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Spray Router with Node Location Dependent Remaining-TTL Message Scheduling in DTNs

Agussalim[1,a)] Masato Tsuru[2,b)]

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Abstract: Delay and disruption tolerant networks (DTNs) adopt the store-carry-and-forward paradigm. Each node stores messages in a buffer storage and waits for either an appropriate forwarding opportunity or the message's expiration time, i.e., its time-to-live (TTL). There are two key issues that influence the performance of DTN routing: the forwarding policy that determines whether a message should be forwarded to an encountered node, and the buffer management policy that determines which message should be sent from the queue (i.e., message scheduling) and which message should be dropped when the buffer storage is full. This paper proposes a DTN routing protocol, called spray- and hop-distance-based with remaining-TTL consideration (SNHD-TTL) which integrates three features: (1) binary spray; (2) hop-distance-based forwarding; and (3) node location dependent remaining-TTL message scheduling. The aim is to better deliver messages which are highly congested especially in the "island scenario." We evaluate it by simulation-based comparison with other popular protocols, namely Epidemic as a baseline and PRoPHETv2 that performs well according to our previous study. Our simulation results show that SNHD-TTL is able to outperform other routing protocols, significantly reduce overhead, and at the same time, increase the total size of delivered messages.

Keywords: delay tolerant networks, store-carry-forward, routing protocol, message scheduling, island scenario.

1. Introduction

Delay and disruption tolerant networks (DTNs) are designed to perform well in practice, even though there is no end-to-end path guarantee, to operate effectively over extreme distances such as those encountered in remote rural areas, space communications or on an interplanetary scale [1]. To deliver a message from source node to destination node over challenged and/or opportunistic networks, store-carry-forward-based routing is used [2]. With this approach, each relay node (e.g., car and bus) has a buffer storage to store messages while they await an appropriate forwarding opportunity or until the time-to-live (TTL) expires. In DTNs, due to the large uncertainty of relay node mobility and reachability between relay nodes, delivering a single copy of a message along a single path to the message's destination is very unreliable. Therefore, a multi-copy approach is often used to help make delivery to the destination more reliable; using this approach, a message is duplicated in the network, and those copies are delivered (i.e., spread) along multiple paths to the destination. In the last decade, many routing protocols have been proposed for DTNs. Two key issues governing DTN routing are as follows: (1) the forwarding policy that determines whether a message should be forwarded (i.e., copied) to an encountered node and (2) the buffer management policy that determines which message should be sent from the queue (i.e., message scheduling) and which message should be dropped when a buffer storage is full. The buffer management policy is important for DTN performance especially during congestion where the resources allocated for forwarding (i.e., transmission bandwidth × contact duration) and for storing (i.e., node's buffer size) are insufficient in relation to the total size or density of messages to be transferred on the network.

In our work[*1], to understand and improve performance of DTN message delivery over multiple separated areas in general, we focus on a specific scenario, i.e., the island scenario, in which a single stationary source node and a single stationary destination node are located on two different islands, (i.e., the large island and the small island), with two message delivery scenarios: (1) the source node located in the large island and the destination node located in the small island (LtoS); (2) the source node located in the small island and the destination node located in the large island (StoL). Our work is expected to be easily extended to more general cases in which a limited number of important destinations (e.g., servers, gateways, special terminals, etc.) are stationary and located at some areas that are different from the source node's areas. In our previous study, we compared several popular DTN routing protocols via simulation and found that there is no single best routing algorithm for the island scenario under different conditions (e.g., congestion levels) [4]. This motivated us to develop a new routing protocol that includes efficient buffer management (involving message scheduling) to increase the performance of DTNs in the island scenario. Generality is also considered, especially under congested conditions. In the island scenario, the source and destination nodes are located in separate areas (e.g.,

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[1] Graduate School of Computer Science and System Engineering, Kyushu Institute of Technology, Iizuka, Fukuoka 820–8253, Japan
[2] Kyushu Institute of Technology, Iizuka, Fukuoka 820–8253, Japan
[a)] agussalim@infonet.cse.kyutech.ac.jp
[b)] tsuru@cse.kyutech.ac.jp

[*1] This paper is an extended version of previously published [3].

islands) connected by limited relay nodes (e.g., a ferry). The ferry periodically shuttles between the two islands and is a bottleneck for end-to-end delivery because it is the only way to convey messages between the islands. More specifically, the messages left behind must wait for the next ferry, which may take a substantial amount of time. Further, since the ferry takes time to make the trip, some messages may expire during the trip.

Considering the above features, we propose a protocol called spray-and-hop-distance-based with remaining-TTL consideration (SNHD-TTL), which integrates the following three techniques: (1) binary-spray; (2) hop-distance-based forwarding; and (3) node location dependent remaining-TTL message scheduling. To deliver each message from the source to the station at the ferry terminal quickly, we use binary spray with an appropriate copy limit. To ensure each message is forwarded between the station and the ferry in the right direction and to prevent unnecessary message transmissions, we use the hop-distance from the destination in the forwarding decision. To give a high priority to messages that will expire if assigned a low priority, we adopt a novel node location dependent remaining-TTL message scheduling. To implement such scheduling, it is assumed that we can estimate the expected time a message takes to reach its destination depends on its current location.

The TTL, initially set by the source node, is a timer which limits the lifetime of a message in the network. When a message is transmitted from a node to another node, the message's TTL is updated by subtracting the time for which the message has been stored in the sending node (measured by its own clock), and thus it indicates the remaining lifetime of the received message[*2]. When the TTL value becomes 0 (i.e., expires), all copies stored in the network nodes are erased [1].

In addition to this introductory section, the rest of this paper is organized as follows. Section 2 summarizes related study regarding forwarding and buffer management policies. Section 3 presents our proposed routing protocol. Section 4 describes the evaluation scenario. Section 5 describes our simulation results. Finally, the conclusion and directions for future work are described in Section 6.

2. Related Studies

2.1 Forwarding

The forwarding policy determines which messages should be forwarded when two nodes encounter one another. If the number of messages that can be forwarded within a contact duration is enough (i.e., the transmission bandwidth is large enough and/or the contact duration is long enough) and the number of messages that can be stored in a node is sufficient, the simplest, fastest, and most reliable way to deliver messages to the destination is Epidemic routing (EP) [5], in which messages are spread to all encountered nodes of the network to maximize the chance of reaching the destination. When two nodes encounter one another, they exchange a list of message IDs and compare those IDs to determine which message is not already in storage in the other node. Next, those messages are forwarded to the other node; however, its resource consumption increases significantly as the number of message copies increases. Several studies have focused on trying to reduce resource consumption [6], [7], [8], [9]. These studies introduced forwarding decisions for controlled flooding, e.g., history-based or utility-based routing. Results of these studies have shown good performance in comparison with simple flooding. One of the most well-known protocols in this category is the probabilistic routing protocol using history of encounters and transitivity (PRoPHET) [10]. In another approach, e.g., SCAR [11], and Spray and Wait [7], a limited number of message copies are implemented in each algorithm for message delivery.

Spray and Wait (SNW) routing [7] uses the capabilities of EP for fast message forwarding and reliable direct transmission, while limiting the number of message copies (i.e., controlled flooding). The approach here consists of the following two phases: (1) a spray phase, described in Section 3.1 and (2) a wait phase in which a relay node moves and waits for the opportunity to directly meet up with the destination. Since the wait phase does not perform well in some scenarios, including our island scenario, Spray and Focus routing (SNF) [7] has been proposed to address this problem; the difference between SNF and SNW is that after the spray phase, SNF uses utility-based forwarding to improve delivery probability. Spray based protocol attracted many researchers to improve its performance. The spray protocol was improved with probability Choice (SWPC) [15], where the continuous encounter time is used to describe the encounter opportunity. Bulut et al. [16] proposed a novel spraying algorithm in which the number of message copies in the network depends on the urgency of meeting the expected delivery delay for that message. The main objective of this protocol is to give a chance for early delivery through small number of copies sprayed in to the network. A combination of Spray and Wait [7] and PRoPHET [10] was proposed in [17] which calculates the number of message copies to be forwarded based on the performance of the receiver node in the spray phase. In the wait phase, the waiting node uses the history of encounters and transitivity of transmission. One other sophisticated scheme is MaxProp [13], in which the path cost is computed based on the meeting probability of each hop along the destination, and the shortest cost path is selected. Note that our previous work [4] showed that PRoPHETv2 (PV2) [12] outperformed MaxProp in the island scenario. As another example, You et al. proposed a hop-count-based heuristic routing protocol for mobile DTNs, which calculates heuristic estimations based on hop count information [14]. In particular, they use a sliding window mechanism and dynamically updates the average hop count matrix.

