Parameter-optimized routing protocols for targeted broadcast messages in smart campus environments

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ABSTRACT

The spread of handheld mobile devices integrated with multiple sensors makes it easy for these devices to interact with each other. These interactions are useful in a variety of applications such as monitoring and notification systems that can be adopted in smart campuses. The performance of these applications depends primarily on the network infrastructure and network protocols. In cases of failure, smart campus requires the provision of effective alternatives that can handle essential services. Hence, this work uses the Wi-Fi mobile ad hoc network (MANET) as an alternative backup to the traditional infrastructure. The dynamic nature of such a network relies on individuals' mobility, this leads to a lack of end-to-end connectivity. To overcome this challenge, delay-tolerant networking (DTN) has been adopted as its primary approach to routing information inside campus. Spray and wait, binary spray and wait (BSW), and probabilistic flooding protocols are deeply assessed to ensure sustained communications in the working environment. The protocols' parameters are comprehensively investigated and optimized. Moreover, the performance metrics that are used in the evaluation are messages consumption, node responsiveness, and coverage. The findings showed that the optimal protocol and its parameters is reliant upon the specific application and resources available.

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1. INTRODUCTION

With the widespread use of smart applications, the concept of Smart Campus is expected to become more important in the coming years and thus will affect the majority of university's services. Smart campus can be considered a set of fixed (stationary) and mobile sensors that can communicate via wired or wireless technologies to realize a particular service (e.g., security systems, building automation systems, operations management, people safety, and emergency) [1], [2]. The university infrastructure or cellular systems are commonly used to exchange data between smart devices and sensors on the campus but in specific cases. For instance, direct wireless network (e.g., MANET) connections can be utilized as a backup infrastructure in emergencies, as well as in the future smart development of specific applications [3], [4]. The implementation of MANET in smart campuses struggle many issues and challenges such as issues related to nodes mobility, varying signal strength in different areas, and limitations in communication range, resulting in unreliable communication [5]. Furthermore, selecting an optimal and efficient routing protocol is crucial when dealing with emergencies, signal attenuation, interference, localization, and power constraints [6]. Therefore, several routing protocols can be utilized for data transmission in smart campuses based on various research studies and directions such as spray and wait, binary spray and wait, and probabilistic flooding [7], [8]. Data transmission in wireless networks that contain mobile nodes takes a long time to reach the destination due to the impact of distribution patterns, mobility patterns, and physical factors. Therefore, this type of network connection is known as a delay/disruption tolerant networking (DTN) because of its lack of "end-to-end" connectivity, which causes significant delays [9]. DTNs have memories to store copies of messages to be exchanged between mobile nodes until they reach their destination, thus overcoming the challenges of intermittent and heterogeneous connectivity in smart campus infrastructure design. Finally, it is worth mentioning that the term (DTNs) also describes networks in which end-to-end connectivity is not available and outages are possible due to wireless radio range limitations and resource constraints [10].

Several routing protocols are considered reliable and adequate for smart campuses applications such as spray and wait and probabilistic flooding protocols [10], [11]. These protocols can address the unique requirements of smart campus environments [12]. Moreover, optimizing and balancing the trade-offs between the parameters of these protocols are considered challenging due to the nature of smart campus environments.

In addition, this research aims to analyze the efficiency of the routing protocols; spray and wait and its binary version, and probabilistic flooding used in (DTNs) for specific applications. The analysis is considered optimization-based approach that test different parameters under these protocols. Benhamida *et al.* [13] proposed solutions for using DTN in IoT applications to address the "end-to-end" connectivity challenges in a specific environment. The study provided a broad survey of the use of DTN solutions in the IoT domain. Similarly, a study performed by Fraire and Finochietto [14] presented the DTN of Things paradigm that covers new capabilities of IoT, its applications, architecture, and services. Furthermore, the authors [15] showed that the DTN routing protocol is still in use, requiring the development of a practical, reliable, and robust protocol for smart applications such as IoT. Allaoui *et al.* [15] proposed hierarchical topology DTN routing for IoT applications. Moreover, Sarros *et al.* [16] discussed how DTN can improve data collection from intermittently connected devices, such as IoT and sensor networks in remote areas.

Furthermore, Diana and Lochin [17] proposed a stochastic probability model to achieve the end-to-end delay distribution for the BSW routing protocol in DTN networks. The model was used to estimate the delay distribution of the BSW protocol in heterogeneous networks, though it lacked a mobility model and focuses on one specific protocol. Li *et al.* [18] reviewed the evolution of DTN protocol testing and evaluation but did not discuss BSW or probabilistic routing approaches. Another study performed by Abdelkader *et al.* [19] evaluated the performance of DTN routing protocols. They also explained the design of real-life scenarios that involved vehicles and pedestrians roaming in a smart city. The study used a low-density network with a maximum of 90 nodes. Moreover, Spaho [8] analyzed the energy consumption of different routing protocols in a DTN using the opportunistic network environment (ONE) simulator. They showed that the results may vary based on specific applications (e.g., smart campuses applications). Abdalla and Salamah [20] compared the performance of DTN protocols such as GeOpps, GeoSpray, MaxProp that are used in vehicular ad hoc networks (VANETs) with position-based routing (e.g., A-STAR, CAR, GyTAR) using the M-grid mobility model. The study showed that the results varied based on the applications of interest in VANETs.

In addition to the previous works in the literature, Shinko *et al.* [21] assessed the performance of VDTN routing protocols in a crossroad scenario. They evaluated the specific dynamics of user mobility and their impact on DTN protocol performance. Madamori *et al.* [22] used DTNs as a backbone for low-cost smart city infrastructure, as an alternative to relying on expensive cellular or Wi-Fi connectivity for IoT devices. Further research is needed to fully understand factors such as predictability, speed, and distribution of human movement within IoT ecosystems. The work of Agussalim *et al.* [23] examined the performance of several DTN routing protocols in a smart city scenario for Surabaya, Indonesia. The study called for more comprehensive testing and analysis. Other studies such as the one performed by Er *et al.* [24] explored the use of VDTNs for data aggregation in smart cities, extending the scope beyond vehicle-based applications. Agussalim and Putra [25] suggested a Surabaya Smart City scenario utilizing VDTN as a low-cost strategy for data collection. The authors improved the routing protocol, such as spray and hop distance (SNHD), which is significantly used in smart city implementation. The study of Goa *et al.* [26] improved the spray and wait routing protocol to address traffic tasks in urban scenarios. The work evaluated the proposed optimization only on the ONE platform, without considering other simulation environments or real-world deployments.

