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RESEARCH ARTICLE

P^{2}URE: Proactive and Probabilistic Uncovered Neighbor-Aware Relay-Selection Method in Multi-Hop FANETs

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ABSTRACT Recently, multi-hop flying ad hoc networks (FANETs) have received considerable attention because of their various advantages, such as ease of deployment, scalability, cost, and latency reduction. However, FANETs still encounter serious problems such as a highly dynamic network topology and the limited on-board battery of unmanned aerial vehicles (UAVs). Thus, to increase the coverage probability while reducing unnecessary packet transmissions, realizing efficient and effective relay selection is important. To resolve these issues, this paper proposes a proactive and probabilistic uncovered neighbor-aware relay selection (P^{2}URE) method that considers FANET's topological dynamics. Specifically, the relay decision factor to identify relay UAV candidates and the probabilistic relay decision to reduce coverage overlaps and minimize redundant packet transmissions are devised. Through extensive simulations, it has been validated that the proposed P^{2}URE method surpasses the benchmark methods in terms of the total number of transmissions, coverage probability, and energy efficiency. This superiority is observed across various network dynamics resulting from variations in the UAV density, speed, neighbor-information update period, and delay interval.

INDEX TERMS Uncovered neighbor, neighbor information update, aerial relay selection, relay decision factor, unmanned aerial vehicle, flying ad hoc network.

I. INTRODUCTION

The Internet of Things (IoT) provides wired and wireless connectivity to all types of devices (e.g., sensors, chips, cars, unmanned aerial vehicles (UAVs)) within a 3D area [1], [2], [3], [4]. The IoT has various technical requirements, e.g., it comprises a massive number of devices, has ultra-high data rates, and is required to be ultra-reliable and have low-latency provisioning, and thus many researchers are actively conducting relevant studies to resolve the associated issues [5], [6], [7].

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In particular, flying ad hoc networks (FANETs) have attracted considerable attention owing to their various advantages, such as cost and latency reduction, scalability, and ease of deployment [8], [9]. Accordingly, FANETs are expected to expand and be applied in various fields, such as military environments, agriculture, logistics, exploration, manufacturing, and monitoring [10], [11].

However, since the network topology in FANETs is more dynamic than that in terrestrial mobile ad hoc networks (MANETs), duplicate packet transmissions occur more frequently, and the mobility of UAVs is significantly affected by their limited on-board battery capacity [12], [13]. In addition, because the signal strength decays exponentially with an increase in the distance between the source and destination in wireless environments, long-distance communications require significant energy consumption to reach each other. Therefore, there is a need for effective multi-hop communications that reduce the energy consumption of UAVs [14], [15], and it is important to select optimal UAV relays (UAV-Rs) while taking into consideration the goals of the multi-hop FANET (i.e., coverage probability, energy efficiency, number of packet transmissions, etc.).

In multi-hop FANET environments, the accurate determination of the UAV-R based on a comprehensive understanding of the local network environment of each UAV is of utmost importance. Hence, the neighbor information (NI) of each UAV is considered to determine the next UAV-R. Using the child UAV classification, an uncovered neighbor set is defined as a candidate set for the UAV-Rs. Furthermore, to reduce unnecessary transmissions while maximizing the coverage probability, this paper proposes a Proactive and Probabilistic Uncovered neighbor-aware aerial REly selection (P^2URE) method that takes into consideration topological dynamics in FANETs. The contributions of this study are as follows:

- An efficient UAV-R selection method, P^2URE, that takes into consideration the characteristics of child UAVs, is proposed to minimize redundant packet transmissions and maximize coverage probability in multi-hop FANETs. Accordingly, identifying the characteristics of uncovered neighbors is very important for achieving these goals. In the following section, the child UAV classification is illustrated, and the types of uncovered neighbors are defined. The child UAV information can be generated through the NI update process. Each UAV-R candidate uses this child UAV information to proactively determine its role as UAV-R.
- Owing to the high mobility of UAVs, the variations in UAV density, and the characteristics of the NI update procedure, FANETs frequently yield redundant transmissions, which have a fatal impact on the network lifetime. To minimize the coverage performance degradation resulting from redundant packet transmissions and to maximize energy efficiency, this paper proposes a probabilistic relay decision method. This method takes into account the number of parent UAVs to reflect the duplication of transmission range between UAVs. In addition, this relaying probability can be fine-tuned via a weighting factor considering network conditions.
- To consider realistic network problems caused by NI update delay, e.g., NI inconsistency problem in multi-hop FANET environments, the delay interval between *NI update initiation* and *NI update complete* is considered for performance evaluation. That is, according to variations in the NI update period and delay interval, we demonstrate the excellent performance of the proposed P^2URE method compared with several benchmark methods.

The remainder of this paper is organized as follows. The related works are presented in Section II. Section III describes the system model and child UAV classification. Section IV presents the proposed uncovered-neighbor-based probabilistic UAV-R selection method for efficient packet transmission. Section V evaluates the performance of the proposed P^2URE method compared to the several benchmark methods. Finally, Section VI presents the conclusions of this study.

II. RELATED WORKS

In flooding, all nodes disseminate packets to all the neighboring nodes within the transmission range of each node, and it has been widely used as a basic strategy for distributing packets in MANET [16], [17]. However, as the network becomes denser and the device mobility increases, the number of duplicate transmissions increases exponentially, resulting in an explosive number of packet collisions and contentions. This problem, which is called a broadcast storm problem (BSP), occurs more frequently in environments with high speed and 3D mobility such as FANET.

Many researchers have proposed heuristic algorithms to efficiently solve the BSP caused by flooding. In [17], [18], and [19], the authors introduced several broadcasting schemes, such as probabilistic broadcasting, counter-based broadcasting, and distance, and location-based broadcasting, to solve the BSP. In the probabilistic broadcasting scheme, the node that receives packets rebroadcasts according to a predetermined probability of p. If $p = 1$, the scheme exhibits behavior identical to that of flooding. Moreover, in a counter-based broadcasting scheme, a node receiving packets counts the number of duplicate packets received during a designated time period. The node relays the received packets when the number of duplicate receptions is less than the threshold. Although this scheme can reduce unnecessary transmissions, the end-to-end latency of the packet delivery remains high. The distance-based broadcasting scheme relays the received packets when the distance between the sender and receiver exceeds the distance threshold. It is almost impossible to determine the optimal distance threshold according to the dynamic network environment. Moreover, location-based broadcasting schemes use the location information of nodes to estimate the coverage area accurately. However, the process of obtaining the location information imposes an additional burden on the network.

In [20], a scalable broadcast algorithm scheme that takes into consideration the neighbor information was proposed; thus, in this scheme, it is assumed that all the nodes know their 2-hop neighbors. Using the neighbor information, the receiver determines whether to relay, which means that the

TABLE 1. Contributions and limits of related studies.