Forwarding a message to the encountered nodes closer to its destination (i.e., at a shorter distance) is one of the basic approaches. However, a key issue is how distance to the destination is defined and estimated (e.g., expected number of hops, expected time, expected success probability, etc.). In this paper, while more sophisticated schemes have been studied and proposed, we adopt the binary spray protocol, described in Section 3.1, with a simple hop-distance-based forwarding approach, which we describe in Section 3.2.

[*2] Note that global clock offset synchronization is not required, but a clock skew synchronization is required which is not strictly due to the time granularity considered in DTN.

2.2 Buffer Management

There are two kinds of buffer management policies: how to select messages to be dropped from the buffer storage when the buffer storage is full, and how to select messages to be sent to a contacted node (i.e., scheduling) within a limited duration of contact and transmission bandwidth. Zhang et al. studied the utilization of traditional buffer management policies, such as drop front (DF) and drop tail (DT). They concluded that the DF policy outperforms DT [20]. Fathima and Wahibanu proposed a buffer management scheme with different queues for handling messages at different priorities. When a buffer is full, a message on a low-priority queue is first dropped to create space for a new message [18].

Most Forwarded (MOFO) [21] increased the efficiency of message replication so that routing agents running on nodes keep track of the number of times each message is forwarded by a node. A similar idea was explored by Naves et al. [22] who proposed Less Probable Sprayed (LPS) and Least Recently Forwarded (LRF), LPS uses the message delivery probability and estimates the number of replicas already disseminated to decide which message to drop. LRF drops the least recently forwarded message based on the assumption that unforwarded message over a certain period of time have already reached several next hops. Elwhishi et al. [23] proposed a new message scheduling framework for epidemic and two-hop forwarding routing in DTNs. It incorporates a suite of novel mechanisms for network states estimation and utility derivation, such that a node can obtain the priority of each messages to be dropped in case of a full buffer.

Krifa et al. proposed sophisticated buffer management schemes called global knowledge-based drop and history-based drop [19]. These approaches use statistical learning to approximate global knowledge. By estimating the number of copies of a message, the authors considered the remaining TTL and developed an optimal joint scheduling and buffer management scheme based on the estimated necessary parameters using locally collected statistics by assuming homogeneous and simply modeled mobility. Another integrated buffer management was proposed [24], that was based on statistics and the analysis of the state of the messages. The delivery history of the node and location information was combined with the relevant information from mutual learning between nodes. Based on the several strategies above, we propose a simple but practical node location dependent remaining-TTL message scheduling that utilizes global knowledge about statistics obtained from message delivery time in each closed area, i.e., island, with the remaining TTL value of each message.

3. Spray- and Hop-distance-based with Remaining-TTL Consideration Routing Protocol (SNHD-TTL)

This section presents the spray-and-hop-distance-based with remaining-TTL consideration (SNHD-TTL) routing protocol, which is illustrated in **Fig. 1**. This protocol combines the following three techniques: (1) binary spray for fast and limited message delivery, with the aim that each message spreads quickly (i.e., with small reduction in the remaining TTL) to a predefined number of nodes, preventing buffer full conditions; (2) hop distance to destination-based forwarding to prevent unnecessary message transmissions to nodes logically-located further from the destination, this feature actually prevents messages being forwarded in the opposite (wrong) direction between islands; and (3) node location dependent remaining-TTL message scheduling which gives priority to the message queue before forwarding to another node. This priority divides the message queue depending on node location and remaining TTL. Here, higher priority is given to messages that have small remaining TTLs that could reach the destination node. The subsections below provide further details regarding each component of this protocol.

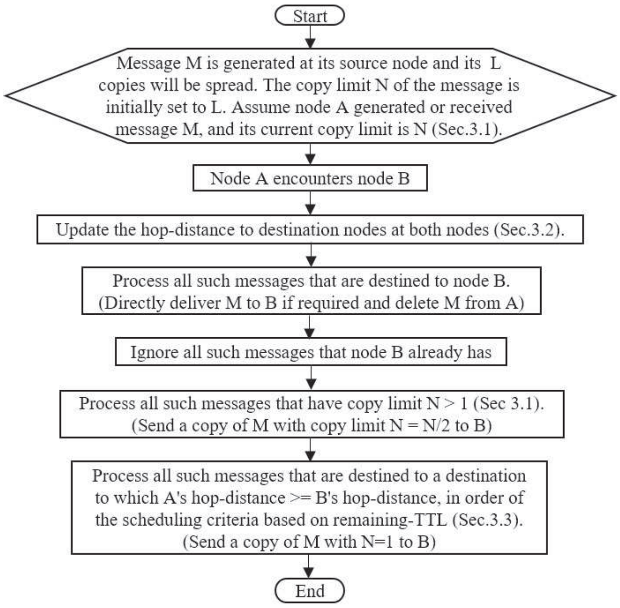


Fig. 1 Flowchart of SNHD-TTL routing protocol.

3.1 Binary Spray

The SNHD-TTL routing protocol employs the "spray phase" mechanism from binary Spray and Wait [7]. This protocol controls the number of messages transmitted by setting up the maximum number of copies created per messages, which can minimize the resource consumption (e.g., bandwidth and buffer storage). To initially spread each newly generated message from its source node to relay nodes while controlling the number of copies, binary spray is used in which a copy limit is defined as the permitted number of copies of a message during the spray phase. Each message has an initial copy limit L which is generated at its source node. For a message with a copy limit of N ($N > 1$) stored at node A, whenever node A encounters another node B which does not have that message, it is forwarded to node B and the message's copy limit is changed to half its original value (i.e., $\lfloor N/2 \rfloor$) at both nodes A and B. For a message with a copy limit of 1 stored at node A, (instead of the "wait phase" in the Spray-and-Wait) SNHD-TTL forwards the message according to the hop distance-based forwarding mechanism described in the next subsection.

3.2 Hop Distance Based Forwarding

After the binary spray phase, (i.e., when the copy limit of mes-

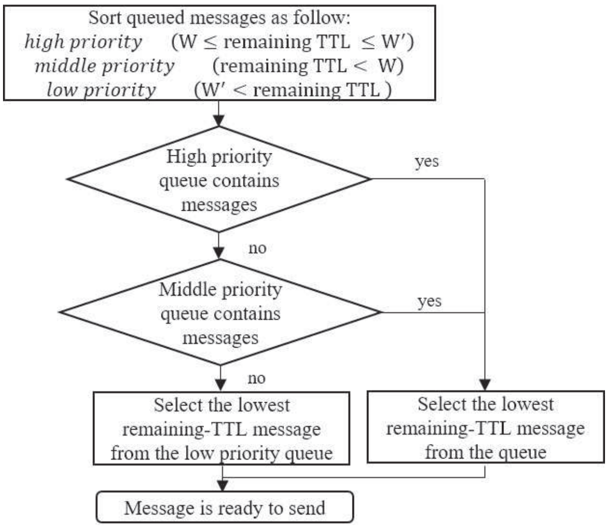


Fig. 2 Flowchart of the Node Location Dependent Remaining-TTL message scheduling.

sages is 1), we use the hop distance to the destination node to determine how to forward that message in order to prevent unnecessary transmission. A node that periodically encounters the destination directly (i.e., a "good" nearest node) has the smallest hop distance value of 1. The update process for hop distance at node A, for example, is as follows. Node A's hop distance to the destination is initially set to "infinity." When node A encounters the destination node, node A will reset its hop distance value to 1. When node A encounters node B other than the destination, A's hop distance will be set so that it is not-greater than the one from "A's current hop distance" and "B's current hop distance plus 1." Messages stored at node A (and not stored at node B) will then be forwarded to node B if and only if node B has an equal or lower hop distance to the destination than that of node A.

