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Analysis of the Most Relevant Factors for Routing in Internet of Space Things Networks

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Abstract: The “Internet of Space Things” (IoST) is an emerging paradigm to provide Internet and data services around the globe. IoST networks can potentially support the deployment of services in underserved areas, such as monitoring inaccessible areas for early warning applications, open ocean and sea ice monitoring, and surveillance of remote ecosystems such as forests and jungles, among others. To enable the IoST paradigm, designing and developing appropriate routing protocols is crucial. This work presents a methodology based on 2k factorial statistical analysis and an in-house developed space simulator (available upon request) to identify the critical factors affecting the performance of routing protocols in “Internet of Space Things” scenarios. The analyzed factors consider reactive and proactive routing approaches, connectivity, and the freshness of routing information. The results provide essential lessons for the research community to design protocols that could adapt under different IoST scenarios. The 2k factorial analysis applied in the study of the routing protocols' performance can be an effective tool for developing specialized routing protocols.

Keywords: routing protocols; 2k analysis; IoST

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1. Introduction

Inter-satellite networking has the potential to make a significant impact in modern society by enabling voice, data, and remote sensing applications in underserved areas [1,2] and deep space missions [3–5]. In the last decade, nanosatellite standards such as CubeSat [6–8] have focused on developing smaller, highly efficient, and cost-effective satellite platforms [9] using commercial off-the-shelf (COTS) components. For instance, CubeSats are satellites built with cubic modules denoted as “units” (U) of $10 \times 10 \times 10$ cm^3 each. Thus, the development costs of CubeSats are lower compared to other satellites [10]. Furthermore, although CubeSats were initially envisioned as an educational and research tool, currently there is a huge interest in developing commercial applications based on this kind of platform [11].

Nanosatellites (e.g., CubeSats) are commonly deployed in low earth orbits (LEO) [12]. With the increasing number of LEO spacecraft, there is a growing interest in developing inter-satellite networking solutions and applications [13,14], leading to the introduction of the Internet of Space Things (IoST) paradigm. In IoST networks, the nodes can be satellites (e.g., picosatellites, CubeSats, microsatellites, small satellites), ground stations, or terrestrial transceivers whose primary mission (function) is not necessarily the retransmission (relay) of packets within an IoST network. Thus, one of the main paradigms proposed for IoST networking involves the formation of ad hoc inter-satellite networks. In an ad hoc IoST network, satellites assume the role of nodes and participate in networking tasks (e.g., packet relay) on a temporary or intermittent basis (depending on each satellite's primary mission) [15,16]. Therefore, in an IoST deployment, satellites can play the role of both network infrastructure in space and as sensors of the physical world [10].

IoST networks have the potential to provide an in-space backhaul for connectivity in places far from the reach of terrestrial telecommunication coverage such as jungles, forests, open oceans, and polar areas [17,18]. Thus, IoST networks can enable the deployment of applications such as early warning systems for natural disasters, ecosystem monitoring, marine species monitoring, and marine weather monitoring (among others) in remote regions where no other communication options are available. However, for the IoST paradigm to be a reality, designing and developing novel networking mechanisms is necessary to deploy effective IoST networks [19].

As the nodes in IoST networks are satellites, they will exhibit high mobility and constrained energy resources [20,21]. Furthermore, the nodes in an IoST network can be microsatellites [22], nanosatellites (e.g., CubeSats) [7], or picosatellites [23]. In that case, low processing capabilities and low storage capacity should be considered essential node characteristics. Additionally, in ad hoc IoST networking, a satellite might have a primary mission not directly related to its possible role as a node in the network [24]. Therefore, its participation in networking tasks (e.g., packet relay) might be limited to idle periods within its primary mission. These issues pose significant challenges to designing inter-satellite networking protocols for IoST applications. Thus, flexible, reconfigurable, and opportunistic networking protocols are required to fulfill the potential offered by ad hoc IoST networks [25].

Mobile ad hoc networks (MANETs) offer flexible and opportunistic communication among mobile nodes forming a network without the need for coordination from a central entity [26–29]. Communication between two nodes of a MANET is carried out if (a) they are located within their radio coverage or (b) there is one or more intermediate nodes able to relay the information from one node to the other. The performance of a MANET is highly dependent on factors such as the routing strategy followed, node mobility, energy constraints, radio channel characteristics, and multiple access mechanisms and physical layer used in the transceiver. Of these factors, as explored in [30–32], the routing strategy is of the utmost importance in MANET deployments, and its performance is closely related to the particular characteristics of the deployment scenario. For instance, a routing protocol for flying ad hoc networks (FANETs) where the nodes are drones should consider energy limitations [33–36]. In contrast, in vehicular ad hoc networks (VANETs) where the nodes are cars, energy limitations are not necessarily a critical issue [37–39]. Furthermore, node mobility also has an impact on the routing strategy performance. For example, in [40], the authors compared the performance offered by the two main routing approaches in MANET, i.e., reactive and proactive routing, for different node speeds in smart city environments. They found that for this scenario, there are differences in the performance offered by proactive and reactive routing depending on the mobility (high or low) of the nodes.

As previously mentioned, one of the main paradigms proposed for IoST networking involves the formation of ad hoc inter-satellite networks, [41,42]. Previously, Refs. [43,44] explored the use of MANET protocols for the formation of ad hoc IoST networks. Although these works have shown the feasibility of using MANET protocols to form IoST networks, they did not study the differences in the performance offered by the main routing strategies in MANETs, namely reactive and proactive routing. Studying these differences is important for the development of new routing protocols for emerging ad hoc networking scenarios such as ad hoc IoST networking. This is because most MANET (including VANET and FANET) protocols have been developed considering as a starting point the adoption of: a reactive routing approach [45,46]; a proactive routing approach [30,47]; or some combination of both routing approaches (e.g., see [48]). Thus, by studying the performance differences and constraints observed and when a proactive (of which optimized link state routing (OLSR) is the base example) or a reactive (of which ad hoc on-demand distance vector (AODV) is the base example) routing approach is used in an ad hoc IoST network, a performance baseline can be provided for the design and development of new ad hoc IoST protocols. To the best of our knowledge, this study has not been previously addressed in the literature. Thus, two of the main contributions of our paper are: performing a comparative analysis of proactive and reactive routing in ad hoc IoST networking; and the identification of critical factors that affect the performance of the routing task in ad hoc IoST networks.

Among the parameters commonly considered when evaluating the performance of routing algorithms are those related to node density and the freshness of control information [49]. These parameters can affect the routing protocol performance in different ways depending on the particular routing strategy adopted (e.g., proactive, reactive, or hybrid). For instance, work done in [50] shows that tuning the freshness control parameters of the base proactive routing protocol, OLSR, improves its routing performance in VANET scenarios compared to the baseline configuration set. In this sense, different configuration sets and the interaction between parameters make challenging the task of identifying, isolating, and analyzing the impact of each parameter on the performance of different routing strategies for ad hoc IoST networking.

