

**MELHORANDO O ENCAMINHAMENTO DE
MENSAGENS EM REDES D2D COM MÚLTIPLOS
SALTOS**

MICHAEL DOUGRAS DA SILVA

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Dissertação apresentada ao Programa de Pós-Graduação em Ciência da Computação do Instituto de Ciências Exatas da Universidade Federal de Minas Gerais como requisito parcial para a obtenção do grau de Mestre em Ciência da Computação.

ORIENTADOR: ANTÔNIO ALFREDO FERREIRA LOUREIRO

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MICHAEL DOUGRAS DA SILVA

IMPROVING D2D MULTI-HOP MESSAGE FORWARDING

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ADVISOR: ANTÔNIO ALFREDO FERREIRA LOUREIRO

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(William Bruce Cameron - "Informal Sociology: A Casual Introduction to Sociological Thinking")

Abstract

Abstract text goes here.

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Chapter 1

Introduction

Mobile devices have become smaller and more powerful over the years. Smartphone based computing and communication has become ubiquitous. Connected services and applications like social networks, instant messaging apps, content distribution systems and games, for example, have imposed several traffic growth in the mobile network. To support this demand we have been improving the network infrastructure. In indoor environments this strategy is feasible, because usually they are smaller and we have more control over the number of devices. However when we are dealing with outdoor environments this approach can be unfeasible, because in this case we have a dynamic scenario in which the number of devices and consequently the traffic demand can be unpredictable.

In the current mobile communication model devices must contact a base station to communicate with other devices or services. Recent works have explored a new communication model in which mobile devices can bypass the base station to communicate directly with near devices. This model is called Device to Device communication or D2D [Yang et al., 2013]. This approach has several applications, for example offload traffic from base stations [Yang et al., 2013, Nunes et al., 2016c, Aijaz et al., 2013, Pyattaev et al., 2013, Andreev et al., 2014, Bastug et al., 2014], to provide proximity based services [Lin et al., 2014a] and to provide extended network coverage under emergency scenarios [Babun et al., 2015].

The D2D communication shows itself as a sensible solution to evolve the mobile network system and improve the devices experience. However there are some characteristics of this scenario that makes the regular Internet communication protocols unapplicable. One of the major characteristics is the absence of end-to-end path between two nodes. This occurs because messages are transmitted when there are contacts between two or more nodes, and these contacts are defined by people mobil-

ity. This fact by itself makes the IP protocol routing mechanism unapplicable, which makes the routing problem one of the major topics of study [Misra et al., 2016]. Other characteristic is the intermittently connections also caused by nodes mobility. In the regular IP protocol nodes after receiving a packet immediately forwards it to the next hop based on its routing table. Due to intermittently connections, nodes can't forward the message immediately in some cases.

These problems were discussed and solutions were proposed in the context of Disruption Tolerant Networks (DTNs) [Fall, 2003]. Regular networks are based on the *store-and-forward* paradigm, in which nodes after receiving a message immediately forward it to other connected node that can help to deliver the message to the destiny. DTN networks define the *store-carry-and-forward* paradigm, in which a node after receiving a message, it stores it in a persistent buffer, and carries it until there is a proper contact to forward the message.

The *store-carry-and-forward* paradigm solves the primary problem of communication, making it possible to transmit a message from a node to another, however there is still some problems to solve. One of the major problems is the connection establishment. In D2D networks the communication process is highly dependent of nodes cooperation and resource sharing. Regarding the connection establishment there is a discussion of the best interface to use. Some works propose the spectrum sharing between D2D connections and regular mobile network connections [Lin et al., 2014b]. The major benefit of using this approach is the higher network performance and the major challenge is to define a good spectrum allocation mechanism to evict communication interference between closer devices and base stations. Some works propose the use of secondary interfaces like WIFI and bluetooth [Mao et al., 2015]. The major benefit of this approach is the reduced interference with closer connections and simplified connection establishment mechanism. The major problem is the reduced network performance.

With a defined communication interface and the data transmission paradigm *store-carry-and-forward* it is possible to forward messages in the network using only D2D communications. However there still an interesting problem to solve: the routing protocol. As said earlier in this scenario there is no predefined end-to-end path between two nodes, so the regular IP routing mechanism does not work [Misra et al., 2016]. There are several proposals to solve this problem, in which the major solutions are based on flooding variations, probability functions and social context exploration. We will discuss the major solutions in depth in the next chapter. One thing to notice is that the algorithms based on utility functions (probability and social context based strategies, mainly) tend to concentrate the network traffic in some nodes with higher

utility values, penalizing them [Chilipirea et al., 2013]. This is a remarkable problem, because in networks that use the *store-carry-and-forward* paradigm nodes need to allocate a buffer to store messages until there is chance to forward it. If the traffic is too high, some nodes can have problems of buffer overflow [Silva et al., 2015].

This work has two major contributions. First we propose a new buffer management strategy called *Space Time Drop* or just ST-Drop that aims to solve the problem of buffer management under high traffic demands. The proposed solution shows a notable performance when combined with social aware and probability based routing algorithms, outperforming classic approaches. The second contribution is the definition of a distributed implementation of a new social aware routing algorithm called Groups-NET proposed in [Nunes et al., 2016c]. We propose a distributed algorithm for detecting and manage groups. The initial experiments show that the algorithm outperforms the BubbleRap algorithm on network overhead metric with compatible delivery ratio. The work is organized as follows. In chapter 2 we discuss the main approaches and algorithms to forward messages in D2D networks. This chapter introduce important concepts to understand the proposed solutions. In chapter 3 we discuss the classic approaches of buffer management and introduce the proposed algorithm ST-Drop. In chapter 4 we introduce the distributed implementation of the Groups-NET algorithm and present some initial results. And in chapter 5 we conclude the work with a summary of the main results and discuss future works to expand the research.

Chapter 2

Message Forwarding in D2D Networks

In D2D networks messages are forwarded using intermediate nodes as relays through the *store-carry-and-forward* paradigm. A node after receiving a message, stores it in a persistent buffer until there is a proper contact to forward the message. The big problem here is how to define when to forward a message upon a contact. If too many copies of a message are generated, the network performance degrades because nodes energy and memory consumption get high. With fewer message copies, fewer paths are explored, so in general the delivery probability degrades as well because there is no predefined end-to-end path between two nodes. This chapter presents the main forwarding protocols proposed to deal with this problem.

Forwarding protocols built on top of D2D networks can be classified in single-hop and multi-hop protocols. Single-hop protocols uses only the direct contacts of a node to provide services. Multi-hop protocols use intermediate nodes to expand the service coverage. This work focus on multi-hop protocols mainly, but in this chapter we take a quick overview of single-hop protocols too.