3.3 Node Location Dependent Remaining-TTL Message Scheduling

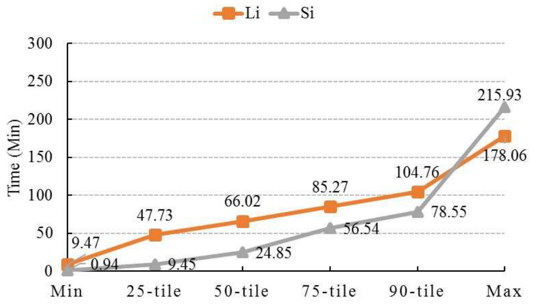
In our proposal, node location, that is the island at which the node runs, is considered to fit in heterogeneous and specific scenarios. **Figure 2** shows a flowchart of our proposed message scheduling algorithm. Some global knowledge about the network, e.g., the statistics of message delivery time from each location, as shown in **Fig. 3** (a) and (b), are used to define two variables, namely the expected minimum "normal" time for a message to reach its destination (W) and the expected maximum "normal" time to reach the destination (W'). Both of these values are dependent on its location. In Section 5.6, we will discuss how to decide W and W' in the system operation.

- W and W' value of large to small island (LtoS) scenario
  Car and bus node in the large island,

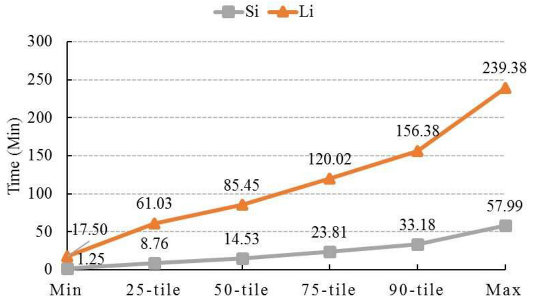
$$W = (\text{50-tile of } Li) + (\text{50-tile of } FT) + (\text{50-tile of } Si) \tag{1}$$

$$W' = (\text{75-tile of } Li) + (\text{75-tile of} FT) + (\text{75-tile of } Si) \tag{2}$$

Station node in the large island,



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Fig. 3 Delivery time report of Epidemic Protocol with 819.2 MB and TTL 240 min.

$$W = (\text{50-tile of } FT) + (\text{50-tile of } Si) \tag{3}$$

$$W' = (\text{75-tile of } FT) + (\text{75-tile of } Si) \tag{4}$$

Car, bus, and station node in the small island,

$$W = \text{50-tile of } Si \tag{5}$$

$$W' = \text{75-tile of } Si \tag{6}$$

- W and W' value of small to large island (StoL) scenario
  Car and bus node in the small island,

$$W = (\text{50-tile of } Si) + (\text{50-tile of } FT) + (\text{50-tile of } Li) \tag{7}$$

$$W' = (\text{75-tile of } Si) + (\text{75-tile of } FT) + (\text{75-tile of } Li) \tag{8}$$

Station node in the small island,

$$W = (\text{50-tile of } FT) + (\text{50-tile of } Li) \tag{9}$$

$$W' = (\text{75-tile of } FT) + (\text{75-tile of } Li) \tag{10}$$

Car, bus, and station node in the large island,

$$W = \text{50-tile of } Li \tag{11}$$

$$W' = \text{75-tile of } Li \tag{12}$$

Here, Li is the message delivery time between a stationary (source or destination) node and the ferry station on the large island, Si is the message delivery time between a stationary (source or destination) node and the ferry station on the small island. We use a 50-tile of the delivery time value as the minimum normal time to deliver a message from each location to the destination, and a 75-tile of the delivery time value as the maximum normal time. FT is the duration the ferry travels between the station on the small island and the station on the large island, including the waiting time at the stations. We define FT as a fixed value, the wait time in the stations is $[0, 30]$ min, and the travel (sailing) time is 15 min. So "the wait time + travel time" is $[15, 45]$. Then, 50-tile is expected to be about 30 min, and 75-tile about 38 min. By combining W and W' with remaining-TTL of each message, the message's priority in the contact duration is determined as follows: the priority is high if $W \leq$ remaining TTL $\leq W'$, middle if remaining TTL $< W$ and low if $W' <$ remaining TTL. Each message class (queue) is processed in order of its priority from high to low. In each message class, in order of message's remaining-TTL (lowest remaining-TTL first), the messages that pass the criteria of the hop distance-based forwarding phase are forwarded to the contacted node. When the buffer storage is full and a new message arrives, a "drop-oldest" policy is used to drop the oldest messages.

4. Evaluation Scenario

As shown in **Fig. 4**, the scenario is based on the map-based model and simulated using *The Opportunistic Network Environment* (*ONE*) *Simulator* [26]. We considered a real-life scenario in which two islands, Large island and Small island, are connected by a ferry between station nodes, with buses and cars as relay nodes and stationary nodes. They can be considered to be source and destination nodes on each of the islands. This scenario is modeled by considering a real situation in Indonesia, and a similar type of scenario can be seen in the literature as well. For example, Ref. [25] considered island-hopping experiments where a stationary node located in three geographically separated groups are connected by three mobile "traveler nodes." In our scenario, during the simulated 840 min period of time, ten mobile nodes (e.g., cars and buses) in the large island and six mobile nodes in the small island move on the map's roads with speeds from 5 to 30 km/h, between random location on each island to deliver messages from each destination node according to the message delivery scenario. The waiting time of the ferry on each island is about 30 minutes, and the traveling time (sailing) of the ferryboat between two islands is 15 minutes.

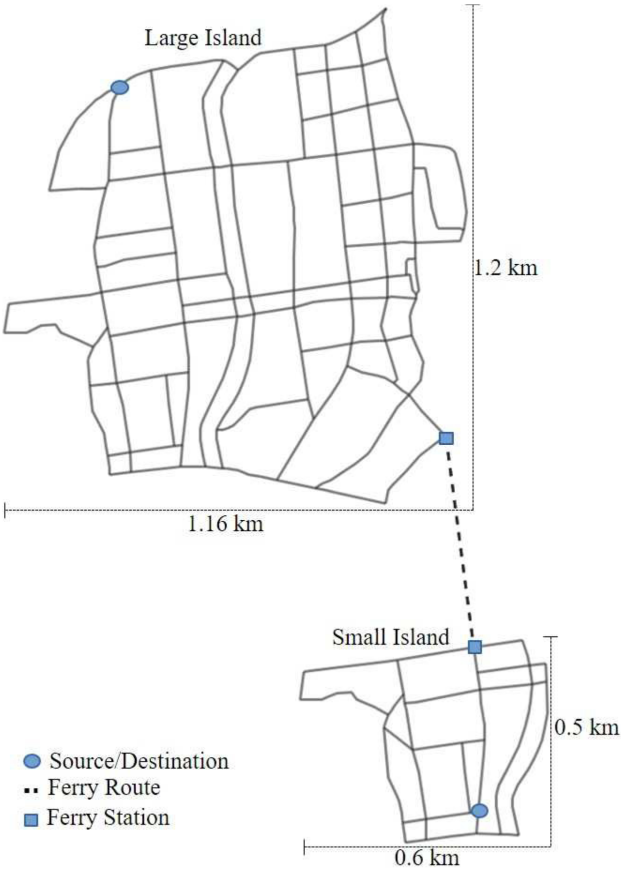


Fig. 4 Simulation scenario: large island and small island connected by ferryboat.

