Computer Networks 169 (2020) 107097

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

# On the throughput optimization for message dissemination in opportunistic underwater sensor networks

Linfeng Liu[a,d], Ran Wang[b,c,*], Gaoxi Xiao[b], Dongyue Guo[d]

[a] School of Computer Science and Technology, Nanjing University of Posts and Telecommunications, Nanjing 210023, China
[b] College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
[c] School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore, 639798, Singapore
[d] Jiangsu Key Laboratory of Big Data Security and Intelligent Processing, Nanjing University of Posts and Telecommunications, Nanjing 210023, China

ARTICLE INFO

*Article history:*
Received 19 July 2018
Revised 28 December 2019
Accepted 2 January 2020
Available online 10 January 2020

*Keywords:*
Opportunistic underwater sensor networks
Message dissemination
Network throughput optimization
Propagation delay

ABSTRACT

Opportunistic underwater sensor networks (OUSNs) are deployed for various underwater applications, such as underwater creatures tracking and tactical surveillance. However, the storage capacity of the sensor nodes in such networks may be insufficient, especially when a wealth of data messages are generated rapidly in some emergency response applications. The message dissemination in OUSNs therefore may differ significantly from those in wireless sensor networks or delay-tolerant networks, where network throughput should be taken as one of the primary objectives of network performance. To this end, the strategies for message storing, disseminating and discarding are investigated, and a Message Dissemination Approach for Storage-Limited (MDA-SL) OUSNs is proposed. In MDA-SL, the messages are preferred to be disseminated to the nodes with higher speed or larger residual storage. In addition, the copies of newer messages are inclined to be discarded when their message holders' storage is full. Simulation results demonstrate the excellent performance of MDA-SL, showing that it can achieve satisfactory network throughput with propagation delay being restricted according to the diverse application requirements.



## 1. Introduction

With the broad deployments of mobile sensor nodes, opportunistic mobile sensor networks (OMSNs) [1,2] are introduced to conduct large-scale sensing at a lower cost compared to that of a ubiquitous static infrastructure of sensing devices. Because of the node mobility, however, the available contacts between nodes may be scarce and short, leading to some unstable communication paths. Opportunistic message dissemination techniques enable the network nodes to communicate in an environment where the contemporaneous end-to-end paths are unavailable or unstable, by allowing a data message to be transferred from source to destination in discrete hops even when an end-to-end communication path never emerges.

As a derivative form of OMSNs, the opportunistic underwater sensor networks (OUSNs) [3] technology enables various underwater applications, such as underwater creatures tracking [4] and tactical surveillance [5]. However, compared with massive collected data, the storage capacities of nodes are usually insufficient [6,7]. What is worse, the network throughput (which is defined as the total number of data messages received per unit time by the destinations of all the multi-hop flows in the network) is significantly restricted because the capacity of nodal storage modules is extremely limited (the space memory is even measured in KB [8], e.g., the chip CC2430 has a flash memory of 128 KB [9]).

As acoustic communication [10] is the typical physical-layer technology in OUSNs, another outstanding feature of OUSNs is the nontrivial propagation delay because acoustic waves are much slower than electromagnetic waves (the speed of acoustic waves is approximately 1,500 m/s in water). Such constraints make it difficult to deliver all the data messages to the destination timely, especially when data messages are generated rapidly in some emergency response applications [11].

Further adding to the above difficulties, OUSNs nodes (floating nodes) may move irregularly under the influences of underwater creatures or water currents. Specifically, some sensors may be directly fastened on irregular mobile carriers (vehicles), making it almost impossible to predict their future trajectories. As shown in Fig. 1, environmental events are monitored by the floating sensor nodes fastened on mobile underwater vehicles (such as whales) or the anchored nodes equipped with floating buoys [12,13] (The cost of anchored nodes is high, hence their number is relatively small in most applications), from which the signals are transmitted to destination sinks through intermittent multi-hop communications.

* Corresponding author.

https://doi.org/10.1016/j.comnet.2020.107097
1389-1286/

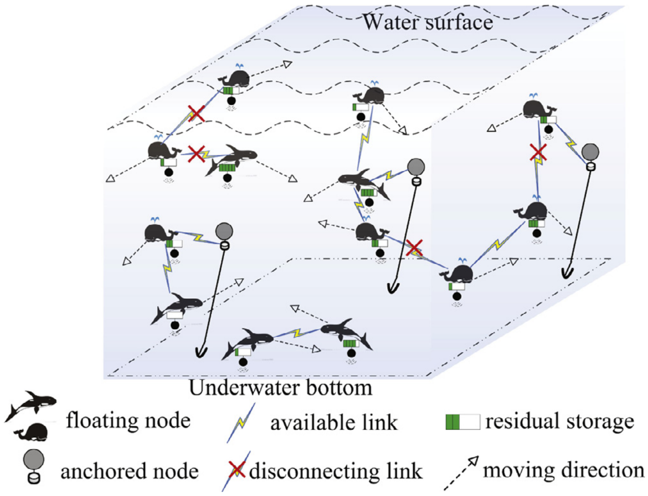



**Fig. 1.** Architecture of an OUSN.

To summarize, the message dissemination techniques in storage-limited OUSNs are still confronted with several challenges:

**1) Limited storage.** The limited storage has a direct impact on the message dissemination especially when the number of data messages existing in networks is considerable. To improve the network throughput, the number of disseminated message copies should be regulated, ensuring that they adapt to the residual storage of nodes. Besides, some stored message copies may have to be discarded due to the new arrivals of other message copies.

**2) Sophisticated mobility of floating nodes.** Complicated underwater environment factors (e.g., water currents and swimming underwater creatures) contribute to the sophisticated mobility of floating nodes. Links between network nodes may appear or disappear over time, and consequently, the historical trajectories can hardly help predict the future trajectories.

**3) Distributed control with good scalability.** OUSNs usually consist of abundant nodes with the task of determining the next hop of their data transmission independently without any centralized decision making. Distributed algorithms have to be developed which must be of reasonably low complexities.

To handle the above challenges, in this paper, we target to helping answer the following three questions: (*a*) **How** should a *message holder* (a node carrying a copy of the data message) select the next-hop forwarders from its neighboring *ordinary nodes* (the nodes not carrying any message copy)? (*b*) **How many** message copies should be disseminated at each time slot? (*c*) **Which** stored message copies should be discarded to make room for newly arriving message copies? We will study on two different cases with and without storage overflow respectively.

The main contributions of this paper are threefold. First, the movement speed and residual storage of nodes are adopted as the crucial metrics for message dissemination decision making to improve the network throughput. We show that the nodes with faster movement and larger residual storage should retain more message copies. Second, message discarding strategy for the case with storage overflow is investigated. It is revealed that older messages being disseminated with fewer copies shall be assigned lower probabilities of being discarded. Last but not least, the proposed Message Dissemination Approach for Storage-Limited OUSNs (MDA-SL) is completely distributed with an acceptable complexity. Thus it is practical and with a good scalability.

The remainder of this paper is organized as follows: Section 2 briefly surveys some existing related studies. Section 3 proposes a network-based system model to describe the message dissemination process. Some primary analyses are reported in Section 4, forming a basis for algorithm designing. Section 5 presents the message dissemination approach (MDA-SL). Section 6 covers some further analyses on MDA-SL including the complexity, the impact of node storage capacity, and approximation ratio, etc. Numerical simulation results for performance evaluation of MDA-SL are reported in Section 7. Finally Section 8 concludes the paper. This work is a significant extension of our early work [14]. Specifically, we introduce a hybrid underwater mobility pattern (consisting of the irregular mobility of floating nodes and the spherical crown mobility of anchored nodes) into the network model, and the influences of anchored nodes movement characteristics on the dissemination problem are carefully evaluated. Besides, more detailed analysis on the performance of the MDA-SL is given from the aspect of the communication maintenance, and the dissemination weight settings of the algorithm are closer to realistic scenarios. Much more abundant simulation results are also provided to further clarify the merits of the proposed MDA-SL.

## 2. Related work

### 2.1. Message dissemination in DTNs or OUSNs

The problem concerning message dissemination in DTNs (Delay-Tolerant Networks) and mobile sensor networks has been extensively studied. The early representative work named Epidemic Forwarding (EF) was proposed in [15], where random pair-wise exchanges of messages among mobile nodes ensured the maximum delivery and the minimum delay. However, numerous redundant message copies were generated gradually in such process. In [16], a distributed adaptive opportunistic routing scheme using a reinforcement learning framework was proposed. The scheme can opportunistically route the packets even in the absence of reliable knowledge about the channel statistics and network models. An optimization framework eased by network coding was proposed for opportunistic routing [17]. The framework was used to define the notions of credits associated with a number of packets in a generation. A primal-dual algorithm was then utilized as the basis to derive a practical protocol.

Some relevant research has been conducted on the message dissemination in underwater sensor networks. Lee et al. [18] presented the Hydraulic Pressure based Anycast Routing Protocol (HydroCast) for reliable underwater event sensing and reporting to one of the surface sinks. HydroCast selected the proper subset of forwarders that maximized the progress greedily and limited the interference. A similar work can be found in [19], where the sequence number, hop count, and depth information were used to determine the direction of the next hop and build a directional trail to the closest sonobuoy. In [20], a generic prediction assisted single-copy routing scheme which can be configured for multiple mobility models was investigated. This scheme differentiated the network mobility patterns according to the short-duration traces, and then defined the features of the best routing paths. Its outstanding advantage was the self-adaptivity for various node mobilities. However, it relied on historical information to instantiate the prediction. Such historical information is hard to be exploited in OUSNs due to the sophisticated mobility of nodes. In [21], the Redundancy Based Adaptive Routing (RBAR) scheme was proposed for underwater sensor networks, and RBAR was demonstrated to satisfy different delay requirements by explicitly controlling the replication process, but the delivery ratio was not very desirable. Zhang et al. developed a Beam width and Direction Concerned Routing protocol (BDCR) for the message dissemination problem [22], which can obtain a high delivery ratio by considering the beam width and three-dimensional direction. Recently, a routing protocol MobiSink (mobile sink) for underwater sensor networks was presented in [23] to balance the load on the intermediate nodes through deploying some mobile sinks in four horizontal regions. Obviously, the cost of these mobile sinks was highly expensive, and thereby the availability of MobiSink was restricted. Coutinho et al. proposed the GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery over void regions (GEDAR) routing protocol [24]. GEDAR was an anycast, geographic and opportunistic routing protocol that routed data packets from sensor nodes to multiple sonobuoys (sinks) at the seas surface. When the node was in a communication void region, GEDAR tried to recover it through the depth adjustments of nodes which were hard to be realized due to the harsh underwater environment.

In fact, the irregular underwater mobility makes the historical trajectories of floating nodes be hardly utilized, and particularly many hypotheses in previous works are too strong with regard to OUSNs. Moreover, the above existing works do not take the throughput optimization into account, which is indeed very important for most of OUSNs applications.

### 2.2. Message dissemination for throughput

The throughput issue has been considered in DTN routings. In [25], a DTN routing algorithm which can find the EDT-optimal route by searching the time-varying topology was designed, and the results showed that this algorithm reduced the delivery time and improved the network throughput. Reference [26] proposed an inter-landmark data routing algorithm, which selected the popular places as landmarks and divided the entire DTN area into some subareas. Wang et al. [27] explored the transient contact patterns of the frequently encountered nodes, and the trace-driven simulations demonstrated that a higher throughput can be obtained, compared with some state-of-the-art DTN routing algorithms based on the encounter history knowledge.

Some attentions have also been paid to the message dissemination techniques for throughput optimization. For instance, Amerimehr et al. [28] gave an analytical study of the network throughput in a two-way relay network, which exploited the network coding to exchange source packets. In [29], a multi-radio multi-channel opportunistic cooperative routing protocol that chose some nodes with the least interference to improve the network throughput was presented. Reference [30] focused on selecting and prioritizing the forwarder list to minimize the energy consumption, and thus presented a routing strategy EEOR which can increase the network throughput. Niu et al. [31] conducted a theoretical analysis on the aggregated throughput capacity of opportunistic routing in WSNs with the consideration for lossy links and transmission fairness. They introduced the concept of the concurrent schedulable set to represent the constraints imposed by transmission conflicts, and then proposed the Opportunistic Routing (OR). Nevertheless, the issue of storage overflow in storage-limited networks is not considered in these works, and thereby the message discarding strategy and its impacts on the network throughput are not investigated.

### 2.3. Motivation of this work

Storage limitation of nodes is an important constraint in OUSNs, especially when the amount of interesting messages are massive. However, this issue has not been taken into account in previous research. The limitation of storage capacity will inevitably affect the network throughput: the storage limitation restricts the amount of message copies that can be stored at nodes, and thus the message deliveries are impaired even though the propagation delay tolerance is sufficiently long. Besides, there are two types of sensor nodes: floating nodes and anchored nodes, with two different mobility patterns, i.e., irregular mobility and spherical crown mobility; and thus the message copies disseminated to floating destination and anchored destination should be treated differently. This paper investigates the problem of message dissemination to optimize the network throughput in storage-limited OUSNs. A few strategies for message storing, disseminating and discarding will be proposed and evaluated.

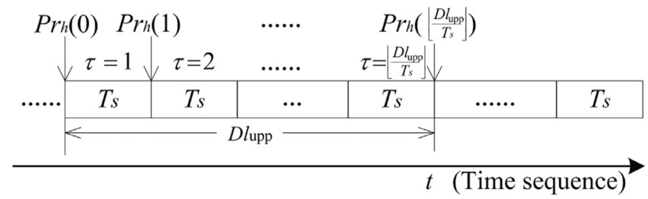



**Fig. 2.** Division of time slots.

## 3. System model and problem formulation

As shown in Fig. 1, there are two types of nodes: floating nodes and anchored nodes. Suppose that $N$ floating nodes and $N_a$ anchored nodes are deployed into an underwater space $\boldsymbol{D}$, where $\boldsymbol{D} \in \mathbb{R}^{+3}$.

