

Evaluating the Performance Characteristics of Opportunistic Routing Protocols during an Emergency Fire & Rescue Scenario involving High-Density Clusters of Victims

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1 Introduction

The aim of this project is to evaluate the performance characteristics of two different opportunistic routing protocols within a real world scenario, simulated by the Opportunistic Network Simulator (ONE). In the chosen scenario, victims of an arson attack are trapped within a museum, trying to contact the local hospital. The scenario is simulated by a network topology that represents the city of Helsinki and its transport network.

To begin, this paper will give a brief overview of opportunistic networks and the 2 routing protocols evaluated in the experiment. Then, the functionality of the ONE simulator will be described and the model of the scenario explained in detail, including its implementation. Using this model, simulations will be run and the results of their performances critically evaluated. A conclusion will then be drawn based on these results, summarising the pros and cons of both opportunistic networks protocols and their use in the observed scenario. Finally, the paper closes with a wider discussion of the usefulness of opportunistic networks in related real world use-cases.

2 Background

In recent years, a growing number of devices have been utilizing mobile networking technology in less traditional environments, ranging from the GPS tracking of wildlife over huge distances [4], to the proposed establishment of an "Interplanetary Internet", capable of transmitting data lightyears in distance [5]. These non-static networks are decentralised and wireless, consisting of constantly mobile nodes, ranging from those with predictable mobility, such as transport systems, (e.g. buses and trams) to those with stochastic mobility, such as military/tactical networks. In all of these new environments, communication coverage is pervasive and essential for day-to-day operations. However, it's impossible to treat them like traditional networks with pre-determined communication paths due to their constant reconfiguration and non-guaranteed connectivity. As a result, computer networks deployed in such environments face new challenges such as large delays, intermittent communication links, and heterogeneous nodes with differing operating systems and network protocols.

2.1 Mobile Ad-Hoc Networks (MANETs)

A Mobile Ad-Hoc Network (MANET) is a self-configuring network of mobile devices, with no fixed infrastructure, connected by wireless links. An important characteristic of a MANET is each node's ability to move independently in any direction, forcing the network to reconfigure itself frequently. Each node acts as a client, server, and router simultaneously in order to transport packets from source to destination, thus nodes communicate with each other in a peer-to-peer fashion [7]. There are several important properties that limit the effectiveness of MANETs [6]:

- Security is difficult to achieve because wireless links are vulnerable, the topology is dynamically changing, and there is no certification authority [8].
- The use of wireless links results in a lower capacity than wired counterparts [6].
- Nodes are mobile devices which rely on exhaustible battery power. Therefore saving energy is an important system design aspect [6].

MANETs assume high connectivity and established routes for transmitting data between nodes in a multi-hop fashion. As a result, the routing process in MANETs requires the discovery of an end-to-end path before data can be transported. However, because the topology is constantly changing in most mobile ad-hoc networks, there may not always be a feasible end-to-end path between source and destination [6]. Resultantly, MANETs perform poorly when connections are intermittent or there are long delays. This problem presents the need for the improved protocols used in opportunistic networks and Delay Tolerant Networks (DTNs).

2.2 Vehicular Ad-Hoc Networks (VANETs)

Vehicular Ad-Hoc Networks (VANETs) are a type of MANET where the network's nodes are represented by vehicles. Though MANETs and VANETs share many characteristics, there are unique challenges exclusive to VANETs that affect their usability, efficiency, and therefore their system design [9]:

- Vehicles have the potential to move at very high speeds which can reduce the length of time available for packet transfer between nodes communicating in proximity to each other [9]. As VANETs also require end-to-end paths to be established before data can be sent, this issue is compounded by the movement of intermediary nodes in multi-hop transmissions. The path may be established before transmission begins, but disrupted before the packet can reach its destination.
- The data transmitted by vehicles may be critical and life-saving, such as information about road accidents and traffic or the location of casualties who need assistance from ambulance crews. It is therefore essential that such information is received correctly and in a timely fashion [9].

It is useful to note that the movement of nodes in a VANET can be considered more predictable than conventional ad-hoc networks because vehicles follow set paths such as roads, railway lines, etc.

2.3 Delay/Disruption Tolerant Networks (DTNs)

In environments where disruptions and delays are expected, traditional networking protocols such as TCP [3] are unsuitable because they assume there is an end-to-end connection with low message loss and minimal delay [2]. In decentralised, mobile ad-hoc networks, nodes are constantly moving and there is likely no feasible end-to-end path between source and destination. In order to combat the challenges presented by delays and disruptions, the assumption of an existing end-to-end path from source to destination is dropped. Instead, routing protocols have been developed which utilise a "store-and-forward" approach where data is gradually transported in single hops and stored in different nodes with the desire of eventually reaching its intended destination [2]. Typically, this approach to network architecture is called Delay/Disruption Tolerant Networking (DTN).