Reference	Category	Method	Main contributions	Limits
[17]–[19]	Probabilistic approach	Probabilistic	Each node that receives packets rebroadcasts according to the predetermined transmit probability.	Difficulties in network adaptive operation
		Counter-based	Each node relays the packets when the number of duplicate receptions is less than the threshold.	High end-to-end latency.
	Location-based approach	Distance-based	Each node relays the packets when the distance between the sender and the receiver is less than the threshold.	The use of GPS causes a lot of energy consumption where UAVs have limited payload and battery capacity.
		GPS-based	It is similar to the distance-based method but uses GPS to obtain location information.	
[24]		P-OLSR	P-OLSR is a table-driven proactive routing protocol utilizing GPS information to adapt to rapid topology changes in FANET.	
[17]–[19]	Neighbor information-based approach	Self-pruning	The self-pruning method utilizes an 1-hop neighbor information to reduce redundant transmissions.	It is not suitable for FANET because it considers only two-dimensional position changes and low-speed mobility.
[20]		SBA	To reduce the broadcast redundancy, the SBA method utilizes a 2-hop neighbor information where the receiver determines whether to relay.	
[21]		NCPR	The NCPR method proposed a neighbor transmission coverage-based probabilistic rebroadcast protocol to reduce routing overhead.	
[22]		NPB	The NPB method devised an efficient broadcast protocol to consider neighbor nodes that did not receive packets.	
[23]		NTAPB	The NTAPB method proposed a network topology awareness-based probabilistic broadcast protocol considering fully connected and non-fully connected network topologies.	
[25]		DNA-BSP	The DNA-BSP method relays packets considering neighborhood characteristics to relieve the BSP problem	Difficulties in expanding to the FANET environments.
[26]	RL-based approach	Q-FANET	To reduce network delay in highly dynamic FANET, the Q-FANET method proposed a Q-learning-based routing.	The efficiency and optimality of tabular Q-learning diminishes in more complex networks.
[27]		QMR	In this study, a Q-learning-based multi-objective optimization routing method was proposed to provide low latency and low energy consumption in FANET.	

coverage area may be extended. The authors of [21] devised a neighbor coverage-based probabilistic broadcasting (NCPR) scheme to reduce the network overhead. NCPR allows nodes that have more neighbors in common with their parent nodes to preferentially relay the received packets. The simulation results demonstrated a 30.8% and 45.9% reduction in network overhead compared to the dynamic probabilistic route discovery scheme and on-demand distance vector-based routing, respectively. Also, the authors of [22] proposed the neighbor-based probabilistic broadcast (NPB) method, which determines packet rebroadcasting delay considering neighbor nodes that did not receive packets, and it calculates the rebroadcasting probability through the additional coverage ratio and the connection factor. Through simulations, they demonstrated that the NPB method improved packet forwarding ratios by 13% to 28% compared to several benchmark methods, including NCPR. To address the limitations of the existing methods, e.g., their challenges in adapting to changes in topology. In [23], the network topology awareness-based probabilistic broadcast (NTAPB) method was proposed to satisfy the requirements of packet delivery ratio and end-to-end delay under fully connected and non-fully connected network topologies. However, the performance evaluation of these existing methods was conducted for an environment with very limited two-dimensional (2D) mobility, and thus, many problems may occur when the NCPR, NPB and NTAPB methods are directly applied to dynamic 3D FANETs.

The authors of [24] proposed predictive optimized link-state routing (P-OLSR), which is OLSR tailored for FANET applications. P-OLSR utilizes global positioning system (GPS) information to predict changes in radio link quality between nodes to adapt to rapid topology changes in FANET. P-OLSR demonstrated superiority in terms of packet delivery, throughput, latency and normalized overheads, compared to OLSR. In [25], a dynamic neighborhood-based algorithm for the broadcast storm problem (DNA-BSP) was proposed to mitigate the BSP problem in FANETs, resulting in a reduction of duplicate messages by over 98%. Unfortunately, there are still several difficulties in applying these methods to dynamic 3D FANET environments, such as severe performance degradation and limited onboard UAV computing capability. Furthermore, a reinforcement learning (RL)-based approach has been studied to overcome various problems in the optimal routing path design for the highly dynamic FANET topology and the limited battery of UAVs. In [26] and [27], the authors tried to reduce the latency and energy consumption arising from highly dynamic FANET routing environments by using Q-learning. Although tabular Q-learning-based approaches are effective in simple network environments, their efficiency diminishes when applied to more complex networks. With this, finding an optimal solution according to the variations in network environments is still one of the big challenges in the RL-based approaches. The contributions and limits of all related studies are summarized in Table 1.

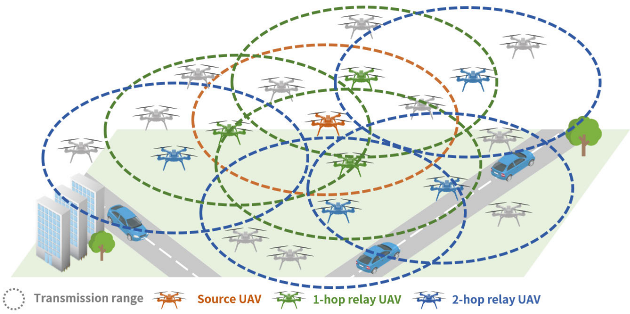


FIGURE 1. System model of multi-hop FANETs.

III. SYSTEM MODEL AND CHILD UAV CLASSIFICATION

This study considers broadcast transmission-based data dissemination in multi-hop FANET environments. For example, as shown in Fig. 1, the source UAV transmits a packet to its 1-hop neighbor UAVs within its transmission range. The selected 1-hop UAV-Rs transmit the received packet to their neighbor UAVs. Similarly, the packets can spread sequentially across the entire network. As the number of UAVs increases, it is crucial to select the optimal UAV-Rs to maximize the coverage probability while minimizing the number of unnecessary relaying transmissions. The notations and symbols used herein are listed in Table 2.

TABLE 2. Notation summary.

Notation	Description
n_i	ith UAV
n_p	Parent UAV of UAV n_i
$\mathcal{N}_{tot}(n_i)$	Set of total neighbor UAVs of UAV n_i
$\mathcal{N}_{cn}(n_i)$	Set of covered neighbor UAVs of UAV n_i
$\mathcal{N}_{un}(n_i)$	Set of uncovered neighbor UAVs of UAV n_i
$\mathcal{N}_{\mathcal{S}_1}(n_i)$	Set of shared child type-1 UAVs of UAV n_i
$\mathcal{N}_{\mathcal{S}_2}(n_i)$	Set of shared child type-2 UAVs of UAV n_i
$\mathcal{N}_{\mathcal{S}_3}(n_i)$	Set of shared child type-3 UAVs of UAV n_i
$\mathcal{N}_{\mathcal{U}}(n_i)$	Set of unique child UAVs of UAV n_i
$\mathcal{N}_{\mathcal{P}}(n_i)$	Set of parent UAVs of UAV n_i
$\mathbf{R}(n_i)$	Relay decision factor of UAV n_i
$\mathbf{R^{th}}$	Relay decision factor threshold
$\mathbf{P}$	Probability factor
$\mathbf{P^{th}}$	Probability factor threshold
$\omega_{\mathcal{S}_3}$	Weight of shared child type-3
$\omega_{\mathcal{U}}$	Weight of unique child
$\omega_{\mathcal{P}}$	Weight of the number of parents
τ_t	t-th time step
ϵ	Hop index
α	NI update period
β	Delay interval
v_i	Moving speed of n_i
w_i	Moving angle of n_i
γ_t	Number of packet transmissions
ρ	Coverage probability
ξ	Energy efficiency
γ_r	Number of packets receptions
Φ_{tot}	Total number of UAVs in network
Φ_r	Number of UAVs that received the packet

