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A novel energy-efficient routing protocol for delay-tolerant networks

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Abstract. In delay-tolerant networks (DTN), energy-efficient node operation is vital due to battery life constraints. Energy consumption significantly impacts data forwarding, necessitating novel energy-efficient routing protocols. We begin by comparing the performance of several protocols, including CASPaR, Direct Delivery, Epidemic, Spray-and-Wait, and PRoPHETv2, using the Opportunistic Network Environment (ONE) simulator. Our findings demonstrate the superiority of CASPaR in terms of message delivery and latency. To further optimize energy usage, we propose EECASPaR, a combination of a threshold algorithm with CASPaR. EECASPaR is a single-copy, congestion-avoidance, energy-efficient protocol suitable for energy-constrained applications, promoting sustainable communication. This protocol considers the remaining node energy to make informed decisions regarding message acceptance or forwarding to neighbor nodes. Through extensive simulations with varying energy thresholds, our results confirm that EECASPaR enhances remaining node energy and reduces the occurrence of dead nodes.

Keywords: delay-tolerant networks, EECASPaR, energy efficient, routing protocols, the ONE simulator.

1. INTRODUCTION

In delay-tolerant networks (DTN), a type of mobile ad hoc network (MANET), there are no direct paths from source nodes to destination nodes. The routing in DTNs is done using a store-and-forward method, where nodes exchange information when they are in the transmission range of each other (Fall et al. 2003). DTNs offer an attractive solution for various Internet of Things (IoT) applications (Bylykbashi et al. 2018; Spaho and Dhoska 2020; Spaho et al. 2018; Spaho et al. 2019), where connectivity challenges are prevalent. In such networks, the primary components consist of wireless devices, including smartphones, laptops, tablets, and sensor nodes – all powered by limited-energy sources, typically batteries. Routing within DTNs is an energy-intensive process. Relay nodes are responsible for storing and forwarding data, which significantly impacts energy consumption. Therefore, energy conservation is a critical consideration, especially in energy-constrained environments, such as disaster response communication networks, where battery replacement or recharging is impractical.

The importance of energy conservation in DTNs extends to the network's overall lifetime. A well-planned strategy that factors in node energy when selecting relay nodes not only enhances data delivery but also prolongs the network's lifespan. Despite its significance, the development of energy-efficient routing protocols for DTNs remains an ongoing research challenge. These protocols have the potential to reduce operational costs associated with maintaining DTNs, including the frequent need for battery replacements or recharging. Additionally, energy consumption in DTNs has environmental implications as it can contribute to a significant carbon footprint. Imple-

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menting energy-efficient protocols is a step toward achieving a more sustainable future.

This research aims to address the challenge of creating a protocol that achieves a high delivery ratio while minimizing energy consumption. We initiated this endeavor by evaluating the performance of four well-established routing protocols: Direct Delivery, Epidemic, Spray-and-Wait,PRoPHETv2, and the Congestion Avoidance Shortest Path Routing (CASPaR) protocol. Simulation results demonstrated CASPaR's superior delivery probability. However, CASPaR, in its original form, does not account for the actual energy levels of selected routing nodes. To address the energy aspect, we propose an innovative approach by integrating a threshold algorithm with the CASPaR protocol, resulting in the creation of the Energy-Efficient CASPaR (EECASPaR). We conducted extensive simulations to analyze the impact of thresholds and message sizes on performance. By considering the energy levels of nodes in routing decisions, we aim to reduce the chances of routing packets through nodes with low energy, thereby mitigating the risk of premature node energy depletion. The primary contribution of this research lies in the novel combination of a threshold algorithm with the CASPaR protocol, leading to the development of EECASPaR, a single-copy, congestion-avoidance, energy-efficient protocol. This protocol is well suited for energy-constrained applications and facilitates eco-friendly and sustainable communication. The novelty of our research is exemplified by the innovative application of these algorithms for energy optimization, a context where such an approach has not been explored previously.

To underscore the significance of our research, we present key figures derived from a comprehensive analysis using the R software. The data, obtained from the SCOPUS database with keywords including "delay-tolerant networks", "energy efficient", and "routing protocols", reveal valuable insights. Notably, Fig. 1 offers a comprehensive visualization of the DTN research domain, showcasing relationships among various sources, keywords, and countries. Prominent sources include the *Ad Hoc Networks* journal, the book *Advances in Delay-Tolerant Networks*, and the *International Journal of Distributed Sensor Networks*. Keywords such as "routing", "delay-tolerant networks", and "DTN" feature prominently. In terms of global contributions, India, China, and the USA emerge as the leading countries in DTN research.