The performance of a DTN depends on the routing protocol used in a given scenario. DTN routing protocols can either be replication based (flooding) or forwarding based [10]:

- In a replication based protocol, when one node encounters another it will forward a copy of its message without deleting its own. This means there are multiple copies of the message in the network with aims to increase the probability that a message will eventually reach its destination. However, in this approach a large amount of resources are used, particularly buffer space. Once the message has been delivered, all existing copies of the message are made redundant but still continue to exist, taking up unnecessary space [10].
- In a forwarding based protocol, a message can only be stored by a single node at a time. In contrast to a replication based scheme, the node forwarding the message deletes its own copy, making the receiver the sole custodian of the message. Forwarding based protocols tend to use heuristics to evaluate encountered nodes and work out which path is most likely to get the message to its destination the quickest.

2.4 Delay/Disruption Tolerant Network (DTN) Protocols

2.4.1 Epidemic

Epidemic [11][12] is a simple replication based routing protocol and is somewhat naïve when compared to more advanced protocols. The objective of the epidemic routing protocol is to pass copies of a message to as many nodes as possible in the hope that it eventually reaches its intended destination with minimal delay. Any node that doesn't already have the message will be given a copy and there can exist as many copies of the message as there are nodes in the network. The protocol is called 'epidemic' because this indiscriminate method of dissemination is similar to the way in which an infectious disease can propagate in a community; spreading when people come into contact with each other.

Theoretically, Epidemic can be seen as an optimal routing protocol if the network's resource are unconstrained. However, in a deployed DTN, the size of each node's message buffer is finite and, because no acknowledgement of receipt is transmitted by the destination node, it is likely that redundant data will still take up unnecessary space in the network. Some research has produced extended versions of the epidemic protocol which mitigate this issue, typically by sending an additional message that confirms receipt and orders 'infected' nodes to delete redundant messages [12].

2.4.2 Spray-and-Wait

Spray-and-Wait [13] is a routing protocol that aims to achieve the advantages of Epidemic's high delivery probability but with far less resource utilisation. It achieves this by disseminating a finite quantity of message copies (spraying) with the recipients storing the message until direct contact with the destination node. The maximum number of messages to spray is typically configured by a variable, L . There are 2 versions of the spray-and-wait protocol: vanilla and binary. The difference between them is the method used to disseminate the message copies to L different nodes.

- **Vanilla** - transmit one copy of the message to the first $L - 1$ nodes encountered. Each node with 1 copy of the message waits until the destination node comes into direct contact.
- **Binary** - start with L copies and transmit $L/2$ copies to the first node encountered. Both these nodes then transmit $n/2$ copies of the message to any new nodes they encounter that do not have the message, where n is the total number of messages a node currently holds. When a node has 1 copy remaining, it waits until the destination node comes into direct contact.

Binary has an advantage over vanilla because messages are disseminated away from the source at a faster rate [13].

2.5 Opportunistic Networks

With MANETs, VANETs and DTNs explained, it is now possible to define an **opportunistic network**. Firstly, MANETs (and by extension, VANETs) are NOT considered opportunistic networks, a result of their assumptions of high-connectivity and established routes for multi-hop data transmission. Opportunistic networks, by definition, only transport data in a single-hop fashion, employing the store-and-forward strategy which can be described in the following way:

3 ONE Simulator

The ONE (Opportunistic Network Environment) Simulator [14][15] is a DTN simulator developed and maintained by researchers on the SINDTN and CATDTN projects and supported by Nokia Research Center (Finland). Where existing DTN simulators focused on solely on routing simulation, ONE combines DTN routing, mobility modelling, and visualisation into one package [14]. It is a complex tool which is extensible and provides useful modules for the reporting and analysis of simulated network

environments.

ONE is useful for comparing, contrasting and analysing the performance of opportunistic networking protocols in different scenarios, making it the ideal tool for this research article. Scenarios (or network models) are comprised of network nodes (hosts) which all possess user-specified networking interfaces, energy sources, buffer-sizes, and computing power. Collections of identical nodes can be defined as groups with default properties, though an individual node’s settings can be overwritten if necessary, for example, to ensure a node uses a different routing protocol from the rest of its group. Nodes act autonomously, passing messages to other nodes within their communication range according to their designated routing protocol.

ONE also makes a comprehensive framework for the mobility of nodes available to the user, allowing them to customise the travel speed of individual nodes or groups of nodes, and even import real-world movement traces for nodes to follow. This high fidelity node mobility framework allows users to easily differentiate between different node types (e.g. pedestrians will move slower than cars and follow a different route) and permits the creation of highly accurate scenarios that use real-world data, or hybrid scenarios which combine real traces with user-defined rules.

The ONE Simulator allows users to define “Message Events” which are scheduled events involving the creation and movement of messages from source to destination. The user can define the minimum and maximum message size and interval between message creations, a range of source and destination nodes, and a prefix identifier for each message. This system is useful because it allows users to design unique messages for specific scenarios (e.g. one large message sent from a specific node to a specific destination).

