An Interference-Free Scheduling for the TDMA Protocol in Multi-hop Underwater Acoustic Grid Networks

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***Abstract*—Underwater acoustic grid network is promising for providing high data rate and wide coverage service. For the scheduled time division multiple access (TDMA) protocols in the underwater acoustic grid networks, scheduling is an essential part to achieve reliable and energy efficient performance. Scheduling not only completely guarantees the interference free transmission in the network, but also makes the the network become energy conservation. Existing scheduling schemes for the underwater acoustic grid networks adopt the transmission power model based on the physical interference model and the protocol interference model could not satisfy the requirements about the complexity and interference free at the same time. Moreover, in these scheduling schemes the transmission from the source node to the destination node could only take a single path, which makes the network unreliable in the underwater environment. This paper formulates a multi-objective integer linear programming based on a special designed transmission power model for the TDMA scheduling in the gird network. Moreover, we improve the spatial diversity of the network through a unique frame structure. Simulation results demonstrate that the proposing scheduling scheme has a better performance than the traditional scheduling scheme.**

I. INTRODUCTION

Underwater acoustic sensor networks have numerous interesting applications, such as offshore monitoring, scientific exploration and military defense. When the underwater applications require high data rate and wide coverage services, the multi-hop grid network with an adequate media access control (MAC) protocol can be considered to apply for its suitable properties.

Recently, scheduling schemes for the TDMA protocol in underwater grid networks are under intensive investigation[1-4]. The sensor deployment and scheduling in the grid network are studied to achieve energy efficiency based on the physical interference model in [1]. This scheduling scheme has a low throughput since it only occupies a single time slot of the whole frame for transmission. The upper bound of the maximum achievable throughput in an N-node network within one interference domain is proved to be $N/2$ in [2]. A scheduling scheme based on the protocol interference model is given in [3], it can make the throughput of the network reach an upper bound of $(N-\eta)/2$, where η denotes the number of columns in the grid network. However, it ignores the interference caused by the concurrent transmission in the grid network and still has interference during the transmission process. An unslotted ρ-scheduling scheme is adopted in [4] to solve the mobility problem of the nodes in the underwater grid networks. In both [3] and [4], the data from the source node are transmitted hop by hop through the nodes on the same vertical line until it reaches the destination node. It is unreliable since the data only pass through a single path from the source node to the destination node.

In this paper, we propose an interference-free scheduling scheme for the TDMA protocol in the underwater acoustic multi-hop grid networks. The scheduling problem is formulated as a constrainted multi-objective integer linear programming (ILP) problem. The objectives are to minimize the energy consumption and maximize the throughput of the underwater grid network. The special designed transmission power model and the interference-free constraints are employed to avoid the interference caused by the concurrent transmission. Moreover, we divide the frame into several segments for the source nodes and add the broadcast and unicast constraint to make the transmission more reliable.

The rest part of this paper is organized as follows. Section II describes the network model including the network schedule model, the underwater path loss model and the transmission power model. Section III provides the constraints and the objective functions of the ILP problem. Section IV gives the simulation results and we compare the throughput and energy consumption of the grid network based on our scheduling scheme and the one of the scheme in [3]. In section V we conclude our work.

II. NETWORK MODEL

We model the acoustic multi-hop grid network as a directed graph $G(V,\xi)$, which is illustrated in Fig. 1. The set of all the nodes is denoted by V and the set of all the edges is denoted by ξ. The nodes set V can be divided into three subsets: the destination or the gateway node set O, the relay node set R and the source node set S.

