Performance Analysis of ERS Techniques for Next-Generation Opportunistic Networks

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***Abstract*—In next-generation networks, mobile devices are equipped with Machine-to-Machine (M2M) communication modules that allow them to interact, self-configure, and communicate with other mobile devices without relying on pre-installed fixed network infrastructure (the so-called opportunistic networks). The combination of opportunistic networks and Internet infrastructure creates unprecedented new capabilities and applications. However, this hybrid architecture also faces challenges, including performance, energy savings, delay, and security. Typical opportunistic network architecture is Mobile Ad hoc Networks (MANETs) and Flying Ad Hoc Networks (FANET). MANETs are a collection of mobile devices equipped with D2D modules to communicate directly with each other mobile nodes without relying on base stations or access point infrastructure. Flying Ad Hoc Networks (FANET), or Drones, are gaining popularity due to their cost-effectiveness, efficiency, and advanced capabilities. Due to the mobility nature of mobile nodes in opportunistic networks, the source nodes use the route discovery procedure to determine an optimal route to the destination node. Several improved ERS techniques have been proposed to enhance performance and reduce the power consumption of opportunistic networks. In this paper, we conduct a detailed analysis of the proposed varying of Expanding Ring Search (ERS) algorithms and consider the performance of these techniques. Experimental results show that the Enhanced BERS technique (EBERS) algorithm significantly improves the energy consumption compared to ERS-based algorithms in large network scales. Finally, we provide some recommendations to selecting suitable ERS techniques with different network scales.**

***Keywords*—Opportunistic Networks (ONs), 5G, Flying Ad Hoc Networks (FANET), Mobile Ad hoc Networks (MANETs), expanding ring search**

I. INTRODUCTION

Opportunistic Networks (ONs) refer to a group of mobile devices that possess the ability to self-configure and establish parameters to connect and exchange data efficiently without the need for base stations [1, 2]. The ONs, similar to mobile radio networks, have demonstrated exceptional advantages in providing communication services through adaptable infrastructure, despite their limited capacities and capabilities. According to Wheeb *et al.* [3], Dobson *et al.* [4], Naser and Wheeb [5], it is expected to make significant contributions to the future development of the Internet. Fig. 1 illustrates the architectural model of ONs.

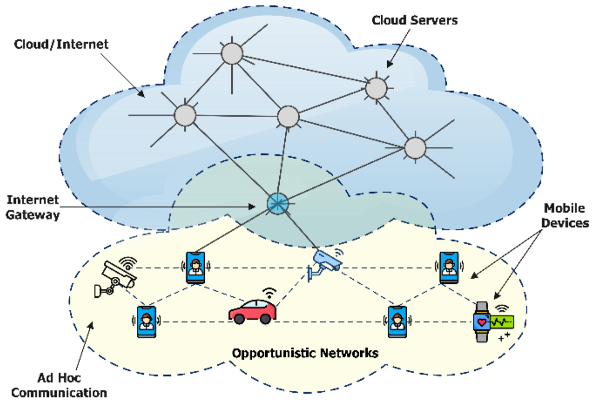

Figure 1. An illustration of the Opportunistic Networks (ONs) model.

The typical architectures of ONs are mobile ad hoc networks and Flying Ad Hoc Networks [6]. In general, due to the mobility of the network nodes in wireless communication environments, disconnection frequently happens [7, 8]. This is the main cause of rerouting and retransmission, leading to increased energy consumption and overall system performance degradation [9]. To solve this problem, different routing solutions have been proposed in [10, 11].

On the other hand, Unmanned Aerial Vehicle systems can operate autonomously or can be remotely controlled. The utilisation of a singular drone system is a prevalent practice [12, 13]. The limited functionality of a single drone system hinders its potential for broader applications. The demand for constructing a multi-drone system to enhance operational efficiency by enabling collaboration among multiple drones has become a crucial requirement.

