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MLOPS: A SIC-Based Minimum Frame Length With Optimized Power Scheduling for UANs

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ABSTRACT Due to the large propagation delay and scarce spectrum resource of the underwater wireless acoustic channels, it is essential to design efficient and reliable multiuser scheduling scheme for underwater network communication systems. The successive interference cancellation (SIC) technology that supports multiple parallel transmissions can improve spectrum efficiency, which is vital for the underwater acoustic networks (UANs). The SIC technology has been widely studied in the underwater network communication systems. However, there is no appropriate technology solving the link scheduling problem in the SIC-based UANs. In this paper, we propose a link-scheduling model for SIC-based UANs and formulate the problem of minimizing the transmission delay and overall network power consumption by combining transmitters scheduling and power allocating. We also present a polynomial-time algorithm named UMLOPS with the complexity of $O(n)$ for unified traffic load, and for weighted traffic load, we present a universal algorithm named WMLOPS with the complexity of $O(n^3)$, where n denotes the number of source nodes. The extensive simulation results reveal that both scheduling frame length and aggregate power consumption of MLOPS significantly outperform those of the existing time-division multiple access protocols in underwater sensor equipped aquatic swarm architecture networks.

INDEX TERMS Link scheduling, power allocating, minimum frame length, successive interference cancellation, underwater acoustic networks.

I. INTRODUCTION

Underwater Acoustic Networks (UANs) have been recently proposed for improving ocean exploration and fulfilling the needs of a multitude of underwater applications [1]. In underwater acoustic environment, the design of protocols encounters two major challenges: long propagation delay and scarce spectrum resource [2], [3].

Due to the severe frequency-dependent attenuation of the acoustic signal on high frequencies, available communication frequencies in water are strictly limited, usually from tens of hertz to hundreds of kilohertz [5]. The majority of artificial acoustic systems utilize the frequency band from 1 kHz to 40 kHz making the acoustic channel crowded [6]. Therefore, the spectrum is a scarce resource in underwater acoustic systems. Moreover, due to high environmental noise at low medium frequencies in UANs, the available acoustic bandwidth depends on transmission distance [4]. In general, the data rate of underwater acoustic modem can hardly exceed 100kbps in a long-range system that operates over several tens of kilometers [2].

Due to the scarce spectrum resource of underwater wireless acoustic channels, it is essential to design efficient and reliable multiuser scheduling scheme for underwater network communication systems. The Non-Orthogonal Multiple Access (NOMA) schemes are introduced to approximate the Shannon channel capacity. Different from the conventional orthogonal multiple access technologies, the NOMA can accommodate much more users via a non-orthogonal resource allocation. At present, there are two dominant NOMA categories schemes, power-domain multiplexing and code-domain multiplexing [7]. The successive interference cancellation (SIC) is a typical power-domain multiplexing scheme which can serve multiple users in the same time-frequency degrees of freedom by splitting them in the power domain. Successive interference cancellation (SIC)

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is a physical layer technique which implements multiple packet reception [8]. SIC enables receiver to detect more than one transmission at once. The receiver decodes received signals successively with an iterative process. The strongest signal from the composite received signal is decoded and removed iteratively. Compared to other new techniques for interference cancellation such as ZigZag decoding [9] and analog network coding [10], SIC does not need any information about the colliding packets. Beyond the larger channel capacity, the SIC is easy to implement in engineering, which effectively overcomes the near far effect. Therefore, the SIC technology has been recognized as a promising candidate for multiuser scheduling in fifth-generation (5G) cellular systems [11]. Since, the SIC technology can improve spectrum efficiency, it has become the focus of research on the UANs in recent years. So far, many scholars have proposed a variety of underwater acoustic receiver supporting SIC [12]– [16].

The link scheduling problem is critical in the UANs as it plays an important role to achieve high quality of service (QoS). Recent advances in underwater acoustic SIC communication technology showed a possibility of improving the spectrum efficiency. The SIC technology cannot eliminate conflicts unless transmissions are properly scheduled. In order to achieve a maximal effectiveness of SIC technology, a careful transmission scheduling is required. However, up to our knowledge, there is no appropriate technology solving the link scheduling problem in the SIC-based UANs.

The Sensor Equipped Aquatic Swarm architecture (SEA Swarm) shown in Fig. 1 is a typical network model for data collection in underwater sensor networks [17]. The SEA Swarm consists of a sink node and few source nodes [18]. The source nodes are deployed in the water and laid to sense environment and sensory data are transmitted and aggregated in the sink node. The underwater source nodes are deployed in different layers and can passively move due to the water currents in the horizontal plane and vibrate slightly in the vertical direction. In this paper, we consider the single-hop uplink SEA Swarm networks. According to the different data loads generated by source nodes in the UANs, there are two cases, unified and weighted traffic loads. Unified data is generated in duty cycle [19], while weighted data is generated by burst traffic [20]. In the unified traffic load, every source node periodically generates data packet with the same frequency, and the amount of data packets produced by source nodes is the same. On the other hand, in the weighted traffic load every node in the network produces data periodically with the same frequency, but the amount of data packets produced by source nodes differs.

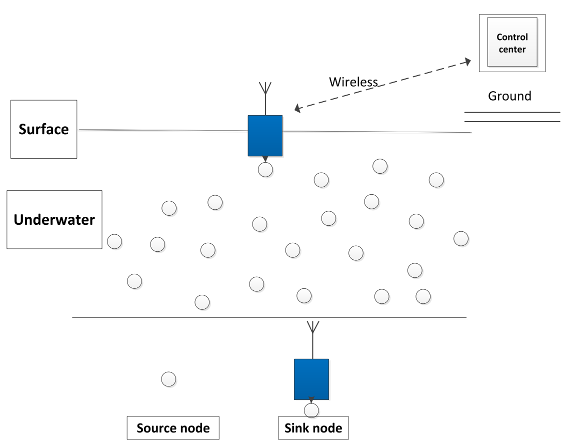

FIGURE 1. SEA Swarm network model.

Here, we consider a single-hop network with n source nodes (sender) and a sink node (receiver) which is equipped with a SIC decoder. In order to fully develop SIC and improve the real-time performance, the SIC is combined with the TDMA and the polynomial-time algorithms are proposed to minimize uplink scheduling frame length for both unified and weighted traffic load UANs. Moreover, for a minimum frame length, a power optimized schedule algorithm is proposed by joint optimization of senders scheduling and power allocating to minimize aggregated power consumption. Since the K-SIC modem where K is larger than 2 may use a lot of power to transmit data, it has not been widely applied yet [12], [13]. We propose the link scheduling model for SIC-based UANs. In addition, we present algorithms for minimizing the frame length with optimized aggregate power. The contributions of this paper are as follows:

(1) We firstly propose the link scheduling model for SIC-based UANs.

(2) With the assumption that sensor nodes can change their transmit power continuously and SIC can decode without remain, we formulated the problem of minimum frame length uplink scheduling in the 2-SIC based UANs, and presented an explicit formula for the minimum uplink scheduling length.

(3) Without above assumptions, we present a polynomial-time algorithm named UMLOPS with complexity of $O(n)$ for unified traffic load by joint power setting and scheduling in 2-SIC based UANs, an universal algorithm named WMLOPS with complexity of $O(n^3)$, where n is the number of source nodes, for weighted traffic load.

The remainder of this paper is organized as follows. In Section II, we review the related works. In Section III, we present the system model and motivation for this paper. In Section IV, we propose the MLOPS for 2-SIC based UANs. In Section V, we present the extensive simulations. Finally, we conclude this paper in Section VI.

II. RELATED WORKS

Based on the mechanism for collision avoidance, the MAC protocols in UANs can be classified into two categories: contention-based protocols and contention-free protocols. However, due to the long propagation delay, the contention-based protocols suffer from serious conflicts especially in the high-traffic networks. The contention-free MAC protocols are normally based on time-division multiple access (TDMA), where each node is allocated with a unique time slot for transmission. Therefore, most scholars believe TDMA-based MAC is very promising [21].

To overcome spatial-temporal uncertainty, Hsu *et al.* [22] proposed a Spatial-Temporal MAC Scheduling protocol (ST-MAC) for energy saving and throughput improvement. In the ST-MAC, the authors explicitly described the conflict delays among transmission links using the Spatial-Temporal Conflict Graph (ST-CG) and ST-MAC model as a vertex-coloring problem of ST-CG.

