BALANCE: A Robust Routing Protocol in Self-Organized Civilian DTN

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Abstract*—Delay-tolerant networking (DTN) architecture has emerged to cope up with loss of continuous connectivity issue that may occur under some environmental conditions such as infrastructure down due to disaster. Bundle protocols generally enhance network delay and reliability by storing and forwarding data-packed bundles on multiple nodes in the same time through flooding algorithm. On the other hand, the flooding mechanism usually incurs a consumption of resources. In this paper, we propose a robust routing protocol called *BALANCE* for self-organized civilian DTN. In civilian contexts, a resource constraint is a primary issue. So, our *BALANCE* sets an objective function to minimize the number of replications over networks by using a regression model for predicting future spreading effect considering the delivering probability. Since the device owners (civilian) could be selfish and decide not to store or forward any bundles, we further introduce a selfish factor applied together with our newly formulated SINR-based function to achieve the delivering probability. We conduct evaluations in stationary and mobile scenarios regarding disaster situations. The results show the highest traded-off values of delivering performance and resource consumption of the proposed protocol compared to widely-used protocols and present our superior in restricted conditions like limited buffer size or selfish participants.

I. Introduction

Delay Tolerant Network (DTN) is a general-purpose overlay network operating on top of base networks like the Internet to deal with high delays and connectivity loss condition [1], found in many contexts such as military networks operating under hostile conditions, atypical media networks in deep-space or underwater, and civilian wireless networks with less or none infrastructure [1][2]. Bundle protocol is a store-and-forward delivering protocol designed for DTN which leverages an application layer for making a decision. Flood-based *Epidemic* bundle routing protocol [3], in which a node always floods messages to all neighbors, has been first launched with hardly-acceptable resource consumption especially under resource-constraint conditions such as transport queue length and buffer storage size. To preserve the resources, some straightforwardly limits the number of flooding, for instance, *Spray and Wait*[16]. Meanwhile, some integrate additional communication to estimate the probability of successful delivering path for smarter decision, for example, *MaxProp* [4], *PROPHET* [5], *SEPR*[7], *CAR* [6], and *MDDV* [19].

We have been leading a national project supported by Ministry of Education in Japan entitled "Large-Scale, Tempo-Spatial Information Gathering Mechanism over DTN-enabled Distributed Micro-modules" where the final goal is to design a computation mechanism over civilian DTN, which plays a vital role to let civilians share the current situations via unstable links between their devices in an early phase of the disaster. An illustration in Fig. 1 presents a situation when an area suddenly floods, infrastructure is down, and only some people who have a boat can travel. A man trapped at his working place wants to hear from his family at home. Such communicating networks generally come together with the following challenges. Firstly, the network-connectivity topology is random and dynamic. Secondly, resource consumption is significant. Thirdly, privacy issues are highly concerned. Civilian location and mobility trajectory of civilians should be secret because disclosing such information could bring many kinds of undesirable attacks and threats to the civilians. Fourthly, all network nodes (civilian) are not under control. In other words, they are equally collaborating with each other and have absolute freedom to make store-and-forward decisions independently. Some of them may be selfish and decide not to store or forward any data, represented by a red guy in the illustrated figure. For disaster contexts, recently-proposed protocols insist on flood-based protocol and reserve resource consumptions on victims by pushing replicating burden to special nodes such as carriers in [8][9][10], and infostations in [11]. Ref.[13] introduces a concept of additional stationary nodes, called *Throw box* and formulates the problem of combined delay and capacity with time-dependent links over DTN. The optimization is further proposed in [14]. Ref.[12] prioritizes messages to shave the routing in the medical treatment context. To the best of our knowledge, none of the existing disaster-context research considers an early phase when rescue teams are still not moving into the area and networks are only composed of civilian who can be selfish.

In this paper, we propose *BALANCE*, a robust routing protocol for operating in self-organized delay tolerant civilian networks. Nodes update connectivity information over time via *Hello* messages and additionally defined Replication-stat Memory (RM) packets. To preserve civilian privacy, we do not include geographic location or any trajectory approximation in the exchanging message. *BALANCE* limits the number of replications in a similar way to *Spray and Wait* method and integrates the prediction technique to estimate and minimize the future-spreading number of replications. The prediction model is built on distance vector routing protocol considering SINR-based estimated link quality together with a selfish factor. The selfish factor is supposed to be available from a reputation esti-