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In wireless network environments, routing approaches can be classified relying on routing techniques or network architectures. According to the network architecture, the routing approaches are classified into flat, hierarchical, and geographic-based routing approaches. According to the routing techniques, the routing approaches are classified into active and on-demand-based routing approaches [14]. Zhang *et al.* [15] have demonstrated that, the reactive-based routing approach provides more efficient energy and effectiveness compared to the active-based routing approach. Two typical reactive routing algorithms that have been proposed by Internet Engineering Task Force (IETF) for MANETs are Ad Hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) protocol [16, 17].

A. Related Works

The traditional approach of these reactive routing solutions is invoking the route discovery procedure via the RREQ control packets by broadcasting from the source node, also known as the Expanding Ring Search (ERS) technique. Indeed, to identify the path from the source node to the destination node in these networks, the reactive routing protocols use the ERS technique to broadcasting Route Requests (RREQ).

Durr-e-Nayab *et al.* [18] proposed a novel routing method based on ERS, machine learning, and random early detection techniques to improve performance and quality of service (QoS) for MANETs. The simulation results show that the proposed solution enhances performance and energy efficiency compared to the traditional solutions.

Pu *et al.* [19] proposed an advanced ERS technique. This method allows network nodes to make STOP/END instructions to block expanding ring search aiming to terminate flooding. The simulation results show that the proposed method improves energy consumption and performance compared to the existing ERS-based methods.

Gwak *et al.* [20] propose two flood-cancellation solutions based on the BERS technique for MANETs by broadcasting the cancellation packet. However, the authors also indicate that flooding cancellation by the broadcasting packet can be another factor of the broadcasting storm, hence, the performance of the solution on depending density and network scales.

The ERS technique is a method where the source node initiates the broadcasting of the RREQ packet to perform a search using multiple rounds. However, this process will not be successful if the destination node cannot be located. This process can potentially result in a substantial depletion of energy resources. In order to address this issue, several advanced ERS techniques have been recently proposed to improve the efficiency and energy usage of next-generation ONs.

B. Motivations and Main Contributions

Firstly, despite the research efforts, most existing solutions [18–20] for MANETs, and FANETs are using advanced AODV or DSR-bassed routing protocols. These protocols use ERS technique to find neighboring nodes in the route discovery procedure. To the best of our knowledge, no study is currently testing the energy efficiency of advanced ERS techniques in ONs. Secondly, in the IoT era, the architecture of networks is scale-large and heterogeneous. Hence a flexible switching method between advanced ERS techniques under different network scales is urgent. Furthermore, it is crucial to thoroughly investigate the switching process between various ERS techniques in ON networks.

Motivated by these limitations, we here modeled the advanced ERS techniques. Then, we evaluate the energy efficiency of advanced ERS techniques and give recommendations for selecting fit ERS techniques. In summary, the contributions of this article are highlighted as follows:

- We provide a literature review of ERS algorithms in the discovery of neighboring nodes for ONs.
- We model and analyze the energy efficiency of different ERS algorithms.
- We consider the energy efficiency of ERS and EBERS and provide recommendations for selecting suitable ERS techniques with different network scales.

C. Paper Structure

The rest of the paper is presented as follows. Section II presents the technique of expanding the search rings. Section III describes the Blocking ERS technique. In Section IV, we consider the energy efficiency of varying broadcast algorithms, and Section V is the conclusion.

II. EXPANDING RING SEARCH TECHNIQUE

Aiming to prevent unnecessary broadcasting of RREQ packets to the network during route discovery, reactive routing protocols such as AODV [21] or DSR [22] use ERS technique. In this section, we perform a deep analysis of ERS technique.

In the route discovery progress, the source node broadcasts the RREQ packet according to increasingly larger rounds to identify the destination node. Aiming to prevent unnecessary broadcasting of RREQ packets throughout the network, reactive routing protocols use the ERS technique.

Fig. 2 describes ERS technique. In this progress, the source node S uses ERS technique to broadcast the RREQ packet in-network to search the feasible routes to destination node D. In the 1st round of search, S has 5 neighbours with $hops = 1$, RREQ packet is sent to these 5 nodes. After a period of RTT (Round Trip Time), the S node does not be received the route information, the S node needs to perform re-broadcasting the RREQ packet with the hops increment 1. While the nodes in round 1 can be received the RREQ packet again, and then they will continue broadcasting RREQ packets to 2nd round of search. In the second search round, N is the node that has information about the route to the destination node. Therefore, N sends the RREP packet to the source node S by unicasting. Then, the data transfer process between the source node S and the destination node D can be initiated.