We assume the ferry and ferry station nodes on each island as a gateway node with a larger buffer size than the mobile node, which is essential so as not to make the gateway a bottleneck. Since the limitation of the ONE simulator which only supports 2,000 MB of maximum buffer storage size, we used the following in the scenario: 1:10 comparison ratio for the buffer size, each mobile node has a 200 MB buffer, then the gateway node has a 2,000 MB buffer. Later in Section 5.8 we also evaluate our proposed method with the increased buffer size ratio of 1:2 since it is close to reality.

The origin of the messages depend on the message delivery scenario. Messages are generated in a stationary source node located on an island and destined to a stationary destination node on the other island. In the LtoS scenario, the source is located on the large island, and in the StoL scenario, the source is located on the small island. The source node generates messages with size 0.4 MB, and various total sizes [204.8 MB, 409.6 MB, 819.2 MB, 1,638.4 MB, and 3,276.8 MB] within 480 min. To change the total size, we control the average time-interval of message generation. The message time-to-live (TTL) of 240 and 480 min are used for each simulation scenario. A larger value of TTL will have more chances for a message to reach its destination, while more messages stored in the network node's for long periods of time will potentially increase the consumption of resources (e.g., bandwidth and buffer space). To adapt the comparison ratio of the buffer size, we decreased the WiFi link interface with a transmission data rate of 1 Mbps and an omni-directional transmission

Table 1 Simulation parameters.

Parameter	Value
Simulation time	840 min
Node buffer size	Car and Bus = 200 MB
	Station A and B, Ferry = 2,000 MB
Interface transmit speed and range	1 Mbps and 25 m
Message lifetime (TTL)	240 and 480 min
Node speed	Bus = 5–20 km/h
	Car = 10–30 km/h
Total size (amount) of originally-generated messages	204.8 MB, 409.6 MB, 819.2 MB 1,638.4 MB, 3,276.8 MB
Message created duration	480 min from the beginning
Message size	0.4 MB
Warm up time	30 min

range of 25 m as scaling. To evaluate our proposal with a different buffer-size and WiFi-rate relation, later in Section 5.8, we increase the transmission rate and transmission range as considered in Refs. [27] and [28] with the increased buffer size ratio of 1:2. In order to get meaningful comparison results, the simulation scenario was executed 10 times using different movement seeds. Each figure shows the average value calculated from these results.

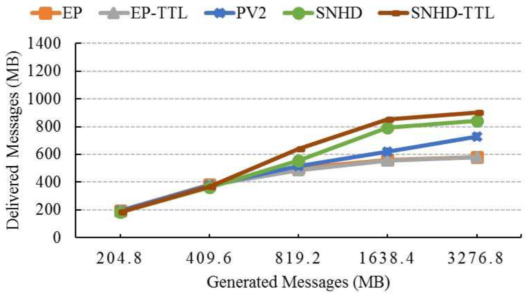
As discussed previously, SNHD-TTL employs binary spray with a parameter of L and the remaining-TTL consideration with parameters of W and W'. As default values, we used an L of 3, and W and W' are obtained from statistics derived from message delivery time of EP with 819.2 MB of the total size of generated messages. Later in Sections 5.5 and 5.6, we examine and discuss the impact of these parameters on SNHD-TTL's performance. **Table 1** summarizes the simulation parameters used in our evaluations.

5. Simulation Results

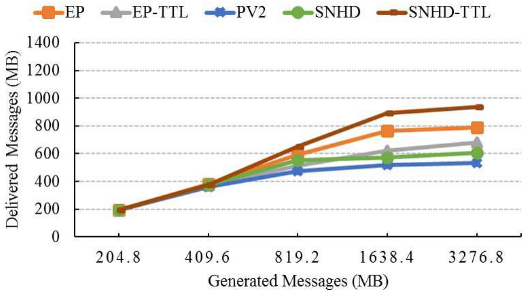
The performance of the SNHD-TTL routing protocol is compared through simulation against two popular DTN routing protocols, EP and PV2, plus two comparative routing protocols, EP-TTL (the EP protocol integrated with node location dependent remaining-TTL message scheduling), and SNHD (our proposed protocol without node location dependent remaining-TTL message scheduling). We used three performance metrics: the total size of delivered messages, overhead ratio, and average latency. The aim of our simulation study is to understand the impact of combining the considered techniques (i.e., binary spray, hop distance-based forwarding, and node location dependent remaining-TTL message scheduling) on improving the performance of DTN routing. We also evaluate the impact of increasing the number of nodes in each island, varying the number of copies L in the spray phase of SNHD-TTL, and sensitivity of W and W' values as obtained from the statistics of the message delivery time on the performance of SNHD-TTL.

5.1 The Total Size of Delivered Messages

The total size of delivered messages is defined as the size of the message multiplied by the number of messages successfully delivered to the destination during the simulation. **Figure 5** (a) and (b) show the total size of delivered messages with a TTL of 240 min under the LtoS and StoL message delivery scenarios. As the total generated size (i.e., the x-axis in the figures) increases, the network becomes congestion. In non- or weakly congested states, the performance of each protocol is similar. On the other hand, in congested states, a significant performance difference among protocols is seen. For the TTL 240 min performance of SNHD-TTL both message delivery scenarios are almost the same and perform the best across all protocols. In the LtoS scenario, EP-TTL and EP achieved lower performance, while in the StoL scenario, EP achieved better performance than EP-TTL, PV2, and SNHD for the 1,638.4 MB and 3,276.8 MB cases.

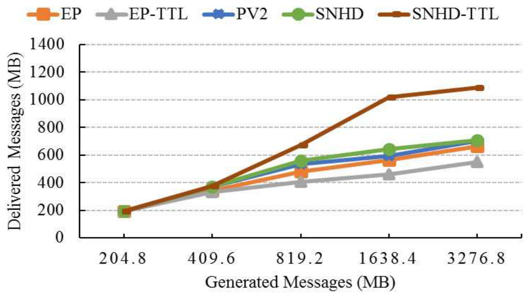


(a) Large to small island (LtoS) scenario

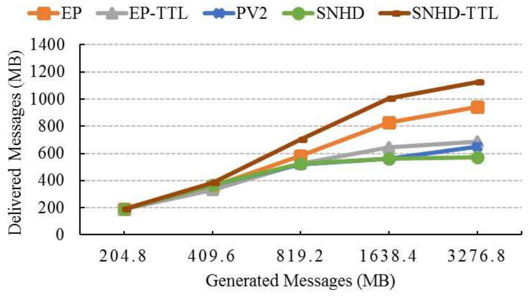


(b) Small to large island (StoL) scenario

Fig. 5 The total size of delivered messages with TTL 240 min.



(a) Large to small island (LtoS) scenario



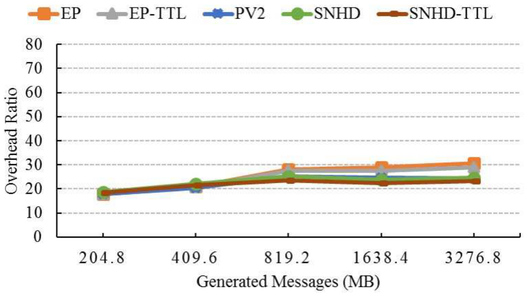
(b) Small to large island (StoL) scenario

Fig. 6 The total size of delivered messages with TTL 480 min.

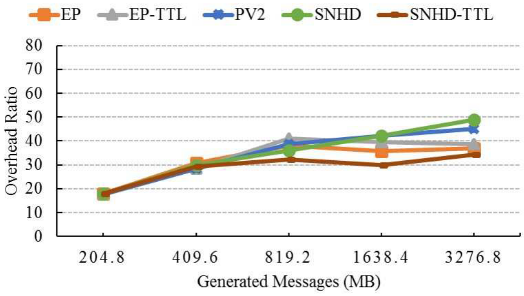
Figure 6 (a) and (b) show the total size of delivered messages with a TTL of 480 min, which indicate performance among all of protocols depends on message delivery scenarios. Compared with Fig. 5 (a) and (b), in both LtoS and StoL scenarios, the performance advantage of SNHD-TTL to other protocols is much greater.

In summary, except in cases of non- or weakly congested states, SNHD-TTL clearly outperformed other protocols irrespective of the delivery scenarios (StoL or LtoS) and TTL (240 min or 480 min).