Finally, based on our extensive investigation of the literature, we found that there is a lack of studies that provide sufficient knowledge or guide information on the selection of the most suitable routing protocol alongside their parameters tuning for smart campus applications as well as on the design of the appropriate infrastructure to implement these applications. The literature has focused on the general implementations and comparisons of routing protocols. The contributions of this research are:

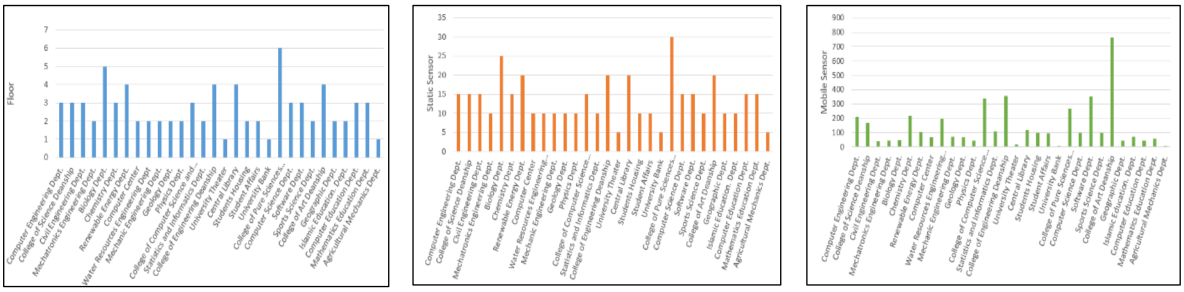
– Develop real-world simulations where the design of smart campus is adoptable to study the selection of the most appropriate protocols for smart campus.
– Provide knowledge guide for designing smart campus infrastructure by simulating real scenarios and tuning all parameters related to three routing protocols; spray and wait, BSW, and probabilistic flooding.

This document is organized as: Section 2 describes the research methodology and its details. Section 3 presents the experimental results and discussing them. The whole work is concluded in section 4.

2. RESEARCH METHOD

2.1. Simulation enviroment

The campus of the University of Mosul (USC-Mosul) is adopted to implement the scenarios of this study. This part of campus includes 30 different buildings distributed over an area estimated at 1 square kilometer as shown in Figure 1. The Figures 1(a)-1(c) contains information about the buildings, their floors, the number of static/mobile sensors (e.g., students, faculties, and staff who use the building). It should be mentioned that each person in the campus carries a smartphone that contains sensors that enable them to use the smart campus services and applications. Moreover, Figure 2 depicts the locations of the buildings on the campus map. The policy of the University of Mosul requires that each building be accompanied by a fixed number of static sensors such as fire detectors, air quality sensors, access control sensors, temperature sensors, humidity sensors, and energy monitoring sensors, which are deployed based on the size and number of floors of each building. All the information in Figure 1 was obtained from the IT team responsible for the campus network infrastructure.



(a) (b) (c)

Figure 1. USC-mosul buildings and statistics about the floors, and the number of dynamic/static sensors: (a) floors, (b) static sensor, and (c) mobile sensor

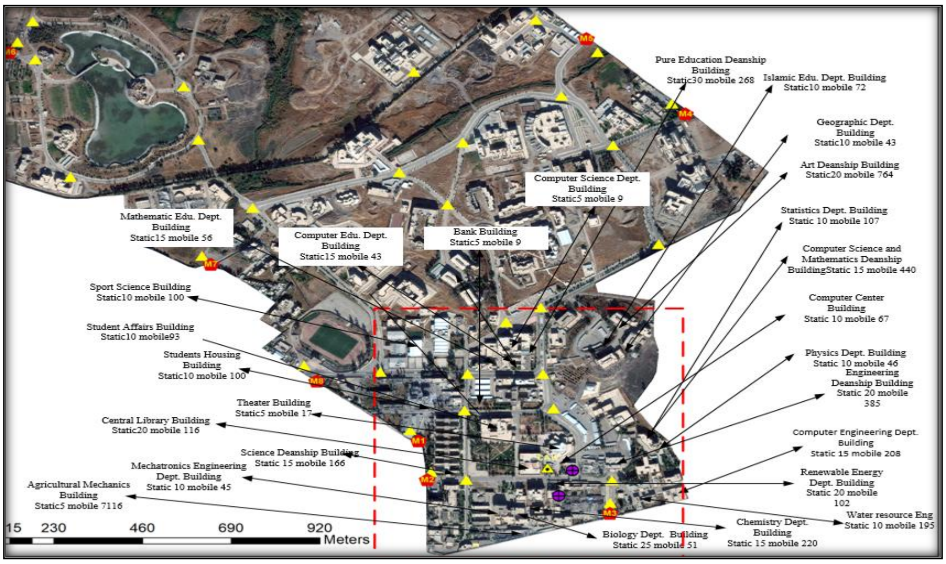


Figure 2. USC-Mosul campus area of study

2.2. Description of smart campus scenarios

In this section, the most common scenarios that the USC-Mosul is trying to adopt were highlighted:
Scenario 1 (Emergency Situation): In the event of any emergency on campus due to natural disasters including fire, flood, earthquake, electrical hazardous, or even rush hours in arrival/departure at the campus gates that may obstruct the movement of people. Such situations may cause confusion and communication failure as it frequently reported. In this case, the university officials need to exploite the MANET network to send notifications to users to remain in their colleges or leave in addition to organizing traffic.
Scenario 2 (Content Dissemination): Due to the large number of staff and students, administrators and lecturers' resort to dissemination of large files (e.g., software updates, security camera recordings, and educational videos) efficiently in order to avoid network congestion and rely on a central server.
Scenario 3 (Safety and Security): To enhance the security policy in campus and create a safe environment, the university has connected more than (100) cameras distributed inside the campus and at the main gates. This accelerates the response to emergencies situations and send a distress call to security personnel inside the campus as well as monitoring guests and tracking any abnormal behaviour that could threaten the safety.
Scenario 4 (Announcements): The administration resorts to using advertisements to send specific information to people inside a building affiliated with a college through social announcements directed to some groups inside the campus, which can contribute to effective communication and targeting specific buildings with related groups. This scenario also includes sending notifications during university events.

2.3. Setting up experiments

The settings of the proposed experiments are illustrated as follows:

- Routing Protocols: Three main routing protocols are used:
  a) Probabilistic flooding: This protocol stands out as a solution for networks with intermittent connectivity where there is no guarantee of the possibility of communication at any time between nodes because it consumes network resources. It relies on the principle of predictability of delivery based on pre-determined probabilities, which can enhance the delivery rate of message and minimize the cost of low-level communication [12].
  b) Spray and wait: It works like its predecessor in networks with intermittent connectivity, but it depends on a strategy involving two phases for routing messages. The first is called Spraying, where the source node sends copies of the message with a pre-defined value (L) to randomly selected nodes. The second is called Wait, where if the destination node is not reached in the spraying phase, the node that has a copy of the message forwards it only to its destination directly [7].
  c) Binary spray and wait: similar to its predecessor (spray and wait) in terms of its working strategy, but it relies on binary distribution. That is, when a node carrying copies of messages (received from the source node) encounters another node that does not carry any copies it sends half of its copies to the new node and so on. This process continues every time it encounters a new node until it has one copy left, direct transmission occurs to the destination at this moment [27].
- Movement Patterns: Levy Flight is the mobility pattern used in this work [28]. Typically, this model making nodes cross the working enviroment borders for this reseon the model is altered by Levy Flight with Exponential Cut-off that make the nodes to move inside the enviroment. Consequently, this model is best pattern for this research that reflect the mobility of staff and students inside the the campus.
- Evaluation Metrics: To evaluate the experiments performance carried out in this work, three metrices were used: 1) Fraction-covered areas within the university are covered by the dynamic nodes. 2) Number of messages produced by nodes in a simulation environment. 3) Fraction of acknowledged nodes, which is the number of nodes received messages. These metrics offer an understanding of the network's performance, message delivery effectiveness, and resource impact on nodes [28], [29].
- Communication: The nodes within the USC-Mosul use Wi-Fi technology for communication whether static or dynamic. Also, 50 meters is proposed as the reliable communication range between nodes where the channels with free noise and communication in a free space.
- Nodes Distribution: The Gaussian approach utilized to represent fixed nodes within the USC-Mosul accurately reveals the actual distribution of buildings on the campus, as illustrated in Figure 1. Similarly, this approach is applied to the distribution of people on the campus. Rather than being concentrated in one location, the nodes in USC-Mosul are spread across various individual places that approximately adhere to a Gaussian distribution [30], [31].