The time is divided into discrete time slots with an equal length $T_s$, as illustrated in Fig. 2, where $t$ represents the absolute time slot, and $\tau$ denotes the relative slot (from the message's birth). The descriptions of the main notations are presented in Table 1.

### 3.1. System model

In OUSNs, each node is with the same communication range $R_c$ and the same storage capacity $S$. The coordinate of $V_i$ ($\forall\ V_i \in \boldsymbol{V}$, where $\boldsymbol{V}$ denotes the node set) at the $t$-th time slot is denoted by $C(i)^{(t)}$, which is expressed as a triple vector $(x(i)^{(t)}, y(i)^{(t)}, z(i)^{(t)})$.

In each time slot, the probability of generating a data message at each node is marked as $p_g$. Each data message is assumed to be with the same size $L_s$. Each generated message is disseminated during a period of $Dl_{\text{upp}}$, and all copies of the message are discarded when the period $Dl_{\text{upp}}$ has been expired.

The mobility of floating nodes is comprised of the autonomous movement controlled by underwater vehicles and the coordinate deviation impelled by underwater external forces [32]. The anchored nodes towed by wires are prone to offset around their static positions, causing each node to move noticeably within a spherical crown surface [12]. Usually, the buoyancy force is large enough, and thus the possible positions of the anchored node shape a spherical crown.

For two nodes $V_i, V_j \in \boldsymbol{V}$, the distance between them at the $t$th time slot is referred to as $d(i,j)^{(t)}$. $(i,j)^{(t)}$ is a feasible link when $d(i,j)^{(t)} \leq R_c$, and the propagation delay of messages on the link $(i,j)^{(t)}$ is expressed as [33]:

$$Delay(i,j)^{(t)} = \frac{L_s}{B} + \frac{d(i,j)^{(t)}}{S_{\text{uw}}}, \tag{1}$$

where $B$ is the channel capacity (in bits per second), and $S_{\text{uw}}$ is the propagation speed of underwater acoustic wave.

### 3.2. Problem objective

In this paper, the objective of the message dissemination problem in storage-limited OUSNs is to maximize the network throughput while the propagation delay of messages is restricted. Suppose

**Table 1**
Description of main notations.

| Parameter | Description | Parameter | Description |
|---|---|---|---|
| $R_c$ | Communication range | $msg(s,\ d)$ | Message from source $V_s$ to destination $V_d$ |
| $R_m$ | Maximum autonomous range | $C(i)^{(t)}$ | Coordinate of $V_i$ at the $t$th time slot |
| $v_m(i)^{(t)}$ | Movement speed of $V_i$ at the $t$th time slot | $\mathcal{V}_m$ | Maximum autonomous movement speed |
| $(i, j)^{(t)}$ | Link from $V_i$ to $V_j$ at the $t$th time slot | $d(i, j)^{(t)}$ | Distance between $V_i$ and $V_j$ |
| $Delay(i,\ j)^{(t)}$ | Propagation delay on link $(i, j)^{(t)}$ | $L_s$ | Size of data packet |
| $B$ | Channel capacity | $S_{uw}$ | Underwater sound speed |
| $Dl_{\text{upp}}$ | Upper bound of propagation delay | $\mathcal{G}(S)$ | Network throughput |
| $Pr_h(\tau)$ | Proportion of holders after $\tau - 1$ time slots | $Pr_{nh}(\tau)$ | Proportion of ordinary nodes |
| $W_f(i \to j)^{(t)}$ | Dissemination weight from $V_i$ to $V_j$ | $\overline{K}$ | Number of standard dissemination copies |
| $P_f(i \to j)^{(t)}$ | Dissemination probability of $V_i$ | $K(\tau)$ | The number of disseminated copies after $\tau$-1 time slots |
| $Pb(d(i,\ j)^{(t)})$ | Probability of $d(i,\ j)^{(t+1)} < R_c$ | $Dr(\tau)$ | Probability of message being delivered during $\tau$ time slots |
| $S(i)^{(t)}$ | Residual storage of $V_i$ at the $t$th time slot | $Da(\tau)$ | Probability of message being delivered at the $\tau$th time slot |

$msg(s,\ d)$ needs to be delivered from the source $V_s$ to the destination $V_d$. The objective function can be formally presented as follows:

$$\max\ \mathcal{G}(S),$$
$$s.t. \sum_{(k,k')^t} Delay(k, k')^{(t)} \le Dl_{\text{upp}},$$

where $(k,\ k')^{(t)}$ is a link on the path from $V_s$ to $V_d$ at the $t$th time slot.

To achieve the objective, the dissemination process of messages will be observed, and in next section some issues (such as selecting new message holders from neighboring ordinary nodes, discarding some stored message copies for new arrivals) are mathematically analyzed to obtain some valuable conclusions for designing the message dissemination algorithm. Besides, the number of standard dissemination copies $\overline{K}$ should be investigated due to the propagation delay restriction of messages.

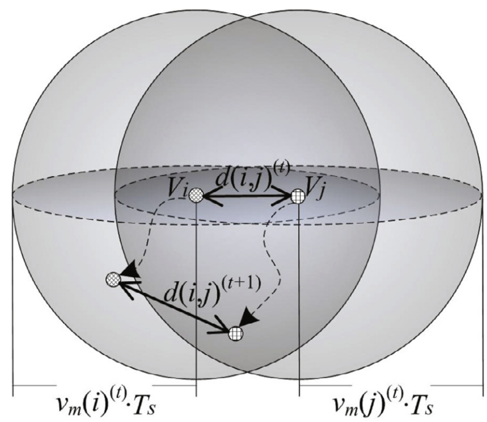



**Fig. 3.** Communication maintaining during two consecutive time slots.

## 4. Problem analysis

To achieve the maximum network throughput when the storage of nodes is limited, the message deliveries are formulated and analyzed mathematically in this section. Based on the analysis, some deductions regarding the impacts of movement speed, residual storage and proportion of message holders at the final time slot on the network throughput can be obtained for designing MDA-SL.

Each message holder is assumed to disseminate $\overline{K}$ copies at each time slot, and then at the final time slot the total number of message holders for each message is $\int_0^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor - 1} (1+\overline{K})^x \mathrm{d}x = \frac{(1+\overline{K})^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor - 1} - 1}{\ln(1+\overline{K})}$. Thus, the maximum $\overline{K}$ which OUSN's storage can undertake should satisfy that $\frac{(1+\overline{K})^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor - 1} - 1}{\ln(1+\overline{K})} = \frac{S}{L_s \cdot p_g}$. Thereby, two cases concerning the storage limitation of nodes will be discussed in the following subsections.

### 4.1. Case I: network throughput without storage overflow

Firstly, suppose $V_i$ is one message holder of $msg(s,\ d)$ at the $t$th time slot, and there is an ordinary node $V_j$ satisfying $d(i,\ j)^{(t)} \le R_c$, as shown in Fig. 3. Then the probability of $d(i, j)^{(t+1)} \le R_c$ ($V_i$ can still communicate with $V_j$ at the $(t+1)$th time slot) is denoted by $Pb(d(i,\ j)^{(t)})$, which is calculated as a conditional probability $\frac{P(d(i,j)^{(t+1)} \le R_c\ \&\ d(i,j)^{(t)} \le R_c)}{P(d(i,j)^{(t)} \le R_c)}$, and will be broken down into the following three sub-cases:

**Sub-case 1**: Both $V_i$ and $V_j$ are anchored nodes. Because the anchored nodes are under the same external force, the offsetting angles of nodes are the same, and the position offsets of nodes are also considered being of an equal value, which has been proven in our previous work [12]. Under such case, we have:

$$Pb(d(i,\ j)^{(t)}) = \begin{cases} 1, & d(i,\ j)^{(0)} \le R_c \\ 0, & d(i,\ j)^{(0)} > R_c. \end{cases}$$

As depicted in Fig. 4, the distance between anchored nodes $V_i$ and $V_j$ at the $t$th time slot is computed as

$$d(i,\ j)^{(t)} = \begin{Bmatrix} (h_i - h_j)^2 + L_{ij}^2 + (h_i - h_j)^2 \cdot \sin\alpha^2 \\ -2(h_i - h_j) \cdot L_{ij} \cdot \sin\alpha \cdot \cos\beta \end{Bmatrix}^{\frac{1}{2}}.$$

where $\alpha,\ \ \beta \in [0, \frac{\pi}{2}]$. There is $d(i,\ j)^{(t)} \le \{(h_i - h_j)^2 + [L_{ij} - (h_i - h_j) \cdot \sin\alpha]^2\}^{\frac{1}{2}} \le d(i,\ j)^{(0)}$, which indicates that the distance between anchored nodes in offsetting status is shorter than that in non-offsetting status, and thus $V_i$ and $V_j$ can maintain the communication with each other if their distance at non-offsetting position is shorter than the communication range.

**Sub-case 2**: Both $V_i$ and $V_j$ are floating nodes. Similar to our previous work [3], we can obtain that $Pb\Big(d(i,\ j)^{(t)}\Big) = \frac{9}{16\pi^2 \cdot {R_m}^6} \cdot \int_{-R_m}^{R_m} \mathrm{d}x_i \int_{-({R_m}^2 - x_i^2)^{\frac{1}{2}}}^{({R_m}^2 - x_i^2)^{\frac{1}{2}}} \mathrm{d}y_i \int_{-({R_m}^2 - x_i^2 - y_i^2)^{\frac{1}{2}}}^{({R_m}^2 - x_i^2 - y_i^2)^{\frac{1}{2}}} \mathrm{d}z_i \cdot \int_{d(i,j)^{(t)} - R_m}^{d(i,j)^{(t)} + R_m} \mathrm{d}x_j \int_{-\{{R_m}^2 - [x_j - d(i,j)^{(t)}]^2\}^{\frac{1}{2}}}^{\{{R_m}^2 - [x_j - d(i,j)^{(t)}]^2\}^{\frac{1}{2}}} \mathrm{d}y_j \int_{\delta_1}^{\delta_2} \mathrm{d}z_j$,

where $\delta_1 = \max\{z_i - [R_c^2 - (x_j - x_i)^2 - (y_j - y_i)^2]^{\frac{1}{2}},\ \ -[{R_m}^2 - (x_j - d(i,\ j)^{(t)})^2 - y_j^2]^{\frac{1}{2}}\}$, and $\delta_2 = \min\{z_i + [{R_c}^2 - (x_j - x_i)^2 - (y_j - y_i)^2]^{\frac{1}{2}},\ [{R_m}^2 - (x_j - d(i,\ j)^{(t)})^2 - y_j^2]^{\frac{1}{2}}\}$.

**Sub-case 3**: One of $V_i$ and $V_j$ is a floating node, and the other is an anchored node. Under this sub-case, the relative movement range can be regarded as $\frac{R_m}{2}$. Thus, $Pb(d(i,\ j)^{(t)}) =$

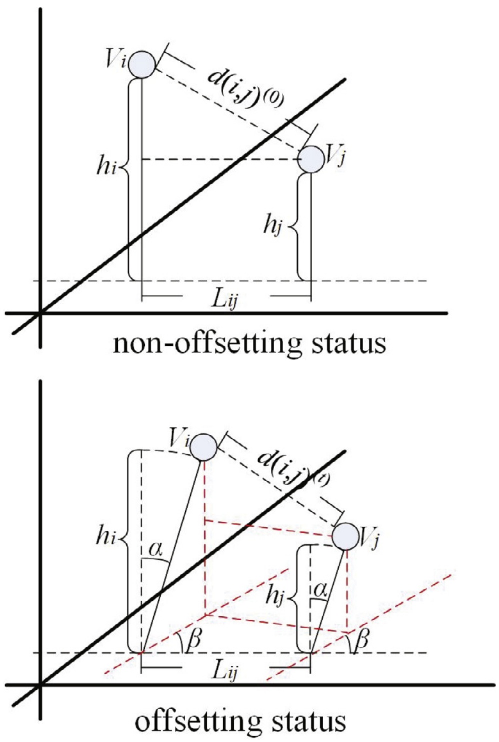



**Fig. 4.** Distance between anchored nodes.

$\frac{36}{\pi^2 \cdot R_m{}^6} \cdot \int_{-\frac{R_m}{2}}^{\frac{R_m}{2}} \mathrm{d}x_i \int_{-\{(\frac{R_m}{2})^2 - x_i^2\}^{\frac{1}{2}}}^{\{(\frac{R_m}{2})^2 - x_i^2\}^{\frac{1}{2}}} \mathrm{d}y_i \int_{-\{(\frac{R_m}{2})^2 - x_i^2 - y_i^2\}^{\frac{1}{2}}}^{\{(\frac{R_m}{2})^2 - x_i^2 - y_i^2\}^{\frac{1}{2}}} \mathrm{d}z_i \cdot \int_{d(i,j)^{(t)} - \frac{R_m}{2}}^{d(i,j)^{(t)} + \frac{R_m}{2}} \mathrm{d}x_j \int_{-\{(\frac{R_m}{2})^2 - [x_j - d(i,j)^{(t)}]^2\}^{\frac{1}{2}}}^{\{(\frac{R_m}{2})^2 - [x_j - d(i,j)^{(t)}]^2\}^{\frac{1}{2}}} \mathrm{d}y_j \int_{\delta_1}^{\delta_2} \mathrm{d}z_j,$

where $\delta_1 = \max\{z_i - [R_c{}^2 - (x_j - x_i)^2 - (y_j - y_i)^2]^{\frac{1}{2}}, -[(\frac{R_m}{2})^2 - (x_j - d(i,j)^{(t)})^2 - y_j^2]^{\frac{1}{2}}\}$, $\delta_2 = \min\{z_i + [R_c{}^2 - (x_j - x_i)^2 - (y_j - y_i)^2]^{\frac{1}{2}}, [(\frac{R_m}{2})^2 - (x_j - d(i,j)^{(t)})^2 - y_j^2]^{\frac{1}{2}}\}$.