To be able to study routing performance in ad hoc IoST networks, a proper simulation testbed must be developed to recreate networking conditions found in space scenarios. Additionally, an adequate analysis methodology must be used to identify the critical factors for route discovery and maintenance in ad hoc IoST networks. Therefore, in this paper,+ we propose the use of a methodology based on 2k factorial statistical analysis and a testbed specifically developed for the analysis of ad hoc IoST networks, to study and identify the impact of critical factors in the performance of reactive and proactive routing approaches in ad hoc IoST networks.

The ST-INETMANET simulation testbed (available upon request) introduced in this paper was developed using OMNET++. To develop ST-INETMANET, we performed all the necessary programming to include realistic CubeSat mobility traces, radio transceivers, and propagation. The results obtained with ST-INETMANET for the proactive and reactive routing approaches in ad hoc IoST networking were then studied using 2k factorial analysis. Using this methodology, we were able to identify critical factors for ad hoc routing in IoST networks. The presented analysis assesses the baseline performance offered by reactive routing approaches by using the AODV protocol [51]. Similarly, the baseline proactive routing approach was analyzed using OLSR [52]. Without loss of generality, we used AODV and OLSR to provide a useful performance analysis baseline for the development of new routing protocols for ad hoc IoST networking, as both protocols are commonly used as reference when evaluating the performance of the routing task in emerging ad hoc networks.

In the following section, we review previous relevant work related to ad hoc IoST networks. Then we introduce the proposed methodology in Section 3, followed by the discussion of the results in Section 4. Lastly, we provide our conclusions in Section 5.

2. Related Work

As mentioned in the introduction, the goals of this paper were: to introduce a methodology for the analysis of the routing task in ad hoc IoST networks; to study and identify the impact of critical factors in the performance of reactive and proactive routing approaches in ad hoc routing for IoST networks; and to provide a useful performance analysis baseline for the development of new routing protocols for ad hoc IoST networking. Thus, prior to introducing our proposed methodology, in this section, we review previous relevant work related to IoST networking.

The IoST paradigm has been previously addressed in [10,18,19,24,41,43,53]. These works studied the feasibility of establishing inter-satellite communication links that extend the Internet of Things (IoT) concept towards networks where the nodes are satellites (or even other kinds of spacecraft), thus defining the IoST paradigm.

The authors in [10] explored the IoST paradigm and conceptually discussed a system architecture that fulfills this paradigm. As well, they discussed the challenges and constraints that must be overcome to successfully deploy IoST applications. Among the main challenges identified in this work, we can mention limited on-board processing capabilities of the nodes; considerable delays in propagation; and constraints introduced in the network topology by temporal variations, which can render satellite links susceptible to interruptions. The conceptual analysis introduced in Ref. [10] was later expanded in [19]. In this contribution, the authors further studied (by means of simulation) the duration of inter-satellite links when satellites with different orbital altitudes are considered as nodes of an IoST system. Additionally, a comparison of the physical layer performance between mmWave and S-band carriers is presented in this work.

In [19], the author's review of the main characteristics of the spacecraft that can potentially become nodes in an IoST network was provided. Based on this review, Ref. [53] further analyzed the feasibility of establishing inter-CubeSats communication links. The results in this work show that it is possible to establish effective communication links between CubeSats. Therefore, we can conclude that CubeSats can effectively participate as nodes in ad hoc IoST networks.

In [41], the authors performed a comparative analysis of features suitable for IoST networking, provided by routing protocols previously developed for other kinds of networks and applications. Notably, this work analyzed the features of protocols developed for snapshot networks, MANETs, delay-tolerant networks, wireless sensor networks, and low earth orbit (LEO) satellite networks. Based on this analysis, a set of routing protocols that might be used for IoST networking was identified. However, it is essential to note that the recommendation was only based on identified protocol features, as no performance analysis was provided. Based on their analysis, the authors concluded that MANET protocols can potentially be used for ad hoc IoST networking. However, in this work, the factors that could affect the performance of these protocols when used for ad hoc IoST networking were not thoroughly studied. In a later work [24], the authors studied the use of MANET routing protocols to form ad hoc IoST networks. In particular, they studied using an ad hoc IoST network to provide connectivity for the polar regions. As the implemented routing protocol in [24] was OLSR, the simulated ad hoc IoST network used a proactive routing approach. The reported results for this experiment showed that providing intermittent muti-hop communication to the polar regions was feasible using ad hoc IoST networking, even with relatively low node densities. Nevertheless, the authors concluded that network disruption is an ad hoc IoST networking issue that must be addressed. In addition to the work reported in [24,41], the authors further explored a proof of concept in [43], demonstrating the behavior inside the local memory when realizing data transmission between two CubeSats. This proof of concept considered using a proactive routing approach designed after OLSR and Better Approach to Mobile Ad hoc Networking (BATMAN) routing protocols. These experiments further confirmed the feasibility of using CubeSats and ad hoc routing protocols for IoST networking.

The previous review of relevant state-of-the-art addressing ad hoc IoST networking showed that it is feasible to use ad hoc routing strategies to enable IoST networks, even when using routing protocols initially developed for MANETs. Nevertheless, these protocols were not specifically designed to cope with the particular characteristics of ad hoc IoST networking. For example, as spacecraft may participate in networking tasks only during idle periods of their primary mission, the node density in an ad hoc IoST network might show high variability. Similarly, because of the different speeds, orbits, and trajectories followed by different spacecraft, the routing strategy in ad hoc IoST networks must cope with highly dynamic changes in the topology.

Therefore, to fulfill the potential offered by ad hoc IoST networking, there is the need to develop new routing protocols specifically designed for this kind of network. Nevertheless, before developing these protocols, the existing conditions of ad hoc IoST network deployments must be investigated to identify critical factors that affect network performance. This is not a trivial task; in this work, we propose a methodology based on 2k factorial analysis to identify such critical factors. The 2k factorial analysis approach has been used in different fields [54,55] to discriminate between the importance of several parameters involved in one process. In the routing research area, a few works have used this methodology [56]. For example, 2k factorial analysis was previously used in [57,58] as a statistical tool to identify the most representative factors affecting message dissemination for traffic safety applications. Here we propose using 2k factorial analysis to find the critical factors involved in the routing task for ad hoc IoST networking, intending to provide a baseline upon which new routing protocols can be designed and validated.