Figure 2 illustrates a co-occurrence network analysis based on abstract words, revealing intriguing insights into the collaborative landscape within the DTN research community.

Of a particular note, based on Fig. 1, is the observation that Europe appears to have a relatively lower level of engagement in this field. As such, this research assumes heightened importance as it represents a collaborative effort between Albania and Estonia, aimed at bridging this

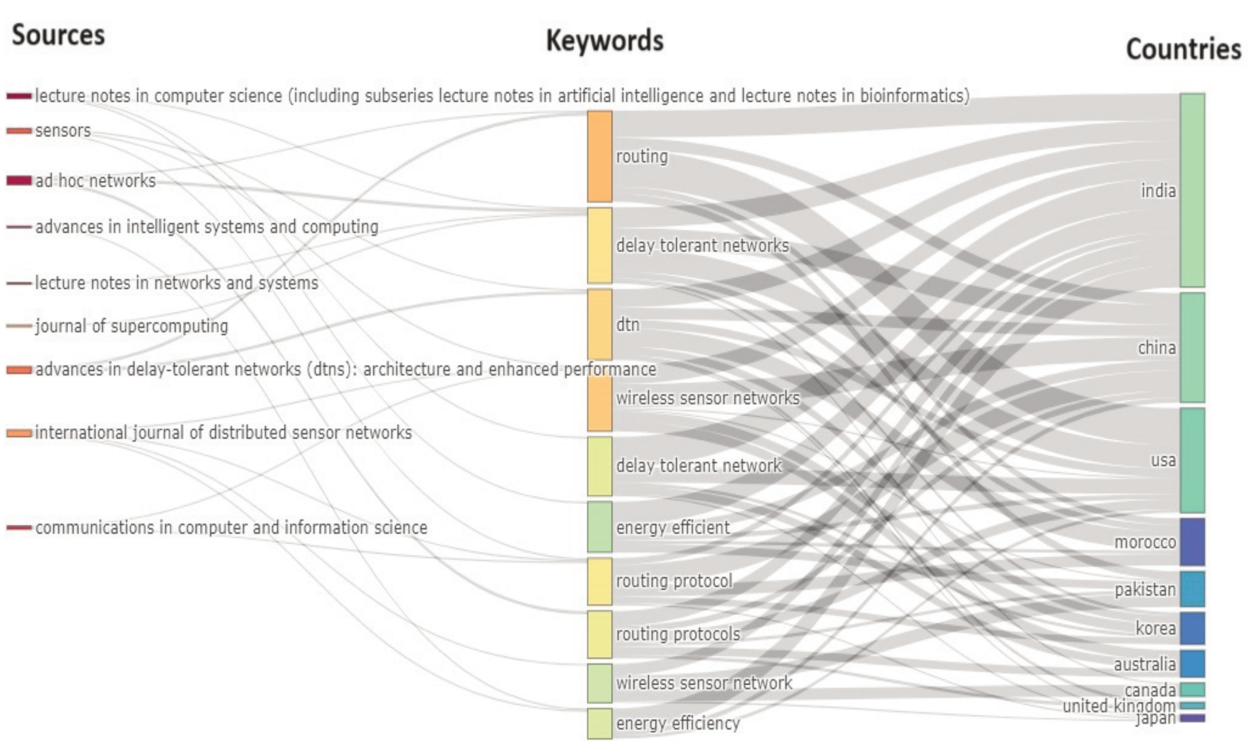

Fig. 1. Sankey diagram showing the relationship between countries, keywords, and sources.