Kredo *et al.* [23] presented a scheduled, collision free TDMA-based MAC protocol, named the STUMP, which leveraged the node position diversity and long propagation delay of an underwater channel. The STUMP uses information on propagation delay to overlap node communication and increase network throughput.

For ad hoc UAN networks that support high-traffic broadcast communication, Diamant *et al.* [24] introduced a new hybrid spatial reuse time-division multiple-access protocol (HSR-TDMA), which is the combination of spatial reuse concept and exploitation of direct sequence spread spectrum. By tracking a time-varying network topology, the HSR-TDMA adaptively optimizes the set of active communication nodes and overcame the near-far, flickering, and formation of islands problems in UANs.

Ma and Lou [25] identified the spatial-temporal link scheduling problem in UANs and proposed a new slotted spatial-temporal conflict graph constructed based on the network topology, conflict relationship, propagation delay and link transmission delay. They presented the efficient scheduling algorithms that have theoretical performance bounds for both unified and weighted traffic load scenarios.

Toward an efficient approach, Zhu *et al.* [26] analyzed the impact of low transmission rates and long preambles on random access-based MAC and handshake-based MAC. Based on the nodal throughput and collision probability models for representative solutions of these two MAC protocol categories, the authors stated that the time sharing-based MAC is quite promising. Thereby, they introduced a Cluster-based On-Demand Time Sharing MAC solution (COD-TS) and developed a throughput model for it.

Anjangi *et al.* [27] proposed a joint scheduling and power control algorithm for arbitrary networks, and demonstrated performance improvement for a large number of random network geometries. With the aid of power control, this algorithm reduces energy consumption and limits interference. In addition, they investigated achievable throughput in randomly deployed underwater acoustic networks by controlling transmission power.

In [28], a heuristic interference graph-based time division multiple access (IG-TDMA) protocol for UANs was introduced. Using the communication network topology modeled as a three-dimensional (3D) scenario and considering the mobility of sensor nodes, authors designed a heuristic interference graph clustering algorithm and formulated the interference scenario as a dynamic interference graph according to the nodes' position distribution and preset interference-free threshold.

To increase the network throughput of spatial reuse, Diamant *et al.* [29] leveraged the near-far effect caused by large propagation delay in UANs and proposed a near-far spatial reuse TDMA (NF-TDMA) algorithm for both contention-free and opportunistic transmissions. The proposed NF-TDMA represents a combination of centralized schedule and distributed schedule used to obtain an optimal channel utilization for a given interference cancellation capability of the system that can opportunistically utilize the information on occurrences of near-far scenarios in UANs to maximize the channel utilization.

Successive Interference Cancellation(SIC) has been used as multi-user detection technique in NOMA [30]. In recent years, many works focus on applying SIC in 5G [11], ZigBee [31] and Wireless Local Area Networks(WLAN) [32]. Scheduling for exploiting the capability of SIC has been intensely investigated. Reference [33] proved that minimum frame length scheduling without power allocation is NP-hard. References [35]– [37] presented frameworks to optimize SIC on fairness, power and minimum flow throughput respectively. To our knowledge, none of the research solved the minimum frame length problem for SIC scheduling in polynomial time.

Based on the above analysis, in order to improve network performance, scholars have put forward many TDMA-based MAC protocols recently. However, none of these protocols are designed by considering the characteristic of SIC underwater acoustic modem.

III. SYSTEM MODEL AND MOTIVATION

A. UNDERWATER ACOUSTIC CHANNEL MODEL

Equation (1) descripts signal to noise ratio (SNR) of underwater acoustic channel [38].

$$\mathrm{SNR} = \frac{P_{\mathrm{r}}}{P_N} = \frac{P_{\mathrm{t}}/A(d,f)}{P_N} = \frac{P_{\mathrm{t}}}{A(d,f)\,P_N} \tag{1}$$

In (1), P_{t} is the transmitting power, P_{r} is the received power, P_N is the noise power of underwater channel, and $A(d,f)$ is the attenuation function of underwater sound which is defined by:

$$A(d,f) = d^{\partial} a(f)^d \tag{2}$$

where d is the distance between transmitter and receiver in km, f is the carrier frequency of underwater acoustic channel in kHz, and $a(f)$ is the absorption coefficient of underwater acoustic channel; further, ∂ is the spreading loss factor, which is normally between 1 and 2, and it is set to 1.5 in this paper.

The acoustic path loss can be better described by the Thorp formula [37]:

$$10\log a(f)\,[dB/km] = \frac{0.11\cdot f^2}{1+f^2} + \frac{44\cdot f^2}{4100+f^2} + 2.75\cdot 10^{-4} f^2 + 0.003 \tag{3}$$

TABLE 1. Notation summary.

$A(\cdot)$	Channel loss function	$a(\cdot)$	Absorption coefficient
α	Remainder factor of SIC	$d(i)$	Distance between S_i and sink
	decoding		
f	Carrier frequency	K	SIC iteration limit
L	Frame length of a scheduling	$L_{\min}$	The minimum frame length of all available scheduling
λ	Decode SINR threshold of sink node.	$N_{w_s}(\cdot)$	Wave noise power
n	Total number of source nodes	n_l	Number of source nodes of which SIC level is l
P_{Int}	Power of interference signals	$P_L(i)$	SIC level of S_i
P_{MAX}	The up limit of transmitting power of all nodes	$P_{max\_t}(i)$	The maximal available transmitting power of S_i
$P_{\max\_r}(i)$	The maximal available received power of signal from S_i	P_N	Noise power
$P_r(i)$	Received signal power from S_i	$\tilde{P}_r(m)$	The minimum received power of the m th last decoded signal
$P_t(i)$	Transmitting signal power of S_i	p_{ij}	The minimum transmitting power of two simultaneous transmissions of vertices in scheduling graph
q_i	Number of time slots allocated to S_i in one frame	r_d	Depth of source node
S	Set of frame length of all available scheduling	S_i	The i th source node
$T_{recv}(i)$	Time that the sink begins to receive signal from S_i	$T_{tran}(i)$	Time that S_i begins transmission
$t(i,w)$	Whether the w th time slot is allocated to S_i	V	Velocity of sound under water
∂	Spreading loss factor		

In the UANs, the noise power P_N is mainly caused by sea waves when f is between 100 Hz and 100 kHz, which can be formulated as follows:

$$P_N = \frac{N_{w_s}(f)}{A(r_d, f)} \tag{4}$$

where r_d is the depth of the source node, w_s is the wind speed, and $N_{w_s}(f)$ is the noise power generated by the waves caused by the wind which can be defined by:

$$N_{w_s}(f) = \frac{10^{5+0.75 w_s^{1/2}} \cdot f^2}{(f+0.4)^4} \tag{5}$$

B. NETWORK MODEL

We consider the SEA Swarm network that consists of one sink node and n source nodes. The ith source node is notated as s_i and the transmission rate of s_i is fixed; s_i can continuously choose its transmit power in the range $(0, P_{max\_t}(i)]$, where $P_{max\_t}(i)$ denotes the maximal available transmitting power of node s_i. The transmitted signal power and received signal power of s_i are respectively labeled as $P_t(i)$ and $P_r(i)$. According to the underwater acoustic channel gain model, the relationship between $P_t(i)$ and $P_r(i)$ is defined by:

$$P_r(i) = A(d(i), f) \cdot P_t(i) \tag{6}$$

where $A(d(i), f)$ is the attenuation function of underwater sound and d (i) is the distance between source node s_i and receiver. In the SEA Swarm, the source nodes and sink node can passively move together with water currents in the horizontal plane and vibrate slightly in the vertical direction, and the distance between them is relatively fixed. For any node, the condition of correctly decoded data is defined by:

$$\frac{P_r(i)}{P_{Int} + P_N} \geq \lambda \tag{7}$$

where λ is the decoding threshold of the receiver. Equation (7) ensures that sink node is within a single-hop transmission range of the maximum transmission power of all source nodes in the network.