For the analysis, we considered the two main approaches for routing in MANETs: proactive and reactive routing. These approaches differ in the mechanism used to search and maintain network routes. Proactive protocols continuously broadcast control packets to search and maintain routes [59]. The de-facto accepted standard for this approach is the "Optimized Link State Routing Protocol" or "OLSR" [52]. On the other hand, reactive routing primarily executes route-search mechanics when information packets need to be disseminated [30]. For this approach, the de facto standard is "Ad hoc On-Demand Distance Vector" (AODV). In addition, there are hybrid protocols that combine the two approaches. The suitability of each approach is closely related to the targeted network topology and its dynamics. Proactive routing protocols are commonly used when network nodes are static or have low mobility [49], as communication links last longer. Conversely, reactive protocols are commonly used in highly dynamic topologies with frequent link disruptions [60]. However, tuning proactive protocols can improve their performance for dynamic topologies, as was shown in [50]. Thus, selecting the routing approach for ad hoc IoST networking is not a trivial task, as critical parameters for protocol performance must be identified first.

To the best of our knowledge, no previous research has formally identified the factors that significantly affect the performance of routing protocols in ad hoc IoST networks. Thus, in the remainder of this paper, we introduce our proposed methodology to identify such factors. Then, we use it to provide a comparative analysis of the performance offered by proactive and reactive routing strategies in ad hoc IoST networking. We aim to provide a baseline analysis that can further be used by the research community in the development of novel routing protocols for ad hoc IoST networks.

3. Methodology

The methodology proposed to analyze the performance of ad hoc routing protocols in IoST networks is summarized in Figure 1.

First, in the proposed methodology, a "base experiment" is defined considering a relevant case of use of ad hoc IoST networking. Then, orbits of potential nodes participating in the network are generated considering actual satellite orbits. With this information, a Monte Carlo simulation of the ad hoc IoST network was performed using our ST-INETMANET simulation testbed developed explicitly for this purpose. The resulting network performance metrics were then formatted to apply the 2k factorial analysis [61].

For this contribution, the proposed methodology was applied to find the most relevant factors affecting the search and maintenance of communication routes in ad hoc IoST networks when proactive and reactive routing approaches are used. In the following subsections, we provide the details of the experiments implemented to perform this analysis.

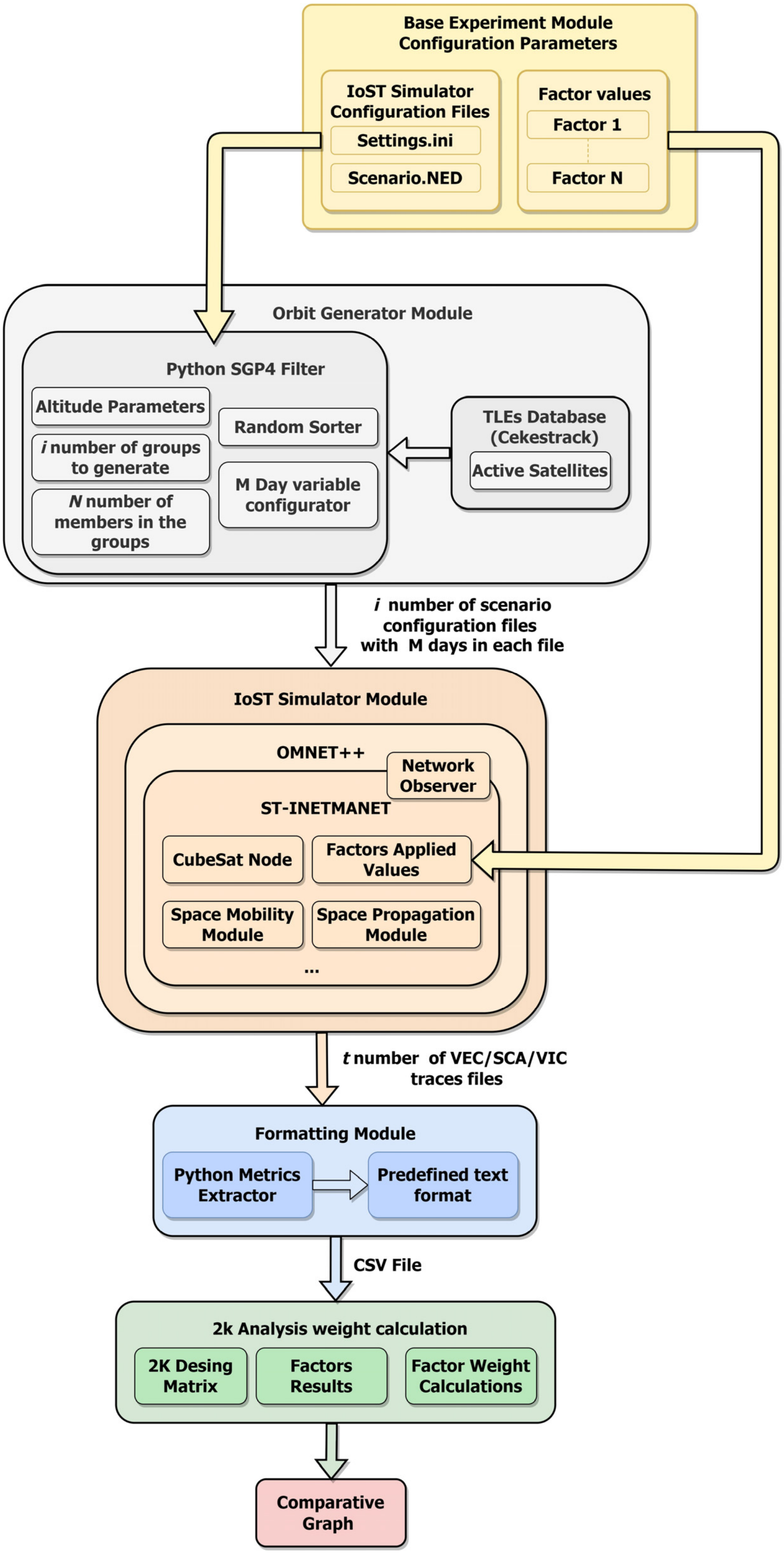


Figure 1. Flowchart of the proposed methodology to analyze the performance of ad hoc routing protocols in IoST networks.

3.1. Base Experiment

The space network mission for the base experiment considers the potential offered by ad hoc IoST networking to provide connectivity for underserved areas during natural or artificial disasters [62]. The base experiment assumes that a remotely located node sends information to an urban center through an ad hoc IoST network. The remote node is located in the Pacific (e.g., buoy) at coordinates (9°35′42.0″ N, 95°08′37.2″ W) for the implementation. The sink is located (31°52′07.7″ N, 116°39′59.1″ W) in an urban center. This scenario arises in early warning systems where an open ocean buoy transmits relevant weather and tide information to a coastal urban center. Depending on the deployment location, the ad hoc IoST network could serve as a primary or backup communication mechanism.

The "IoST Configuration files" generated as the output of this submodule contain the parameters that define the mission scenario to be executed in the IoST Simulator. The most relevant configuration parameters for this module are the number of groups (G), the number of members of each group (N), and the number of simulation days (M).