Let $U = \frac{R_c}{\sqrt[3]{\frac{|\boldsymbol{D}|}{N}}}$ to simplify the notation. The expected probability that $V_i$ and $V_j$ maintain the communication during two consecutive time slots is expressed as $\frac{\sum_{k=1}^{U} Pb(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}) \cdot k^2}{\sum_{k=1}^{U} k^2}$. Consequently, the number of nodes that can maintain the communications with $V_i$ during two consecutive time slots is written as $\frac{\frac{4}{3}\pi N \cdot R_c{}^3}{|\boldsymbol{D}|} \cdot \frac{\sum_{k=1}^{U} Pb(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}) \cdot k^2}{\sum_{k=1}^{U} k^2}$.

Hence, the number of different neighbours of $V_i$ during two consecutive slots is $\frac{\frac{4}{3}\pi N \cdot R_c{}^3}{|\boldsymbol{D}|} \cdot [1 - \frac{\sum_{k=1}^{U} Pb(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}) \cdot k^2}{\sum_{k=1}^{U} k^2}]$. That is, if $V_i$ does not find $V_d$ in its neighbourhood at the $t$-th time slot, then the probability of $V_d$ existing in $V_i$'s neighbourhood at the $(t+1)$th time slot is expressed as $\frac{\frac{4}{3}\pi R_c{}^3}{|\boldsymbol{D}|} \cdot [1 - \frac{\sum_{k=1}^{U} Pb(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}) \cdot k^2}{\sum_{k=1}^{U} k^2}]$.

Therefore, as described in Fig. 5, the probability of $msg(s, d)$ being delivered during $\tau$ time slots is denoted by $Dr(\tau)$ and can be expressed recursively from the following equation:

$$Dr(\tau) = Dr(\tau - 1) + Da(\tau) \cdot \{1 - Dr(\tau - 1)\}. \tag{2}$$

Note that $Da(\tau)$ is the probability of $msg(s, d)$ being delivered at the $\tau$th time slot, particularly there is $Dr(0) = 0$, which implies that the destination does not hold a copy of $msg(s, d)$ at the beginning. We have:

$$Da(\tau) = \left\{ \begin{array}{l} \left[ 1 - \frac{\sum_{k=1}^{U} Pb\left(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}\right) \cdot k^2}{\sum_{k=1}^{U} k^2} \right] \cdot (1 + \overline{K})^{\tau} \\ + \left[ (1 + \overline{K})^{\tau+1} - (1 + \overline{K})^{\tau} \right] \end{array} \right\} \cdot \frac{\frac{4}{3}\pi R_c{}^3}{|\boldsymbol{D}|},$$

which shows that $Da(\tau)$ is calculated as the sum of two parts: the probability of old message holders encountering the destination; and the probability of new message holders (at the current slot) encountering the destination.

A Bernoulli differential equation $\frac{\mathrm{d}Dr(\tau)}{\mathrm{d}\tau} + Da(\tau + 1) \cdot Dr(\tau) = Da(\tau + 1)$ can be derived from (2), and thus $Dr(\tau)$ is further expressed as:

$$\begin{aligned} Dr(\tau) = & \left\{ \int Da(\tau + 1) e^{\int Da(\tau+1)\mathrm{d}\tau} \mathrm{d}\tau + C_1 \right\} \\ & \cdot e^{-\int Da(\tau+1)\mathrm{d}\tau} = C_1 \cdot e^{-\int Da(\tau+1)\mathrm{d}\tau} + 1. \end{aligned} \tag{3}$$

Thus, the achieved delivery ratio is equal to $Dr(\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \rfloor)$. Thereby,

$$\mathcal{G}(S) = \frac{N \cdot p_g}{T_s} \cdot Dr\left( \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \right),$$

which indicates that a larger number of the disseminated copies will give rise to a larger network throughput under Case I.

### 4.2. Case II: network throughput with storage overflow

To analyze the case concerning storage overflow, a differential equation is constructed to observe the dissemination process, where message holders (or ordinary nodes) are likely to discard (or receive) the message copies until the period $Dl_{\mathrm{upp}}$ has been expired. The proportion of message holders (or ordinary nodes) is defined as the proportion of the number of message holders (or ordinary nodes) to the total number of nodes, and denoted by $Pr_h(\tau)$ (or $Pr_{nh}(\tau)$):

$$Pr_h(\tau) + Pr_{nh}(\tau) = 1 \tag{4a}$$

$$\frac{\mathrm{d}Pr_h(\tau)}{\mathrm{d}\tau} = -\beta(\tau) \cdot Pr_h(\tau) + \alpha(\tau) \cdot Pr_{nh}(\tau) \tag{4b}$$

$$\frac{\mathrm{d}Pr_{nh}(\tau)}{\mathrm{d}\tau} = \beta(\tau) \cdot Pr_h(\tau) - \alpha(\tau) \cdot Pr_{nh}(\tau), \tag{4c}$$

where the proportion variations of message holders and ordinary nodes over time are expressed as the first-order derivatives $\frac{\mathrm{d}Pr_h(\tau)}{\mathrm{d}\tau}$ and $\frac{\mathrm{d}Pr_{nh}(\tau)}{\mathrm{d}\tau}$, respectively. As illustrated in Fig. 6, $\alpha(\tau)$ and $\beta(\tau)$ are the transition probabilities between the states of *message-holding* or *ordinary*. Formulas (4a) and (4b) are clearly Bernoulli equations. Hence, the expressions of $Pr_h(\tau)$ and $Pr_{nh}(\tau)$ are given as:

$$Pr_h(\tau) = e^{-\int\{\beta(\tau)+\alpha(\tau)\}\mathrm{d}\tau} \cdot \left\{ \int \alpha(\tau) \cdot e^{\int\{\beta(\tau)+\alpha(\tau)\}\mathrm{d}\tau} \mathrm{d}\tau + C_2 \right\}$$

$$Pr_{nh}(\tau) = e^{-\int\{\beta(\tau)+\alpha(\tau)\}\mathrm{d}\tau} \cdot \left\{ \int \beta(\tau) \cdot e^{\int\{\beta(\tau)+\alpha(\tau)\}\mathrm{d}\tau} \mathrm{d}\tau + C_3 \right\},$$

where $C_2$ and $C_3$ are constants. At the start of the $\tau$th time slot (from the birth of $msg(s, d)$), the number of message holders is $Pr_h(\tau - 1) \cdot N$. Thus, under Case II, $Da(\tau)$ can be rewritten as:

$$Da(\tau) = \frac{\frac{4}{3}\pi \cdot N \cdot R_c{}^3}{|\boldsymbol{D}|} \cdot \left\{ \begin{array}{l} \left[ 1 - \frac{\sum_{k=1}^{U} Pb\left(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}\right) \cdot k^2}{\sum_{k=1}^{U} k^2} - \beta(\tau - 1) \right] \\ \cdot Pr_h(\tau - 1) + \alpha(\tau - 1) \cdot Pr_{nh}(\tau - 1) \end{array} \right\}, \tag{5}$$

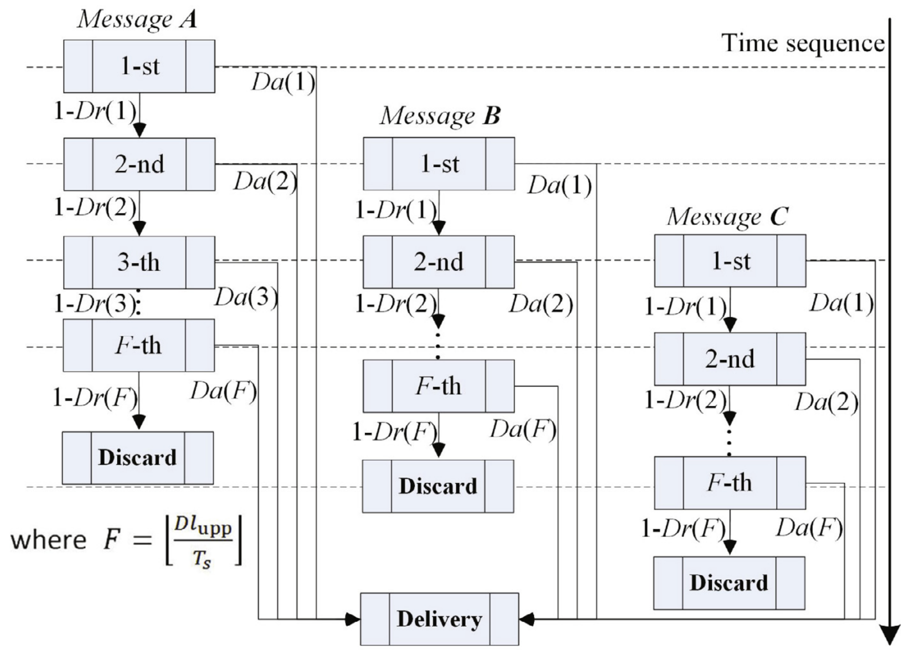



**Fig. 5.** Dissemination process of data messages.

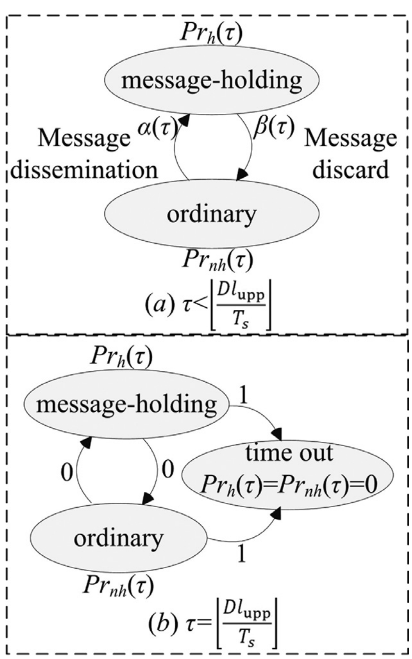



**Fig. 6.** State transitions between message-holding state and ordinary state.

where $\frac{\frac{4}{3}\pi\cdot N\cdot R_c{}^3}{|\mathbf{D}|}\cdot\{1-\frac{\sum_{k=1}^{U}Pb(k\cdot\sqrt[3]{\frac{|\mathbf{D}|}{N}})\cdot k^2}{\sum_{k=1}^{U}k^2}-\beta(\tau-1)\}\cdot Pr_h(\tau-1)$ denotes the probability of delivery achievement by the destination node existing in the neighbourhood of message holders, and $\frac{\frac{4}{3}\pi\cdot N\cdot R_c{}^3}{|\mathbf{D}|}\cdot\alpha(\tau-1)\cdot Pr_{nh}(\tau-1)$ denotes the probability of delivery achievement by making the destination node become a message holder. (5) expresses that some stored message copies may be discarded for accepting the newly arriving ones, and the discarding strategy will be introduced in Section 5.

### 4.3. Deductions

The node movements typically are not too fast. Hence at least one interaction is considered to be completed at each node encounter, even though the two nodes move towards the opposite directions, and thus $2\mathcal{V}_m\cdot T_s\le R_c$. Based on that, the following Theorem 1 and Theorem 2 prove that the network throughput will be increased if the nodes with faster movement speed or with larger residual storage become the message holders.