We assume that a perfect K-SIC decoder is installed in the sink, which means that at most K signals which transmit in parallel can be decoded and no any residual error are considered. In addition, we assume the sink node received β signals simultaneously and their received powers are $\{P_r(1), P_r(2), \ldots P_r(\beta)\}$. Without loss of generality, we assume $P_r(1) > P_r(2) > \ldots P_r(\beta)$. In our models, we only consider interferences that are generated by packet transmissions from other nodes in this network. As a result, all these interferences share the same frequency, which suggests that the sum of power of all interference reflects the total power of interference, i.e. $P_{Int} = \sum_i P_r(i)$. Under the classic model, any signal will be decoded successfully only if its signal to interference plus noise ratio (SINR) is not less than receiver decoding threshold λ. For any signal, the condition of correct decoding is given by:

$$\frac{P_r(i)}{\sum_{j=i+1}^{K} P_r(j) + P_N} \geq \lambda \quad 1 \leq i \leq K \tag{8}$$

We also assume that network is synchronized and scheduling scheme is TDMA-based, i.e. frame is divided into multiple time slots, and one or multiple source node can transmit within each time slot. Time slots discussed in following passages refer to receiving time slots, and transmitting time slots are derived as follows:

$$T_{tran}(i) = T_{recv}(i) - d(i)/V \tag{9}$$

where $T_{tran}(i)$ and $T_{recv}(i)$ denote transmitting time and receiving time of node s_i respectively. $d(i)$ is the distance between node s_i and the receiver and V is sound speed under water.

Syed and Heidemann [39] proposed a protocol named the Time Synchronization for High Latency (TSHL) and validate by simulations that TSHL can correct clock offset and skew in a reliable and efficient manner. Hence, time synchronization in our paper is realizable.

C. PROBLEM FORMULATION

To improve both time and energy efficiency, we firstly propose an uplink scheduling technology for the SIC-based underwater acoustic networks, named the Minimum frame Length with the Optimized Power Scheduling (MLOPS).

Since different data loads can be generated by source nodes in the UANs, we propose two MLOPS algorithms, one for unified traffic load and one for weighted traffic load. Therefore, the proposed MLOPS consists of unified minimum frame length with optimized power scheduling (UMLOPS) algorithm for unified traffic load and weighted minimum frame length with optimized power scheduling (WMLOPS) algorithm for weighted traffic load. We formulate the problem of minimizing the transmission delay and overall network power consumption for SIC-based UANs by combining transmitters scheduling and power allocating. In order to improve time efficiency, a transmitters scheduling scheme is proposed to minimize the uplink scheduling length for SIC-based UANs. Based on a minimum scheduling frame length in the transmitters scheduling scheme, a power allocating scheme is proposed to minimize the overall network power consumption. Thus, the uplink scheduling technology for the SIC-based underwater acoustic networks can be represented as follows:

1) A set of scheduling frame length for all scheduling policies satisfying SIC power conditions in equation (8) is denoted as S,

$$L_{\min} \in S, \quad \forall L \in S,\ L \geq L_{\min} \tag{10}$$

2)

$$\begin{aligned} &\text{minimize} \sum_{\mathrm{i}=1}^{\mathrm{n}} P_{\mathrm{t}}(i) \\ &s.t.\ L = L_{\min} \end{aligned} \tag{11}$$

where L is the scheduling frame length and $L_{\min}$ is the minimum scheduling frame length. In the case of the unified traffic load each source node will be scheduled once, and in the case of the weighted traffic load, each source node can be scheduled more than once. To get the minimum frame length, we arrange transmitting nodes into fewest groups where these nodes are able to transmit simultaneously. In this paper, we assume the uplink UAN consists of one sink node with the perfect K-SIC decoder and n source nodes that can set their transmit power $P_t(i)$ in the range $(0, P_{\max\_t}(i)]$ and their distance to the sink node is $d(i)$ $(i = 1 \cdots n)$.

We use $t(i, w) = 1$ to denote the wth time slot allocated to node s_i and $t(i, w) = 0$ for other situations. The scheduling should meet following restrains:

$$\sum_{i=1}^{N} t(i, w) \leq K \tag{12}$$

$$\sum_{j=1}^{L_{\min}} t(i, w) = q_i \tag{13}$$

where q_i denotes the number of time slots allocated to the transmitting node s_i in one frame.

Assume that sink node receives M signals simultaneously and their received powers are $\{P_{\mathrm{r}}(1), P_{\mathrm{r}}(2), \ldots, P_{\mathrm{r}}(M)\}$. Without loss of generality, we assume $P_{\mathrm{r}}(1) > P_{\mathrm{r}}(2) \ldots > P_{\mathrm{r}}(M)$. To decode all the signals correctly, the following conditions should be satisfied:

$$\frac{P_r(1)}{\sum_{i=2}^{M} P_r(i) + P_N} \geq \lambda, \frac{P_r(2)}{\sum_{i=3}^{M} P_r(i) + P_N} \geq \lambda, \cdots, \frac{P_r(m)}{\sum_{i=m+1}^{M} P_r(i) + P_N} \geq \lambda, \cdots, \frac{P_r(M)}{P_N} \geq \lambda \tag{14}$$

The minimal solution of (14) can be found by (15):

$$\begin{aligned} &\tilde{P}_{\mathrm{r}}(M) = \lambda P_N, \tilde{P}_{\mathrm{r}}(M-1) = \lambda(P_N + \tilde{P}_{\mathrm{r}}(M)), \ldots, \\ &\tilde{P}_{\mathrm{r}}(\mathrm{m}) = \lambda(P_N + \sum_{i=m+1}^{M} \tilde{P}_{\mathrm{r}}(i)), \ldots, \tilde{P}_{\mathrm{r}}(1) = \lambda(P_N + \sum_{i=2}^{M} \tilde{P}_{\mathrm{r}}(i)) \end{aligned} \tag{15}$$

When multiple signals are received simultaneously, if a signal is decoded as the mth last signal, the received power of that signal must not be less than $\tilde{P}_r(m)$. The maximum transmission power of the source nodes is $P_{\max\_t}(i)$ $(i = 1 \cdots n)$. The distance between each source node and sink node is $d(i)$ $(i = 1 \cdots n)$. Hence, the maximum received power is defined by:

$$P_{\max\_r}(i) = \frac{P_{\max\_t}(i)}{A(d_i, f)} \quad (i = 1 \cdots n) \tag{16}$$

We use the SIC-Level in Definition 1 to define the place the received signal being successfully decoded.

Definition 1: If the signal from the source node can be decoded as the last m signal and it cannot be decoded as the last $m+1$ signal, then the received power of that signal is defined as:

$$\tilde{P}_r(m+1) > P_{max\_r}(i) \geq \tilde{P}_r(m) \tag{17}$$

Thus, we denote the SIC-Level of the signal m as $P_L(i) = m$.

Lemma 1: If signals transmitted by n source nodes in the same time slot can be decoded correctly and the SIC-Level of these signals obeys $max\left(P_L\left(i\right)\right) \leq m, i = 1, 2, \cdots, n$, then $n \leq m$.

Proof: We prove Lemma 1 using the contradiction. We assume that $n > m$, which means at least $m + 1$ signals in the time slot are decoded sequentially. According to the Definition 1 and pigeon hole principle [40], there must be a source node whose decoded sequence is the last $m+1$ which is contradictory to $P_L\left(i\right) \geq m+1$.

Lemma 1 demonstrates that number of source nodes, which can be scheduled in the same time slot, is limited by their SIC-level. Therefore, we use this principle to calculate the minimum frame length.

IV. MLOPS DESIGN FOR 2-SIC BASED UANs

In this section, we elaborate the design of MLOPS for 2-SIC for a special case of $K = 2$. Since there are only two SIC-levels in 2-SIC based UANs, the SIC-level of transmitting nodes is limited to 1 or 2 and maximally two source nodes are permitted to transmit in the same time slot in order to avoid collision. The goal to minimize the frame length equals to the pairing as many source nodes as possible.

A. MLOPS FOR UNIFIED TRAFFIC LOAD

Since in the unified traffic load scheme each source node will be scheduled once, we only need to consider the SIC-level of nodes to avoid collision. According to Lemma 1, any pair of nodes that can be arranged in the same time slot must contain at least one node of SIC-level 2. Taking in consideration the difference of SIC-level distribution of transmitting nodes, we calculate the minimum frame length using two methods and formulate them in Theorem 1.