For buffer management, we compared EP with EP-TTL and SNHD with SNHD-TTL. For EP-TTL, we found that this method did not significantly improve performance as compared with EP,

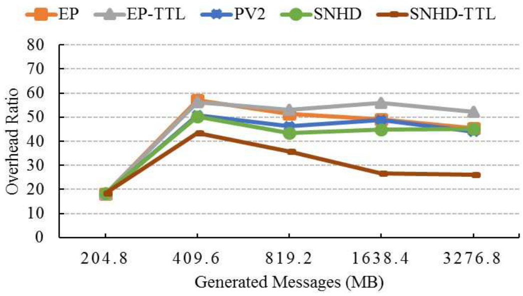


(a) Large to small island (LtoS) scenario

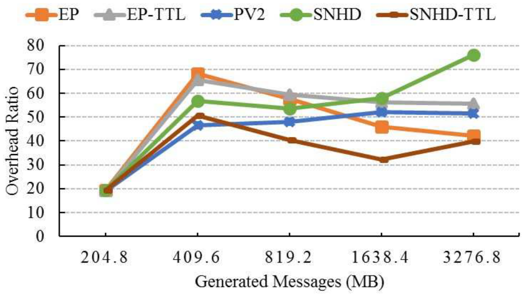


(b) Small to large island (StoL) scenario

Fig. 7 Overhead ratio with TTL 240 min.



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Fig. 8 Overhead ratio with TTL 480 min.

even for the StoL scenario in the 1,638.4 MB and 3,276.8 MB cases. For the LtoS scenario with a TTL value of 480 min, the performance of original EP was better than EP-TTL. Conversely, our proposed message scheduling had an impact on the performance of SNHD. More specifically, SNHD-TTL was better as compared with SNHD.

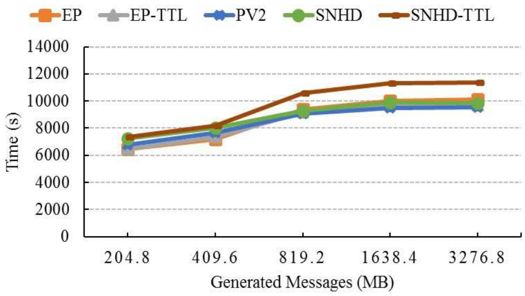
5.2 Overhead Ratio

The overhead ratio is based on how many additional messages were relayed for each delivered message. This is reflected as transmission efficiency. **Figure 7** (a) and (b) present the overhead ratio of LtoS and StoL scenario with TTL 240 min. The overhead increased as the total size of generated message increased, but each protocol behaved differently. In the LtoS scenario, the overhead ratio of all routing protocols in the congested state fluctuated about 20 to 30 messages, while in the StoL scenario the fluctuation is about 35 to 50 messages. SNHD-TTL shows lower overhead than the other protocols at 819.2 MB. There were more congested cases especially in StoL scenario. The overhead ratio for TTL 480 min is illustrated in **Fig. 8** (a) and (b). Compared with Fig. 7 (a) and (b), generally, a longer TTL (480 min) results in a larger overhead, except for the no congestion case. The characteristics seem more complicated depending on the algorithm of each protocol and message delivery scenario. SNHD-TTL also shows lower overhead than the other protocols, especially in the LtoS scenario.

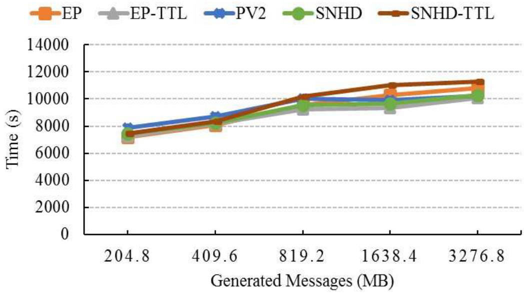
Our implementation of binary spray, hop distance-based forwarding, and node location dependent remaining-TTL message scheduling in SNHD-TTL, decreased the number of copies of each message as compared with the other routing protocols. As explained in Section 3, SNHD-TTL gives priority to messages which are very young and that are stored only at a few nodes (less than L) are first. Messages with a moderate remaining-TTL in relation with its current location are second, messages with a short remaining-TTL are next, and messages with sufficient remaining-TTL are last. This would result in an effective use of limited resources (i.e., the number of messages to be forwarded within each valuable contact duration) in congested states. On the other hand, SNHD implements binary spray and hop distance-based forwarding, and EP-TTL implements node location dependent remaining-TTL message scheduling. Both of these failed to achieve low overhead. In some cases, they have a higher overhead than the other protocols, which implies a combination of these three techniques is necessary to achieve effective message delivery.

5.3 Average Latency

Figure 9 (a) and (b) show the average latency for TTL values of 240 min and **Fig. 10** (a) and (b) show the average latency for TTL values of 480 min under both message delivery scenario. The average latency is the average time difference between the message generation time at the source and the message received time at the destination over all successfully delivered messages. Increasing the message TTL value increased the average latency of all routing protocols. In congested states, SNHD-TTL exhibited a higher latency than the other protocols while it significantly outperformed other protocols in terms of the total size of delivered messages. Increasing the message TTL from 240 min to 480 min increased the average latency of all routing protocols, especially for SNHD-TTL, which increased from approximately 200 min to 420 min. In the StoL scenario, the average latency of all protocols except for SNHD-TTL achieved almost similar performance. It was about 130 min to 180 min when TTL is 240 min, and about 130 min to 300 min when TTL is 480 min. Then in the

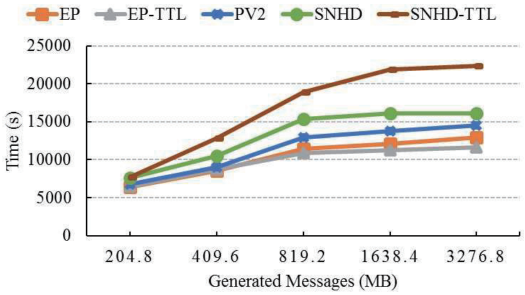


(a) Large to small island (LtoS) scenario

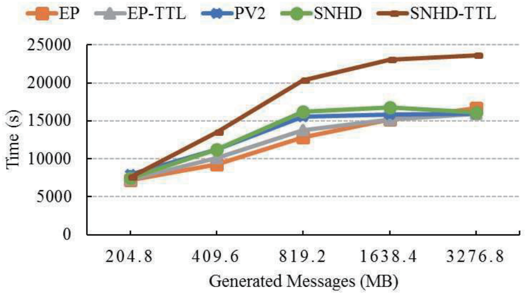


(b) Small to large island (StoL) scenario

Fig. 9 Average latency with TTL 240 min.



(a) Large to small island (LtoS) scenario



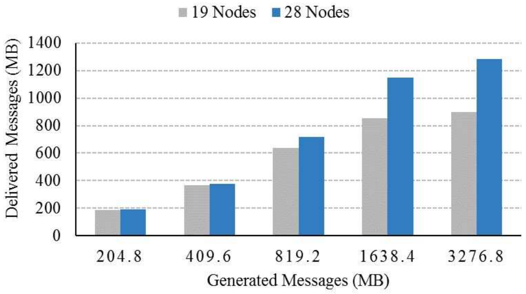
(b) Small to large island (StoL) scenario

Fig. 10 Average latency with TTL 480 min.

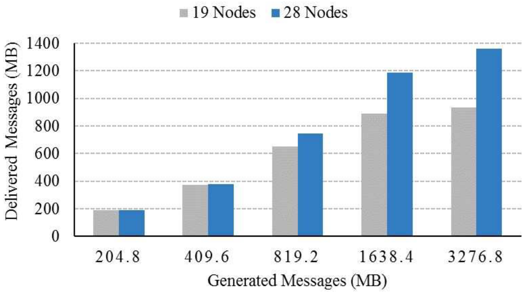
LtoS scenario, the difference among protocols varies, depending on the size of the generated messages. For example, EP has a lower latency in the 409.6 Mb case and then becomes higher than the other protocols except for SNHD-TTL in the 819.2 MB and 1,638.4 MB cases when TTL is 240 min.