Classification of the child UAVs is required to differentiate between covered and uncovered neighbors. Fig. 2 presents an overview of P^{2}URE operation. The parent UAV is defined as a UAV with one or more neighboring UAVs within its transmission range, and the child UAV is a UAV located within the transmission range of the parent UAV. The total set of the child UAVs of ith UAV (n_i) is given by $\mathcal{N}_{tot}(n_i) = \mathcal{N}_{cn}(n_i) \cup \mathcal{N}_{un}(n_i)$ where $\mathcal{N}_{cn}(n_i)$ and $\mathcal{N}_{un}(n_i)$ represent the sets of covered neighbors and uncovered neighbors, respectively. Whether the child is covered or uncovered is determined by whether the child is within the transmission ranges of n_i's parent UAVs. $\mathcal{N}_{cn}(n_i)$ includes the shared child type-1 UAVs ($\mathcal{S}_1(n_i)$) and shared child type-2 UAVs ($\mathcal{S}_2(n_i)$). If the child UAV is included in the transmission range of the same-hop UAVs as UAV n_i, it is classified as a shared child type-1 UAV; otherwise, it is classified as a shared child type-2 UAV. In addition, $\mathcal{N}_{un}(n_i)$ includes the shared child type-3 UAVs ($\mathcal{S}_3(n_i)$) and a unique child ($\mathcal{U}(n_i)$). Similarly, if the child UAV is included in the transmission range of the same-hop UAVs as UAV n_i, it is classified as a shared child type-3 UAV, otherwise, it is classified as a unique child UAV. Namely, the uncovered neighbors are a combination of shared child type-3 UAVs and unique child UAVs.

In the case of covered neighbors, because they may have already been selected as relays and there is likely to be a significant overlap in the transmission ranges with previous UAV-Rs, this paper does not consider the covered neighbors as the next relay candidates. Thus, this paper considers the uncovered neighbors as the next UAV-R candidates. As it is unlikely that unique child UAVs will be selected as the next relay from other UAVs, selecting them as a UAV-R can contribute to improving the overall network performance. Subsequently, the shared child type-3 UAVs are considered the next relay candidates. However, shared child type-3 UAVs may have a high coverage overlap ratio and cause many redundant transmissions compared to unique child UAVs. Specifically, Fig. 3 presents the number of shared child type-3 UAVs and unique child UAVs according to the increase in the total number of UAVs in the entire network. This

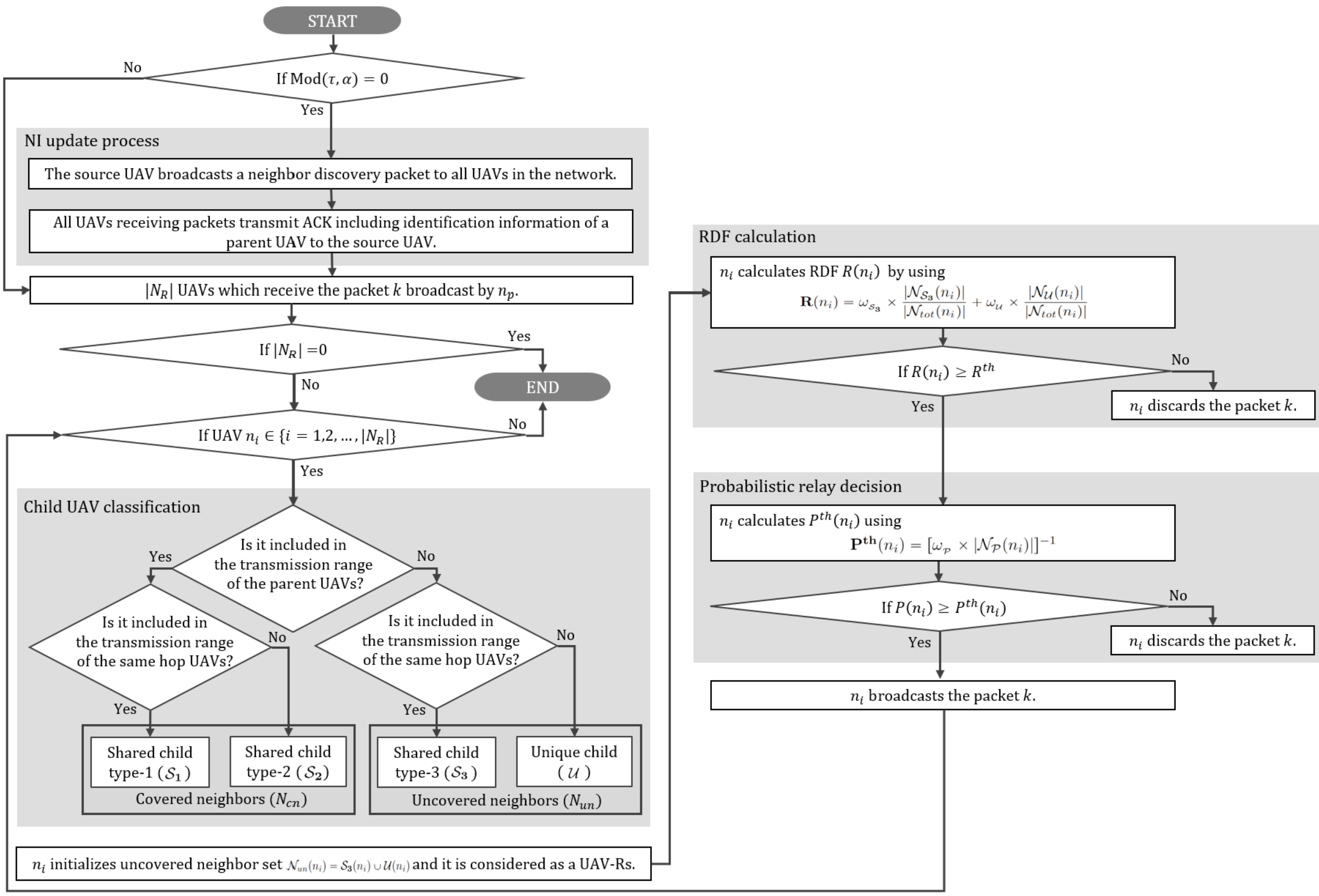


FIGURE 2. Flowchart of the proposed P^{2}URE framework.

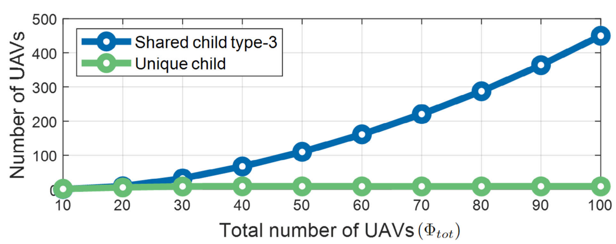


FIGURE 3. Number of shared child type-3 UAVs and unique child UAVs versus the total number of UAVs in the entire network.

figure shows that the number of shared child type-3 UAVs and unique child UAVs changes according to the change in UAV density. In the case of a low UAV density, the distance between neighboring UAVs is relatively large; thus, the ratio of unique child UAVs is greater than that in the case of a high UAV density. In contrast to the case of a low UAV density, the distance between neighboring UAVs is significantly less than that in the case of a high UAV density; thus, the number of shared child type-3 UAVs is significantly greater than the number of unique child UAVs. In addition, even with a high UAV density, if the transmission range is small, the unique coverage ratio can be greater due to reduced coverage overlap. Thus, it is required to develop a relay selection method considering child characteristics based on various network conditions such as UAV density, transmission range, mobility, and number of relay hops.