Theorem 1: The minimum frame length for unified traffic load $L_{\min}$ is defined by:

$$L_{\min} = \begin{cases} n_1, & n_1 \geq n_2 \\ \left\lceil \dfrac{n}{2} \right\rceil, & n_1 < n_2 \end{cases} \tag{18}$$

where n_l denotes the number of source nodes of level l and n denotes the number of all source nodes.

Proof: We will discuss the situation that SIC-level 1 nodes no less than SIC-level 2 nodes and vice versa separately.

1. When $n_1 \geq n_2$, according to Lemma 1, only one SIC-level 1 nodes can be scheduled per time slot, so there must be at least n_1 time slots. Since the number of SIC-level 2 nodes is not larger than number of SIC-level 1 nodes, every SIC-level 2 node can be paired with a SIC-level 1 node, thus no additional time slot is needed.

2. When $n_1 < n_2$, the number of SIC-level 2 nodes is larger than number of SIC-level 1 nodes, so n_2-n_1 SIC-level 2 nodes remain after all SIC-level 1 nodes are paired. Any two of these n_2-n_1 nodes can transmit in the same time slot without collision when transmitting power adjusted properly, so these nodes can be grouped into $\left\lceil \frac{n_2-n_1}{2} \right\rceil$ pairs. The total number of time slots is then: $n_1 + \left\lceil \frac{n_2-n_1}{2} \right\rceil = \left\lceil \frac{n}{2} \right\rceil$.

Theorem 2: If channel losses of source nodes i and j are $A\left(d(i), f\right)$, $A\left(d(j), f\right)$ and $A\left(d(i), f\right) \geq A\left(d(j), f\right)$, their aggregate power consumption is not optimized when signal from i is decoded in the first order and signal from j is decoded in the second order.

Proof: If signal from node i is decoded as the second last signal, i.e. the first signal of 2-SIC, transmitting power of node s_i does not change with the time slot, and it is $P_t\left(i\right) = A\left(d\left(i\right), f\right) \cdot \tilde{P}_r\left(2\right)$. Therefore, the transmitting power will not change until decoding order of signals from the nodes changes. When $n_1 \geq n_2$, the signals from SIC-level 1 nodes cannot be decoded as the second last signal, so any available scheduling with the pre-determined minimum frame length will share the same aggregate power. When $n_1 < n_2$, the aggregate power change of a swap between any last decoded node s_i and any second decoded node s_j from this scheduling is defined by:

$$\begin{aligned} \Delta P &= P_t(i) + P_t(j) - (P_t'(i) + P_t'(j)) \\ &= A(d(i), f)\tilde{P}_r(1) + A(d(j), f)\tilde{P}_r(2) \\ &\quad - A(d(i), f)\tilde{P}_r(2) - A(d(j), f)\tilde{P}_r(1) \\ &= (A(d(i), f) - A(d(j), f))(\tilde{P}_r(1) - \tilde{P}_r(2)) \end{aligned} \tag{19}$$

$\because A(d(i), f) \leq A(d(j), f)$ and $\tilde{P}_r(1) < \tilde{P}_r(2)$ $\therefore$ $\Delta P \geq 0$. Therefore, the aggregate power of this scheduling is optimal for the minimum frame length.

B. MLOPS FOR WEIGHTED TRAFFIC LOAD

Here we consider the case where the traffic loads of source nodes differ. In this scenario, the packet generation rate (PGR) varies among source nodes. The sink node collects information from received packets during each scheduling cycle and then updates scheduling frame for better channel efficiency. According to the learning-automata-based time-division multiple-access protocol (LTDMA) [41], after each iteration of frame update, the scheduling frame will contain a certain number of time slots, which are assigned to source nodes. Since the SIC is adopted in this paper, multiple source nodes may share the same time slot, so we use transmitting opportunity to replace time slots above. For instance, if node s_i is assigned to two time slots in a frame by the LTDMA algorithm, we say that node s_i has two transmitting opportunities, of which both belong to node s_i. Similar to the unified traffic loads schedule, the goal is to minimize the number of transmitting opportunity groups in which source nodes are able to satisfy SIC condition for simultaneous transmitting. However, since one source node cannot transmit two signals to the sink node concurrently, the groups in weighted traffic load schedule must not allow one source to appear more than once. As a result, the method to calculate the minimum scheduling frame length is not suitable.

We construct an undirected edge-weighted graph $G' = \left\{V', E'\right\}$, where V' denotes the set of transmitting opportunities for all source nodes in one frame. For 2 vertices whose source nodes are neither the same nodes nor both SIC-level 1 nodes, an edge is added between these two vertices. Weight of edge between two vertices is $P_{MAX} - p_{ij}$ where P_{MAX} is an extremely large number and p_{ij} denotes the minimum transmitting power of two simultaneous transmissions of vertices i and j, i.e.

$$p_{ij} = \min \Big\{ A(d_i, f)\tilde{P}_r(1) + A(d_j, f)\tilde{P}_r(2), \\ A(d_i, f)\tilde{P}_r(2) + A(d_j, f)\tilde{P}_r(1) \Big\} \quad (20)$$

Then, we apply Edmonds's Blossom algorithm on G' to get the maximum weighted matching, which is the minimum frame length with aggregate power optimized scheme.

C. MLOPS WITHOUT ASSUMPTIONS

In this part, we do not use assumptions that transmitting power could be continuously adjusted and SIC decoding is perfect.

Compared to being fixed as their counterpart on land, underwater sensors swung with flow within extend of radius. As a result, the maximal received power of sensors in this paper is an upper bound of the power, instead of the actually received power. The difference between the upper bound and the power derived when transmitting power of source nodes can be changed continuously is defined by:

$$\Delta P_r(i) = 2\,|(A(d(i), f) - A(d(i) + R_i, f))|\, P_r(i) \quad (21)$$

where R is the swinging radius of the transmitting sensor. Equation (21) shows that the difference caused by $P_t(i)$, $A(d(i), f)\Delta P_t(i)$, can be ignored if it is much less than $\Delta P_r(i)$ defined by:

$$\Delta P_t(i) \gg \frac{2\,|(A(d(i), f) - A(d(i) + R_i, f))|}{A(d(i), f)} P_t(i) \quad (22)$$

The SIC decoding is imperfect, which means some power remains from the first decoded signal, and that remainder is unknown, but here we assume that remainder is linear, i.e. $P_{remain}(i) = \alpha P_r(i)$, where α is remainder factor. Then, the calculation of 2-SIC threshold is as follows:

$$\tilde{P}_r(1) = \lambda(P_N + \alpha \tilde{P}_r(2)) \\ \tilde{P}_r(2) = \lambda(P_N + \tilde{P}_r(1)) \quad (23)$$

$$\because \lambda \geq \therefore 1 \frac{\sqrt{P_N^2 + 4P_N + 4\alpha \tilde{P}_r(2)} - P_N}{2P_N + 2\alpha \tilde{P}_r(2)} \geq 1 \quad (24)$$

Since $\alpha > 0$, $\tilde{P}_r(1) > \lambda P_N$, there may exist source nodes which can transmit packet to the sink nodes, but cannot transmit packet to any other source node. We define that these nodes are SIC-level 0 nodes and their number is n_0. Then, the minimum frame length for weak assumption is $\hat{L}_{\min} = L_{\min} + n_0$.

If α satisfies (24), the corresponding SIC-level can be calculated. The Algorithm 1 named UMLOPS is presented here to get the minimal frame length with an optimized power for 2-SIC based unified traffic load scenario.

According to (21) and (22), it is obvious that UMLOPS generates minimum frame length scheduling in $O(n)$ time.

Example 1: For a SEA Swarm network with a topology as presented in Fig. 2, the network parameters are: $\lambda = 1.3$, $P_{\max\_t} = 78$(dB), $P_N = 20$(dB), remainder factor is 0.1, path loss rate is 7 dB/km and distance from each source node to the sink node is as given in Table 2.

As a scenario of UMLOPS, the sink node in this example supports the 2-SIC receiver and packets are generated in unified way among source nodes such that every source node is able to transmit all its packets in a time slot in the scheduling frame.

