Reliable Broadcasting for Safety Services in Dense Infrastructureless Peer-Aware Communications

Nhu-Ngoc Dao, Duc-Nghia Vu, Arooj Masood, Woongsoo Na, Sungrae Cho*

School of Computer Science and Engineering, Chung-Ang University, Seoul 06974, Korea

Abstract

The IEEE 802.15.8 project has introduced peer-aware communication (PAC) as a promising technology enabling high-quality proximity services in dense infrastrutureless ad hoc environments. PAC applications cover a variety of high-assurance services, especially those related to safety such as hazard alerts, emergency exit guidance, and relative position in cases where networking facilities have been destroyed or unavailable. To support these services effectively, PAC must overcome the massive device density to provide a reliable broadcast protocol for rapidly disseminating urgent information across the entire network. As such, we propose a reliable rumor broadcast (RRB) scheme for safety services in a dense infrastructureless PAC network. The proposed RRB scheme takes advantage of neighboring relations among PAC devices (PDs) to broadcast rumor abstract information instead of transmitting heavy broadcast frames. The broadcast frames are only forwarded based on requests from neighboring PDs. In the RRB scheme, rumor frames aim to reduce the broadcasting overhead, while the use of neighboring relations ensures reliable communications across the entire network. Simulation analysis demonstrates that the proposed RRB scheme achieves outstanding performance compared with that of existing algorithms in terms of overhead reduction and energy efficiency while maintaining a better transmission reliability improvement.

Keywords: reliable broadcast, safety service, infrastructureless peer-aware communication, IEEE 802.15.8

1. Introduction

An urban Internet of things (IoT) system is a future smart-city solution, that gathers and analyzes urban data via the collaboration and interaction among IoT devices in order to efficiently manage and forecast city flows and developments [1, 2]. Urban IoT systems can be applied in a wide variety of domains, such as assisting the elderly, home automation, intelligent healthcare, autonomous transport, smart manufacturing, and hazard mitigation assistance [3]. Although the next generation of convergence networks will provide a broad communication infrastructure (e.g., mobile, satellite, and WiFi networks) satisfying many of the aforementioned services, high-assurance services, in particular, specially require rigorous reliability for massive devices, even when the networking infrastructure is unavailable or destroyed. The reliability in communication defines an ability that messages transferred among devices are guaranteed to reach their destinations correctly [4]. Among these aforementioned applications, safety services such as hazard alerts, emergency exit guidance, and relative positions are considered to be the most important [5, 6]. For instance, in the IoT-enabled scenarios where an IoT data can be encapsulated into a frame, the number of frame loss is of vital importance. Such as, within high packet loss, autonomous vehicles cannot correctly update the notification from smart transport system; that results in unsafe navigation and control, even causing traffic collisions. High frame loss might lead to synchronization problem among guidance lights in case of emergency for a smart city or stadium. Since the safety services stringently require their emergency information to be delivered to all users in the network, a reliable broadcast protocol is crucial, especially in such an infrastructureless ad hoc communication environment. To overcome these severe challenges, peer-aware communication (PAC) is a

---

*Corresponding author

Email address: `dnngoc@uclab.re.kr`, `dnvu@uclab.re.kr`, `arooj@uclab.re.kr`, `wsna@uclab.re.kr`, `srcho@cau.ac.kr` (Nhu-Ngoc Dao, Duc-Nghia Vu, Arooj Masood, Woongsoo Na, Sungrae Cho)

promising technology. In PAC, a large number of IoT-enabled PAC devices (PDs) in close proximity communicate and interact directly at a scalable rate, without needing the support of infrastructure entities. As standardized by IEEE 802.15.8 [7], because one of the main uses of a PAC network (PACNET) is to allow PDs to be aware and to develop social relationships in proximity, the PDs are able to establish interactive communications by sharing and cooperating with information. Envisioned safety applications, services, and scenarios of the PAC technologies have been described in the technical report #802.15-12-0684-00-0008 [8].

In such a safety service, broadcasts are important networking operations, used to disseminate network information, as well as device- and user-generated data to other PDs. The PDs propagate the data through network-wide broadcasts, which are operations that transmit frames to every other PD in the network. In a multihop PACNET, every PD acts as a router to transmit frames to their assigned destinations. Network-wide broadcasts are realized by re-broadcasting the frames received by each PD [9, 10]. Network-wide broadcasts cause broadcast storms on a large-scale PACNET, which is known as *flooding* [11]. Because PACNETs are known to be densely deployed at a scalable level, network-wide traffic is assumed to be very high, leading to the jamming of broadcast traffic. Thus, broadcast storms can affect the transmission reliability and throughput significantly through channel contention, high collisions, and frame losses [12].

To overcome these problems in ad hoc mobile networks, many different broadcast techniques have been proposed in the literature [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. They can be classified into either (i) *deterministic* or (ii) *stochastic* broadcasting approaches. In the former, frames, forwarding decisions are always deterministic. In the later, forwarding decision is based on random choices. Both of these techniques are designed to reduce unnecessary retransmissions of the same frame. However, they are limited by transmission reliability, throughput and significant overhead on the network. Moreover, the existing techniques acquire global knowledge of the entire network, which is unsupportable in PACNET. The limitations are exacerbated in large-scale infrastructureless PACNETs since PAC applications are characterized by high-assurance services.

As a solution to control the degree of the rebroadcast problem in dense PACNETs, we propose a reliable broadcast scheme called the reliable rumor broadcast (RRB), which significantly decreases the number of unnecessary retransmissions by using an abstract message (i.e., a *rumor* frame), prior to the forwarding of a broadcast frame. In designing our RRB scheme, we exploit the inherent socially aware feature of PDs to facilitate broadcast operations in the PACNET. That is, when a PD receives a broadcast frame, it transmits a rumor frame to announce the receipt of the broadcast frame. Upon receiving the rumor, the neighboring PDs (next-hop PDs in the routing table) re-rumor the broadcast information within their transmission range. In this way, the PDs spread the abstract information of the broadcast to the entire network, and the data frame is only broadcasted when the PDs overhear their transmitted rumors from the other PDs (a.k.a on-demand response). In this way, the RRB scheme minimizes data rebroadcasts significantly, while saving network resources and maintaining the broadcast reliability of the dense PACNET.

In summary, the contributions of this study are three-fold:

- First, we propose an RRB scheme to provide reliable broadcasting for safety services in a PACNET. The RRB scheme significantly reduces unnecessary broadcast flooding across the entire network by first sending rumors of information. The scheme operates on neighboring relation among PDs to ensure high reliability.

- Second, broadcast transmissions are analyzed using a discrete-time Markov chain model. The analysis shows theoretical expressions of performance metrics based on various networking factors, such as network density, broadcast traffic, and transmission range.

- Third, a simulation is performed using OPNET modeler [35] to ensure the reputation and correctness of the results. The RRB scheme is compared to other schemes (piggyback and fullACK schemes) in terms of overhead reduction and energy efficiency while maintaining a better transmission reliability improvement.

The remainder of this paper is organized as follows. We survey existing related works in section 2. Section 3 describes the system model and our proposed RRB scheme. Section 4 provides a theoretical analysis of the proposed scheme, and we evaluate the performance of our proposed scheme in section 5. Finally, we draw conclusions and suggest future directions in section 6.

2. Related Works

In this section, we survey existing broadcast techniques in mobile ad hoc network environments [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. To facilitate the analysis of existing techniques, we classify them as either (i) *deterministic* [13, 14, 15, 16, 17, 18, 19, 20, 21, 22] or (ii) *stochastic* [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34] broadcasting approaches. In the former, there are no random decisions involved in forwarding the rebroadcast frames. In the later, forwarding decisions on rebroadcasts are based on random choices. In addition, forwarding decisions are based on either (i) information about current network state (context-aware) or (ii) knowledge of their neighbors and their related strategies (neighbor-knowledge) or (iii) fixed or adaptive probability (context-oblivious). Simple flooding, hyper flooding, dominant pruning and multipoint relay schemes can be classified as deterministic broadcasting schemes. On the other hand, probabilistic, area-based and cluster-based approaches can be grouped as stochastic broadcasting approaches [9].