IV. P^{2}URE: PROACTIVE AND PROBABILISTIC UNCOVERED NEIGHBOR-AWARE RELAY SELECTION METHOD

A. RELAY DECISION FACTOR (RDF) DESIGN

This paper defines a relay decision factor (RDF) for efficient UAV-R selection while considering the child UAV characteristics. The RDF of n_i ($\mathbf{R}(n_i)$) can be calculated by considering shared child type-3 UAVs and unique child UAVs as follows:

$$\mathbf{R}(n_i) = \omega_{\mathcal{S}_3} \times \frac{|\mathcal{N}_{\mathcal{S}_3}(n_i)|}{|\mathcal{N}_{tot}(n_i)|} + \omega_{\mathcal{U}} \times \frac{|\mathcal{N}_{\mathcal{U}}(n_i)|}{|\mathcal{N}_{tot}(n_i)|}, \quad (1)$$

where $\omega_{\mathcal{S}_3}$ and $\omega_{\mathcal{U}}$ are the weighting factors for shared child type-3 UAVs and unique child UAVs, respectively, and $\omega_{\mathcal{U}} = 1 - \omega_{\mathcal{S}_3}$. $\mathcal{N}_{\mathcal{S}_3}(n_i)$ and $\mathcal{N}_{\mathcal{U}}(n_i)$ are sets of the shared child type-3 UAVs of UAV n_i and unique child UAVs of UAV n_i, respectively. From equation (1), if $\mathbf{R}(n_i)$ is greater than or equal to the RDF threshold ($\mathbf{R^{th}}$), UAV n_i determines to be a candidate for the current packet relay. Each UAV received the packet finally determines whether to forward the received packet or not according to the following procedure.

Algorithm 1 Detailed Procedure of Proposed P^2URE Algorithm for Multi-Hop FANET

```
if n_i receives the packet k broadcast by n_p then
    n_i initializes an uncovered neighbor set N_un(n_i) by using N_un(n_i) = S_3(n_i) ∪ U(n_i).
    n_i calculates RDF R(n_i) by using
    R(n_i) = ω_U × |U(n_i)|/|N_tot| + ω_S3 × |S_3(n_i)|/|N_tot(n_i)|.
    if R(n_i) ⩾ R^th then
        n_i calculates P^th(n_i) using
        P^th(n_i) = [ω_P × |N_P(n_i)|]^{-1}.
        if P(n_i) ⩽ P^th(n_i) then
            n_i broadcasts k.
        else
            n_i discards k.
        end if
    else
        n_i discards k.
    end if
end if
```

B. PROBABILISTIC RELAY DECISION

As shown in Fig. 3, if the UAV density of the multi-hop FANET increases, the ratio of the number of shared child type-3 UAVs to the number of unique child UAVs increases exponentially. There is a high possibility of a significant overlap in the transmission areas of the shared child type-3 UAVs compared to that of the unique child UAVs. This coverage overlap may cause rapid battery depletion in UAVs. Thus, to minimize unnecessary transmissions that do not contribute to the coverage probability improvement should be prioritized. In this study, to minimize duplicate relay transmissions without reducing the coverage probability, in the proposed P^2URE method, a probabilistic relay decision method is applied that takes into consideration the UAV density. In particular, UAV n_i, which becomes one of the UAV-R candidates from equation (1), can calculate its relaying probability threshold ($\mathbf{P}^{\mathbf{th}}(n_i)$) as follows:

$$\mathbf{P}^{\mathbf{th}}(n_i) = [\omega_{\mathcal{P}} \times |\mathcal{N}_{\mathcal{P}}(n_i)|]^{-1}. \tag{2}$$

Here, $\omega_{\mathcal{P}}$ is the weighting factor for the number of parents and $|\mathcal{N}_{\mathcal{P}}(n_i)|$ denotes the number of parent UAVs of n_i. If the randomly generated value $\mathbf{P}(n_i) \in [0, 1]$ is less than or equal to $\mathbf{P}^{\mathbf{th}}(n_i)$, then UAV n_i finally becomes a UAV-R. As the number of parents of UAV n_i increases, $\mathbf{P}^{\mathbf{th}}(n_i)$ decreases. That is, the greater the UAV density, the lower $\mathbf{P}^{\mathbf{th}}(n_i)$ is. Through this, coverage overlap problems caused by unnecessary relaying transmissions can be reduced. In addition, $\mathbf{P}^{\mathbf{th}}(n_i)$ can be fine-tuned using $\omega_{\mathcal{P}}$.

The detailed procedure of the proposed P^2URE method is presented in Algorithm 1.

C. NI UPDATE CONSIDERING UAV MOBILITY AND DELAY INTERVAL

NI can be obtained through the NI update process initiated by the source UAV. That is, the source UAV broadcasts a neighbor discovery packet to gather information about the neighboring UAVs before choosing UAV-Rs. Upon receiving the neighbor discovery packet successfully, each UAV sends an ACK packet containing the neighboring UAVs information to the sender. Through the successive NI update procedures, each UAV, including the source UAV, can update NI. In this paper, the above process is called the *NI update process*, and each UAV can acquire the uncovered neighbor information from this process. Subsequently, UAV-R selection are conducted by using the uncovered neighbors set obtained through this process.

Unfortunately, the dynamics of the FANET topology result in frequent and rapid changes in the NI. Thus, if the NI update is not performed according to the network environment changes, the NI inconsistency problem occurs, which results in network performance degradation, as shown in Fig. 4. In this figure, [A-1] represents a case wherein the ($\epsilon+1$)-hop UAVs, which were within the transmission range of the (ϵ)-hop UAV at time step τ_t, move out of the transmission range of the (ϵ)-hop UAV at time step τ_{t+1}, and consequently, cannot receive packets from the (ϵ)-hop UAV. In this paper, the time interval, τ_{t+1} - τ_t, is defined as τ. In the case of [A-2], the (ϵ-1)-hop UAV has no (ϵ)-hop UAVs to receive its packet in τ_t. Hence, it is determined that there is no need to forward the packet. However, the ($\epsilon+1$)-hop UAVs can move into the transmission range of the (ϵ)-hop UAV in τ_{t+1} in practice, which results in coverage probability degradation.

Problems such as [A-1] and [A-2] can be resolved by updating the NI whenever the network environment changes. However, frequent NI updates can cause a significant hardware burden and battery-depletion problems due to overhead in multi-hop FANET environments. In addition, as shown in Fig. 5, it is assumed that the NI update requires β time steps, from *NI update initiation* to *NI update complete*. This also significantly affects the network performance degradation. In this study, α and β are referred to as the *NI update period* and *delay interval*, respectively. Network performance can vary greatly depending on how α and β are determined due to the overhead caused by NI update. Fig. 5 presents the example of the NI update procedure when $\alpha = 5$ and $\beta = 2$. As shown in this figure, the NI information requested to be updated at τ_5 can be applied at τ_7 owing to the delay interval. From τ_2 to τ_6, NI_0, which is the NI information at τ_0, is used to calculate the RDF value, and from τ_7 to τ_{13}, NI_5 is used to calculate the RDF value.

V. PERFORMANCE EVALUATION

This study considered the multi-hop FANET environments. The simulations were conducted on a computer equipped with an i5-12600 CPU 3.30 GHz and 32.0 GB of RAM memory and using a time-driven simulator, MATLAB.