5.4 Impact of Increasing Number of Nodes in Each Island on The Total Size of Delivered Messages

In this evaluation, we increased the number of nodes on both islands. In the large island, the number of nodes is increased from 10 (6 cars and 4 buses) to 15 (9 cars and 6 buses), then in the small island it is increased from 5 (3 cars and 2 buses) to 9 (6 cars and 3 buses). **Figure 11** (a) and (b) show the total size of delivered messages as the number of nodes increases. In general, increasing the number of nodes will increase the performance compared with the default number of nodes. Increasing the number of nodes increased the number of messages that can be stored in the buffer storage on the network as well as the number of messages that can be exchanged by contacts between nodes. This decreased the delay time of messages to reach the destination node. As shown in **Fig. 12** (a) and (b), the average latency of 28 nodes is lower than 19 nodes in the LtoS and StoL scenarios.



(a) Large to small island (LtoS) scenario

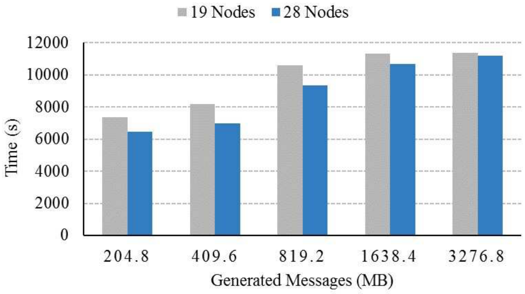


(b) Small to large island (StoL) scenario

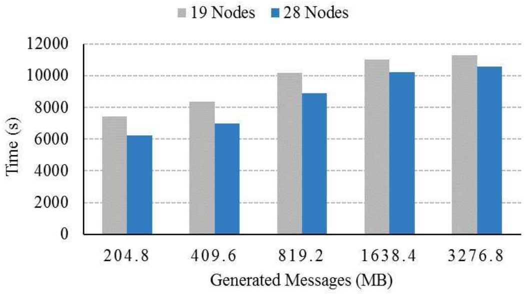
Fig. 11 Impact of increasing the number of nodes on the total size of delivered messages.

5.5 Impact of Varying the Number of copies (*L*) on The Total Size of Delivered Messages

As shown in **Fig. 13** (a) and (b), we evaluated the impact of the number of generated message copies (*L*) in the spray phase on the performance of SNHD-TTL in terms of the total size of delivered messages. In the LtoS scenario, varying *L* had a significant impact in cases where the size of generated messages totaled 819.2 MB or more. Note that the total size of delivered messages for all *L* values was almost the same for the cases from 204.8 MB to 409.6 MB, because the network capacity was large enough for all messages. When a congested state occurred, the larger number of copies caused a decrease in performance, because as *L* increased, the number of message transmissions also increased. Then in the StoL scenario, the total size of delivered messages with different *L* values achieved similar performance except in the 3,276.8 MB case, where small *L* values achieved better performance than the other values. **Figure 14** (a) and (b) show the impact of the *L* values on the average latency. In the LtoS sce-

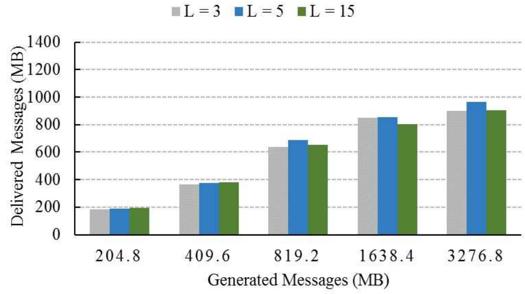


(a) Large to small island (LtoS) scenario

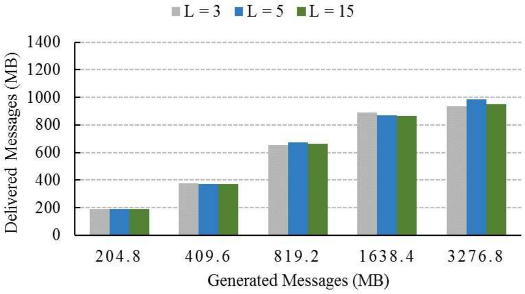


(b) Small to large island (StoL) scenario

Fig. 12 Impact of increasing the number of nodes on the average latency.



(a) Large to small island (LtoS) scenario



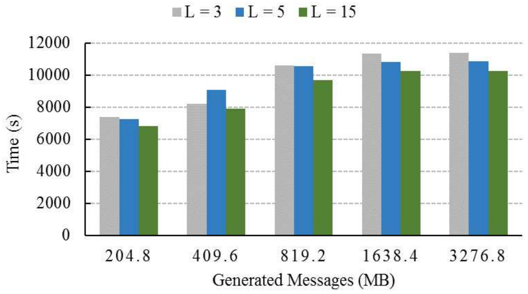
(b) Small to large island (StoL) scenario

Fig. 13 L impact on the total size of delivered messages.

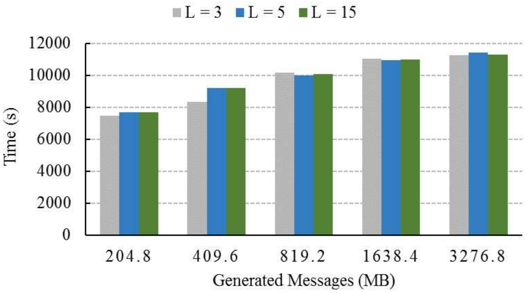
nario the number of L values significantly affected the average latency. Increasing the L values will decrease the average latency while in the StoL scenario the average latency is almost the same as all of the L values.

5.6 Impact of W and W' on SNHD-TTL's Performance

Node location dependent remaining-TTL message scheduling used the statistics of delivery time in order to determine W and W' values. In the previous subsections, we used statistics from the delivery time of EP with 819.2 MB of the total size of generated messages to determine W and W' to serve as the baseline. We assume they can be roughly estimated beforehand from information obtained by some means, e.g., simulations or real field node measurements.



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Fig. 14 L impact on the average latency.

Table 2 W and W' value from EP.

Msg. Gen. Size	Value	Li Node	Station Li	Si Node
204.8 MB	W	69.36	37.01	7.01
	W'	89.47	47.51	9.51
409.6 MB	W	81.10	37.46	7.46
	W'	107.79	48.33	10.33
819.2 MB	W	120.87	54.85	24.85
	W'	179.80	94.54	56.54
1,638.4 MB	W	175.81	105.19	75.19
	W'	275.17	171.37	133.37
3,276.8 MB	W	184.80	110.89	80.89
	W'	309.12	210.42	172.42

Table 2 provides W and W' values according to the total size of generated messages which are calculated from the delivery time report in Fig. 3 using the formula in Section 3.3. "Msg. Gen. Size" column contains information about the total size of the originally generated messages. The "Li Node" column contains W and W' values for the mobile node on the large island. The "Station Li" column contains W and W' values for the station node on the large island. The "Si Node" column contains W and W' values for the station node and the mobile node on the small island.

For calculating the LtoS scenario, from Fig. 3 we get the 75-tile and 50-tile values for the large island as $(Li) = 85.27$ min and 66.02 min respectively. Then for the small island, we have $(Si) = 56.54$ min and 24.85 min respectively. Then for the ferry traveling time (FT) we used fixed values of 38 min for the 75-tile, and 30 min for the 50-tile which are determined based on the trav-

Table 3 W and W' value from SNHDTTL using W and W' value in case with 819.2 MB case in Table 2.

Msg. Gen. Size	Value	Li Node	Station Li	Si Node
204.8 MB	W	70.66	38.24	8.24
	W'	93.08	51.24	13.24
409.6 MB	W	74.93	37.19	7.19
	W'	101.70	48.20	10.20
819.2 MB	W	104.13	38.79	8.79
	W'	152.44	52.59	14.59
1,638.4 MB	W	140.56	39.77	9.77
	W'	181.62	53.53	15.53
3,276.8 MB	W	148.53	43.29	13.29
	W'	195.86	60.22	22.22

Table 4 W and W' value from SNHDTTL using W and W' value in Table 3.