The simple flooding-based methods [13, 14, 15, 16, 17, 18] are a broadcasting technique where a source node broadcasts a packet to all of its neighbors. Each of the neighbors then rebroadcasts the packet exactly once, and this process continues until all mobile nodes in the network have broadcasted the packet. For instance, Ho *et al.* [15] propose flooding as an alternative solution to multicast routing in highly dynamic mobile ad hoc networks. Khan *et al.* [36] discuss hyper-flooding for highly mobile and frequently partitioned networks whereby additional rebroadcasts are made upon receiving a hello message from a newly discovered neighbor. On the other hand, Kang *et al.* [13] propose broadcasting with relay retransmissions for wireless local area network (WLAN). In this scheme, sender broadcasts data frame with ACK request information element (IE). Nodes send ACK frames or NACK frames first. If there is an NACK frame or absence of all ACK frames, any node or access point (AP) notices this ACK failure and if there is any device that has received the frame successfully, retransmits the frame by broadcasting to other devices which fail to receive the frame previously. In this scheme, the probability of transmissions increases when the channel is fair between nodes. In [16], Tseng *et al.* show how serious the broadcast storm problem can become in a flooding-based method, and propose several schemes to alleviate this problem. In addition, Maltz *et al.* [17] suggest multicast and broadcast operations that utilize the dynamic source routing (DSR) protocol to flood packets throughout a network. However, because the flooding-based method causes rebroadcasts from each mobile node in the network, it is very costly and introduces serious problems such as redundancy, collision, contention, and high bandwidth utilization. In other words, flooding-based broadcasting is inefficient because it consumes unnecessary mobile node resources and network bandwidth.

Dominant-pruning based methods [19, 20, 21, 22] propose self-pruning and dominant-pruning algorithms. These methods maintain and exchange knowledge on mobile node neighbors using periodic transmissions of a *Hello* packet. The rebroadcast decision is made based on when the sender mobile node v_i includes the adjacent node list $N(v_i)$ in the broadcast packet. When mobile node v_j receives the packets, it checks whether the set $N(v_j) \setminus (N(v_i) \cup v_i)$ is empty. If it is empty, v_j does not rebroadcast the packet, assuming that all neighbors have already received the packet. Dominant-pruning methods extends this sharing of adjacent node lists up to two hops. The sending node selects adjacent nodes that should rebroadcast the packet and records their IDs in the packet as a forwarding list. An adjacent mobile node that is requested to rebroadcast the packet again checks the forward list. If the mobile node identifies any new mobile nodes in the list, it rebroadcasts the packet. In this way, the method requires an extra transmission overhead in exchanging the adjacent node lists and a computation overhead in comparing lists at the mobile node level.

Probability-based methods [26, 23, 24, 25, 27, 28, 29] differs from the flooding-based method in that each node decides to rebroadcast the packet based on a fixed or adaptive probability p. Fixed probabilistic schemes use a pre-defined forwarding probability value so every node in the network has the same forwarding probability. While, adaptive probabilistic schemes are based on local or global knowledge, such as network density, nodes speed and distance, energy and artificial intelligence based techniques to determine the forwarding probability [37]. On receiving broadcast packets, the mobile node sets its rebroadcast probability. When the probability parameter is set too high, this approach behaves much like the simple flooding method. The counter based probabilistic schemes allows a mobile node to maintain a counter variable k used during the random access delay (RAD) time to determine the number of received broadcast packets before it decides to rebroadcast. As the value of counter variable increases, the probability of rebroadcasting the packet decreases accordingly. For instance, Liarokapis *et al.* [26] propose an adaptive probability based scheme, which locally makes a decision about the density volume of the network and adjusts the probability threshold accordingly. A fuzzy logic probabilistic scheme [23] has been proposed that makes the forwarding decision on rebroadcast, wherein the scheme adapts the hello packet time interval depending on the network conditions and relative changes in the network measured through fuzzy logic based method. On the other hand, Yassein *et al.* [24] propose counter based probabilistic scheme with dynamic thresholds to increase the successful delivery rate of broadcast frames. In [30], Zhang *et al.* propose neighbor discovery-based probabilistic broadcasting approach for highly mobile adhoc networks by combining the additional coverage ratio and nodes connectivity factor, that also can recover from frequent link breakages and path failures. The probabilistic broadcasting approach becomes challenging in a sparsely deployed environment. In this case, the mobile node waits for the period of RAD, and then sets a high rebroadcast probability, causing a rebroadcast storm from all mobile nodes in the network.

The area-based methods [27, 31] rely on determining a mobile node's position and a distance calculation. A mobile node employing the distance-based method determines its own location, for example, using a global positioning system (GPS) mechanism, which it attaches to the broadcast packet. The mobile node receiving the broadcast notes the location of the source mobile node and compares the distance d between itself and every other neighbor that has already made a rebroadcast. The rebroadcast decision depends on the value of d. If the value is calculated too low, the rebroadcast coverage is not very large, and if the value of d is set high, the rebroadcast coverage area is larger and the mobile node decides to rebroadcast the packet. This method incurs an additional computation overhead on battery-sensitive mobile nodes.

Cluster-based methods [32, 33, 34] divide the mobile nodes in the network into a number of clusters or subsets. Each cluster has several gateways and is represented by a cluster head (CH), which is elected in the cluster based on various CH algorithms. Only cluster heads and gateways are responsible for rebroadcasting, where a cluster head broadcasts within its cluster members, and gateways broadcast within other clusters. Foroozan and Tepe [32] present a stability-based clustering algorithm that categorizes the network traffic into internal traffic and external traffic for a mobile node. For internal traffic, only the cluster-head and gateway rebroadcast packets. For external traffic, the border nodes may rebroadcast the traffic, in addition to the CH and gateways. In this way, they simplify the gateway node selection process by the cluster head locally in its own cluster, without any knowledge about other clusters. Lou and Wu [33] propose a static and a dynamic cluster-based virtual backbone infrastructure for broadcasting based on the concept of connected dominating sets. In this way, they show that the static cluster-based backbone is costly and unnecessary, whereas building a dynamic cluster-based backbone on demand is a better approach for the broadcast process. In addition, Stojmenovic *et al.* [34] propose restricting broadcasting to internal nodes in the cluster only, because any other node is directly connected to one of the internal nodes. These cluster-based methods are considered inefficient in terms of rebroadcast savings because maintaining the cluster structure of mobile nodes requires a considerable communication overhead over the wireless channel. As we can observe from the above, the existing techniques are not appropriate for a PAC and have limitations, especially in a densely deployed and fully distributed PACNET environment.

Although the existing methods have contributed effective broadcast routing algorithms in general mobile ad hoc network environments, they are inappropriate for a PACNET, either because of their central entity installation or because they do not consider device density.

3. Reliable Rumor Broadcast Scheme

3.1. System Model

In this study, we assume a multi-hop mesh topology in a PACNET (as shown in Fig. 1) according to the IEEE 802.15.8 mesh formation [7]. The PACNET consists of N PDs deployed in a square area of wireless communications with dimension $D \times D$ m^2, where D is border length of the area. PDs in the PACNET are deployed in a fully distributed way according to a two-dimension Poisson-point process (PPP) with density λ. The PDs can broadcast data frames simultaneously for the same or different applications. A frame broadcasted from a PD can be received by all PDs within the PDs' communication range. Without loss of generality, we assume that a PD is equipped with omnidirectional antenna and is located in the centre of its communication area. All PDs broadcast with fixed transmission power, resulting in a constant communication range. The transmission time or broadcast frame length is the same for all PDs, and denoted by T. We further assume that the time axis is divided into slots, with duration equal to δ. For direct broadcasts between neighbors, the carrier-sense multiple access with collision avoidance (CSMA/CA) protocol is considered, where the contention window is denoted as W. PDs transmit at the start of each slot and the number of slots used in transmitting a packet is $\tau = T/\delta$. At the beginning of each slot, a ready-to-transmit PD tries to transmit its broadcast frame adopting the IEEE 802.15.8 policy [38], which allows to

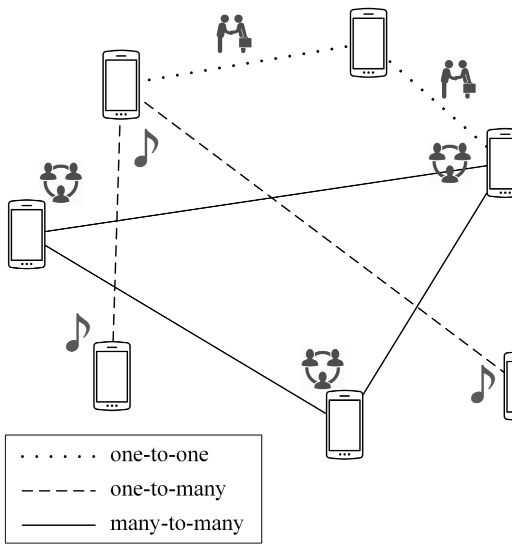


Figure 1: Infrastructureless peer aware communications [7].