Creating custom scenarios involves the editing of the ONE simulator’s config file. This file contains all the settings that the simulator uses each time it is loaded. It is extremely customisable and allows the user to change the amount of nodes, what protocol they use, where they are positioned, how they travel and much more. To simulate a given scenario using ONE, the user needs to ensure the correct config file for that scenario is included as the ‘default_settings.txt’ file in the ONE source folder. For this paper, each scenario is represented by an individual config file.

The ONE Simulator provides a GUI that allows users to inspect each node present in the model. The user can also inspect the path of individual messages, pause the simulation, and change the speed of the GUI’s refresh rate. ONE succeeds in using this GUI to create an accurate visualisation of the user-specified network model. Nodes are clearly represented by prefix identifiers, above an underlayed map image (in this case, an image of Helsinki’s transit network). Relationships between nodes are represented by direct lines drawn between them and these consistently update with the simulation data. Messages in each node’s buffer are represented by small stacks of squares next to each node’s name. The range of each node’s network interface is represented as a green circle. When another node is positioned within this circle, message transfer may commence.

The ONE Simulator provides a comprehensive report feedback system which records and statistically analyses many different aspects of a simulation, providing the user with .txt output files. Users can specify which reports to generate in ONE’s config file. Examples of reports include statistics on delivery-rate, latency, the number of created connections, and the level of buffer occupancy, just to name a few. The evaluation section of this paper was produced using data from the reports created from each simulation.

Finally, the ONE Simulator is open-source and can therefore be extended in any way the user sees fit. This typically includes the modification of existing class files or the creation of new ones. For example, to use an unimplemented routing protocol the user would have to write a new set of source

files to include in the software package. The ONE Simulator is very well documented and including new functionality is generally a straightforward process and there are many well-structured classes to inherit from too; the software was built with extension in mind.

4 Experiment

4.1 Scenario Description

The aim of this paper is to evaluate the performance characteristics of the Epidemic and Spray-and-Wait routing protocols within a pseudo-real world scenario. The scenario in question is described in this section:

“Kiasma”, the Helsinki museum of contemporary art has become the subject of an arson attack conducted by a group of nefarious criminals. Trapped inside the museum are a number of civilian victims who require immediate rescue and assistance from the city’s emergency services. In order to do so, the local Helsinki hospital must be contacted. Messages are created by the trapped victims, relayed to vehicles passing local to the museum, and hopefully delivered to their final destination: the Helsinki hospital several streets away. This scenario has been created using the ONE simulator. However, three slightly different versions of the scenario will each be simulated to evaluate how both routing protocols perform. In each scenario the number of trapped victims (and therefore the density of the message source node cluster) is increased. This experiment was designed to to simulate a victim’s likely response in such a chaotic scenario: contacting and finding their friends and family who are trapped in the building with them first. Accordingly, messages are likely to be first sent to other victims trapped in the museum before reaching passing vehicles outside.

Scenario	Description
1	One trapped victim is simulated by a single node in the network that moves randomly within a small pre-defined range and creates its own messages (Figure 1).
2	10 trapped victims are simulated by a single node each. Each node moves randomly within a small pre-defined range and is able to create its own messages (Figure 2).
3	20 trapped victims are simulated by a single node each. Each node moves randomly within a small pre-defined range and is able to create its own messages. (Figure 3).

4.2 Assumptions

Assumptions

4.3 Common Simulation Parameters

Some common settings have been selected for every scenario. All nodes utilise network interfaces which conform to the 802.11p standard [16]. This standard defines wireless access in vehicular environments (WAVE) and is used in the real world for vehicle-to-vehicle communication [16]. A range of 250 metres and a transfer rate of 10MB/s has been selected as a close representation of this standard, taking into consideration limitations such as obstructed signal strength in built-up urban areas. All messages in the simulation represent emergency information which is typically small in size (50-500KB) and uses a relatively short time-to-live (TTL) of 60 minutes. This short TTL ensures large amount of messages do not amass, congesting the network unnecessarily.

Parameter	Value
Simulation Time	120 Minutes
Node Types	Cars, Pedestrians, Static (Hospital)
Message Size	50-500KB
Message TTL	60 minutes
Network Interface	Wi-Fi 802.11p
Network Range	250 metres
Network Rate	10MB/s
Buffer Size	10MB

4.4 Group Parameters

Talk about cluster movement here

4.4.1 Scenario 1

4.4.2 Scenario 2

4.4.3 Scenario 3

5 Evaluation

5.1 Evaluation Criteria Definitions

Definitions

5.2 Scenario 1

In this scenario, one trapped victim is simulated by a single node in the network that moves randomly within a small pre-defined range and creates its own messages.