2.4. Experiment features

The simulator that is used for simulating the USC-Mosul is NetLogo. Moreover, the University of Mosul environment is simulated in terms of dimensions, node mobility, and routing strategy, in addition to adjusting the parameters and other details of the simulator as shown in Tables 1 and 2. It is worth noting that in this study, three scenarios were simulated where each scenario used one of the previously mentioned routing protocols (probabilistic flooding, spray and wait, and binary spray and wait) respectively with changing the value of the parameter (δ = 0.1, 0.5, 0.9) respectively in the first scenario. As for the second and third scenarios, the parameter (L = 3, 5, 7, 10, 20) was changed respectively as well. Note that each scenario was run for 30 times when making each change. For rapid implementation of these experiments, the distributed processing principle was activated, which enables the simulator to distribute the loads on the CPU cores of the workstations. Finally, the results are stored in the form of. CSV files and (R language) are used to plot the results.

Table 1. Specifications of the experimental setup for simulating the USC-mosul

Item	Value
Static nodes (SN)	405
Mobile nodes (MN)	4219
SN Range of communication	Wi-Fi (50 m)
MN Range of communication	Wi-Fi (50 m)
SN distribution	Lattice deployment
MN distribution	Normal (Gaussian) deployment
Routing protocols	Probabilistic flooding, spray and wait and its binary version
Pattern of movements for MN	Levy flight with exponential cutoff
Frequency of execution	30

Table 2. Parameter tuning of the experiments

Parameter	Value	Description
Delta	0.1, 0.5, 0.9	Probabilistic flooding adjustment is a critical parameter in probabilistic flooding protocols that helps balance reliability and efficiency in message dissemination across a network.
Alpha	1.55	Alpha (α) Levy flight movement patterns adjustment improves routing protocols by optimizing data paths through adaptive exploration and exploitation of routes, enhancing efficiency, load balancing, and energy conservation.
Cutoff Length	3, 5, 7, 10, 20	It refers to a predefined distance threshold that determines the maximum allowable distance for communication between nodes in a network.
Cutoff Time	850	It refers to a specified time threshold that dictates how long a node will wait for a response or acknowledgment before considering a route as inactive or failed.
Back Time	100	It refers to the duration a node waits before attempting to re-establish communication or a route after a failure or timeout occurs.

3. RESULTS AND DISCUSSION

3.1. Results

Three main experiments were designed, one for each protocol, based on the considered scenarios. The output results of each experiment represent the average of 30 runs. These runs produced different results due to the presence of a dynamic pattern of nodes that can be deployed differently in each experiment. Consequently, averaging the 30 runs reveals the actual behaviour of the experiments. To verify the results, boxplots were used to illustrate the findings and provide valuable insights into the central tendency, spread, and skewness of data as well as enrich with a better understanding of the overall performance and variability of experimental conditions. The analysis approach of this work enables to draw meaningful conclusions and identify any areas that warrant further investigation the experiments (as observed later in this section).

The results of the experiments for the implemented protocols BSW, spray and wait, and probabilistic are summarized in Table 3 aiming at giving an overall view of the behavior and then take more insight. In the experiments, the parameter L dealt with (spray and wait and BSW protocols), while delta is a parameter that dealt with probabilistic protocol. The two parameters were involved to explain their impact on the behavior of the protocols. In addition, three metrics were taken into account for comparison in order to measure the performance of the network; 1) the number of messages consumed that were copied and distributed across the network. 2) the places covered with communications. 3) Acknowledged nodes which describe the probability of receiving an acknowledgment (ACK), which can be expressed as a percentage of nodes participating in the transmission. Finally, the time of full convergence (in hours) is the time required to achieve full convergence of the working area and the average time (in hours), that is required to finish the experiments.

As shown in Table 3, for BSW, the number of messages was significantly increased from 448 to 1271 with higher L factor values from 3 to 20, which increased to 180%, while the time required to finish experiments decreased from 295.2 to 234.3, which means the decrease of 20%. The number of acknowledged nodes is also raised from 0.1455 at L3 to 0.2895 for L20, which in turn speeded up message delivery but will add overhead to the network. On the other hand, the results of the spray and wait protocol exposed that the number of messages consumed grew gradually from 502 at L3 to 1267 at L20 to reach 152% percentage when the time required to complete the experiments declined from 396.8 to 163.2 representing a 59% reduction with the same change in the L factor. Furthermore, the number of acknowledged nodes rose from 0.1628 at L3 to 0.2908 for L20, this variation resulting in greater overhead on the network compared to the BSW protocol. Finally, the results of the probabilistic protocol showed that the number of messages consumed diminished from 3876 to 3565, an 8% reduction as Delta increased from 0.1 to 0.9. In the same way, the time required to finish the experiments dropped from 7.78 hours to 3.86 hours, a 50% decrease with the same change in Delta. The number of acknowledged nodes also declined from 0.84 at Delta 0.1 to 0.772 at Delta 0.9. As the probabilistic protocol requires less amount of time compared to other protocols, it imposed a higher overhead on the network than BSW and spray and wait.

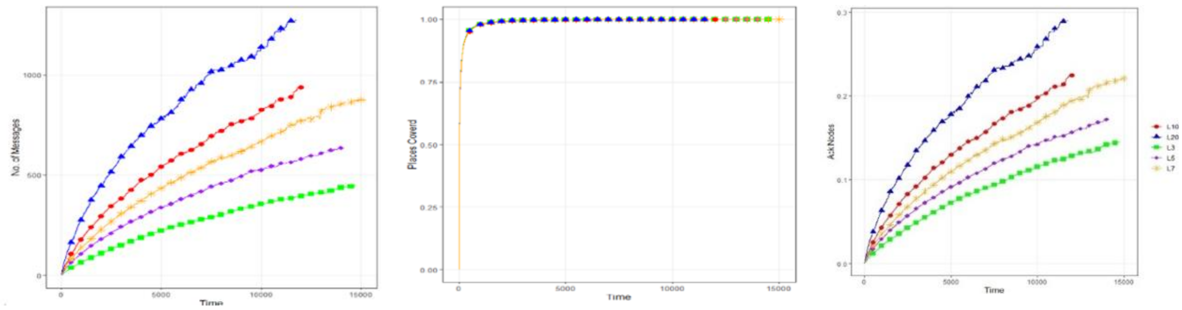
Table 3. The peak observation of the results