2.1 Single Hop Protocols

Single hop protocols eliminate the routing problem by exploring only the direct neighbors of a node. Protocols in this category usually explore people group or cluster formation to provide local services for data offloading. One example of solution that uses this approach is a protocol called WiGroup proposed in [Wang et al., 2015]. This protocol defines user groups in which there is a group owner that is responsible for connecting to the base station and actuate as an intermediate access point. The other

members of the group uses the group owner to access network service. A similar solution is proposed in [Zheng et al., 2014] which uses social relationship analysis in the group formation algorithm.

The major benefits of these solutions are the reduced number of connections to the base station and it is possible to define cache strategies at group level. Single hop protocols are a sensible solution for data offloading. They are specially good for using in events with high number of people in the same area, like in stadiums and big concerts [Wang et al., 2015]. However, in environments with high mobility they do not perform well, because in this scenario groups are unstable. To handle these scenarios solutions based on multi-hop protocols are recommended.

2.2 Multi Hop Protocols

Multi hop protocols use intermediate nodes to forward messages in the network. These protocols can be used for *unicasting* communication, in which a message is forwarded from a source to a single destination node. And can also be used for *multicasting* communication, in which a message is forwarded from a source to multiple destination nodes. The major multi hop protocols were defined in the context of Disruption Tolerant Networks (DTNs). Forwarding algorithms usually explore the unicast communication to validate the solution, because if unicast works well, the protocol can be extended to work in multicasting mode [Misra et al., 2016].

Multi hop protocols can be classified as single copy and multi copy. Single copy protocols, as the name suggests, keeps just one copy of a message in the network as in classic networks. First Contact and Direct Delivery are the major protocols in this category [Misra et al., 2016]. In the First Contact protocol messages are forwarded every time a node get in contact with other nodes. The message is forwarded until it reaches the destination. After forwarding a message the node drops the local copy. In Direct Delivery a node carries a message until it get in contact directly with the destination node. These protocols are too simple and shows low performance in dynamic scenarios.

Multi copy protocols create multiple copies of each message to explore multiple paths. This approach is sensible, because since there isn't a predefined path, exploring multiple paths can improve delivery ratio. However creating a high number of message copies in the network will increase nodes' power and memory consumption, what in practice can degrade the network performance. So a good forwarding algorithm should achieve a good balance of delivery ratio and message copies overhead. Message delivery

is not guaranteed in this scenario, so the delivery ratio refers to the percentage of created messages delivered to the destination. The message overhead refers to the proportional number of copies per created message. It is also important to notice that multi hop protocols are designed to work with content that does not have strict delivery time constraints. Traditional networks have acceptable delivery time of few milliseconds, in contrast in D2D multi hop we consider delivery times of some days, a week or higher depending on the used approach.

The Epidemic protocol is the simplest multi copy algorithm [Vahdat et al., 2000]. It uses the flooding strategy, in which at each encounter nodes exchange all messages they have. Considering a scenario with unlimited nodes' buffer sizes, the Epidemic consists of the upper bound for the delivery ratio and for the network overhead, since it always transmits messages in all encounters. However, due to the enormous number of message copies in the network, when the buffer sizes are limited, this strategy may not achieve a high delivery ratio. There are some approaches derived from epidemic that use a controlled flooding strategy. The best example is the Spray and Wait protocol [Spyropoulos et al., 2005], in which the source node forwards a predefined number of message copies during its contacts. Nodes that received the message then use the direct delivery approach to forward the message to the destination. There is also a variation called Binary Spray and Wait [Spyropoulos et al., 2005] in which the source node starts with L messages. At each encounter the source forwards $\frac{L}{2}$ copies until there is only 1 copy left, then it uses the direct delivery strategy. Other nodes take the same approach of the source, but they start with the number of copies received. Both approaches show good delivery ratio with low overhead, however the authors discuss that this approach has low performance in scenarios with low mobility, because nodes with only a copy will carry the message until they encounter with the destination. So they propose a modified version called Spray and Focus [Spyropoulos et al., 2007], in which nodes with only one copy left can forward the message like a single copy protocol, dropping the local copy. The forwarding decision is based on an utility function that uses a timer that counts the last time a node had a contact with the destination. The authors have shown that this Spray and Focus has better performance than Spray and Wait in scenarios with lower mobility.

More advanced protocols reduce the number of message copies adding a decision mechanism to define if a node should send a message copy or not when an encounter occurs. The Prophet protocol is a good example of such protocols [Lindgren et al., 2003]. Prophet uses nodes' contacts history to measure the probability of a given node to deliver the message. When two nodes get in contact, they will exchange only the messages for which the other node has a greater delivery probability. The basic idea in

Prophet is to assign higher probabilities of meeting again to pairs of nodes that have met more recently. Through experiments the authors show that Prophet outperforms previous solutions.

In recent years, researchers have been exploring social aware forwarding strategies. The idea is that, since contacts are driven by human mobility, if we can understand social relationship patterns we can improve protocols. A good example of such algorithms is Bubble Rap [Hui et al., 2011]. It is a social-aware algorithm that exploits the concept of community and network node's popularity. In this algorithm, each node is assigned to at least one social community. Social communities are defined as sets of more densely interconnected nodes (groups of nodes that have more contacts among themselves). The popularity of the nodes is measured by the number of distinct contacts a given node in the network has along the time. The basic idea of Bubble Rap is to forward the message to nodes with greater global popularity until it reaches a member of the destination communities. Then the message is forwarded based on the local popularity (node popularity considering only members of the destination community) until it reaches the destination node. Through experiments the authors show that Bubble Rap outperforms previous solutions including the Prophet protocol. Other recent social aware protocol is the Groups-NET [Nunes et al., 2016b]. This solution explores the idea of regularity of people encounters in groups to forward the messages. This protocol is explored in depth in chapter 4.

Chapter 3

ST-Drop: A Novel Buffer Management Strategy

In D2D multi hop forwarding protocols nodes need to cooperate and act as relays to messages of other nodes. As result of this cooperative behavior, each node needs to share its own resources with the network, for example, allocating memory to the message in a buffer. This buffer is used to temporarily store messages being forwarded, and its capacity is limited. Consequently, the network traffic load, combined with the way a given forwarding algorithm operates, can overflow the devices' buffers. In single copy protocols this problem is alleviated because the number of messages in the network is relatively lower. However, in multi hop protocols this is a real problem, because multiple copies of a message are spread in the network, so the traffic can grow very quickly. Besides allowing multiple copies of a message, a central entity with global network knowledge usually does not exist. As consequence, nodes do not know when a message is delivered to the destination. Even when the message is delivered in multi copy forwarding algorithms, copies of this message remain in the network until they exceed their TTLs (time to live) or are dropped by other mechanism [Bindra and Sangal, 2012]. Therefore, a good buffer management mechanism is a critical requirement in this scenario.

