SPECIAL SECTION ON FUTURE NETWORKS: ARCHITECTURES, PROTOCOLS, AND APPLICATIONS

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 30, 2017, accepted February 23, 2017, date of publication March 20, 2017, date of current version May 17, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2684912

OEFS: On-Demand Energy-Based Forwarding Strategy for Named Data Wireless Ad Hoc Networks

RANA ASIF REHMAN[1], (Member, IEEE), SYED HASSAN AHMED[2], (Member, IEEE), AND BYUNG-SEO KIM[3], (Member, IEEE)

[1]Department of Computer Science, National University of Computer and Emerging Sciences, Chiniot-Faisalabad Campus, 35400, Pakistan
[2]School of Computer Science and Engineering, Kyungpook National University, Daegu 41566, South Korea
[3]Department of Computer and Information Communication Engineering, Hongik University, Sejong City 30016, South Korea

Corresponding author: B.-S. Kim (jsnbs@hongik.ac.kr)

This work was supported in part by the basic science Research Program through the National Research Foundation of Korea funded by the Ministry of Education under Grant 2015R1D1A1A01059186, in part by the International Science and Business Belt Program through the Ministry Of Science, and in part by the ICT and Future Planning under Grant 2016K000280.

ABSTRACT The futuristic Internet paradigm, named data networking (NDN), was recently introduced to solve the severe issues of current Internet architecture, such as complex usage, poor resource utilization, inefficient mapping, scalability, location dependence, and so on. Communication in NDN is based on content names decoupling from their locations. NDN also provides strong built-in functionalities, like multi-path routing, security primitives, flow balance mechanisms, and in-networking caching. Similarly, NDN-based mobile ad hoc networks are highly dynamic in nature whereby the participating nodes have experienced highly challengeable environments and constraints, such as channel fluctuations, intermittent connectivity, and low battery power. In this environment, if a node has limited residual energy, after sending a few packets, it will die soon. Furthermore, all of its pending request entries are also destroyed, which further exacerbates the communication process. To cope with this problem, we have proposed a novel protocol called the on-demand energy-based forwarding strategy (OEFS) that takes the residual energies of the nodes into account during the entire communication process. For the performance evaluations, we have used NDNSIM, which is specially designed for NDN-based networks. The simulation results show that the our OEFS outperform the existing state-of-the-art protocol in terms of content download time, interest retransmissions, the total number of Interest propagation, and data redundancy in the network. We also find the effect of OEFS on the energy threshold and show that OEFS enables mobile nodes to consume less amount of energy.

INDEX TERMS Energy, content, interest, wireless, named data networking, information centric.

I. INTRODUCTION

Due to the fast proliferation of technologies, the latest wireless devices have evolved. These devices have embedded features, such as browsing, media players, cameras, and messages, which make them like multimedia devices [1]. Today, the major part of Internet traffic consists of video streaming, web browsing, photo sharing, and music, and according to a Cisco report [2], these types of traffic increased eight times over the past five years. According to Google [3], a total of more than 1 trillion unique URLs have been processed and in the past three years, the number of domain names doubled. Similarly, [4] identified that 95% of Internet traffic is content-based and it increased 32% from 2010 to 2015. Currently, Internet architecture is host-to-host based and involves various kinds of problems, such as complex usage, poor resource utilization, inefficient mapping, scalability, security, location dependency, ubiquitous computing, and so on. Due to the remarkable growth of digital media, social networks, smartphone applications, and e-commerce, it is now required to treat the Internet as a distributed network. For the last two decades, content delivery networks (CDN) and peer-to-peer (P2P) architectures have been used as an overlay for content-centric networks [5] to fulfill the objectives. However, these solutions are not good enough for future application requirements. From a futuristic perspective, there is a need to create a new Internet architecture that can deal with all these coming application's demands.

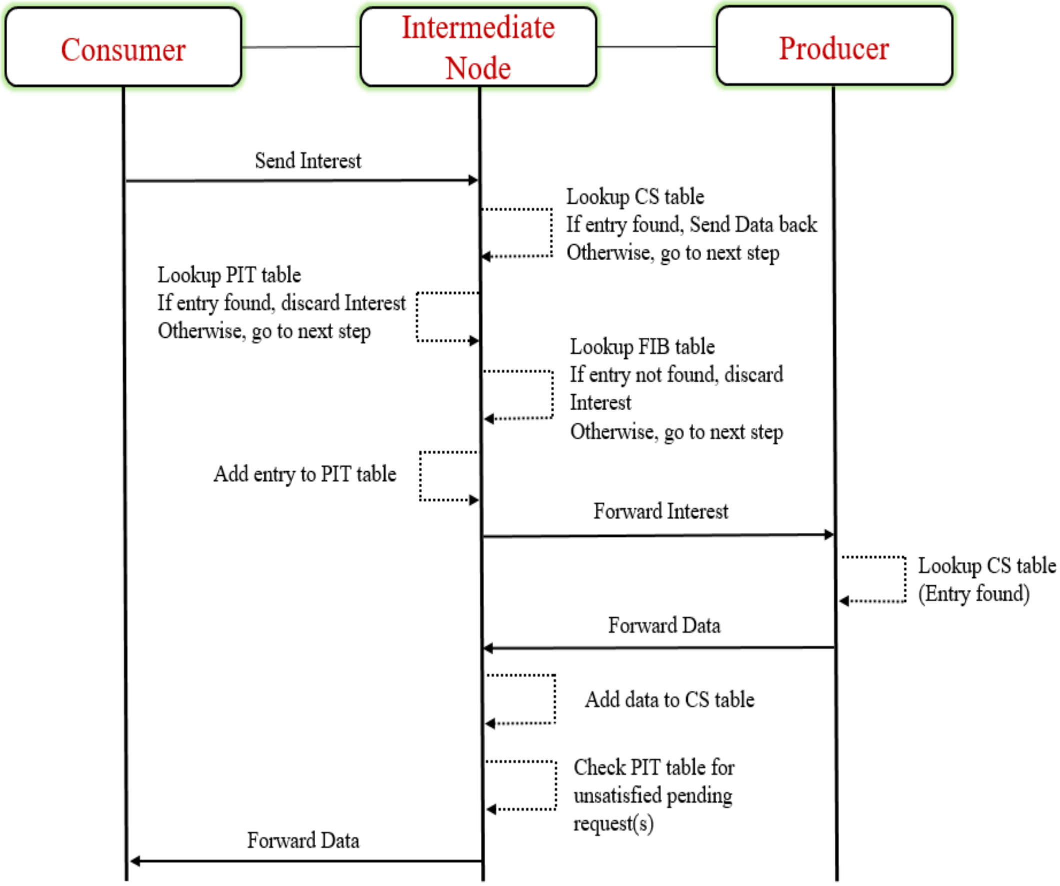


FIGURE 1. NDN communication process.

To cope with this need, information-centric networking (ICN) [6] was introduced as a futuristic Internet architecture that changes the notion of Internet architecture from a sender-driven host-to-host structure to a receiver-driven content-based architecture. In ICN, the communication paradigm is mainly focused on content (what) instead of location (where). ICN has gained remarkable interest in both industry and academia, and it is considered as a third generation evolution in the field of telecommunication by connecting nodes with content [7]. In addition, ICN provides enhanced support in the areas of mobility, security, and scalability, and in efficient content retrieval methods. As compared to the current host-based Internet architecture, the ICN paradigm does not induce any additional control overhead, such as address resolution, add-on security mechanisms, and congestion control. Various active ICN projects across the world like PURSUIT [8], 4WARD [9], COMET [10], CCN [11], CONVERGENCE [12], COAST [13], and more are working in this arena. Among all these projects, named data networking (NDN) [14] received a lot of attention in the research community after Jacobson's [11] revolutionary paper came out. NDN has simpler and faster communication operations and it replaces the current narrow waist of IP architecture with named content.

