A Location-Aided Flooding Mechanism in Community-based IoT Networks

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***Abstract*—This paper proposes a location-aided flooding mechanism to disseminate data in community-based IoT networks. Inspired by two heuristics obtained from the analysis of optimal flooding problem, the proposed mechanism allows wireless nodes to cancel a duplicate packet transmission in a distributed way when all of their neighbors have received that packet in advance. Extensive evaluations have been done in two different scenarios, i.e., a random uniform distribution of wireless nodes and a real distribution of wireless nodes in the Sumida ward of Tokyo. It has been validated that the proposed mechanism is not only able to increase the success ratio of data delivery, but also capable of reducing the delay of data delivery significantly, e.g., in the best case, the proposed mechanism improves the success ratio of conventional mechanisms by 47.3% and reduces the delivery delay by 92.0%.**

Fig. 1. Community-based IoT infrastructure of vending machines.

I. Introduction

Japan is one of the advanced countries in the world and it is facing to various social issues in aged population, healthcare, disaster reduction/prevention, safety, security, etc. The concept of smart city that utilizes the Internet-of-Things (IoT) technologies to strengthen social infrastructures opens a new door for innovative solutions to the aforementioned issues and also creates a big commercial market.

As an example, beverage vending machines are ubiquitously deployed in the urban area of Japan. These vending machines are placed every hundred meters so that customers can easily and frequently access them when they feel thirsty. From the view of constructing IoT system, a few hundred meters well-fit the one-hop communication range of related wireless transmission protocols like Zigbee [1] based on IEEE 802.15.4 and Wi-SUN [2] based on IEEE 802.15.4e/g. Therefore, our research group are corporating with a beverage company to implement a community-based IoT infrastructure by equipping Wi-SUN communication units on the vending machines [3]. As depicted in Fig. 1, the resulting IoT infrastructure is expected to play an important role on collecting sensing data for several community-based applications like nursing-care, safety/security, air pollution monitoring, and watching-over elderly/children. Needless to say, other suitable social infrastructures like smart meters, trash cans, and telegraph poles can also be used to implement this concept.

The current trend of implementing IoT systems is to collect sensing data greedily, transmit them to a powerful cloud, and try to discover valuable knowledge behind the "Big Data" by various intelligent but resource-consuming approaches. However, during the discussion with our industrial partners, it is understood that many kinds of sensing data are only valuable to the local area and also only when they are still fresh, e.g., safety/security solutions and watching-over solutions for elderly people suffer from dementia would belong to this category. Therefore, instead of simply uploading data to the cloud by internet, delivering sensing data to their nearby consumers by the local IoT networks of these social infrastructures would produce a more economic design and lower service latency for some smart city applications.

Flooding is a suitable strategy to meet the previous demand of delivering sensing data in the local community. In a naive implementation of flooding [4], every wireless node simply broadcasts a newly received data packet in a multi-hop way and the packet will reach all nodes in the area (assuming that there is no separation). Therefore, it is easy to be implemented in resource-constrained social infrastructures like vending machines or smart meters and is also adaptive to their deployment topology. However, it has been realized that this kind of simple flooding mechanism suffers from a phenomenon named "flooding storm" [5], i.e., the duplicate packet transmissions occur collisions in the wireless medium and can lead to serious network congestions. Consequently, this paper proposes an effective flooding mechanism to disseminate local sensing data in the community-based IoT networks. Evaluation results have validated that the proposed flooding mechanism not only improves the success ratio of data delivery, but also reduces the delay of data delivery significantly.

Following the literature review in Sect. II, Sect. III introduces the system model and the assumptions of community-based IoT networks discussed in this paper. The formalization and analysis of the optimal flooding problem is discussed in Sect. IV. Section V presents our proposed flooding mechanism, and Sec. VI shows its evaluation results. Conclusions are drawn and future work is discussed in the last section.