This chapter presents a buffer management algorithm for D2D multi hop and multi copy forwarding algorithms, named Space-Time Drop (ST-Drop). This algorithm explores the local information to measure the time and space coverage of the message in the network. The basic idea is that a message with a greater time and space coverage is more likely to have been delivered, so it can be dropped first. Through experiments with a real mobility trace containing 115 nodes and a synthetic mobility trace containing 500 nodes, we show that ST-Drop enables routing protocols to achieve a good delivery ratio

with low network overhead. With the purpose of evaluating the performance of ST-Drop when applied to different types of opportunistic routing algorithms, we consider an epidemic based, a probabilistic, and a social aware algorithm. Using three well known forwarding algorithms, we show that ST-Drop helps the forwarding protocols to achieve a good delivery ratio with low overhead.

3.1 Buffer Management in D2D Networks

In D2D networks, users must devote a fraction of their devices' storage to be used as a buffer that temporarily stores the messages carried by them. The basic idea to manage such buffer, to avoid its overflow while maintaining opportunistic forwarding efficiency, is to use congestion control mechanisms. [Silva et al., 2015] have classified congestion control mechanisms and provided an extensive review of message drop policies used in opportunistic networks. In this section, we go over some of the state-of-art message drop policies highlighting their specific features.

[Lindgren and Phanse, 2006] proposed the Evict Most Forwarded (MOFO) drop policy, which uses the idea that a message forwarded a large number of times has a higher probability to be delivered, even if it is dropped locally. They also proposed the Evict Shortest Life Time First (SHLI) drop policy, which is based on the idea that it makes more sense to spend resources on messages that have a greater TTL, because, intuitively, these messages have a higher probability to be delivered. The Drop Largest policy [Rashid and Ayub, 2010] selects big size messages to drop first, because, by doing this, more space is freed from the buffer. Other basic policy is FIFO, in which, as the name suggests, messages that arrived first are dropped first.

[Rashid et al., 2013] proposed the Message Drop Control Source Relay (MDC-SR) buffer management algorithm, in which nodes stop receiving incoming messages when the buffer occupancy achieves a defined upper bound, except when the node is the destination of the message. With this approach, the algorithm decreases the number of message drops in the network. Through experiments they showed that MDC-SR optimized the performance of Epidemic, Prophet and First Contact routing algorithms in terms of delivery ratio and network overhead.

[Krifa et al., 2008] proposed the Global Knowledge Based Drop (GBD-Drop) buffer management algorithm, in which they first assume a global knowledge of the network to decide which messages to drop, achieving an optimal performance. They proposed a distributed version of the algorithm that uses statistic learning to approximate the global knowledge of the network. Through experiments they showed that

the centralized and distributed versions of the algorithm outperform the basic drop policies. The GDB-Drop can also be configured to achieve a better average delivery delay or better average delivery ratio.

Rashid et al. proposed the E-Drop buffer management algorithm [Rashid et al., 2011]. In this algorithm, messages with size greater or equal to the incoming message are dropped first when it is needed to free space in the buffer. In the case of an incoming message with size greater than the messages in the buffer, it works like the FIFO policy. This policy minimizes the drop of messages because it will usually remove only one message from the buffer to receive the incoming message. Through simulations, using mobility models, they show that E-Drop outperforms the MOFO algorithm.

[Li et al., 2009] proposed the N-Drop buffer management algorithm, in which messages transmitted more than a predefined constant are dropped first. Through simulations, they showed that this algorithm outperforms FIFO when used with Epidemic routing algorithm. [Ayub and Rashid, 2010] also proposed the T-Drop buffer management algorithm, in which messages with size in a predefined range T are dropped first. Through simulations the authors show that this algorithm outperforms FIFO when applied to the routing algorithms Epidemic and Prophet.

[Naves et al., 2012] proposed two new buffer management policies. The first one is named Least Recently Forwarded (LRF), and it drops messages that were forwarded more recently. The second one is named Less Probable Sprayed (LPS) and it drops messages that have less probability to be delivered first. Through experiments with Epidemic and Prophet routing algorithms using real-data traces, the authors showed that both algorithms outperform FIFO and MOFO in delivery ratio and overhead.

The aforementioned buffer management algorithms are based on only one local metric, for example buffer time, forward count, TTL and message size. These metrics represent a good choice, because they are independent of the routing algorithm. However, their isolated meaning can be insufficient to decide whether to drop a message or not. We have combined basic metrics to create a new buffer management algorithm named Space-Time Drop (ST-Drop). In the following section, we describe the ST-Drop algorithm.

3.2 The ST-Drop Algorithm

The ST-Drop formulation starts with the idea that a message with a greater space and time coverage in the network has a greater probability to have been already delivered, so it can be dropped first. Based on this idea, we have defined a space coefficient S_c that

measures the space coverage of the message in the network, and the time coefficient T_c that measures the time coverage of the message in the network. Therefore, to compute the space-time coverage ST_c , we use the simple function:

$$ST_c = S_c \cdot T_c. \quad (3.1)$$

With this first formulation, we do not define how to compute S_c and T_c . Buffer management algorithms for D2D networks are ideally implemented in a distributed way, so we have to be restricted to local information. Besides this, we want to keep ST-Drop independent of the routing algorithm. Consequently, we decided to combine the metrics used by the basic algorithms to compute our defined metrics S_c and T_c .

The first issue is how to measure the space coverage. In cellular networks, the contacts are driven by human mobility. Intuitively we can say that a message carried by only one person will have less opportunities to be forwarded than a message carried by two or more people, because it will be restricted to the mobility of only one person. Thus, we can say that the number of devices carrying a message is a sensible measure of the space coverage of the message, because the space coverage of a message is a direct result of the combination of the devices' mobility. Therefore, we use the same metric used by the MOFO algorithm to measure the space coverage, i.e., the number of times a message was forwarded by a node. The forward counter is a local measure of the number of devices carrying a message.

The second issue is how to measure the time coverage. FIFO exploits the time the messages have been carried by a node to decide which message to drop first. Using only this metric we could drop a recently created message and let a message with almost ending TTL in the buffer. SHLI uses the TTL of messages to decide which message should be dropped first. Using only this metric we could let a message with a huge TTL indefinitely in the buffer of a node that has low delivery probability for it. Also, in a real scenario, messages may have different TTL values. Thus, messages with relative low initial TTL would be penalized. Therefore, ST-Drop combines the idea of FIFO and SHLI, normalizing the carrying time CT , that is the time a message is stored in the buffer of a node, with the TTL of the message, defining T_c as:

$$T_c = \frac{CT}{TTL}. \quad (3.2)$$

With this formulation, we can now compute the space-time coverage using only local information. The ST-Drop policy is formalized in Algorithm 1. ST-Drop is called only when there is no available space in the buffer to receive an incoming message. The algorithm sorts the messages in reverse order by their ST_c values and store them

in a list. The messages with ST_c equals 0 are removed from the list, which implies that they will never be dropped. The algorithm considers that dropping a message with space-time equals 0 is not fair, because the message was not forwarded so far. Then, the first message of the list is dropped until enough space is freed for the new message or the list becomes empty. If enough space is freed, then the algorithm returns a confirmation to receive the incoming message. Otherwise, the device must reject the incoming message.