In this technique, the source node initializes the Time-To-Live (TTL) value and RTT in the header of the RREQ packets. If the RTT expires and no route is found, the source node re-broadcasts the RREQ packet to the larger search round by incrementing the TTL value. The process of increasing the TTL is repeated until the TTL reaches a certain threshold or the RREQ packets are broadcasted to the entire network. The route search by incrementing the TTL parameter to extend the search round starting from the source node can cause overload and waste resources, especially in scale-large networks.

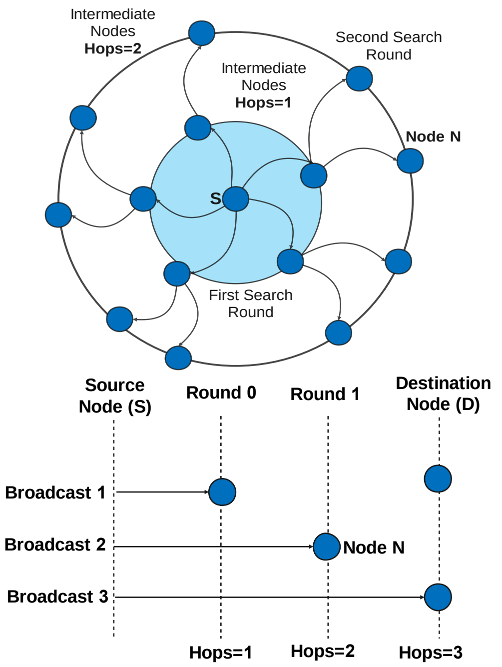

Figure 2. An illustration of the TTL-based ERS technique.

III. Blocking ERS Technique

In order to improve the ERS technique, the Blocking ERS (the so-called BERS) is proposed to reduce energy consumption by improving the RREQ control packet broadcast mechanism [23]. Instead of using a TTL sequence number, BERS uses a process control packet, denoted END, that stores the maximum number of hops, denoted H.

The route discovery process of BERS is similar to that of ERS, except that, for each subsequent search round, BERS does not resend broadcast packets from source node S, but the RREQ broadcast sending process is initialized at intermediate nodes. Each intermediate node will act as a source node S and perform the job of broadcasting to the next search round.

Fig. 3 describes the process of broadcasting RREQ control packets based on the BERS technique. Specifically, the source node broadcasts an RREQ packet containing information about the hop number H, which has an initial value of 1. Neighbours in the first round will receive an RREQ packet with $H = 1$ and the first search round is set. If no route is found, after waiting for time T, nodes on 1st round continue to broadcast the RREQ packet with hop index H increased ($H = 2$), and the search cycle continues extended as the ERS technique. The waiting time T is determined as follows:

$$T = 2 \times Hoptime \quad (1)$$

where $Hoptime$: defined is the period to transmit a packet in a hop.

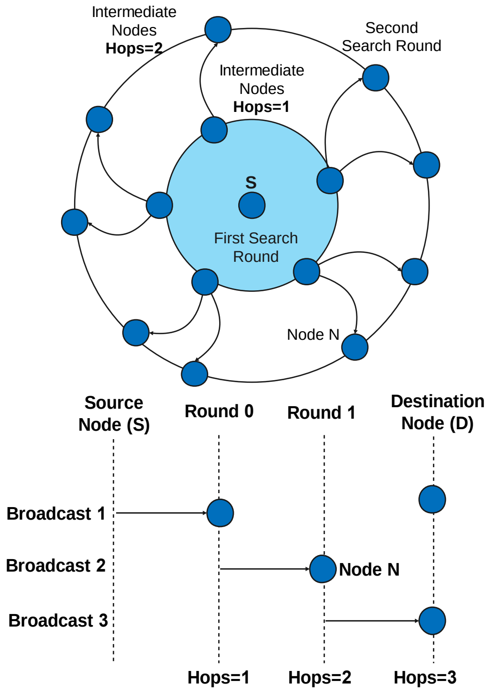

Figure 3. An illustration of the BERS technique.