Parameter	Epidemic
Messages Created	243
Messages Started	56976
Messages Relayed	56975
Messages Dropped	53841
Messages Delivered	99
Delivery Probability	40.7%
Overhead Ratio	574.5
Average Latency	786.4
Median Hop Count	6

Parameter	SWB6	SWB12	SWB18	SWB24	SWB30
Messages Created	243	243	243	243	243
Messages Started	1257	2667	3995	5308	6580
Messages Relayed	1256	2666	3993	5306	6578
Messages Dropped	821	1632	2492	3459	4438
Messages Delivered	84	122	145	161	166
Delivery Probability	34.6%	50.2%	59.7%	66.3%	68.3%
Overhead Ratio	13.9	20.8	26.5	31.9	38.6
Average Latency	1302.3	1079.5	1189.9	1076.6	1102.1
Median Hop Count	3	4	4	4	4

Parameter	SWV6	SWV12	SWV18	SWV24	SWV30
Messages Created	243	243	243	243	243
Messages Started	1266	2557	3366	3657	3731
Messages Relayed	1265	2555	3364	3655	3729
Messages Dropped	835	1687	2410	2712	2780
Messages Delivered	96	138	163	164	166
Delivery Probability	39.5%	56.8%	67.1%	67.5%	68.3%
Overhead Ratio	12.2	17.5	19.6	21.3	21.5
Average Latency	1718.7	1177.9	1235.4	1263.2	1278.1
Median Hop Count	2	2	2	2	2

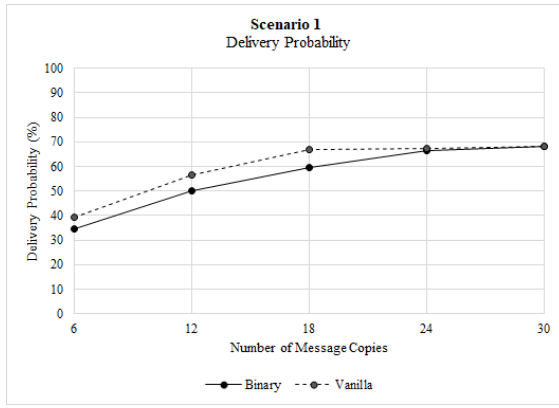


Figure 1: Comparison of delivery probability between vanilla and binary spray-and-wait in scenario 1

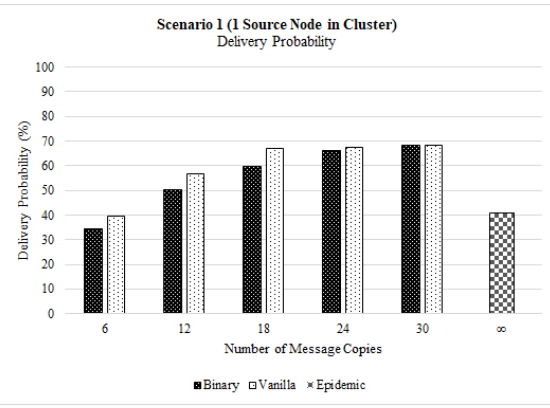


Figure 2: Comparison of delivery probability across all protocols in scenario 1

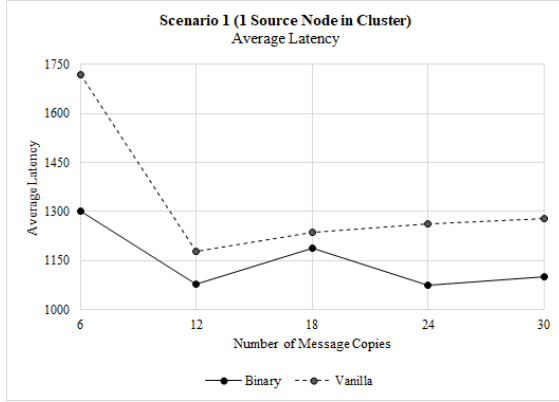


Figure 3: Comparison of average latency between vanilla and binary spray-and-wait over various message copies in scenario 1

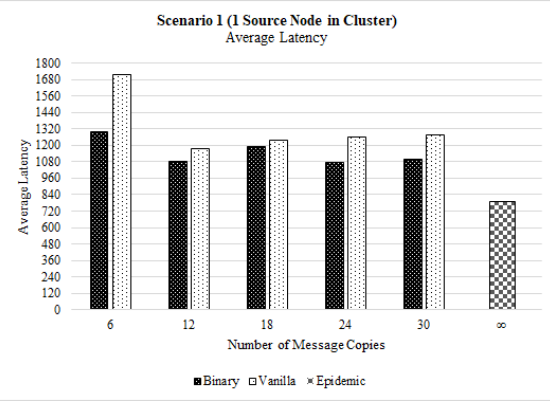


Figure 4: Comparison of average latency across all protocols in scenario 1

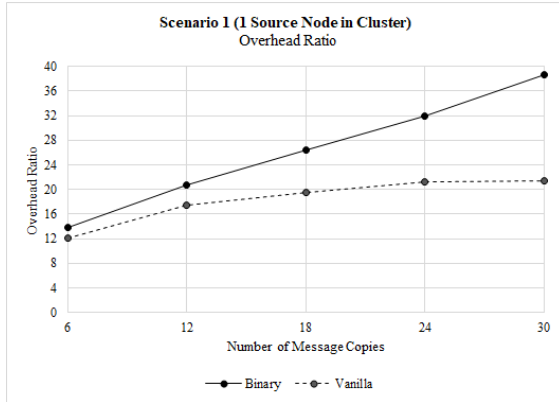


Figure 5: Comparison of overhead ratio between vanilla and binary spray-and-wait over various message copies in scenario 1