Algorithm 1 ST-Drop algorithm

Input: incomingMessage

Input: buffer

Output: receive

```

1: if incomingMessage.size > buffer.capacity then
2:   return false
3: end if
   Sort the messages in reverse order by  $ST_c$  :
4: msglist = sort(buffer)
   Remove messages with  $ST_c == 0$ 
5: msglist.filter()
   Drop messages until enough space is freed
6: incsize = incomingMessage.size
7: available = buffer.availablespace
8: while available < incsize and not msgList.empty do
9:   msg = msglist.removefirst()
10:  buffer.drop(msg)
11:  available += msg.size
12: end while
13: if available < incsize then
14:   return false
15: else
16:   return true
17: end if

```

3.3 Simulation Methodology

In this section, we describe the simulations we have performed to evaluate ST-Drop. Firstly, we describe the metrics for D2D opportunistic communication that we have evaluated, then we present the opportunistic routing algorithms in which we have applied ST-Drop, next we describe the two mobility traces used to emulate the network nodes' mobility and their proximity contacts, and finally we discuss the parameters and configurations we used in our experiments.

3.3.1 Metrics

With the goal of comparatively evaluating ST-Drop with other message drop policies, we used the following traditional opportunistic network metrics:

- **Delivery ratio:** evaluates the percentage of successfully delivered messages along the time;
- **Network Overhead:** measures the number of retransmissions per created message in the network, i.e., the number of D2D transmissions that each algorithm performs along the time normalized by the number of created messages.

Message drop policies for D2D networks should achieve cost-effective delivery considering these metrics, i.e., the highest possible delivery ratio with the lowest possible network overhead. Successfully delivered messages are those which the base station will not need to deliver itself, thus using less bandwidth. A high number of message re-transmissions (high overhead) may negatively impact the users' experience by, for example, increasing devices' energy expenditure.

3.3.2 Opportunistic Forwarding Algorithms

We used algorithms based on three different approaches to study the behavior of our solution when integrated with different routing algorithms. The first routing algorithm is the Epidemic [Vahdat et al., 2000], also known as Flooding. This algorithm is considered as one of the most basic ones as it is not based on utility functions or similar metrics. In this algorithm, at each encounter between two nodes, they exchange all the messages they have in their respective buffers. The second routing algorithm that we considered is the Prophet [Lindgren et al., 2003]. This algorithm uses a delivery probability as utility function to decide whether to forward a message or not. And the third is the Bubble Rap [Hui et al., 2011]. It is a social-aware algorithm based on the concept of community and network node's popularity. These algorithms were presented with more details in chapter 2.

We are using routing algorithms based on epidemic-based routing, probabilistic functions and social-context. In this way, we can evaluate the impact of different types of routing algorithms when using ST-Drop.

3.3.3 Mobility Traces

We have used two mobility traces to emulate nodes' mobility. The first one is the NCCU trace [Tsai and Chan, 2015], a real-world dataset that monitors the mobility

of 115 students inside a campus for 15 days. The second one is a synthetic trace generated by the Small World in Motion (SWIM) mobility model [Kosta et al., 2010]. This trace is based on a state-of-the-art mobility model that captures the existence of social communities influencing human mobility and it simulates the mobility of 500 people for 11 days. We have chosen the two traces to test ST-Drop under different network scales.

3.3.4 Execution

We used The ONE simulator [Keränen et al., 2009] to emulate the execution of the opportunistic routing algorithms using different message dropping policies. It is a discrete event simulator focused on opportunistic networks. By default, the simulator does not support custom buffer management algorithms and the Bubble Rap routing algorithm, therefore we implemented these features¹.

To test the ST-Drop, we defined the buffer capacity and a network traffic model. As discussed in [Grasic and Lindgren, 2012], there is no pattern when it comes to define a traffic model to test solutions in this scenario. Thus, we chose sensible values in our simulation. The buffer capacity was defined as 1GB. Messages have seven days of TTL and are generated at random times within the trace duration. Message sizes are chosen from the interval [50MB,100MB] with uniform probability. The source and destination pair for each created message is also selected with uniform probability among the nodes in the network.

We have defined two network traffic load levels based on the number of nodes of each scenario. The first load level generates messages equals to 50% of the number of nodes at each day, and the second generates 100%. Table 31 summarizes the number of messages generated in each traffic load level:

Table 31: Network Traffic Load Scenarios

Scenario		Messages/Day	Total
NCCU	50	58	522
	100	115	1035
SWIM	50	250	1250
	100	500	2500

We have emulated each scenario with each traffic level 10 times using different seeds to generate message's sources and destinations, and messages size. The average

¹The source code is available at <https://github.com/micdoug/the-one/tree/58e207ac44d5012fac5d103da781d30266164216>

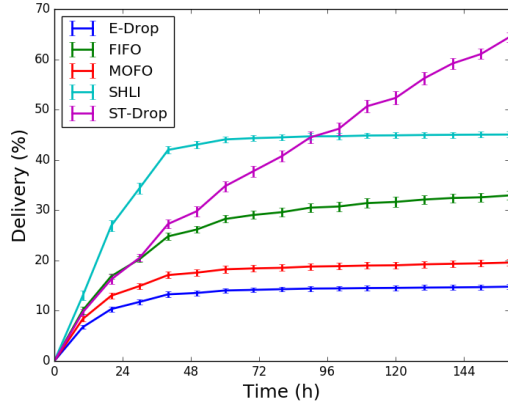
delivery ratio and the average network overhead of each scenario were computed and presented with 95% confidence intervals.

3.4 Results

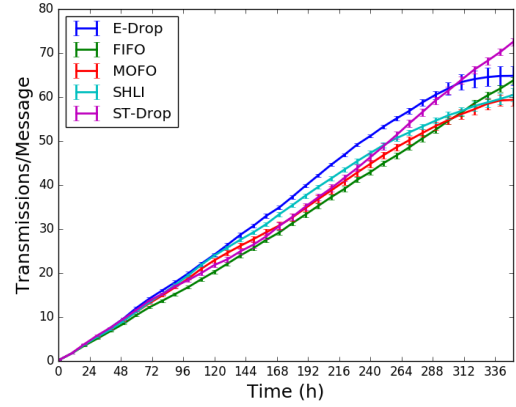
The simulation results for NCCU100 and NCCU50 are presented in Figures 31 and 32, respectively. The results of SWIM100 e SWIM50 are expressed in Figures 33 and 34, respectively. The delivery ratio values were obtained considering the time spent to delivery each message since its creation time. The result is presented in a way that it can be analysed with different TTL values, for example, considering only points under the time value 48 in the x axis, we will get the delivery ratio with TTL of 48 hours.