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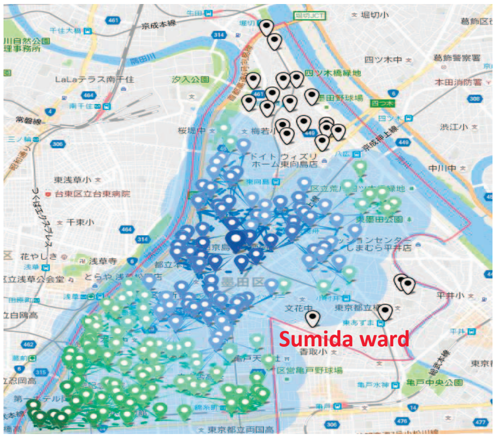


Fig. 2. IoT networks in the sumida ward of Tokyo, Japan.

II. Related Work

A naive implementation of data flooding in wireless networks was the simple flooding mechanism introduced by Williams et al. [4]. Once a node receives a new data packet, it immediately broadcasts it again. Its main drawback is the "flooding storm" problem, i.e., with the increase of node density in the network, there is a drastical increase of packet transmission collisions, packet losses, and network traffic [6]. Tseng et al. proposed several counter-based and gossiping-based algorithms to alleviate the phenomenon of "flooding storm" [7]. The counter-based flooding algorithm keeps the node from broadcasting a data packet in case that multiple copies of the packet have been received already. There is a tradeoff on the selection of the counter threshold, i.e., a low threshold provides high saving in packet transmissions while decreasing the success ratio of delivering packets to nodes in the area, and vice versa. In the gossiping-based algorithm, every node broadcasts a newly received data packet with a pre-defined probability. Many different variations of gossiping-based algorithm were presented by different researchers to determine the probability of broadcasting a packet [8, 9, 10]. Recently, Kokuti et al. presented three different gossiping-based mechanisms [11] , and have validated their superiorities to the previous work. The Distance-Based Handshake Gossiping mechanism (DBHG) determines the probability of broadcast in terms of the distance between the packet transmitter and receiver. The Valency-Based Handshake Gossiping (VBHG) mechanism adds the knowledge of nodes' degrees to DBHG. Finally, the average valency-based handshake gossiping mechanism (AVBHG) further considers past decisions for calculating the probability. Another interesting flooding mechanism was proposed by Liu et al. [12] to discover idle resources in the nearby mobile device. However their strategy requires a centralized infrastructure to analyze flooding statistics in advance and that does not fit the topology of wireless ad-hoc networks discussed in this paper. Finally, Ruiz et al. provide a comprehensive survey of this research topic in [6] .

III. System Model

A. Community-based IoT Networks

In this paper, we assume a number of social infrastructures equipped with a GPS receiver and a short-range wireless communication unit (i.e., Wi-SUN) are deployed in a community or any other kind of local area. The transmission range of these IoT-enabled social infrastructures (ISIs) is R, and their communications are bi-directional. Therefore, when an ISI transmits a packet, other ISIs with a distance less than R from the transmitter can receive the packet. Heterogeneous sensors also exist in the area to sense the statuses of the community and its residents, e.g., the position of wandering elderly people, the crowd of children, road traffic and PM 2.5 pollution. Sensors transmit sensing data to nearby ISIs, and these data are flooded in their IoT networks. Any community-based IoT application can receive these fresh sensing data from its closing ISIs to implement their functions conveniently. Figure 2 illustrates a snapshot of our planned IoT networks of vending machines deployed in the Sumida ward of Tokyo, Japan, e.g., 74.84% area of Sumida ward can be covered by a network consists of 225 vending machines, when the transmission range of vending machines is 400 meters.[1]

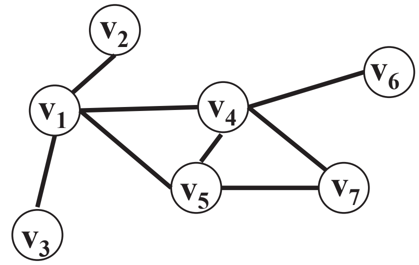


Fig. 3. The graph representation of network topology.