A. SIMULATION ENVIRONMENTS

This section presents five benchmark methods for a performance comparison with the proposed P^{2}URE method. The following provides a detailed description of the benchmark methods considered in this study.

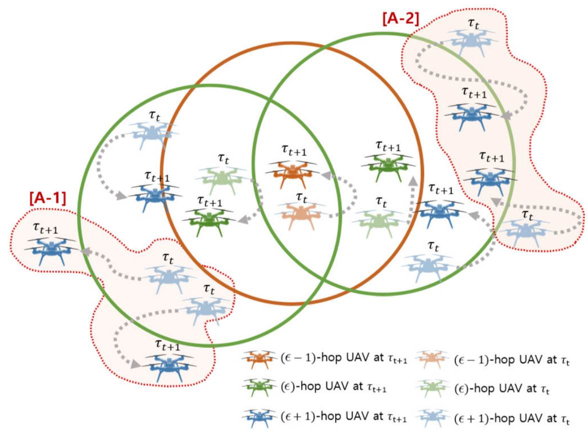


FIGURE 4. NI inconsistency problem in FANET.

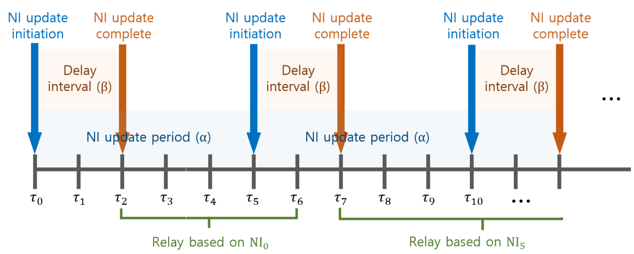


FIGURE 5. NI update period and delay interval.

- **Flooding (FL)**: In the flooding method, each UAV that receives a packet must act as a relay, resulting in the maximum coverage probability among the benchmark and proposed methods. However, this method is highly energy inefficient because it requires all the UAVs within the transmission range of the parent UAVs to act as relays.
- **Probabilistic broadcast (PB)**: Each UAV that receives a packet performs a relay with probability p. This method conducts a relay in a stochastic manner regardless of the UAV conditions. Hence, the performance is unstable.
- **Selected fixed-number relay-X (SFR-X)**: In this method, the (i)-hop transmitter UAV selects a pre-determined number (X) of $(i+1)$-hop UAV-Rs by considering the following conditions.
  1) Transmitter UAV determines the child UAVs with the most uncovered child UAVs as the next-hop UAV-Rs.
  2) If the number of child UAVs with the same number of uncovered child UAVs is greater than X, the transmitter UAV selects the child UAVs with more unique child UAVs among them as the next-hop UAV-Rs.
  3) Excluding the selected UAVs, repeat the above process until X UAV-Rs are filled.

  After that, each $(i+1)$-hop UAV-R selects X $(i+2)$-hop UAV-Rs by considering the above conditions. The above process is repeated until the last hop. This study considers two SFR methods, SFR-3 and SFR-4 wherein $X = 3$ and 4, respectively.
- **NPB [22]:** This neighbor-based probabilistic broadcast method utilizes the UAVs' neighbor information to determine the relaying probability. In detail, based on the adaptive connectivity factors and neighbor information as UAV density changes, it determines packet relays to prevent duplicate packet broadcasts.

To evaluate the performance of the benchmark methods and the proposed P^{2}URE method, this paper takes into consideration several performance metrics such as the total number of packet transmissions (TNT, γ_t), coverage probability (CP, ρ), and energy efficiency (EE, ξ). A detailed description of these performance metrics is presented below:

- **Total number of packet transmissions (TNT, γ_t)**: This is the total number of packet transmissions for all the UAVs. It can also be used as fundamental information for evaluating the network-wide energy efficiency.
- **Coverage probability (CP, ρ)**: This is the ratio of the number of UAVs that received the packet at least once (Φ_r) to the total number of UAVs in the entire network (Φ_{tot}).

$$\rho = \frac{\Phi_r}{\Phi_{tot}}. \tag{3}$$

- **Energy efficiency (EE, ξ)**: This is the ratio of the number of packet receptions (γ_r) to the total number of packet transmissions (γ_t).

$$\xi = \frac{\gamma_r}{\gamma_t}. \tag{4}$$

The simulation begins with UAVs randomly positioned within the network area of 1000 $[m]$ × 1000 $[m]$ and moves according to the modified 3D random walk model at every time step [28]. UAVs can move at an altitude between the minimum UAV altitude of 110 $[m]$ and the maximum UAV altitude of 130 $[m]$. In this model, the position of UAV n_i at each time step (τ) can be expressed as follows:

$$x_i(\tau_t) = x_i(\tau_{t-1}) + v_i(\tau_t)\sin\theta(\tau_t)\cos\phi(\tau_t), \tag{5}$$

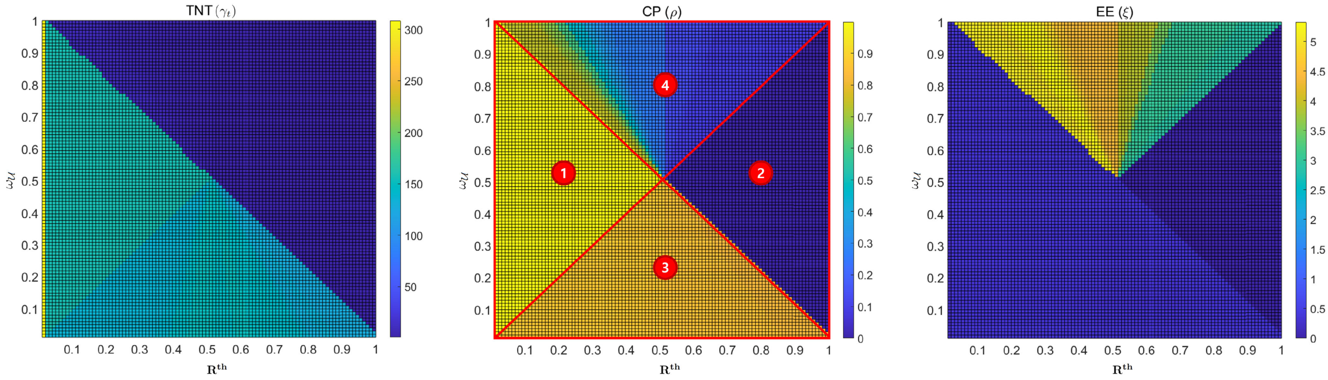
$$y_i(\tau_t) = y_i(\tau_{t-1}) + v_i(\tau_t)\sin\theta(\tau_t)\sin\phi(\tau_t), \tag{6}$$

$$z_i(\tau_t) = z_i(\tau_{t-1}) + v_i(\tau_t)\cos\theta(\tau_t), \tag{7}$$

where $v_i(\cdot)$ $(0 \leqslant v_i \leqslant v_{\max})$, $\theta(\cdot)$ $(0 \leqslant \theta_i < 180^\circ)$, and $\phi_i(\cdot)$ $(0 \leqslant \phi_i < 360^\circ)$ are the moving speed, polar angle, and azimuth angle of UAV n_i, respectively. $v_i(\cdot)$, $\theta_i(\cdot)$, and $\phi_i(\cdot)$ are randomly selected within their specified ranges. The simulation parameters are listed in Table 3.