Msg. Gen. Size	Value	Li Node	Station Li	Si Node
204.8 MB	W	91.23	39.66	9.66
	W'	129	47.52	9.52
409.6 MB	W	104.08	38.13	8.13
	W'	155.88	49.81	11.81
819.2 MB	W	109.05	42.82	12.82
	W'	260.20	159.67	121.67
1,638.4 MB	W	131.55	47.42	17.42
	W'	362.63	228.25	190.25
3,276.8 MB	W	153.38	46.12	16.12
	W'	229.22	77.80	39.80

eling time and waiting time of the ferry on each island. From each formula in Section 3.3, we get W and W' of EP 819.2 MB as follows:

- Li Node, using Eqs. (1) and (2)

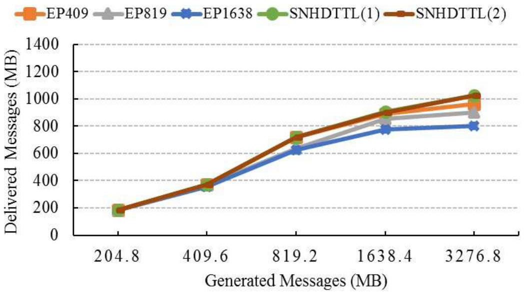
$$W = 66.02 + 30 + 24.85 = 120.87$$
$$W' = 85.27 + 38 + 56.54 = 179.80$$

- Station Li, using Eqs. (3) and (4)

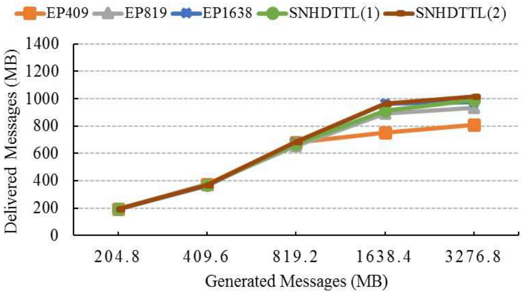
$$W = 30 + 24.85 = 54.85$$
$$W' = 38 + 56.54 = 94.54$$

- Si Node, using Eqs. (5) and (6)

$$W = 24.85$$
$$W' = 56.54$$



(a) Large to small island (LtoS) scenario



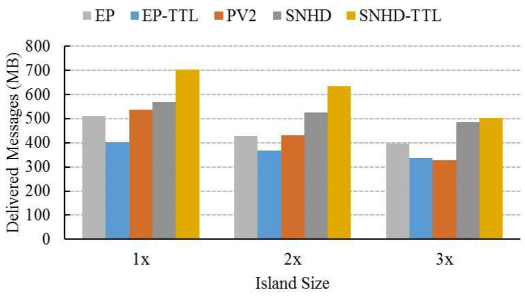
(b) Small to large island (StoL) scenario

Fig. 15 W and W' impact on the total size of delivered messages.

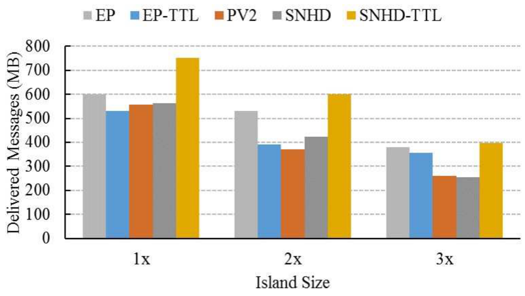
In this subsection, we show the impact of W and W' values on the message delivery performance, and discuss how to find and calibrate appropriate W and W' values. As shown in **Table 3**, new W and W' values are determined from the statistics of the message delivery time of SNHD-TTL as obtained by simulation using the W and W' values for the case of 819.2 MB from Table 2. Then, as shown in **Table 4**, different new W and W' values are determined from the statistics of the message delivery time of SNHD-TTL as obtained by the simulation using previously determined W and W' values for each message generated size case from Table 3. For example, we simulate SNHD-TTL with the 204.8 MB message generated size using W and W' values for the case of 204.8 MB in Table 3. We compare the total size of delivered messages of SNHD-TTL using different W and W' values. In **Fig. 15** (a) and (b), EP409, EP819, and EP1638 mean SNHD-TTL using W and W' values obtained from the message delivery time statistics of EP in each of 409.6 MB, 819.6 MB and 1,638.4 MB cases in Table 2, respectively. Those cases are intended to represent a static SNHD-TTL that uses the same W and W', irrespective of message generated sizes, i.e., congestion states. Note that EP819 is equivalent to the default SHND-TTL as evaluated in previous subsections. SNHDTTL(1) and SNHDTTL(2) mean the SNHD-TTL using the W and W' values obtained from SNHD-TTL in each corresponding message generated size case as shown in Tables 3 and 4, respectively. Those cases are intended to represent an adaptive SNHD-TTL that uses the different W and W' in response to message generated sizes, (i.e., congestion states) and thus we call them SNHDTTL-adaptive.

In the LtoS scenario, as shown in Fig. 15 (a), if the message generated size is small, (i.e., 204.8 MB and 409.6 MB cases) the performance is not affected by W and W'. However, when the message generated size is large, EP1638 achieved the lowest performance. EP819 achieved lower performance than EP409, SNHDTTL(1), and SNHDTTL(2) in the 638.4 MB and 3,276.8 MB cases. SNHDTTL(1) and SNHDTTL(2) achieved the best performance. In the StoL scenario as shown in Fig. 15 (b), when the message generated size is small, (i.e., 204.8 MB, 409.6 MB, and 819.2 MB cases) the performance is not affected by W and W'. EP409 achieved the lowest performance when the message generated size is large, (i.e., 1,638.4 MB and 3,276.8 MB cases). SNHDTTL(1) showed slightly lower performance than EP819, EP1638 and SNHDTTL(2) in the 1,638.4 MB case.

These results indicate that the use of the same W and W' independent of message generated sizes may cause performance degradation in some cases and it is difficult to determine a sin-

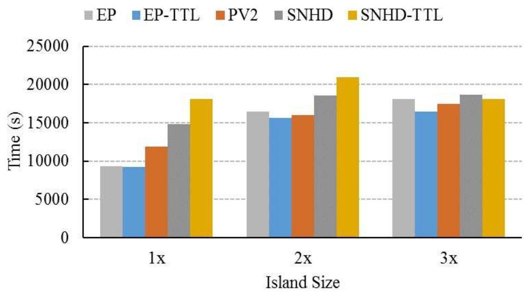


(a) Large to small island (LtoS) scenario

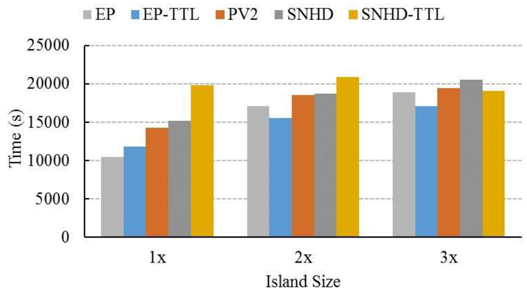


(b) Small to large island (StoL) scenario

Fig. 16 The size of island impact on the total size of delivered messages.



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Fig. 17 The size of island impact on the average latency.

gle best pair of W and W' (i.e., EP409, EP819, and EP1638). In contrast, SNHDTTL(1) and SNHDTTL(2), that is SNHDTTL-adaptive, showed similar and stable performance. In addition, in some cases (StoL scenario in the 1,638.4 MB and 3,276.8 MB cases), SNHDTTL(2) achieved better performance than SNHDTTL(1). Therefore, an adaptive calibration of W and W' by updating them during operation should be considered. The statistics of message delivery time is required, to determine W and W' for each location. Sharing this information among nodes in an online manner is also needed. This could be possible by recording the history of TTL updates in all or some messages, monitoring them at stationary landmark nodes (the ferry stations and the destination in our scenario), and distributing this information, for example.