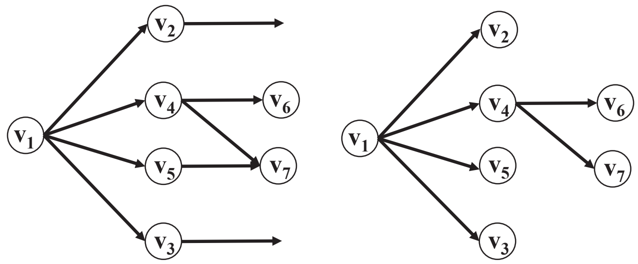
B. System Representation

With the previous assumptions, the topology of community-based IoT networks can be represented by an undirected graph. Every node in the graph represents an ISI, and every edge between a pair of nodes denotes a wireless link between them, i.e., two nodes are within the transmission range of each other. Figure 3 depicts a network topology that consists of seven nodes. We say two nodes connected by an edge are neighbors. Without loss of generality, $N(v_i)$ indicates all neighbors of the node v_i, e.g., $N(v_1)$ indicates a set of nodes v_2, v_3, v_4, and v_5 in Fig. 3. Finally, $|\cdot|$ denotes the number of nodes in a set, e.g., $|N(v_1)| = 4$ in Fig. 3.

IV. The Optimal Flooding Mechanism

As described in Sect. I, the simple flooding mechanism generates many duplicate packet transmissions and leads to severe collisions and congestions in the wireless medium. The network topology depicted in Fig. 3 is used to illustrate this issue. Assume that v_1 generates a data packet and its sequence number is s, i.e., P_s. Since v_1 wants to flood P_s in the network, it broadcasts P_s and all of its neighbors receive it. According to the simple flooding mechanism, once a node receives a new packet, it immediately broadcasts it again. Therefore, nodes v_2, v_3, v_4, and v_5 broadcast P_s again, and their neighbors v_6 and v_7 can receive P_s. This process is depicted in Fig. 4(a). However, as indicated in Fig. 4(b), since v_4 can deliver P_s to

[1] According to the experiment results in [3], the transmission range of Wi-SUN devices is about 800 meters in a line-of-sight environment.



(a) Simple flooding (b) Optimal flooding

Fig. 4. The formalization of flooding problem.

v_6 and v_7, there is no need for v_2, v_3, and v_5 to broadcast P_s. Needless to say, these meaningless packet transmissions congest the wireless medium. Consequently, an optimal flooding mechanism should deliver a packet to all nodes in the area with a minimum amount of packet transmissions.

It has been proved that solving the optimal flooding mechanism in a network is equivalent to find its minimum connected dominating set (MCDS) [13].[2] This strategy is not realistic to our community-based IoT networks, because of two main reasons. First, this is a centralized algorithm that is hard to be implemented in wireless ad-hoc networks discussed in this paper. Secondly, it is not scalable to the size of network, since huang et al. [14] have proved that the problem of finding MCDS in a network is NP-complete.

V. The Proposed Location-Aided Flooding Mechanism

Although the optimal flooding mechanism described in Sect. IV is not realistic to our application scenario, it provides two heuristics for the design of our proposed flooding mechanism: (1) A node with more neighbors that haven't received a packet should have a higher priority to broadcast the packet earlier; and (2) A node should cancel its broadcast of a packet in case all of its neighbors have received it already. For example, assume that v_1 in Fig. 3 broadcasts a packet P_s, its neighbors receive this packet at the same time. Regarding v_2 and v_3, there is no need to broadcast P_s again, since all of their neighbors (i.e., v_1) have received P_s already. It is clear that v_4 has two neighbors (v_6 and v_7) that haven't received P_s, while v_5 has only one (v_7). In case that v_5 broadcasts P_s before v_4, only v_7 can receive it. Then, v_4 have to broadcast P_s again to deliver it to v_6. However, when v_4 broadcasts P_s earlier than v_5, both v_6 and v_7 can receive it. After overhearing the P_s broadcasted by v_4 (v_4 and v_5 are neighbors), v_5 do not have to broadcast P_s again, since all of its neighbors have received it already. As a result, v_4 should have a higher priority to broadcast P_s earlier than v_5.