3.2. Orbit Generator

In IoST networks, satellite orbits describe the mobility of the nodes. Network topology is directly related to node mobility and parameters such as minimum link duration [30,31].

Commonly the two-line element sets (TLEs) contain encoded orbital elements upon which orbits for actual satellites can be calculated [63]. The Orbit Generator module in Figure 1 downloads TLEs from the Celestrack database [64]. These data are then formatted to feed the IoST simulator mobility module. Using the TLE data and the SGP4 model described in [65], orbits are generated for each satellite. Sets of satellites following orbits with particular characteristics can be defined using SGP4 equations to program different scenarios in the Orbit Generator (e.g., a simulation can include a predefined number of satellites in low, medium, or geostationary orbits).

The "IoST Configuration files" provided by the Base Experiment module are the input of the Orbit Generator. The module downloads all TLEs that comply with the simulation constraints. Afterward, a selection of satellites participating in the IoST network is made following predefined criteria or randomly. The outputs of this module are $I = G \times N \times M$ files appropriately formatted to be used in the IoST Simulator module.

3.3. IoST Simulator—ST-INETMANET

We developed an enhanced framework for OMNET++ called ST-INETMANET [66] to perform the base experiment. ST-INETMANET allows the simulation of ad hoc IoST networks using the files provided by the Orbit Generator.

ST-INETMANET's main modules are: "CubeSatNode", which represents the network's basic satellite nodes; and "Space Mobility Module", which defines the node's movement. A "Space Propagation Module" simulates space–space and space–Earth communication between nodes. The "Network Module" implements the routing protocols.

The "Network Observer submodule" captures all node information and traces when performing a simulation. Traces formatted for the OMNET++ Metrics Analyzer are stored in files called VEC, SAC, and VIC. The proposed base experiment running in the simulator is presented in Figure 2.

3.4. Module for 2k Factorial Analysis Weight Calculation

This module provides a tool to perform 2k factorial analysis based upon the results provided by ST-INETMANET. A formatting stage parses the VEC, SAC, and VIC files to generate CSV files with a predefined format. Formatted results are then used to calculate all the 2k factorial analysis weights using a predefined design matrix. Then, the module outputs a plot with 2k factorial analysis results and a file with numeric results.

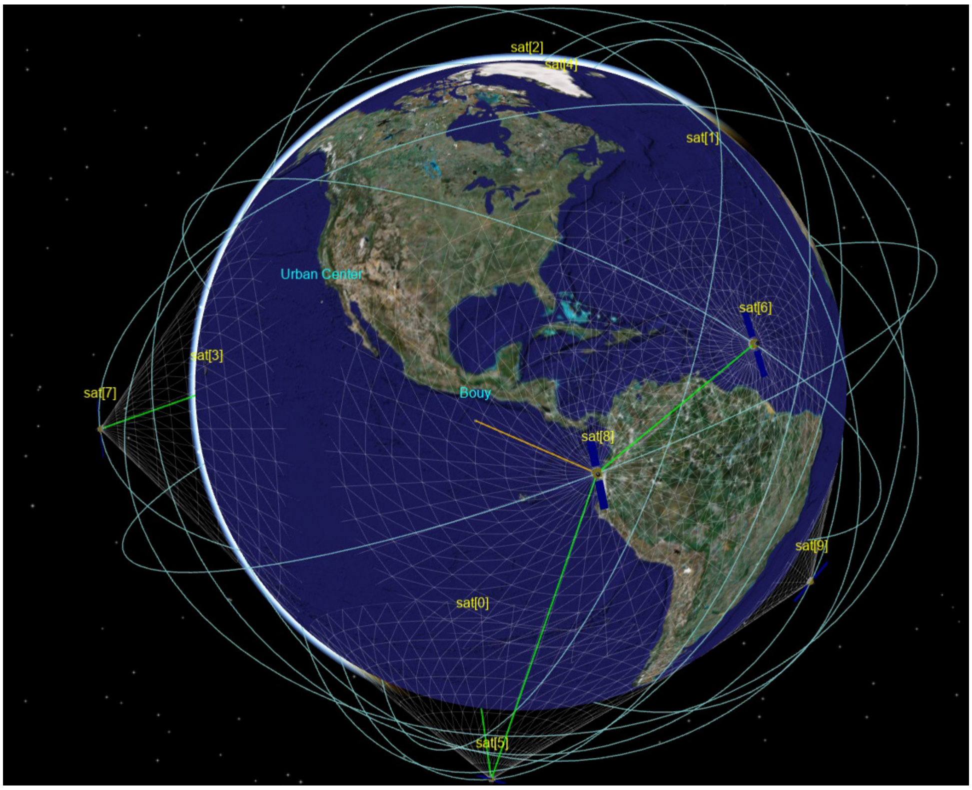


Figure 2. Simulation scenario with the selected coordinates for a buoy and urban center.

All developed modules can be provided upon request.

3.5. Routing Approaches Considered for the Analysis

As previously mentioned, the routing approach, reactive or proactive, is a factor that could affect the dissemination of information packets in ad hoc IoST networks. The reactive and proactive approaches are implemented in this work using the routing protocols considered as the de facto standards for each approach, namely AODV [51] and OLSR [52]. This section presents the main features of the base experiment for our evaluation. Network, mobility, and routing algorithm parameters are provided in Table 1.

Table 1. Simulator parameters.

Layer	**Configuration**
Transport layer	Simple Transport Layer (Not ACKS or Retransmissions mechanisms enabled)
Network layer	OLSR and AODV for routing.
Link layer (MAC)	Simple MAC.
Physical layer (PHY)	750 kbps with 1500 km of radio range
Orbit Parameters	**Configuration**
Max altitude	2000 km (LEO)
Parameter	**Value**
Number of nodes (density)	20,240
Number of groups with 20 and 240 nodes	30 and 30
Number of trials per parameter set and satellite group	10
Starting date for all trials	Monday, 3 May 2021
Days and hours for ad hoc IoST network communication attempts per trial	Monday, Wednesday, and Thursday at 12 a.m.
ad hoc IoST Network communicationSimulation time per attempt	600 s
Number of packets sent per communication attempt.	100
Satellite Model	ONION CubeSat Small platform

3.5.1. Reactive Routing Approach

The reactive routing approach aims at sending packets only when it is necessary to transmit information. Thus, reactive routing could prevent the waste of resources, especially considering the power and processing limitations of ad hoc IoST nodes.

The "Ad hoc On-Demand Distance Vector" (AODV) routing protocol is the de facto standard for reactive routing [51]. AODV initiates the basic discovery process by broadcasting a "Route Request" (RRQ) packet to find the destination node. Each intermediate node rebroadcasts the "RRQ" packet, increasing the hop counter until the "RRQ" packet reaches the "Time to Live" hop limit or finds the destination. Upon "RRQ" packet reception, the destination node unicasts a "Route Reply" (RRP) packet towards the source node to establish the route through intermediate nodes.