Fig. 1. Self-organized Civilian Delay Tolerant Networks

mation mechanism such as local voting from past experiences, which is out of this paper scope. We conduct simulation with two different scenarios: Stationary source-destination with Speedy Mobile Vehicles (SMV) and Mobile Pedestrian (MP). We compare our proposed protocol with three well-known routing protocols: (1) *Epidemic*[3], (2) *Spray and Wait*[16] and (3) *MaxProp*[4]. Normally, the higher amount of replications increases the probability of delivery, which might also imply better latency. *MaxProp* and *Epidemic* both focuses on delivery time while *Spray and Wait* focus on reducing the replications. The results show that our proposed *BALANCE* locates between both ways but closer to the better one. For instance, in the non-constraint Speedy Mobile Vehicles (SMV) scenario, we reduce about 16 generated bundles/minute with only average 5 seconds delivery time while *Spray and Wait* spends more than 15 seconds in average to reduce 14 bundles/minute. For buffer-limit environments, *BALANCE* gains comparable or even higher delivering ratio while keeping the number of generated replications in the middle, especially when some nodes become selfish and refuse to store or forward the data.

The rest of this paper is organized as follows. Section II discusses on related work and summarizes our contributions. Section III explains the proposed method. Section IV shows experimental results. Section V gives the conclusion.

II. Related Work

The developing path of routing protocols toward Delay Tolerant Networks has been well-summarized in many tutorials and surveys [1][2][17]. Broadly categorized groups are deterministic, where network topology is known, and stochastic, where network behavior is random. Particularly for the latter, it can be further broken down into four sub-groups with respect to the way they make a store-and-forward decision. Those are *Epidemic-based*, *Estimation-based*, *Model-based*, and *Node Movement Control based*. Epidemic approaches do not require connectivity knowledge of networks. On the other hand, estimation-based approaches exploit probabilistic estimation using historical connectivity information. Model-based and node-movement-control based approaches exploit node mobility pattern, which may intimidate civilian privacy. Some approaches further require controllability on nodes which is invalid in a self-organized manner. In this section, we will mention only potential approaches in epidemic-based and estimation-based groups.

A. Epidemic-based Approach

Epidemic has been introduced as a first routing solution for DTN in [3]. It performs a flooding-based store-and-forward mechanism. The communication between any two encountering nodes can be simply illustrated as shown in Fig. 2. Each node periodically broadcasts a *Hello* message which contains identifiers of its stored bundles. When a node hears other's *Hello*, it will request for not-yet-stored bundles and update delivered record to the *Hello* sender. Epidemic decision at the *Hello* sender is always copying and forwarding the requested bundles. This protocol provides an optimal path to deliver the message but coming up with considerably-high resource consumption. The straightforward resolution is to limit the replications to just a few numbers as proposed in [18]. Although it works well in high-mobility and covered networks, at the same time, it is too restricted in general cases which network density might be low and not well-covered. Meanwhile, to limit the spreading of bundles, *Spray-And-Wait* routing protocol comes with two phases [16]. The first phase is **spray phase** that is to forward a limited number of message copies to relay nodes (neighbors) which will further do direct transmission. The second phase is **wait phase** that is to wait for delivering confirmation. This approach is in-between the epidemic and hop-limit approaches.

B. Estimation-based Approach

With an extra communication between encountering nodes, the likelihood of successful delivery can be estimated and exploited in many ways. Some perform estimation only on the next-hop. For example, *MaxProp* exploits hop-count to destination for bundle prioritizing [4]. *PROPHET* constructs a probabilistic metric called delivery predictability, $P(a, b)$, of node a for the known destination b [5], aged by a factor over time. *CAR*[6] uses *Kalman Filter* to predict the context of the host with the highest probability to deliver if there is a path to destination. Meanwhile, *SEPR*[7] finds the end-to-end shortest expected path to the destination and then decides which node will forward the message. However, none of them sets an objective at minimizing the number of replications and considers the factor of selfishness which could occur in the civilian context.

C. Contributions

We summarize our contribution in this paper as follows: (1) pointing out context-specific challenges in self-organized ad-hoc civilian wireless networks and discuss applicability on existing routing protocols, (2) introducing a novel algorithm to determine successful delivering probability regarding SINR link metric and selfish factor, (3) proposing a robust routing protocol considered as an integrated outcome of hop-limit flooding-based and estimation-based approaches named *BALANCE*, (4) modeling a lightweight algorithm to estimate future replication spreading after supposed delivering time applying regression techniques, and (5) presenting well balancing between the delivery performance and resource-consumption saving of the proposed protocol.