Despite the last three decades of continuous effort in regard to the strengths and limitations of current Internet architecture, NDN provides built-in strong functionalities, such as multipath routing, security primitives, flow balance mechanisms, and in-networking caching. In addition, every piece of content is uniquely identifiable by its name, and communication is mainly focused on content names decoupling from their location. In NDN, two different types of messages, called Interest and Data packets, are used for communication. Moreover, three types of tables, content store (CS), pending Interest table (PIT), and forwarding information base (FIB), are used for achieving particular purposes using the Interest and Data packets without using IP address. In CS, Data packets composing content are cached for future usage. If some other neighbor nodes require the same content in the near future, they can fetch the content from nearest node that has the content in its CS. On the other hand, PIT table is used for the manipulation of Interest packets. It contains all the pending request entries that other nodes request for particular Data packets. FIB table is utilized for forwarding purposes. It contains the incoming/outgoing interfaces information and populated by using a routing protocol that periodically updates it. A canonical communication process in NDN is illustrated by Fig. 1, in which a consumer node

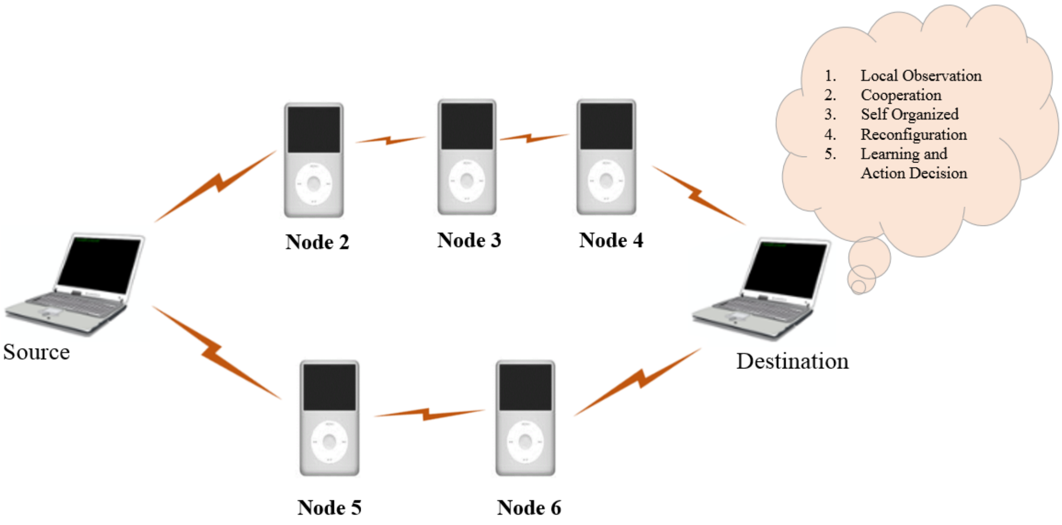


FIGURE 2. NDN-based mobile ad hoc networks.

sends its Interest packet toward a provider node to get the required Data packet. Previously, most of the work on NDN focused on wired networks. However, it is also considered an effective approach for wireless ad hoc networks [15] and cognitive radio ad hoc networks [16]–[18].

NDN-based mobile ad hoc networks consist of digital and resource-constrained devices that can communicate directly with each other by using a limited range of wireless transmissions, as shown in Fig. 2. Moreover, in these networks, channel conditions are highly unpredictable, dynamic, and unstable. Due to a node's mobility, network topology changes from time to time and nodes randomly appear and disappear from the network.

Since nodes in NDN-based multihop ad hoc networks have limited battery power, if a node sends a lot of Interest packets, it will lose energy and eventually die sooner or later (hereinafter, we will call a node with insufficient energy an affected node). In addition, all the pending request entries in its PIT will be destroyed. Consequently, it cannot forward the desired Data packets toward neighbor nodes, which further degrades network performance.

To cope with this situation, we propose a novel protocol called the on-demand energy-based forwarding strategy (OEFS), which takes the node's residual energy into account before sending packets. The key contributions of this paper are highlighted as follows:

- Propose a reactive protocol, called OEFS, in which energy-based packet forwarding enhances the lifetimes of nodes as well as the network.
- Find an optimal value for the energy threshold, in order to make efficient packet forwarding decisions.
- Reduce the probability of collisions due to the flooding of Interest and Data packets in the networks.
- Extensive evaluations on the performance of the proposed protocol by using ndnSIM [19], which provides the official environment for NDN simulations.

The rest of the paper is organized as follows. Section II provides an overview of recent related work and describes the problem in NDN-based mobile ad hoc networks. In Section III, the formulation and description of the proposed protocol is explained in detail. Section IV describes and analyzes the simulation results, and conclusions are presented in Section V.

II. RELATED WORK

In early times, various content-based [20] and opportunistic models [21] were used as overlay solutions to fulfill content-centric requirements. However, these solutions were based on conventional TCP/IP architecture. Nowadays, NDN gets more attention in the wireless area, thanks to its simple robust communication mechanism. The authors of previous work [22] applied the NDN approach to tactical and emerging mobile ad hoc networks (MANETs). To cope with the unpredictable and disruptive wireless environments, they introduced two further schemes: Interest aggregation and packet collision avoidance. To achieve this goal, two new packets (Reply, Request) were added to the conventional packets, which causes more network overhead. In [23], the authors proposed a scheme to mitigate the video packet loss in NDN-based wireless networks. Due to an in-network caching feature, a timeout algorithm was proposed to handle the fluctuations in route-trip time estimation. Moreover, the proposed protocol also tunes the exact timeout value.

Ameadeo et al. [24] proposed a protocol called the enhanced content-centric multihop wireless network (E-CHANET) for IEEE802.11-based wireless ad hoc networks. Unlike conventional NDN, E-CHANET introduces an additional table, called the provider table. In this protocol, Interest packets are flooded based on the distance from the provider node. In a high mobility case, this approach does not work well because when the provider node moves from one place to another, then it needs to reconsider its path establishment mechanism again, which further degrades the network

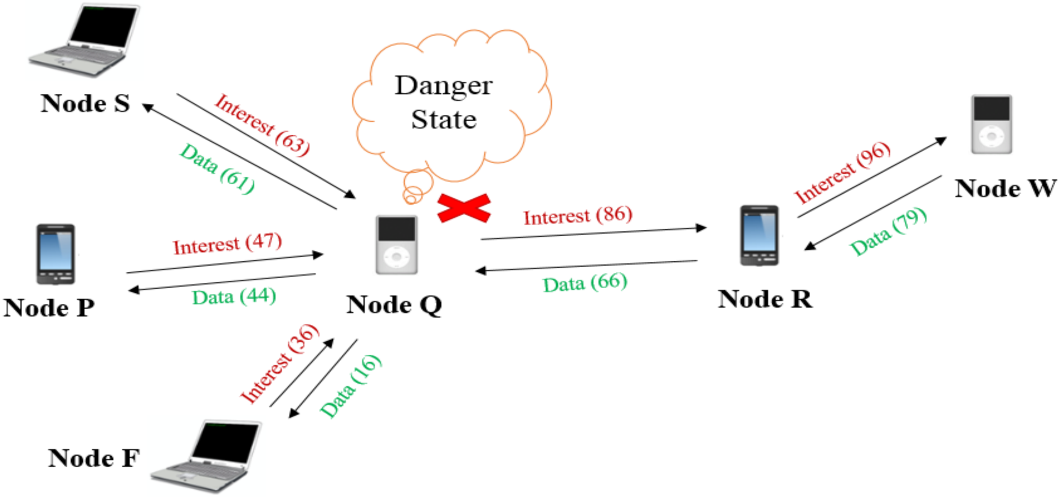


FIGURE 3. Problem scenario.

performance in terms of content download time [25]. Moreover, this scheme does not consider the residual energy of the node in its forwarding mechanism. As a result, a lot of affected nodes die in the network, which further decreases the network's lifetime.