3.5.2. Routing Approaches Considered for the Analysis

The counterpart of the reactive routing approach is the proactive routing approach, which generates route discovery and maintenance processes regardless of whether nodes have information to send. In this approach, the most representative routing protocol is the well-known "Optimized Link State Routing Protocol" or OLSR.

In OLSR, nodes periodically exchange one-hop broadcast packets called "Hello Packets" to build their one-hop neighborhood. In addition, OLSR categorizes specific neighbors as "Multipoint Relays" or MPRs. This MPR must reach all nodes within the 2-hop neighborhood of the node. In addition, nodes periodically send "Topology Control" or TC packets, which are used to know the network topology. TC packets are flooding through the MPR nodes.

3.6. Experimental Setup

This section presents the main features of the base experiment for our evaluation. Table 1 summarizes the base parameters of the experimental setup, which will be explained in the following paragraphs.

Communication is modeled inside the nodes by four top layers and one omnipresent layer defined inside the scenario. In combination, all of the layers resemble the OSI model from bottom to top: Physical layer (PHY), Link layer (MAC), Network layer, and Transport layer.

With the revolution in accessibility to space started by initiatives such as the CubeSat standard, major global organizations such as "Thales Alenia Space" are developing projects in the emerging IoST paradigm. "Project ONION" [25] is one of the most representative projects that includes a definition of a spacecraft platform for different resources depending on the mass characteristics of the satellite.

ONION defines three types of platforms: micro (maximum of 100 kg), heavy (between 100 kg and 1000 kg), and conventional (1000 kg and more). In addition, it describes three types of radio transceivers: small, medium, and heavy, all with a radio range of 1500 km. This work modeled all the satellites as micro platforms with medium transceivers. Thus, the PHY layer of each node is configured to simulate a radio transceiver with a data rate of 750 kbps and a maximum radio range of 1500 km.

As this work focuses on evaluating the performance of the routing strategies in ad hoc IoST networks, basic MAC and transport layers are used in the experimental setup. The MAC layer explicitly provides packet encapsulation, decapsulation, and optional out-of-band acknowledgment. The Transport layer uses datagrams and a simple connectionless approach without handshakes, acknowledgments, or retransmissions (e.g., as in UDP).

The Network layer provides a unique identifier to each node. Additionally, a "Routing" module is implemented in this layer. Thus, the rules followed by a particular routing protocol are implemented in this module for each node. As previously mentioned, in this contribution, we implemented the OLSR routing protocol in this module to evaluate the proactive routing approach. Similarly, the AODV routing protocol was implemented to evaluate the reactive routing approach. Once implemented, the protocols could be interchanged in the experimental testbed whenever needed.

3.7. Factors Considered in the Analysis of Routing Strategies for Ad Hoc IoST Networks

The efficiency of routing algorithms for ad hoc networks can be assessed by measuring their performance related to their efficiency in establishing and maintaining routes. There are different factors that can affect routing protocol performance, such as active or reactive routing approach, node density, node behavior, etc. Specifically, the factors considered for our analysis of the routing task in ad hoc IoST networking are described next:

1. *Routing scheme*: Selecting the routing approach is not trivial, as the participant nodes' characteristics and network topology changes must be considered [67,68]. The two main approaches are reactive and proactive, with AODV and OLSR being the most representative protocols, respectively.
2. *Density*: A low number of participating nodes (low density) in the network reduces contention. However, this also reduces the route establishment options. Therefore, the number of nodes in the network (density) is a relevant factor in the proposed analysis. As previously explained, densities of 20 and 240 nodes were considered for our analysis.
3. *Node behavior*: In ad hoc IoST networks, satellites could eventually avoid participation because of events such as low energy or primary mission priorities. Therefore, it is essential to research the impact of node availability to partake in routine tasks. In particular, we studied the impact of having 20% of satellites in a group unable to participate in networking tasks.
4. *Hello message period (HMP):* Hello messages are broadcast packets used by routing protocols to periodically share control information with other nodes, such as geographic location, number of neighbors, and battery level. The nodes use this information to update neighbors and routing tables and perform actions related to the particular routing strategy implemented. Neighborhood information reliability is directly related to HMP [69]. However, there is a trade-off between node information reliability and the overhead caused by the periodic messages. Considering the relevance of Hello messages, this work included HMP as a relevant factor in the 2k factorial analysis.
5. *Neighbor's refresh time (NRT):* Each node maintains a neighbors table to store the routes previously found and their on-hop neighbors. Note that the age of the information in the neighbors table represents the freshness of the routing information. This work defines the NRT as the time a node is stored in the neighbors table after the last update. A short NRT allows the routing protocol to achieve early detection of broken links. However, packet loss because of interference or propagation issues could occur. Thus, a short NRT could unnecessarily trigger repair mechanisms with the consequent waste of resources. Therefore, it was relevant to analyze the impact of varying the NRT on routing performance.
6. *Number of retransmissions:* Packet retransmission is a simple and efficient strategy to cope with errors at the MAC and PHY layers. However, this mechanism can lead to increased network overhead. As retransmissions could delay the route discovery process when the network topology changes, this was a factor considered in the analysis.

Considering the number of parameters for 2k factorial analysis, the number of satellite groups generated, the number of trial repetitions per parameter and group combinations, and the different routing approaches studied, the total number of simulations performed for the analysis presented in this work is given by (1)

$$\text{Total\_number\_of\_Simulations} = 2^5 \times 30 \times 10 \times 2 = 19{,}200 \quad (1)$$

3.8. Evaluation Metric

The "Packet Delivery Ratio" (PDR) was the main routing metric used in this paper to measure the impact of the different considered factors previously described. This metric measures the ratio between the received and sent packets, as shown in (2)

$$PDR = (Received\_Packets\_At\_Destiny)/(Send\_Packets\_In\_Sender\_Node) \quad (2)$$

Note that although there are other relevant routing performance metrics such as end-to-end delay or overhead (among others), PDR provides a general assessment of routing performance, in the sense that a properly working routing algorithm will provide a high PDR.

4. Discussion

This section presents the results obtained from the proposed methodology.

4.1. Results from the Applied 2k Factorial Analysis

Table 2 provides the parameter values used for the analysis of routing strategies for ad hoc IoST networks presented in this work. The factors are as referenced. Figure 3 presents 2k factorial analysis results obtained with the proactive algorithm OLSR and the reactive algorithm AODV. This figure shows that density (e5) is the more relevant factor in the two approaches. This outcome can be explained because this factor is closely related to network connectivity, availability and quality of routing paths, and the PDR.

Table 2. Simulator parameters.