Algorithm 1 (UMLOPS): Algorithm to Get Minimal Frame Length With an Optimized Power for 2-SIC Based Unified Traffic Load

Input: source nodes to be scheduled

1. Source nodes are leveled by 2-SIC threshold
2. allocate a new time slot to each SIC-level 1 node and set its power as $A(d_i, f)\tilde{P}_r(1)$
3. if $n_1 >= n_2$
4. put every SIC-level 2 node to existing time slot in order
5. else
6. use BFPRT [42] to select $\lceil \frac{n_2 - n_1}{2} \rceil$ SIC-level 2 nodes in descending order of path loss;
7. allocate a new time slot to each of the selected nodes and set their power as $A(d_i, f)\tilde{P}_r(1)$;
8. end if
9. put remain SIC-level 2 nodes into existing time slot in order and set their power as $A(d_i, f)\tilde{P}_r(2)$.
10. end if
11. allocate a new time slot to each SIC-level 0 node and set power of SIC-level 0 nodes as $A(d_i, f)\lambda P_N$

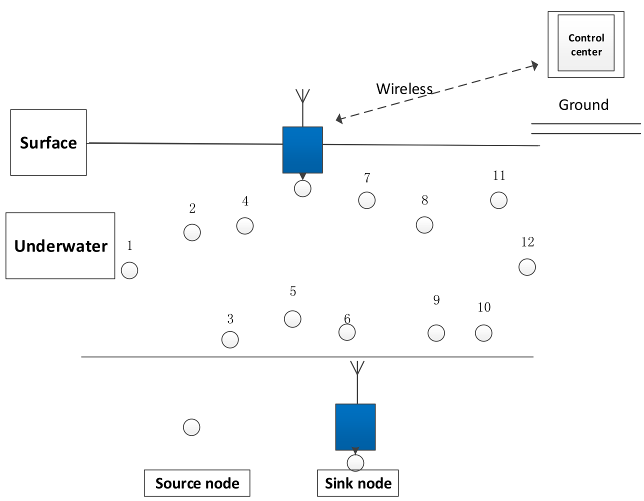

FIGURE 2. Example Network.

TABLE 2. Distances from source nodes to sink node.

Node ID	Distance (km)	Node ID	Distance (km)
1	1.71	7	1.19
2	1.60	8	1.14
3	1.68	9	1.82
4	0.87	10	2.03
5	1.43	11	1.55
6	1.58	12	1.96

According to (14): $\tilde{P}_r(1) = 31.69(dB)$, $\tilde{P}_r(2) = 67.20(dB)$ and according to (15) and Definition 1, $P_{\max\_r}(i)$ and $P_L(i)$ have values presented in Table 3.

TABLE 3. Maximum received power and SIC-level of source.

Node ID	$P_{\max\_r}(i)$ (dB)	$P_L(i)$	Node ID	$P_{\max\_r}(i)$ (dB)	$P_L(i)$
1	66.03	1	7	69.67	1
2	66.80	1	8	70.02	2
3	66.24	1	9	65.26	1
4	71.91	2	10	63.79	1
5	67.99	2	11	67.15	1
6	66.94	1	12	64.28	1

From Table 3, we can know that number of nodes in each level is: $n_1 = 9$, $n_2 = 3$. In step 2, time slots 1 to 9 are allocated to nodes 1, 2, 3, 6, 7, 9, 10, 11, 12 and their power are set to values lower than 43.66, 42.89, 43.45, 42.75, 40.02, 44.43, 45.9, 42.54 and 45.41 (dB), respectively. Because $n_1 > n_2$, in step 3 the minimum frame length is 9. In step 4, nodes 4, 5, 8 are scheduled into time slot 1 to 3, respectively, and their corresponding power are set to values higher than 73.29, 77.21 and 75.18 (dB). The results are expressed in Table 4.

Similarly, the MLOPS can be generated by adopting the Edmonds's Blossom algorithm on graph G, and we propose Algorithm 2 named the WMLOPS for 2-SIC based weighted traffic load scenario.

The time complexity of the WMLOPS is equal to that of the Edmonds's Blossom algorithm, which is O(n^3).

Example 2: This example relates to the WMLOPS. We use the same topology and most parameters as in Example 1 except the load of source nodes. In Example 2, the PGR ratio of source nodes is as presented in Table 5, and P_{MAX} is 10000 dB.

In this example, we consider the stable situation, which means that ratio of transmission opportunities of nodes is equal to the GPR ratio of nodes. As a result, after step 1 one frame contains 1, 1, 1, 3, 2, 1, 2, 1, 4, 1, 2 and 1 transmission opportunities for nodes 1 to 12, respectively.

TABLE 4. Result of example 1.

Time slot	1	2	3	4	5	6	7	8	9
1st decoded node	4	5	8						
Power	73.29	77.21	75.18						
2nd decoded node	1	2	3	6	7	9	10	11	12
power	43.66	42.89	43.45	42.75	40.02	44.43	45.9	42.54	45.41

Algorithm 2 (WMLOPS): Algorithm to Get Minimal Frame Length With an Optimized Power for 2-SIC Based Weighted Traffic Load

Input: transmission opportunities to be scheduled

1. transmission opportunities are leveled by 2-SIC threshold
2. *opportunityList*:=*SelfAdaptiveTDMA-nodeListByLevel*(0);
3. *AddVertex(G, opportunityList);*
4. M = *Size*(*opportunityList*);
5. for 1 <= i <= M
6.   for i <= j <= M
7.   if *NodeOf*(i) != *NodeOf*(j) && ($P_L(i)$ == 2||$P_L(j)$ == 2)
8.   *AddEdge*($G, i, j, P_{\text{MAX}} - p_{ij}$);
9.   end if
10.   end for
11. end for
12. schedulingTable:= EdmondsBlossom(G);
13. allocate a new time slot to each SIC-level 0 node and set power of SIC-level 0 nodes as $A(d_i, f)\lambda P_N$

TABLE 5. Ratio of GPR.

Node ID	1	2	3	4	5	6	7	8	9	10	11	12
Ratio of PGR	1	1	1	3	2	1	2	1	4	1	2	1

Because the graph generated by steps 2 to 10 is too complex to be illustrated, we pick nodes 1, 3, 5, 8 and pairs composed of transmission opportunities of any two of these nodes to explain graph construction. First, we use vertex i_x to denote the xth transmission opportunity of node s_i and edge (i_x, j_y) where $P_{MAX} - (i_x, j_y) = p_{ij}$ is the minimum aggregate power of nodes s_i and s_j when i_x and j_y are in the same time slot. Obviously, $(i_x, j_y) = (j_y, i_x)$. Then, we have vertices 1_1, 3_1, 5_1, 5_2, 8_1 and their edges as presented in Table 6. If there is no edge between two vertices, the weight is 0.

In the last step, we employ the Edmonds's Blossom algorithm on the graph generated after step 10 and get the maximum weighted matching, which is the final result.

V. SIMULATION

In this section, we discuss the performance of proposed MLOPS algorithm. We divided the simulation into two parts. In the first part, we validated the MLOPS algorithm, and in

TABLE 6. Edge weight among nodes 1, 2, 3, and 5.

	1_1	3_1	5_1	5_2	8_1
1_1	0	0	9879.13	9879.13	9881.16
3_1	0	0	9879.34	9879.34	9881.37
5_1	9879.13	9879.34	0	0	9883.12
5_2	9879.13	9879.34	0	0	9883.12
8_1	9881.16	9881.37	9883.12	9883.12	0

the second part, we compared the MLOPS with the traditional TDMA and NF-TDMA protocols [29].

A. SIMULATION SETUP

Simulations were performed on Aqua-Sim which is an underwater sensor network simulation extension package based on Network Simulator 2 [43].

We evaluated the protocols in the SEA Swarm networks, where at most 16 nodes with the maximum transmission range of 3000 m were randomly located in the 2D region of 1500m × 1000 m and this topology enabled a full connectivity among all nodes. In this network, many source nodes moved as a group with the water current. We adopted the Meandering Current Mobility (MCM) Model [44] to model the motility of each sensor node. We set the wind speed w_s to 25 m/s, fixed sound speed to 1500 m/s, and carrier frequency to 10 kHz. The acoustic modem communication parameters of source node were as follows. The transmission rate was 1000 bps, the maximum transmission power was 170 dB, and the transmission power could be discreetly adjusted. The source nodes were equipped with a 2-SIC receiver containing the liner remainder α.The data packet length was 2000 bits and the length of single time slot was 2 s. The scheduling length was the number of slots for scheduling, and the source nodes were sending all the data packets. In the unified traffic load scenario, all the source nodes generated data packets in a time slot with the same packet generation rate. In the weighted traffic load scenario, the source nodes generated data packets in a time slot with different weights given by the LTDMA [41].