Table 1: Description of key symbols used in this paper.

Symbols	**Description**
D	Border length of wireless communication area.
λ	Deployment density of PDs in the wireless communication area.
T	Transmission time of a broadcast frame.
δ	Length of a time slot.
τ	Number of time slot used to transmit a broadcast frame.
ρ	Probability that a PD has a frame to broadcast.
p	Probability that a ready-to-transmit PD transmits a frame adopting IEEE 802.15.8 [7].
$W, W_{\min}, W_{\max}$	The current, minimum, and maximum values of transmission window.
N	Average number of PDs in the transmission area of a PD.
F	Average number of neighboring PDs of a PD.
$S_i, S_t, S_r, S_a, S_n, S_k, S_w$	Steady-state probability of states ”idle”, ”transmit broadcast frame”, ”receive broadcast frame”, ”transmit rumor frame”, ”receive rumor frame”, ”transmit ACK”, and ”wait for ACK”, respectively.
$T_i, T_t, T_r, T_a, T_n, T_k, T_w$	Life time of states ”idle”, ”transmit broadcast frame”, ”receive broadcast frame”, ”transmit rumor frame”, ”receive rumor frame”, ”transmit ACK”, and ”wait for ACK”, respectively.
p_{ij}	Probability that a PD transits from state S_i to state S_j.
D_t, D_a, D_k	Frame size of broadcast, rumor, and ACK frames, respectively.

transmit a frame following the Bernoulli process with parameter p, where $0 < p < 1$. Table 1 summarizes description of mathematical symbols used in this paper.

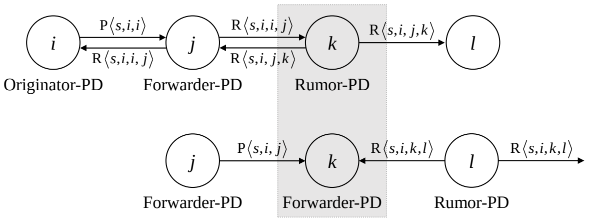


Figure 2: Positions and roles of PDs in the proposed RRB scheme.

When a PD has a broadcasting frame, it broadcasts this frame to all neighboring PDs, and the frame contains information that needs to be shared between all PDs for various services in the PACNET. Denote the broadcasting frame by $\mathrm{P}\langle s, o, f\rangle$, where s, o, and f are the sequence number, originator-PD address, and forwarder-PD address, respectively. Fig. 2 depicts the positions and roles of participating PDs in the proposed RRB scheme.

3.2. Protocol Design

The proposed RRB scheme design is inspired by rumor information spreading, in which abstract information is forwarded first, and the full information is transmitted later, if necessary. Rumor behavior has two great advantages, namely, fast abstract forwarding and acknowledgement, depending on the context. Fast abstract forwarding alleviates the bandwidth requirements of the PACNET by reducing the rate of unnecessary data frame transmissions, while playing the ACK role in a suitable context replaces the conventional ACK. In the RRB scheme, a rumor frame is denoted by $\mathrm{R}\langle s, o, f, r\rangle$, where r is the rumor-PD address. Because the PACNET is considered a dense environment, the RRB scheme operates selectively based on the relations between neighboring PDs, which are developed using mutual unicast conversations, as in [39, 40]. Let F_i denote the set of neighboring PDs in the *i-th* PD. The RRB scheme consists of two algorithms: (i) *the broadcast frame-handling* algorithm, and (ii) *the rumor-frame handling* algorithm.

3.3. Broadcast Frame Handling

Algorithm 1 shows the pseudocode of our proposed broadcast frame-handling procedure. We consider the broadcast frame in two cases: (i) generated by the PD itself, and (ii) received from other PD. First, when the *i-th* PD generates a broadcast frame, the PD assigns a sequence number to identify the broadcast frame. The sequence number starts with 0, and is then increased by 1 for each broadcast frame generation until it reaches

Algorithm 1 Broadcast Frame Handling in *i-th* PD.

```
    $P\langle s, o, f\rangle$: Broadcast frame.
    $R\langle s, o, f, r\rangle$: Rumor frame.
    $F_i$: The set of neighboring PDs.
    $F_i^{(s,o)}$: The set of neighboring PDs that have broadcast info $P\langle s, o, \_\rangle$.
 1: $P.[s] \leftarrow 0$;
 2: if A broadcast frame is generated then
 3:     $P.[o] \leftarrow$ i-th PD address;
 4:     $P.[f] \leftarrow$ i-th PD address;
 5:     Broadcast $P\langle s, o, f\rangle$;                ▷ Send the broadcast.
 6:     $P.[s]$++;                        ▷ Return to 0 when reaching 127.
 7: if A broadcast frame is received then
 8:     Add $P.[f] \rightarrow F_i^{(s,o)}$;                ▷ Consider as ACK.
 9:     if The broadcast frame is duplicated then
10:         Discard;
11:     else
12:         if $F_i^{(s,o)} == F_i$ then
13:             Send ACK;
14:         else
15:             $R.[r] \leftarrow$ i-th PD address;
16:             BroadcastRumor();
    %BroadcastRumor() definition
    BroadcastRumor()
17:     $t = 1$;
18:     do
19:         Broadcast $R\langle s, o, f, r\rangle$;      ▷ Rumor the broadcast info.
20:         $t++$;
21:         Wait for a timer;
22:     while $t \le k$ AND $F_i^{(s,o)} != F_i$        ▷ k is the max. attempts.
```

Algorithm 2 Rumor Frame Handling in *i-th* PD.

```
    $P\langle s, o, f\rangle$: Broadcast frame.
    $R\langle s, o, f, r\rangle$: Rumor frame.
    $F_i$: The set of neighboring PDs.
    $F_i^{(s,o)}$: The set of neighboring PDs that have broadcast info $P\langle s, o, \_\rangle$.
 1: if $R\langle s, o, f, r\rangle$ is received then
 2:     if $R.[o] != $ i-th PD AND ($R.[f] ==$ i-th PD OR Null) then
 3:         Broadcast $P\langle s, o, f\rangle$;      ▷ Response of broadcast request.
 4:         if $R.[f] ==$ Null then
 5:             Remove $R.[r] \rightarrow F_i^{(s,o)}$;
 6:     else
 7:         if $R.[r] \in F_i$ then
 8:             Add $R.[r] \rightarrow F_i^{(s,o)}$;      ▷ Temporally consider as ACK.
 9:             if i-th PD does not have the broadcast info. yet. then
10:                 $R.[f] \leftarrow R.[r]$;
11:                 $R.[r] \leftarrow$ i-th PD address;
12:                 BroadcastRequest();
13:         else
14:             Discard;
    %BroadcastRequest() definition
    BroadcastRequest()
15:     Broadcast $R\langle s, o, f, r\rangle$;              ▷ Request the broadcast.
16:     Wait for a timer;
17:     if No $P\langle s, o, f\rangle$ response then
18:         $R.[f] \leftarrow$ Null;
19:         Return to Line 15;
```

127. Then the sequence is reset to 0 for a new cycle. Because *i-th* PD is the originator-PD, both P.[o] and P.[f] are assigned as the *i-th* PD address (see lines 1–6 in Algorithm 1). In contrast, when the *i-th* PD receives a broadcast frame, the PD marks the forwarder-PD (R.[f]) as already having the broadcast information. In addition, P.[s] and P.[o] are used to verify the duplication (i.e., the *i-th* PD has already received this frame in advance). If a duplication exists, the received broadcast frame is discarded (see lines 7–10 in Algorithm 1). Otherwise, if all neighboring PDs in F_i have received the broadcast information, the *i-th* PD returns an ACK frame (see lines 11–13 in Algorithm 1). Conversely, if least one neighboring PD in F_i does not yet have this broadcast information, the *i-th* PD updates R.[r] using its address and then broadcasts the corresponding rumor frame (see lines 14–16 in Algorithm 1).