Reference Name	Factor Name	Low (−)	High (+)
e1	Neighbor's refresh time (NRT)	2 × (HMP)	3 × HMP
e2	Number of Retries (RET)	2	7
e3	Hello message period (HMP)	0.1 s (AODV) 0.2 s (OLSR)	1 s (AODV) 2 s (OLSR)
e4	Node behavior (NBH)	0% of unreachable nodes	20% of unreachable nodes
e5	Density	20 nodes	240 nodes

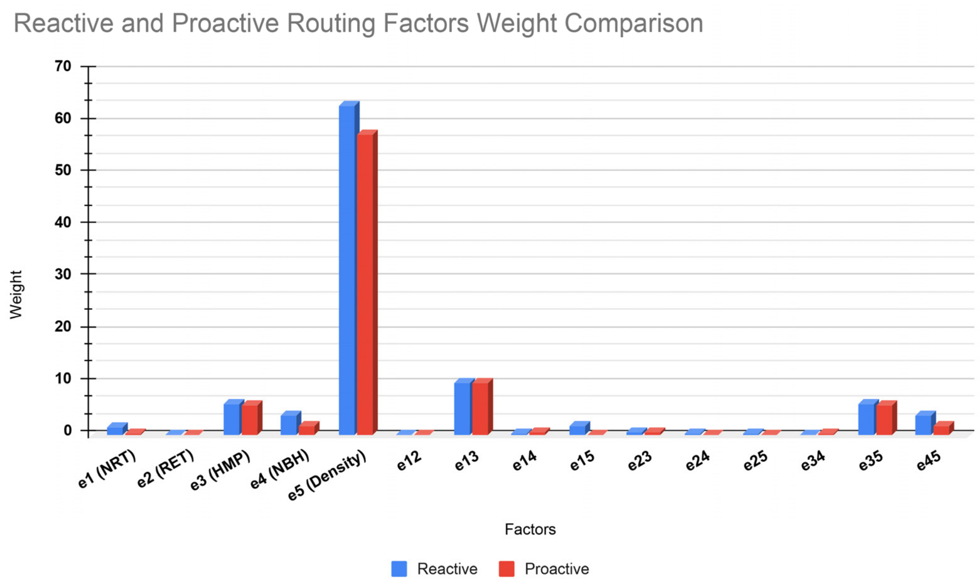


Figure 3. Analyzed factors and their combinations according to the 2k factorial analysis with proactive (OLSR) and reactive (AODV) routing approaches.

The NRT and HMP (e13) combination shows the second weight overall; thus, this is the most relevant combination. NRT defines the time a node is stored in the neighbors table.

The freshness of routing information depends on NRT and HMP; thus, its combination captures the dynamic of the network topology in terms of the links currently available. Note that the third-highest weight in Figure 3 belongs to HMP; hence, it is the second most relevant individual factor. Considering this, and the NRT and HMP combination weight, it can be stated that the dynamic of the network topology in ad hoc IoST networking must be properly addressed when designing routing protocols for this kind of network. The density and HMP combination are relevant as well (fourth weight in Figure 3), which further reinforces our previous statement.

4.2. Analysis of Factor Values Providing the Best Performance

In this subsection, we further analyze the impact of the two most relevant factors identified in the 2k factorial analysis: Density and the NRT–HMP combination. Our goal is to identify which factor values provide the best routing performance in terms of the PDR.

4.2.1. Density

Results are presented in Figure 4 for low and high density values. The results show that density plays a significant role in the network's performance. The change from low to high density increases the PDR from 9.8% and 14.6% to 84% and 80% for the reactive and proactive approaches, respectively.

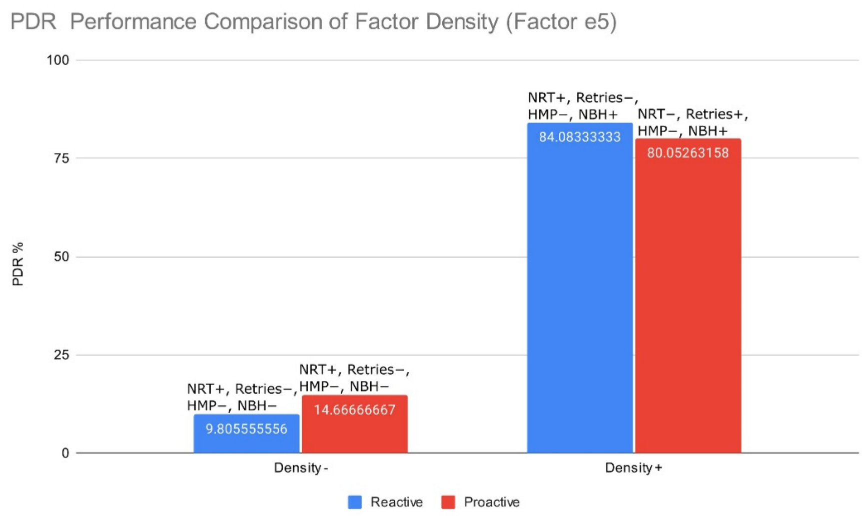
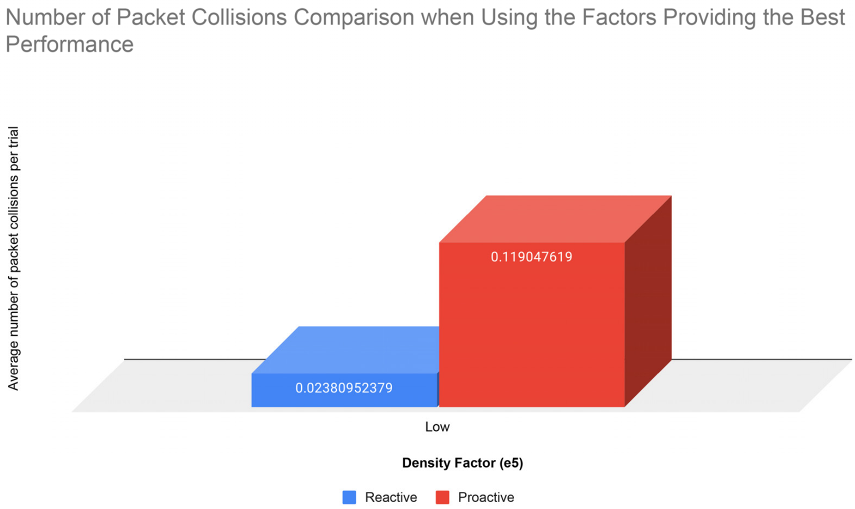


Figure 4. Comparison of factor density between the best scenarios of a proactive and reactive routing approach in IoST with high and low connectivity.