The 2nd round of search is established after no route returns in period T. Assuming that node N of the 2nd search round stores a route to the destination node. Hence, node N sends the RREP packet to the source node by unicasting. When the source node S received an RREP packet that determines a feasible route to the destination node, the RREQ broadcast process should be stopped. To solve this issue, S broadcasts the END packet according to the TTL-based ERS technique to all nodes that have the same hop number as the first RREP packet returned.

Aiming to barrier the flooding broadcast RREQ packets in cases where no route is found, Pu *et al.* [24] proposed an advanced BERS-based technique, the so-called Enhanced BERS technique ($EBERS$). Specifically, in this EBERS technique, the source node inserts maximum travel information (H_{max}) into the RREQ packet header. When an intermediate node receives the RREQ packet, this node compares the H and H_{max} values, if $H > H_{max}$, the RREQ packet is immediately dropped. To develop the above idea, the authors have built four algorithms, specifically as follows.

Algorithms 1 and Algorithms 2 are deployed at source and intermediate nodes, respectively, while Algorithms 3 and Algorithms 4 deal with the problem of limitations the ERS technique.

Algorithm 1. Mobile Source Node

1: Broadcast RREQ packets, establish ($H = 1$; H_{max}) values
2: Waiting for the source node to receive RREP packets or $H_{now} = H_{max}$ (expired time)
3: If $RREP \neq \emptyset$ Then
4: Broadcast END (consists of H_r value) to the same as ring search, H_r;
//(The ring search of the first RREP packet);
5: Establish the data transmission processing;
6: Discard incoming RREP packets;
7: End If

Algorithm 2. Intermediate Nodes

1: **If** Received the RREQ packet **then**
2: Invoke RREQ Procedure;
3: **End if**
4: **If** Received the RREP packet **then**
5: Unicast Reply RREP packet;
6: **End if**
7: Waiting END packet
8: **If Received** END packet **then**
9: Invoke END Procedure;
10: **End if**

Algorithm 3. RREQ Procedure

1: **If** ($H_{RREQ} > H_{max}$) **then**
2: Discard RREQ packets
3: Remove the S-D path in its cache
4: E**lse**
5: **If** (Exists a route in the cache) **then**
6: Unicast Reply RREP packet (including H_r) to the destination node
7: E**lse**
8: Waiting a period $T = 2\ x\ Hoptime$
9: **While** T **do**
10: **If** Received END packet **then**
11: Invoke END Procedure
12: **Else If** Received the RREP packet **then**
13: Forwarding RREP packet
14: E**nd if**
15: **End while**
16: **If** (No received END, RREP packets then a period T) **then**
17: (Update the value for H_{RREQ})&(Broadcast send RREQ)
18: **End if**
19: E**nd if**
21: **End if**

Algorithm 4. END Procedure

1: **If (**Received END)&($H_{END} \leq H_r$) **then**
2: Forwarding END packet
3: **Else**
4: Discard the END packet
5: **End if**
6: Remove the S-D path in its cache
7: End Procedure

IV. Performance Evaluation

To assess the effectiveness of the proposed techniques and their adaptability to new-generation ONs in terms of network density and scale, we used MATLAB software version 8.5 to evaluate the energy efficiency of the EBERS technique. The main parameters used for this evaluation are summarized in Table I. The detailed issues are presented as follows.

TABLE I. Simulation Parameters

Parameter	Value
Area	5,000×50,000 m^2
Number of Nodes	[0–1000]
Number of Hops	[0–20]
Radio Type	802.11b
Data Rate	2 Mbps
Amount of consumed energy to send a packet	1DV
Packet Size	512 Bytes
Traffic Type	CBR
Radio type	802.11 b
Channel frequency	2.4 GHz
Simulation Time	300 (s)

A. *Analysis of Energy Effectiveness*

For the EBERS technique, the consumed energy during the route discovery process can be considered as the total of the $States$ 03:

1) Search for a node with route information, denoted by EBERS_{Enery1};
2) Send the RREP packet by unicasting to the source node, denoted EBERS_{Enery2}.
3) Send the END packet to request the end discovery process, denoted EBERS_{Enery3}.