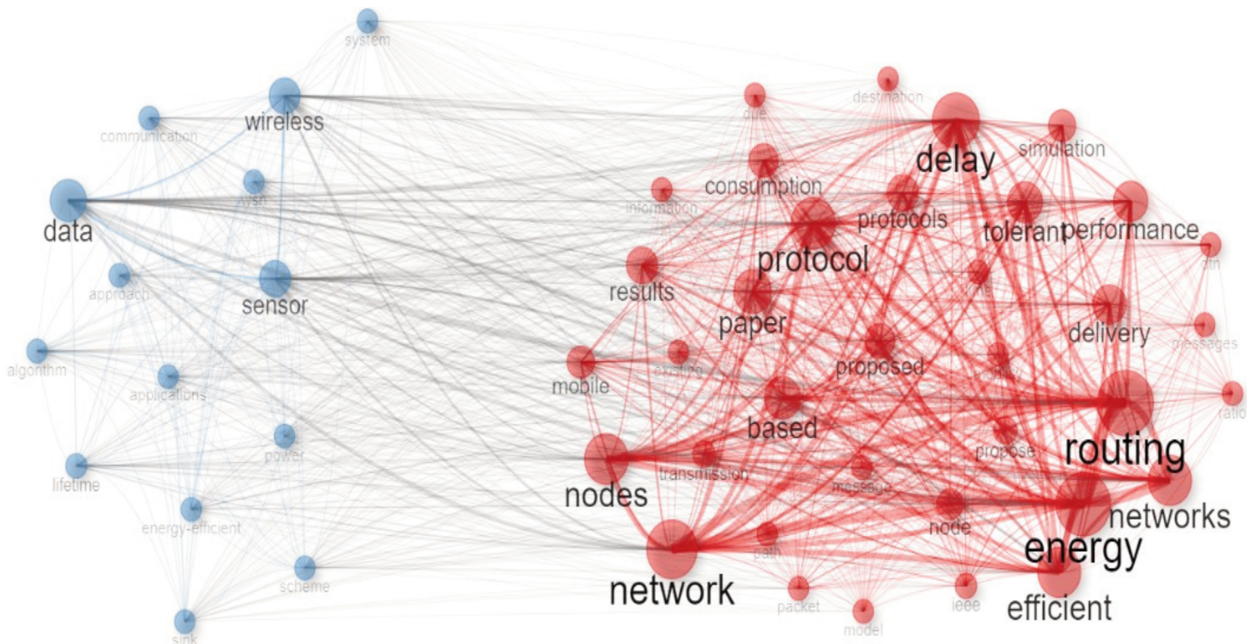

Fig. 2. Co-occurrence network analysis based on abstract words in R.

regional gap and contributing to the advancement of DTN research within Europe.

In light of Figs 1 and 2, it is evident that our work not only addresses a critical research gap in the DTN domain but also seeks to bolster international collaboration, with the goal of enhancing the contributions of European countries in this vital area of study.

2. ROUTING PROTOCOLS FOR DTNS AND BACKGROUNDS

This section briefly describes the different popular routing protocols for DTNs used for the simulations and related work on energy efficient protocols for DTNs.

2.1. Routing protocols in DTNs

2.1.1. Direct Delivery

Direct Delivery, as proposed by Spyropoulos et al. (2004), relies on a single message copy circulating through the network. The source node stores the message until it encounters the destination node. If no encounter happens, the message remains in the buffer until its TTL expires.

2.1.2. Epidemic

Epidemic, introduced by Vahdat and Becker (2000), is a multi-copy flooding-based protocol. It involves nodes sending message copies to all encountered nodes, provided there is sufficient storage space. Messages are saved in the buffer only when both space and new messages are available, resulting in high delivery ratios but increased overhead.

2.1.3. Spray-and-Wait

Spray-and-Wait, a multi-copy protocol developed by Spyropoulos et al. (2005), employs a binary variant. It consists of two phases, distributing a fixed number of message copies in the first phase and enabling direct transmission in the second phase if the destination is not reached initially.

2.1.4. PRoPHETv2

PRoPHETv2, proposed by Lindgren et al. (2004), is a multi-copy protocol that enhances delivery predictability compared to its predecessor, PRoPHET. It forwards data based on predicted probabilities, reducing network resources, and improving delivery chances.

2.1.5. CASPaR

CASPaR, introduced by Stewart et al. (2017), utilizes a single message copy and aims to establish direct routes, when possible, prevent congestion, and adapt to changing network conditions. It considers buffer availability, historical connectivity, and sends requests for cost to neighbor nodes for congestion control.

2.2. Energy-efficient routing protocols in DTNs

Efforts to address energy efficiency in DTNs include the following protocols: Shabalala et al. (2020) propose energy-efficient variants of Epidemic and Max-Prop protocols, reducing energy consumption through threshold and acknowledgment mechanisms. Bista and Rawat (2017) introduce an energy-aware variant of the Epidemic protocol, considering remaining energy and available buffer space, leading to improved network life and data delivery. Kang and Chung (2017) present an energy-aware protocol that factors in battery level, node type, and delivery predictability, demonstrating advantages over PRoPHET routing. Kaviani et al. (2016) devise new routing protocols, harnessing available energy to enhance energy utilization. By optimizing the utilization of scarce energy resources, their approaches increase packet delivery rates by as much as 13 percent. Khalid et al. (2016) propose an energy-aware version of the History-Based Prediction for Routing (HBPR) protocol, which removes unnecessary packet transmissions based on node energy. Dhurandher et al. (2014) use a genetic algorithm to select the best relay nodes, reducing residual energy and dead nodes. Mottaghinia and Ghaffari (2018) develop a protocol using fuzzy inference systems to optimize routing and buffer management based on distance and energy considerations, leading to enhanced data delivery rates and reduced transmission overhead. Khan et al. (2022) focus on evaluating energy consumption in protocols using different mobility models without proposing energy reduction mechanisms. Triadi et al. (2019) introduce decision-making-based game theory to enhance energy efficiency in urban DTNs by reducing scanning processes. These protocols aim to optimize energy utilization while addressing challenges related to network congestion, a crucial concern in intermittent and resource-limited DTNs. Congestion avoidance strategies help improve resource management and data delivery efficiency.