In [26], the authors proposed a bloom filter-based forwarding approach. A node mitigates the packet collisions by adopting a forwarding rule. According to this rule, a node can only forward the packet if it does not receive the neighborhood information in a list that was previously sent by other neighbor nodes. However, this approach utilizes the periodic beacon information, which increases the overhead, especially in resource-constrained wireless ad hoc networks.

The authors in [27] proposed a new scheme called neighbor-aware information forwarding (NAIF) to reduce the Interest packet flooding in the network. An intermediate node decides to forward or drop the packet based on its data retrieval rate and distance from the consumer node. In [28], a direction-selective forwarding scheme was proposed for content retrieval in mobile cloud. Two additional types of packets, called command packet (CMD) and acknowledgement packet (ACK), are used to select the forwarder node in each quadrant, which increases the network overhead. The authors in [29] proposed a proactive-based packet broadcasting scheme for multi-hop wireless NDN in which forwarding information is updated periodically by using eligible forwarder selection (EFS) and EFS acknowledgement (EFS-ACK) packets in addition to the Data and Interest packets. An eligible forwarder node is selected based link quality and hop distance value.

However, in all the aforementioned schemes, no one has used the node's residual energy concept in its communication mechanism, which is an essential aspect, especially while considering NDN-based resource-constrained wireless ad hoc networks.

A. MOTIVATIONS FOR OEFS

Figure. 3 describes the problem scenario in NDN-based multi-hop ad hoc networks. Node P acts as a requester, and it is interested in getting content from provider node W. Node Q and R act as relay nodes and forward the Interest packets to node W after adding corresponding entries in their PIT tables. For example, if nodes S and F require different content, node Q forwards their Interest packets to node W. Moreover, the numbers in parentheses (i.e. Interest (86), Data (66) etc.) show the sequence numbers of Interest and Data packets transmitted in the network. Due to heavy traffic, if node Q has less residual energy, it cannot send much traffic to node R and will die soon without sending the desired Data packets to its neighbor nodes.

As a result, all pending PIT entries are destroyed, which further degrades the network performance due to excessive packet flooding over the networks. In addition, the neighbor nodes (i.e., Node S, Node F, etc.) still wait for their desired content, which increases the content retrieval time.

III. PROPOSED PROTOCOL

A. PROTOCOL FORMULATION

Let V be the set of nodes in which $node_f$ can be reached by $node_g$ with a certain power level (Pow_{th}) in its dynamic range. Assume that the initial energy of $node_f$ is e_{ini} and $e_{ini} > 0$. Let e_{tran} be the energy required by $node_f$ to transmit information to $node_g$. Similarly, e_{recv} and e_{lis} are energies consumed by $node_g$ for receiving information and listening to the channel, respectively. The energy consumed by a node, e_{cons}, is the summation of energy consumption in all receiving, listening, and transmitting states. Each node is equipped with an omni-directional antenna. When $node_f$ transmits some packets to $node_g$, and the distance between both nodes is Z, the received power can be expressed as follows [30].

$$Pow_r(Z) = \frac{Pow_t M_t M_r \lambda^2}{(4\pi)^2 Z^q p}, \tag{1}$$

where M_r and M_t represent the gains of the antennas of a receiver and a transmitter, respectively and p indicates the power loss during transmission. λ is a wavelength and q is the propogation loss factor which is normaly between 2 to 4. If $M_t = M_r = 1$ and $p = 1$, the received signal power is

$$Pow_r(Z) = \frac{Pow_t \lambda^2}{(4\pi)^2 Z^q}. \tag{2}$$

For the successful delivery of information, the received power needs to be more than a certain threshold Pow_{th}. Therefore, the signal power at the sender must be above that $Pow_{th}(4\pi)^2 Z^q/\lambda^2$. By using the procedure in [31], the energy consumed by a node in all three states can be calculated as follows:

$$e_{tran} = \left(e_{elec} + \frac{Pow_{th}(4\pi)^2 Z^q}{\lambda^2 d_r}\right) S_{bits}, \tag{3}$$

$$e_{recv} = \left(e_{elec} + e_r\right) O_{bits}, \tag{4}$$

$$e_{lis} = e_{elec}\left(1 - \frac{S_{bits}}{d_r} - \frac{O_{bits}}{d_r}\right) d_r, \tag{5}$$

where e_{elec} represents the energy consumed per bit in the transmitter electronics, e_r shows the energy consumed per bit in the receiver, d_r is the physical data rate of the node in the unit of bit per second, and S_{bits} and O_{bits} represent the received and transmitted data bits, respectively. Therefore, the lifetime of a node, $n_{lifetime}$, can be expressed as follows:

$$n_{lifetime} = e_{res}/e_{cr}, \tag{6}$$

where e_{cr} represents the energy consumption rate, and e_{res} indicates the node's residual energy, which can be described as follows:

$$e_{res} = e_{ini} - e_{cons}, \tag{7}$$

$$e_{cons} = e_{tran} + e_{recv} + e_{lis}. \tag{8}$$

We have defined two types of node states. A node is in its Safe State if

$$Safe_{state} = e_{res} > e_{thres}. \tag{9}$$

Otherwise, it is in its Danger State if

$$Danger_{state} = e_{res} < e_{thres}. \tag{10}$$

where e_{thres} represents the energy threshold. e_{thres} is an important factor of the OEFS protocol and its optimal value is set after we performed extensive simulation experiments. Further details about e_{thres} will be discussed in Section 4-C.1.

B. PROTOCOL DESCRIPTION

We propose a novel protocol, called OEFS, for NDN-based mobile ad hoc networks. The proposed protocol considers a node's residual energy status in its communication process. Two types of packets, Interest message (INTMsg) and Data message (DATAMsg), are introduced. The necessary fields for both packets are shown in Tables 1 and 2. In OEFS, each node in the network has two types of data structures, content store (CoS) and Interest information table (IIT), for the management of INTMsg and DATAMsg packets. The structure of a node in OEFS is represented in Fig. 4. In contrast to conventional NDN, proposed OEFS protocol do not take into account the FIB data structure due to its on-demand and reactive communication process. FIB data structure needs to be periodically populated by using a routing protocol. This phenomena causes an additional overhead especially in resource constrained NDN-based mobile ad hoc networks. Unlike previous proposed approaches, the OEFS protocol does not use any additional control packet or data structure.

TABLE 1. **INTMsg message format.**

Field	Description
INTMsg Name	Requested content name
Nonce	Random value use to avoid duplication of INTMsg
INTMsg Lifetime	Lifetime of INTMsg, specified in seconds
Options	Information regarding order preference, exclude filter, etc.

TABLE 2. **DATAMsg message format.**

Field	Description
DATAMsg Name	Requested content name
DATAMsg length	Length of the requested content
DATAMsg type	Information about the content type, such as text, audio, video, etc.
DATAMsg Content	Actual data payload
Signature Type	Represents the type of signature, such as SHA256, empty signature, SHA256 with RSA, etc.

In the proposed protocol, if a node is in the Danger State, it does not forward incoming INTMsg packets. Instead, it focuses more on satisfying pending request entries in its IIT by sending requested Data packets to neighbor nodes. As a result, it reduces the INTMsg packet flooding in the network and increases the lifetime of the node by reducing the number of transmissions. Moreover, to reduce the collisions among the INTMsg and DATAMsg packets, each node, before transmission, defers and listens to the channel for a randomly chosen time (D_{INTMsg}, $D_{DATAMsg}$). If the same INTMsg or DATAMsg packet is received within the time, the node discards its pending packet in order to avoid collisions and redundancy in the network. In the following sections, the processes for a relay node to handle INTMsg and DATAMsg packets are exemplified in detail.

1) PROCESS FOR RECEIVED INTMsg PACKET IN OEFS

The processing of INTMsg packet at relay node can be explained in the following steps.

Step 1. When a node receives a packet, it checks to see if it is an INTMsg packet.