For the ERS technique, the consumed energy during the route discovery process can be considered as the total of the $States$ 02:

1) Search for a node with route information, denoted by ERS_{Enery1}.
2) Send the RREP packet by unicasting to the source node, denoted ERS_{Enery2}.

— Let H_r be the number of hops from the source node to the destination node;
— n_i is the number of nodes at the i^{th} search round ($i = 1, 2, ..., H_r - 1$).

We assume that the amount of consumed energy per node when performing tasks of broadcast and unicast send packets such as RREQ, RREP, and END is the same, and is 1 unit of energy, denoted as $1DV$ unit. Obviously, the process of replying the RREP packet to the source node is the same in both techniques, so the energy consumption in the $States$ 02 for both techniques is the same, calculated as follows.

$$ERS_{Enery2} = \text{EBERS}_{Enery2} = n_r x H_r \quad (2)$$

where, n_r is the number of nodes that store the route information to the source node at r^{th} search round.

At $States$ 01, we can model the amount of consumed energy of by mathematic equations, as follows.

$$ERS_{Enery1} = H_r + \sum_{i=1}^{H_r-1} \sum_{j=1}^{i} n_j \quad (3)$$

$$EBERS_{Enery1} = 1 + \sum_{i=1}^{H_r-1} n_i \quad (4)$$

where, n_j is the number of nodes that store the route information to the source node at j^{th} search round.

At $State$ 03 of the EBERS techniques, the source node will broadcast the END packet to all network nodes in the coverage range that has a number of hops less than H_r, according to the TTL-based ERS techniques, so the energy consumption can be modelled by the following equation.

$$EBERS_{Enery3} = 1 + \sum_{i=1}^{H_r-1} n_i \quad (5)$$

Finally, the total amount of energy consumption during the route discovery process of these techniques can be determined as follows.

$$ERS_{Enery} = H_r + \sum_{i=1}^{H_r-1} \sum_{j=1}^{i} n_j + n_r x H_r \quad (6)$$

$$EBERS_{Enery} = 2x(1 + \sum_{i=1}^{H_r-1} n_i) + n_r x H_r \quad (7)$$

$$E_{save} = H_r - 2 + \sum_{i=1}^{H_r-1}((\sum_{j=1}^{i} n_j) - 2n_i) \quad (8)$$

Eq. (8) presents the energy efficiency of the EBERS technique compared to ERS technique. Obviously, Eq. (8) presented that, in a scale-small network environment, when the number of network nodes or a low number of hops, the energy effectiveness of the EBERS technique is not highlighted compared to ERS technique, even in some cases $E_{save} \leq 0$, when that, ERS should be deployed. Opposite, in a scale-large network environment, the number of network nodes or the number of hops is high, and the energy effectiveness of the EBERS technique ($E_{save} \geq 0$) is outstanding compared to ERS technique, when that, EBERS should be deployed. A comparison the amount of energy consumption between ERS and EBERS techniques is presented in Table II.

TABLE II. A COMPARISON THE ENERGY CONSUMPTION BETWEEN ERS AND EBERS TECHNIQUES

ERS		EBERS	
Round	Energy Consumption	Round	Energy Consumption
0	1	0	1
1	$1 + n_1$	1	n_1
2	$1 + n_1 + n_2$	2	n_2
⋮	⋮	⋮	⋮
$H_r - 1$	$1 + n_1 + n_2 + \cdots + n_{H_r-1}$	$H_r - 1$	n_{H_r-1}

B. Simulation Scenarios

To highlight the relationship between energy efficiency, the number of network nodes (density) and the number of hops (network scale), we use MATLAB software to consider the effectiveness of the ring search techniques on a $3D$ graph, as presented in Fig. 4.