	Parameters	Messages	Fraction of places covered	Fraction of nodes acknowledged	Time full convergence	Average Time (hour)
Binary spray and wait	L3	448	0.9998	0.1455	295.2	295.3
	L5	636	1	0.1729	238.5	280.02
	L7	876	1	0.2209	266	300
	L10	936	1	0.2248	202.02	241
	L20	1271	0.9998	0.2895	234.3	234.6
Spray and wait	L3	502	1	0.1628	289.2	396.8
	L5	720	1	0.1945	261.16	349.3
	L7	856	0.9999	0.2162	275.6	276.42
	L10	990	0.9994	0.2378	233	260
	L20	1267	0.9994	0.2908	163.2	163.5
Probabilistic	Delta 0.1	3876	0.9281	0.84	7.78	7.78
	Delta 0.5	3767	0.9028	0.815	4.46	4.46
	Delta 0.9	3565	0.8919	0.772	3.86	3.86

Figure 3 depicts the benchmarking of the BSW protocol. It also highlights the average maximum message consumption, the average maximum covered area, and the average maximum percentage of nodes that received messages, respectively. Figure 3(a) reflects a clear inverse relationship between message consumption and the time required for message delivery. As the L factor increases, message consumption grows, while the time of message delivery decreases. However, an exclusion was observed at L=7, where the protocol showed a deviation from its typical behavior. This anomaly suggests that aspects such as network dynamics or node distribution might have impacted the message delivery process. Despite the increase in the number of messages, the time taken also increased for two reasons: The first reason is the movement patterns characteristic at the USC, and the second is the challenge of locating an adjacent node that assists in relaying the message. Additionally, there is a decline in the rate of message increase likened to the initial starting point. For example, when changing the L factor from (3 to 7) the number of messages increases by double, while changing the factor from (10 to 20) the messages rise slightly. On the other hand, Figure 3(b) shows that the areas covered by communications are almost fully achieved across all cases as the spray factor (L) increases from 3 to 20. This comes at the expense of time, as a higher L reduces the time needed for full convergence, as indicated in Table 4. Meanwhile, Figure 3(c) shows that increasing the spray factor (L) leads to a greater number of reachable ACK nodes in the same given time frame. It can also be useful in understanding the trade-offs between the spray factor and the ACK node dissemination performance in a binary spray-and-wait protocol, which is a common technique used in delay-tolerant network environments. The number of ACK nodes reached is an important metric, as it indicates the level of message delivery confirmation in the network.

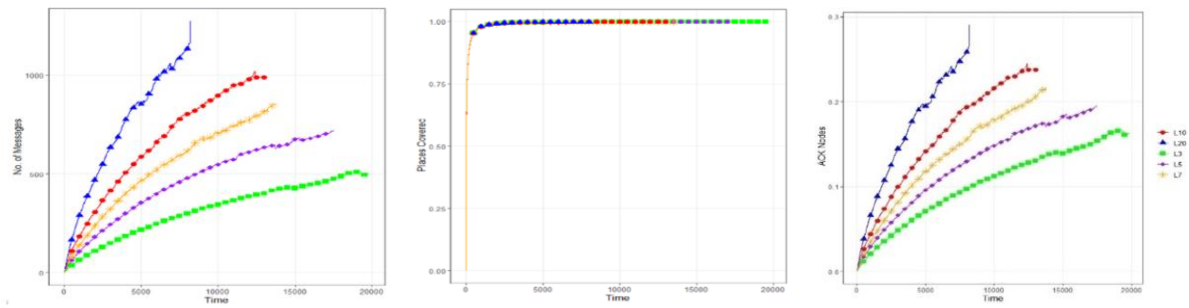
Figure 4 depicts the benchmarking of the spray and wait protocol under the impact of changing the spray factor (L= 3, 5, 7, 10, 20) for the same metrics in the previous protocol. As the spray factor increases the number of messages consumed increases as shown in Figure 4(a), but the time required for the message to reach its destination decreases Table 4. Also, the coverage places were almost obtained completely as shown in Figure 4(b) at a time rate that decreases as the spray factor (L) increases. Figure 4(c), demonstrates that the number of nodes that receive data messages (ACK) increases when spray factor (L) increases. This behavior is expected because, with more nodes, there will be more possible paths for the message to travel, and eventually will lead to more message duplication and potential message loss.

Moreover, it is observed that the BSW protocol outperforms the spray and wait protocol in two ways; First, it takes less time to route the message to its destination, due to the binary distribution strategy it adopts. Second, the number of nodes receiving the messages (ACK) is less, which reduces the overhead and consumption of network resources.



(a) (b) (c)

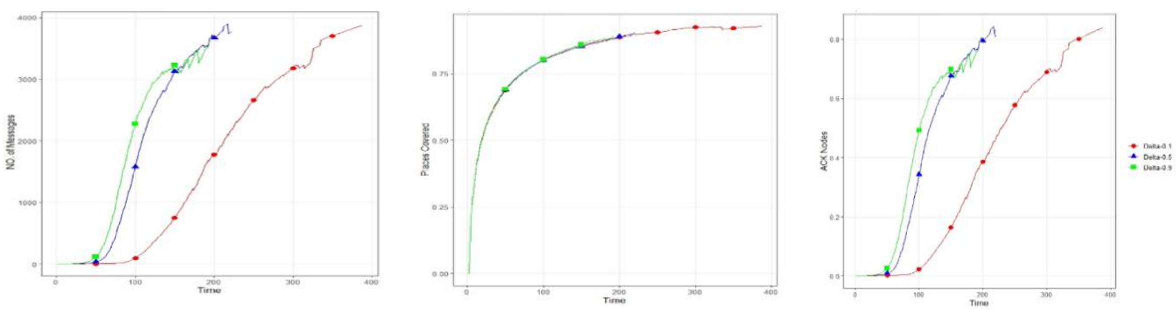
Figure 3. Benchmarking the binary spray and wait in terms of: (a) messages, (b) USC-mosul places covered, and (c) acknowledged nodes, for different values of L-factor



(a) (b) (c)

Figure 4. Benchmarking the spray and wait protocols in terms of in terms of: (a) messages, (b) USC-mosul places covered, and (c) acknowledged nodes, for different values of L-factor

Figure 5 depicts the probabilistic flooding protocol benchmarking. Therefore, in Figure 5(a) an inverse relationship was observed between increasing the factor (delta = 0.1, 0.5, 0.9) and the number of messages consumed, which is expected because a higher delta value indicates a higher probability of the node forwarding the message. The increase in delta value was accompanied by a decrease in the covered places obtained and the number of nodes that received data messages (ACK) as shown in Figures 5(b) and 5(c) respectively, which reduces the overhead and consumption of network resources. Finally, a slight increase in delta affected the time metric, which was reduced by half for the message to reach its destination.