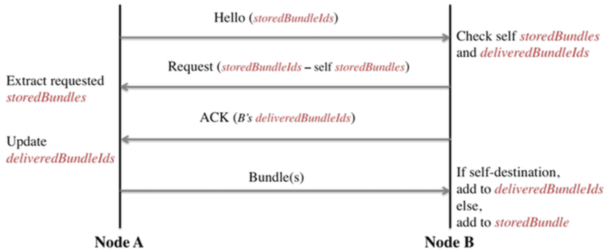

Fig. 2. Basic Bundle Protocol (Epidemic)

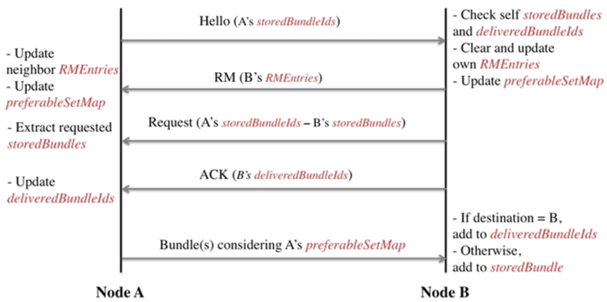

Fig. 3. BALANCE Bundle Protocol

III. BALANCE

BALANCE is DTN routing protocol aiming at providing a good trade-off between delivery performance, which reflected by message elapsed time of arrival (ETA) and delivery ratio, and resource saving, which reflected by the number of generated bundles. To achieve that, it requires an additional message containing current estimation results called *RM* (Replication-stat Memory). An extension of bundle communication in *BALANCE* is depicted in Fig. 3. There are four main communicating steps when two nodes encounter, described as follows.

Step 1. Like common protocols, any node, denoted by *A*, periodically broadcasts the *Hello* message containing the summary vector of stored bundles.

Step 2. Whenever another node, denoted by *B*, receives the *Hello* message, it will first check its stored bundles. If some not-yet-stored bundles exist, it will extract *RM* entries and send back to the *Hello* sender. If the last broadcasting passes for a specific update interval, instead of sending to just the sender, it will broadcast the *RM* to all current neighbors. Accordingly, the control message (*RM*) is triggered by a rational update interval as well as event of encountering some nodes, not by the frequent timeout interruption like the *Hello* message.

Step 3. After that, same as the conventional procedure, node *B* requests not-yet-stored bundles through a *Request* message and notifies already-delivered messages through the *ACK* message.

Step 4. Node *A* updates snapshot knowledge about neighbors from *RM* with a renew expiration time and clear delivered bundles according to *ACK*. Next, it computes a preferable set of neighbors called *preferableSetMap*, to which messages for any known destination are forwarded. The *preferableSetMap* is derived from a minimizing-replication preferable-selection mechanism. Accordingly, it will do a replication and forward the message to the requesting node (*B*) when *B* is in the computed set.

A. Replication-stat Memory: RM

A *RM* entry is composed of the following information: (1) factors for third order polynomial regression prediction model for replication estimation (2) expected elapsed time on arrival (ETA) (3) expected failure probability (4) expected replications, and (5) computation timestamp. When a node receives a *RM*, it will compute elapsed time from the message timestamp and failure probability corresponding to the sender. The failure probability (P_{fail}) is computed from multiplication of link quality metric (P_{lq}) and selfish probability (P_{self}). According to an analysis about link quality metrics, SINR (Signal-to-Interference-Plus-Noise Ratio) is one of the best parameters to indicate the link quality value [15]. There are many link-quality measurement methods using SINR value [20][21]. From a number of experiments and results in [22], a communication link is perfectly connected when SINR is more than 15 dB and becomes unconnected when SINR goes lower than 10 dB. Between them, the link quality drops drastically, which we fit the experimental results to an exponential function. So, we compute P_{lq} of node t at node q as below:

$$P_{lq}(q,t) = \begin{cases} 1; \ SINR(q,t) \geq 15 \\ 0.01e^{0.921 \times SINR(q,t) - 9.21}; \ 10 < SINR(q,t) \leq 15 \\ 0; \ otherwise \end{cases}$$

For P_{self}, we presume a reputation estimation protocol calculated from past history among nodes over networks. P_{self} refers to the probability that a node will not cooperate on store-and-forward the data. Correspondingly, the success delivering probability $P_{success} = (1 - P_{self}) \times P_{lq}$. The failure probability is the inverse of success probability, $P_{fail} = 1 - P_{sucess}$. We construct an initial *RM* from the direct-encountering elapsed time and failure probability attached with an expiration time.

B. Minimizing-replication Preferable-selection Mechanism

A preferable set is a candidate set for a specific destination of top k neighbors ranking by expected replication in ascending order with consideration of failure probability as a secondary factor. To achieve the preferable set mapping to each node, we propose a minimizing-replication preferable-selection mechanism, presented as a flowchart in Fig. 4. The first step is to sort the neighbors according to the expected replication number in their Replication-stat Memory (RM) information. Note that, *RM* exchange is asynchronous and averaged over a time window. The second step is to greedy add next member of the sorted entries to the candidate list. Next step is to compute the replication spreading model and estimate expected ETA, failure probability, and future replication numbers with respect to the current candidate list. The member