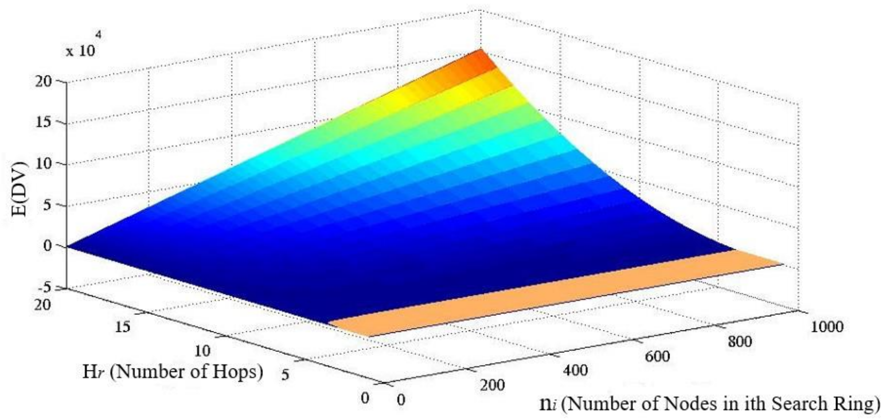

Figure 4. The relationship between node density, and network size with energy efficiency of the EBERS technique.

Simulation results indicated that the scale-large networks, the number of hops ($H_r > 7$) and the number of nodes over 200 will result in $E_{save} > 0$. Moreover, the energy efficiency E_{save} rapidly increases when node density and network size increase. Contrastly, when $H_r < 7$ or the number of nodes is less than 200 nodes, $E_{save} < 0$, this shows that EBERS is not effective for small-scale networks. In these scenarios, ERS or BERS techniques should be deployed.

Obviously, the E_{save} of the system is proportional to the size and density of the network. Energy efficiency increases rapidly when the network is large-scale and densely distributed. Besides advantages, a key limitation of the EBERS technique is it can miss destination nodes in some complex network architecture cases.

Recently, graph-based deep learning techniques have proven outstanding effectiveness to solve communication problems in MANET and FANET. For example, Wang *et al.* [25] propose a graph neural network (GNN)-based approach to select efficient and scalable routes for FANETs. Li *et al.* [26] applied GNN to model the internetwork structure to a graph structure to achieve the optimal routes at a low cost to FANETs. Jiang [27] present a comprehensive survey of applied graph-based deep-learning techniques to address communication issues in networks. In our opinion, the selection of the H_{max} value of the EBERS technique should be determined based on edge and fog computing solutions and deep learning techniques [28–30].

V. Conclusion

Opportunistic Networks are gaining prominence as a viable solution in the realm of next-generation networks, particularly in the context of Internet of Things, 5G and beyond mobile networks. The self-configuration, self-establish, and self-communication capabilities allow ONs to be widely applied in most domains to serve humans. However, energy efficiency will still be a specific challenge in ONs. One of the most energy consumption operations of ONs is the broadcast of RREQ control packets. In this work, we analyze advanced RREQ control packet broadcast techniques.

Analyses have shown that, for ONs networks with low size and density (when $H_r < 7$ or the number of nodes is less than 200 nodes), ERS technique should be used. In contrast, for ONs with large scale and high density ($H_r > 7$ and the number of nodes over 200), the EBERS technique should be used. To clarify the energy efficiency, we perform simulations on MATLAB. The simulation results again demonstrate the correctness of theoretical analysis that the EBERS technique improves significantly energy efficiency compared to the ERS technique with large-scale ONs.

We anticipate widespread adoption of the EBERS technique for the ONs of future IoT systems. Future works will concentrate on evaluations and analyses in real-world settings, with prototypes set up in various situations.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, N.M.Q., D.M.L., and D.V.A; methodology, N.M.Q., A.C., D.M.L., D.V.A.; software, D.V.A., P.D.K., and D.M.L.; validation, N.M.Q., A.C., and D.M.L.; formal analysis, N.M.Q.; investigation, N.M.Q. and D.M.L.; resources, N.M.Q., D.V.A., P.D.K., and D.M.L.; writing—original draft preparation, N.M.Q., D.M.L., and D.V.A.; writing—review and editing, N.M.Q., D.V.A., and A.C.; visualization, N.M.Q., D.V.A., P.D.K., and D.M.L.; supervision, N.M.Q., A.C., and D.V.A.; project administration, N.M.Q., D.V.A, D.M.L., and A.C. All authors have read and agreed to the published version of the manuscript.

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