Step 2. In the case of an INTMsg packet, it first checks its nonce and lifetime value. If it is a duplicate or expired packet, then the node discards it.

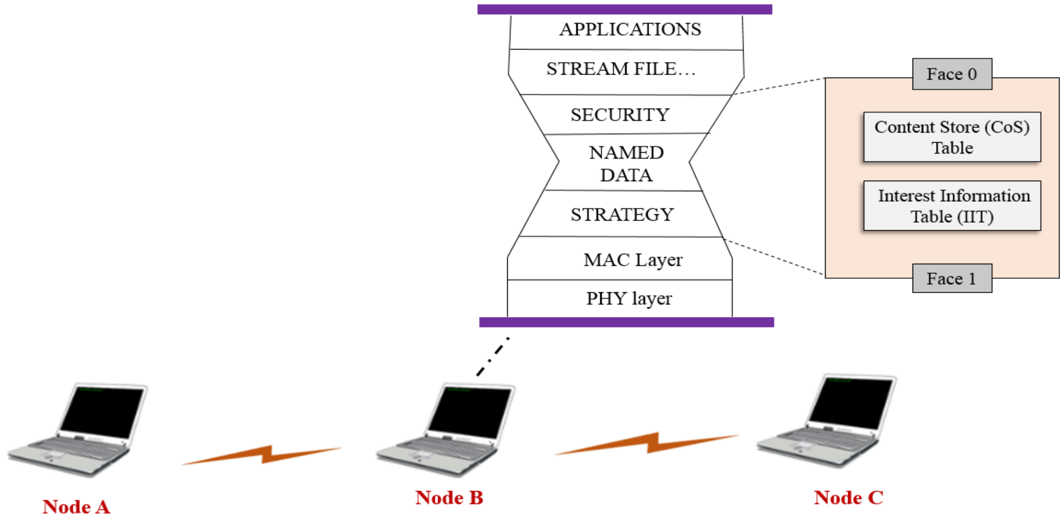


FIGURE 4. Proposed OEFS node architecture.

Step 3. The node looks up its CoS to find the desired DATAMsg packet. If it is found, the node defers and listens to the channel for $D_{DATAMsg}$ time.

Step 3.1. If the same DATAMsg packet is detected during this time, then the node discards its own DATAMsg packet.

Step 3.2. Otherwise, it forwards the packet and discards the corresponding entry from the IIT.

Step 4. If the DATAMsg packet is not in its CoS, it looks up its IIT for any existing entry.

Step 5. If an entry is found in IIT (which means that some other nodes have already requested the same DATAMsg packet), then the node discards the packet.

Step 6. In the case of no IIT entry, the node checks the node's residual energy, e_{res}.

Step 6.1. If e_{res} is less than e_{thres}, the node is in the Danger State. It adds the corresponding entry to its IIT and discards the INTMsg packet for further transmission.

Step 6.2. Otherwise, the node is in the Safe State. It inserts the IIT entry, and waits and listens to the channel for D_{INTMsg} time.

Step 6.2.1 If the same INTMsg or DATAMsg packet is received during this time, the node discards the current packet.

Step 6.2.2 Otherwise, it forwards the INTMsg packet to the other nodes.

A flow chart of handling an INTMsg packet at the relay node is shown in Fig. 5.

2) PROCESS FOR RECEIVED DATAMsg PACKET IN OEFS

When a relay node receives a DATAMsg packet, it follows the process as described below:

Step 1. When a node receives a packet, it checks to see if it is a DATAMsg packet.

Step 2. In the case of a DATAMsg packet, the node looks up its IIT for any corresponding entry related to the packet.

Step 3. If there is no other entry, the DATAMsg packet is supposed to be marked as unsolicited and it is discarded.

Step 4. Otherwise, the node saves the current DATAMsg packet in its CoS.

Step 5. The node looks up its IIT to check the pending requests from other nodes.

Step 5.1. If all requests for the INTMsg packets are satisfied, it discards the corresponding entries from IIT.

Step 5.2. Otherwise, it defers and listens to the channel for $D_{DATAMsg}$ time.

Step 5.2.1. If the same DATAMsg packet is detected during this time, the node gives up its own transmission.

Step 5.2.2. Otherwise, it forwards the DATAMsg packet to other nodes.

A flow chart of handling a DATAMsg packet is shown in Fig. 6.

IV. PERFORMANCE EVALUATION

A. SIMULATION SETTINGS

To evaluate the performance of OEFS, we used an ndnSIM [19] software module that is based on Network Simulator-3 (NS-3) [32]. To evaluate the performance of the proposed protocol, we considered a scenario as shown in Fig. 7, in which the nodes were equipped with IEEE802.11g-based radio interfaces. Furthermore, each node utilizes the well-known random walk mobility model [33]. By using this, the nodes can freely move anywhere. The speed of the node is $2 - 4$ m/s. The nakagami propagation model was used to take multipath effects into account. The energy of

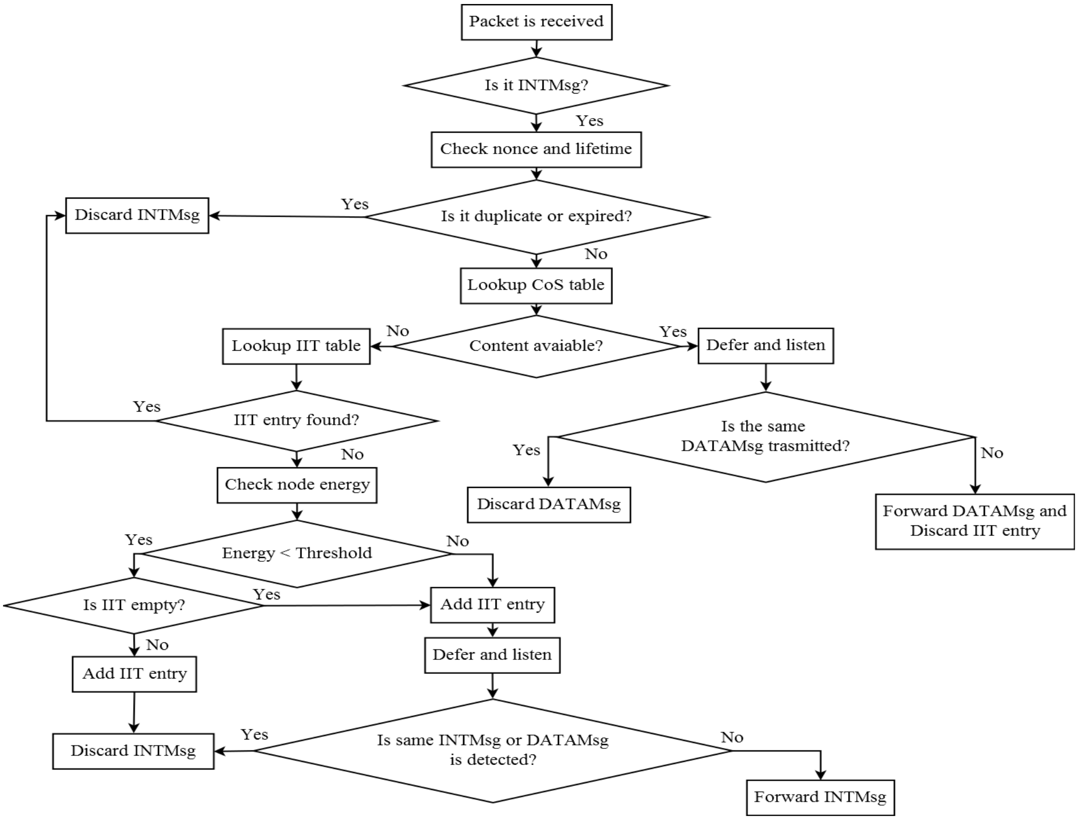


FIGURE 5. Process for when a relay node receives an INTMsg packet.

each node was initially set to 100 joule. In addition, the energy consumption in receiving, transmitting, and idle states were set to 0.9603W, 1.74W, and 0.6699W, respectively [24].