B. RESULTS AND DISCUSSION

The performance behaviors of the benchmark and proposed P^{2}URE methods are analyzed in terms of the following four



(a) TNT (γ_t) (b) CP (ρ) (c) EE (ξ)

FIGURE 6. (a) γ_t, (b) ρ, and (c) ξ of proposed P²URE method according to variations in $\omega_{\mathcal{U}}$ and $\mathbf{R^{th}}$.

TABLE 3. Simulation parameters.

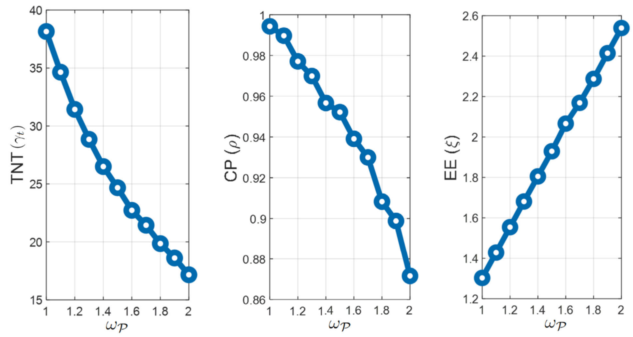
Parameter	Value
Episode	1000
Network area	$1000m \times 1000m$
UAV Transmission range	$300m$
Maximum UAV altitude	$130m$
Minimum UAV altitude	$110m$
Total number of UAVs ($\lvert\Phi_{tot}\rvert$)	50
Weight of shared child type-3 ($\omega_{\mathcal{S}_3}$)	0.5
Weight of unique child ($\omega_{\mathcal{U}}$)	0.5
RDF threshold ($\mathbf{R^{th}}$)	0.1
NI update period (α)	1
Delay interval (β)	5
Maximum UAV speed (v_{max})	$25m/s$
Maximum UAV polar angle (θ_{max})	180°
Maximum UAV azimuth angle (ϕ_{max})	360°

aspects: 1) number of parent and child UAVs, 2) UAV density, 3) UAV speed, and 4) NI update period and delay interval.

1) $\omega_{\mathcal{S}_3}$, $\omega_{\mathcal{U}}$, $\mathbf{R^{TH}}$, AND $\omega_{\mathcal{P}}$

Fig. 6 presents the 3D plot of the three performance metrics (TNT (γ_t), CP (ρ), and EE (ξ)) of the proposed P²URE method for various RDF combinations, wherein the total number of UAVs in the network is 50. To analyze the performance of the proposed P²URE method according to the various weighting factors in Equation (1), the simulation was conducted in an environment in which mobility and probabilistic relays were not considered. In these figures, the x-, y-, and z-axes represent the RDF threshold ($\mathbf{R^{th}}$), unique child ($\omega_{\mathcal{U}} = 1 - \omega_{\mathcal{S}_3}$), and each performance metric, respectively.

As shown in Fig. 6b, each sub-figure in Fig. 6 can be divided into four sub-areas according to the RDF combinations. Sub-area ① represents the case wherein $\mathbf{R^{th}} \leqslant \min(\omega_{\mathcal{S}_3}, \omega_{\mathcal{U}})$. This sub-area has the best CP of 0.99 because a more significant number of UAVs participate in UAV-Rs; however, it has a low EE of 0.32 compared to other sub-areas owing to its considerably high number of packet transmissions. Furthermore, sub-area ② represents the case wherein $\mathbf{R^{th}} \geqslant \max(\omega_{\mathcal{S}_3}, \omega_{\mathcal{U}})$. In this sub-area, stringent selection criteria for relays often result in frequent disruptions in the packet forwarding paths. Hence, the CP converges to almost zero.



(a) TNT (γ_t) (b) CP (ρ) (c) EE (ξ)

FIGURE 7. (a) γ_t versus $\omega_{\mathcal{P}}$. (b) ρ versus $\omega_{\mathcal{P}}$. (c) ξ versus $\omega_{\mathcal{P}}$ of the P²URE method when $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, and $\mathbf{R^{th}} = 0.1$ in multi-hop FANET environments.

Sub-areas ③ and ④ represent the cases wherein $\omega_{\mathcal{U}} \leqslant \mathbf{R^{th}} \leqslant \omega_{\mathcal{S}_3}$ and $\omega_{\mathcal{S}_3} \leqslant \mathbf{R^{th}} \leqslant \omega_{\mathcal{U}}$, respectively. Sub-area ③ has a CP of 0.83-0.87. It can be observed that the shared child type-3 UAVs, which already comprise a significant portion, have no significant influence on the change in CP even if $\mathbf{R^{th}}$ increases owing to $\omega_{\mathcal{S}_3}$ and $\omega_{\mathcal{U}}$. Sub-area ④ has a CP of 0.08-0.74. As $\omega_{\mathcal{U}}$ increases, it frequently occurs that $\mathbf{R}$ of UAV n_i does not exceed $\mathbf{R^{th}}$. Therefore, the CP decreases significantly as $\mathbf{R^{th}}$ increases.

Fig. 7 shows the TNT, CP, and EE against $\omega_{\mathcal{P}}$ of the proposed P²URE method in the multi-hop FANET environments. In particular, the UAVs mobility was not considered, and simulations were conducted under $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, and $\mathbf{R^{th}} = 0.1$. From equation (2), it can be observed that CP decreases as $\omega_{\mathcal{P}}$ increases. Thus, when $\omega_{\mathcal{P}}$ increases from 1 to 2, the TNT is reduced by more than half from 38.15 to 17.17 (see Fig. 7a), but the CP does not decrease significantly from 0.99 to 0.87 (see Fig. 7b), which results in a significant improvement in the EE from

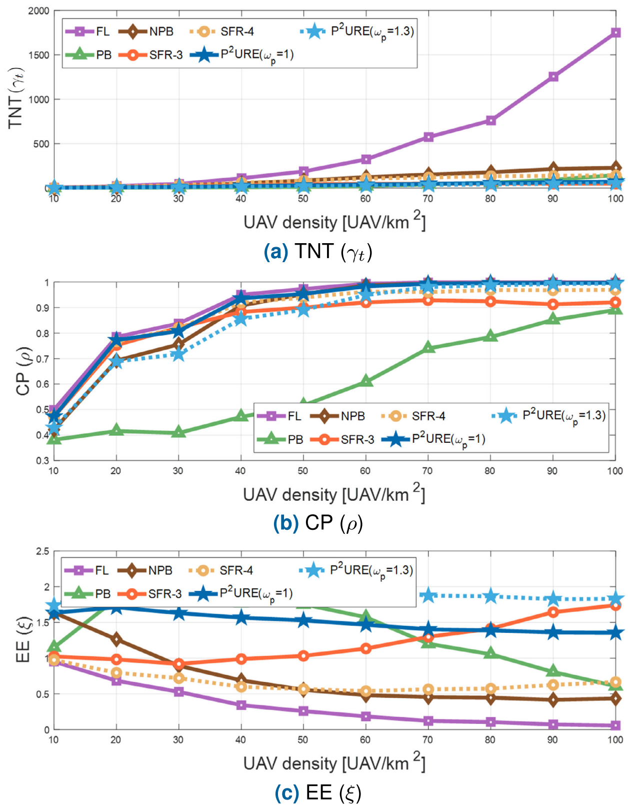


FIGURE 8. **(a) γ_t versus UAV density, (b) ρ versus UAV density, and (c) ξ versus UAV density of the benchmark and proposed methods in multi-hop FANET environments.**

1.30 to 2.15 (see Fig. 7c). Based on this observation, it can be concluded that it is possible to improve EE without causing a significant degradation in the CP.