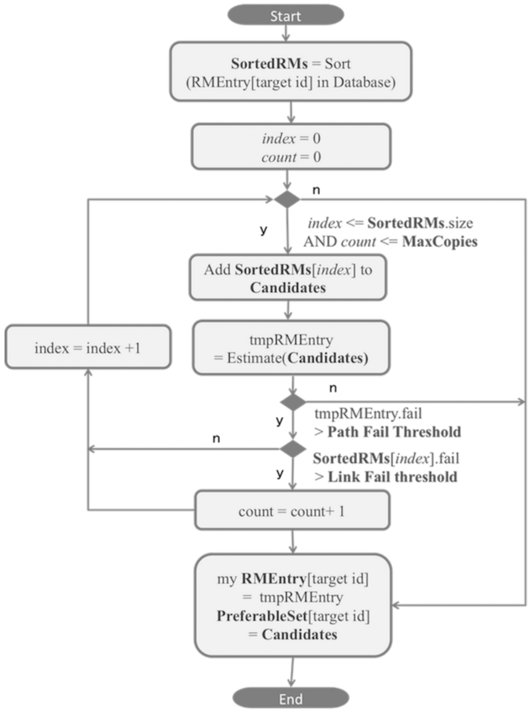

Fig. 4. Minimizing-replication preferable-selection mechanism

will be counted if the failure probability is more than the failure threshold, one of the preliminary configurations. Then, it will continue picking up the next member and repeating the above steps until it meets any of the following conditions: (1) the failure threshold condition is passed, (2) no next member, and (3) the counted members reach the maximum copy limit. Note that, the uncounted member is the member that violates the link failure threshold. After that, the final step is to update the *RM* entry and set the selected candidate set to forward data to each target as the preferable set.

C. Replication Estimation Method

To estimate the replication number, we apply a polynomial regression model across the message elapsed time on arrival (ETA). The estimation method is summarized in Fig. 5. When a host node, q, receives *RM* message, it will obtain ETA and success probability to send message to the sender neighbor, r, $(ETA_{q,r}, P_{sucess}(q,r))$ as explained in minimizing-replication Preferable-selection mechanism. Firstly, a message will be successfully sent to the target node, t, by forwarding to node r within the expected elapsed time, $ETA_{q,r,t} = ETA_{q,r} + ETA_{r,t}$ if the expected path from node r is success and the path from other nodes with lower expected time are failed. Correspondingly, the probability to reach the target within $ETA_{q,r,t}$ is:

$$p_{qrt} = P_{success}(q,r,t) \prod_{s \in C, s \neq r, ETA_{s,t} < ETA_{r,t}} P_{fail}(q,s,t);$$

where $P_{success}(q,r,t) = P_{success}(q,r)(1 - Fail_{r,t})$ and $P_{fail}(q,s,t) = (1 - P_{success}(q,s)) + P_{success}(q,s)Fail_{s,t}$

Thus, the expected ETA (ETA_{expect}) $= \frac{\sum_{r \in C} p_{qrt} ETA_{qrt}}{\sum_{r \in C} p_{qrt}}$.

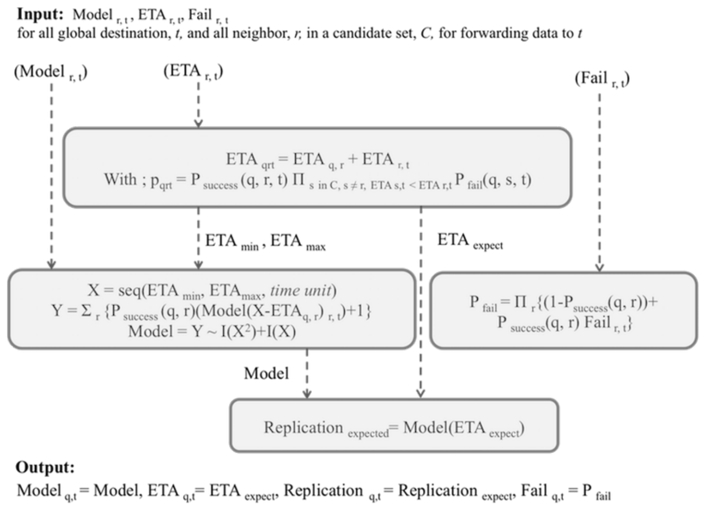

Fig. 5. Replication estimation method (Model=prediction model, Replication=predicted replication number, Fail=fail delivery probability)

To construct the prediction model, we generate a time sequence from the minimum ETA to the maximum ETA. For each candidate r, an predicted replication at each point of time is 1 (q, r replicant) plus the predicted number after forwarding from prediction model of r ($Model_{r,t}$) at the considering point deducted by first one-hop $ETA_{q,r}$ and multiplied with the probability of transmission success. Accordingly, we fit the coordinate series (X, Y), where Y is the summation of expected replications from all candidates in terms of elapsed time and X is the time sequence of ETA, to third order polynomial regression model. With this model, the expected replication can be derived from the time point at expected ETA. For the failure probability of this estimation is probability that all candidates fail to deliver (i.e., $\prod_{r \in C} P_{fail}(q,r,t)$).