The content consisted of 4,000 DATAMsg packets and the size of each DATAMsg packet was 1040 bytes. Initially, the content is stored on producer node. By using the leave a copy everywhere (LCE) policy, each node can cache DATAMsg packets in its CoS, and the maximum size of each CoS is 10,000 packets. The least recently used (LRU) policy was used for the management of the DATAMsg packets in the CoS. The data rate was set to 6 Mbps. Each simulation time was 700 seconds and the results are presented in the form of averages of 10 timed runs. Table 3 presents a summary of the simulation parameters.

B. PERFORMANCE METRICS

The performance of the proposed OEFS protocol was compared with the well-known E-CHANET [24] protocol. E-CHANET protocol was previously proposed for NDN-based wireless ad hoc networks and now it is considered as a good candidate for the performance comparison especially while working in this arena. Similar to the E-CHANET scheme, the proposed OEFS protocol also utilizes a reactive-based forwarding approach. The following four performance metrics were used to evaluate the performance of the proposed protocol.

1) CONTENT DOWNLOAD TIME

Defined as the average time required by the consumer node to download all the DATAMsg packets of the content.

2) INTEREST RETRANSMISSIONS

Defined as the average number of INTMsg packets retransmitted by the consumer node to get all the DATAMsg packets of the desired content.

3) TOTAL NUMBER OF INTERESTS

Defined as the total number of INTMsg packets plus INTMsg retransmitted packets issued by the consumer and relay nodes to retrieve the desired DATAMsg packets.

4) DATA REDUNDANCY

Defined as the average number of duplicated DATAMsg packets received by a consumer node due to the multi-homing feature of the NDN.

C. SIMULATION RESULTS

We analyzed the performance of both protocols by considering the impact of the energy threshold, the node density, and the number of consumer and producer pairs in the network. In the following sections, the related results will be explained in detail.

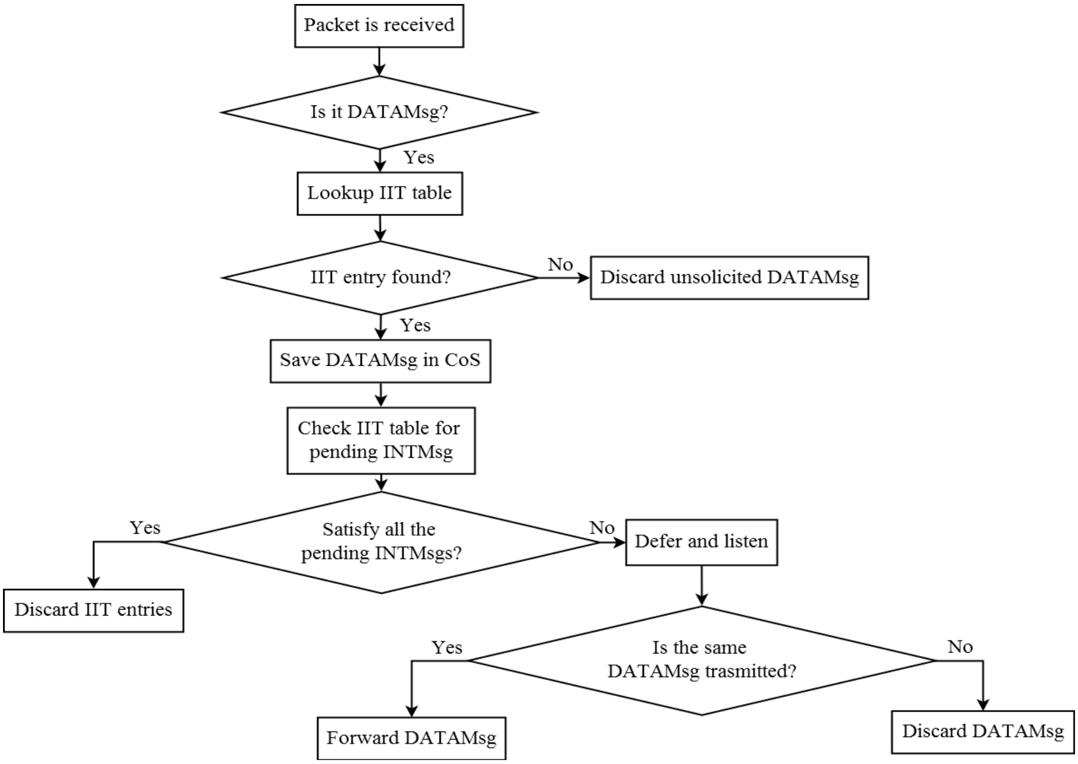


FIGURE 6. **Process for when a relay node receives a DATAMsg packet.**

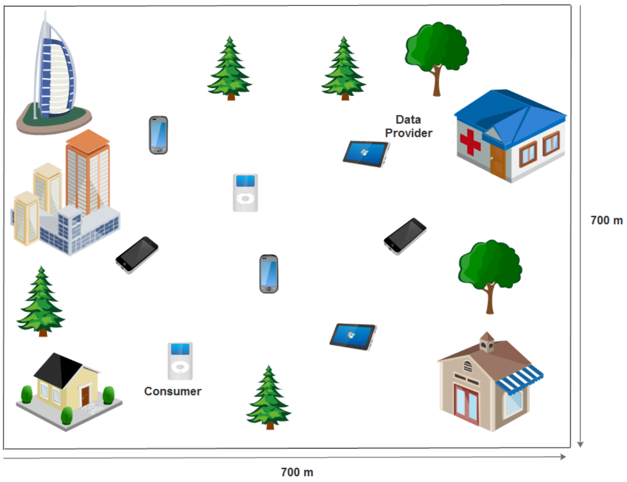


FIGURE 7. **Simulation scenario (700 *m* × 700 *m*).**

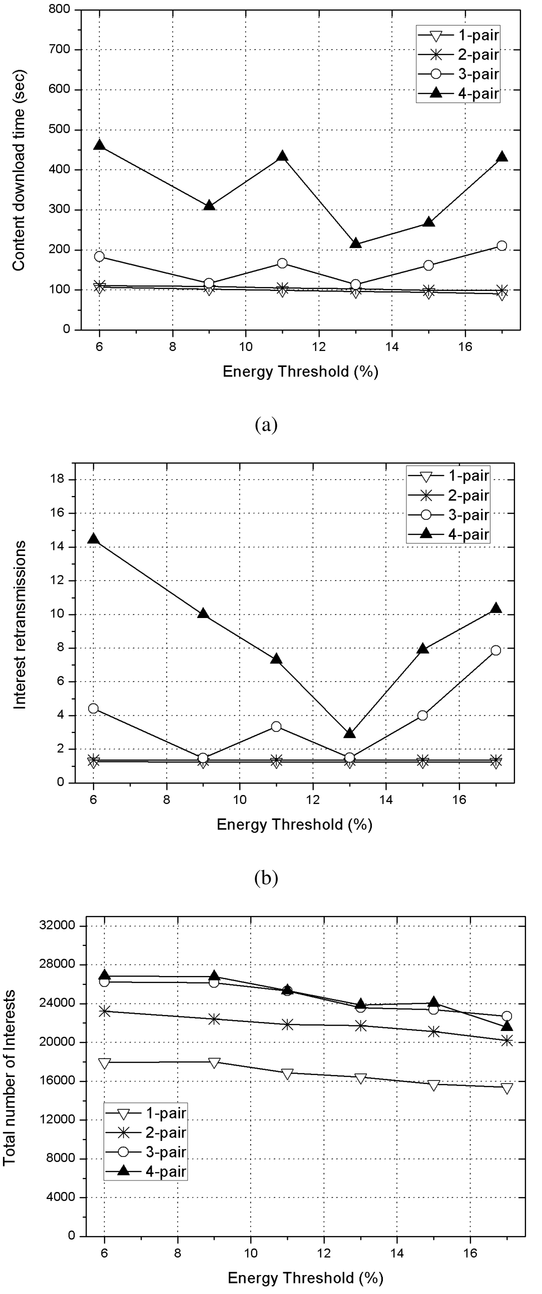
TABLE 3. **Simulation parameters.**

Parameter	Value
Propagation Delay Model	Constant Speed
Propagation Loss Model	Nakagami
Technology	IEEE802.11g
Mobility Model	Random Walk
Energy Model	EnergyModel
Area (m × m)	700 × 700
Node Speed	2-4. m/s
Initial Energy	100 J.
Simulation Time	700 s.
CoS Size	10000 packets
Rx Sensitivity	-86 dBm
Tx Power	18 dBm
Replacement Policy	LRU
Content Size	4000 packets
Packet Size	1040 bytes
Nodes	20-100.
Data Rate	6 Mbps
Power Consumption (tx)	1.74 W
Power Consumption (rx)	0.9603 W
Power Consumption (idle)	0.6699 W