A. The Framework of Location-Aided Flooding Mechanism

Based on the previous two heuristics, a location-aided flooding mechanism (abbreviated as LAF) is designed in this paper. Again, we use the network topology shown in Fig. 3 to illustrate it in the following descriptions. The proposed algorithm consists of six steps:

[2]A connected dominating set is a set of nodes such that all nodes in the network are the within transmission range of at least one of its members.

The Proposed Location-Aided Flooding Algorithm

```
/****** The preparation phase ******/
Broadcasts "positioning message" to notify its location.
Receives the "positioning messages" from its neighbors.

/****** The running phase ******/
while (receives a packet P_s)
    Calculates the coverage area of P_s;
    Updates the number of neighbors that haven't received P_s,
    and assume that there are K such neighbors;
    if (K == 0)
        Cancels the broadcast of P_s;
    else
        Updates the timer to broadcast P_s;

    if (the timer of broadcasting P_s expires);
        Broadcasts P_s;
        Break from the while loop;
```

(1) In the preparation phase, every node generates a single-hop "positioning message" to broadcast its GPS position to all neighbors. Since the placements of social infrastructures discussed in this paper do not change frequently in reality, it is enough to execute this operation with a period of one or a few days.

(2) When v_1 broadcasts a data packet P_s, its neighbors (v_2, v_3, v_4, and v_5) receive this packet and calculate the coverage area of this transmission based on the position of v_1 and the transmission range R of wireless communication units.

(3) By combining the positions of neighbors received in step (1) and the coverage area of P_s calculated in step (2), v_2, v_3, v_4, and v_5 count the number of their neighbors that haven't received P_s, e.g., v_4 has two such neighbors, v_5 has one such neighbors, while v_2 and v_3 have no such neighbor.

(4) v_2, v_3, v_4, and v_5 set a timer that is inverse proportional to the number of their neighbors that have not received P_s, e.g., v_4 should set a shorter timer than v_5 since v_4 has two such neighbors while v_5 has only one. When the number of such neighbors is zero, the node cancels its broadcast of P_s, e.g., v_2 and v_3 should cancel their broadcasts to avoid meaningless transmission.

(5) Before the timer expires, every node overhears P_s broadcasted by its neighbors, and executes steps (3) and (4) recursively to update its timer of broadcasting P_s, e.g., when v_5 overhears P_s broadcasted by v_4, it cancels the broadcast of P_s, since all of its neighbors have received P_s now.

(6) When its timer of broadcasting P_{sec} expires, every node broadcasts P_{sec} by the usual CSMA/CA scheme.

The pseudo-codes of LAF for every node are listed in the algorithm table.

B. Timer Setting

In the step (4) of the proposed LAF, a node should set a timer of broadcasting P_s that is inverse proportional to the number of its neighbors haven't received P_s yet. Let N denotes the number such neighbors and T_{max} denotes the maximum delay of the timer. The timer used in this paper is given by

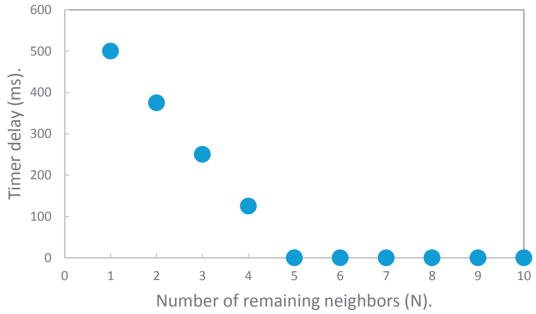


Fig. 5. Distribution of the timer delay.