3. THE PROPOSED ENERGY-EFFICIENT PROTOCOL

The CASPaR protocol did not consider the energy level of the nodes it selected for routing. Taking into account the current energy level of nodes when selecting a route can help routing packets avoid passing through nodes with low energy levels, thereby decreasing the risk of nodes running out of energy. Nodes that have higher energy levels have more chances of successfully delivering messages. Therefore, considering the actual node energy when selecting a route can improve the chances of successful message delivery, especially when the network is sparsely populated. Considering the actual node energy when selecting a route can help optimize energy consumption by minimizing the energy expended during message forwarding and reducing the need for energy-intensive operations such as message storage.

When nodes with higher energy levels are selected as relays, they can forward messages for a more extended period, reducing the risk of network partition or message loss due to node depletion.

Single-copy routing protocols have lower overhead since they involve sending only one copy of the data. This conserves network resources, minimizes contention, and is generally more energy-efficient, which can be crucial in wildlife tracking and remote monitoring scenarios with resource-constrained devices.

When working with battery-powered wildlife tracking devices, energy efficiency is a primary concern. Single-copy routing reduces the energy required for data storage, transmission, and processing, thus prolonging the device's battery life.

For these reasons, we propose a combination of the threshold algorithm proposed in Kaviani (2016) and the CASPaR protocol to implement Energy Efficient CASPaR (EECASPaR). Similar work is done in Kaviani et al. (2016), where the algorithm has been successfully applied in a similar context and has demonstrated effectiveness in improving energy efficiency for protocols such as Epidemic, Direct Delivery, Spray-and-Wait, and PRoPHET.

Recognizing the advantages of Direct Delivery, a single-copy routing protocol known for its low overhead ratio and energy consumption but lacking high delivery probability, we explored another single-copy and congestion avoidance protocol, CASPaR, in this study.

The combination of the threshold algorithm and the CASPaR protocol was tested to see their novel use for energy optimization in wildlife tracking and remote monitoring applications. The novelty lies in the application of these algorithms for energy reduction during routing computations.

In the EECASPaR protocol, if the current node's energy is less than the threshold value, it will not accept to forward messages, and this process is shown in Algorithm 1. A major part of Algorithm 1 has been taken from Khalid et al. (2016), where a minimum energy threshold is set so that whenever the energy level of an encountered relay node (not the destination) is checked and found to be less than that threshold, the message will not be sent to that node.

If the energy level falls below the threshold, the nodes will not be used for the forwarding process, and the remaining energy can be used only for emergency situations. If the threshold value equals zero, then we have a protocol that does not make decisions based on residual energy. If we have the threshold value at 100%, then we are using the direct delivery algorithm.

In the proposed EECASPaR protocol, we need to find the route with the lowest cost. After finding the node as part of a low-cost route, the energy is checked. EECASPaR considers the node energy to determine whether the node will be used for the routing process. The threshold algorithm enables the user to specify threshold boundary energy. Depending on the application, a given threshold value can be chosen. When the node energy is less than the threshold energy value, the node will send the packet if it directly contacts the destination node. To conserve energy, this node cannot be used to receive data from or forward data to the other nodes. When the threshold value is zero, the protocol will not make decisions based on residual energy. When the threshold value is set to one, direct delivery will be performed. This process is presented in Algorithm 2 (Kaviani 2016).

Algorithm 1. Routing in EECASPaR, partly taken from Khalid et al. (2016)

Step1: updateRangeStatus();
updateProximityProbability();
updateStorageCosts();
updateTransmissionCosts();
Step2: Select the next neighbor node (NN)
Step3: **If** energy level of NN < minimum energy threshold (MET) **and**
NN is not destination node (DN) **then** go to Step2
Step4: **If** energy level of NN > minimum energy threshold (MET) **and**
NN is not destination node (DN) **then** go to Step2
If NN is DN then **forward** M to NN
end

Algorithm 2. Threshold algorithm

void int receiveMessage(**Message m, Host from**) {
if (Ecurrent < Eth) **then**
//Do not accept **m** for forwarding
return RCV FAIL LOW ENERGY ...}
void int startTransfer(Message m) {
if (Ecurrent < Eth) then
//Do not forward m
return TRY LATER LOW ENERGY ...}
end

4. SIMULATION SCENARIOS AND RESULTS

The CASPaR and EECASPaR routing protocols are implemented using the simulator proposed by Keränen et al. (2009). The ONE simulator is chosen because it offers several advantages over other simulators. It is specifically designed to simulate DTNs, is open source, provides a variety of realistic mobility models, and can be integrated with other tools to extend its functionality.

