global information, but it can achieve close to the optimal solution with $O(n^2)$ complexity. A summary of the observed TSP algorithms is presented in Table I.

The following two subsections describe two main operational modes of TRUMAC protocol: basic channel access and contention-based access.

B. Basic channel access algorithm

The basic operation employs token-ring access. Two TSP algorithms were utilized to decide the next token holder: the nearest-neighbor algorithm and random neighbor selection. The motivation behind selecting these algorithms is driven by their properties described in Table I. In particular, the nearest-neighbor algorithm is able to provide a close-to-optimal transmission schedule while supporting a sufficient amount of nodes. The random selection returns a less efficient schedule but does not require global topological information. This becomes a significant advantage in real-world deployments since the algorithm would not require extra overhead to collect topological information. In addition, random selection may improve the output result over time if an adaptive mechanism is applied that learns about the previous selection of senders.

The basic channel operation is presented in Alg. 1. The algorithm starts by having the network nodes generate a transmission schedule, which could adopt either the nearest-neighbor TSP algorithm or the random selection algorithm. Then, a network node initiates the data transmission by sending the first data packet, with the next-sender information attached. Next, the network nodes overhear packet transmissions and record the next-sender information that has already been used.

Algorithm 1 Basic channel access algorithm

Initialize list of available nodes $L = \{0, 1, 2, ..., N\}$, where N - max. number of nodes
Initialize $states$ of all nodes to RX
Initialize list of overheard nodes $M = \{\ \}$
Initialize selection algorithm $S = \{ Random, Nearest\ neighbor, etc. \}$
if $ID(node) == ID_{start}$ **then**
  $State(node) = TX$
end if
while $L \neq M$ **do**
  if $State(node) == TX$ **then**
    Select next sender i from L, so that $i \notin M$, according to S
    Generate and attach header with $ID_{next\ sender}$
    Send packet/token
    $State(node) = RX$
  end if
  if $State(node) == RX$ **then**
    Update list of overheard nodes M
    if $ID(node) == ID_{next\ sender}$ **then**
      $State(node) = TX$
    end if
  end if
end while

Afterward, when the next-sender receives the data packet, it selects the new next-sender from the list of available senders and sends its data packet further. This continues until all nodes in a network have their data packets sent. Then, the transmission round ends, and a new round starts.

C. Contention-based access

The basic channel access assumes that every node in a network should always have a data packet ready to be sent. While this is true when the application traffic is high and persistent, this assumption breaks when a network experiences low or bursty traffic, which is common in UWSNs. In case a node has no data packet to send, the basic channel algorithm will need to send an "empty" packet (i.e., a token) to keep the transmission schedule going. Consequently, this will lead to an extensive energy drain in a network since the nodes would waste energy sending empty tokens and polluting the channel with unnecessary interference.

To avoid this behavior, in addition to the basic token-ring operation, we introduce a contention-based access method, that is triggered when the user traffic is low. This method, while being effective, is also simple to implement, making it a practical solution for UWSNs. For example, if a next-sender in the transmission schedule does not have a data packet to send, the transmission schedule breaks, and the nodes stop transmitting for a pre-defined time interval. When a data packet comes from the application, the nodes start to contend for a new transmission schedule by sending packets in ALOHA mode. Whatever node sends its data packet first - wins, *i.e.* a new transmission schedule is established, with the rest of the nodes following the new schedule.

Algorithm 2 Contention-based modification to the basic algorithm

if $State(node) == TX$ **then**
  if data packet does not exist **then**
    Backoff for time T
    Return to TX state
  end if
  if data packet exists **then**
    Proceed to **Alg. 1**
  end if
end if

It can be noticed that the introduction of contention-based access breaks the collision-free feature of the protocol. Indeed, when nodes enter the backoff phase for random time T (see Alg. 2), several nodes may send data packets at similar times, causing packet collisions. However, the contention-based feature is triggered only when the traffic is low, thus - the probability of collision remains low as well. This is confirmed by network simulations in Section V. When the traffic intensifies, the contention-based access is naturally transitioned to the basic collision-free operation. In addition, the energy savings from the contention-based access significantly outweigh the adverse effects of collisions.

V. Simulation Experiments

In this section, the protocol is evaluated in the NS-3 network simulator [12] with Aqua-Sim-NG [13] plugin, which enables simulations of underwater network environments. The following two subsections evaluate the performance of the protocol's schedule selection algorithm, and compare its network performance with TDMA [4] and ALOHA [2] channel access.