TABLE I. Evaluation parameters under random distribution of ISIs.

Size of Area	1000×1000 m
Number of ISIs	100
Number of sensors	50
Transmission range	250 m
Packet transmission time	10 ms
Packet generation interval	from 0.5 to 3 seconds
Size of routing queue	50 packets
Total number of generated packets	10000 packets
The maximum delay of timer (T_{max})	100 ms

$$T_{delay} = \begin{cases} T_{max}, & \text{N}= 1; \\ \frac{T_{max}}{1-N_{thresh}} \times N - \frac{T_{max}\times N_{thresh}}{1-N_{thresh}}, & 1 < N < N_{thresh}; \\ 0, & N \geq N_{thresh}; \end{cases} \quad (1)$$

where N_{thresh} is a threshold of N. Figure 5 indicates the distribution of T_{delay} when $T_{max} = 500$ ms and $N_{thresh} = 5$.

In this paper, the average number of neighbors for one node (i.e., the degree of one node in graph theory) is used as N_{thresh}, since it is a common metric to depict network topology. As a result, N_{thresh} increases with the density of nodes in the area. We believe the value of T_{max} should be set according to different network applications, e.g., a longer T_{max} for delay-tolerant applications, while a shorter T_{max} for delay-sensitive applications. Since this paper mainly aims at illustrating the efficiency of the proposed LAF, the optimization of timer parameters is left for future work. Finally, it should be noted that any other timer scheme that satisfies the requirement described at the beginning of this subsection can be integrate to LAF smoothly.

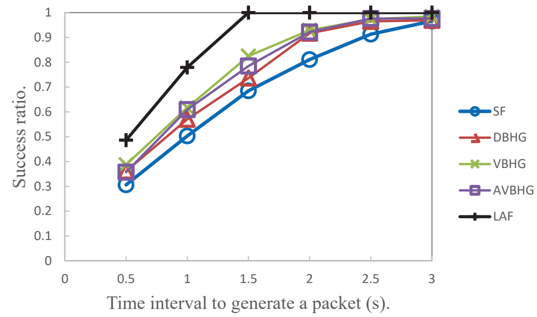
VI. Evaluations

This section presents the evaluation results of the proposed LAF. We compared it with DBHG, VBHG, AVBHG proposed by Kokuti et al. [11], and the simple flooding mechanism (SF) described by Williams et al. [4] in the following evaluations. These mechanisms were evaluated by three criteria, i.e., worst success ratio, packet delivery delay, and average packet transmission.

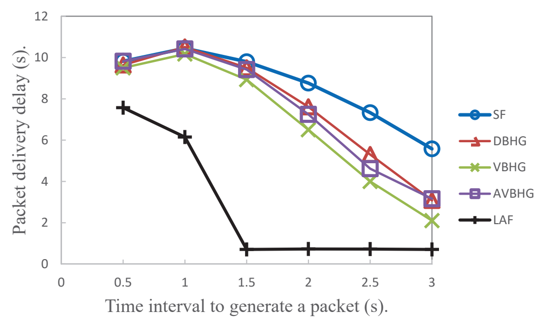
Worst success ratio: it is defined as the worst percentage of packets received by an ISI. Assuming that 10000 packets were generated by sensors in the evaluation but the worst-performed ISI only received 8000 of them, the worst success ratio is 80%.

Packet delivery delay: it is defined as the time consumed by a packet to reach all ISIs in the area.