2) UAV DENSITY

Fig. 8 presents the TNT, CP, and EE versus UAV density of the benchmark and proposed methods in multi-hop FANET environments. These simulation results are obtained by changing the total number of UAVs within the same-sized network from 10 to 100 to analyze the tendency according to the UAV density. As shown in Fig. 3, because the relative ratio of shared child type-3 UAVs and unique child UAVs changes with an increase in the UAV density, the performance of the proposed and benchmark methods is significantly affected by a change in the UAV density.

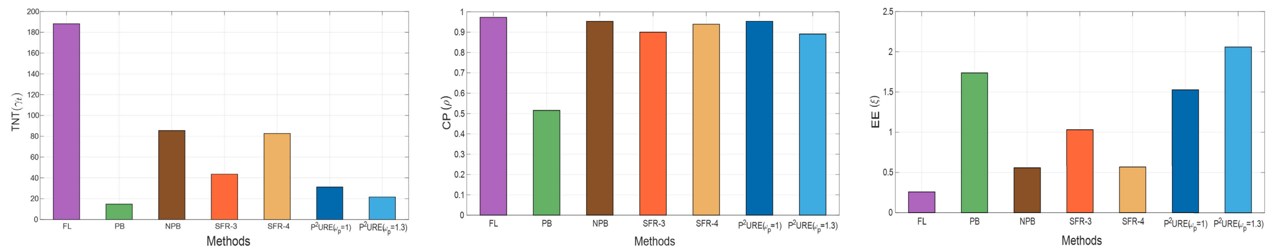
Fig. 8a presents the TNT for each method. From this figure, as the UAV density increases, the TNT of all the methods increases. In particular, because all the UAVs that receive packets perform relays in FL, the TNT increases rapidly compared with other benchmark methods. For example, when the number of UAVs is 100, and the TNT of the FL is 1750.90. With the exception of FL, the other methods provided a smaller TNT in the same environment, not exceeding 250, and it was observed that NPB, SFR-4, PB, P^{2}URE ($\omega_{\mathcal{P}} = 1$), SFR-3, and P^{2}URE ($\omega_{\mathcal{P}} = 1.3$) have TNTs are in the descending order. As SFR-3 and SFR-4 select a fixed number of relays, TNT does not increase significantly, irrespective of the UAV density. Moreover, it is worth noting that the proposed P^{2}URE method has a TNT greater than SFR-3 and less than SFR-4.

From Fig. 8b, it can be observed that FL has the highest CP among all the methods because all the UAVs receiving packets participate in relaying. The CP value of the proposed P^{2}URE ($\omega_{\mathcal{P}} = 1$) method closely follows that of the FL method. Furthermore, the proposed P^{2}URE ($\omega_{\mathcal{P}} = 1.3$) method exhibits a relatively low CP when the number of UAVs is small owing to its small relaying probability. However, above 70, it gradually converges to FL, and when the number of UAVs is 100, P^{2}URE ($\omega_{\mathcal{P}} = 1$) and P^{2}URE ($\omega_{\mathcal{P}} = 1.3$) have a CP of 0.9974 and 0.9935, respectively. When the number of UAVs is 100, NPB has a high CP of 0.9969 due to its high TNT of 229.37, which is the second largest value after FL. Although SFR-3 and SFR-4 have similar TNTs, because the number of relays is fixed and limited, their CPs approximately converge to 0.9206 and 0.9604, respectively. In addition, the PB method exhibits a high CP when the number of UAVs is large, but a low CP in an environment wherein the number of UAVs is small.

Fig. 8c presents EE versus UAV density of the benchmark and proposed P^{2}URE methods. NPB shows a good CP with a large number of UAVs but has the lowest EE after FL due to a high TNT of 200 or more. Both SFR-3 and SFR-4 exhibit a significantly lower TNT than FL, which results in a more significant improvement in the EE compared to FL. P^{2}URE ($\omega_{\mathcal{P}} = 1.3$) has a slightly smaller CP than P^{2}URE ($\omega_{\mathcal{P}} = 1$), but also has a smaller TNT; therefore it has the highest EE value among the benchmark and proposed methods.

3) UAV SPEED

The performance of multi-hop FANETs is heavily influenced by the speed of UAVs. To evaluate the effects of different UAV speeds, tcbwe varied the maximum speeds of UAVs from 5 m/s to 25 m/s under 50 UAVs, $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, $\mathbf{R}^{\mathbf{th}} = 0.1$, and $\omega_{\mathcal{P}} = 1$. Table. 4 and Fig. 9 present the TNT, CP, and EE of the proposed P^{2}URE and benchmark methods according to variations in the UAV speed. As the speed increases, the NI becomes inaccurate owing to topological variations, which cause transmission failure. Thus, as the UAV's speed increases, the TNT and CP of all the methods decrease, as shown in Table 4 and Fig. 9. In the case of FL, the performance degradation caused by an increase in the UAV's speed can be effectively minimized because every UAV that receives packets actively participates in relaying. This characteristic contributes to the maintenance of a relatively stable performance even at high speeds. In contrast, the CP of SFR-3 and SFR-4 suffered significant degradation from 0.98 and 0.99 when $v_{max} = 5$ m/s to 0.89 and 0.93 when $v_{max} = 25$ m/s. These values represent 9.2% and 6.1% performance reductions, respectively. Similarly, the CP performance of NPB reduces by 4.0% when v_{max} increases from 5 m/s to 25 m/s. The proposed P^{2}URE ($\omega_{\mathcal{P}} = 1$) method achieves a CP performance that is highly comparable to FL,

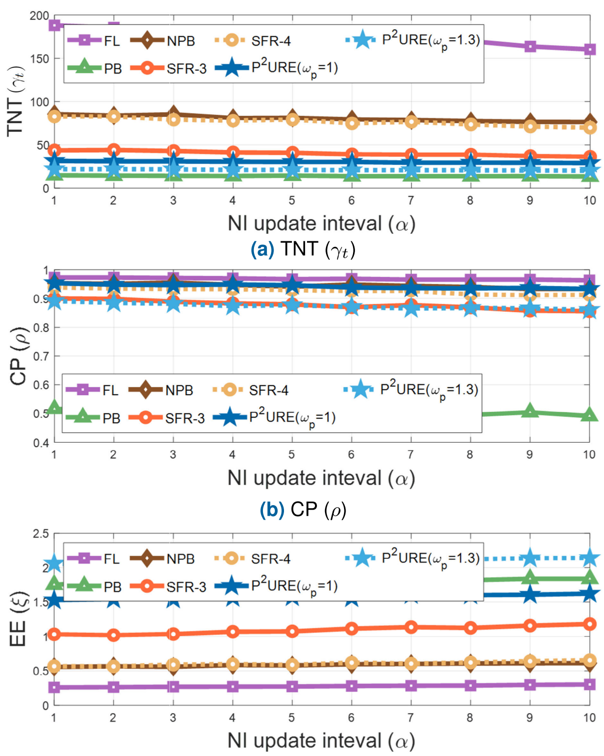


(a) TNT (γ_t) (b) CP (ρ) (c) EE (ξ)

FIGURE 9. (a) γ_t versus method, (b) ρ versus method, (c) ξ versus method under 50 UAVs, $v_{max} = 25\ m/s$, $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, and $R^{th} = 0.1$.