**Theorem 1.** *As long as the node movements are not too fast ($\mathcal{V}_m\le\frac{R_c}{2T_s}$), still allowing at least one interaction to be completed at each node encounter, a faster movement speed of nodes will produce a higher network throughput.*

**Proof**: Note that the first-order derivative of $\mathcal{G}(S)$ with respect to $\mathcal{V}_m$ is $\frac{\mathrm{d}\mathcal{G}(S)}{\mathrm{d}\mathcal{V}_m}=\frac{N\cdot p_g}{T_s}\cdot\frac{\mathrm{d}Dr(\lfloor\frac{Dl_{upp}}{T_s}\rfloor)}{\mathrm{d}\mathcal{V}_m}$, where

$$\frac{\mathrm{d}Dr(\tau)}{\mathrm{d}\mathcal{V}_m}=\frac{\mathrm{d}\int Da(\tau+1)\cdot e^{\int Da(\tau+1)\mathrm{d}\tau}\mathrm{d}\tau}{\mathrm{d}\mathcal{V}_m}\cdot e^{-\int Da(\tau+1)\mathrm{d}\tau}+\frac{\mathrm{d}e^{-\int Da(\tau+1)\mathrm{d}\tau}}{\mathrm{d}\mathcal{V}_m}\cdot\left\{\int Da(\tau+1)\cdot e^{\int Da(\tau+1)\mathrm{d}\tau}\mathrm{d}\tau+C_1\right\}.$$

To simplify the analytical expression, we define $f(\mathcal{V}_m)=\frac{1+\overline{K}}{\ln(1+\overline{K})}\cdot\{\overline{K}+1-\sum_{k=1}^{U}Pb(k\cdot\sqrt[3]{\frac{|\mathbf{D}|}{N}})\cdot k^2/\sum_{k=1}^{U}k^2\}\cdot\frac{\frac{4}{3}\pi\cdot R_c{}^3}{|\mathbf{D}|}$. Then, $\int Da(\tau+1)\mathrm{d}\tau=f(\mathcal{V}_m)\cdot(1+\overline{K})^{\tau}$, and thus $\frac{\mathrm{d}Dr(\tau)}{\mathrm{d}\mathcal{V}_m}$ can be rewritten as:

$$\frac{\mathrm{d}Dr(\tau)}{\mathrm{d}\mathcal{V}_m}=-C_1\cdot\frac{\mathrm{d}f(\mathcal{V}_m)}{\mathrm{d}\mathcal{V}_m}\cdot(1+\overline{K})^{\tau}\cdot e^{-f(\mathcal{V}_m)\cdot(1+\overline{K})^{\tau}}.$$

Since we typically have the special value of $Dr(\tau)$, i.e., $Dr(0)=0$, from which we can obtain that $e^{-f(\mathcal{V}_m)}\cdot\{e^{f(\mathcal{V}_m)}+C_1\}=0$ and $C_1=-e^{f(\mathcal{V}_m)}$. Obviously, $Pb(d(i,\ j)^{(t)})$ is inversely proportional to $\mathcal{V}_m$ according to the definition of $Pb(d(i,\ j)^{(t)})$. Therefore, there are $\frac{\mathrm{d}f(\mathcal{V}_m)}{\mathrm{d}\mathcal{V}_m}>0$ and $\frac{\mathrm{d}Dr(\tau)}{\mathrm{d}\mathcal{V}_m}>0$, which indicates that a faster movement produces a higher network throughput. □

**Theorem 2.** *Before the nodes' storage is full, message copies should be disseminated to the nodes with more residual storage to achieve a higher network throughput.*

**Proof.** Suppose $V_k$ is one of the message holders of *msg*(*s, d*) at the *t*th time slot, and there is an ordinary node $V_i$ satisfying $d(k, i)^{(t)} \le R_c$. At the *t*th time slot (*msg*(*s, d*) has experienced $\tau$ time slots from its birth), if the storage capacity of $V_i$ has not been full, then the probability of $V_i$ receiving and storing one *msg*(*s, d*) copy is calculated as $\frac{\overline{K}\cdot(1+\overline{K})^{\tau}}{N}$; and it is expected that after $\tau_f$ time slots the storage of $V_i$ will be full, where $\tau_f$ satisfies the equation $p_g \cdot \sum_{\kappa=0}^{\tau_f+t}(1+\overline{K})^{\kappa} = S(i)^{(t)}$. Apparently, more copies of *msg*(*s, d*) can be stored if the nodes with larger residual storage are selected to store the new *msg*(*s, d*) copies, and thus achieving a higher network throughput. □

**Theorem 3.** *Network throughput will be increased with the growth of the proportion of message holders at the* $\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor$*-th time slot.*

**Proof.** The total number of message copies is $N \cdot p_g \cdot \sum_{\tau=0}^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor -1} \prod_{\widetilde{\tau}=0}^{\tau}[1+K(\widetilde{\tau}+1)]$ during the $\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor$ time slots, but the total storage capacity is $N \cdot S$, where there is $N \cdot S < N \cdot p_g \cdot \sum_{\tau=0}^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor -1} \prod_{\widetilde{\tau}=0}^{\tau}[1+K(\widetilde{\tau}+1)]$ in the case of storage overflow. The full storage indicates that the stored message copies have reached the upper limit of storage, and the following equation should be established:

$$N^2 \cdot p_g \cdot \sum_{\widetilde{\tau}=1}^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor} Pr_h(\widetilde{\tau}) = \frac{N \cdot S}{L_s},$$

which indicates there are $N^2 \cdot p_g \cdot Pr_h(\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor)$ message copies to be discarded, and we can obtain the approximate equation $\int_0^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor} Pr_h(\tau)\mathrm{d}\tau \approx \frac{S}{L_s \cdot p_g \cdot N} + \frac{1}{N}$.

At each time slot, the number of newly generated message copies is $N \cdot p_g + N^2 \cdot p_g \cdot \sum_{\widetilde{\tau}=0}^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor -1} Pr_h(\widetilde{\tau}) \cdot K(\widetilde{\tau}+1)$, and the number of discarded message copies is calculated as $N^2 \cdot p_g \cdot \sum_{\widetilde{\tau}=0}^{\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor -1} \beta(\widetilde{\tau}) \cdot Pr_h(\widetilde{\tau})$. Because the number of discarded message copies is equal to the number of newly generated message copies due to the storage limit, there must be

$$N \cdot Pr_h\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor\right) + N \cdot \sum_{\widetilde{\tau}=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor -1} \beta(\widetilde{\tau}) \cdot Pr_h(\widetilde{\tau}) = 1 + N \cdot \sum_{\widetilde{\tau}=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor -1} Pr_h(\widetilde{\tau}) \cdot K(\widetilde{\tau}+1),$$

which yields

$$\sum_{\widetilde{\tau}=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor -1} \{Pr_h(\widetilde{\tau}+1) - Pr_h(\widetilde{\tau})\} = Pr_h\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor\right) - \frac{1}{N}.$$

Therefore, $Dr(\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor)$ can be derived as:

$$Dr\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor\right) \approx 1 + C_1 \cdot \exp\left\{ -\frac{\frac{4}{3}\pi {R_c}^3 \cdot N}{|\boldsymbol{D}|} \cdot \left[ \begin{array}{l} Pr_h\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor\right) - \frac{1}{N} \\ + \left(1 - \frac{\sum_{k=1}^{U} Pb\left(k \cdot \sqrt[3]{\frac{|\boldsymbol{D}|}{N}}\right) \cdot k^2}{\sum_{k=1}^{U} k^2}\right) \\ \cdot \left(\frac{S}{L_s \cdot p_g \cdot N} + \frac{1}{N}\right) \end{array} \right] \right\} \tag{6}$$

where $C_1 = -e^{f(\mathcal{V}_m)} < 0$, and the increase of $Pr_h(\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor)$ will enhance the network throughput. □

| Message Type | Time | Self-Information | | Data Set | Sent To | Data |
|---|---|---|---|---|---|---|
| *inquire_msg* | Slot sequence | $V_i$ | $C(i)^{(t)}$ | *Msg_list*(*i*) | NULL | NULL |
| *reply_msg* | Slot sequence | $V_j$ | $C(j)^{(t)}$ | *Msg_list*(*j*) | $V_i$ | NULL |
| *data_msg* | Slot sequence | $V_i$ | $C(i)^{(t)}$ | NULL | $V_j$ | *msg*(*s,d*) |

**Fig. 7.** Message structures.

The conclusions of Theorem 1 and Theorem 2 indicate that ordinary nodes moving faster and retaining more residual storage should be selected as the new message holders to improve the network throughput. These conclusions will be reflected by the expression of dissemination weight in Step 2 of MDA-SL. Theorem 3 suggests that the copies of older messages should be kept to enlarge the $Pr_h(\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor)$, and the copies of newer messages should be discarded in priority to improve the network throughput. However, the copies of newer messages cannot be absolutely discarded because the excessively discards of newer ones also result in the reduction of $Pr_h(\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor)$ or even the disappearances of some newly generated messages. This implies that the value of $\vartheta$ should be properly set, as verified in Section 7.4. The conclusion of Theorem 3 will be applied to design the discard probability in Step 5 of MDA-SL.

## 5. Dissemination algorithm

In this section, a Message Dissemination Approach for Storage-Limited OUSNs (MDA-SL) is designed to optimize the network throughput. Two issues in the message dissemination, namely the selection of new message holders and the selection of discarded message copies respectively, are carefully addressed. Note that MDA-SL is a completely distributed algorithm, where global computations and message interactions (such as the interactions for real-time position of the destination) are not needed. The cost of running MDA-SL thereby is very low. The detailed description and illustration of MDA-SL are given as follows:

***Step*** 1. At the start of the current time slot (suppose at the *t*th time slot, *msg*(*s, d*) has experienced $\tau$ time slots), in the range $R_c$ each holder $V_i$ should broadcast an *inquire_msg* after a random backoff time *random*(0, $t_b$), where $t_b$ denotes the maximum backoff time. Each *inquire_msg* includes a quadruplet $(ID, t, C(i)^{(t)}, Msg\_list(i))$, as shown in Fig. 7.

***Step*** 2. Once receiving the *inquire_msg* from $V_i$, each neighbouring node $V_j$ replies a *reply_msg* (Fig. 7) after a random backoff time. If $V_d$ has received an *inquire_msg* from one message holder, it will purposely send a *data_msg* (Fig. 7) to $V_d$ subsequently, and then Step 6 is carried out; otherwise, each message holder calculates the dissemination probabilities from itself to its neighbouring nodes as:

**Case I**: If either $V_d$ or $V_j$ is not an anchored node, the dissemination weight $W_f(i \to j)^{(t)}$ from $V_i$ to $V_j$ is defined as:

$$W_f(i \to j)^{(t)} = \begin{cases} 0, & if\ msg(s,d) \in Msg\_list(j) \\ \left(1 + \frac{v_m(j)^{(t)} - v_m(i)^{(t)}}{\mathcal{V}_m}\right)^{\varepsilon} \cdot \left(1 + \frac{S(j)^{(t)}}{S}\right)^{\epsilon}, & otherwise, \end{cases} \tag{7}$$

where $\varepsilon$ and $\epsilon$ are preset constants. Formula (7) indicates that the message holders prefer to disseminate message copies to those nodes moving faster and retaining more residual storage.

**Case II**: If both $V_d$ and $V_j$ are anchored nodes, then $W_f(i \to j)^{(t)}$ should be defined as:

$$W_f(i \to j)^{(t)} = \begin{cases} 0, & if\ msg(s,d) \in Msg\_list(j) \\ \left(1 + \frac{v_m(j)^{(t)} - v_m(i)^{(t)}}{v_m}\right)^{\varepsilon} \cdot \left(1 + \frac{S(j)^{(t)}}{S}\right)^{\epsilon} \cdot (1 + \triangle_1), & otherwise, \end{cases}$$

where $\triangle_1$ is a positive increment in dissemination weight. The movements of anchored destinations are restricted within the spherical crown surface, hence leading to the easier message deliveries with anchored destination nodes. Accordingly, the message copies will be disseminated via other anchored nodes preferentially.

***Step*** 3. The dissemination probability of $V_i$ at the $t$th time slot is computed as:

$$P_f(i \to j)^{(t)} = K(\tau) \cdot \frac{W_f(i \to j)^{(t)}}{\sum_{d(i,k)^{(t)} \le R_c} W_f(i \to k)^{(t)}}, \tag{8}$$

which suggests that the dissemination probability grows with the increase of the movement speed and the residual storage of $V_j$. $K(\tau)$ is the number of disseminated copies and is obtained as:

$$K(\tau) = \overline{K} \cdot \frac{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor - \tau}{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor - \tau + 1} - 1. \tag{9}$$

(9) indicates that the number of disseminated copies decreased over time.

***Step*** 4. On the basis of $P_f(i \to j)^{(t)}$, $V_i$ makes a decision on whether to disseminate a $msg(s, d)$ copy to $V_j$. If $V_j$ receives a $msg(s, d)$ copy from $V_i$, and there is $S(j)^{(t)} > 0$, then the list of message copies stored by $V_j$ is updated as $Msg\_list(j) \leftarrow Msg\_list(j) \bigcup msg(s,d)$, and go to Step 7; otherwise, if $S(j)^{(t)} = 0$ then Step 5 is carried out.

***Step*** 5. To make room for the newly received $msg(s, d)$ copy, a stored copy of other message should be selected to be discarded. The discard weight $DW_j(s', d')^{(t)}$ of $msg(s', d')$ ($msg(s', d') \in Msg\_list(j)$) is defined as:

$$DW_j(s',d')^{(t)} = \begin{cases} K_j(s',d')^{(t)} \cdot \left(1 - \frac{\tau(s',d')}{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor}\right)^{\vartheta}, & if\ V_d\ is\ anchored, \\ K_j(s',d')^{(t)} \cdot \left(1 - \frac{\tau(s',d')}{\left\lfloor \frac{Dl_{\text{upp}}}{T_s} \right\rfloor}\right)^{\vartheta} \cdot (1 - \triangle_2), & otherwise, \end{cases}$$

where $\tau(s', d')$ denotes the number of time slots $msg(s', d')$ has experienced, and $K_j(s', d')^{(t)}$ is the number of $msg(s', d')$ copies stored by neighbouring nodes of $V_j$. $\triangle_2$ is a decrement in discard weight to reduce the possibility of discarding the message copies which are disseminated to anchored destination nodes. Then, the $msg(s', d')$ copy is selected to be discarded according to the discard probability $DP_j(s', d')^{(t)}$:

$$DP_j(s',d')^{(t)} = \frac{DW_j(s',d')^{(t)}}{DW_j(s,d)^{(t)} + \sum_{msg(s',d') \in Msg\_list(j)} DW_j(s',d')^{(t)}}, \tag{10}$$

which implies that the copy of the message which is newer and has more copies in the neighbourhood of $V_j$ is more likely to be discarded.

***Step*** 6. If the $msg(s', d')$ copy is selected to be discarded, then $Msg\_list(j) \leftarrow Msg\_list(j) \setminus msg(s',d')$ and $Msg\_list(j) \leftarrow Msg\_list(j) \bigcup msg(s,d)$.