Considering the Epidemic routing, the delivery ratio in the NCCU100 and NCCU50 scenarios is expressed in Figures 31a and 32a, respectively. We can see that the delivery ratio of ST-Drop policy is higher than E-Drop and MOFO for almost all the simulation time. It is also higher than FIFO for time values higher than 48 hours and is higher than SHLI for time values higher than 120 hours. We can also see that the different traffic loads have not changed the behavior of the policies. The delivery ratio changed proportionally for the tested policies. The overhead results of NCCU100 and NCCU50 are expressed in Figures 31b and 32b, respectively. In these two figures, we can see that the overhead results in the two traffic levels have similar behavior. All drop policies have overhead values very similar for almost all the simulation time. But we can see that in the last four days, ST-Drop continues to grow while others get small values. This is happening because in the last four days the delivery probability of ST-Drop continues to grow too, while other policies do not, consequently the overhead increase is expected in Epidemic when more messages are delivered. The delivery ratios in the SWIM100 and SWIM50 scenarios are expressed in Figures 33a and 34a, respectively. In these figures, we can see that all drop policies have similar results for delivery ratio considering the confidence interval. And, as in NCCU scenario, with both traffic levels, we can see a similar behavior. The overhead in the SWIM100 and SWIM50 scenarios is expressed in Figures 33b and 34b, respectively. Again, we can see similar behavior under the two traffic levels.

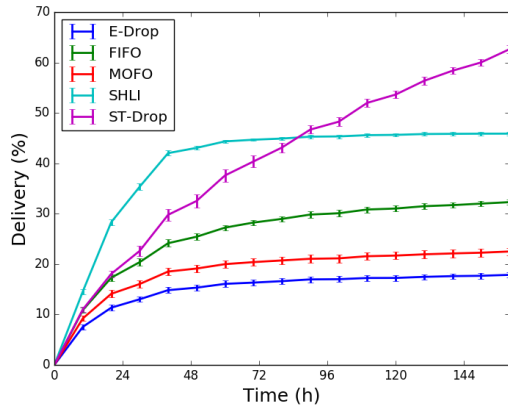
Considering the Prophet algorithm, the delivery ratio in the NCCU100 and NCCU50 scenarios is expressed in Figures 31c and 32c, respectively. We can see that the delivery ratio of ST-Drop is higher than FIFO, MOFO and E-Drop for almost all time values, and is higher than SHLI for time values higher than 120 hours. Again, we can see that under different traffic levels the results show similar behavior. The



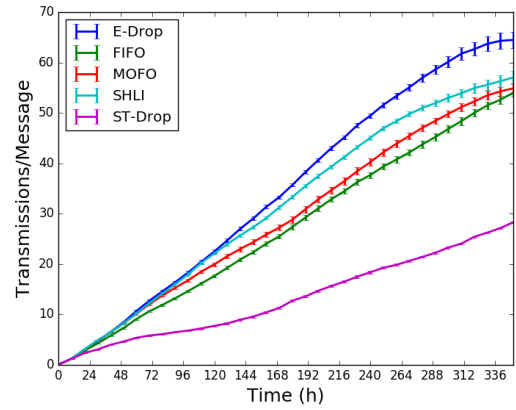
(a) NCCU100 - Delivery Epidemic



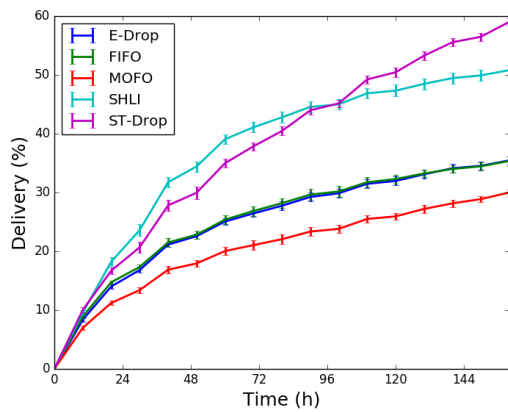
(b) NCCU100 - Overhead Epidemic



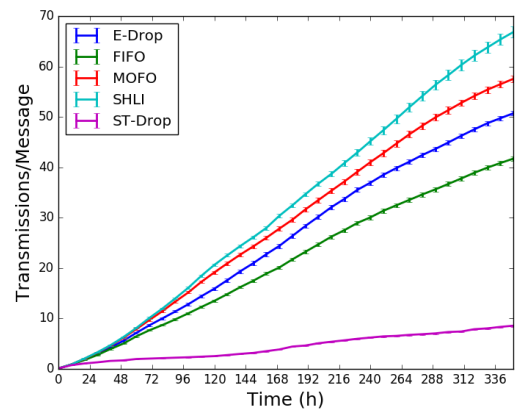
(c) NCCU100 - Delivery Prophet



(d) NCCU100 - Overhead Prophet

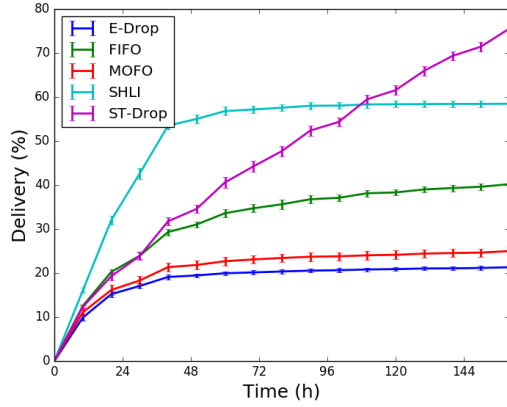


(e) NCCU100 - Delivery Bubble

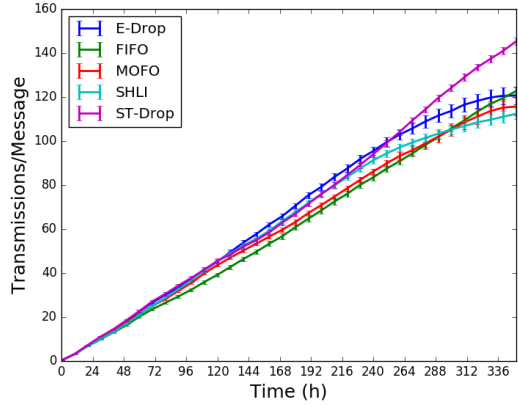


(f) NCCU100 - Overhead Bubble

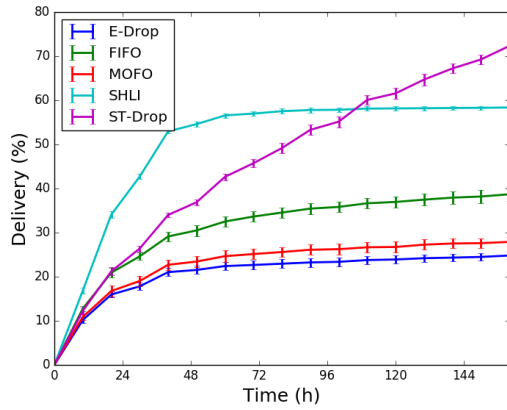
Figure 31: Comparison of message drop policies in the NCCU trace with 100% traffic