IV. Experimental Results

A. Simulation Settings

The simulation has been conducted by Scenargie version 2.1 which comes with implementations of well-known bundle protocols, *Epidemic*, *Spray-And-Wait*, and *MaxProp*. Based on the provided DTN example, we create two scenarios considering disaster circumstances: (1) Stationary source-destination with Speedy Mobile Vehicles (SMV) and (2) Mobile Pedestrian (MP). Both are composed of ten nodes connecting to each other through wireless ad-hoc links over IEEE 802.11g protocol. The simulation applies ITU-R P.1411 for propagation data and prediction method on 2.4 GHz frequency band.

1) Stationary source-destination with speedy Mobile Vehicles (SMV): This scenario simulates communications among stationary load side units. We state three situations: (1) the health-care unit sends patient status to the broadcast station, (2) the broadcast station delivers a treatment suggestion to the health-care unit, and (3) the building unit reports fire damages to the fire station. We located all relevant units far from each other than one-hop reach. So, it requires any probe vehicles

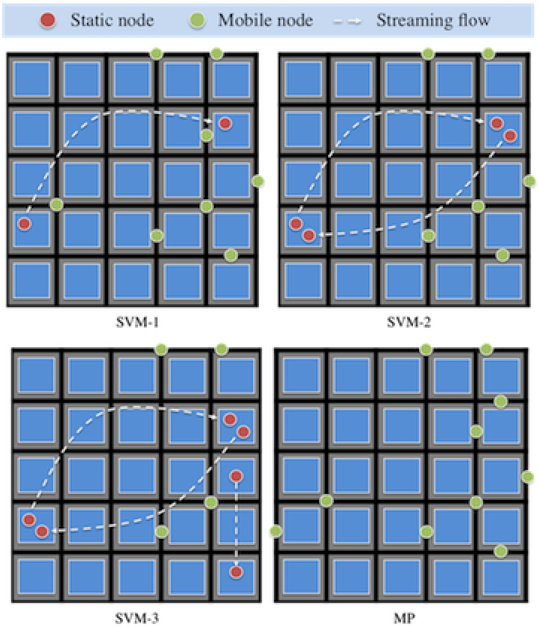

Fig. 6. Simulation Scenario Illustration: (top and left bottom) Stationary source-destination with Speedy Mobile Vehicles (right bottom) Mobile Pedestrian

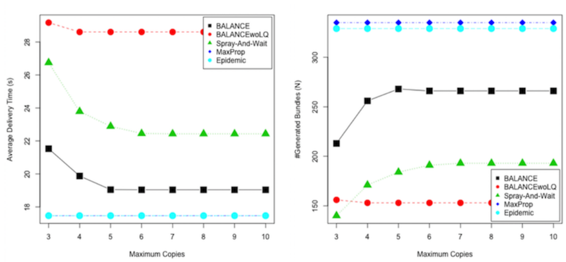

Fig. 7. Results from SMV-1 scenario: (left) Average delivery time (right) Number of generated bundles

moving on the road to relay the message. There are three sub-scenarios. The first sub-scenario has only the first streaming while the second sub-scenario adds the second streaming and the third sub-scenario additionally adds the third streaming. The source and destination of streaming are stationary while the rest are moving with speed from 15 to 20 m/s. The illustration for each of sub-scenarios is depicted in Fig. 6.

2) Mobile Pedestrian (MP): This scenario simulates communications among mobile pedestrians to share their information or status over the disaster area as depicted in Fig. 6. The moving speed is random from 2 to 5 m/s for all nodes. Similarly to the first scenario, there are three sub-scenarios. The first scenario has only one stream while the second and third scenarios have two and three streams respectively.

B. Results

To evaluate the performance of our proposed method, *BALANCE*, we have conducted simulations with both resource-unlimited and resource-limited environments. In our exper-

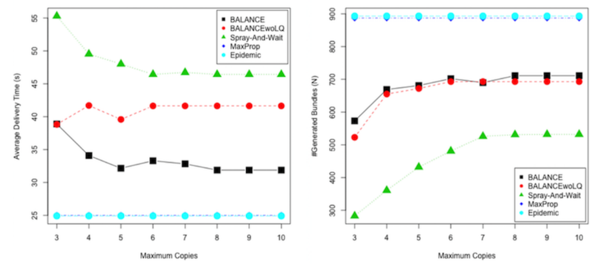

Fig. 8. Results from SMV-2 scenario: (left) Average delivery time (right) Number of generated bundles