1) IMPACT OF THE ENERGY THRESHOLD

In the first round of simulations, we analyzed the impact of the energy threshold (e_{thres}) on the forwarding process in mobile ad hoc networks and found an appropriate value for e_{thres} that attained the best results. Each consumer node can download its required content from any producer node.

Figure 8(a) represents the content download time as a function of the energy threshold. In the case of one or two pairs, changing the energy threshold does not make any significant difference in the content download times. However, as we increase the number of pairs from three to four, the traffic load in the network is also increased. In the case of a low e_{thres} value (i.e., 6%, 11%, etc.), too many nodes are in a Safe State and are fully participating in the communication process. As a result, the network becomes congested, which increases the probability of packet collisions. That is why, at this point, the content download time is high.

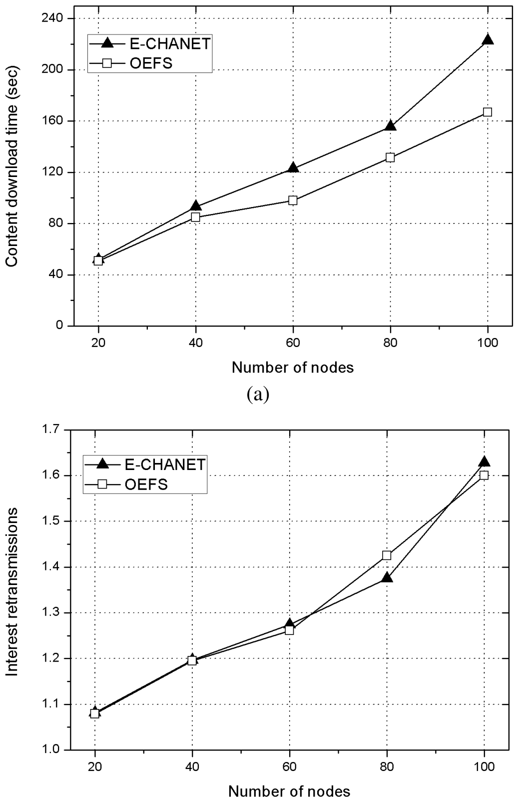


(a)

(b)

(c)

FIGURE 8. **(a) Content download time as a function of the energy threshold, (b) Interest retransmissions as a function of the energy threshold, and (c) total number of Interests as a function of the energy threshold.**



(a)

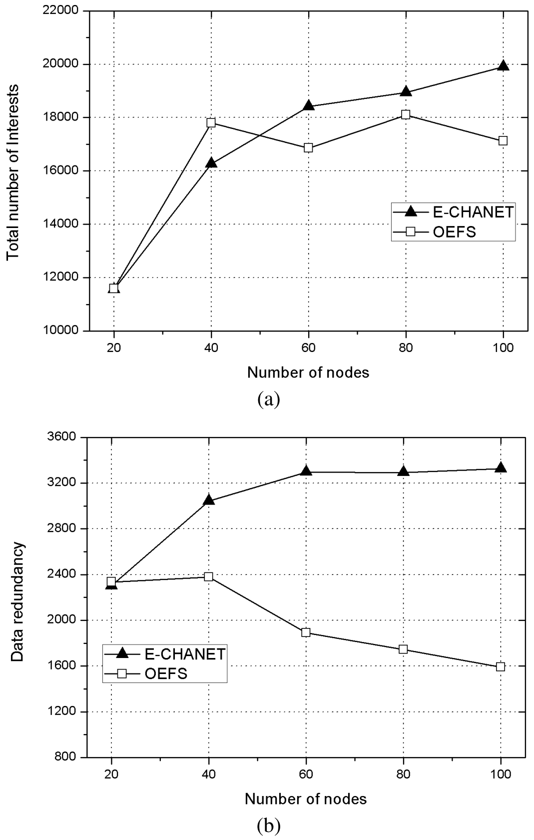
(b)

FIGURE 9. **(a) Content download time as a function of the number of nodes and (b) Interest retransmissions as a function of the number of nodes.**

Furthermore, due to packet loss, the consumer nodes are forced to trigger more INTMsg packets, which further increases the Interest retransmissions as well as the total number of Interest packets as shown in Fig. 8(b) and Fig. 8(c), respectively. As we increase the e_{thres} value, better performance is achieved up to a certain value of e_{thres} (i.e., 13%). After this value, performance becomes worse in terms of the content download time and Interest retransmissions. The reason for this is that as the e_{thres} value increases (i.e., 15% or 17%), the content download time again increases because more of the participating nodes are in the Danger State. Therefore, the nodes discard the incoming INTMsg packet transmissions and only focus on satisfying their pending IIT entries. As a result, both content retrieval time and Interest retransmissions increase. On the other hand, at a value of 13%, we attain better performance. For further results, we set the e_{thres} value to 13%, which achieved better results as compared to other threshold values.

2) IMPACT OF NODE DENSITY

In Fig. 9, we compare the content download time and Interest retransmissions of the proposed OEFS protocol with the E-CHANET protocol. One consumer/producer pair is used in these simulations. As the number of nodes increases, the content download time increases, because more packets are injected into the network. At the initial stage, the content download time of the OEFS protocol is the same as that of the E-CHANET protocol. However, in a dense network environment, OEFS outperforms E-CHANET. The reason is that the OEFS protocol takes the node's residual energies into account in its forwarding mechanism. When a node has less residual energy, then it cannot forward INTMsg packets and it pays more attention to DATAMsg packet forwarding. As a result, there is less traffic in the network. In addition,



(a)

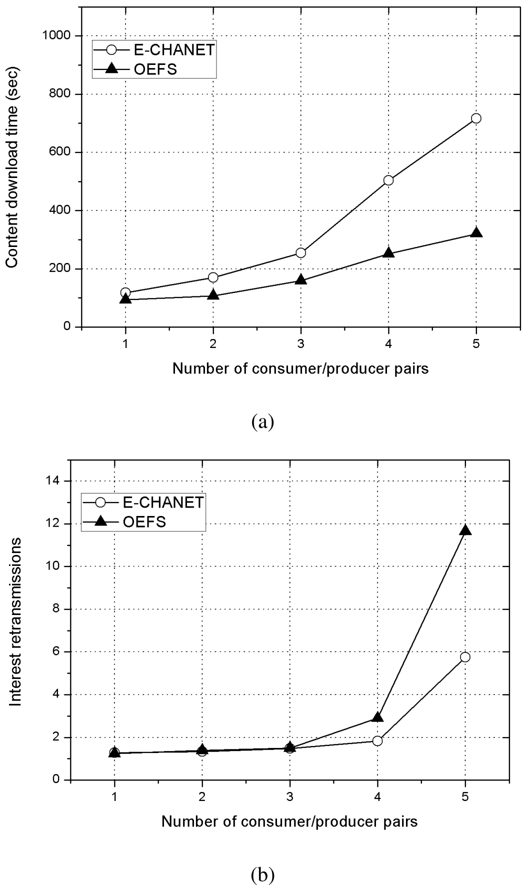
(b)

FIGURE 10. **(a) The total number of Interests as a function of the number of nodes and (b) Data redundancy as a function of the number of nodes.**

packet collision probability is low, which makes the content download time shorter.