***Step*** 7. The above steps will be repeated until $V_d$ receives one copy of $msg(s, d)$ or the period $Dl_{\text{upp}}$ has been expired. If $msg(s, d)$ copy has been delivered to $V_d$ before the expiration of period $Dl_{\text{upp}}$, an announcement message originated from $V_d$ will be propagated to all the message holders of $msg(s, d)$ to stop the further dissemination and discard all $msg(s, d)$ copies. The size of announcement message is very small and can be piggybacked with other messages. Thus the effect of broadcast is negligible.

Note that $T_s$ is set as the minimum period during which each node can accomplish the procedure of Step 1 to Step 6, and the execution time is mainly occupied by message transmissions. *inquire_msg*, *reply_msg* and *data_msg* are assumed to be with the same size $L_s$, and hence $T_s = 3(\frac{L_s}{B} + \frac{R_c}{S_{\text{uw}}})$.

A sequence diagram of MDA-SL is given in Fig. 8, where $V_j$ and $V_k$ are selected as the new message holders by $V_i$. Since the storage of $V_j$ has been full, $V_j$ discards one of the stored message copies for the new arrival.

Especially, each node stores several different message copies simultaneously, and thus each node should compute the dissemination weight and the dissemination probability for each stored message copy. That is, in Step 2 and Step 3, several dissemination weights and dissemination probabilities are computed simultaneously by each node. Besides, in Step 4 the copies of different messages will be selectively disseminated to different neighbouring nodes, respectively.

The pseudo-code of MDA-SL is given in Algorithm 1.

**Algorithm 1** MDA-SL pseudo-code

**Require:** : $\boldsymbol{D}, V_s, V_d, msg(s,d)$;
**Ensure:** : $msg(s,d)$ is delivered during the period $Dl_{\text{upp}}$;

```
msg(s,d) is generated at the t-th time slot;
τ ← 0;
while (msg(s,d) ∉ Msg_list(d) and τ < ⌊Dl_upp / T_s⌋) do
    for all V_i ∈ V do
        V_i broadcasts an inquire_msg;
    end for
    while d(i,j)^(t) ≤ R_c and msg(s,d) ∉ Msg_list(j) do
        V_j sends a reply_msg to V_i;
    end while
    Dissemination probabilities are computed;
    msg(s,d) copies are disseminated to new message holders;
    if V_j receives msg(s,d) copy from V_i then
        if S(j)^(t) > 0 then
            Msg_list(j) ← Msg_list(j) ⋃ msg(s,d);
        else
            msg(s',d') is selected to be discarded;
            Msg_list(j) ← Msg_list(j) \ msg(s',d');
            Msg_list(j) ← Msg_list(j) ⋃ msg(s,d);
        end if
    end if
    t ← t + 1; τ ← τ + 1;
end while
```

## 6. Algorithm analysis

In this section, the number of transmitted messages and time complexity of MDA-SL are given through analyzing the complexity of each step. The results can be used to measure the execution cost of MDA-SL; the impact of node storage capacity on the network throughput is analyzed by observing the variation of $\frac{\mathrm{d}Dr(\lfloor \frac{Dl_{\text{upp}}}{T_s} \rfloor)}{\mathrm{d}S}$; the approximation ratio of network throughput is calculated to demonstrate that MDA-SL can achieve the maximum throughput approximatively.

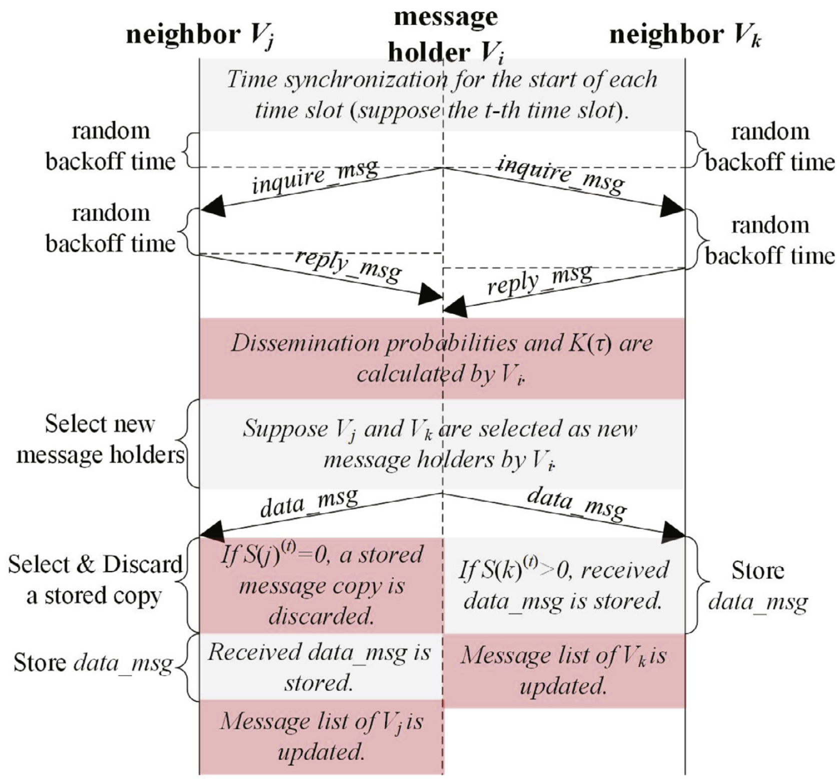



**Fig. 8.** Sequence diagram of MDA-SL.

**Table 2**
Complexity of MDA-SL.

| Step | Number of transmitted messages | Time complexity |
|---|---|---|
| 1 | O($N$) | 0 |
| 2 | O($N^2$) | O($N^2$) |
| 3 | O(1) | O($N^2$) |
| 4 | O($N$) | O($N$) |
| 5 | 0 | O($N^2$) |
| 6 | O(1) | O(1) |
| 7 | O(1) | O(1) |

### 6.1. Complexity

Table 2 shows the number of transmitted messages and time consumption of each step in MDA-SL. In Step 1, each node broadcasts an *inquire_msg*. When $p_g$ is large enough such that each node is supposed to store at least one message copy. Therefore the total message amount will reach $N$ in the worst case; in Step 2, there will be $N^2\cdot\frac{\frac{4}{3}\pi\cdot R_c^3}{|\mathbf{D}|}$ *reply_msg* to be transmitted; Step 4 makes each message holder disseminate $\frac{S}{L_s}$ different messages, and thus the number of transmitted messages of Step 4 is O($N$); In Step 6, there are at most $\lfloor\frac{Dl_{\text{upp}}}{T_s}\rfloor$ repetitions of Step 1 to Step 6. As a result, the total number of transmitted messages of MDA-SL is at most O($N^2$).

The computations of MDA-SL are mainly yielded in Step 2, Step 3 and Step 5. In Step 2 and Step 3, there is a total of $N\cdot\frac{N\cdot\frac{4}{3}\pi\cdot R_c^3}{|\mathbf{D}|}\sim$ O($N^2$) dissemination weights and probabilities to be computed; in Step 5, each node will averagely receive $N\cdot p_g\cdot\sum_{\tau=0}^{\lfloor\frac{Dl_{\text{upp}}}{T_s}\rfloor-1}Pr_h(\tau)\cdot K(\tau+1)$ message copies, which are disseminated by neighbouring nodes, and hence there is a total of $N^2\cdot p_g\cdot\sum_{\tau=0}^{\lfloor\frac{Dl_{\text{upp}}}{T_s}\rfloor-1}Pr_h(\tau)\cdot K(\tau+1)$ discard weights and probabilities to be computed. Therefore, the time complexity of MDA-SL is O($N^2$).

### 6.2. Impact of node storage capacity

To investigate the impact of $S$ on the network throughput, according to (6) we give the expression of $\frac{\mathrm{d}Dr(\lfloor\frac{Dl_{\text{upp}}}{T_s}\rfloor)}{\mathrm{d}S}$:

$$-\frac{C_1\cdot\frac{4}{3}\pi\cdot R_c^3}{L_s\cdot p_g\cdot|\mathbf{D}|}\cdot\left(1-\frac{\sum_{k=1}^{U}Pb\left(k\cdot\sqrt[3]{\frac{|\mathbf{D}|}{N}}\right)\cdot k^2}{\sum_{k=1}^{U}k^2}\right)$$
$$\cdot\exp\left\{-\frac{\frac{4}{3}\pi\cdot R_c^3\cdot N}{|\mathbf{D}|}\cdot\left[\begin{array}{l}Pr_h\left(\left\lfloor\frac{Dl_{\text{upp}}}{T_s}\right\rfloor\right)-\frac{1}{N}\\ +\left(1-\frac{\sum_{k=1}^{U}Pb\left(k\cdot\sqrt[3]{\frac{|\mathbf{D}|}{N}}\right)\cdot k^2}{\sum_{k=1}^{U}k^2}\right)\\ \cdot\left(\frac{S}{L_s\cdot p_g\cdot N}+\frac{1}{N}\right)\end{array}\right]\right\}. \tag{11}$$

There are $C_1<0$ and $1-\frac{\sum_{k=1}^{U}Pb(k\cdot\sqrt[3]{\frac{|\mathbf{D}|}{N}})\cdot k^2}{\sum_{k=1}^{U}k^2}\geq 0$. Thus $\frac{\mathrm{d}Dr(\lfloor\frac{Dl_{\text{upp}}}{T_s}\rfloor)}{\mathrm{d}S}>0$, indicating that a larger storage capacity $S$ produces a larger $Dr(\lfloor\frac{Dl_{\text{upp}}}{T_s}\rfloor)$ and a higher network throughput.

### 6.3. Approximation ratio of network throughput

The maximum network throughput $\mathcal{G}^*(S)$ is achieved when each generated message is assumed to be delivered during the period $Dl_{\text{upp}}$, and thus $\mathcal{G}^*(S)=\frac{N\cdot p_g}{T_s}$. The approximation ratio of MDA-SL throughput to the maximum throughput is calculated as:

$$\frac{\mathcal{G}(S)}{\mathcal{G}^*(S)}=\frac{\frac{N\cdot p_g}{T_s}\cdot Dr\left(\left\lfloor\frac{Dl_{\text{upp}}}{T_s}\right\rfloor\right)}{\frac{N\cdot p_g}{T_s}}=Dr\left(\left\lfloor\frac{Dl_{\text{upp}}}{T_s}\right\rfloor\right).$$

Usually, there is $\overline{K} \ll N$. When $N$ is large enough, $\frac{\mathcal{G}(S)}{\mathcal{G}^*(S)}$ can be approximatively rewritten as:

$$\frac{\mathcal{G}(S)}{\mathcal{G}^*(S)} \approx 1 - \exp\left\{-\frac{4\pi \cdot R_c{}^3 \cdot N}{3|\boldsymbol{D}|} \cdot \left[Pr_h\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor\right) - \frac{1}{N}\right]\right\}.$$

Besides, by the expression of $Pr_h(\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor)$ provided in Appendix A, there is $\frac{\overline{K}}{N} \cdot (\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor - 1 + \ln \frac{2}{\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor + 1}) - \frac{\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor^{\vartheta+1} - 1}{\sum_{\tilde{\tau}=0}^{\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor - 1}(\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor - \tilde{\tau})^{\vartheta}} \cdot \frac{\sum_{\tau=0}^{\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor - 1}\prod_{\tilde{\tau}=0}^{\tau}[1+K(\tilde{\tau})]}{(\vartheta+1)\cdot\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor \cdot N^2} \le Pr_h(\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor) \le 1$, from which the value range of $\frac{\mathcal{G}(S)}{\mathcal{G}^*(S)}$ is given as:

$$1 - \exp\left\{-\frac{4\pi \cdot R_c{}^3}{3|\boldsymbol{D}|} \cdot \left[\overline{K} \cdot \left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - 1 + \ln \frac{2}{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor + 1}\right) - \frac{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor^{\vartheta+1} - 1}{\sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - 1}\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - \tilde{\tau}\right)^{\vartheta}} \cdot \frac{\sum_{\tau=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - 1}\prod_{\tilde{\tau}=0}^{\tau}\left[1+K(\tilde{\tau})\right]}{(\vartheta+1)\cdot\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor \cdot N}\right] - 1\right\}$$
$$\le \frac{\mathcal{G}(S)}{\mathcal{G}^*(S)} \le 1 - \exp\left\{-\frac{4\pi \cdot R_c{}^3 \cdot (N-1)}{3|\boldsymbol{D}|}\right\},$$

where $\overline{K} \cdot (\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor - 1 + \ln \frac{2}{\lfloor \frac{Dl_{\text{upp}}}{T_s}\rfloor + 1}) - 1$ is usually much larger than the value of the following expression:

$$\frac{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor^{\vartheta+1} - 1}{\sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - 1}\left(\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - \tilde{\tau}\right)^{\vartheta}} \cdot \frac{\sum_{\tau=0}^{\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor - 1}\prod_{\tilde{\tau}=0}^{\tau}\left[1+K(\tilde{\tau})\right]}{(\vartheta+1)\cdot\left\lfloor \frac{Dl_{\text{upp}}}{T_s}\right\rfloor \cdot N},$$

and it reveals that MDA-SL can achieve a network throughput close to the maximum throughput.

### 6.4. Variable time slot

If the nodes are sparsely deployed, the assumption of fixed time slots is not proper, because the three message transmissions (*inquire_msg*, *reply_msg* and *data_msg*) may be not necessary for each node, e.g., a message holder does not receive any *reply_msg*s from ordinary nodes. Under this case, the time slot can be terminated earlier than the fixed time slot, and thus the further dissemination can be started in advance.