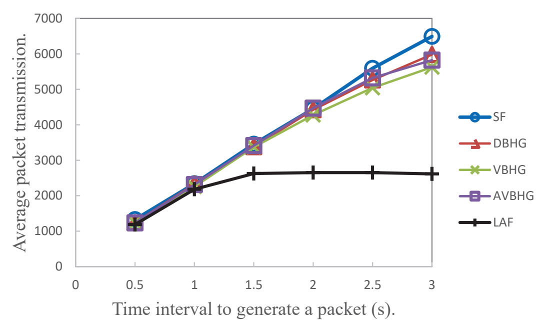
Average packet transmission: it is defined as the average number of packets transmitted by every ISI in the evaluation. All following results are the average of 100 evaluation trials.



(a) Worst success ratio.



(b) Packet delivery delay.



(c) Average packet transmission.

Fig. 6. Evaluation performances under the random distribution of ISIs.

A. Random Distribution of IoT-Enabled Social Infrastructures

In this scenario, we assume that 100 ISIs were distributed in a rectangle area of 1000×1000 meters based on the random uniform distribution. There are also 50 sensors in the area, and these sensors transmit sensing data packets periodically.

TABLE II. Evaluation parameters under the real distribution of ISIs.

Size of Area	10.8 km^2
Number of ISIs	225
Number of sensors	50
Transmission range	400 m
Packet transmission time	10 ms
Packet generation interval	from 0.5 to 3 seconds
Size of routing queue	50 packets
Total number of generated packets	10000 packets
The maximum delay of timer (T_{max})	100 ms

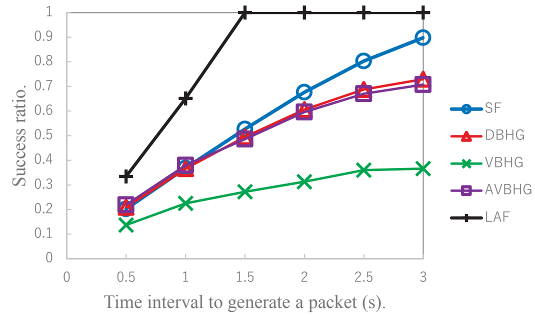
The transmission range of ISIs and sensors is 250 meters. The transmission time of a data packet is 10 ms.[3] When an ISI receives multiple packets, it buffers them in its routing queue with a capacity of 50 packets. Since only fresh data is concerned in this paper, we assume the life-time of data packets is 30 seconds, and out-of-time packets are discarded by ISIs directly. In every round of evaluation, 10000 packets were generated by sensors. Table I summarizes evaluation parameters used in this scenario.

Figure 6(a) shows the worst success ratios of the previous five mechanisms with different intervals of packet generation. When the interval for sensors to generate a packet is short, too many data packets were transmitted in the IoT networks and caused network congestion. Part of these packets were discarded by ISIs when their routing queues are full, and this decreased the success ratio of packet delivery significantly. It is clear that all mechanisms achieved better success ratios with the increase of packet generation interval. Nevertheless, the proposed LAF performed better than all other mechanisms no matter the interval of packet generation, e.g., when the interval is 1.5 seconds, the worst success ratio of LAF is 100%, at least 18% higher than other mechanisms.

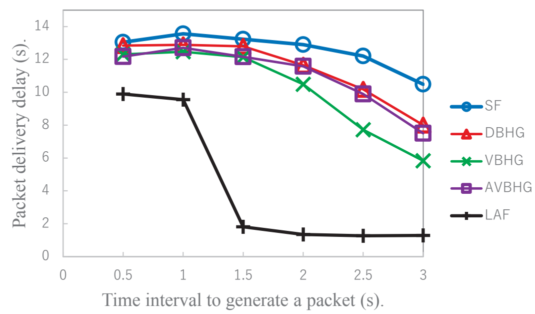
Figure 6(b) shows the packet delivery delays of the five mechanisms with different intervals of packet generation. Consistent to the results shown in Fig. 6(b), when the interval is short and there is network congestion, the time consumed by a packet to reach all ISIs largely increases. Again, the proposed LAF achieved much shorter delivery dealys than other methods no matter the interval of packet generation, e.g., when the interval is 1.5 seconds, packets can be delivered to all ISIs in 0.724 second by using LAF, at most 8.0% of other mechanisms.