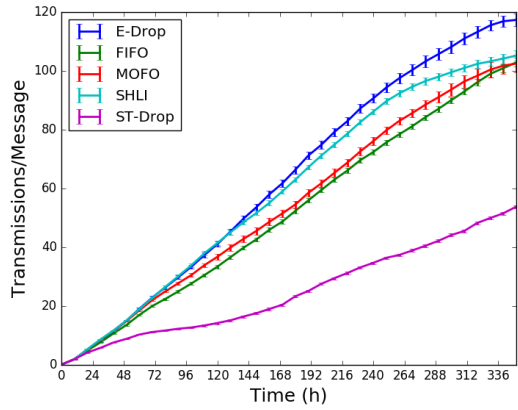
(a) NCCU50 - Delivery Epidemic



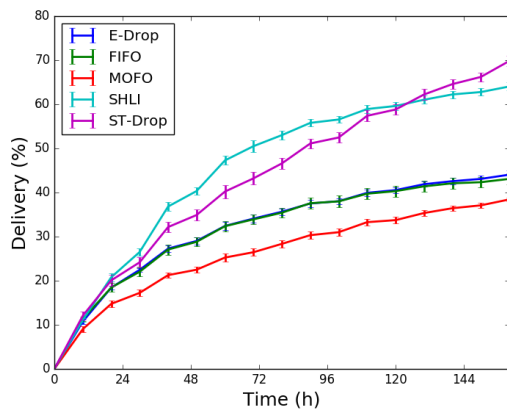
(b) NCCU50 - Overhead Epidemic



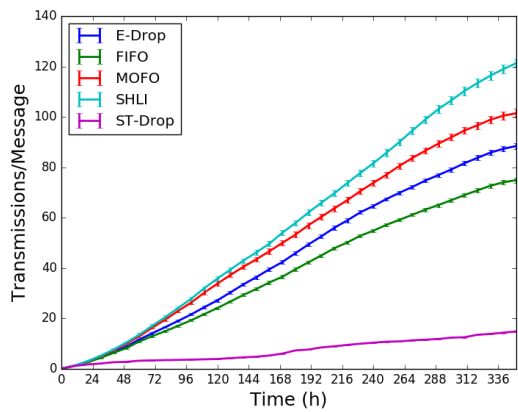
(c) NCCU50 - Delivery Prophet



(d) NCCU50 - Overhead Prophet

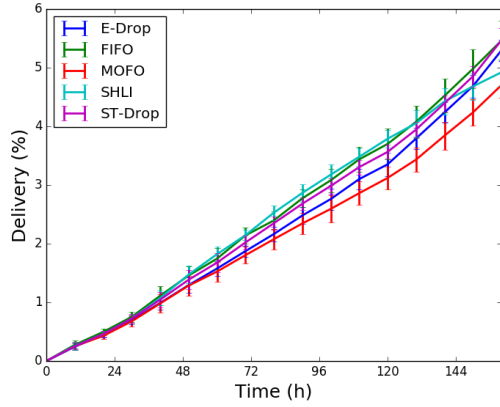


(e) NCCU50 - Delivery Bubble

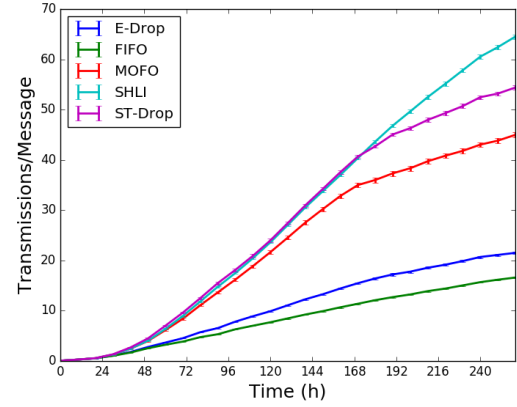


(f) NCCU50 - Overhead Bubble

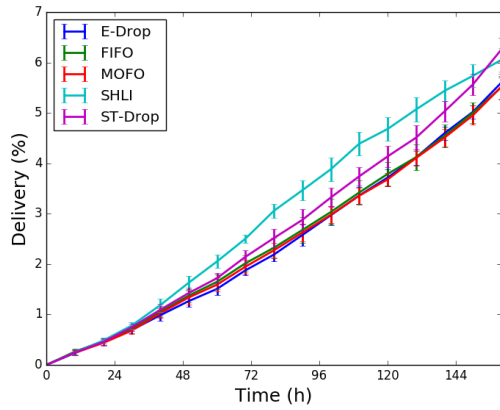
Figure 32: Comparison of message drop policies in the NCCU trace with 50% traffic