Table 1. Simulation parameters

Parameters	Values
Number of nodes	100
Simulation time	3600 s
Area size	1 km × 1 km
Movement model	RandomWayPoint
Interface type	Radio
Transmission speed	10 MBps
Transmission range	100 m
Message TTL	300 min
Packet size	0–500k, 500k–1M, 1M–1.5M, 1.5M–2M
Speed of movement	0.5–1.5 m/s
Message size	10k, 50k
Interval of events	1–5 s
Threshold values	0.1, 0.2, 0.3, 0.4, 0.5, 0.6

Wildlife tracking and remote monitoring often take place in challenging and remote environments, where traditional network communication protocols may not be effective due to intermittent connectivity and long delays. DTN protocols are particularly well suited for these applications because they can handle the sporadic and unpredictable nature of data exchanges.

To mimic a real-world scenario for wildlife tracking or remote monitoring, a network with 100 mobile nodes moving according to the RandomWayPoint mobility model with a speed varying from 0.5 m/s to 1.5 m/s in a one square kilometer area was simulated. The source and destination were chosen randomly. The interface transmission of the devices was 10 MBps, and the transmission range was 100 m. Other parameters used are presented in Table 1.

These metrics were considered in our evaluation: delivery probability, latency, number of sent packets, overhead ratio, remaining energy, and dead nodes. The delivery probability is a very important parameter when evaluating a routing protocol. In DTNs, because communication is realized through opportunistic contacts, a successful delivery of the packet at the destination may not occur all the time.

Figure 3 shows the simulation of the delivery probability results for five protocols with different seeds. Using different seeds in simulations helps address the inherent randomness present in many simulation scenarios and enables us to evaluate whether the observed patterns or differences in the data are robust and not merely a product of the unique conditions associated with a single seed. Each simulation was repeated several times using different random seeds for node mobility. From the results obtained, we noticed that there is a marked difference between the CASPaR protocol and Spray-And-Wait compared to the other three protocols mentioned above, Epidemic, Direct Delivery, and PRoPHETv2. In terms of delivery probability, the CASPaR protocol performed the best with a value of 88.5%. This happens because, al-

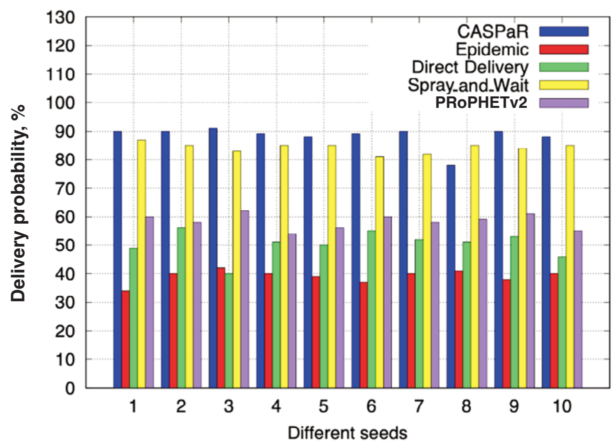

Fig. 3. Results of delivery probability for different seeds with different protocols.

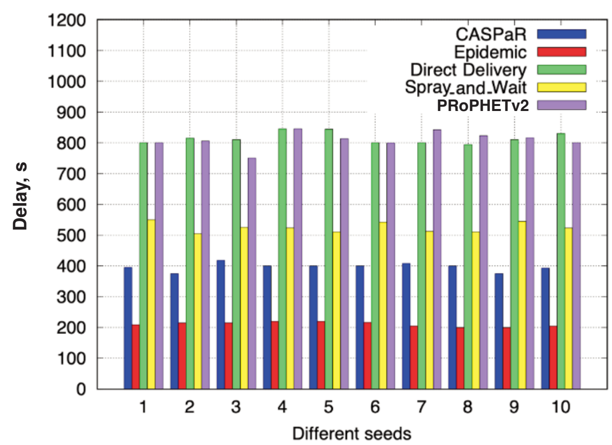

Fig. 4. Delay results for threshold with different protocols.

though nodes do not possess direct knowledge of the network state beyond their neighbors, they acquire information about the entire network through the spread of costs. This enables each node to have knowledge not only from a local perspective but also from a global perspective, leading to a more efficient packet routing.