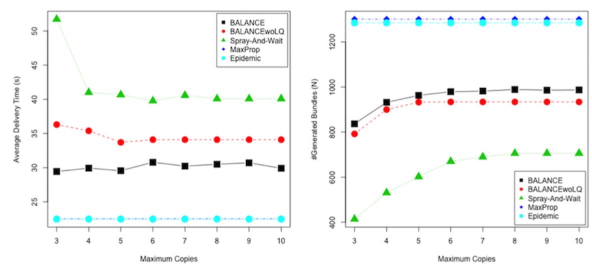

Fig. 9. Results from SMV-3 scenario: (left) Average delivery time (right) Number of generated bundles

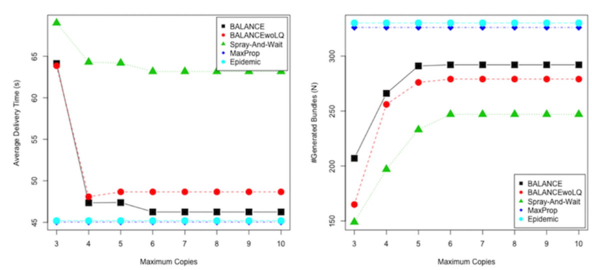

Fig. 10. Results from MP-1 scenario: (left) Average delivery time (right) Number of generated bundles

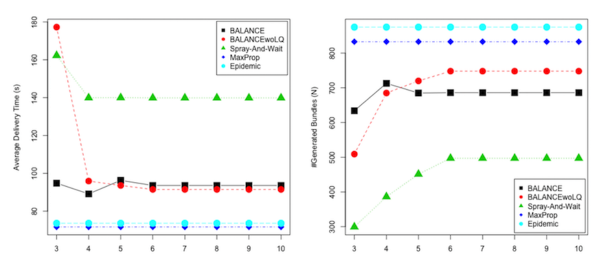

Fig. 11. Results from MP-2 scenario: (left) Average delivery time (right) Number of generated bundles

iment, the term *resource* refers to a bundle buffer capacity. We compared our proposed *BALANCE* with three well-known protocol, including *Epidemic*, *Spray and Wait*(Spray-And-Wait) and MaxProp, and the case if we apply a min-

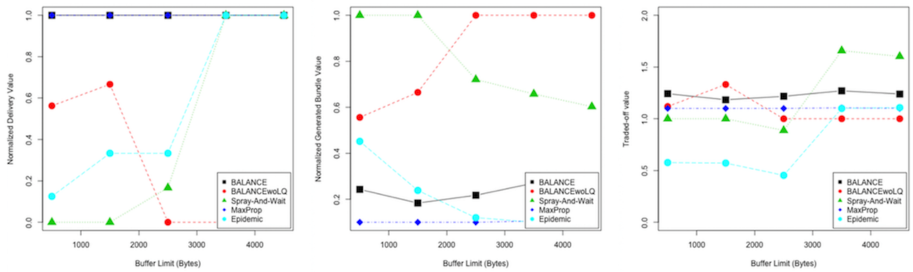

Fig. 13. Results from SMV-1 scenario: (left) Normalized Delivery Value (middle) Normalized Generated Bundle Value (right) Traded-Off value

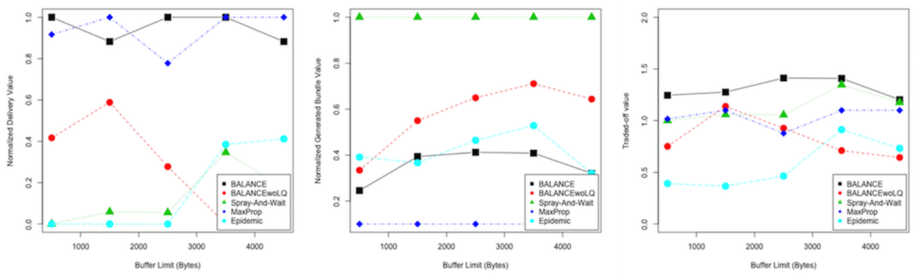

Fig. 14. Results from SMV-2 scenario: (left) Normalized Delivery Value (middle) Normalized Generated Bundle Value (right) Traded-Off value

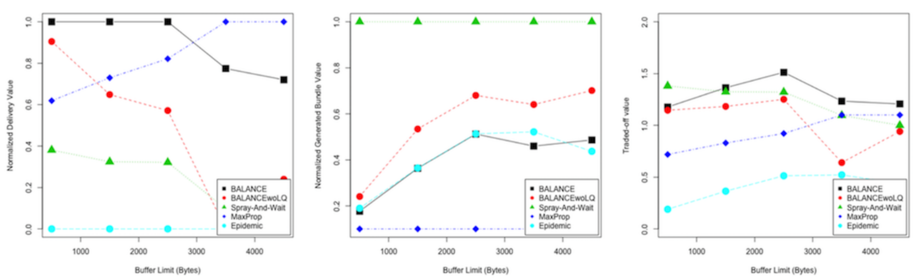

Fig. 15. Results from SMV-3 scenario: (left) Normalized Delivery Value (middle) Normalized Generated Bundle Value (right) Traded-Off value