In the simulation, each run lasted for one hour and we reported an average value of 50 runs with 95% confidence interval. The following performance metrics were evaluated in the simulation: (a) the scheduling frame lengths: the total number of time slots, which reflects the network throughout and scheduling delay; and (b) the Aggregate Transmit Power, which denotes the total network energy consumption for scheduling the data packets:

$$\begin{aligned} &\textit{Scheduling length} \\ &\quad = \frac{\#\text{Received data packets}}{\textit{Simulation}\ \text{duration}} \end{aligned} \tag{25}$$

$$\begin{aligned} &\textit{Aggregate Transmit Power} \\ &\quad = \frac{\sum(\textit{time slot} * \textit{transmission power})}{\textit{Simulation}\ \text{duration}} \end{aligned} \tag{26}$$

1) PERFORMANCE EVALUATION

To find how the minimum scheduling length changes with the number of source nodes and liner remainder α, the additional simulation experiments were conducted. The simulation parameters of performance evaluation are described in Table 7.

2) PERFORMANCE COMPARISON

Here we demonstrate the merits of the proposed MLOPS algorithm in the SEA Swarm network and compare them with the merits of the traditional TDMA and NF-TDMA protocols. In the simulations, for the traditional TDMA protocol, different communication links were not permitted to transmit in the same time slot simultaneously, and only one communication link was selected for an individual transmission. The NF-TDMA protocols were TDMA-based MAC protocols that utilize the spatial reuse concept and allow different communication links to transmit simultaneously and exploit the near-far effect caused by a large propagation delay in underwater acoustic communications to schedule simultaneously. The simulation parameters of performance comparison are given in Table 8.

TABLE 7. Simulation parameters of performance evaluation.

Description	Value
Wind speed w_s	25 m/s
Carrier frequency f	10 kHz
Max transmit power	170 dB
Length of time slot	2 s
Length of data packet	2000 bits
Transmission rate	1000 bps
Maximum transmission range	3000 m
Sound speed	1500 m/s
Simulation region	1.5 km × 1.5 km
Number of source nodes n	2-16
Liner remainder factor α	0.05, 0.1, 0.2

TABLE 8. Simulation parameters of performance comparison.

Description	Value
Wind speed w_s	25 m/s
Carrier frequency f	10 kHz
Max transmit power	170 dB
Length of time slot	2 s
Length of data packet	2000 bits
Transmission rate	1000 bps
Maximum transmission range	3000 m
Sound speed	1500 m/s
Simulation region	1.5 km × 1.5 km
Number of source nodes	16
Liner remainder factor α	0.1

B. PERFORMANCE EVALUATION RESULTS AND ANALYSIS

1) SCHEDULING FRAME LENGTH FOR DIFFERENT α

The scheduling length for all α and n in the unified traffic load scenario and weighted traffic load scenario is illustrated in Fig. 3 and Fig. 4, respectively. It is obvious that in both cases the optimal scheduling length almost linearly increases with the number of source nodes for all α.

Certainly, for the same number of source nodes, the scheduling length is shorter for smaller α. Therefore, the experiment results coincide completely with our theorem. The change of α affects the number of nodes at different power levels, which further affects the scheduling frame length. If we take $n = 16$ as an example, for $\alpha = 0.05$, the number of nodes in power level 1 and level 2 is 3 and 13, respectively; for $\alpha = 0.1$, the number of nodes in

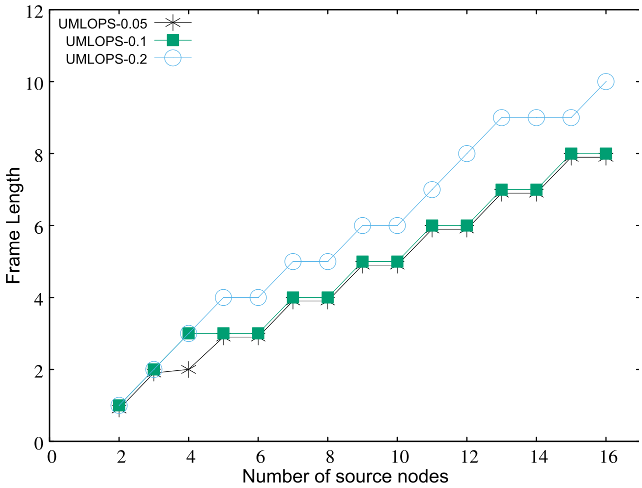

FIGURE 3. Scheduling frame length for unified traffic load.

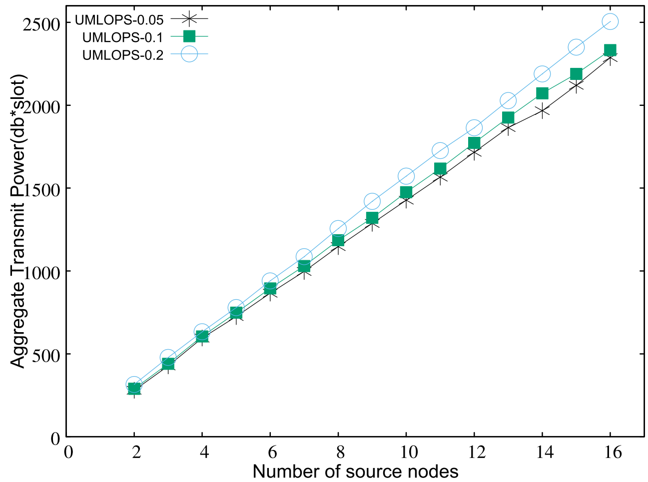

FIGURE 5. Aggregate transmit power for unified traffic load.

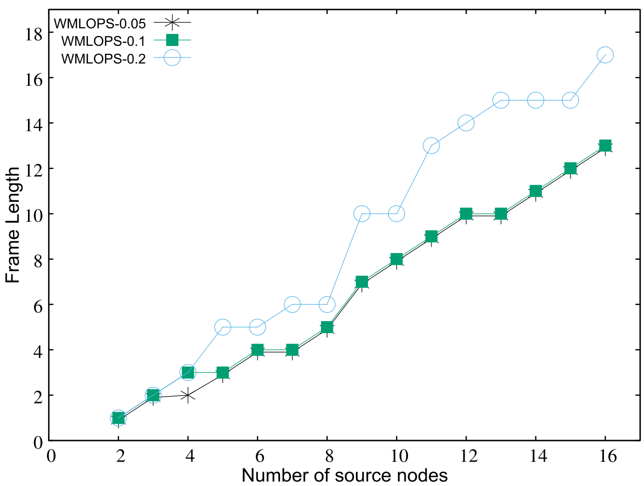

FIGURE 4. Scheduling frame length for weighted traffic load.

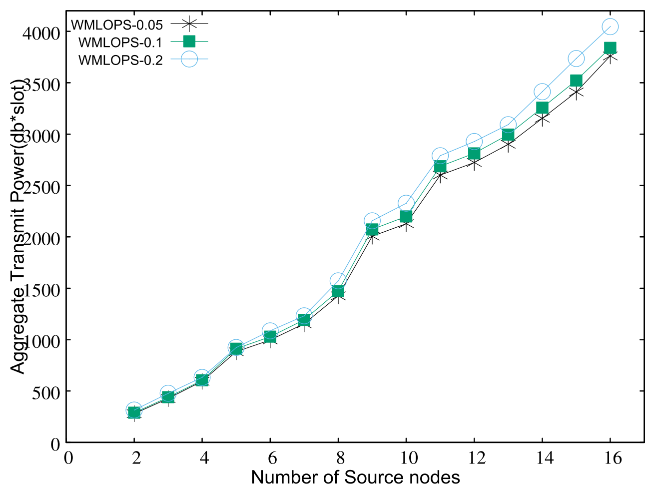

FIGURE 6. Aggregate transmit power for weighted traffic load.

power level 1 and level 2 is 6 and 10, respectively; and for $\alpha = 0.2$, the number of nodes in power level 1 and level 2 is 10 and 6, respectively. According to the Theorem 1, the distribution of nodes in different power levels determines the scheduling length directly. Compared to the unified traffic load scenario, the source nodes in the weighted traffic load scenario are allocated with different slots in each frame. Thus, for $\alpha = 0.2$, the distribution of nodes in different power levels changes more obviously with the increase of number of source nodes in the weighted traffic load scenario.