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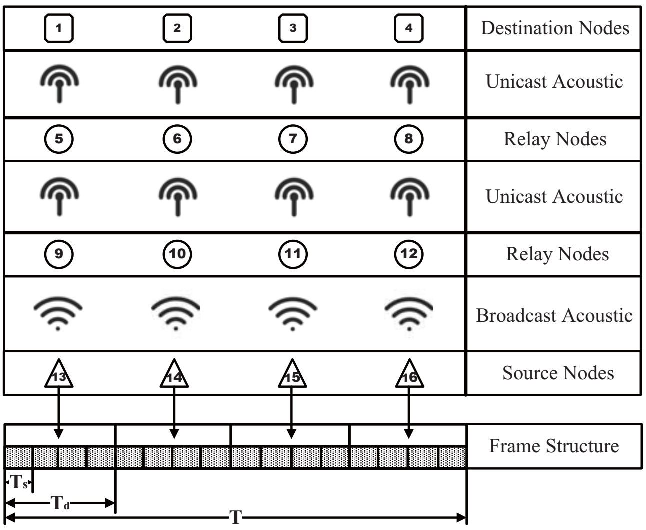


Fig. 1. Network model

A. Network schedule model

Our network scheduling model is based on the TDMA protocol. Any two nodes of the network can be denoted by u and v, respectively. The edge (u,v) denotes the directed edge from the node u to v. In our model the frame length T is divided into serval successive segments, each source node occupies a unique segment for transmission. The length of each segment is T_d, it is divided into numerous small time slots for transmission. The length of each time slot is T_s. The status $X_{(u,v)}(t)$ at time slot t of the edge (u,v) is defined as follows:

$$X_{(u,v)}(t) = \begin{cases} 1, & (u,v) \text{ is occupied,} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

The corresponding coordinates of the node u and v are denoted by x_u and x_v, respectively. The propagation delay between the node u and v can be quantized as follows:

$$D(u,v) = \frac{d(u,v)}{T_s c}, \tag{2}$$

where c is the sound propagation speed and $d(u,v) = \|x_u - x_v\|$ is the distance between the node u and v.

B. Underwater Path Loss Model

In the underwater acoustic signal propagation, there is a characteristic length K. When the transmitter node and the receiver node are at a close distance, usually smaller than K, the transmitting energy experiences a spherical spread. When the distance between the transmitter node and the receiver node becomes larger than $10K$, the transmitting energy spread becomes cylindrical. When the distance is between K and $10K$, the transmitting energy spread becomes a hybrid of spherical and cylindrical spread. Empirically speaking, the characteristic length K can be obtained by dividing the water depth by 2 roughly [5].

As we know, the horizontal and vertical underwater channel is quite different. So the transmission loss is also determined by the direction of transmitting signal. In summary, the underwater path loss between the transmitter node and the receiver node is:

$$H(d,\theta) = AS(d,\theta)e^{-\alpha d}, \tag{3}$$

where A is transmission anomaly coefficient, α is absorption coefficient, $S(d,\theta)$ is the energy spread coefficient which is corresponding to the coordinates of the transmitter node and the receiver node. The distance between the transmitter node and the receiver node is d. The angle between the direction of the transmitting signal and horizontal plane is θ. Specifically, $S(d,\theta)$ is equal to [5]:

$$\begin{cases} d^{-2}, & if\ dcos\theta \le K, \\ d^{-2}(dcos\theta/K)^{log_{10}(dcos\theta/K)/2}, & if\ K < dcos\theta \le 10K, \\ d^{-1}K^{-1}cos\theta\sqrt{0.1}, & if\ dcos\theta > 10K. \end{cases} \tag{4}$$

C. Transmission power model

Transmission power model based on the physical and protocol interference model are two common models in TDMA scheduling problems of the underwater acoustic grid networks.

The physical interference model [6] depends on the signal to interference plus noise ratio (SINR) of the receiver node. The signal power of the receiver node is determined by the power of the transmitter node $P_{(u,v)}(t)$ and the path loss between the transmitter node and the receiver node $H(d(u,v),\theta)$. As shown in Fig. 2, the interference caused by the transmission of other edges ξ' in the network is $\sum_{(w,z)\in\xi'} P_{(w,z)}(t')H(d(w,v),\theta')$. According to the physical layer of the network, we could get a threshold γ_{phy} that when the SINR of the receiver node beyond the threshold, the signal could be successfully demodulated [6]. We assume the underwater environment noise is N_s and the physical interference model could be expressed as below:

$$SINR = \frac{P_{(u,v)}(t)H(d(u,v),\theta)}{N_s + \sum_{(w,z)\in\xi'} P_{(w,z)}(t')H(d(w,v),\theta')} \ge \gamma_{phy}. \tag{5}$$

Taking advantage of the physical interference model, the scheduling could ensure the completely interference free transmission in the network. However, the physical interference model needs to consider the status and the power of all the transmitter nodes at the same time. Thus the constraints of physical interference is non-linear and the number of the non-linear constraints is proportional to the square of the number of the edges in the network. This makes the scheduling problem difficult to solve.