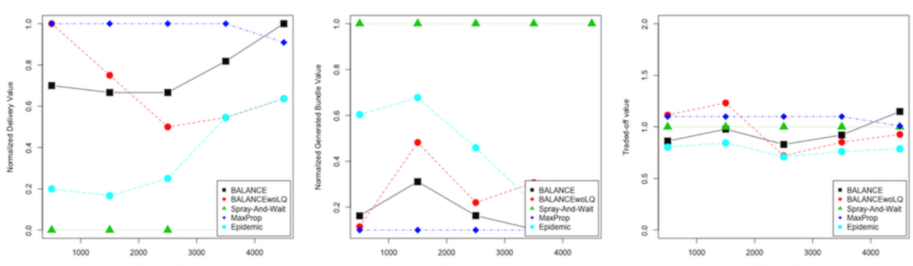

Fig. 16. Results from MP-1 scenario: (left) Normalized Delivery Value (middle) Normalized Generated Bundle Value (right) Traded-Off value

imizing replication mechanism without link quality concern (*BALANCEwoLQ*). For the resource-limited case, we provide enough buffer space to keep all received bundles but vary the maximum copy limit which affects performance on our method and *Spray and Wait*. For the other case, we limited the size of buffer from 2 to 9 messages. Note that, sources generate a 500-bytes bundle every 10s for 500s application-running time.

In the resource-unlimited environment, the sub-scenario results from Stationary source-destination with speedy Mobile Vehicles (SMV) are shown in Fig. 7, Fig. 8, and Fig. 9, respectively, likewise, results from Mobile Pedestrian (MP) are presented in Fig. 10, Fig. 11, and Fig. 12. We observed

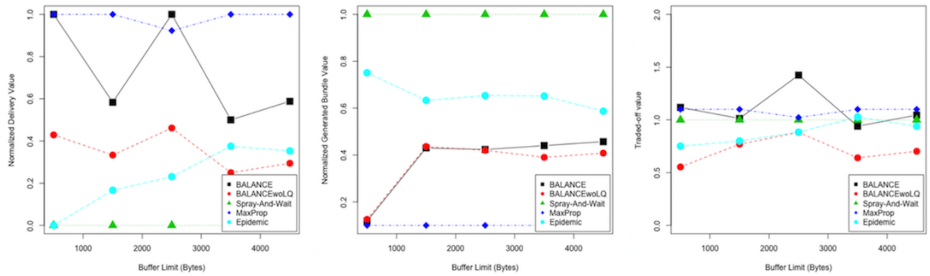

Fig. 17. Results from MP-2 scenario: (left) Normalized Delivery Value (middle) Normalized Generated Bundle Value (right) Traded-Off value

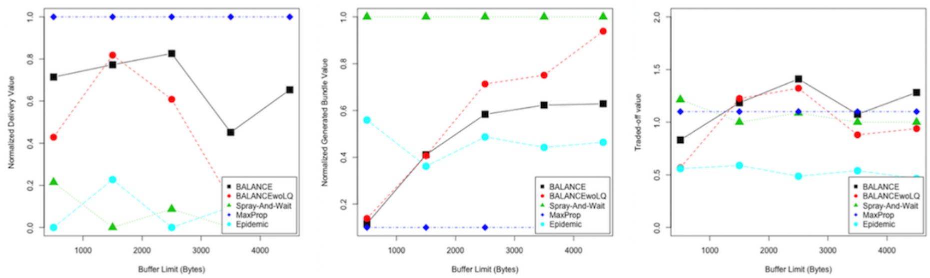

Fig. 18. Results from MP-3 scenario: (left) Normalized Delivery Value (middle) Normalized Generated Bundle Value (right) Traded-Off value

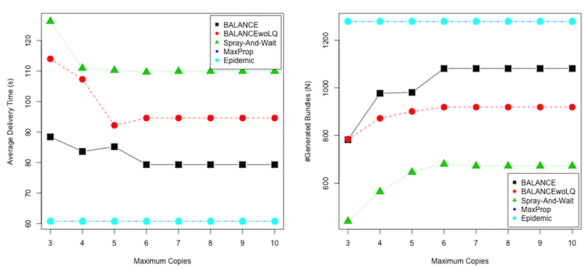

Fig. 12. Results from MP-3 scenario: (left) Average delivery time (right) Number of generated bundles