Before the message dissemination of a message holder, at least an *inquire_msg* has been broadcasted, and a duration of $\frac{T_s}{3}$ is required for the *inquire_msg* broadcasting. Thus, two cases regarding the length of time slots should be considered: ($a$) the message holder does not receive any *reply_msg*s from the ordinary nodes after the *inquire_msg* broadcasting, and then the next *inquire_msg* broadcasting will be launched by the message holder after a duration of $\frac{T_s}{3}$; ($b$) the message holder has received at least one *reply_msg* from the ordinary nodes after the *inquire_msg* broadcasting, and then three message transmissions (*inquire_msg*, *reply_msg* and *data_msg*) will consume the duration of $T_s$. Hence, $\frac{T_s}{3}$ is taken as the minimum unit time, and the expression of $Pr_h(\tau+1)$ is rewritten as:

$$Pr_h(\tau+1) \approx Pr_h(\tau) + \sum_{k=1}^{\overline{K}-1}\left(\frac{\frac{4}{3}\pi \cdot R_c{}^3}{|\boldsymbol{D}|}\right)^k \cdot \left(1 - \frac{\frac{4}{3}\pi \cdot R_c{}^3}{|\boldsymbol{D}|}\right)^{Pr_{nh}(\tau)\cdot N-k} \cdot \frac{k}{3}$$
$$+ \sum_{k=\overline{K}}^{Pr_{nh}(\tau)\cdot N}\left(\frac{\frac{4}{3}\pi \cdot R_c{}^3}{|\boldsymbol{D}|}\right)^k \cdot \left(1 - \frac{\frac{4}{3}\pi \cdot R_c{}^3}{|\boldsymbol{D}|}\right)^{Pr_{nh}(\tau)\cdot N-k} \cdot \frac{\overline{K}}{3},$$

where $\tau \in [0, \lfloor \frac{3Dl_{\text{upp}}}{T_s}\rfloor - 1]$. Note that the part of $(\frac{\frac{4}{3}\pi \cdot R_c{}^3}{|\boldsymbol{D}|})^k \cdot (1 - \frac{\frac{4}{3}\pi \cdot R_c{}^3}{|\boldsymbol{D}|})^{Pr_{nh}(\tau)\cdot N-k}$ denotes the probability of $k$ ordinary nodes sending *reply_msg*s to a message holder at the $\tau$th time slot. Obviously, the mechanism of variable time slot will expedite the message propagation, while more stored messages (copies) will be discarded due to the storage limitation of nodes.

**Table 3**
Simulation parameters.

| Parameter | Description | Value |
|---|---|---|
| $N$ | Number of nodes | 1500 |
| $N_a$ | Number of anchored nodes | 500 |
| $\lvert\boldsymbol{D}\rvert$ | Deployment space | $40 \times 100 \times 50\text{m}^3$ |
| $S$ | Storage of each node | 120 KB |
| $R_c$ | Communication radius | 15 m |
| $\mathcal{V}_m$ | Maximum movement speed | 1.5 m/s |
| $L_s$ | Size of each data message | 2000 B |
| $B$ | Channel capacity | 8 kbps [39] |
| $S_{\text{uw}}$ | Underwater sound speed | 1500 m/s |
| $T_s$ | Time slot | 6.02 s |
| $t_b$ | Maximum backoff time | 0.5 s |
| $Dl_{\text{upp}}$ | Upper bound of propagation delay | 50 s |
| $\varepsilon$ | Exponent parameter | 0.8 |
| $\epsilon$ | Exponent parameter | 0.3 |
| $\vartheta$ | Exponent parameter | 0.7 |
| $\overline{K}$ | Number of standard dissemination copies | 2 |
| $p_g$ | Probability of message generation | 0.05 |
| $BER$ | Bit error rate | 0.01 |
| $\psi$ | Maximum offsetting angle | $\frac{\pi}{6}$ |
| $\triangle_1$ | Increment in dissemination weight | 0.2 |
| $\triangle_2$ | Decrement in discard weight | 0.15 |

## 7. Simulation evaluation

In this section, MDA-SL is evaluated by observing the performance variations with respect to different model parameters and by comparing with other algorithms (OR, BDCR and EF). MDA-SL is realized in ONE (Opportunistic Networks Environment) [36], which is a simulation environment that can generate node mobility using different movement models and forward messages between nodes with various routing algorithms. IEEE 802.15.4 is adopted for medium access control (MAC), where the carrier sensing and collision avoidance techniques are adopted to avoid the collisions of message transmissions.

At the beginning, $N$ mobile nodes and $N_a$ anchored nodes are evenly deployed into the underwater space. Some typical characteristics of shallow-water channels [37], such as large signal attenuation, transmission error, and long propagation delay, are adopted to depict the propagation of acoustic wave in shallow water environment. Especially, note that each underwater sensor node equips a miniature acoustic modem [38] which is different from the ordinary acoustic modem equipped to ships or submarines because the ordinary acoustic modem is typically with large size, expensive price and large energy consumption. Thus, the communication distance of each sensor node is much shorter than the communication distance of an ordinary acoustic modem.

The delay from the algorithm calculation is neglected, and the simulation results are the average of 500 executions. Initial speed vector of water current is $(0.15, 0.2, 0.1)\,\text{m/s}$ and the values of other parameters utilized are shown in Table 3.

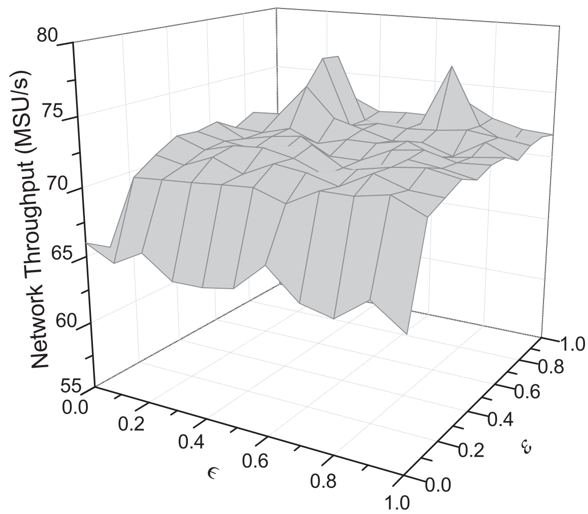
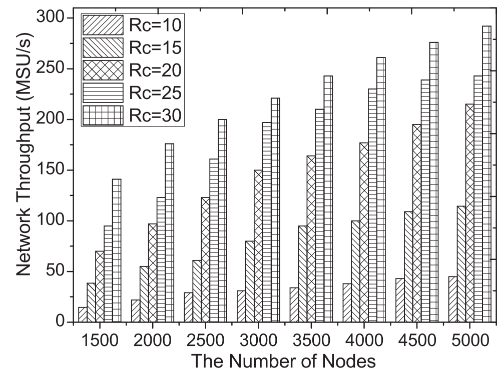
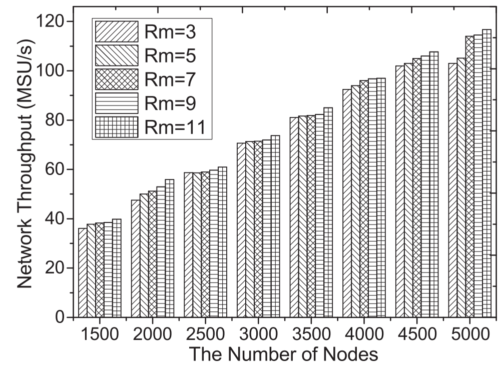



**Fig. 9.** Network throughput vs. $\varepsilon$ and $\epsilon$.




(a) Network Throughput vs. $R_c$




(b) Network Throughput vs. $R_m$

**Fig. 10.** Impacts of $R_c$ and $R_m$ (where $R_m = \mathcal{V}_m \cdot T_s$).

### 7.1. Impacts of $\varepsilon$ and $\epsilon$

Fig. 9 illustrates the impacts of $\varepsilon$ and $\epsilon$ on the network throughput. $\varepsilon$ (or $\epsilon$) shows the weight of the movement speed (or the residual storage) considered in selecting the new message holders. In the figure, two observations are obtained: (***a***) When $\varepsilon$ or $\epsilon$ is set to 0, the results are extremely poor. The minimum throughput is 64.4 MSU/s when $\varepsilon$=0. This is because both the movement speed and residual storage are important indices for one node whether to become a new message holder. Because the movement speed of nodes typically cannot be too fast to interrupt the message transmissions between neighbouring nodes, a higher movement speed generally indicates a larger probability of encountering the destination node. Besides, a larger residual storage indicates a smaller probability of discarding the stored message copies. (***b***) the curved surface fluctuates slightly with the variation of $\varepsilon$ or $\epsilon$, and a largest throughput (76.9 MSU/s) can be achieved when $\varepsilon$=0.8 and $\epsilon$=0.3. This phenomenon suggests that proper settings of $\varepsilon$ and $\epsilon$ will boost the performance of MDA-SL.

### 7.2. Impacts of $\mathrm{R_c}$ and $\mathrm{R_m}$

In Fig. 10(a), it is shown that the network throughput bar with a larger $R_c$ is higher than others because the nodes will have more neighbouring nodes when each node is with a larger communication range, implying that the probabilities of encountering the destination nodes are increased. Similarly, the network throughput increases as $N$ grows, and the highest throughput is 292 MSU/s ($N = 5000$ and $R_c = 30$ m). $R_m$ denotes the maximum movement range at each time slot.

As shown in Fig. 10(b), the network throughput bar with a larger $R_m$ is higher than others, because a faster movement makes it easier for the message holders to encounter the destination nodes, and thus messages are delivered more timely. Consequently, the network throughput is increased, and this phenomenon agrees with the conclusion in Theorem 1. In MDA-SL, the message copies are inclined to be disseminated to the nodes moving more quickly, as described in Step 2.

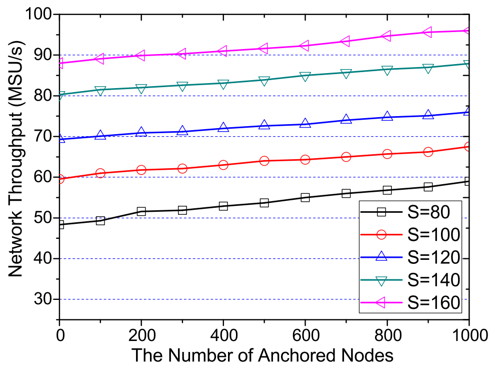
### 7.3. Impacts of S, $\mathrm{N_a}$ and $\mathrm{Dl}_{upp}$

As depicted in Fig. 11(a), the network throughput will increase with the growth of $S$ when $Dl_{\mathrm{upp}}$ is fixed. This behaviour is attributed to the fact that a larger storage capacity reduces the amount of discarded message copies in Step 5, hence more message copies can be retained. It is also shown that having more anchored nodes will enable a higher network throughput. This is because the number of messages with anchored destination nodes increases when more anchored nodes are deployed, and these message deliveries are easier than those with floating destination nodes, which elevates the network throughput consequently.

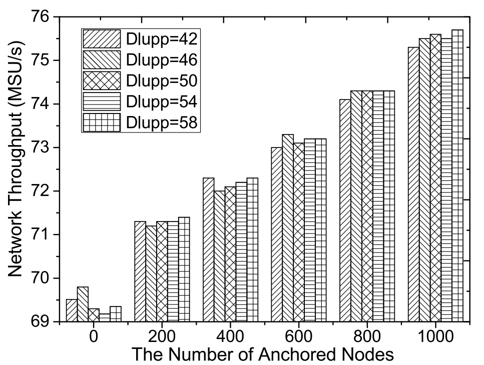
In Fig. 11(b), the network throughput variation fluctuates erratically when the delay constraint $Dl_{\mathrm{upp}}$ increases. The reason is that although a larger delay constraint offers a longer period for message copies to be stored and disseminated, the total storage capacity remains fairly constant, and thus there are more discarded message copies at each time slot. MDA-SL seeks to deliver messages as soon as possible, so $Dl_{\mathrm{upp}}$ will not make an obvious impact on the network throughput when $Dl_{\mathrm{upp}}$ has been large enough.

### 7.4. Settings of $\overline{K}$ and $\vartheta$

The proper setting of $\overline{K}$ is vital for MDA-SL: if $\overline{K}$ is too large, many message copies may be discarded without sufficient dissemination. On the contrary, if $\overline{K}$ is too small, the network capacity will not be saturated, and thus the optimal network throughput cannot be achieved. Appendix B has analysed the optimal setting of $\overline{K}$, and Fig. 12 provides the simulation validation. The network throughput continues to climb up with the increase of $\overline{K}$ until $\overline{K} \approx 2$, afterward, the curved surface drops sharply. This phenomenon verifies the conclusion in Appendix B. Besides, Fig. 12 also illustrates that network throughput fluctuates slightly with the variation of $\vartheta$, and the optimal network throughput is 82.16 MSU/s when $\vartheta = 0.3$ ($\overline{K}$




(a) $S$ and $N_a$




(b) $Dl_{\text{upp}}$ and $N_a$

**Fig. 11.** Network throughput vs. $S$, $N_a$ and $Dl_{\text{upp}}$.

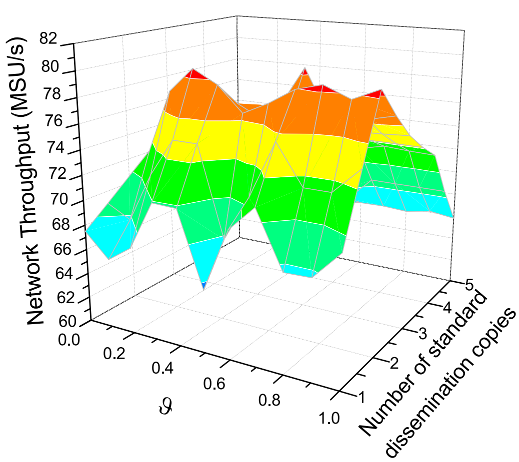



**Fig. 12.** Network throughput under different settings of $\overline{K}$ and $\vartheta$.

is set 2). This phenomenon indicates that a proper value of $\vartheta$ can improve the network throughput.