The second in performance was the Spray-and-Wait protocol, with about 5% lower delivery probability. The third was PRoPHETv2, with a value of 59%, followed by Direct Delivery with 49.8%, and lastly, the Epidemic protocol with a 50% average delivery probability. The Epidemic protocol replicates messages from the source node to the neighboring nodes in a flooding manner, which can lead to frequent network congestion. As a result, its delivery ratio is not as effective as those of the other routing protocols.

Spray-and-Wait, PRoPHETv2, and Epidemic are multiple-copy protocols. Storing and forwarding multiple copies of data consumes more energy, especially on resource-constrained devices with limited battery life. Each copy requires energy for storage, maintenance, and transmission, which can significantly drain the battery of wildlife tracking devices.

The second parameter considered is the average delay. This is a parameter that is defined as the average total time for all packets to reach the destination. Delay is a very significant metric as it not only indicates the quantity of packets reaching the destination but is also indirectly related to delivery probability.

Based on the simulations performed, the results are presented in Fig. 4. We have noticeable differences among the protocols in the value of the average delay of sending packets to the destination. Obviously, the best protocol for the average delay metric is the Epidemic protocol. However, since this protocol has a lower delivery probability than the other protocols (Direct Delivery, Spray-And-Wait, PRoPHETv2, and CASPaR), we can say that it is worth using the CASPaR protocol. The average delay for the Epidemic protocol is around 210 s, while for CASPaR it is twice that, around 400 s, but it is significantly more efficient than the other three protocols (Direct Delivery, Spray-And-Wait, and PRoPHETv2). Third in terms of the average delay is Spray-And-Wait, with an average delay of 530 s. Direct Delivery and PRoPHETv2 have a delay of about 800 s.

In order to decide the optimal threshold value and obtain more accurate results regarding the energy, we conducted different simulations for the values of the threshold varying from 0.1 to 0.6. Figure 5 shows the results for the number of sent packets versus the threshold, and Fig. 6 shows the overhead versus the threshold. From the simulation results presented in Figs 5 and 6, the optimal number of sent packets and the overhead are obtained with

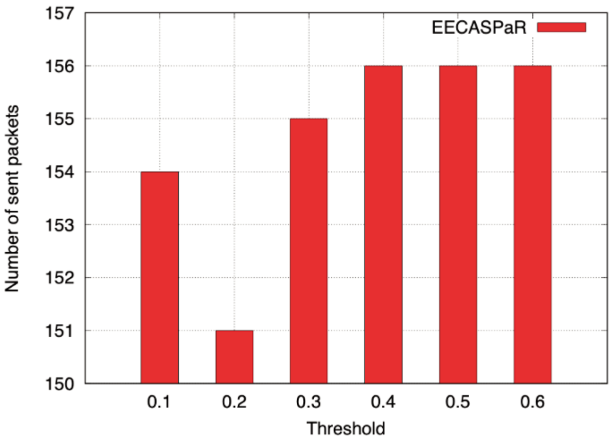

Fig. 5. Results for the number of sent packets vs the threshold for EECASPaR.

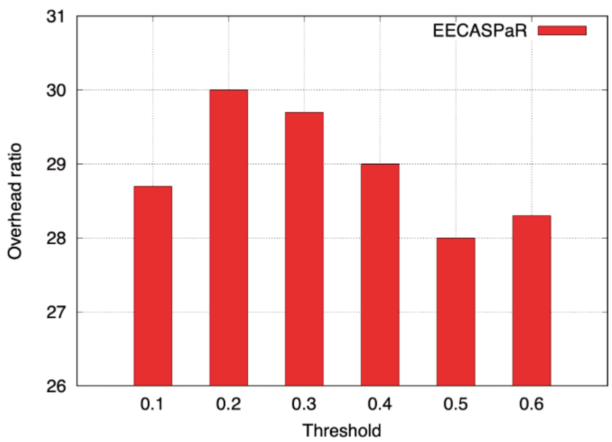

Fig. 6. Results for the overhead ratio vs the threshold for EECASPaR.

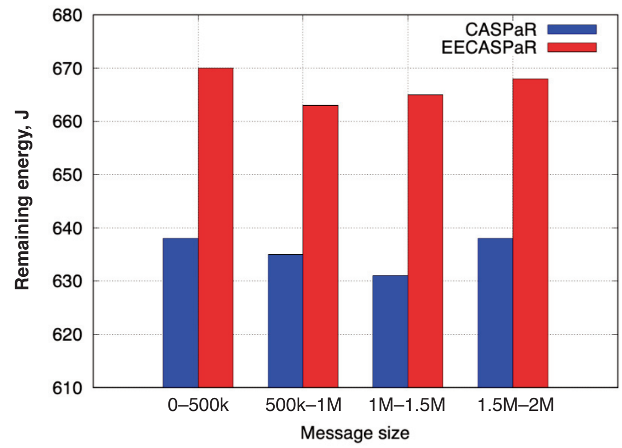

Fig. 8. Results for the remaining energy vs the message size for CASPaR and EECASPaR.

a threshold value of 0.5, which can also be confirmed by Fig. 7, which is a 3D plot of the data.