The protocol interference model [7] is illustrated in Fig. 3. The model considers the situation with one interference domain and defines two ranges: the transmission range R_d and the interference range R_i. The transmission range is the maximum distance between the receiver node u and the transmitter node z that the receiver node u can correctly decode the received data without any transmitting interference. The interference range is the maximum distance between the other node w and the receiver node u, that the transmission between the node v and the node u can be interfered by the

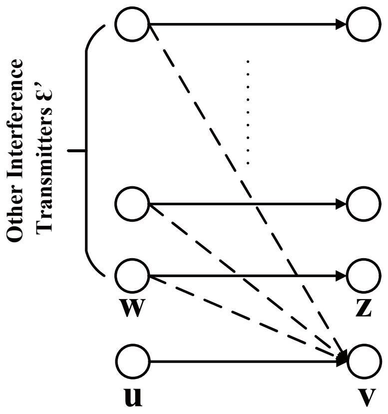


Fig. 2. Physical interference model

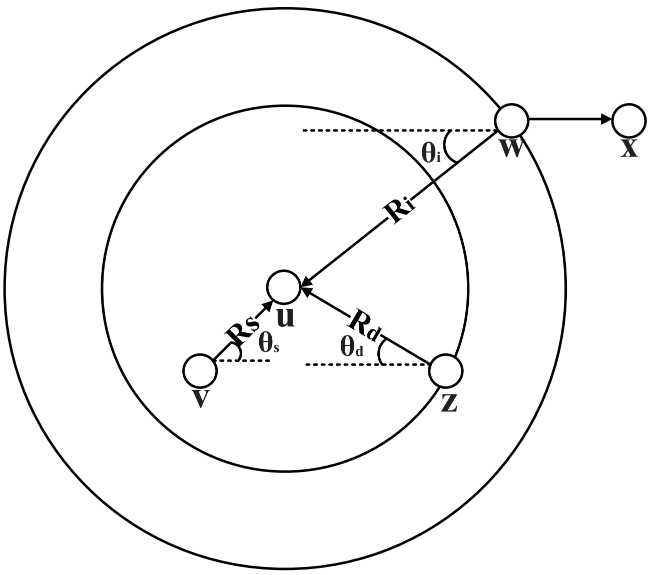


Fig. 3. Protocol interference model

node w. We assume that the underwater environment noise is N_s. The implicit expression of R_d and R_i can be shown as:

$$\frac{P_{(z,u)}(t)H(R_d,\theta_d)}{N_s}=\gamma_{phy}, \tag{6}$$

$$\frac{P_{(v,u)}(t)H(R_s,\theta_s)}{N_s+(P_{(w,x)}(t)H(R_i,\theta_i)}=\gamma_{phy}, \tag{7}$$

where $P_{(w,x)}$ denotes the transmitting power of the node w, R_s denotes the distance between the node u and the node v, θ_d denotes the angle between the direction from the node z to the node u and the horizontal plane, θ_i denotes the angle between the direction from the node w to the node u and the horizontal plane, θ_s denotes the angle between the direction from the node v to the node u and the horizontal plane.

The constraint of protocol interference model is linear. Based on the protocol interference model the scheduling problem becomes a LP optimal problem and easy to solve. We can see that the protocol interference model only considers the interference of the single interference domain. However, the receiver node may receive the interference brought by more than one transmitter nodes in our model.