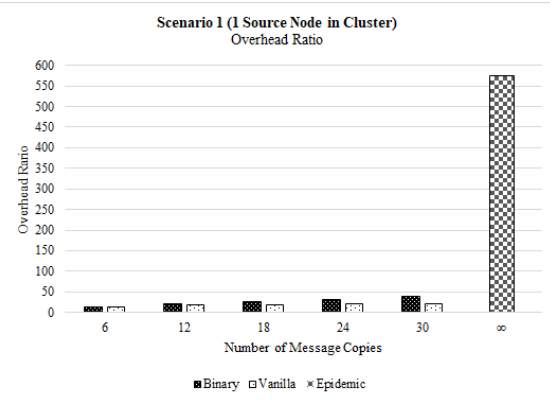


Figure 6: Comparison of overhead ratio across all protocols in scenario 1

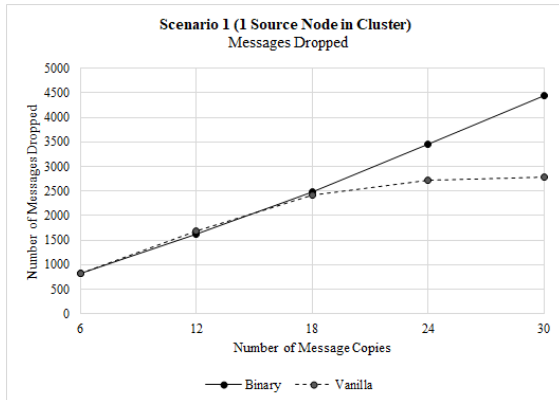


Figure 7: Comparison of messages dropped between vanilla and binary spray-and-wait over various message copies in scenario 1

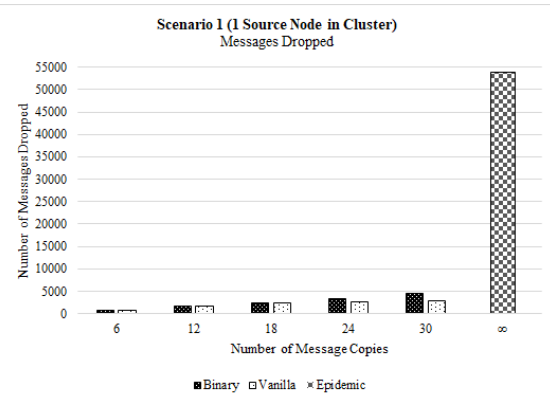


Figure 8: Comparison of messages dropped across all protocols in scenario 1

5.3 Scenario 2

In this scenario, 10 trapped victims are simulated by a single node each. Each node moves randomly within a small pre-defined range and is able to create its own messages.

Parameter	Epidemic
Messages Created	243
Messages Started	329498
Messages Relayed	329491
Messages Dropped	326090
Messages Delivered	91
Delivery Probability	37.5%
Overhead Ratio	3619.8
Average Latency	1083.9
Median Hop Count	16

Parameter	SWB6	SWB12	SWB18	SWB24	SWB30
Messages Created	243	243	243	243	243
Messages Started	1215	2714	4212	5648	6940
Messages Relayed	1215	2714	4212	5648	6940
Messages Dropped	1124	2332	3088	4026	5090
Messages Delivered	0	45	115	163	169
Delivery Probability	0%	18.5%	47.3%	67.1%	69.6%
Overhead Ratio	N/A	59.3	35.6	33.7	40.1
Average Latency	N/A	1621.4	1464.7	1392.1	1316.6
Median Hop Count	0	4	4	4	4

Parameter	SWV6	SWV12	SWV18	SWV24	SWV30
Messages Created	243	243	243	243	243
Messages Started	1215	2703	4154	5418	6158
Messages Relayed	1215	2703	4154	5418	6158
Messages Dropped	1122	2324	3079	3976	4728
Messages Delivered	0	35	100	122	121
Delivery Probability	0%	14.4%	41.2%	50.2%	49.8%
Overhead Ratio	N/A	76.2	40.5	43.4	49.9
Average Latency	N/A	1592.8	1667.1	1536.2	1514.8
Median Hop Count	0	2	2	2	2