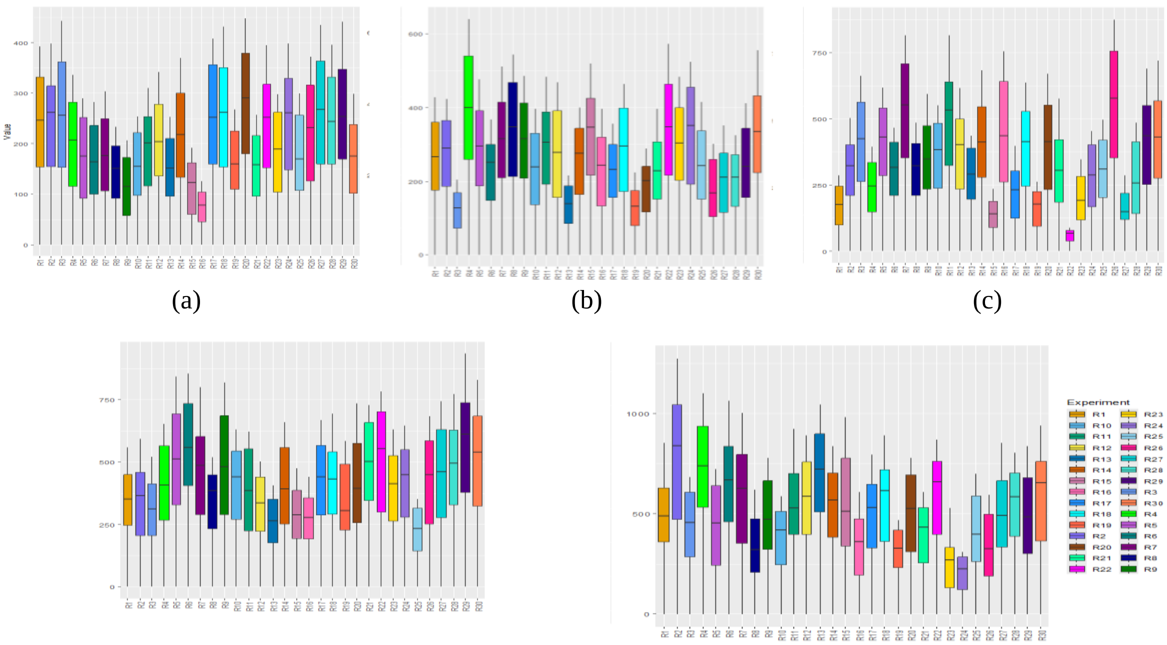


(a) (b) (c)

Figure 5. Benchmarking the probabilistic flooding in terms of in terms of: (a) messages, (b) USC-mosul places covered, and (c) acknowledged nodes, for different values of delta

Furthermore, the three routing protocols across the three metrics were evaluated. Figures 6 to 14 present the boxplot analysis for all experiments conducted. The figures show multiple-coloured bars, each representing a different replicate (R1, R23, R10, etc.), where R denotes a run, for each experiment. The y-axis displays the value measured such as the number of messages, the fraction of covered places, and the fraction of acknowledged nodes, whereas the x-axis lists the different experiments. This type of visualization allows for a comparison of the values across the various replicates and experiments. As can be seen in the following figures, all runs contain outliers as a result of the mobility pattern used in the experiments. Figures 6(a)-6(e), Figures 7(a)-7(e), and Figures 8(a)-8(c) show the boxplot of the number of data messages when varying the parameters L (for spray and wait) and delta (for probabilistic flooding). At the first quartile of each run, it is an evident that the performance is nearly stable with delay in spray and wait and binary spray and wait. This is reasonable because the node location on the map could be far enough to get fast messages, therefore the simulations consume longer time to initiate spreading messages, especially with no intermediate nodes to transfer messages. Moreover, the figures also show a relatively different number of messages for the same protocol parameters. This is a normal situation considering the routing protocol algorithm. Some experiments for calculating messages show chief values for at least one of the replicates, indicating they may be outliers.

Every experiment reflects different levels of consistency among its replicates. While some replicates show tightly clustered values, others show much greater variation. As the results of certain experiments differed across replicates, it may be an indication of how the mobility pattern affected the experimental conditions. Similarly, Figures 9(a)-9(e), Figures 10(a)-10(e), and Figures 11(a)-11(c) show the fractions of covered places in the USC-Mosul using the three routing protocols when varying the parameters L and Delta. However, it can be observed that many outliers are shown in the figures. The reason behind this behavior is that when the simulations start, most of the area are not reached by the nodes, which causes most of the areas not covered. A different pattern is noticed when testing the variations in the fraction of acknowledged nodes in USC-Mosul, as illustrated in Figures 12(a)-12(e), Figures 13(a)-13(e), and Figures 14(a)-14(c). From an application perspective, the fraction of acknowledged nodes and their response to an event indicate that the message reaches a larger portion of the population. However, this increased sharing may strain system capacity by consuming critical node resources, which potentially affects the overall reliability and response time of the system. The boxplot reveals mostly stable behaviour when observing the fraction of acknowledged nodes in USC-Mosul. While instability can pose a weakness in system design, it is essential to predict performance and prepare plans accordingly. On the other hand, this variability also provides valuable insight into the predictability of node participation in responses.

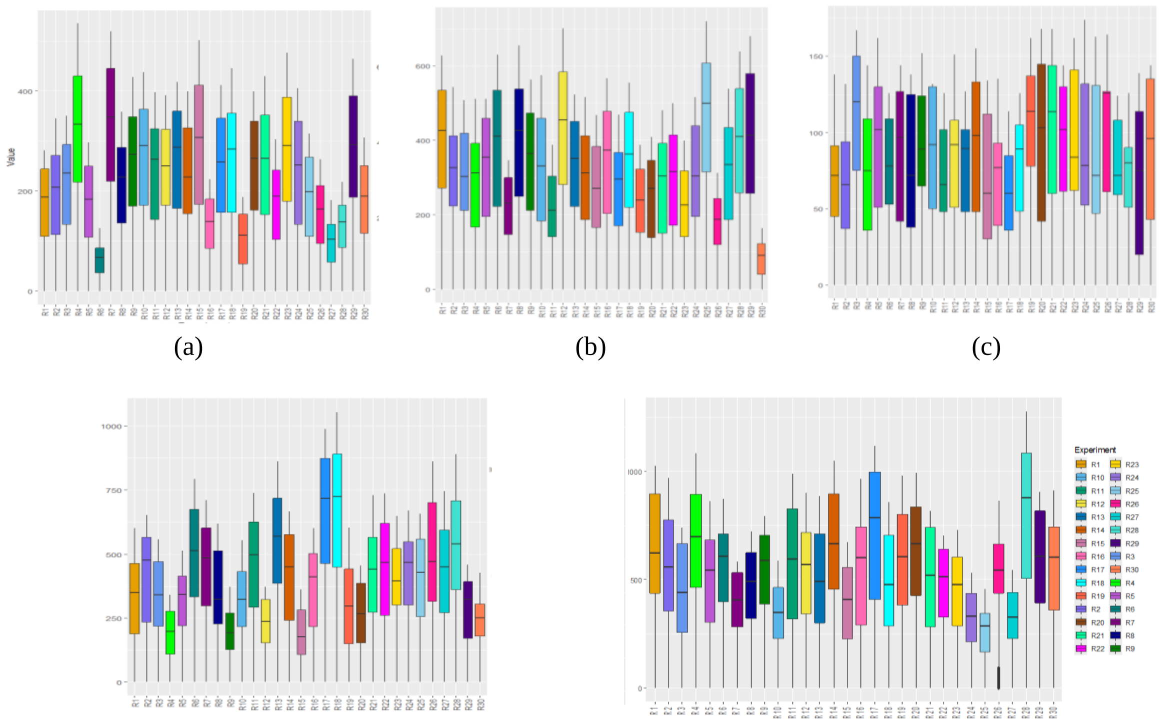


(a) (b) (c)