On the other hand, E-CHANET does not consider any energy-related concepts in its forwarding process. Therefore, many nodes die quickly, due to a shortage of battery power. This increases the content retrieval time and the number of Interest retransmissions.

Figure 10 shows the performance of both protocols by taking the total number of Interests and Data redundancy into account. At the beginning, in the case of the OEFS protocol, the number of participating nodes is less. In addition, traffic congestion is low at that time. Therefore, many nodes are in the Safe State and take part in the communication frequently. However, as the number of nodes increases, the packet transmissions also increase over the network. Due to insufficient energy, many nodes are in the Danger State, and they do not transmit INTMsg packets further. As a result, fewer INTMsg packets are transmitted, which further reduces the duplication of the DATAMsg packets in the network. That is why, in both cases, OEFS outperforms E-CHANET. The E-CHANET protocol does not consider the residual energies of the nodes and the nodes continuously transmit Interest packets. Due to more Interest packets in the network, duplicated Data packets also increase. This degrades network performance and also increases the probability of collisions among the packets.



(a)

(b)

FIGURE 11. **(a) Content download time as a function of the number of consumer/producer pairs and (b) Interest retransmissions as a function of the number of consumer/producer pairs.**

3) IMPACT OF THE NUMBER OF CONSUMER/PRODUCER PAIRS

We also evaluated the performance of both of the OEFS and E-CHANET protocols by increasing the number of consumer and producer pairs in the network that consists of 50 nodes, as shown in Fig. 11. In the case of one pair, both protocols perform nearly the same, but as the number of pairs increases from two to five, the performance degradation is more evident for the E-CHANET protocol. The reason is that as we increase the number of consumer and producer pairs in the network, the network becomes more congested, because every consumer wants the desired content from its provider. Since the proposed mechanism takes the residual energies of the nodes into account, fewer nodes in the proposed method transmit INTMsg packets. As a result, the probability of packet collisions becomes low.

In Fig. 11(b), unlike E-CHANET, the OEFS protocol injects more Interest retransmissions into the network. In the OEFS protocol, when nodes have insufficient energy, INTMsg packet transmissions are stopped. Therefore, the consumer nodes are again forced to trigger the same INTMsg packets to get the desired DATAMsg packets. Consequently, the number of Interest retransmissions increases compared to the E-CHANET protocol.

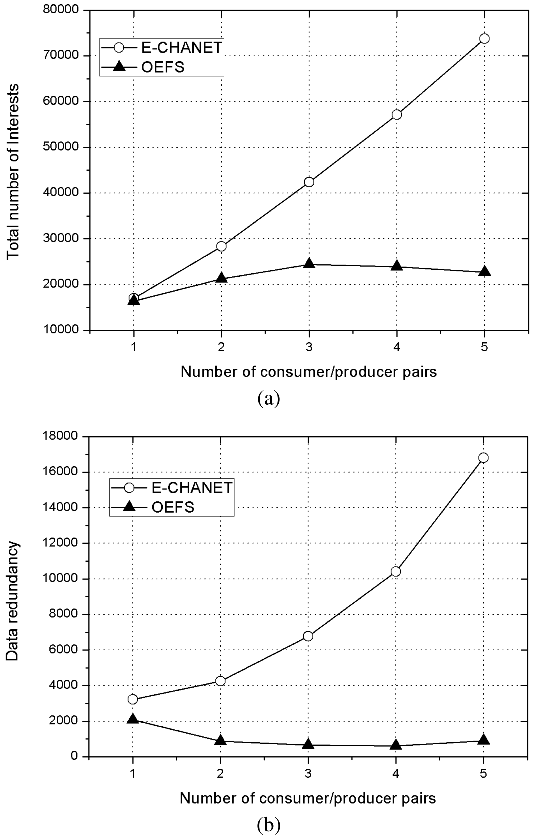


FIGURE 12. **(a) The total number of Interests as a function of the number of consumer/producer pairs and (b) Data redundancy as a function of the number of consumer/producer pairs.**

In Fig. 12, the performance of both protocols is measured in terms of the total number of Interest retransmissions and Data redundancy as a function of the consumer and producer pairs. The proposed OEFS protocol performs better than the E-CHANET protocol in both cases. In the case of OEFS, as the number of pairs increases, the more nodes are affected in the network due to energy constraints, and they give more priority to DATAMsg packets instead of INTMsg packet transmissions. Consequently, the total number of transmitted Interest packets over the network decreases. In addition, controlling INTMsg packet flooding mitigates the number of duplicated DATAMsg packets compared to the non-energy-based E-CHANET protocol.

V. CONCLUSIONS

In this paper, an on-demand protocol called OEFS was proposed for NDN-based mobile ad hoc networks. The OEFS protocol has four unique characteristics. First, it considers the residual energies of the nodes in its communication process. Second, its energy-based forwarding mechanism enhances node lifetimes as well as network performance. Third, when nodes are in Danger States, they focus more on the delivery of Data packets to satisfy the pending requests of their neighbor nodes. Fourth, to mitigate packet collisions, it reduces the Interest and Data packet flooding in the networks.

The results of extensive simulations show that OEFS outperforms other conventional schemes in terms of average content download time, the number of Interest retransmissions, the duplication of Data packets, and the total number of Interest propagations in the network.

REFERENCES

[1] C.-L. Hu, C.-A. Cho, C.-J. Lin, and C.-W. Fan, "Design of mobile group communication system in ubiquitous communication network," *IEEE Trans. Consum. Electron.*, vol. 56, no. 1, pp. 88–96, Feb. 2010.

[2] *Cisco Visual Networking Index: Forecast and Methodology: 2011–2015*, CISCO, USA, May 2012. [Online]. Available: http://www.cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/index.html

[3] (2015). "We Knew the Web Was Big," Google Blog. [Online]. Available: http://googleblog.blogspot.com/2008/07/we-knew-web-was-big.html

[4] M. Ul Haque, K. Pawlikowski, A. Willig, and L. Bischofs, "Performance analysis of blind routing algorithms over content centric networking architecture," in *Proc. Int. Conf. Comput. Commun. Eng. (ICCCE)*, Jul. 2012, pp. 922–927.

[5] A. Passarella, "A survey on content-centric technologies for the current Internet: CDN and P2P solutions," *Comput. Commun.*, vol. 35, no. 1, pp. 1–32, 2012.

[6] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, Jul. 2012.

[7] J. Kurose, "Information-centric networking: The evolution from circuits to packets to content," *Comput. Netw.*, vol. 66, pp. 112–120, Jun. 2014.

[8] (2014). *Pursuit: Pursuing a Pub/Sub Internet*. [Online]. Available: http://www.fp7-pursuit.eu/

[9] M. Brunner, H. Abramowicz, N. Niebert, and L. M. Correia, "4WARD: A European perspective towards the future Internet," *IEICE Trans. Commun.*, vol. E93.B, no. 3, pp. 442–445, 2010.

[10] (2015). *Comet: Content Mediator Architecture for Content-Aware Networks*. [Online]. Available: http://www.comet-project.org/

[11] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, "Networking named content," in *Proc. 5th Int. Conf. Emerg. Netw. Exper. Technol.*, 2009, pp. 1–12.