3.4. Rumor Frame Handling

The rumor-frame handling activities are described in Algorithm 2. When the *i-th* PD receives a rumor frame, if the broadcast information was not generated by the *i-th* PD (i.e., R.[o] is not equal to the *i-th* PD address), but the forwarder-PD address derived from the rumor frame indicates either the *i-th* PD or *Null* (i.e., R.[f] is equal to the *i-th* PD address or *Null*), the *i-th* PD responds with the corresponding broadcast frame (see lines 1–3 in Algorithm 2). In case R.[f] = *Null*, R.[r] is removed from the set $F_i^{(s,o)}$ of neighboring PDs that have the broadcast information; see lines 4–5. Note that R.[f] is set *Null* to handle the case if the PD meets a connection problem to the previous rumor-PD. A *Null*-R[f] rumor frame can be responded by any PDs that have the corresponding broadcast frame. In contrast, if the rumor-PD address derived from the rumor frame (i.e., R.[r]) belongs to the neighboring PD set F_i, first, the *i-th* PD temporally marks this PD as already having the broadcast information (i.e., add this PD to the set $F_i^{(s,o)}$); see lines 7–8 in Algorithm 2. If a *Null*-R[f] rumor frame is received from this PD during waiting timer, i.e., `time_out`, this PD will be removed from the set $F_i^{(s,o)}$. Next, if the *i-th* PD does not yet have the broadcast information, the PD updates R.[f] and R.[r] using the obtained R.[r] and its address, respectively. Hereafter, the *i-th* PD sends a rumor frame to spread the broadcast information, as well as to request the broadcast frame for itself (see lines 9–12 in Algorithm 2). Conversely, if R.[r] does not belong to the neighboring PD set F_i, the *i-th* PD discards the rumor frame (see lines 13 and 14 in Algorithm 2).

3.5. A Prime Example

Fig. 3 illustrates a 6-PD network scenario for the proposed RRB scheme. Let PD$_0$ be the originator-PD that initiates the broadcast process. Black links indicate neighboring relation between two PDs. In order to analyze an error case, we assume that the link between PD$_2$ and PD$_6$ will break due to their movements after PD$_6$ sends a rumor frame to request the full broadcast frame from PD$_2$. Details are described as follows.

According Algorithm 1, PD$_0$ initially sends out a broadcast frame $\mathrm{P}\langle 0,0,0\rangle$ (Fig. 3(a)), which is received by PD$_1$, PD$_2$, and PD$_3$. Since PD$_1$ and PD$_2$ are neighboring PDs of PD$_0$, their neighboring PD sets $F_1^{(0,0)}$ and $F_2^{(0,0)}$ are updated to be {0} and {0}, respectively. In the next turn, PD$_1$ and PD$_2$ transmit two rumor frames $\mathrm{R}\langle 0,0,0,1\rangle$ and $\mathrm{R}\langle 0,0,0,2\rangle$ following Algorithm 2, for two purposes: (i) to ACK the successful reception of broadcast frame to PD$_0$, and (ii) to send a rumor broadcast information to further neighboring PDs (i.e., PD$_4$, PD$_5$, and PD$_6$); see Figs. 3(b) and 3(c). Because PD$_3$ has already received the broadcast frame $\mathrm{P}\langle 0,0,0\rangle$ directly from PD$_0$, PD$_3$ considers the rumor frames from PD$_1$ and PD$_2$ to be ACKs. Fig. 3(c) shows that the neighboring PD sets $F_0^{(0,0)}$, $F_3^{(0,0)}$, and $F_6^{(0,0)}$ are updated to be {1,2}, {1,2}, and {2}, respectively; since these neighboring PD sets fully cover all of their neighboring PDs, PD$_0$, PD$_3$, and PD$_6$ identify that the broadcast frame transmission is reliable from their perspectives. Because all neighboring PDs of PD$_3$ already have the broadcast information, PD$_3$ returns an ACK to PD$_1$ and PD$_2$ for a "broadcast already received" notification (Fig. 3(d)). Next, after receiving the rumor frame $\mathrm{R}\langle 0,0,0,1\rangle$, PD$_4$ broadcasts rumor frame $\mathrm{R}\langle 0,0,1,4\rangle$, for two purposes: (i) to request the broadcast frame from PD$_1$, and (ii) to send the rumor of broadcast information to PD$_5$ (Fig. 3(e)). PD$_5$ also considers the rumor frame of PD$_1$ as an ACK, the neighboring PD sets $F_5^{(0,0)}$, therefore, is updated to be {4}, resulting in a reliable broadcast frame transmission from its perspective. Similarly, PD$_6$ sends rumor frame $\mathrm{R}\langle 0,0,2,6\rangle$ to request the broadcast frame from PD$_2$ (Fig. 3(f)). After receiving rumor frame $\mathrm{R}\langle 0,0,1,4\rangle$, PD$_1$ responds by broadcasting frame $\mathrm{P}\langle 0,0,1\rangle$ to PD$_4$. Because PD$_5$ is in the transmission range of PD$_1$, PD$_5$ directly receives the broadcast frame as well (Fig. 3(g)).

Similarly, PD$_2$ transmits broadcast frame $\mathrm{P}\langle 0,0,2\rangle$ to respond to the request by PD$_6$ (Fig. 3(h)). However, PD$_6$ moves far away from PD$_2$ after sending the rumor frame $\mathrm{R}\langle 0,0,2,6\rangle$. Therefore, the broadcast frame $\mathrm{P}\langle 0,0,2\rangle$ is not received by PD$_6$. The waiting timer reaches `time_out` at PD$_6$. In order to handle this communication error, PD$_6$ resets R[*f*] field to *Null* and rebroadcasts a rumor frame $\mathrm{R}\langle 0,0,\_,6\rangle$ to request the broadcast frame from any PDs in the coverage area (Fig. 3(i)). In Fig. 3(j), assume that PD$_5$ hears this frame, then PD$_5$ sends broadcast frame $\mathrm{P}\langle 0,0,5\rangle$ to respond to the request by PD$_6$. Because PD$_4$ also received the broadcast frame from PD$_5$, PD$_4$ considers the frame as an acknowledgement. As a result, PD$_4$ broadcasts an ACK for a "broadcast already received" notification to PD$_1$ and PD$_5$ (Fig. 3(k)). Similarly, PD$_6$ return its ACK for the same purpose to PD$_5$ (Fig. 3(l)); thus, PD$_5$ identifies a reliable broadcast frame transmission from its perspective. Finally, all PDs successfully obtain the broadcast frame making a reliable frames transmission.

4. Theoretical Analysis

In order to evaluate the amount of broadcast traffic in the PACNET, where the proposed RRB scheme is applied, we develop a discrete-time Markov chain (DTMC) model for each PD. Fig. 4 shows the state transition diagram of a PD in a broadcast transmission. Let the steady-state probabilities of the Markov chain be denoted by S_i, S_t, S_r, S_a, S_n, S_k, and S_w, where *i*, *t*, *r*, *a*, *n*, *k*, and *w* represent the states of "idle", "transmit full frame", "receive full frame", "transmit rumor frame", "receive rumor frame", "transmit ACK" and "wait for ACK", respectively. According Fig. 4, the steady-state probabilities are given by