Figure 6(c) shows the average packet transmissions of every ISIs by using the previous five mechanisms with different intervals of packet generation. It is very clear that the proposed LAF reduced the number of packet transmissions significantly compared with other methods, e.g., when the interval is 3 seconds, every ISI with LAF only transmitted 2614.2 packets on average, at most 46.4% of other mechanisms. It is a little counterintuitive that the average packet transmissions of all five methods are similar when the transmission intervals are short. However, as shown in Fig. 6(a), LAF achieved a higher success ratio than other methods in these situations. It indicates that LAF enabled ISIs to transmit more new data packets with limited bandwidth resources, while other methods suffered from duplicate packet transmissions that wasted bandwidth resources.

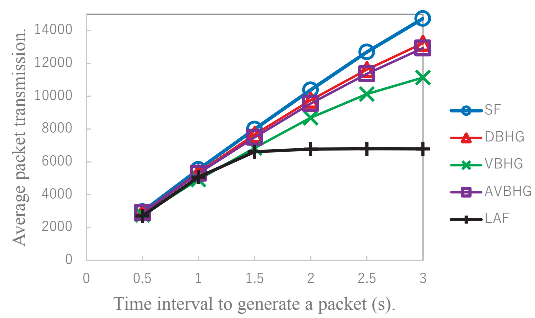
[3]For our planned real application, the size of data packets is around 100 bytes, and the communication capacity of Wi-SUN standard is about 100 kb/s.



(a) Worst success ratio.



(b) Packet delivery delay.



(c) Average packet transmission.

Fig. 7. Evaluation performances under the real distribution of ISIs.

B. Real Distribution of Vending Machines in the Sumida Ward of Tokyo

Since the proposed LAF is assumed to be used in our planned IoT networks of vending machines in the Sumida ward of Tokyo, we also used the real distribution of vending machines shown in Fig. 2 to evaluate its performance. In this scenario, 225 ISIs (i.e., IoT enabled vending machines) exist in an irregular area of 10.8 km^2, and their placements are determined by a beverage company in advance. Since the placements of sensors have not been determined yet, we assume that they are randomly distributed in the area according to uniform distribution. Other evaluation parameters are summarized in Table. II, and their meanings have been explained in the previous subsection.

Figure 7 shows the performances of different mechanisms in this scenario. Consistent to the results obtained under the random distribution of ISIs, the proposed LAF performed much better than other mechanisms on all criteria, e.g., when the interval was 1.5 seconds, LAF achieved a worst success ratio of 100% (at least 47.3% higher than other mechanisms) with a delay of 1.81 seconds (at most 14.9% of other mechanisms). The outstanding performance of LAF benefits from its ability of refraining meaningless packet transmissions as illustrated in Fig. 7(c), e.g., when the interval was 3 seconds, LAF reduced the number of packet transmissions by at least 53.6% of other mechanisms.

VII. Conclusions

A location-aided flooding mechanism is introduced in this paper to facilitate data dissemination in community-based IoT networks. The proposed mechanism allows wireless nodes to calculate the coverage area of their received packets, and force them to cancel a packet transmissions when all of their neighbors have received that packet already. Evaluation results have validated that the proposed mechanism refrains duplicate packet transmission, and alleviates the network congestion caused by "flooding storm". Consequently, it not only increases the success ratio of packet delivery, but also reduces the delay of packet delivery significantly. In the best case, the proposed mechanism improves the success ratio of conventional mechanisms by 47.3%, decreases the packet delivery delay by 92%, and reduces the number of packet transmissions by 53.6%.

Regarding future work, we are considering to improve the proposed mechanism so that it can be used to mobile situations, e.g., other than fixed social infrastructures, running buses and taxis are also good platforms to disseminate data in the community. In addition, we are also evaluating the effects of different timer settings on the proposed flooding mechanism.

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