## 7.5. Comparison with centralized method

The optimal results from theoretical analysis can be achieved by a centralized method, where the limitation of the communication range of nodes is relaxed, and thus the global-optimal new message holders can be found. In order to evaluate the performance of MDA-SL, we introduce a centralized method adopting the assumption that each node can obtain the real-time information of all other nodes, such as their coordinates, movement speed and residual storage. The centralized method certainly outperforms MDA-SL, though the realization cost (the global interactions) is too heavy to undertake in actual OUSNs. The centralized method is taken as a theoretical yardstick to measure the performance of MDA-SL, as shown in Fig. 13. Fig. 13 indicates that the two curves remain close to each other, which suggests the MDA-SL can achieve the performance close to that of the centralized method. In addition, the gap of network throughput between MDA-SL and the centralized method becomes smaller with the increase of $N$. Such simulation results verify that MDA-SL can achieve similar outcomes compared to that of the centralized method, especially in a densely deployed OUSN.

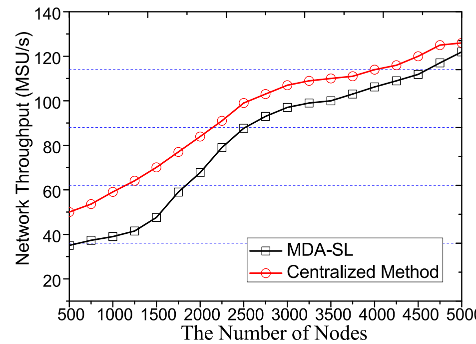


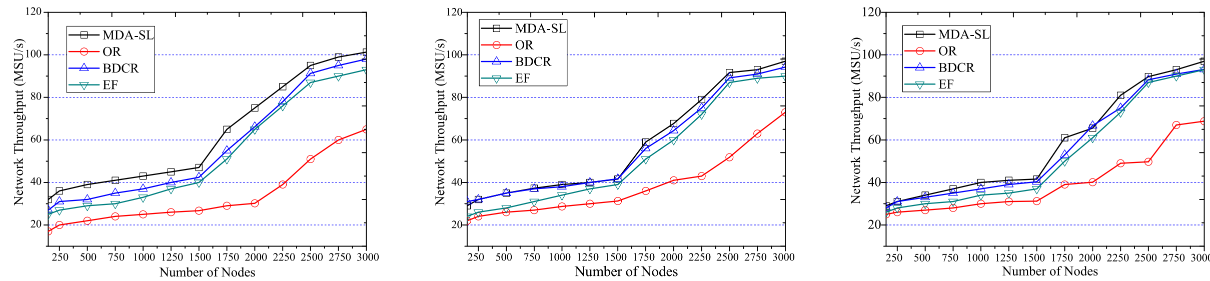

**Fig. 13.** Comparison with centralized method.

## 7.6. Comparisons under different mobility models

To further analyze the merits of the proposed MDA-SL, we compare MDA-SL with other algorithms under different mobility models, including underwater mobility model, Random Waypoint Model [34] and Mobility Vector Model [35], to obtain extensive results. Given the simulation results in Figs. 14 and 15, we can observe that MDA-SL outperforms other algorithms (OR, EF, BDCR) in terms of the network throughput and propagation delay under different mobility models. The reason is that MDA-SL adopts the special strategies for message storing, disseminating and discarding, and thus the message copies will be delivered to destination nodes as soon as possible, i.e., the network throughput is enhanced and the propagation delay is shortened.

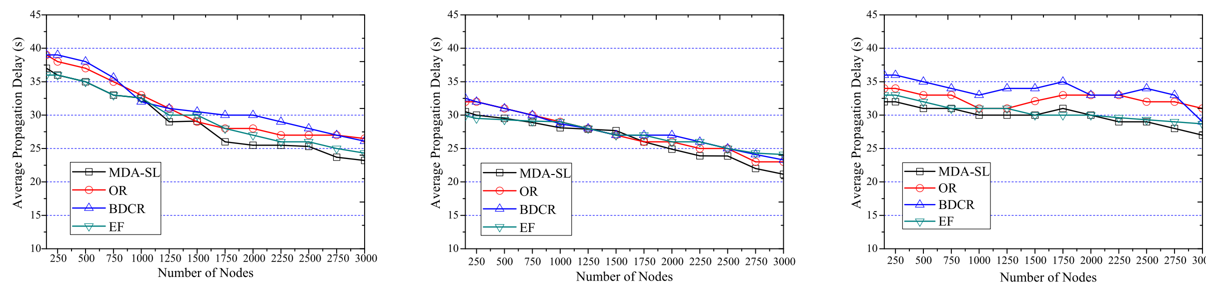
With regard to algorithms OR, EF, BDCR and other related works, they do not take into account the limited storage of underwater nodes, and thereby a large number of message copies have to be casually discarded due to the uncontrolled dissemination. Especially, note that the network throughput of EF is still lower than that of MDA-SL. Although EF usually outperforms other algorithms in term of network throughput since it adopts the epidemic dissemination manner, however due to the limited storage of underwater nodes, many of the excessive message copies cannot be stored and delivered during the period $Dl_{\text{upp}}$, making its network throughput to be reduced accordingly. Specifically, in Fig. 14 the network throughputs of MDA-SL, EF and BDCR are very close and the gaps become larger with the increase of $N$. This is because the discarded message copies are quite rare when $N$ is small, and the algorithms' performances are with only small differences. The number of message copies is rising quickly with the increase of $N$, and selecting some of the stored message copies to be discarded becomes very important. The network throughput of OR is still lower than that of MDA-SL, because OR does not take into account the limited storage of nodes.

In Fig. 15, the average propagation delay fluctuates and decreases slowly with the increase of $N$. The reason is that better choices of message holders may be identified when the nodes are




(a) Mobility Vector Model (b) Underwater Mobility Model (c) Random Waypoint Model

**Fig. 14.** Comparisons of network throughput under different mobility models.




(a) Mobility Vector Model (b) Underwater Mobility Model (c) Random Waypoint Model

**Fig. 15.** Comparisons of propagation delays under different mobility models.

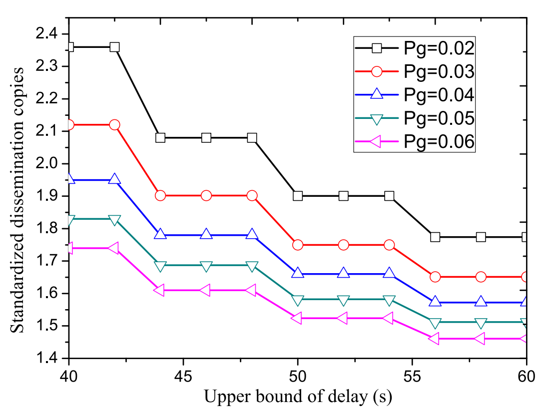



**Fig. 16.** $\overline{K}$ vs. $Dl_{\text{upp}}$ and $p_g$.

deployed more densely, and thus the propagation delay is shortened. Note that however the effect of deployment density on propagation delay is not significant. Particularly, the curve of EF is close to others due to the limited storage of nodes, though it adopts an epidemic mechanism to disseminate messages. This shows that the control of disseminated copies in MDA-SL is beneficial for the reduction of propagation delay as well.

There are various applications (or scenarios) of OUSNs, and some simulation parameter settings may be much different in different applications (or scenarios). The simulation conclusions can provide beneficial reference values to the different applications (or scenarios) with different simulation settings, and MDA-SL can be available for different applications (or scenarios) by adjusting some algorithm parameters (such as $\overline{K}$, $\triangle_1$ and $\triangle_2$) according to the simulation conclusions.

## 8. Conclusions

This study explored the message dissemination problem for the network throughput optimization in storage-limited OUSNs. The limited storage of nodes restricts the amount of stored message copies, which then impairs the message deliveries, even when the upper bound of the propagation delay is sufficiently large. The strategies for message storing, disseminating and discarding were investigated: at each time slot, message holders shall tend to disseminate message copies to those nodes moving faster and owning more residual storage, and the stored copies of newer messages should be easier to be discarded when the receivers' storage has been full. Time synchronization is also an important issue for message dissemination, yet it has been neglected temporarily in this work. To handle the issue, some existing researches (such as [40]) can be applied in MDA-SL directly.

Both the mathematical analyses and simulations suggest that MDA-SL can achieve a satisfactory network throughput in storage-limited OUSNs. Therefore, it was shown that MDA-SL is suitable for storage-sensitive or data-massive applications in OUSNs, such as the OUSNs for submarine tactical observation and underwater disaster forecasting (oceanic volcano activities).

## Declaration of Competing Interest

The authors declared that they have no conflicts of interest to the work "On the Throughput Optimization for Message Dissemination in Opportunistic Underwater Sensor Networks (Authors: Linfeng Liu, Ran Wang, Gaoxi Xiao and Dongyue Guo)" submitted to "Computer Networks". We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

## CRediT authorship contribution statement

**Linfeng Liu:** Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing, Data curation, Funding acquisition, Resources, Formal analysis. **Ran Wang:** Methodology, Writing - review & editing, Investigation, Visualization, Formal analysis. **Gaoxi Xiao:** Writing - review & editing, Supervision, Project administration. **Dongyue Guo:** Software, Validation, Data curation.


## Acknowledgments

This research is supported by National Natural Science Foundation of China under Grants Nos. 61872191, 61801215, 61872193; Six Talents Peak Project of Jiangsu Province under Grant no. 2019-XYDXX-247.


## Appendix A. Expression of $Pr_h(\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \rfloor)$

When nodes are densely deployed, the number of message copies stored by neighbouring nodes is approximately equal to 1. Let $\mathbb{E}(\beta(\tau))$ denote the expected probability of a message holder discarding a stored copy of the message that has experienced $\tau$ time slots. According to Step 5 in MDA-SL, $\mathbb{E}(\beta(\tau))$ is expressed as:

$$\begin{aligned}\mathbb{E}(\beta(\tau)) &= \frac{\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tau\right)^{\vartheta}}{\sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta} \cdot N \cdot p_g} \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left[N \cdot \beta(\tilde{\tau}) \cdot Pr_h(\tilde{\tau})\right] \cdot \frac{N \cdot p_g}{N} \\ &= \frac{\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tau\right)^{\vartheta}}{\sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta}} \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left[\beta(\tilde{\tau}) \cdot Pr_h(\tilde{\tau})\right]. \end{aligned} \tag{12}$$

Due to the storage limit of nodes, the total number of messages (and their copies) is equal to the summation of three parts: the number of discarded message copies, the number of stored message copies and the number of expired message copies. Thus we have

$$\begin{aligned} N \cdot p_g \cdot \sum_{\tau=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \prod_{\tilde{\tau}=0}^{\tau} \left[1 + K(\tilde{\tau})\right] = \\ \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot N \cdot p_g \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left[N \cdot \beta(\tilde{\tau}) \cdot Pr_h(\tilde{\tau})\right] \\ + \frac{N \cdot S}{L_s} + \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot N^2 \cdot p_g \cdot Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right), \end{aligned}$$

which yields

$$\begin{aligned} \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left[\beta(\tilde{\tau}) \cdot Pr_h(\tilde{\tau})\right] = \frac{\sum_{\tau=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \prod_{\tilde{\tau}=0}^{\tau} \left[1 + K(\tilde{\tau})\right]}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot N} \\ - \frac{S}{L_s \cdot \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot N \cdot p_g} - Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right), \end{aligned} \tag{13}$$

Moreover, the proportion of message holders at the final time slot is $Pr_h(\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \rfloor) = \frac{1}{N} \cdot \sum_{\tau=0}^{\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \rfloor - 1} [1 + K(\tau) - \mathbb{E}(\beta(\tau))]$. There is

$$Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right) \approx \frac{1}{N} \cdot \int_0^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left[1 + K(\tau) - \mathbb{E}(\beta(\tau))\right] \mathrm{d}\tau \tag{14}$$

According to (1), (2) and (3), we can obtain that

$$Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right) \approx \frac{\left\{\begin{aligned} &(\vartheta + 1) \cdot \overline{K} \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta} \\ &\cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1 + \ln \frac{2}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1}\right) - \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor^{\vartheta+1} - 1\right) \\ &\cdot \left(\frac{\sum_{\tau=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \prod_{\tilde{\tau}=0}^{\tau} \left[1 + K(\tilde{\tau})\right]}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot N} - \frac{S}{L_s \cdot \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot N \cdot p_g}\right) \end{aligned}\right\}}{(\vartheta + 1) \cdot N \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta} - \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor^{\vartheta+1} + 1}, \tag{15}$$

where $\sum_{\tau=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \prod_{\tilde{\tau}=0}^{\tau} \left[1 + K(\tilde{\tau})\right]$ can be approximatively written as:

$$\begin{aligned} \int_0^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \frac{\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - x\right) \cdot \overline{K}^{x+1}}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1} \mathrm{d}x = \\ \frac{\overline{K}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor} \cdot \left(\ln \overline{K} + 1\right) - \overline{K} \cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \ln \overline{K} + 1\right)}{\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1\right) \cdot \left(\ln \overline{K}\right)^2}. \end{aligned}$$