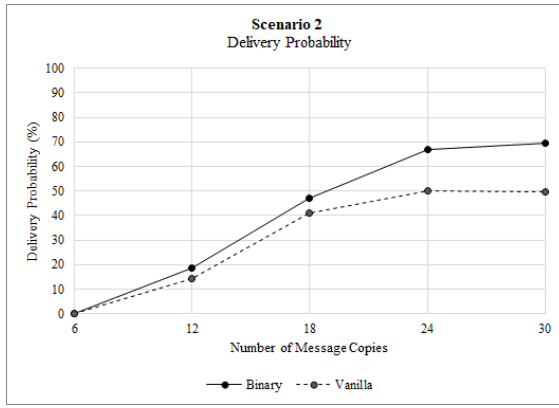


Figure 9: Comparison of delivery probability between vanilla and binary spray-and-wait in scenario 2

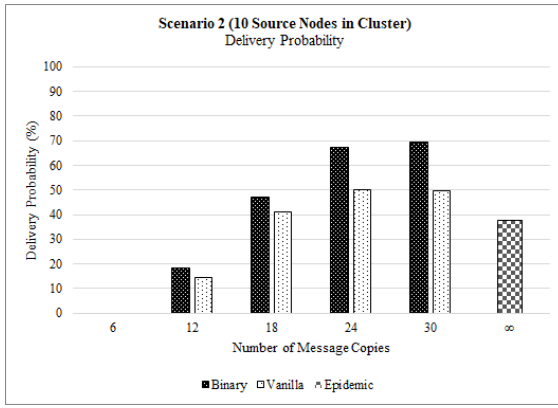


Figure 10: Comparison of delivery probability across all protocols in scenario 2

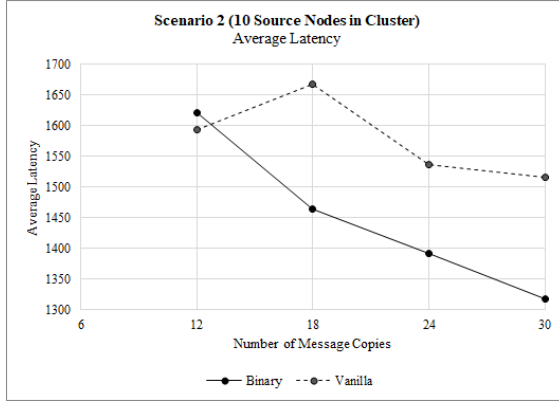


Figure 11: Comparison of average latency between vanilla and binary spray-and-wait over various message copies in scenario 2

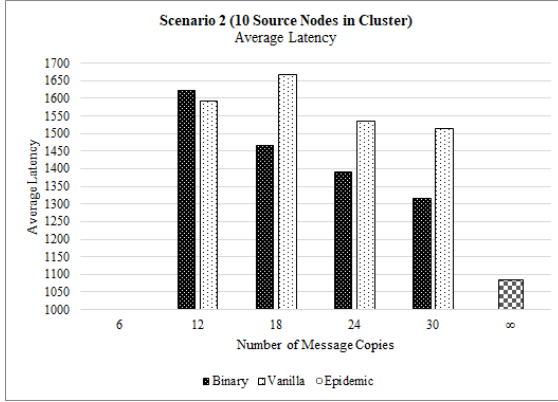


Figure 12: Comparison of average latency across all protocols in scenario 2

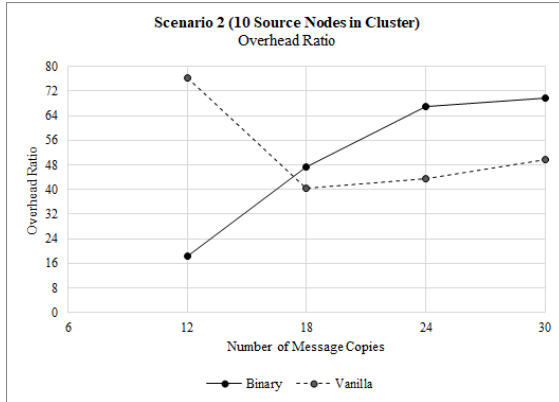


Figure 13: Comparison of overhead ratio between vanilla and binary spray-and-wait over various message copies in scenario 2

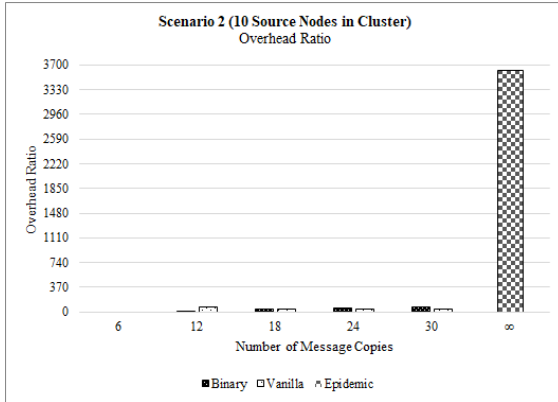


Figure 14: Comparison of overhead ratio across all protocols in scenario 2

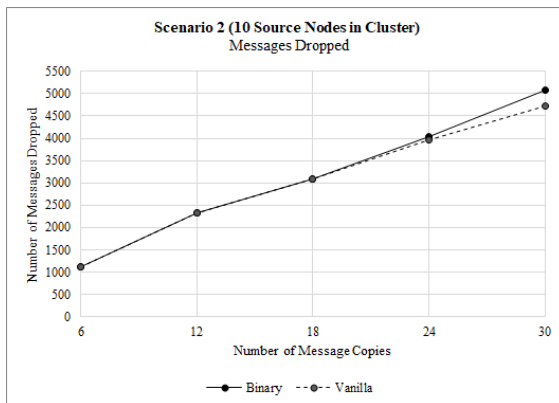


Figure 15: Comparison of messages dropped between vanilla and binary spray-and-wait over various message copies in scenario 2