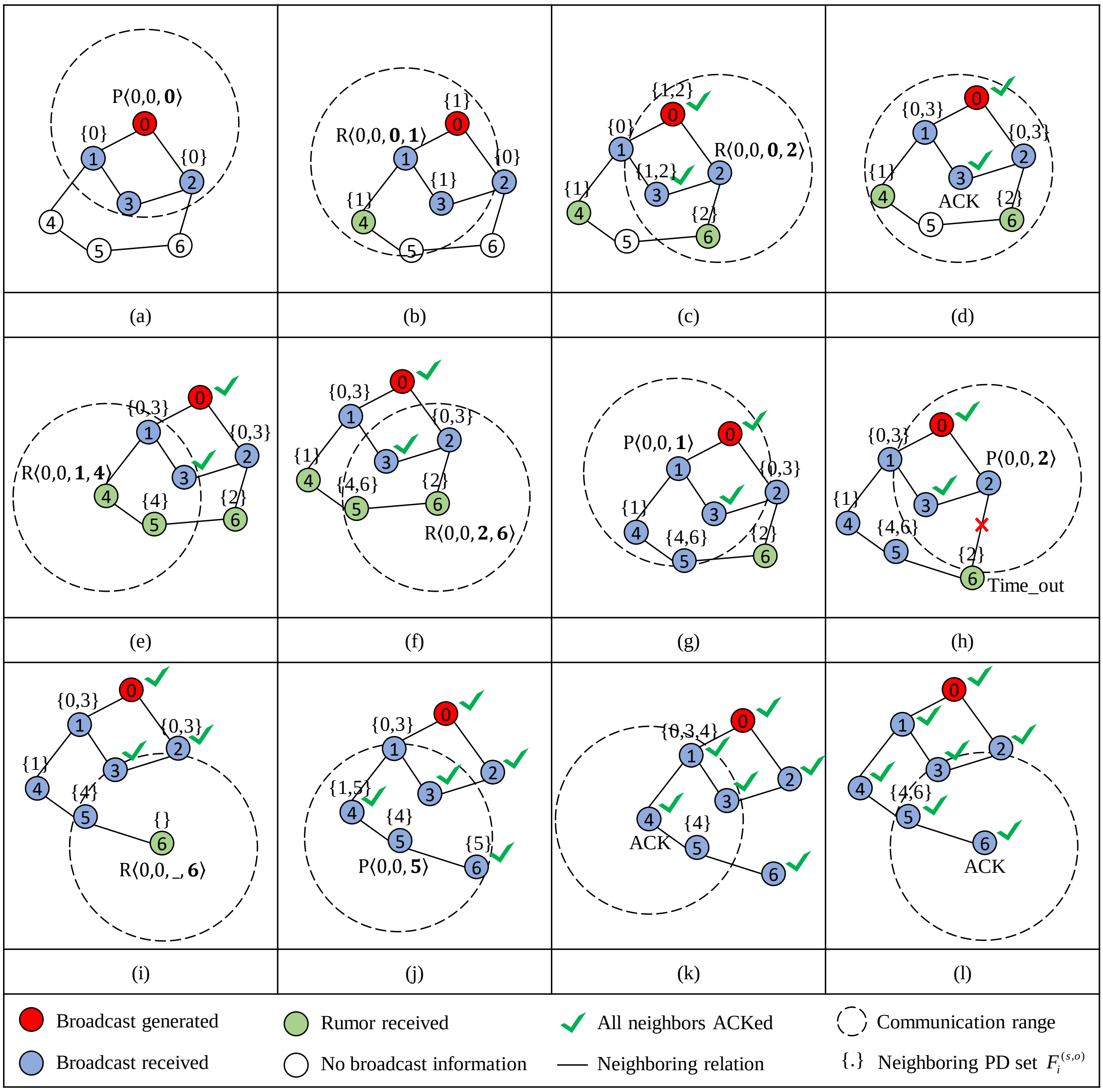
$$
\begin{aligned}
S_i &= S_a p_{ai} + S_n p_{ni} + S_w p_{wi} + S_k p_{ki} + S_r p_{ri}, && (1)\\
S_a &= S_r p_{ra} + S_n p_{na}, && (2)\\
S_n &= S_i p_{in}, && (3)\\
S_t &= S_i p_{it} + S_n p_{nt} + S_w p_{wt}, && (4)\\
S_w &= S_t p_{tw}, && (5)\\
S_k &= S_r p_{rk}, && (6)\\
S_r &= S_i p_{ir}. && (7)
\end{aligned}
$$

The total steady-state probability of a PD in the broadcast transmission is equal to one. That is,

$$S_i + S_a + S_n + S_t + S_w + S_k + S_r = 1. \tag{8}$$

Next, we need to calculate the transition probabilities. According the random access scheme utilized in IEEE 802.15.8 [7, 38], the probability of a PD that broadcasts a data frame in each slot is given by:

$$p = \rho \frac{1}{W}, \tag{9}$$



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Figure 3: An example of the proposed RRB scheme.

where the contention window $W = \min(2^k W_{\min}, W_{\max})$ and k is the number of transmission attempts [38]. On the other hand, the average number of PDs in the transmission area of a PD is defined by

$$N = \lambda\pi D^2. \tag{10}$$

Adopting the Poisson distribution, the probability of i number of PDs in the transmission area of a PD (including itself) is given by

$$p(i) = \frac{N^i}{i!} e^{-N}. \tag{11}$$

Therefore, p_{ir}, the probability that a PD transits from ”idle” state to ”receive broadcast frame” state, is derived from the probability of a PD transmitting successfully and $i-2$ remaining devices not transmitting (no collision

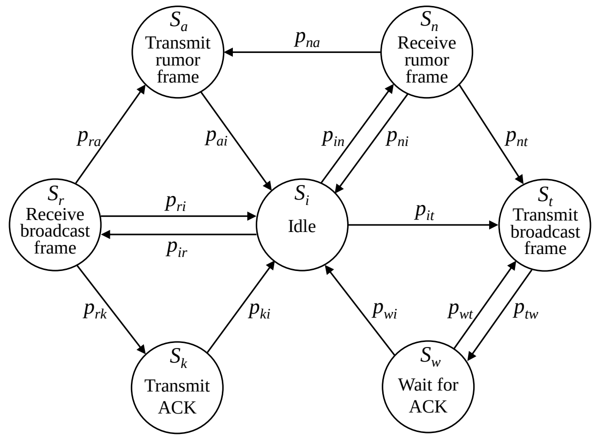


Figure 4: State diagram of a PAC device in RRB-based broadcast transmission.

occurs), as is

$$\begin{aligned}
p_{ir} &= \sum_{i=0}^{\infty}(i-1)p(1-p)^{i-2}\frac{N^i}{i!}e^{-N} \\
&= \frac{p}{(1-p)^2}\sum_{i=0}^{\infty}(i-1)\frac{[N(1-p)]^i}{i!}e^{-N(1-p)}e^{-pN} \\
&= \frac{p}{(1-p)^2}\Bigg[\sum_{i=0}^{\infty} i\frac{[N(1-p)]^i}{i!}e^{-N(1-p)} \\
&\quad -\sum_{i=0}^{\infty}\frac{[N(1-p)]^i}{i!}e^{-N(1-p)}\Bigg]e^{-pN} \\
&= \frac{p}{(1-p)^2}[N(1-p)-1]e^{-pN} \\
&= \frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}. \qquad (12)
\end{aligned}$$

On the other hand, p_{it}, the probability that a PD transits from "idle" state to "transmit broadcast frame" state, is calculated by the probability of a PD broadcasting a data frame in each slot. Then,

$$p_{it} = p = \frac{\rho}{W}. \qquad (13)$$

Since $p_{it} + p_{ir} + p_{in} = 1$, p_{in}, the probability that a PD transits from "idle" state to "receive rumor frame" state, is obtained by

$$p_{in} = 1 - \left(\frac{\rho}{W} + \frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}\right), \qquad (14)$$

In addition, p_{wi}, the probability that a PD transits from "wait for ACK" state to "idle" state, is given by the probability of the channel is collisionless when a PD broadcasts a frame.

$$\begin{aligned}
p_{wi} &= \sum_{i=0}^{\infty}(1-p)^{i-2}\frac{N^i}{i!}e^{-N} \\
&= p_{ir} \\
&= \frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}. \qquad (15)
\end{aligned}$$

Since $p_{wi} + p_{wt} = 1$, p_{wt}, the probability that a PD transits from "wait for ACK" state to "transmit broadcast frame" state, is obtained by

$$p_{wt} = 1 - \frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}. \qquad (16)$$

According the state diagram in Fig. 4, p_{ai}, p_{tw}, and p_{ki} are on their own in terms of the transition probability. Therefore, they are obtained by

$$p_{ai} = 1, \qquad (17)$$

$$p_{tw} = 1, \qquad (18)$$

$$p_{ki} = 1. \qquad (19)$$

Assume there are M applications served in the PAC-NET. Following Zipf's distribution [41], the probability f_l that a l-ranked (among M) application is used by a PD is given by

$$f_l = f(l; s, M) = \frac{1}{l^s H_{M,s}}, \qquad (20)$$

where the harmonic number $H_{M,s} = \sum_{m=1}^{M}\frac{1}{m^s}$, $m \in \mathbb{N}$. According Pareto's law (the 80-20 rule) [42], $s = \log_4 5 = 1.16$.