(d) (e)

Figure 6. Variations in the number of messages spread in USC-mosul using the binary spray and wait for 30 runs, where the subfigures: (a) to (e) corresponds to L=3,5,7,10, and 20 respectively

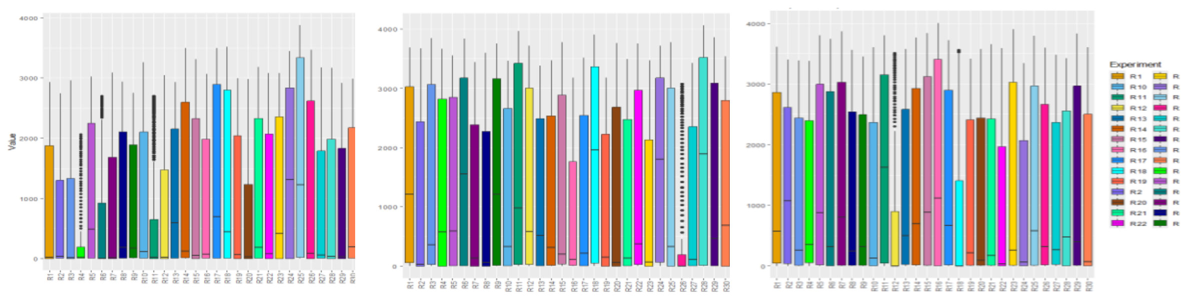
This enables early assessment of the network's message transmission load and channel utilization, offering a clearer understanding of the potential impact on the DTN. This information supports evaluating the scalability and capacity planning required to accommodate the anticipated load. Instability can challenge performance predictability, but understanding the level of node participation in specific applications is essential to making informed decisions regarding network resources and optimizing communication channels. Considering this factor during the design and implementation stages allows us to mitigate the negative effects of instability and ensure effective message transmission and network performance. Across multiple graph experiments, there appear to be consistent patterns, such as certain experiments consistently showing higher or lower values compared to others. Also, the box plots reveal varying degrees of variability within each experiment, with some having tightly clustered replicates and others displaying a broader spread of values. Besides, several individual data points appear to be outliers, significantly deviating from the main distribution. There may be a mobility factor influencing the outcomes yield outliers. It could indicate differences in experimental conditions at each run.



(a) (b) (c)

(d) (e)

Figure 7. Variations in the number of messages spread in USC-mosul using the spray and wait for 30 runs, where the subfigures: (a) to (e) corresponds to L=3,5,7,10, and 20 respectively



(a) (b) (c)

Figure 8. Variations in the number of messages spread in USC-mosul using the probabilistic flooding, where the subfigures: (a) to (c) corresponds to Delta=0.1,0.5, and 0.9 respectively

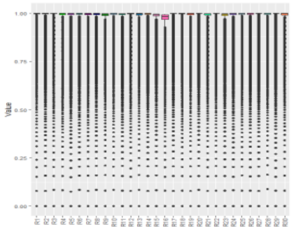
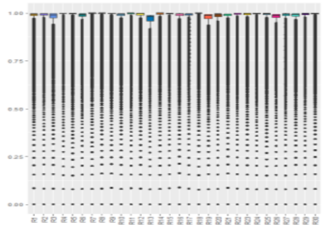
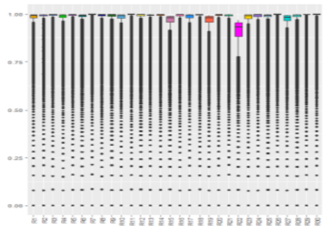
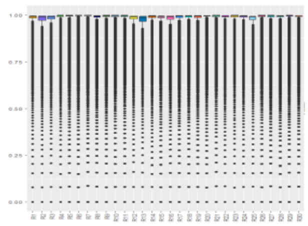
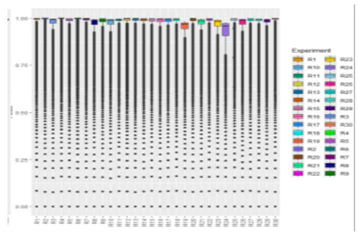
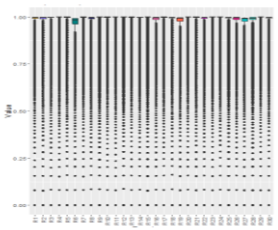
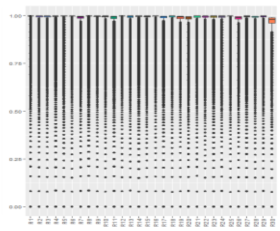
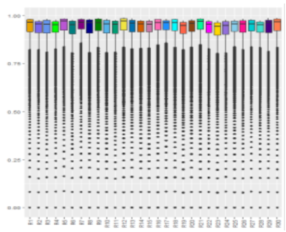
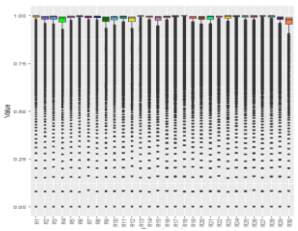

(a)

(b)

(c)

(d)

(e)

Figure 9. Variations in the fraction of covered places in USC-mosul using the binary spray and wait, where the subfigures: (a) to (e) corresponds to L=3,5,7,10, and 20 respectively


(a)

(b)

(c)

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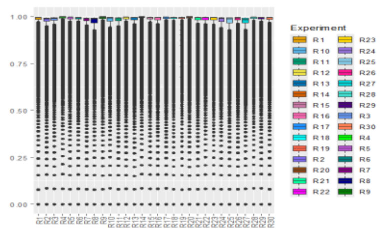

(e)

Figure 10. Variations in the fraction of covered places in USC-mosul using the spray and wait, where the subfigures: (a) to (e) corresponds to L=3,5,7,10, and 20 respectively