Extensive simulations were carried out to compare CASPaR with EECASPaR. The results for the remaining energy versus the message size are presented in Fig. 8. Based on the results, EECASPaR performs better in terms of the remaining energy compared with CASPaR. EECASPaR is an improved version of CASPaR, where considering the energy of the nodes for sending packets to the destination has a positive impact.

Figure 9 presents the results of the number of dead nodes versus the message size. EECASPaR has fewer dead nodes. Dead nodes refer to nodes with an energy value less than the threshold. The EECASPaR protocol selects nodes that have an energy level above a certain threshold for routing, resulting in a small number of dead nodes. For messages between 0–500K, when CASPaR is used, three nodes are dead from the 100 nodes considered. When using EECASPaR, there are no dead nodes with the increase in message size, i.e., EECASPaR performs better than the CASPaR protocol.

As a short discussion on the results, the primary objective was to address the critical issue of limited battery life in DTN nodes, emphasizing the importance of energy-efficient node operation for sustainable communication.

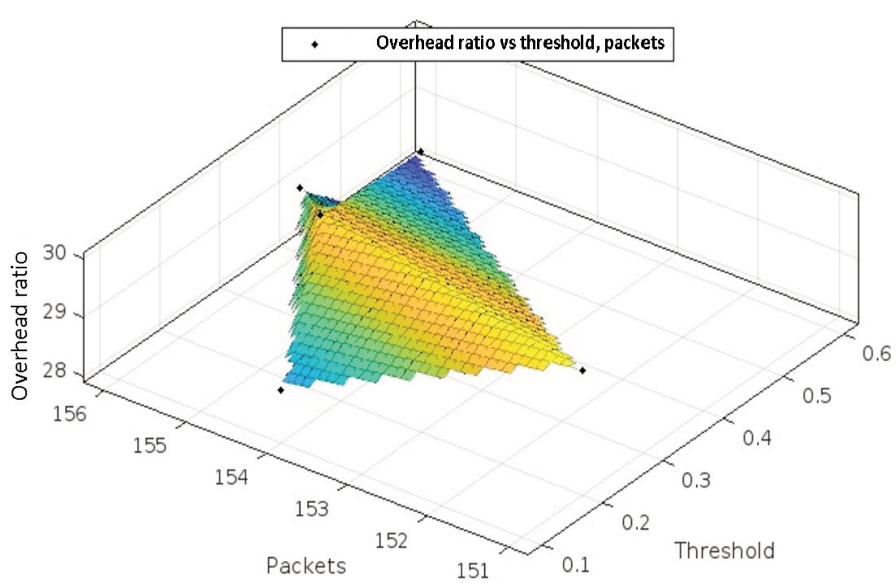

Fig. 7. MATLAB 3D plot showing the relationship between the threshold, overhead ratio and the number of packets.

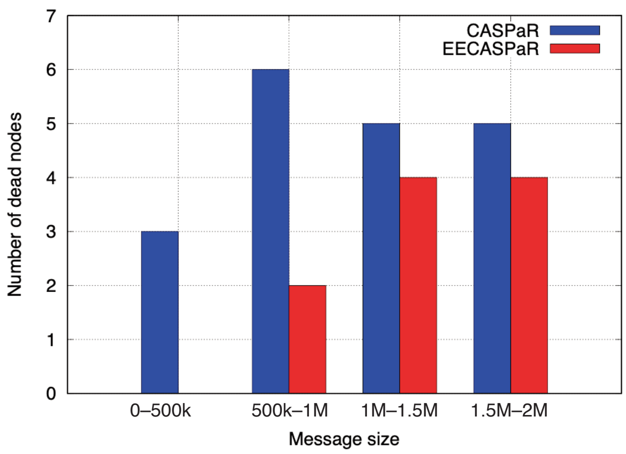

Fig. 9. Results for the number of dead nodes vs the message size for CASPaR and EECASPaR.

Performance comparison: The comparison of various existing protocols, namely CASPaR, Direct Delivery, Epidemic, Spray-and-Wait, and PRoPHETv2, using the ONE simulator, served as a foundation for this research. The results unequivocally demonstrated the superior performance of CASPaR, particularly in terms of message delivery probability and latency. This initial finding justified the choice of CASPaR as the base protocol for further enhancement.