In addition, a PD is known to be a neighboring PD of another PD if two PDs use the same applications (therefore, two PDs have the same broadcast domain). Adopting the Poisson distribution, the average number F of neighboring PDs of a PD is given by

$$\begin{aligned}
F &= \sum_{l=1}^{\infty} f_l\left(f_l\sum_{i=0}^{\infty} i\frac{N^i}{i!}e^{-N}\right) \\
&= \frac{N}{H_{M,s}^2 H_{M,2s}}. \qquad (21)
\end{aligned}$$

Consequently, the probability p_{rk} that a PD transits from "receive broadcast frame" state to "transmit ACK" state is derived from the probability of all neighboring PDs already having received the information of the broadcast frame and this is the first time the frame arrives at the PD. Therefore,

$$\begin{aligned}
p_{rk} &= p(1-p)^{F-1}[p_{in}+p_{ir}]^F \\
&= \frac{\rho}{W}\left(1-\frac{\rho}{W}\right)^{F-1}[p_{in}+p_{ir}]^F \\
&= \frac{\rho}{W}\left(1-\frac{\rho}{W}^{F-1}\right)\Bigg[1-\left(\frac{\rho}{W}+\frac{\rho[N(W-\rho)-W]}{(w-\rho)^2}e^{\frac{-N\rho}{W}}\right) \\
&\quad + \frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}\Bigg]^F \\
&= \frac{\rho}{W}\left(1-\frac{\rho}{W}\right)^{F-1}\left(1-\frac{\rho}{W}\right)^F \\
&= \frac{\rho}{W}\left(1-\frac{\rho}{W}\right)^{2F-1}. \qquad (22)
\end{aligned}$$

On the other hand, the probability p_{ri}, the probability that a PD transits from "receive broadcast frame" state to "idle" state is derived from the probability of all neighboring PDs of the PD already received the frame or this is not the first time the frame arrives at the PD.

$$\begin{aligned}
p_{ri} &= \left(1-\frac{\rho}{W}\left(1-\frac{\rho}{W}\right)^{F-1}\right)(p_{in}+p_{ir})^F \\
&= \left(1-\frac{\rho}{W}\left(1-\frac{\rho}{W}\right)^{F-1}\right)\left(1-\frac{\rho}{W}\right)^F. \qquad (23)
\end{aligned}$$

Because $p_{ri}+p_{rk}+p_{ra}=1$, p_{ra}, the probability that a PD transits from "receive broadcast frame" state to "transmit rumor frame" state, is obtained by

$$p_{ra} = 1-\left(1-\frac{\rho}{W}\right)^F. \qquad (24)$$

The probability p_{na} that a PD transits from "receive rumor frame" state to "transmit rumor frame" state can be derived from the probability of there being at least one neighboring PD of the PD that does not receive the frame. Therefore,

$$\begin{aligned}
p_{na} &= 1-(p_{in}+p_{ir})^F \\
&= 1-\left(1-\frac{\rho}{W}\right)^F. \qquad (25)
\end{aligned}$$

In addition, the probability p_{nt} that a PD transits from "receive rumor frame" state to "transmit broadcast frame" state, represents the probability that a PD broadcasts a rumor frame, and then receives a rumor frame from its neighboring PDs for a request of the frame. As a result, p_{nt} is given by

$$\begin{aligned}
p_{nt} &= p_{na}p_{in} \\
&= \left(1-\left(1-\frac{\rho}{W}\right)^F\right)\left[1-\left(\frac{\rho}{W}+\frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}\right)\right]. \qquad (26)
\end{aligned}$$

Since $p_{na}+p_{ni}+p_{nt}=1$, p_{ni}, the probability that a PD transits from "receive rumor frame" state to "idle" state, is obtained by

$$\begin{aligned}
p_{ni} &= \left(1-\frac{\rho}{W}\right)^F-\left(1-\left(1-\frac{\rho}{W}\right)^F\right) \\
&\quad \times\left[1-\left(\frac{\rho}{W}+\frac{\rho[N(W-\rho)-W]}{(W-\rho)^2}e^{\frac{-N\rho}{W}}\right)\right]. \qquad (27)
\end{aligned}$$

Consequently, the throughput ($\mathcal{R}$) of a PACNET with N PDs can be calculated as

$$\mathcal{R} = \frac{N(S_tD_t+S_aD_a+S_kD_k)}{S_iT_i+S_tT_t+S_rT_r+S_aT_a+S_nT_n+S_kT_k+S_wT_w}. \qquad (28)$$

where D_t, D_a, and D_k are the frame size of broadcast, rumor, and ACK frames, respectively, while T_i, T_t, T_r, T_a, T_n, T_k, and T_w are the life time of "idle", "transmit broadcast frame", "receive broadcast frame", "transmit rumor frame", "receive rumor frame", "transmit ACK", and "wait for ACK" states, respectively. In Equation 28, the numerator $N(S_tD_t+S_aD_a+S_kD_k)$ is total bits generated for the broadcast transmission while the denominator $S_iT_i+S_tT_t+S_rT_r+S_aT_a+S_nT_n+S_kT_k+S_wT_w$ is total time used to broadcast the frame throughout the network.

5. Performance Evaluation

5.1. Simulation Setup

In this section, we evaluate the performance of the proposed scheme compared to that of the *piggybacking* [43] and *fullACK* [14] schemes. The fullACK scheme supports reliable broadcasting based on its rebroadcast-upon-receive policy and the ACK return to notify a successful receipt. The piggybacking scheme reduces the ACK response by piggybacking ACK information on the rebroadcasted frame. To simulate these schemes, we use the OPNET modeler [35] and monitor the data transmission metrics during 500 simulation timeslots for each network topology. There are 50 random network topologies have been generated, where a fully distributed infrastructureless PAC environment is setup

Table 2: Simulation parameters

Parameters	Value
Transmission type	Broadcast
Topology size	500 m × 500 m
Number of nodes	200
Number of network topologies	50
Broadcast frame size	1500 bytes
Notification frame size	28 bytes
Bandwidth	10 Mbps
Transmit power	15 dBm
Traffic volume	{0, 100, 200, 300, 500, 750} frame/s
CW_{min}	2^4
CW_{max}	2^{10}
DIFS	50 μs
SIFS	20 μs
Traffic type	Constant bit rate (CBR)
Number of channels	1
Maximum number of retransmissions	5
Waiting timer	5× DIFS
Simulation time	500 timeslots

within 500×500 m^2 and 200 PDs are distributed randomly. Each PD in the network independently generates broadcast frames to spread in the whole network to represent various data path transmissions in order to ensure the generality. In addition, 5 scenarios were conducted, where the traffic volume is changed from 100 frame/s to 750 frame/s. The simulation parameters are listed in Table 2.

5.2. Theoretical Verification

The theoretical network throughput ($\mathcal{R}$) as formalized in Equation (28) is verified by comparing it to the simulated network throughput. To ensure the similar environment parameters, the traffic type is set constant bit rate (CBR) and the transmission windows W is observed from the simulated OPNET CSMA/CA protocol for each transmission. In addition, the number of applications served in the PACNET is given by 50. The results are demonstrated in Figure 5 referred to be "Theoretical RRB" and "Simulated RRB". In all captured points, the simulated network throughput is higher than the theoretical one. The differences might be caused by the collision and retransmission behaviors of the CSMA/CA protocol in OPNET simulation environment. On the other hand, it is seen that there are insignificant differences between the network throughput metrics given the theoretical calculation and simulated observation when the traffic volume is low or high since low traffic rate leads to few transmission errors occurred and high traffic rate results in a saturated environment. The difference increases within medium traffic volume. In summary, the theoretical formulation is considered as an approximation to the simulated values.

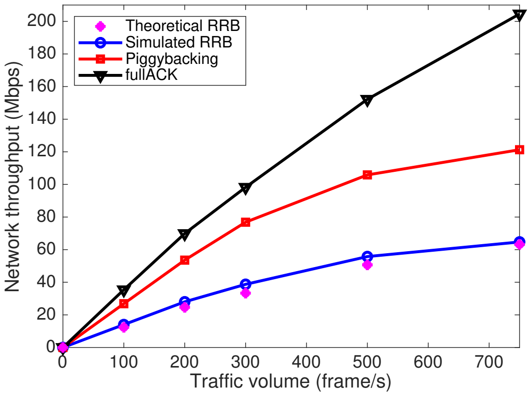


Figure 5: Total network throughput.