To overcome the disadvantages of the physical and protocol interference model, we develop a new transmission power model that is more suitable for the grid network. It considers the multiple interference domains and is relative easy to solve. In our network model we assume the data transmitted by the source node can be received by several relay nodes, the data transmitted by the relay node can be received by another relay node or the destination node. Hence, we set the power of the source node as a fixed value, and the power of the relay node depends on the minimum SINR it required. Our transmission power model in general is given by:

$$P_{(u,v)}(t)=\begin{cases}\frac{\gamma_{phy}N_s}{H(d(u,v),\theta)}, & u\in R,(u,v)\in\xi_{out}(u),\\ P_s, & u\in S,(u,v)\in\xi_{out}(u),\end{cases} \tag{8}$$

where N_s is the known environment noise, $\xi_{out}(u)$ is the edge set through which the node u could send out the data.

Our transmission power model requires that no other nodes could interfere the receiver node when it is receiving data. Only when this constraint is satisfied, the data could be successfully decoded and forwarded. The constraint formulated by our transmission power model is linear and could ensure all the interference in the network be eliminated.

III. Scheduling Problem Formulation

For each source node occupying a unique segment, we formulate a general scheduling problem for each source node during the segment it has occupied. Our scheduling problem is formulated as the ILP based on our network model.

The first constraint is formulated based on the causality that the data transmitted by the relay nodes at time slot t should be received at the time slots before t. We take the relay node v as an example. While the propagation delay in our network is fractional and the index of time slot is integer, the data could be transmitted by the node u at time slot 0 to $t-\lceil D(u,v)\rceil-1$. Meanwhile the data transmitted by the node v could be at time slot 0 to t. We formulate the constraint that at any time slot t the data transmitted should less than or equal to the data received by the node v as follows:

$$\begin{aligned}&\sum_{(v,w)\in\xi_{out}(v)}\sum_{r=0}^{t}X_{(v,w)}(r)\\ &-\sum_{(u,v)\in\xi_{in}(v)}\sum_{r=0}^{t-\lceil D(u,v)\rceil-1}X_{(u,v)}(r)\le 0,\\ &v\in R, w\in R\cup O, u\in R\cup S,\\ &0\le t<N_d-1, N_d=\lceil\frac{Td}{Ts}\rceil,\end{aligned} \tag{9}$$

where $\xi_{in}(v)$ is the edge set through which the node in the network could sent out data to the node v, N_d is the total number of time slots in the segment.

In our model, the responsibility of the relay nodes is to forward the message generated by the source node and the relay nodes would not generate data by themselves. Our scheduling guarantee the energy efficiency of the network that all the data transmitted by the source nodes could be received by the destination nodes. Therefore, there is another constraint following that the total data received by the relay nodes should be equal to the data it transmitted during the whole segment length T_d:

$$\begin{aligned}&\sum_{(v,w)\in\xi_{out}(v)}\sum_{r=0}^{N_d-1}X_{(v,w)}(r)\\ -&\sum_{(u,v)\in\xi_{in}(v)}\sum_{r=0}^{N_d-\lceil D(u,v)\rceil-2}X_{(u,v)}(r)=0,\\ &v\in R, w\in R\cup O, u\in R\cup S.\end{aligned}\tag{10}$$

The following constraint makes sure that the data transmitted from the node u to v at the time slot t and the one transmitted from the node w to z at the time slot $t+\lceil D(u,v)-D(w,v)\rceil$ or $t+\lceil D(u,v)-D(w,v)\rceil-1$ would not transmit simultaneously. It is because that the transmission from node w to z generates additional interference to the node v, and the SINR threshold of the node v would not be exceeded under such constraint.

$$\begin{aligned}&2X_{(u,v)}(t)+X_{(w,z)}(t+\lceil D(u,v)-D(w,v)\rceil)\\ &+X_{(w,z)}(t+\lceil D(u,v)-D(w,v)\rceil-1)\le 2,\\ &u\in R\cup O, w\in V, (u,v)\in\xi_{out}(u), (w,z)\in\xi_{out}(w),\\ &u\ne w, 0\le t\le N_d-1.\end{aligned}\tag{11}$$