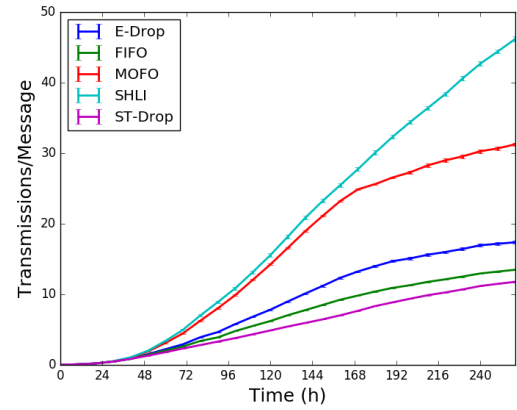
(a) SWIM100 - Delivery Epidemic



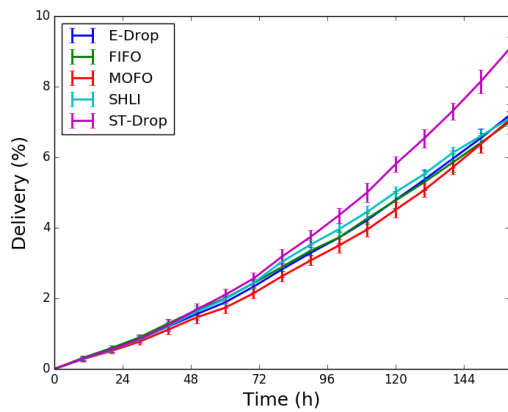
(b) SWIM100 - Overhead Epidemic



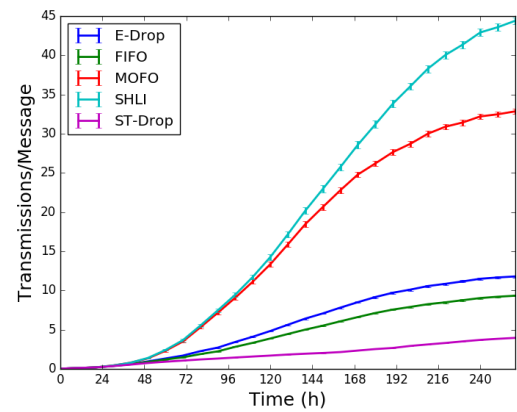
(c) SWIM100 - Delivery Prophet



(d) SWIM100 - Overhead Prophet

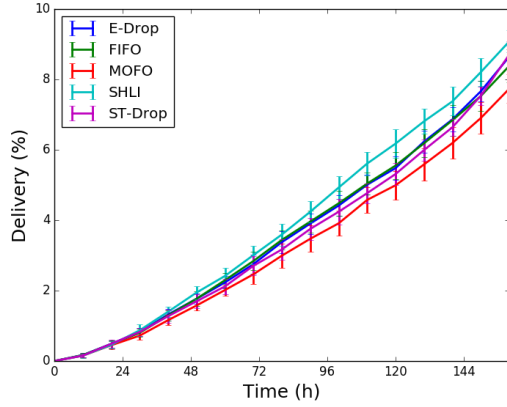


(e) SWIM100 - Delivery Bubble

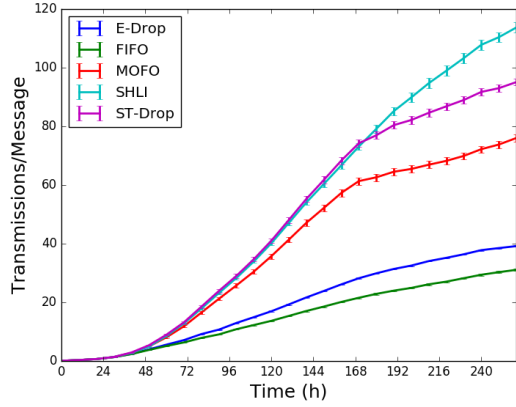


(f) SWIM100 - Overhead Bubble

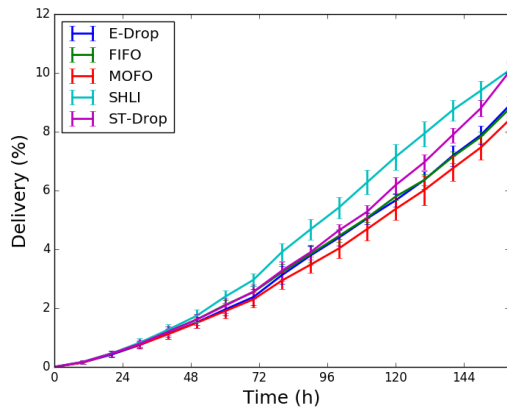
Figure 33: Comparison of message drop policies in the SWIM trace with 100% traffic



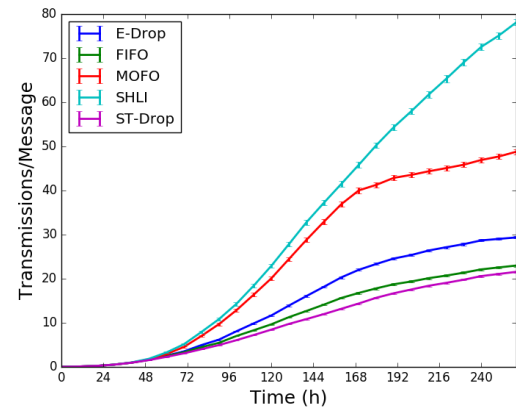
(a) SWIM50 - Delivery Epidemic



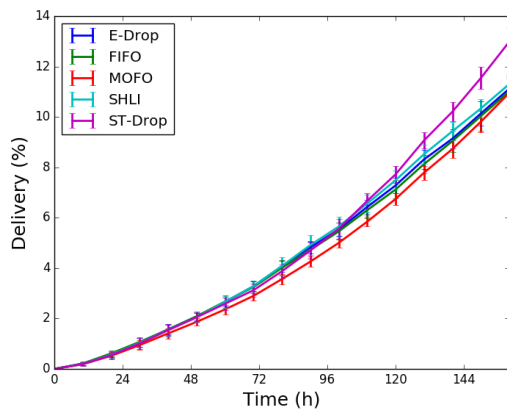
(b) SWIM50 - Overhead Epidemic



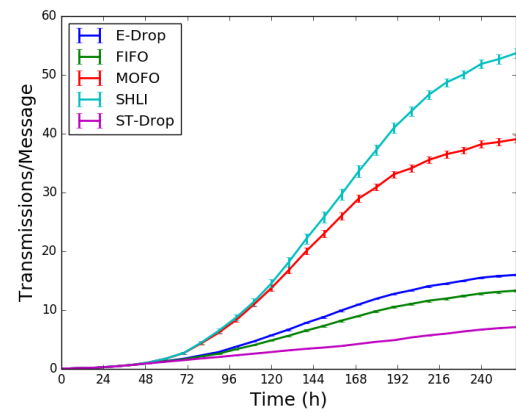
(c) SWIM50 - Delivery Prophet



(d) SWIM50 - Overhead Prophet



(e) SWIM50 - Delivery Bubble



(f) SWIM50 - Overhead Bubble

Figure 34: Comparison of message drop policies in the SWIM trace with 50% traffic

overhead in the NCCU100 and NCCU50 scenarios is expressed in Figures 31d and 32d, respectively. We can see again that the results show similar behavior for both traffic levels. In this case, ST-Drop obtained the best results during all simulation time. The delivery ratio in the SWIM100 and SWIM50 scenarios is expressed in Figures 33c and 34c, respectively. Again, we see similar behavior under both traffic levels. The delivery ratio is similar for all drop policies, except for time values between 72 and 144 hours where SHLI obtained slightly better results. The overhead in the SWIM100 and SWIM50 is expressed in Figures 33d and 34d, respectively. In this case, we obtained the same behavior of NCCU scenarios, in which ST-Drop obtained the best results during all simulation time.

Finally, we analyze the policies when used with Bubble Rap routing. The delivery ratio in the NCCU100 and NCCU50 scenarios is expressed in Figures 31e and 32e, respectively. We can see similar behavior under both traffic levels. The ST-Drop obtained a higher delivery ratio than FIFO, E-DROP and MOFO for almost all time values, and higher values than SHLI for time values higher than 120. The overhead in the NCCU100 and NCCU50 scenarios is expressed in Figures 31f and 32f, respectively. As with Prophet routing, in this scenario the ST-Drop obtained the best results during all simulation time, and we can see similar behavior under both traffic levels. The delivery ratio in the SWIM100 and SWIM50 scenarios is expressed in Figures 33e and 34e, respectively. Again, we see similar behavior under both traffic levels. The delivery ratio is similar for all drop policies, but ST-Drop obtained slightly better results for time values greater than 120 hours. The overhead in the SWIM100 and SWIM50 is expressed in Figures 33f and 34f, respectively. In this case, we obtained the same behavior of NCCU scenarios, in which ST-Drop obtained the best results during all simulation time.