EECASPaR protocol: The proposed EECASPaR protocol, a fusion of the threshold algorithm with CASPaR, emerged as a promising solution to optimize energy consumption during routing in DTNs. By considering the remaining node energy in decision-making processes for message delivery, EECASPaR exhibited substantial improvements over CASPaR in extensive simulations, specifically in terms of reduced dead nodes and increased remaining network energy.

Effectiveness and implementation: EECASPaR demonstrated both effectiveness and practicality. Its simplicity in implementation, combined with notable performance improvements, positions it as a viable solution for energy-constrained applications. The protocol's reliance on a predefined and fixed threshold value, while contributing to its ease of implementation, raises considerations for scenarios with high communication demands or real-time communication needs.

Application in IoT deployments: In the context of IoT deployments, especially in remote or outdoor settings, EECASPaR showcased its potential to optimize energy usage for sensor data transmission. The protocol's ability to minimize message replication ensures prolonged sensor device lifespans by conserving energy resources.

Beyond protocol-specific applications: The contributions of this research extend beyond a specific protocol. The insights gained and solutions proposed are relevant to a diverse set of challenges within the realm of DTNs. Furthermore, these findings resonate with analogous issues in the broader field of networking and communication.

The EECASPaR protocol represents a significant advancement in the quest for energy-efficient routing in DTNs. Its positive impact on network energy conservation and mitigation of dead nodes positions it as a valuable contribution to the evolving landscape of sustainable communication protocols.

5. CONCLUSIONS AND FUTURE WORK

This study introduced a novel energy-efficient routing protocol based on a threshold algorithm and the CASPaR protocol to reduce energy consumption during routing in DTNs. EECASPaR takes into account the remaining energy of nodes when selecting nodes for message delivery. Various simulations were conducted to compare CASPaR with Epidemic, Spray-and-Wait, Direct Delivery, and PRoPHETv2 protocols, and the results demonstrated that CASPaR outperforms these protocols in terms of delivery probability. Additionally, we compared CASPaR with the proposed EECASPaR, implementing the threshold algorithm with varying threshold values. The evaluation results revealed that the EECASPaR protocol significantly outperformed CASPaR, particularly in terms of reducing or eliminating dead nodes and increasing remaining network energy.

The proposed energy-efficient protocol employing the threshold approach is both easy to implement and effective. However, it relies on a predefined and fixed threshold value, and it may not perform optimally in scenarios characterized by high communication demands or the need for real-time communication.

In IoT deployments, especially in remote or outdoor settings, this protocol can optimize energy usage for sensor data transmission, ensuring longer sensor device lifespans. This protocol reduces the need for frequent message replication, thereby conserving energy resources and extending device lifespans. The findings from our research on the energy-efficient single-copy congestion avoidance protocol extend beyond the specific protocol itself. They provide valuable insights and solutions applicable to a diverse set of challenges within the domain of DTNs and correspond to analogous issues within the broader field of networking and communication.

In the future, we would like to extend our research with an adaptive approach by integrating artificial intelligence and machine learning techniques to develop intelligent routing protocols that can learn and adapt to changing network conditions and select the most energy-efficient route based on current network conditions.

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Uudne energiatõhus marsruutimisprotokoll viivitust taluvatele võrkudele

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Viivitust taluvate võrkude (DTN) sõlmed on sageli akuga elektroonsed seadmed, mille energiatõhusus on ülioluline. Energiatarbimine mõjutab oluliselt andmesuunamist, mistõttu on vaja uusi energiatõhusaid marsruutimisprotokolle. Artiklis võrreldakse mitme protokolli, sealhulgas CASPaR, Direct Delivery, Epidemic, Spray-and-Wait ja PRoPHETv2, tulemusi ONE (Opportunistic Network Environment) simulaatoris. Järeldused näitavad CASPaRi protokolli sõnumi edastamise ja latentsuse paremust. Energiakasutuse tõhustamiseks pakutakse välja EECASPaR, mis ühendab künnisealgoritmi CASPaRiga. EECASPaR on ühekordne, ummiku vältimiseks mõeldud energiatõhus protokoll, mis sobib energiapiiranguga rakendustele, soodustades säästvat suhtlust. Tehes informeeritud otsuseid sõnumi vastuvõtmise või edastamise kohta naabersõlmedele, arvestab see protokoll sõlme järelejäänud energiaga. Ulatuslikud simulatsioonid erinevate energiakünnistega kinnitavad, et EECASPaR parandab sõlmede järelejäänud energiat ja vähendab surnud sõlmede arvu.