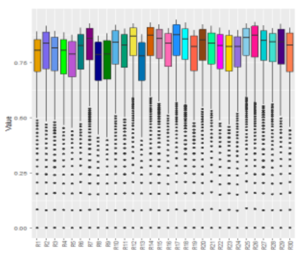
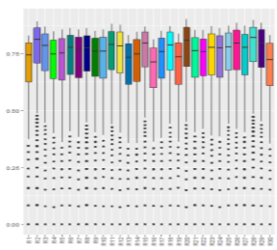
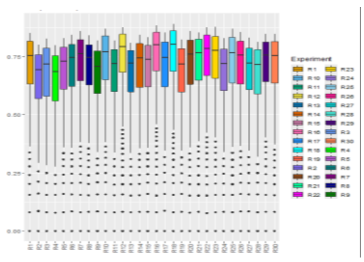
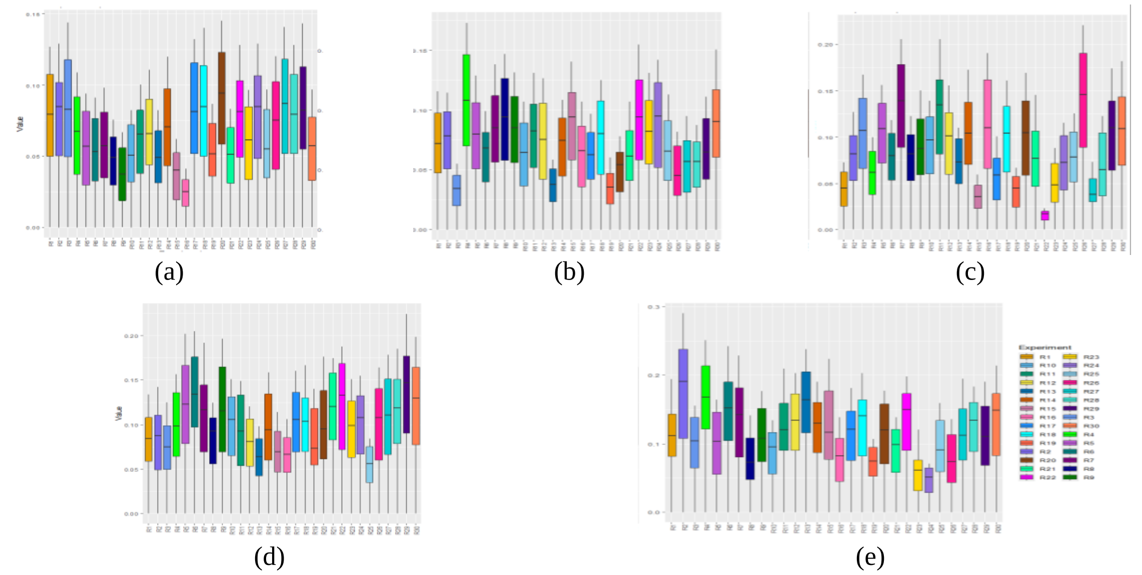

(a)

(b)

(c)

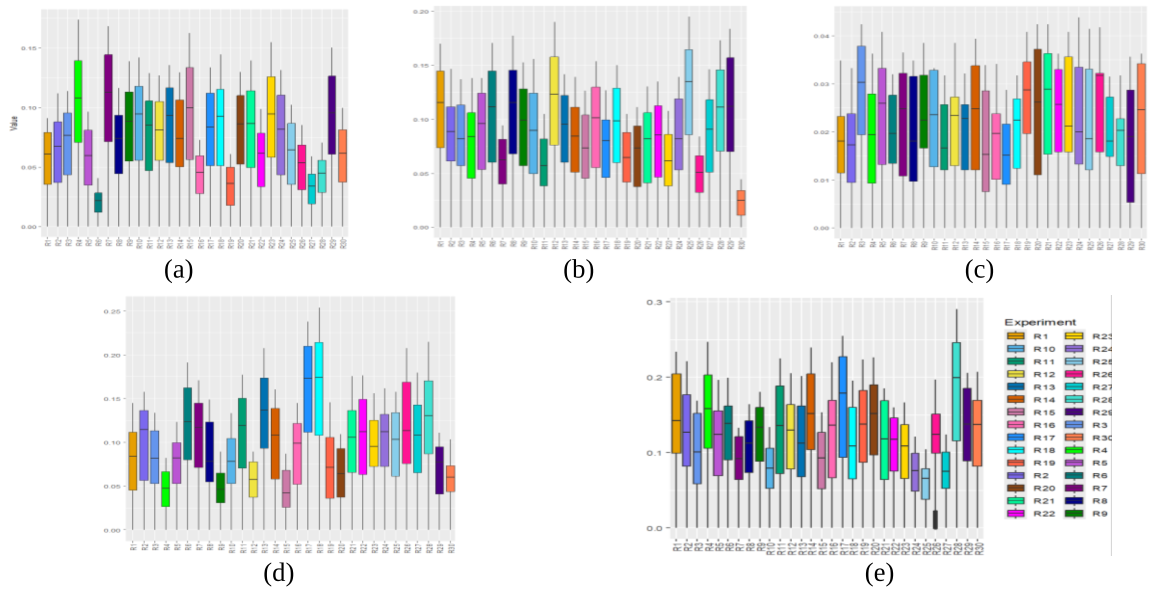
Figure 11. Variations in the fraction of covered places in USC-mosul using the probabilistic flooding, where the subfigures: (a) to (c) corresponds to Delta=0.1,0.5, and 0.9 respectively



(a) (b) (c)

(d) (e)

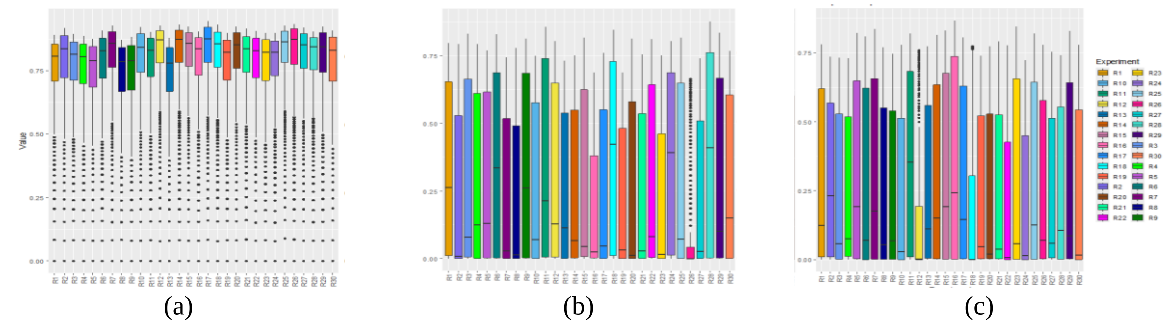
Figure 12. variations in the fraction of acknowledged nodes in USC-mosul using the binary spray and wait, where the subfigures: (a) to (e) corresponds to L=3,5,7,10, and 20 respectively



(a) (b) (c)

(d) (e)

Figure 13. Variations in the fraction of acknowledged nodes in USC-mosul using the spray and wait, where the subfigures: (a) to (e) corresponds to L=3,5,7,10, and 20 respectively



(a) (b) (c)

Figure 14. Variations in the fraction of acknowledged nodes in USC-mosul using the probabilistic flooding, where the subfigures: (a) to (c) corresponds to Delta=0.1,0.5, and 0.9 respectively

3.2. Discussion

This section highlights the main observations of this work. Based on Figures 9(a)-9(e), 10(a)-10(e), and 11(a)-11(c), in several runs, outliers appear, reflecting unstable behaviour. The dynamic behavior of the network, where nodes are distributed in random areas within the university campus, causes unstable behaviours in some cases. As the median values and distributions of the experiments vary widely, there are likely significant factors that influence the results. This behavior does not occur often since most runs exhibit stable outputs. Moreover, the boxplots reveal wide ranges of variance among many experiments, with some exhibiting tightly clustered replicates while others show much broader distributions. Therefore, it is important to highlight the design of a smart campus where the Initial phase should include basic network protocol features as well as the mobility patterns of people. This research primarily involved the Levy flight with exponential cutoff movement pattern that is closely replicates the actual movement patterns observed across the university campus during different times and applications. The measurement of covered areas in the campus is strongly influenced by the node's mobility that follows the Levy Flight model, reflecting human movement patterns. Additionally, the results must be statistically significant in conjunction with the previous analysis. To evaluate the variations in the approaches used in this study, a one-way Analysis of Variance (ANOVA) was applied. Regression models were rebuilt for each evaluation metric, with two hypotheses testing as follows:

Number of Messages:
The null hypothesis (*H0*) is formalized as follows:

$$H0: \mu_{BSpray\ \&\ Wait}(messages) = \mu_{Probabilistic\ Flooding}(messages) = \mu_{Spray\ \&\ Wait}(messages)$$

The alternative hypothesis (*H1*) is formalized as follows:

$$H1: \mu_{BSpray\ \&\ Wait}(messages) \neq \mu_{Probabilistic\ Flooding}(messages) \neq \mu_{Spray\ \&\ Wait}(messages)$$

Fraction of Acknowledged Nodes:
The null hypothesis (*H0*) is formalized as follows:

$$H0: \mu B_{Spray\ \&\ Wait}(a - nodes) = \mu_{Probabilistic\ Flooding}(a - nodes) = \mu_{Spray\ \&\ Wait}(a - nodes)$$

The alternative hypothesis (*H1*) is formalized as follows:

$$H1: \mu_{BSpray\ \&\ Wait}(a - nodes) \neq \mu_{Probabilistic\ Flooding}(a - nodes) \neq \mu_{Spray\ \&\ Wait}(a - nodes)$$

Time Expenditure:
The null hypothesis (*H0*) is formalized as follows:

$$H0: \mu_{BSpray\ \&\ Wait}(time) = \mu_{Probabilistic\ Flooding}(time) = \mu_{Spray\ \&\ Wait}(time)$$

The alternative hypothesis (*H1*) is formalized as follows:

$$H1: \mu_{BSpray\ \&\ Wait}(time) \neq \mu_{Probabilistic\ Flooding}(time) \neq \mu_{Spray\ \&\ Wait}(time)$$

The confidence level of all the tests was 97% (α=0.03). The ANOVA results for all the models demonstrated that the p-value was significantly less than the confidence level. Meaning that all the null hypotheses of the models were rejected, accepting the alternative hypotheses and the results of this work were statistically significant. In other words, there is a significant difference in the performance and there exists a difference in the performance when varying the experiments settings. Finally, each routing protocol is useful in particular situations. For example, some situations may be critical in terms of propagated time, resources, or maximum coverage area. For clarity, it is important to list examples of applications in USC-Mosul and their network communication requirements, which can be relatively generalized to any smart campus:

1- Disaster response and emergency communication networks: In emergency situations, fast message delivery and low latency are vital. In this type of application, the trade-off of higher channel utilization produced from large corporate nodes and energy consumption may be acceptable, where the priority is convergence and rapid communication. The objective function can be formalized as follows:

Objective function: The main goals are to minimize time and maximize the ACK ratio, it is given by:

min(T) (Time)

Objective:

max(A) (ACK Ratio)

where T is the time (in hours) and A is the ACK ratio.

2- IoT Applications: The IoT and sensors in university campus networks often have resource-constrained devices with limited processes, data storage, and energy. The trade-off of slightly higher latency may be suitable in these applications, where the focus is on maximizing the lifetime of the network and minimizing resource usage. The objective function can be formalized as follows:

Objective function: the primary goal is to minimize message transmission while optimizing coverage and can be represented as:

min(M) (Messages)

Objective:

max(C) (Coverage Time)

where M is the number of messages and C represents coverage time (or full convergence time).

3- Advertisement message inside campus: The use of advertisement messaging systems applications requires a specific approach in (DTN), where discontinuous connectivity and long delays are common. It is crucial to ensure reliable message delivery, even when disruptions occur frequently. As a result, minimizing latency is more important than minimizing delivery times, as slightly longer delivery times may be an acceptable compromise. Moreover, given the limited resources available on DTN devices, such as memory and battery power, the advertisement messaging solution must be highly optimized for efficient resource consumption. **Objective function:** The key objectives are to maximize the ACK ratio and maximize coverage and can be formalized as follows:

max(A) (ACK Ratio)

Objective:

max(C) (Coverage Time)

where A is the ACK Ratio and C represents coverage time (or full convergence time).

Based on the results shown above, the optimal values of the parameters used for each application in USC-Mosul can be summarized in the recommendations provided in Table 4.

Table 4. Recommended parameter values and their applications adopted in the USC-mosul or similar campuses

Application	Recommended protocol	Parameter value	Description
Disaster and emergency response	Probabilistic flooding	Delta 0.1	This setting has the highest fraction of nodes acknowledged, also has the lowest time to full convergence, which is also desirable.
IoT Applications	Binary spray and wait	L3	This setting has the lowest messages consumption, also has the highest Fraction of places covered.
Advertisement inside campus	Probabilistic flooding	Delta 0.1	This setting has the highest fraction of nodes acknowledged; it also has the highest fraction of places covered.
Limited resources or constrained computing devices	Binary spray and wait	L3	Minimizing messages consumption is essential for devices with limited resources, as it decreases the global communication overhead and power.
Constrain network devices resources	Binary spray and wait	L3	Minimize messages consumption helps reduce the number of messages sent over the network, lowering the chances of congestion. Enhance the Fraction of nodes acknowledged to ensure that messages are effectively reaching their destination. Minimize time to full convergence: Faster convergence can help clear the network of old messages, reducing congestion.
Device management	Spray and wait	L7 and L10	Tradeoff between coverage, node acknowledgment, and convergence time, and where a to some extent higher message consumption is acceptable.

4. CONCLUSION

This work evaluated the performance of three routing protocols; BSW, spray and wait, and probabilistic flooding under different dynamic conditions in smart campus. The metrics used were message consumption, network coverage, and acknowledgment rates. The findings demonstrated the distinct strengths and limitations of each protocol in relation to specific network demands and application scenarios. The BSW protocol proved to be efficient in time-sensitive applications, minimizing overhead while ensuring reliable message delivery. Comparatively, the spray and wait protocol provided extensive network coverage, though it required higher message consumption and more time. Meanwhile, the probabilistic flooding protocol, though optimized for rapid delivery, induced significant overhead due to its probabilistic forwarding approach. The ANOVA test confirmed the variability in performance among protocols, further emphasizing the importance of selecting routing strategies based on specific application requirements. Also, the impact of the Levy Flight mobility model on protocol performance highlighted the importance of aligning network design with realistic human movement patterns, especially in environments like smart campuses. By understanding the trade-offs inherent in each protocol, this research offers practical insights that can inform the deployment of DTNs and contribute to optimized design strategies for robust, scalable communication systems.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Karam Mheide Al-Sofy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Jalal Khalid Jalal	✓	✓	✓	✓	✓	✓	✓		✓		✓			
Fajer F. Fadhil	✓		✓				✓	✓	✓		✓			
Basim Mahmood	✓	✓		✓		✓				✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

INFORMED CONSENT

There is no informed consent associated with this research.

ETHICAL APPROVAL

This research is a simulation-based study that does not involve humans or animals.

DATA AVAILABILITY

All the data used in this research were generated by the authors through simulations. The data can be sent to other researchers upon request to the corresponding author, Karam Mheide Al-Sofy.

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