5.3. Numerical Analysis

Figure 5 shows the total network throughput according to the traffic volume in the network. In the figure, our proposed RRB scheme has the lowest network throughput generation compared to the piggypbacking and fullACK schemes. It is worth noting that lower network throughput is better since the identical input traffic volume is transmitted to multiple PDs. The achieved results reflect, the RRB scheme pre-forwarded the rumor frames than full broadcast frames in advance. While the full broadcast frame is only transferred to the PDs on request. On the contrary, remaining schemes rely on neighboring relations that define next hop frame delivery without considering transmission range. Therefore, these schemes generate rebroadcasting storms in such a dense PACNET environment. Numerical results show that the piggybacking and fullACK schemes result in an increased network throughput, which are (on average) 1.92 and 2.69 times greater than the RRB scheme.

From an overhead perspective, Fig. 6 illustrates the simulation results. The overhead consists of notification frames (i.e., rumor and ACK frames), redundant broadcast frames, and headers and piggybacked ACK information in broadcast frames. In the proposed RRB scheme, overhead is reduced significantly. Logging information reveals that almost all of the overhead is due to rumor frame transmission and broadcast frame headers; meanwhile, the number of redundant frames is inconsiderable. In the fullACK scheme, the rebroad-

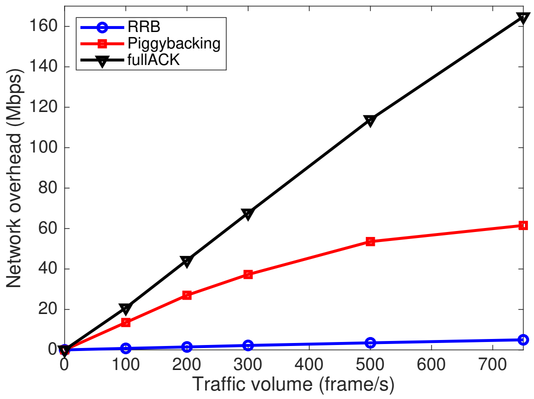


Figure 6: Total network overhead.

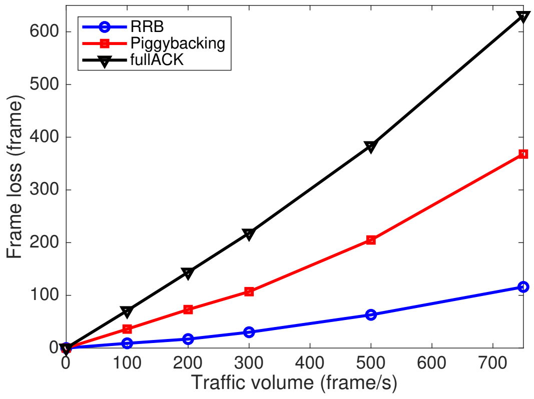


Figure 7: Frame loss in entire network.

cast operation is based on next-hop neighboring relations. Moreover, an ACK frame is returned to the sender whenever a broadcast frame is successfully received. However, the transmission range of a PD can cover multi-hop neighboring relations in dense PACNET environment. Therefore, significant broadcast redundancy occurs resulting in exponential overhead volume. In the piggybacking scheme, the overhead is reduced approximately a half due to reductions of ACK frame transmission, collisions, and rebroadcasts.

As a result, Fig. 7 depicts average number of broadcast frame loss in entire network. For instance, within 100-frame/s input traffic scenario, 100 (frames) × (200 − 1) (number of remaining PDs except the originator-PD of the frames), resulting in 19900 frames should be received to achieve a full reliability (i.e., all of PDs successfully receive the broadcast frames). However, the simulation results reveal that 19891, 19864, and 19829 frames received successfully, where the RRB, piggybacking, and fullACK schemes are applied, respectively. It depicts the negative impact of collisions (due to massive transmissions and rebroadcasts) causing frames losses in the network. The fullACK scheme obtains the worst achievement (71 frames loss) compared to the piggybacking (36 frames loss) and RRB (9 frames loss) schemes. Statistical analysis shows that the RRB scheme has an average number of frame loss, which is 72.28% and 85.39% less than the piggybacking and fullACK schemes, respectively.

In term of network reliability, our simulation results show high performance in all schemes; see Fig. 8. To be particular, the RRB, piggybacking, and fullACK schemes achieve reliability of 99.94%, 99.80%, and 99.62% on average, respectively. In other words, the RRB scheme reduces the loss rate compared to the piggybacking and fullACK schemes from 0.20% and 0.38% to 0.06%, respectively. The communication reliability improvement of the RRB scheme over the others is because of the collision reductions by using rumor frames instead of rebroadcasting full frames immediately.

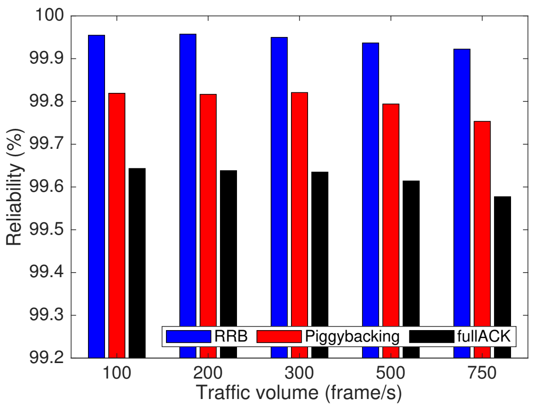


Figure 8: Network reliability.

Figure 9 demonstrates the energy consumption per frame in order to broadcast the frame over the entire network. Adopting IEEE 802.15.8 [7], the transmit power of PD is set 15 dBm. The energy consumption per frame is obtained by multiplying the transmit power by transmission duration of total bits of the frame and overheads generated for broadcasting the frame. It is observed that the RRB scheme achieved best performance because of

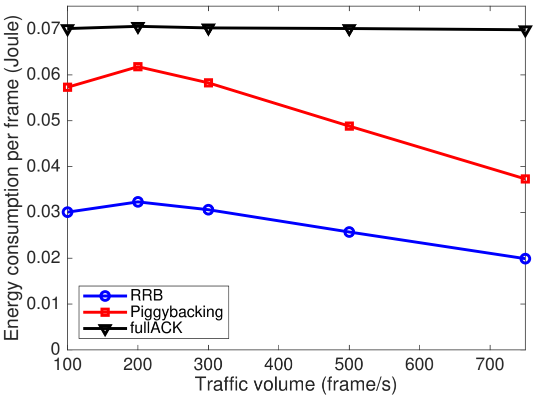


Figure 9: Average energy consumption per frame.

its advantageous traffic and collision reductions. The performance of the fullACK scheme remained (approximately 0.070 J) when the input traffic volume is adjusted due to its simple reactions for each broadcast frame received. On the other hand, the RRB and piggybacking schemes showed highest energy consumption (approximately 0.028 J and 0.053 J, respectively) when the input traffic volume reached 200 frame/s approximately. The energy consumption decreased as the input traffic volume increased. This is because these two schemes performed better reactions to reduce the collision probability whereas the actual number of collisions increased in proportion to the traffic volume. Statistical analysis shows that the RRB scheme reduces the energy consumption per frame broadcast by 47.42% and 60.52% compared to the piggybacking and fullACK schemes, respectively.

6. Conclusion

This paper proposed a reliable broadcast scheme, namely RRB, for safety services in dense infrastructureless peer-aware communications. The proposed RRB scheme takes advantage of neighboring relations among PAC devices (PDs) to broadcast rumor frame, an abstract information, instead of transmitting large broadcast frames. While the full broadcast frames are delivered on demand. Simulation analysis proved the outperformance of the RRB scheme compared to the existing solutions in terms of overhead reduction and energy efficiency while maintaining a better transmission reliability improvement. Future study should consider a comprehensive theoretical analysis compared to a testbed-based implementation to complete the study. Moreover, a dynamic retransmission policy should be additionally developed to flexibly adapt to the collision conditions with a strict consideration of network traffic, wireless channel quality, and user mobility. In addition, machine learning-based context awareness could be utilized as a feasible approach for collision predictions.

Acknowledgements

This work was supported in part by the Institute for Information and Communications Technology Promotion Grant funded by the Korea Government (a study on core technology of 5G mobile communication using millimeter wave band) under Grant 2018-0-00889 and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (NRF-2018M1A3A3A02066018).

References

[1] M. V. Moreno, F. Terroso-Sáenz, A. González-Vidal, M. Valdés-Vela, A. F. Skarmeta, M. A. Zamora, V. Chang, Applicability of big data techniques to smart cities deployments, IEEE Transactions on Industrial Informatics 13 (2) (2017) 800–809.

[2] N.-N. Dao, M. Park, J. Kim, J. Paek, S. Cho, Resource-aware relay selection for inter-cell interference avoidance in 5G heterogeneous network for Internet of things systems, Future Generation Computer Systems.