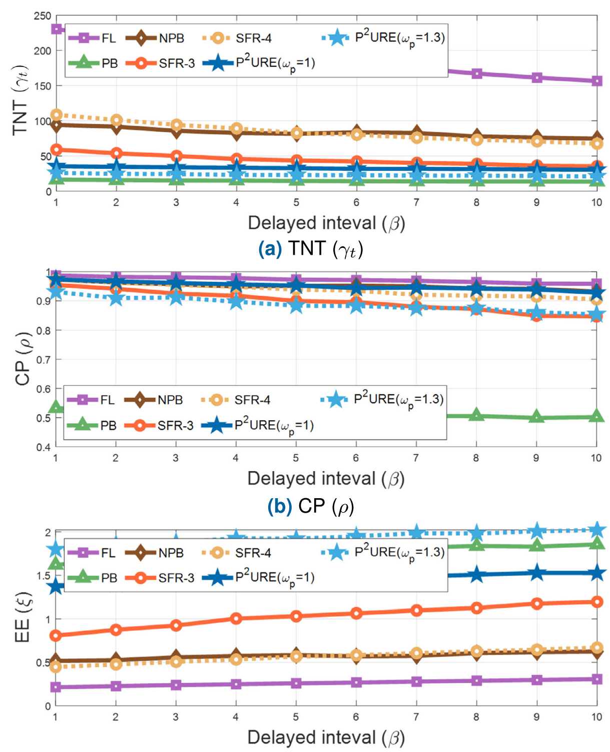
TABLE 4. γ_t, ρ, and ξ of proposed P^{2}URE and benchmark methods according to variations in UAV speed ($v_{max} = \{5, 10, 15\ m/s\}$) under 50 UAVs, $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, and $R^{th} = 0.1$.

Methods	$v_{max} = 5\,[m/s]$			$v_{max} = 10\,[m/s]$			$v_{max} = 15\,[m/s]$		
	TNT (γ_t)	CP (ρ)	EE (ξ)	TNT (γ_t)	CP (ρ)	EE (ξ)	TNT (γ_t)	CP (ρ)	EE (ξ)
FL	266.8600	0.9939	0.1862	215.7040	0.9941	0.2304	206.5850	0.9893	0.2394
PR	18.5260	0.5914	1.5962	15.4270	0.5109	1.6558	15.3560	0.5192	1.6907
SFR-3	67.3550	0.9829	0.7297	58.4360	0.9673	0.8277	53.7270	0.9523	0.8862
SFR-4	124.2690	0.9906	0.3986	107.9790	0.9796	0.4536	99.7210	0.9746	0.4887
NPB	107.8780	0.9924	0.4600	92.2760	0.9856	0.5340	87.5820	0.9764	0.5574
P^{2}URE ($\omega_{\mathcal{P}} = 1$)	37.2730	0.9916	1.3302	34.4150	0.9816	1.4261	32.6270	0.9774	1.4978
P^{2}URE ($\omega_{\mathcal{P}} = 1.3$)	27.3290	0.9622	1.7604	24.7740	0.9338	1.8846	23.6190	0.9312	1.9713



(a) TNT (γ_t) (b) CP (ρ) (c) EE (ξ)

FIGURE 10. (a) γ_t versus α, (b) ρ versus α, (c) ξ versus α of benchmark and proposed methods under 50 UAVs, $v_{max} = 25\ m/s$, $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, and $R^{th} = 0.1$.



(a) TNT (γ_t) (b) CP (ρ) (c) EE (ξ)

FIGURE 11. (a) γ_t versus β, (b) ρ versus β, (c) ξ versus β of benchmark and proposed methods under 50 UAVs, $v_{max} = 25\ m/s$, $\omega_{\mathcal{U}} = 0.5$, $\omega_{\mathcal{S}_3} = 0.5$, and $R^{th} = 0.1$.

while exhibiting a remarkable improvement in the EE. The RDF and probabilistic relay decision of the proposed P^{2}URE method contribute to enhancing adaptability to environmental changes.

4) NI UPDATE PERIOD AND DELAY INTERVAL

Figs. 10 and 11 present the TNT, CP, and EE against the NI update period and delay interval, respectively. Because the FANET topology is dynamic, a large α and β result in NI inaccuracy, which causes the degradation of CP. In addition, topological variations make the relay selection more difficult, which also results in a decrease in the TNT. Irrespective of the variations in α and β, P^{2}URE ($\omega_{\mathcal{P}} = 1$) and P^{2}URE ($\omega_{\mathcal{P}} = 1.3$) have a greater EE compared to the benchmark methods. Especially, P^{2}URE ($\omega_{\mathcal{P}} = 1.3$) exhibits an excellent EE performance owing to its transmission efficiency. From these figures, in the case of the application of the proposed P^{2}URE method in practice, it can be observed that the compactly designed NI update procedure significantly affects the FANET performance.

5) DISCUSSION

In summary, it was shown that various performance results of P^{2}URE can be derived depending on the combinations of $\omega_{\mathcal{S}_3}$, $\omega_{\mathcal{U}}$, $\mathbf{R^{th}}$, and $\omega_{\mathcal{P}}$. That is, it is possible to derive adaptive and multifaceted simulation results according to various network environments and system requirements. Various packet forwarding methods were considered as benchmark algorithms, and network-wide performance comparisons were conducted according to the variations in UAV density, UAV speed, NI update period, and delay interval in FANET. Simulation results demonstrated the robustness of the proposed P^{2}URE method with respect to the coverage probability even in network environments with high/low UAV density and very fast UAV speed. In addition, it is confirmed that energy-efficient operation is possible by reducing the number of duplicate packet transmissions without the degradation of coverage probability through $\omega_{\mathcal{P}}$ of the probabilistic relay decision method.

VI. CONCLUSION

This paper proposed a P^{2}URE method to facilitate data dissemination in multi-hop FANETs. P^{2}URE takes into consideration uncovered neighbors (shared child type-3 UAVs and unique child UAVs) as relay candidates, and the RDF and probabilistic relay decision of the proposed P^{2}URE contribute to reducing unnecessary packet relays without degrading the CP performance. To measure the performance of the benchmark and proposed methods, this paper considered the TNT, CP, and EE as performance metrics. Furthermore, using variations in the UAV density, UAV speed, and NI update period and delay interval, we conducted a performance comparison of the proposed P^{2}URE method with several benchmark methods such as FL, PB, SFR-3, and SFR-4. From the simulation results, this paper demonstrated that P^{2}URE outperforms the benchmark methods and is adaptable to dynamic environmental changes. Furthermore, the compact design of the NI update procedure is crucial in multi-hop FANETs. For further work, additional investigation considering packet transmission/reception overhead and channel error rate is still needed to improve the applicability of the proposed approach. Moreover, to achieve energy-efficient FANETs, it is advisable to consider the application of distributed deep reinforcement learning techniques.

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(Yerin Lee and Jimin Jeon contributed equally to this work.)

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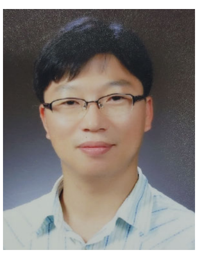

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