In the simulation scenario, a number of nodes were arbitrarily deployed in a circular area within a maximum transmission range, representing a swarm of nodes traveling towards random directions with low: 0.5 *m/s*, and medium: 3 *m/s* speeds. Poisson distribution was chosen to simulate application traffic similar to such kinds of applications. The channel parameters were chosen based on typical UWSN scenarios. A more detailed list of simulation parameters can be found in Table II.

A. Algorithm evaluation

Fig. 3 shows the performance of the *nearest-neighbor* TSP algorithm against the *random selection*, under low and medium velocities. With the fixed amount of traffic, the number of nodes in a network gradually increases, showing a Packet Delivery Ratio (PDR) - a ratio between received and generated packets during the simulation.

It can be noticed, that both random selection and greedy algorithms show similar performance when the speed of nodes is medium. This is explained by a dynamic topology of a network, that makes the transmission schedules generated by the greedy method less efficient, as the network operates and

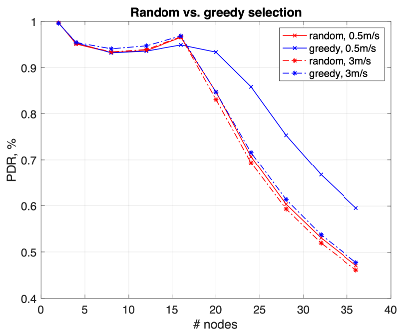

Fig. 3. PDR under different velocities (%)

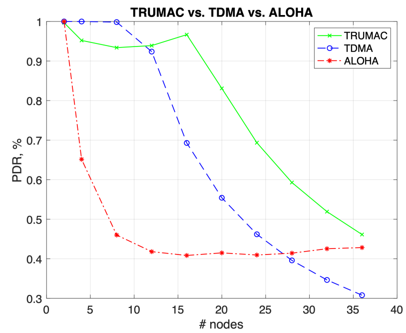

Fig. 4. Packet Delivery Ratio (%)

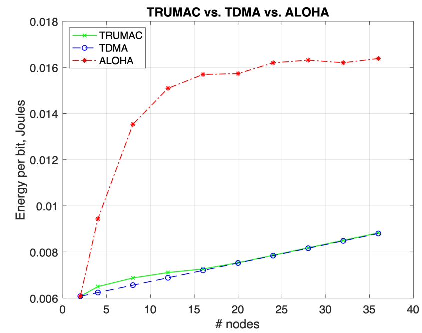

Fig. 5. Energy per bit (joules)

changes its formation. In contrast, the random selection makes a decision locally, independently from the network topology. When the speed of the nodes is low, the nearest-neighbor method shows better performance than the random selection. This is because the optimal schedule persists throughout the network's operation, since the nodes are nearly static.

Both greedy and random selections demonstrate similar results under medium network mobility. Considering the importance of fully decentralized network operation in the context of AUV swarm, the random selection becomes a more suitable method for actual deployment. Therefore, we consider the random selection as the default algorithm for TRUMAC protocol, comparing its performance with the relevant protocols in the next subsection.

B. Protocols comparison

In additional round of simulations, TRUMAC protocol with random selection was compared with TDMA and ALOHA. These protocols were chosen because: 1 - both protocols are widely used in UWSNs applications; 2 - each of them represent a different class of protocols, i.e. contention-based access for ALOHA, and contention-free access for TDMA. The velocity of the nodes was fixed to medium (3 *m/s*).

Fig. 4 shows the scalability of the protocols in terms of PDR. TRUMAC shows the best results, capable of accommodating up to 16 nodes above the 90% PDR threshold. ALOHA's performance is far inferior compared to the other two protocols. Starting from 4 nodes, ALOHA causes a significant amount of collisions as the number of nodes increases. TDMA performs better than ALOHA, however, its PDR quickly degrades after 14 nodes.