[3] A. Zanella, N. Bui, A. Castellani, L. Vangelista, M. Zorzi, Internet of things for smart cities, IEEE Internet of Things Journal 1 (1) (2014) 22–32.

[4] M. Abolhasan, T. Wysocki, E. Dutkiewicz, A review of routing protocols for mobile ad hoc networks, Ad Hoc Networks 2 (1) (2004) 1–22.

[5] W. Na, Y. Lee, J. Yoon, J. Park, S. Cho, Fully distributed multicast routing protocol for IEEE 802.15.8 peer-aware communication, International Journal of Distributed Sensor Networks 11 (8) (2015) 531710.

[6] N.-N. Dao, M. Park, J. Kim, S. Cho, Adaptive MCS selection and resource planning for energy-efficient communication in LTE-M based IoT sensing platform, PloS One 12 (8) (2017) e0182527.

[7] IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC) (February 7, 2018).

[8] E. Zeira, Q. Li, S. Jin, Some details for draft application matrix for 802.15.8-PAC, Doc#: 802.15-12-0684-00-0008, IEEE P802.15 TG8 standardization (2012).

[9] P. Ruiz, P. Bouvry, Survey on broadcast algorithms for mobile ad hoc networks, ACM Computing Surveys (CSUR) 48 (1) (2015) 8.

[10] N. Anjum, D. Karamshuk, M. Shikh-Bahaei, N. Sastry, Survey on peer-assisted content delivery networks, Computer Networks 116 (2017) 79–95.

[11] A. Boukerche, Algorithms and protocols for wireless, mobile Ad Hoc networks, Vol. 77, John Wiley & Sons, 2008.

[12] N.-N. Dao, Y. Kim, S. Jeong, M. Park, S. Cho, Achievable multi-security levels for lightweight IoT-enabled devices in infrastructureless peer-aware communications, IEEE Access 5 (2017) 26743–26753.

[13] B. Kang, M. Kim, J. Kim, High reliable broadcasting protocol in wlan using retransmission, in: Proceedings of IEEE International Conference on Ubiquitous and Future Networks (ICUFN), 2016, pp. 781–783.

[14] S.-J. Choi, I.-W. Kim, C.-G. Kang, M.-S. Jeong, Y.-J. Lim, Flooding method in ad-hoc network, uS Patent 7,532,598 (May 12 2009).

[15] C. Ho, K. Obraczka, G. Tsudik, K. Viswanath, Flooding for reliable multicast in multi-hop ad hoc networks, in: Proceedings of the 3rd ACM International workshop on Discrete algorithms and methods for mobile computing and communications, 1999, pp. 64–71.

[16] Y.-C. Tseng, S.-Y. Ni, E.-Y. Shih, Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network, IEEE Transactions on Computers 52 (5) (2003) 545–557.

[17] D. Maltz, D. Johnson, A simple protocol for multicast and broadcast in mobile ad hoc networks (2000).

[18] D. Braginsky, D. Estrin, Rumor routing algorthim for sensor networks, in: Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications, 2002, pp. 22–31.

[19] R. Hajlaoui, H. Guyennet, T. Moulahi, A survey on heuristic-based routing methods in vehicular ad-hoc network: Technical challenges and future trends, IEEE Sensors Journal 16 (17) (2016) 6782–6792.

[20] W. Lin-zhu, F. Ya-qin, Y. Yang, S. Min, Heuristic algorithm based on flooding structure in wireless ad hoc networks, in: Proceeding of IEEE International Conference on Information Engineering (ICIE), Vol. 1, 2010, pp. 243–246.

[21] O. S. Eyobu, J. Joo, D. S. Han, A broadcast scheme for vehicle-to-pedestrian safety message dissemination, International Journal of Distributed Sensor Networks 13 (11) (2017) 1550147717741834.

[22] A. R. V. da Silva, L. S. Ochi, B. J. da Silva Barros, R. G. S. Pinheiro, Efficient approaches for the flooding problem on graphs, Annals of Operations Research (2018) 1–22.

[23] D. Liarokapis, A. Shahrabi, Fuzzy-based probabilistic broadcasting in mobile ad hoc networks, in: Proceedings of IFIP Wireless Days (WD), 2011, pp. 1–6.

[24] M. B. Yassein, S. F. Nimer, A. Y. Al-Dubai, A new dynamic counter-based broadcasting scheme for mobile ad hoc networks, Simulation Modelling Practice and Theory 19 (1) (2011) 553–563.

[25] F. J. Ros, P. M. Ruiz, I. Stojmenovic, Acknowledgment-based broadcast protocol for reliable and efficient data dissemination in vehicular ad hoc networks, IEEE Transactions on Mobile Computing 11 (1) (2012) 33–46.

[26] D. Liarokapis, A. Shahrabi, A probability-based adaptive scheme for broadcasting in manets, in: Proceedings of the 6th International Conference on Mobile Technology, Application & Systems, ACM, 2009, p. 46.

[27] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, J.-P. Sheu, The broadcast storm problem in a mobile ad hoc network, Wireless Networks 8 (2/3) (2002) 153–167.

[28] Y. Sasson, D. Cavin, A. Schiper, Probabilistic broadcast for flooding in wireless mobile ad hoc networks, in: Proceedings of IEEE Wireless Communications and Networking (WCNC), Vol. 2, 2003, pp. 1124–1130.

[29] J. Cartigny, D. Simplot, Border node retransmission based probabilistic broadcast protocols in ad-hoc networks, in: Proceedings of the 36th IEEE Annual Hawaii International Conference on System Sciences, 2003, pp. 10–pp.

[30] X. M. Zhang, E. B. Wang, J. J. Xia, D. K. Sung, A neighbor coverage-based probabilistic rebroadcast for reducing routing overhead in mobile ad hoc networks, IEEE Transactions on Mobile Computing 12 (3) (2013) 424–433.

[31] J. N. Pelton, S. Madry, S. Camacho-Lara, Handbook of satellite applications, Springer Publishing Company, Incorporated, 2017.

[32] F. Foroozan, K. Tepe, A high performance cluster-based broadcasting algorithm for wireless ad hoc networks based on a novel gateway selection approach, in: Proceedings of the 2nd ACM international workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks, ACM, 2005, pp. 65–70.

[33] W. Lou, J. Wu, A cluster-based backbone infrastructure for broadcasting in manets, in: Proceedings of IEEE International Parallel and Distributed Processing Symposium, 2003, pp. 8–pp.

[34] I. Stojmenovic, M. Seddigh, J. Zunic, Dominating sets and neighbor elimination-based broadcasting algorithms in wireless networks, IEEE Transactions on Parallel and Distributed Systems 13 (1) (2002) 14–25.

[35] OPNET modeler 14.5, Available: `https://www.opnet.com`.

[36] A. A. Khan, I. Stojmenovic, N. Zaguia, Parameterless broadcasting in static to highly mobile wireless ad hoc, sensor and actuator networks, in: Proceedings of IEEE International Conference on Advanced Information Networking and Applications (AINA), 2008, pp. 620–627.

[37] D. Reina, S. Toral, P. Johnson, F. Barrero, A survey on probabilistic broadcast schemes for wireless ad hoc networks, Ad Hoc Networks 25 (2015) 263–292.

[38] B. Kwak, J. Kim, N. Song, J. Rhee, Random access scheme for CAP and peering period, Doc#: 802.15-15-0725-01-0008, IEEE P802.15 TG8 standardization (2015).

[39] W. Na, N.-N. Dao, S. Cho, Reliable multicasting service for densely deployed military sensor networks, International Journal of Distributed Sensor Networks 11 (8) (2015) 341912.

[40] J. Yu, L. Park, J. Park, S. Cho, C. Keum, Cor-MAC: Contention over reservation MAC protocol for time-critical services in wireless body area sensor networks, Sensors 16 (5) (2016) 656.

[41] L. A. Adamic, B. A. Huberman, Zipf's law and the Internet., Glottometrics 3 (1) (2002) 143–150.

[42] M. E. Newman, Power laws, Pareto distributions and Zipf's law, Contemporary Physics 46 (5) (2005) 323–351.

[43] J. Lee, W. Na, S. Cho, Energy-efficient reliable broadcast protocol for WSNs based on IEEE 802.15.5, International Journal of Distributed Sensor Networks 10 (5) (2014) 501534.