5.7 Impact of Increasing the Size of Island

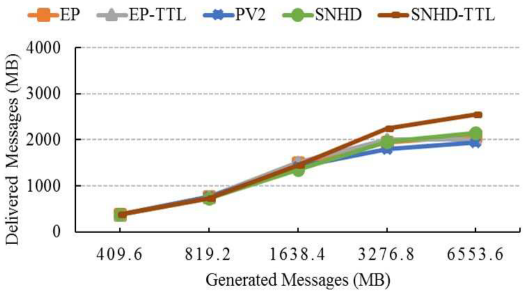
This evaluation shows the impact of increasing the size of the island on the performance of all routing protocols. We increased the island size by using two larger maps that are enlarged by 2x and 3x from the original map as shown in Fig. 4, respectively, and set the scenario parameters by 480 min of TTL value, 819.2 MB of the total size of generated messages and increasing the number of nodes from 19 nodes in the original scenario to 28 nodes. We determined the W and W' values according to each island size using message delivery reports of EP 819.2 MB. **Figure 16** (a) and (b) show the impact of increasing the size of the island on the total size of delivered messages. In general, as the size of the island increases, the performance of all routing protocols decreases and, at the same time, the advantage of our proposed SNHDTTL protocol using a single (W, W') also decreases even though it still works with a better or almost equal performance to other protocols. These results suggest, in larger island scenarios, we need to consider not only refining the selection of (W, W') but introducing another refinement such as area partitioning.

Increasing the size of the island also affects the average latency as shown in **Fig. 17** (a) and (b). When the island size increased 3x the average latency of all protocols also increased and become similar. These results indicate the difference between SNHDTTL and the other protocols will become smaller for larger island scenarios.

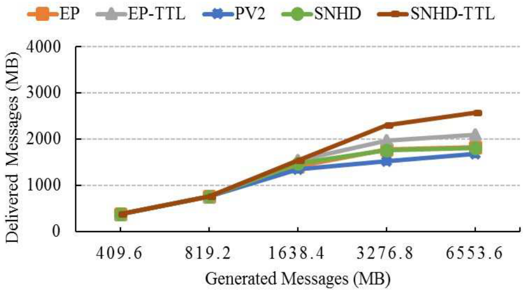
5.8 Impact of Increasing Buffer Size and WiFi Transmit Rate and Range

In Section 4, we discussed about our simulation scenario. Due to the limitation of the maximum buffer size in the ONE simulator, we used a comparison ratio 1:10 for the buffer size of nodes (i.e., 2,000 MB for the gateway nodes, and 200 MB for mobile nodes), with a WiFi transmission rate and range of 1 Mbps and 25 m, respectively. In this section we discuss about the impact of increasing the buffer size ratio and WiFi transmit rate and range. We decreased the comparison ratio of buffer size from 1:10 to 1:2 (i.e., gateways nodes is 2,000 MB and mobile nodes is 1,000 MB), and increased the WiFi transmission rate and range to 4.5 Mbps and 30 m, as considered in Refs. [27], and [28]. We also omitted 204.8 MB and added 6,553.6 MB as the largest of the total size of generated messages. Since a congestion state of this new scenario occurred when the total size of generated messages was 3,276.8 MB, the W and W' values are determined by message delivery report of EP 3,276.8 MB.

Increasing the buffer size and WiFi transmit rate and range affected the performance of all routing protocols as shown in **Figs. 18** and **19**. Increasing the buffer size of mobile nodes will increase the total capacity of the network. A congestion state started when the total size of generated message is 3,276.8 MB

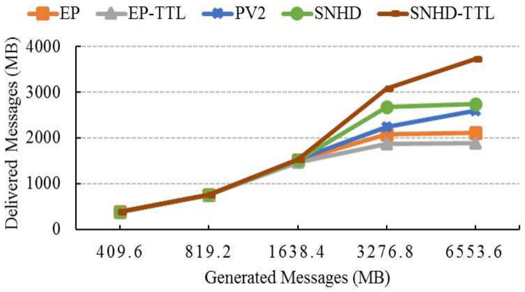


(a) Large to small island (LtoS) scenario

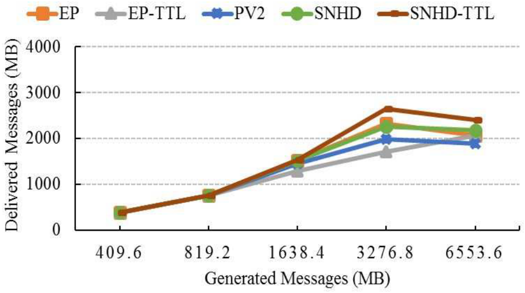


(b) Small to large island (StoL) scenario

Fig. 18 Buffer size and WiFi transmit rate and range increasing impact on the total size of delivered messages TTL 240 min.



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Fig. 19 Buffer size and WiFi transmit rate and range increasing impact on the total size of delivered messages TTL 480 min.

while in the original scenario, it is 819.2 MB. Increasing the WiFi transmit rate and range increased the number of messages that can be transferred in a single moment of contact. Figure 18 (a) and (b) show the performance of all protocols in TTL 240 min. They achieved almost the same performance from 409.6 MB to 1,638.4 MB then in 3,276.8 MB and 6,553.6 MB, SNHDTTL achieved better performance than the other protocols.

Then for TTL 480 min (Fig. 19 (a) and (b)), the performance of all routing protocols increase compared with TTL 240 min. In both LtoS and StoL scenarios, SNHDTTL achieved better performance compared to the other protocols when the total size of generated messages is 3,276.8 MB or more. Unfortunately in StoL scenario (Fig. 19 (b)), although the total size of generated messages increases twice to 6,553.6 MB the performance of all protocols except EP-TTL decreased.

6. Conclusions and Future Work

In this paper, we have proposed the spray-and-hop-distance-based with remaining-TTL consideration (SNHD-TTL). This routing protocol integrated three techniques: binary spray, hop distance-based forwarding, and node location dependent remaining-TTL message scheduling, to fit on the island scenario with two message delivery scenarios (i.e., large island to small island, and small island to large island). Global knowledge about statistics obtained from message delivery time is used for TTL-based message scheduling. Applying these combined techniques, we observed that SNHD-TTL outperformed the other evaluated routing protocols. Results also showed that in congested states, a smaller number of message copies was better in the spray phase. Increasing the number of nodes resulted in better performance for all routing protocols due to the capacity of the network (i.e., buffer storage) being increased. It is also suggested that static W and W' values independent of congestion states are not very effective, although appropriate static values showed to work to some extent in our scenarios. In our future work, we aim to develop a way to dynamically learn and estimate W and W' in practical system operation. For scenarios with multiple sources and destinations, we may need to introduce more sophisticated hop distance based forwarding. In addition, we will also consider introducing the network coding techniques as suggested in Ref. [25].

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Agussalim received B.Ed. in electrical engineering education from State University of Makassar, Indonesia (UNM) in 2007, M.E. in electrical engineering with a major in informatics engineering from Hasanuddin University, Indonesia (UNHAS) in 2012. He is currently a doctoral student in the Department of Information System, Graduate School of Computer Science and System Engineering, Kyushu Institute of Technology, Japan. His research interests include delay, disruption, disconnection tolerant networks (DTNs) and multihop wireless network. He is a student member of IEICE.

Masato Tsuru received B.E. and M.E. degrees from Kyoto University, Japan in 1983 and 1985, respectively, and then received his D.E. degree from Kyushu Institute of Technology, Japan in 2002. He worked at Oki Electric Industry Co., Ltd., Nagasaki University, and Japan Telecom Information Service Co., Ltd. In 2003, he moved to the Department of Computer Science and Electronics, Kyushu Institute of Technology as an Associate Professor, and has been a Professor in the same department since April 2006. His research interests include performance measurement, modeling, and management of computer communication networks. He is a member of ACM, IEEE, IEICE, IPSJ, and JSSST.