TRUMAC outperforms TDMA in terms of PDR, because the protocol tries to find a transmission schedule that minimizes the delay between the nodes' positions. In contrast, TDMA has a fixed slot duration that must accommodate maximum latency between any pair of nodes in a network, to provide collision-free operation. This means, on average, a total duration of a transmission round in TDMA is greater than an average transmission round in TRUMAC. Therefore, an average waiting time until a packet is transmitted is less for TRUMAC. This allows the protocol to achieve higher channel utilization with collision-free access leveraging the spatial-temporal property of the channel described earlier.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulation time (seconds)	1000
Application traffic	Poisson, 0.15 pkts/sec
Number of nodes	2 - 36
Packet length (bytes)	100
Channel speed (bps)	10000
Packet Tx time (ms)	80
Sound speed (m/s)	1500
TSP algorithms	Nearest-neighbor, random
Topology	Random 1-hop deployment
Mobility model	Random waypoint

Fig. 5 shows how much energy each of the protocols spends in order to receive a bit of information. ALOHA appears to be the most energy-hungry, since the data packets are transmitted immediately after they appear at the MAC layer. Since the major part of energy consumption is taken up by transmission events, ALOHA consumes the most power. As for TRUMAC and TDMA, the protocols show similar results, with TRUMAC consuming slightly more power when the amount of nodes is below 20. This can be explained by two factors: 1 - TRUMAC tends to use the contention-based access when the traffic is low so, some packets get collided and lost; 2 - TRUMAC makes more transmissions per round than TDMA, which increases the energy consumption.

VI. Testbed Experiments

Outside of NS-3 simulations, TRUMAC protocol was also implemented in the Aqua-Net software [14], and tested with BlueBuzz [15] acoustic modems. Aqua-Net provides implementations of transport, routing, and MAC protocols for underwater communications. BlueBuzz acoustic modem integrates an onboard computer for data encoding, an onboard microcontroller (MCU) for Frequency-Hopping Shift Keying (FHSK) modulation, an analog board with a transducer.

An experiment was conducted in an acoustic tank with four BlueBuzz modems, creating a 4-node fully connected static network. Each node ran the Aqua-Net communication stack,

TABLE III
EXPERIMENT PARAMETERS

Parameter	Value
Number of nodes	4
Average number of TX events per node	5400
Application Layer	Periodic sender app: from 1 to 100 bps 10% jitter
Routing Layer	Static, fully connected
MAC Layer	TRUMAC vs. ALOHA
PHY Layer	BlueBuzz modem, max speed: 151 bps

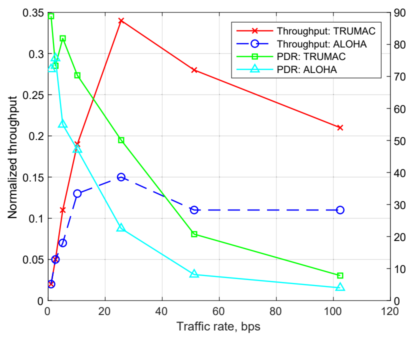

Fig. 6. Normalized throughput and PDR from real experiment

with the application layer generating fixed-size messages sent periodically. TRUMAC and ALOHA protocols were compared at the MAC layer. The details of the experiment setup are presented in Table III. In the experiment, two performance metrics were evaluated: PDR and the normalized throughput (in relation to the maximum data rate that the PHY-layer modem supports).

Fig. 6 shows the normalized throughput and PDR. It demonstrates that TRUMAC outperforms ALOHA up to *2x times*, achieving higher channel utilization. TRUMAC ensures more packet receptions with fewer collisions/drops. At low data rates, the performance of both protocols is comparable, as TRUMAC tends to shift to contention-based mode, which permits a certain degree of collisions and packet drops. However, as the traffic rate escalates, ALOHA swiftly saturates the channel, leading to increased collisions, while TRUMAC transitions to more efficient contention-free operation.

VII. Conclusion & Future Work

TRUMAC protocol implements a token-ring based transmission scheme, and provides an efficient way of accessing an underwater channel shared by multiple nodes. Our study indicates that, by leveraging the spatial-temporal property of the underwater channel, TRUMAC outperforms conventional TDMA and ALOHA schemes, accommodating more nodes and achieving higher performance in terms of PDR and network throughput. In terms of energy consumption, TRUMAC outmatches ALOHA and shows a performance similar to TDMA. In addition, TRUMAC does not require network synchronization, and it operates fully decentralized, which makes the protocol practical for real-world deployments.

In considering future developments, various directions for improving the protocol present themselves. First, further research may be undertaken to refine the algorithms utilized in the determination of the optimal transmission schedule. This may encompass an exploration of more sophisticated TSP algorithms, as well as the potential introduction of an adaptive algorithm to reinforce the random selection approach. Second, a thorough examination of the contention-based aspect of the protocol is warranted to enhance its PDR in low traffic scenarios. Additionally, comprehensive performance evaluations should be conducted in both simulated and real-world environments to scrutinize the protocol's energy-related attributes and its scalability.

Acknowledgment

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