In our network model the source node can broadcast the data it generated, and multiple relay nodes can receive and forward it. This redundancy facilitates spatial diversity of the data generated by the source node. However, for energy efficiency we limit the data forwarded by the relay node can only be received by another relay node or the destination node. As a result, we arrive at the following broadcast and unicast constraint:

$$\sum_{(u,v)\in\xi_{out}(u)}X_{(u,v)}(t)\le 1, u\in R, 0\le t\le N_d-1.\tag{12}$$

Due to the half-duplex characteristic of the underwater acoustic modem, the transducer of the modem could not be the transmitter and the receiver at the same time. So the following constraint delegates that the relay nodes in the network cannot transmit and receive data at the same time slot:

$$\begin{aligned}&2X_{(v,w)}(t_{(v,w)})+X_{(u,v)}(t_{(v,w)}-\lceil D(u,v)\rceil)\\ &+X_{(u,v)}(t_{(v,w)}-\lceil D(u,v)\rceil-1)\le 2,\\ &(u,v)\in\xi_{out}(v), (v,w)\in\xi_{in}(v), v\in R, u\in V,\\ &0\le t_{(v,w)}\le N_d-1.\end{aligned}\tag{13}$$

Finally, our aim is to maximize the throughput and minimize the power consumption of the underwater grid network. For a better optimal solution we normalize the transmission power and the throughput as follows:

$$\begin{aligned}\min\ &\sum_{(v,w)\in\xi_{out}(v)}\sum_{k=0}^{N_d-1}X_{(v,w)}(k)\frac{P_{(v,w)}(k)}{P_{max}} \qquad (14)\\ &-\sum_{(u,z)\in\xi_{out}(u)}\sum_{r=0}^{N_d-1}X_{(u,z)}(r)\\ &u\in S, v\in V, w\in V, z\in V,\\ s.t.\ \ &(9)-(13), \qquad (15)\end{aligned}$$

where P_{max} denotes the maximum transmission power over the whole network.

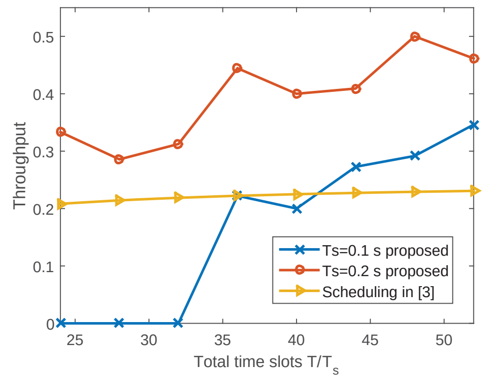
IV. Simulation Results

In our simulations, all the nodes are arranged in a 800 m $\times$ 800 m 2D grid network. The distance between adjacent rows and adjacent columns is 200 m. The network structure is the same as the one in Fig. 1. There are in total four source nodes, eight relay nodes and four gateway nodes. The maximum power for transmission of all the nodes is set as 1 mW and the noise of the underwater environment is 10 nW. In our simulations we set the T_s as 0.1 s and 0.2 s, and the T_d could varies from $6T_s$ to $13T_s$.