2) AGGREGATE TRANSMIT POWER FOR DIFFERENT α

The aggregate transmit power for all values of α and n for unified and weighted traffic load scenarios is illustrated in Fig.5 and Fig. 6 respectively. As shown in Fig. 5 and Fig. 6, for the fixed number of source nodes, the aggregate transmit power will be greater for larger α, which is consistent with the fact that source node needs larger transmitting power if it is decoded with more remainder. In addition, the changes of α affect the distribution of nodes in different power levels. If the number of nodes in power level 2 is greater than the scheduling length, the UMLOPS will turn down the transmission power of some source nodes in the power level 2, thus the aggregate transmit power will be further reduced.

C. PERFORMANCE COMPARISON RESULTS AND ANALYSIS

1) PERFORMANCE COMPARISON FOR UNIFIED TRAFFIC LOAD SCENARIO

The scheduling length, delay, throughput, aggregate transmit power and energy efficiency for unified traffic load scenario are demonstrated in Fig. 7, Fig. 8, Fig. 9, Fig. 10 and Fig. 11 respectively. In Fig. 7, we can see that performance of the traditional TDMA protocol is the worst, which is because at each time slot, only one communication link is permitted to transmit in the simulated network. The performance of the proposed MLOPS protocol is still better than that of the NF-TDMA, especially when the packet rate is high, which is because the NF-TDMA protocol utilizes the near-far effect

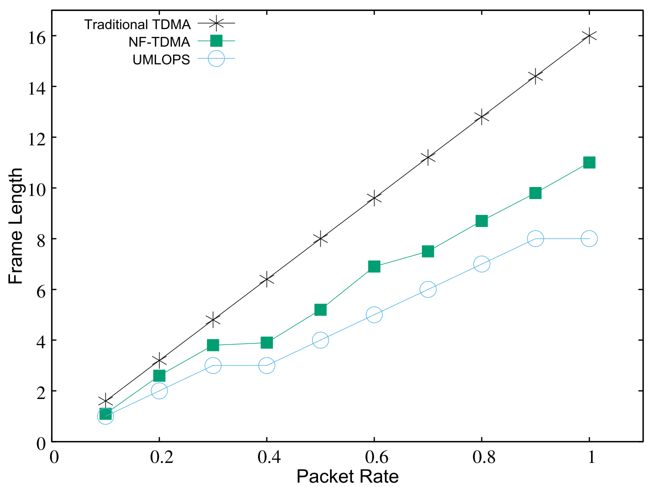

FIGURE 7. Scheduling frame length in unified traffic load scenario.

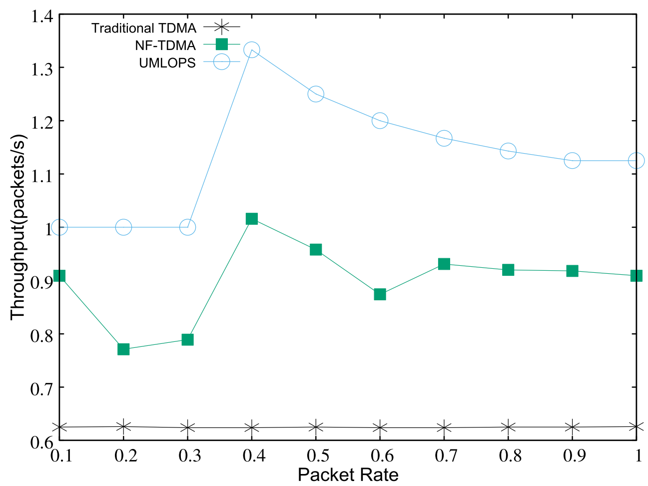

FIGURE 9. Throughput in unified traffic load scenario.

and allows different communication links to transmit simultaneously. However, the simulated network is a single-hop network and all the source nodes transmit data packets to the sink node. Thus, it is hard to utilize the near-far effect achieving spatial reuse in NF-TDMA. In addition, similar to the MLOPS, the NF-TDMA also uses the interference cancellation capabilities and scheduling length is smaller than in the traditional TDMA protocol. However, the scheduling scheme is designed for an ad-hoc network, which is not an optimal solution for the star network because in the star network, the sink node is responsible for receiving the data packets from all source nodes and the source nodes in NF-TDMA cannot launch the transmission of opportunistic packets. Due to shorter frame length, MLOPS achieve better delay and throughput than traditional TDMA and NF-TDMA, as shown in Fig.8 and Fig.9.

As shown in Fig. 10 and Fig.11, we can observe that aggregate transmit power of the traditional TDMA protocol

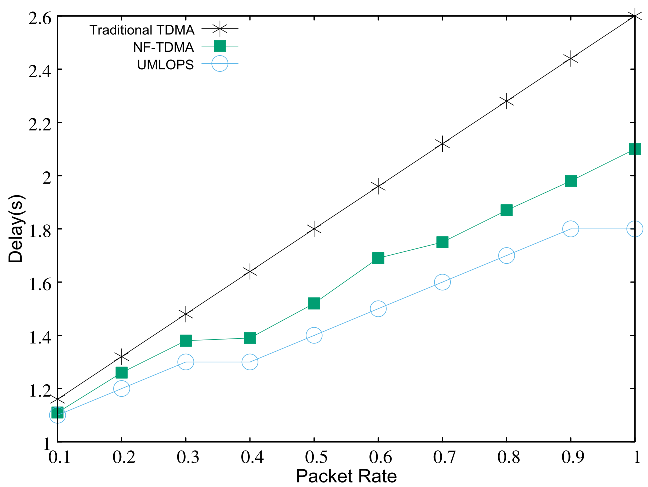

FIGURE 8. Delay in unified traffic load scenario.

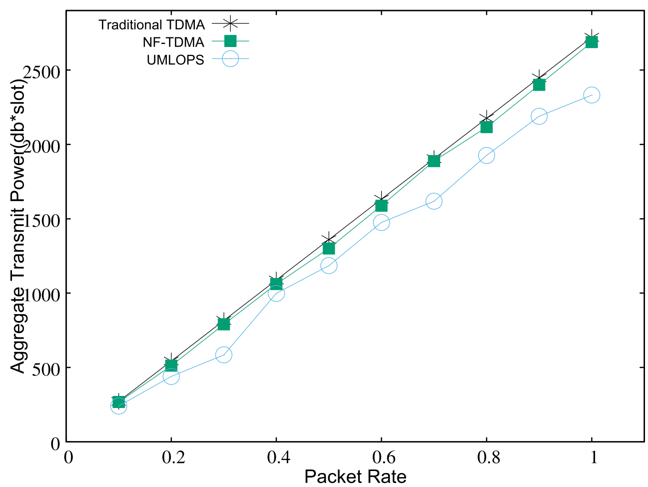

FIGURE 10. Aggregate transmit power in unified traffic load scenario.

is the highest, the aggregate transmit power of the NF-TDMA protocol is slightly less but still much higher than that of the proposed MLOPS protocols, and vice versa in the situation of energy efficiency. The main reason for that is that both the traditional TDMA and NF-TDMA protocols do not have the proper power control mechanism, thus the aggregate transmit power of these two protocol cannot be reduced effectively. In the MLOPS protocol, the power-allocating scheme can reduce the transmission power of some source nodes to minimize aggregate power consumption without affecting the scheduling length, which leads to better energy efficiency.

2) PERFORMANCE COMPARISON FOR WEIGHTED TRAFFIC LOAD SCENARIO

The scheduling length, delay, throughput, aggregate transmit power and energy efficiency for weighted traffic load scenario are demonstrated in Fig. 12, Fig. 13, Fig. 14, Fig. 15 and Fig. 16, respectively. As shown in these prictures, the performance of MLOPS is the best among all protocols. For the

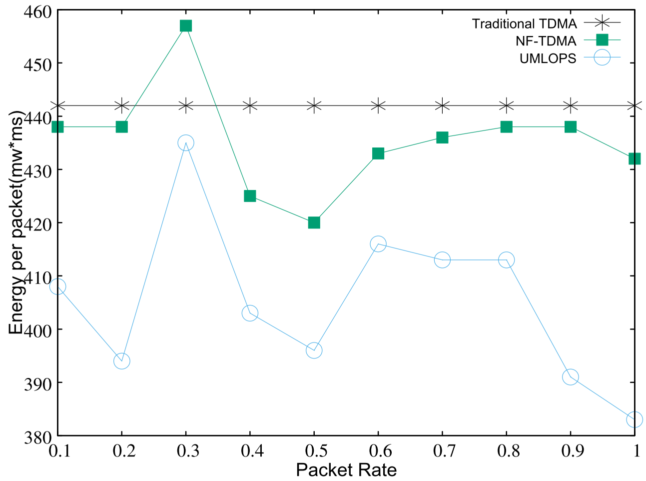

FIGURE 11. Energy efficiency in unified traffic load scenario.