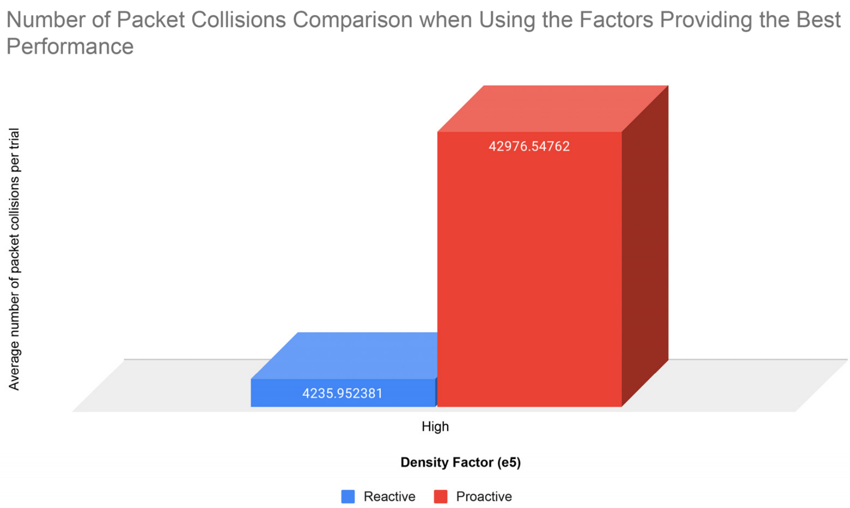
The parameters with the best performance in low connectivity scenarios are the same for both routing approaches: large NRT, a low number of retransmissions, short HMP, and 0% of unreachable nodes (NBH−). In mission-agnostic scenarios with a low density of nodes, the routing task benefits from having a maximum number of available nodes willing to participate in packet relay. At the same time, these results highlight that for low node density ad hoc IoST network deployments, large NRT with the combination of a short HMP should be preferred. The previous result indicates that the updated neighbor information is needed as quickly as possible for this case, but with more time for each neighbor as valid in the routing table (e.g., a node needs to fast-track possible changes in its neighborhood). However, the low number of participating nodes implies that it is preferable to try to send packets through older nodes rather than having no nodes in the routing table at all. Note that this applies to both routing approaches analyzed.

A short HMP also provides the best performance for high-density scenarios. However, the best value for the NRT factor is different for each routing approach. A high NRT value leads to the best performance for the reactive protocol. In contrast, a low NRT parameter works better for the proactive routing approach.

Note that the reactive algorithm outperforms the proactive approach in ad hoc IoST scenarios with high node density. Conversely, the proactive algorithm performs better in low node density scenarios. This change can be explained considering that a short HMP (low value) and short NRT (low value) increase the control information for the proactive approach. Thus, the number of packet collisions in an ad hoc IoST network with high node density should be considerably higher for proactive routing than reactive routing. This is confirmed by the results presented in Figure 5, which compare the average number of packet collisions per trial obtained using the proactive and reactive approaches analyzed in this work. Note that the results presented in Figure 5 were obtained using the factors that provide the best performance for each routing strategy. These results confirm that the average number of packet collisions in an ad hoc IoST network with high node density is significantly higher for the proactive approach than the reactive approach. Thus, this explains why, for an ad hoc IoST network with high node density, a higher PDR was achieved when using the reactive routing approach (see Figure 4).



(**A**)



(**B**)

Figure 5. Comparison of the average number of collisions in the best scenario from the factors results of a proactive and reactive routing approach in IoST with the density factor (e5). (**A**) Low node density; (**B**) high node density.

4.2.2. Combined Factor of NRT and HMP (Information Freshness e13)

The NRT and HMP parameters were fixed in the second experiment to analyze the impact of route information freshness on the routing protocol performance. Finding a stable route in dynamic scenarios such as those arising in ad hoc IoST networks is of paramount importance. Thus, detecting broken links on the fly becomes crucial. Results presented in Figure 6 consider a high value in NRT and HMP (low routing information freshness), a low value in NRT and HMP (high routing information freshness), and their intermediate combinations.

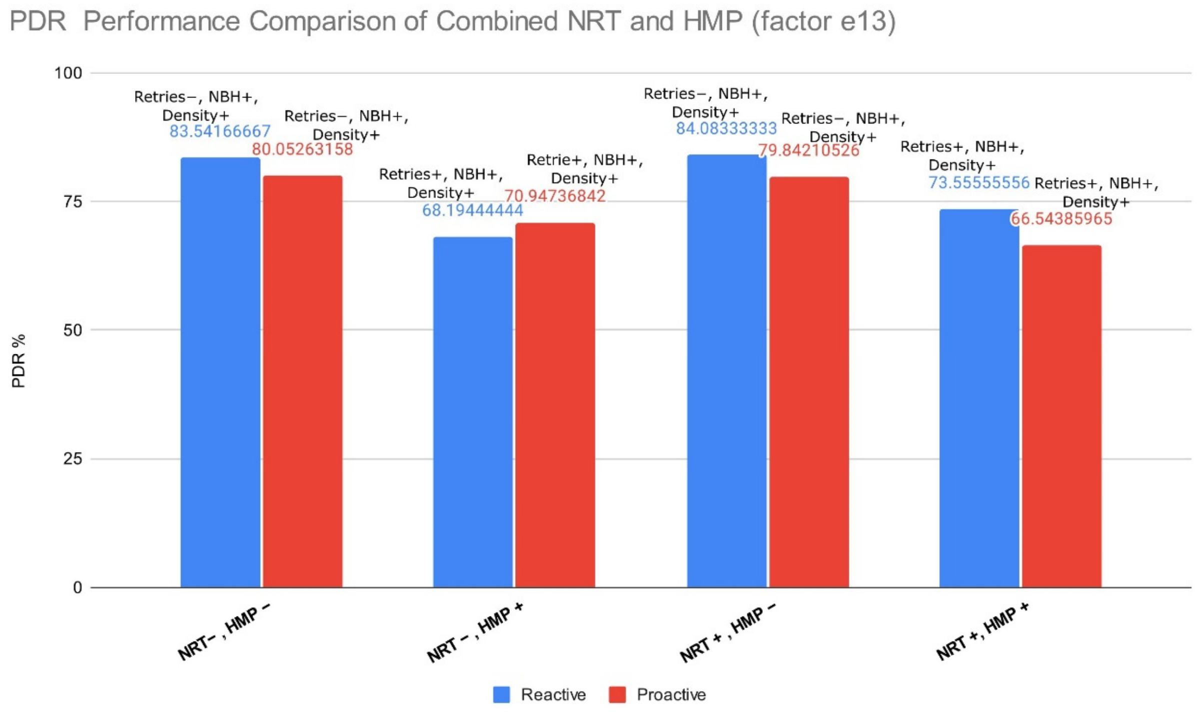


Figure 6. PDR Comparison between the best scenarios from the combination of values of the combined factor e13.