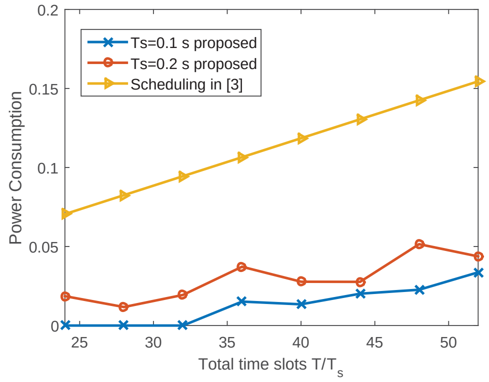
We formulate the ILP problem based on the parameters and the constraints above. Then we solve the ILP problem by the YAMLIP toolbox [8]. Simulation results in Fig. 4(a) and Fig. 4(b) show the performance of the grid network among the scheduling schemes. We test three scheduling schemes in total: the proposing scheduling scheme with $T_s=0.1s$ and $T_s=0.2s$, respectively, and the scheduling scheme in [3]. Considering the scheduling scheme in [3] is not completely interference free, we obtain the performance of the scheduling in [3] by removing part of the scheduling which could not be successfully received by the receivers. The simulation results show the scheduling scheme we proposed has a larger throughput and lower energy consumption in an adequate number of total time slots compared to the scheduling scheme proposed by [3]. This benefits from the interference free scheduling we proposed, which would not waste any energy for transmission. Another result is that the proposing scheduling scheme with $T_s=0.2s$ has a larger throughput than the one with $T_s=0.1s$. However, the source node needs to wait for a longer time for the transmission in its unique segment of the next frame due to the larger T_s. In Fig. 4(c), we test the throughput of the source node 13 when the relay node 5 in the grid network fails and could not forward the data to the gateway node. In this scenario, the throughput of the source node 13 becomes zero when we adopt the scheduling in [3]. The reason is the scheduling in [3] only forward the data through a single path. However, the source node 13 in the proposing scheduling could still transmit data to the gateway node as we increase the spatial diversity of the data.

V. Conclusion

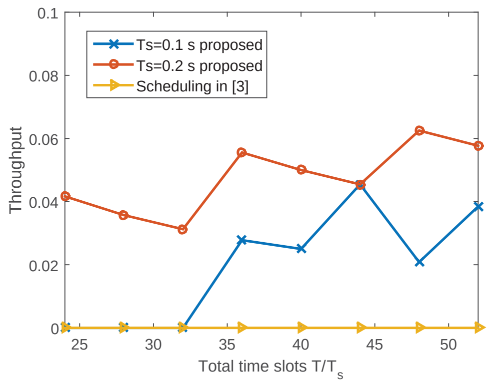
This paper proposes a new scheduling scheme for the TDMA protocol in multi-hop underwater acoustic grid networks. The proposed scheme could guarantee the completely



(a) Throughput



(b) Power consumption



(c) Throughput of node 13 when node 5 fails

Fig. 4. Simulation results

interference free and benefit from spatial diversity in the grid network. Moreover, we optimize the throughput and the energy consumption of the network in the scheme. The simulation results show that our scheduling scheme achieves both energy efficiency and information reliability in the grid network.

References

[1] L. Badia, M. Mastrogiovanni, C. Petrioli, S. Stefanakos, and M. Zorzi, "An optimization framework for joint sensor deployment, link scheduling and routing in underwater sensor networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 11, no. 4, pp. 44-56, 2007.

[2] M. Chitre, M. Motani, and S. Shahabudeen, "Throughput of networks with large propagation delays," *IEEE J. Ocean. Eng.*, vol. 37, no. 4, pp. 645-658, Oct. 2012.

[3] S. Lmai, M. Chitre, C. Laot and S. Houcke, "Throughput-Maximizing Transmission Schedules for Underwater Acoustic Multihop Grid Networks," *IEEE J. Ocean. Eng.*, vol. 40, no. 4, pp. 853-863, Oct. 2015.

[4] P. Anjangi and M. Chitre, "Unslotted transmission schedules for practical underwater acoustic multihop grid networks with large propagation delays," *in Proc. IEEE UComms*, Lerici, pp. 1-5, Aug. 2016.

[5] Robert J U. *Principles of underwater sound*, New York: McGraw-Hill Book Company, 1983.

[6] P. Gupta and P. Kumar, The capacity of wireless networks, *IEEE Trans. on Information Theory*, vol. 46, no. 2, pp. 388-404, 2000.

[7] Fengji Ye, Su Yi and B. Sikdar, "Improving spatial reuse of IEEE 802.11 based ad hoc networks," *in Proc. IEEE GLOBECOM*, San Francisco, pp. 1013-1017, Dec. 2003 .

[8] J. Lofberg, "YALMIP : a toolbox for modeling and optimization in MATLAB," *in Proc. IEEE International Symposium on Computer Aided Control Systems Design*, Taipei, pp. 284-289, Sept. 2004.