## Appendix B. The Setting of $\overline{K}$

The network throughput is affected by $\overline{K}$, the value of which is usually preset before the MDA-SL execution. To find the optimal setting of $\overline{K}$, $\frac{\mathrm{d}Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right)}{\mathrm{d}\overline{K}}$ is firstly given as:

$$\frac{\mathrm{d}Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right)}{\mathrm{d}\overline{K}} = \frac{\left\{\begin{aligned} &(\vartheta + 1) \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta} \\ &\cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1 + \ln \frac{2}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1}\right) - \frac{\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor^{\vartheta+1} - 1\right)}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1\right) \cdot N} \\ &\cdot \left[\begin{aligned} &\frac{\overline{K}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \ln \overline{K} - 1\right) - \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \left(\ln \overline{K} - 1\right)}{\left(\ln \overline{K}\right)^2} \\ &+ \frac{\overline{K}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \ln \overline{K} - 2\right) - \ln \overline{K} + 2}{\left(\ln \overline{K}\right)^3} \end{aligned}\right] \end{aligned}\right\}}{(\vartheta + 1) \cdot N \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta} - \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor^{\vartheta+1} + 1}. \tag{16}$$

Apparently, when $\overline{K}$ is small we have $\frac{\mathrm{d}Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right)}{\mathrm{d}\overline{K}} > 0$, and with the continuous increase of $\overline{K}$ there is $\frac{\mathrm{d}Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right)}{\mathrm{d}\overline{K}} < 0$ conversely. Thus, the optimal setting of $\overline{K}$ is obtained when $\frac{\mathrm{d}Pr_h\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor\right)}{\mathrm{d}\overline{K}} = 0$ and should satisfy the following equation:

$$\left\{\begin{aligned} &\frac{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1\right) \cdot N}{\left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor^{\vartheta+1} - 1\right)} \cdot \sum_{\tilde{\tau}=0}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1} \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - \tilde{\tau}\right)^{\vartheta} \\ &\cdot (\vartheta + 1) \cdot \left(\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor - 1 + \ln \frac{2}{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor + 1}\right) \end{aligned}\right\}$$

$$= \left\{ \begin{array}{l} \dfrac{\overline{K}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor -1} \cdot \left( \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \ln \overline{K} - 1 \right) - \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \left( \ln \overline{K} - 1 \right)}{\left( \ln \overline{K} \right)^2} \\ + \dfrac{\overline{K}^{\left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor -1} \cdot \left( \left\lfloor \frac{Dl_{\mathrm{upp}}}{T_s} \right\rfloor \cdot \ln \overline{K} - 2 \right) - \ln \overline{K} + 2}{\left( \ln \overline{K} \right)^3} \end{array} \right\},$$

which indicates that a larger $\overline{K}$ should be set with a smaller $Dl_{\mathrm{upp}}$ or $p_g$. This is because the number of disseminated copies should be increased to amplify the proportion of message holders at the final time slot, when a short propagation delay is given for the message dissemination or new messages are generated slowly. Some example results are shown in Fig. 16.

## Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.comnet.2020.107097.

## References


[1] M.D. Francesco, S.K. Das, Data collection in wireless sensor networks with mobile elements: A survey, ACM Transactions on Sensor Networks 8 (1) (2011). Article 7.

[2] L. He, L. Kong, Y. Gu, J. Pan, T. Zhu, Evaluating the on-demand mobile charging in wireless sensor networks, IEEE Trans. Mob. Comput. (2015), doi:10.1109/TMC.2014.2368557.

[3] L. Liu, Y. Liu, On exploring data disseminating problem in opportunistic underwater sensor network using mobility-irregular vehicles, IEEE Trans. Veh. Technol. 64 (10) (2015) 4712–4726.

[4] R. Davis, M. Baumgartner, A. Comeau, et al., Tracking whales on the scotian shelf using passive acoustic monitoring on ocean gliders, IEEE OCEANS 16, Monterey, USA, 2016.

[5] B.G. Ferguson, K.W. Lo, Acoustic detection, localization, and tracking of tactical autonomous aerial and underwater vehicles, J. Acoust. Soc. Am. 140 (4) (2016).

[6] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin, P. Corke, Data collection, storage, and retrieval with an underwater sensor network, in: the 3rd International Conference on Embedded Networked Sensor Systems, 2005, pp. 154–165.

[7] R. Martin, J.H. Cui, S. Han, Tracer assisted passive named data routing for underwater sensor networks, in: OCEANS 2014-TAIPEI, 2014, pp. 1–8.

[8] P. Rawat, K.D. Singh, H. Chaouchi, et al., Wireless sensor networks: a survey on recent developments and potential synergies, J. Supercomput. 68 (1) (2014) 1–48.

[9] Z. Xin, X. Wu, Q. Zhang, L. Hu, Research on the communication of the serial port between the host personal computer and CC2430, Adv. Mater. Res. 791–793 (2013) 1974–1977.

[10] V.K. Trivedi, P. Kumar, Carrier interferometry coded single carrier FDMA (CI/SC-FDMA) for next generation underwater acoustic communication, Wirel. Pers. Commun. (2017), doi:10.1007/s11277-017-4119-1.

[11] K. Lorincz, D.J. Malan, T.R.F. Fulford-Jones, et al., Sensor networks for emergency response: challenges and opportunities, IEEE Pervasive Comput. 3 (4) (2004) 16–23.

[12] L. Liu, R. Wang, F. Xiao, Topology control algorithm for underwater wireless sensor networks using GPS-free mobile sensor nodes, J. Netw. Comput. Appl. 35 (6) (2012) 1953–1963.

[13] D. Pompili, T. Melodia, I. Akyildiz, Three-dimensional and two-dimensional deployment analysis of underwater acoustic sensor network, Elsevier Ad Hoc Netw. 7 (4) (2009) 778–790.

[14] L. Liu, R. Wang, D. Guo, X. Fan, Message dissemination for throughput optimization in storage-limited opportunistic underwater sensor networks, in: IEEE International Conference on Sensing, Communication and Networking, (SECON), London, UK, 2016.

[15] F. Li, J. Wu, Localcom: A community-based epidemic disseminating scheme in disruption-tolerant networks, in: IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (IEEE SECON), 2009, pp. 574–582. Rome, Italy, USA.

[16] A.A. Bhorkar, M. Naghshvar, T. Javidi, B.D. Rao, Adaptive opportunistic routing for wireless ad hoc networks, IEEE/ACM Trans. Netw. 20 (1) (2012) 243–256.

[17] B. Radunovic', C. Gkantsidis, P. Key, P. Rodriguez, Toward practical opportunistic routing with intra-session network coding for mesh networks, IEEE/ACM Trans. Netw. 18 (2) (2010) 420–433.

[18] U. Lee, P. Wang, Y. Noh, et al., Pressure routing for underwater sensor networks, in: IEEE International Conference on Computer Communications (Infocom 2010), 2010. San Diego, CA.

[19] Y. Noh, U. Lee, P. Wang, et al., VAPR: void-aware pressure routing for underwater sensor networks, IEEE Trans. Mob. Comput. 12 (5) (2013) 895–908.

[20] Z. Guo, B. Wang, J. Cui, Generic prediction assisted single-copy routing in underwater delay tolerant sensor networks, Elsevier Ad Hoc Netw. 2013 (11) (2013) 1136–1149.

[21] G. Zheng, Z. Peng, B. Wang, et al., Adaptive routing in underwater delay tolerant sensor networks, in: 6th International ICST Conference on Communications and Networking in China, 2011, pp. 1044–1051. Harbin, China.

[22] S. Zhang, D. Li, A beam width and direction concerned routing for underwater acoustic sensor networks, in: 2013 IEEE 9th International Conference on Mobile Ad-hoc and Sensor Networks, 2013, pp. 17–24. Las Vegas, USA.

[23] P.M. Shah, I. Ullah, T. Khan, Mobisink: cooperative routing protocol for underwater sensor networks with sink mobility, in: 2016 IEEE 30th International Conference on Advanced Information Networking and Applications Switzerland, 2016, pp. 189–197.

[24] R.W.L. Coutinho, A. Boukerche, L.F.M. Vieira, Geographic and opportunistic routing for underwater sensor networks, IEEE Trans. Comput. 65 (2) (2016) 548–561.

[25] Y. Wu, Z. Yang, Q. Zhang, A novel DTN routing algorithm in the GEO-relaying satellite network, in: 11th International Conference on Mobile Ad-hoc and Sensor Networks (MSN), Shenzhen, China, 2015.

[26] K. Chen, H. Shen, DTN-FLOW: Inter-landmark data flow for high-throughput routing in DTNs, IEEE/ACM Transactions on Networking 23 (1) (2015) 212–226.

[27] W. Wang, Y. Bai, P. Feng, Y. Gu, S. Liu, W. Jiang, J. Huang, DTN-knca: a high throughput routing based on contact pattern detection in DTNs, in: IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC), Tokyo, Japan, 2018.

[28] M.H. Amerimehr, F. Ashtiani, Delay and throughput analysis of a two-way opportunistic network coding-based relay network, IEEE Trans. Wirel. Commun. 13 (5) (2014) 2863–2873.

[29] J. Wen, M. Wu, B. Lv, D. Wang, Opportunistic cooperative routing in multi-radio multi-channel wireless sensor networks, IEEE International Conference on Communications (2013) 276–280. Budapest.

[30] X. Mao, S. Tang, X. Xu, X. Li, H. Ma, Energy-efficient opportunistic routing in wireless sensor networks, IEEE Trans. Parallel Distrib.Syst. 22 (11) (2011) 1934–1942.

[31] X. Niu, L. Cui, Throughput capacity of opportunistic routing in wireless sensor networks, International Journal of Distributed SensorNetworks 2010 (2010). Article ID 148359.

[32] L. Liu, P. Wang, R. Wang, Propagation control of data forwarding in opportunistic underwater sensor networks, Comput. Netw. 114 (2017) 80–94.

[33] S. Ibrahim, J.H. Cui, R. Ammar, Surface-level gateway deployment for underwater sensor networks, IEEE Military Communications Conference 2007 (2007) 1–7. Sanfrancisco, CA.

[34] C. Bettstetter, H. Hartenstein, et al., Stochastic properties of the random waypoint mobility model, ACM/Kluwer Wirel. Netw. 10 (5) (2004) 555–567.

[35] X. Hong, J.K. Taek, M. Gerla, et al., A mobility framework for ad hoc wireless networks, in: The Second International Conference on Mobile Data Management, 2001, pp. 185–196.

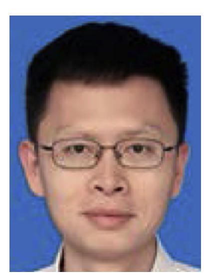
[36] A. Keränen, J. Ott, T. Kärkkäinen, The ONE simulator for DTN protocol evaluation, The 2nd International Conference on Simulation Tools and Techniques, 2009.

[37] M.C. Domingo, Overview of channel models for underwater wireless communication networks, Phys. Commun. 1 (3) (2008) 163–182.

[38] D. Sarriá, O. Pallarés, J. del Río-Fernández, A. Mànuel-Làzaro, Low cost OFDM based transmitter for underwater acoustic communications, 2013 MTS/IEEE OCEANS, Bergen, Norway, 2013.

[39] A.A. Syed, W. Ye, J. Heidemann, T-lohi: a new class of MAC protocols for underwater acoustic sensor networks, in: The 27th Conference on Computer Communications (INFOCOM 2008), Phoenix, USA, 2008.

[40] N. Chirdchoo, W.S. Soh, K.C. Chua, MU-sync: a time synchronization protocol for underwater mobile networks, The 3rd ACM International Workshop on Underwater Networks (WUWNet), San Francisco, 2008.

**Linfeng Liu** received the B. S. and Ph. D. degrees in computer science from the Southeast University, Nanjing, China, in 2003 and 2008, respectively. At present, he is a full professor of the School of Computer Science and Technology, Nanjing University of Posts and Telecommunications, China. His main research interest lies in the areas of wireless sensor networks and multi-hop mobile wireless networks protocols. He has published more than 60 peer-reviewed papers in some technical journals or conference proceedings, such as IEEE Transactions on Parallel and Distributed Systems, ACM Transactions on Autonomous and Adaptive Systems, IEEE Transactions on Vehicular Technology, Computer Networks, Journal of Network and Computer Applications, IEEE SECON, GLOBECOM, ICC, WCNC, CSCWD.

**Ran Wang** currently is an associate professor with the College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics, China. He received his B.E. in Electronic and Information Engineering from Harbin Institute of Technology (HIT), P.R. China in 2011 and Ph.D. in Computer Engineering from Nanyang Technological University (NTU), Singapore in 2016. He has authored or coauthored over 40 papers in top-tier journals and conferences. He received the Nanyang Engineering Doctoral Scholarship (NEDS) Award, Singapore and innovative and entrepreneurial Ph.D. Award of Jiangsu Province, China in 2011 and 2017, respectively. His current research interests include intelligent management and control in smart grid, network performance analysis and evolution of complex networks, etc.

**Gaoxi Xiao** received the Ph.D. degree in computing from the Hong Kong Polytechnic University, Hong Kong, in 1998. He was a Postdoctoral Research Fellowwith PolytechnicUniversity, Brooklyn, New York, NY, USA, in 1999 and a Visiting Scientist at the University of Texas at Dallas during 1999-2001. He joined the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, in 2001, where he is currently an Associate Professor. His research interests include complex systems and networks, optical and wireless networking, smart grid, system resilience, and Internet technologies. He serves as an Academic Editor for PLOS ONE and IEEE Transactions on Network Science and Engineering.

**Dongyue Guo** is a master student of Nanjing University of Posts and Telecommunications. His current research interests include the areas of mobile opportunistic networks and wireless sensor networks.