In general, all combinations benefit from a higher value in node density (e5 = Density+) and lower NBH percentage (e4 = NBH−). Both routing approaches improve their performance for the high freshness scenario. The reactive protocol exceeds the performance of the proactive protocol in most cases. As observed in Figure 7, this is due to the increase in the number of packet collisions with the proactive approach, which negatively impacts its routing performance.

For low routing information freshness, the best combination parameters involved many retries and a high percentage of NBH for both routing approaches. The proactive approach performed the worst when configured with this combination, with 66% of PDR, confirming that information freshness is essential for this routing approach.

The best combination for the reactive routing approach was a large NRT and short HMP with an 84.08% in PDR. In contrast, this approach performed the worst in a configuration with a short NRT and large HMP, with 68% of PDR. This reinforces the observation made for low densities, that for the reactive approach it is preferable to try to send packets through older nodes rather than having no nodes in the routing table at all.

In contrast with the reactive strategy, the best combination for the proactive approach was with short NRT and short HMP. This is because the proactive approach benefits from having fresher information in the routing tables.

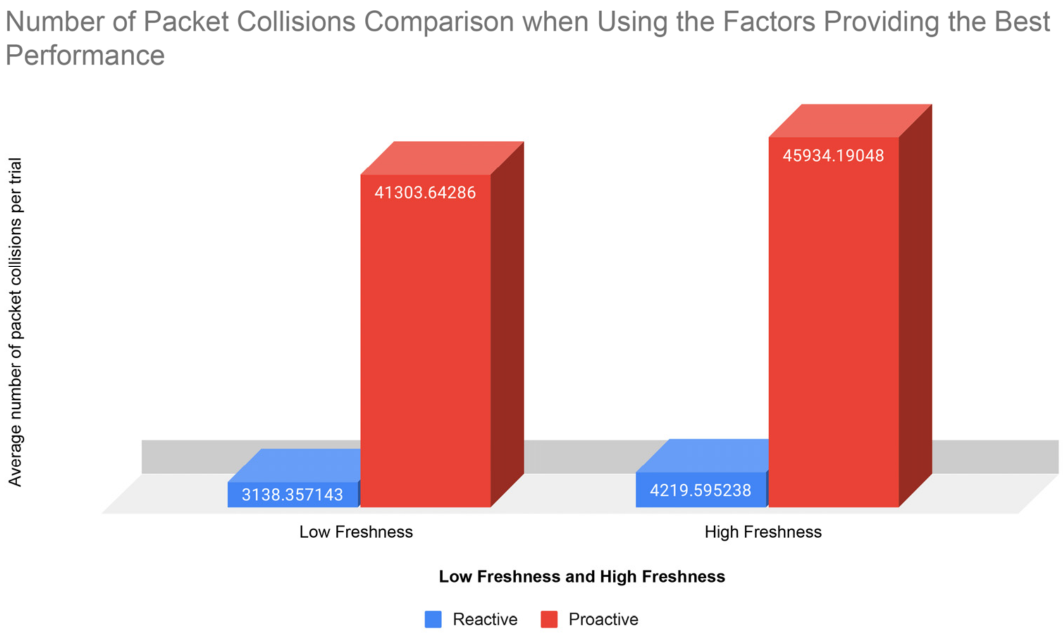


Figure 7. Comparison between the percentage of collisions from results of low freshness and high freshness.

5. Conclusions

This work proposed a methodology based on the 2k factorial analysis to find the most relevant factors affecting routing protocol performance in ad hoc IoST networks. To this end, we developed an enhanced framework called ST-INETMANET to include ad hoc IoST networking capabilities in OMNET++ and proposed using 2k factorial analysis to study the performance of different routing strategies in this kind of network.

In general, the 2k factorial analysis provided in Section 4 shows that Density is the most critical of the investigated factors for the routing task in ad hoc IoST networks. Then, the NRT and HMP combination is in second place, followed by HMP alone in third place. Next, we further discussed which factor combinations provide better routing performance for the analyzed proactive and reactive routing approaches.

The routing approach selection for different ad hoc IoST networking scenarios varies depending on the connectivity conditions. The proactive approach achieves the best performance for low node density (Density−) scenarios when the values of NRT and HMP are set to low. However, in a high node density (Density) scenario, the contention caused by the control messages (reflected in the increase in the number of packet collisions within the network) bound the routing performance. In this case, the low contention native of the reactive routing approach manages to perform better. Still, more connectivity represents better performance for both approaches.

The freshness of routing information is a crucial factor in ad hoc IoST networking. A short HMP leads to a better performance in the evaluated scenario for both proactive and reactive routing approaches. However, the periodicity of the NRT parameter must be configured according to the routing approach adopted. A short NRT helps to quickly identify broken links but also could increase errors because a temporary packet loss could be miss-identified as a permanently broken link. This could unnecessarily trigger the repair mechanism if a proactive routing approach is used in an ad hoc IoST network. Therefore, the NRT value must be carefully chosen for this approach to identify broken links without unnecessarily increasing control overhead. High routing information freshness mainly benefits the proactive routing approach with a gain of 14%.

Nevertheless, it is essential to highlight that, for high node densities (Density+), the reactive routing approach outperforms the proactive routing approach for most freshness combinations analyzed. This can be explained by the significantly higher average packet collisions observed in the ad hoc IoST network when the proactive routing approach is used. This is compared to the number of packet collisions observed when implementing the reactive routing approach.

From the analysis and corresponding discussion presented in this work, we can provide the following guidelines when addressing the routing tasks for ad hoc IoST networking:

- If the expected number of nodes participating in the ad hoc IoST network is low, then a proactive routing approach might provide better performance than reactive routing.
- However, if proactive routing is used, care must be taken in tuning the information freshness parameters to achieve good routing performance.
- For low node density, the best performance for both approaches is achieved when all considered nodes are willing to participate in ad hoc IoST networking tasks (NBH−).
- A large NRT with a combination of a short HMP should be preferred for IoST networks with low node density. The previous statement is for both routing approaches (see Figure 4).
- For an ad hoc IoST network with high node density (Density+), the reactive approach provided the highest PDR and the lowest number of packet collisions.
- Thus, if the node density in an ad hoc IoST network is expected to be high, then a reactive routing approach might be better suited for the routing task than a reactive routing approach.

Note that these guidelines can be used as a baseline for designing specific routing strategies for ad hoc IoST networking. For instance, if an ad hoc IoST deployment has significant node density variability (e.g., from low to high node density), then the analysis and discussion presented in this paper can be used as a basis for the design of hybrid routing strategies addressing this issue. In future research, we will explore the design of such hybrid protocols for ad hoc IoST networking.

Based on the presented results and the corresponding discussion, we consider that the evaluation and analysis methodology for routing strategies in ad hoc IoST networking proposed in this work, the comparative analysis between proactive and reactive routing performed, and the identification of the corresponding critical factors for the routing task provide a baseline upon which the research community can explore the design and implementation of novel routing strategies for ad hoc IoST networks.

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