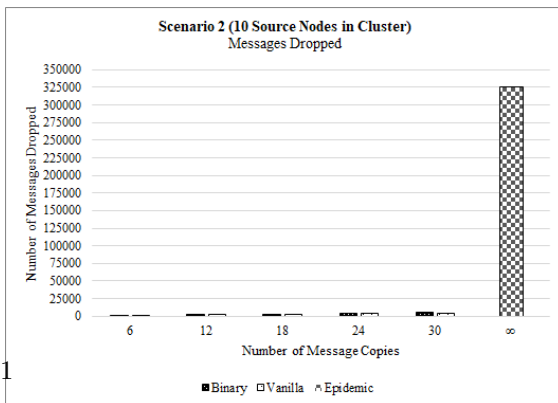


Figure 16: Comparison of messages dropped across all protocols in scenario 2

5.4 Scenario 3

In this scenario, 20 trapped victims are simulated by a single node each. Each node moves randomly within a small pre-defined range and is able to create its own messages.

Parameter	Epidemic
Messages Created	243
Messages Started	600047
Messages Relayed	600034
Messages Dropped	596036
Messages Delivered	90
Delivery Probability	37%
Overhead Ratio	6666.0
Average Latency	1052.1
Median Hop Count	11

Parameter	SWB12	SWB24	SWB36	SWB48	SWB60
Messages Created	243	243	243	243	243
Messages Started	2673	5632	8463	10847	12083
Messages Relayed	2673	5632	8463	10847	12082
Messages Dropped	2250	4668	6400	8368	9572
Messages Delivered	0	60	127	155	148
Delivery Probability	0%	24.7%	52.3%	63.8%	60.9%
Overhead Ratio	N/A	92.9	65.6	69.0	80.6
Average Latency	N/A	1589.3	1421.1	1400.4	1409.0
Median Hop Count	0	5	5	5	5

Parameter	SWV12	SWV24	SWV36	SWV48	SWV60
Messages Created	243	243	243	243	243
Messages Started	2676	5623	8240	9588	9809
Messages Relayed	2676	5623	8240	9588	9809
Messages Dropped	2246	4656	6414	7746	7987
Messages Delivered	3	58	101	105	111
Delivery Probability	1.2%	23.9%	41.6%	43.2%	45.7%
Overhead Ratio	891.0	95.9	80.6	90.3	87.4
Average Latency	1834.4	1660.8	1482.6	1491.6	1544.6
Median Hop Count	2	2	2	2	2

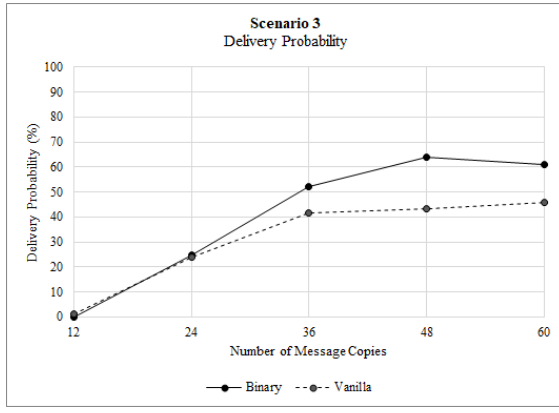


Figure 17: Comparison of delivery probability between vanilla and binary spray-and-wait in scenario 3

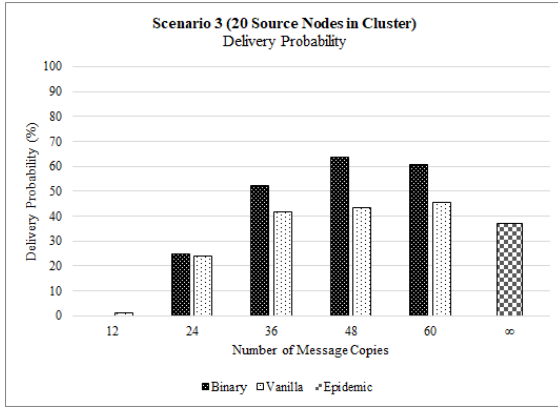


Figure 18: Comparison of delivery probability across all protocols in scenario 3

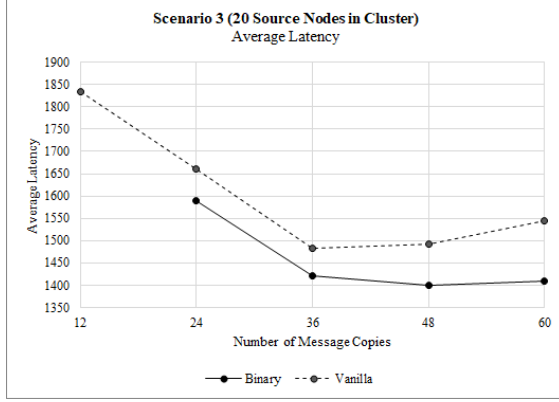


Figure 19: Comparison of average latency between vanilla and binary spray-and-wait over various message copies in scenario 3