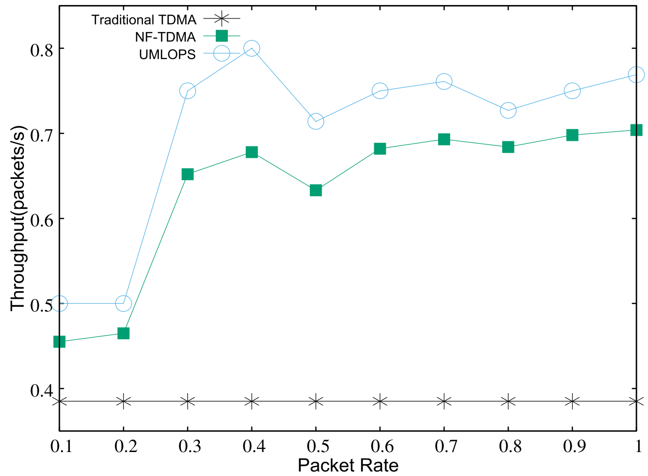

FIGURE 14. Throughput in weighted traffic load scenario.

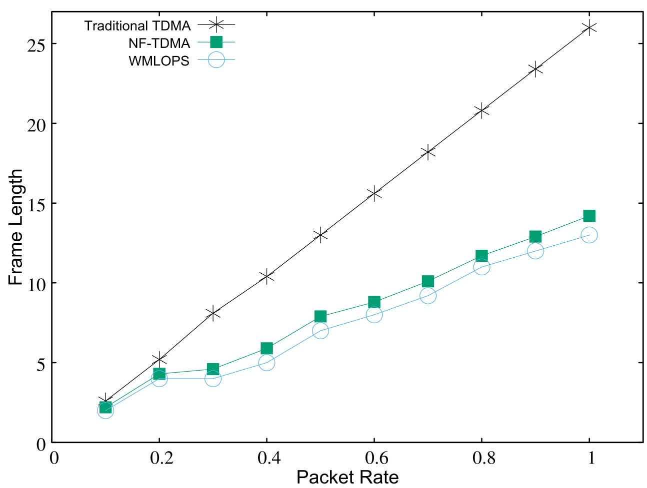

FIGURE 12. Scheduling frame lengths in weighted traffic load scenario.

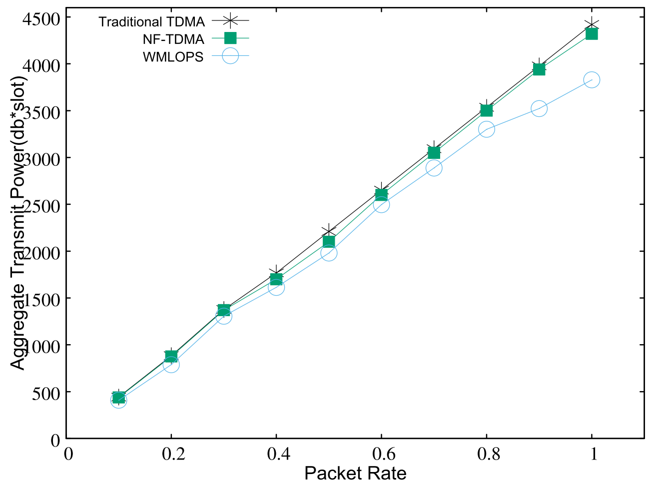

FIGURE 15. Aggregate transmit power in weighted traffic load scenario.

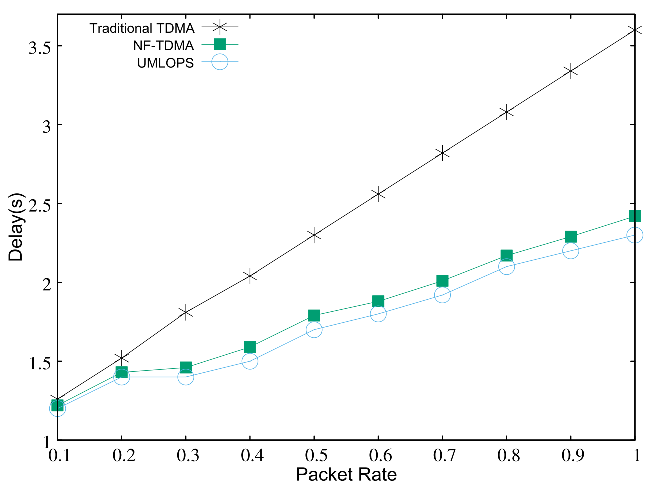

FIGURE 13. Delay in weighted traffic load scenario.

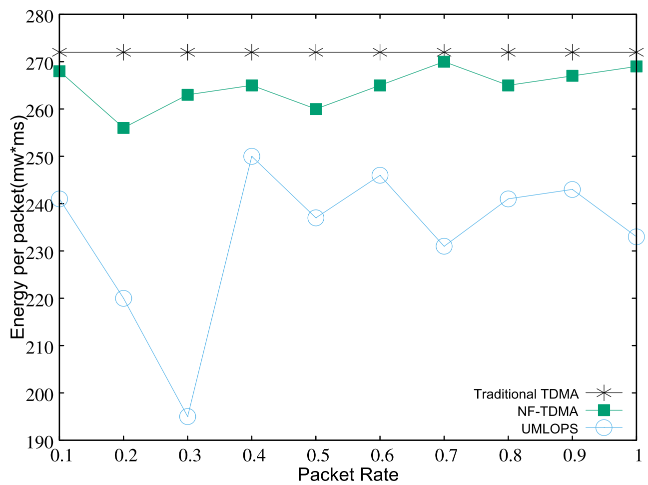

FIGURE 16. Energy efficiency in weighted traffic load scenario.

load of 1.0 packets/s, the scheduling length performance of MLOPS outperforms the performances of the traditional TDMA and NF-TDMA by 98% and 10% respectively. The delay of MLOPS outperforms those of traditional TDMA and NF-TDMA by 100% and 5%. The throughput of MLOPS outperforms those of traditional TDMA and NF-TDMA by

100% and 10%. Moreover, the aggregate transmit power performance of MLOPS outperforms those of the traditional TDMA and NF-TDMA by 15% and 13%, respectively. Compared to the unified traffic load, the scheduling length and aggregate transmit power are much higher in the weighted traffic load scenario because more data packets are sent.

VI. CONCLUSIONS AND FUTURE WORKS

In the paper, we propose the MLOPS algorithm for the SIC-based underwater acoustic networks to improve both delay and energy efficiency. The proposed MLOPS algorithm considers two types of traffic loads, thus it is consisted of two sub-algorithms: UMLOPS algorithm for unified traffic load and WMLOPS algorithm for weighted traffic load. We formulate the problem of minimizing the transmission delay and overall network power consumption by combining transmitters scheduling and power allocating. Our conclusions are as follows. The minimum frame length in uplink scheduling in 2-SIC based UANs can be calculated by an explicit formula; and the uplink scheduling problem of unified and weighted traffic load scenarios for 2-SIC based UANs is solvable in polynomial time. An optimal power scheduling scheme is also provided in this paper. The simulation results reveal that both scheduling frame length and aggregate power consumption of MLOPS significantly outperform the existing TDMA protocols in underwater SEA Swarm networks.

In our future work, we will explore an efficient polynomial algorithm for K-SIC. The link scheduling problem of K-SIC may be NP-hard, and some heuristic algorithms can be explored for solving the problem.

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As for all content of this paper, the authors alone take the responsibilities.

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Authors' photographs and biographies not available at the time of publication.