[12] (2014). *Convergence: Host Centric to Content-Centric*. [Online]. Available: http://www.ictconvergence.eu/

[13] (2014). *Coast: Content Aware Searching Retrieval and Streaming*. [Online]. Available: http://www.coast-fp7.eu/

[14] L. Zhang *et al.*, "Named data networking," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, Jul. 2014. [Online]. Available: http://doi.acm.org/10.1145/2656877.2656887

[15] M. Amadeo, C. Campolo, A. Molinaro, and G. Ruggeri, "Content-centric wireless networking: A survey," *Comput. Netw.*, vol. 72, pp. 1–13, Oct. 2014.

[16] R. A. Rehman, J. Kim, and B.-S. Kim, "NDN-CRAHNs: Named data networking for cognitive radio ad hoc networks," *Mobile Inf. Syst.*, vol. 2015, May 2015, Art. no. 281893.

[17] R. A. Rehman and B.-S. Kim, "Content centric networking approach in cognitive radio ad hoc networks," in *Proc. 13th Int. Conf. Frontiers Inf. Technol. (FIT)*, Dec. 2015, pp. 309–313.

[18] P. Si, H. Yue, Y. Zhang, and Y. Fang, "Spectrum management for proactive video caching in information-centric cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 8, pp. 2247–2259, Aug. 2016.

[19] A. Afanasyev, I. Moiseenko, and L. Zhang, "ndnSIM: NDN simulator for NS-3," NDN, USA, Tech. Rep. NDN-0005, Oct. 2012. [Online]. Available: http://named-data.net/techreports.html

[20] F. Guidec and Y. Mahéo, "Opportunistic content-based dissemination in disconnected mobile ad hoc networks," in *Proc. IEEE Int. Conf. Mobile Ubiquitous Comput., Syst., Services Technol. (UBICOMM)*, Nov. 2007, pp. 49–54.

[21] J. Scott, J. Crowcroft, P. Hui, and C. Diot, "Haggle: A networking architecture designed around mobile users," in *Proc. 3rd Annu. Conf. Wireless On-Demand Netw. Syst. Services (WONS)*, 2006, pp. 78–86.

[22] S. Y. Oh, D. Lau, and M. Gerla, "Content centric networking in tactical and emergency MANETs," in *Proc. IEEE IFIP Wireless Days (WD)*, 2010, pp. 1–5.

[23] L. Han, S.-S. Kang, H. Kim, and H. P. In, "Adaptive retransmission scheme for video streaming over content-centric wireless networks," *IEEE Commun. Lett.*, vol. 17, no. 6, pp. 1292–1295, Jun. 2013.

[24] M. Amadeo, A. Molinaro, and G. Ruggeri, "E-CHANET: Routing, forwarding and transport in information-centric multihop wireless networks," *Comput. Commun.*, vol. 36, no. 7, pp. 792–803, 2013.
[25] M. Amadeo, C. Campolo, and A. Molinaro, "Forwarding strategies in named data wireless ad hoc networks: Design and evaluation," *J. Netw. Comput. Appl.*, vol. 50, pp. 148–158, Apr. 2014.
[26] F. Angius, M. Gerla, and G. Pau, "BLOOGO BLOOm filter based GOssip algorithm for wireless NDN," in *Proc. 1st ACM Workshop Emerg. Name-Oriented Mobile Netw. Design-Archit., Algorithms, Appl.*, 2012, pp. 25–30.
[27] Y.-T. Yu, R. B. Dilmaghani, S. Calo, M. Y. Sanadidi, and M. Gerla, "Interest propagation in named data MANETs," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, 2013, pp. 1118–1122.
[28] Y. Lu, B. Zhou, L.-C. Tung, M. Gerla, A. Ramesh, and L. Nagaraja, "Energy-efficient content retrieval in mobile cloud," in *Proc. 2nd ACM SIGCOMM Workshop Mobile Cloud Comput.*, 2013, pp. 21–26.
[29] D. Kim and Y.-B. Ko, "A novel message broadcasting strategy for reliable content retrieval in multi-hop wireless content centric networks," in *Proc. 9th Int. Conf. Ubiquitous Inf. Manage. Commun.*, 2015, p. 108.
[30] W. Feng and J. M. H. Elmirghani, "Lifetime evaluation in energy-efficient rectangular ad hoc wireless networks," *Int. J. Commun. Syst.*, vol. 23, no. 12, pp. 1500–1520, 2010. [Online]. Available: http://dx.doi.org/10.1002/dac.1121
[31] M. Bhardwaj, T. Garnett, and A. P. Chandrakasan, "Upper bounds on the lifetime of sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, vol. 3. Jun. 2001, pp. 785–790.
[32] NS3. (2013). *Network Simulator 3*. [Online]. Available: http://www.nsnam.org
[33] K.-H. Chiang and N. Shenoy, "A 2-D random-walk mobility model for location-management studies in wireless networks," *IEEE Trans. Veh. Technol.*, vol. 53, no. 2, pp. 413–424, Mar. 2004.

RANA ASIF REHMAN (M'17) received the M.Sc. degree in computer science from Bahauddin Zakariya University, Multan, Pakistan, in 2010, the M.S. degree in computer science from International Islamic University, Islamabad, Pakistan, in 2012, and the Ph.D. degree in electronics and computer engineering from Hongik University, South Korea, in 2016, under the supervision of Prof. B.-S. Kim. In 2013, he was a Lecturer with the University of Sargodha, Lahore Campus, Pakistan. He is currently an Assistant Professor with the Department of Computer Science, National University of Computer and Emerging Sciences, Chiniot-Faisalabad Campus, Pakistan. His research interests include the design and development of energy efficient routing protocols, cross layer architectures, caching and forwarding schemes for cognitive radio ad hoc networks, and named data networking-based wireless networks. He is currently a member of the KSII, the IEEE Computer Society, the IEEE Signal Processing Society, and the IEEE Young Professionals.

SYED HASSAN AHMED (S'13–M'17) received the B.S. degree in computer science from Kohat University of Science and Technology, Pakistan, and the master's combined Ph.D. degree in computer engineering from the School of Computer Science and Engineering, Kyungpook National University (KNU), South Korea, in 2017. In 2015, he was a Visiting Researcher with the Georgia Institute of Technology, Atlanta, GA, USA. His research interests include sensor and ad hoc networks, cyber-physical systems, vehicular communications, and future Internet. He has authored more than 70 international journal and conference articles in addition to two Springer brief books. From 2014 to 2016, he received the Best Research Contributor Award in the workshop on Future Researches of Computer Science and Engineering, KNU. In 2016, he also received the Qualcomm Innovation Award at KNU. He is an ACM Member while serving several reputed conferences and journals as a TPC and a Reviewer.

BYUNG-SEO KIM (M'02) received the B.S. degree in electrical engineering from Inha University, Inchon, South Korea, in 1998, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University, USA, of Florida in 2001 and 2004, respectively, under the supervision of Dr. Y. Fang. From 1997 to 1999, he was with Motorola Korea Ltd., Paju, South Korea, as a Computer Integrated Manufacturing Engineer in advanced technology research and development. From 2005 to 2007, he was with Motorola Inc., Schaumburg, IL, as a Senior Software Engineer in networks and enterprises, where he was involved in designing protocol and network architecture of wireless broadband mission-critical communications. From 2012 to 2014, he was the Chairman of the Department of Computer and Information Communication Engineering, Hongik University, South Korea, where he is currently an Associate Professor. His work has appeared in more than 123 publications. He also holds 19 patents. His research interests include the design and development of efficient wireless/wired networks, including link-adaptable/cross-layer-based protocols, multi-protocol structures, wireless CCNs/NDNs, Mobile Edge Computing, physical layer design for broadband PLC, and resource allocation algorithms for wireless networks. He was a Guest Editor of the *Journal of the Institute of Electrics and Information Engineers* and a TPC Member of the IEEE VTC 2014-Spring and the EAI FUTURE 2016 conferences. He is currently a Lead-Guest Editor of the annual special issue of the *International Journal of Distributed Sensor Networks*. He is also was a member of the Sejong-city Construction Review Committee and the Ansan-city Design Advisory Board.

• • •