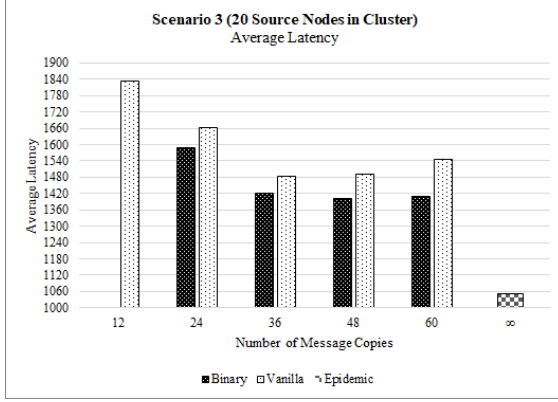


Figure 20: Comparison of average latency across all protocols in scenario 3

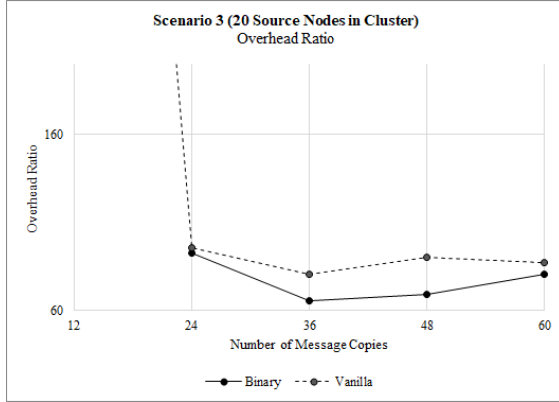


Figure 21: Comparison of overhead ratio between vanilla and binary spray-and-wait over various message copies in scenario 3

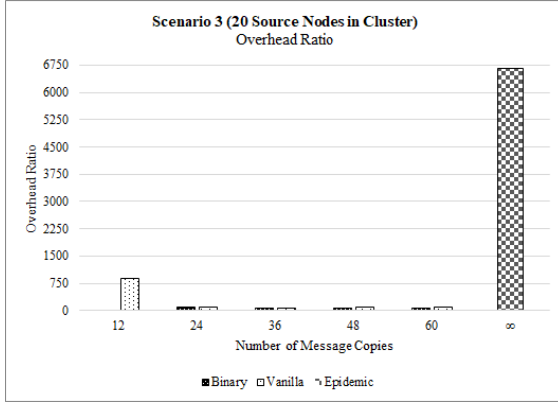


Figure 22: Comparison of overhead ratio across all protocols in scenario 3

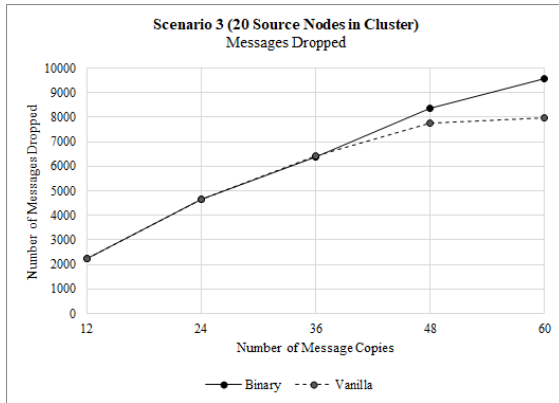


Figure 23: Comparison of messages dropped between vanilla and binary spray-and-wait over various message copies in scenario 3

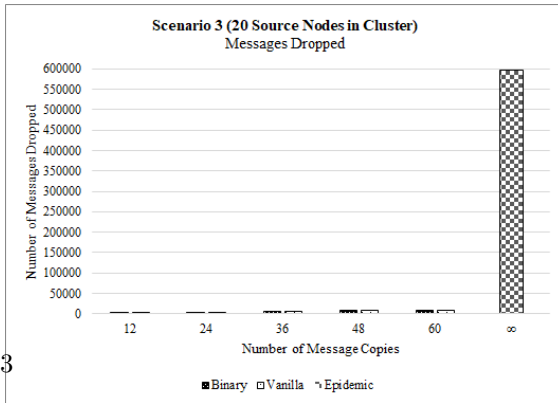


Figure 24: Comparison of messages dropped across all protocols in scenario 3

6 Conclusion

Conclusion

7 Wider Discussion

Wider Discussion

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