that *Epidemic* and *MaxProp* provides minimum delivery time but generate a lot of bundles. On the other hand, *Spray and Wait* reduces a significant amount of bundles but comes up with explicitly-higher delivery time. Meanwhile, our proposed method always stays between both sides, however, closer to the good one. Regarding with the most traditional method, *Epidemic*, in the SVM scenario, *BALANCE* reduces about 16 bundles/min with just 5s longer delivery time in average regardless of maximum-copy limit while *Spray and Wait* increases the delivery time up to 15s in average with 30 bundles/min reduction. For MP scenario, *BALANCE* spends 14s longer with 12 bundles/min reduction while *Spray and Wait* got more 36s to deliver all messages with 31 bundles/min reduction. Without resource constraints, MaxProp approach has no significant difference to *Epidemic*. We also noticed that the results of *BALANCE* without link-quality is unpredictable due to invalid replication estimation. Moreover, our proposed method incurs smaller control messages, in concrete, about 245 messages/min on average compared to *MaxProp*.

In case of the resource-limited environment, we showed the performance with following matrices, providing that D_i and B_i refer to the number of messages delivered at destinations and the number of bundles generated to relay the messages by applying algorithm i, respectively:

1) Normalized Delivery Value (D)

$$\text{normalized } D_i = \frac{D_i - \min(D_i)}{\max(D) - \min(D)}$$

2) Normalized Generated Bundle Value (B)

$$\text{normalized } Bi = n^{\beta}$$

where $\beta = -\frac{1}{\max(B)-\min(B)}(B_i - \min(B_i))$

3) Traded-off value
$value_i$ =*normalized* D_i+*normalized* B_i

The results of above matrices from the SVM scenario are presented in Fig. 13, Fig. 14, and Fig. 15, likewise, the results from the MP scenario are presented in Fig. 16, Fig. 17, and Fig. 18 in order. Our proposed method provides comparable or even better delivery ratio comparing to *MaxProp* approach in some cases while always reserves lower bundle spread. Consequently, *BALANCE* gains highest traded-off value in most cases, specifically, 16 of total 30 cases. The second rank is *MaxProp* with 6 of 30 cases. *Spray and Wait* and *BALANCE without link-quality concern* have the same value that is 4 of 30 cases. The average values from all cases are 1.18, 1.11, 1.06, 0.94, 0.65 for *BALANCE*, *Spray and*

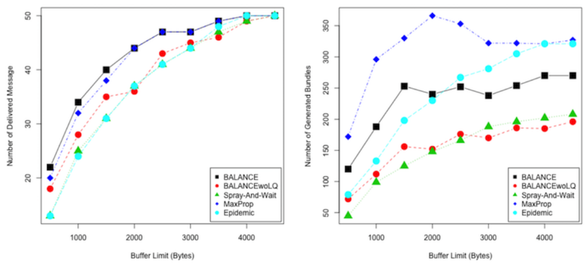

Fig. 19. The number of delivered message and generated bundles when 30% of nodes are completely selfish over varied buffer constraints in SVM-1

Wait, *MaxProp*, *BALANCE without link-quality concern*, and *Epidemic*, respectively.

Above experiments, all, assume that every node is well-cooperated. Next, we set 30% of them to act selfishly by not forward or send any bundle data in the scenario SVM-1. The result in Fig. 19 presents the number of delivered message and the number of generated bundles varying the buffer constraints. The proposed protocol gains even higher delivering performance compared to *MAX Prop* while keeping in-between in terms of generated number of bundles.

Furthermore, to justify the selected model, we measure an Akaike information criterion (AIC) value, which represents the goodness of fit, on bundle transmission logs of both scenarios. Our proposed third-order polynomial model achieves the best, minimum, value (16.7) comparing to Simple Linear (20.0), Gaussian (22.8), and Poisson (23.9) models.

V. Conclusion

This paper has mainly focused on self-organized civilian delay tolerant networks which usually further facing with node privacy concern and absolute uncontrollability. Under such restrictions, we propose a robust routing protocol named *BALANCE*. Its goal is to balance the delivering performance and resource consumption over the whole networks. We formulate a function to determine a success probability on delivery based on link quality metric (SINR) and selfish factor from reputation systems. With consideration of success probability, we model a lightweight regression algorithm to approximate the spreading numbers of replications for each forward decision. *BALANCE* ranks the decisions orderly by that approximated number and performs under a hop-limited threshold. We conduct simulations in two scenarios under disaster situations. The first one simulates communications between stationary load-side units through mobile probe vehicles. The second one simulates communications between mobile pedestrians. With enough buffer, *BALANCE* performs in-between but closer to the better one comparing to delivery-time-focused *MaxProp*, *Epidemic* and replication-focused *Spray and Wait*. Furthermore, it mostly achieves the highest traded-off value of delivery performance and reduced resource consumption under restricted situations, which are a limited resource and mixed-up selfish nodes.

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