In general, the ST-Drop policy obtained better delivery ratio values for all the three routing algorithms. For the overhead ratio, ST-Drop obtained the best results in all scenarios with Prophet and Bubble Rap routing algorithms. The SHLI policy obtained better results with low TTLs because in this policy, messages that spent more time in the network are dropped first, so it is expected that most delivered messages, when using this policy, have low delivery time. But when we consider all TTL range, ST-Drop obtained better results than SHLI.

It is worth mentioning that, in the Prophet algorithm, the ST-Drop overhead was much lower when compared to the other strategies. With respect to Bubble Rap, this result is even better, since ST-Drop reaches overhead values that are three times smaller than the second-best policy. This latter observation is particularly important because, as of today, social-aware algorithms such as Bubble Rap are considered the

state-of-art for cost-effective opportunistic routing. This assertion can be reassured by contrasting the delivery ratio and overhead values for Epidemic, Prophet, and Bubble Rap. In both mobility traces, we can see that Bubble Rap achieves the best delivery ratio and the lowest overhead, especially when used together with ST-Drop.

3.5 Conclusion and Future Work

This work proposed a new buffer management algorithm for D2D opportunistic networks named Space-Time-Drop (ST-Drop). This algorithm uses the idea that a message with more space and time coverage can be dropped first, because it is more likely that such message has already been delivered. We have combined the idea of basic drop policies to measure the space and time coverage of a message using local information. Therefore, our solution can be easily deployed in distributed environments. We evaluated our solution with simulations in Epidemic, Prophet, and Bubble Rap routing algorithms using three different traffic loads with two different mobility traces. We showed that our solution achieves higher delivery ratio with the three routing algorithms and much lower overhead values with Prophet and Bubble Rap. Considering all combinations of the evaluated opportunistic routing algorithms and buffer management policies, the ST-Drop combined with Bubble Rap achieved, in all experiments, the best cost-effectiveness, i.e., the highest delivery ratio with the lowest network overhead. This result shows that ST-Drop significantly contributes for improving the cost-effectiveness of opportunistic D2D Networks.

As future work, we plan to apply ST-Drop to other opportunistic D2D routing algorithms. Since ST-Drop exhibited good performance in social-aware algorithms, it is interesting to apply it in other recent social-aware routing strategies, such as Groups-Net [Nunes et al., 2016b]. We also highlight the possibility of exploring more metrics to measure space and time coverage. Information obtained from the device's context, such as battery information and actual spatial information (GPS), could be used to improve ST-Drop.

Chapter 4

Groups NET Distributed Implementation

In this chapter we present an overview of message forwarding algorithms for D2D networks. The first section presents the main contributions to the topic, discussing the state-of-art forwarding algorithms. Then we introduce an implementation proposal of Groups NET algorithm [add-reference] in a distributed environment. The implementation detail is explained in two parts: the first covers the group detection algorithm and the second the forwarding implementation itself.

4.1 Introduction

Introduce the challenge of forwarding messages in this scenario of dynamic nodes movement.

The main solutions were initially proposed in the context of DTNs (Delay Tolerant Networks) or are derived from them, since the two types of networks share some intrinsic characteristics.

Add a brief description about message forwarding in D2D.

Add description for the following algorithms:

* Epidemic routing * Prophet * Bubble Rap * Original Groups NET

4.2 The Distributed Groups NET

In this section we propose a distributed implementation of Groups NET forwarding algorithm. The solution is comprised of two stages: The first stage is group detection,

in which nodes use neighborhood discovery to infer social group meeting using a local algorithm. The second stage is message forwarding, in which nodes use the generated group data to decide when to forward a message or not. The following sections describe in details the two stages.

4.2.1 Mobile Group Detection

The mobile group detection algorithm proposed here is derived from the ideas presented in [Nunes et al., 2016a]. A group is defined as a set of people that get in contact on a given point of space and time. The authors show that group encounters have some level of regularity along the time (mainly at daily and weekly basis). This property can be used by forwarding algorithms.

In the original proposal the authors use a approach to detect groups based on global network knowledge. They basically build a contact graph considering a pre-defined time interval, and for each graph is used the Clique Percolation community detection algorithm. Each community detected by the algorithm is considered a group meeting in that time window. Then a metric called *Group Correlation Coefficient* is used to detect instances of the same group across multiple time windows.

With this approach the authors show that groups usually have regular encounters along the time (specially in daily and weekly basis). But they also discuss that the detection approach is unfeasible for a distributed environment, because it assumes a global network knowledge. However, authors also discuss that implementing a distributed solution for this should be a simple task, because in the local scope nodes can use neighborhood discover strategies and process regular neighbors encounters to decide their group encounters.

In this work we expanded this idea to build a distributed solution for group detection. It is composed of four processes that are executed concurrently by each node using basically neighborhood inspection and some basic additional parameters. In the following sections each process is explained.

4.2.1.1 Device's Local Group Detection

This process is responsible for processing nodes' local contacts and decide when a group meeting happens. The algorithm is very simple. Each node keeps two lists of devices. The first is the *friends* list (lets call it FL) that keeps track of current nodes considered as friends, i.e, members of a group that have a recent encounter. The second list is the *strangers* list (lets call it SL), that keeps track of recent nodes' contacts that are not yet considered as friends. Each entry in these lists have a contact counter that

keeps track of consecutive contacts with that node, and also have a inactive counter that keeps track of consecutive periods of time without contact with that node.

The node inspects its neighborhood at each predefined *time interval* and based on current neighbors it updates the friends and strangers list. This update is based on two predefined parameters: the *friend threshold* and *inactive threshold*. Lets call these parameters as FT and IT respectively. Based on these parameters the following steps are executed:

- At each time interval a node collects its current neighbors (lets call it CN).
- The first step is to update the counters of friends list. For each current neighbor that is present in the friends list, we increase the contact counter and reset the inactive counter. For each node present in the friends list that is not a current neighbor we reset the contact counter and increase the inactive counter.
- The second step is to update the strangers list. For each current neighbor that is present in the strangers list we reset the inactive counter and increase the contact counter. If the contact counter reaches the friend threshold the node is promoted to friends list. For each node that is present in strangers list but is not a current neighbor we reset the contact counter and increase the inactive counter. If the inactive counter reaches the inactive threshold the node is removed from the strangers list. Nodes that are current neighbors and are not present in both friends and strangers list are added in the strangers list with contact counter equals 1.
- As a final step, we check the number of nodes in the friends list that are considered inactive. A node is considered inactive when the inactive counter reaches the inactive threshold. If more than 50 percent of the nodes in the friends list is inactive, the friend list is archived and considered as a group meeting that happened in the past. When this happens we clear the friends and strangers list and restart the algorithm.

In the end this algorithm creates a list of local detected group meetings. This list is used by the local group combination process to detect instances of the same group with multiple encounters along the time.

4.2.1.2 Local Group Combination

In this step each mobile device process groups discovered in the previous step to discover groups that have multiple encounters along the time. The algorithm is based on a

metric called *Group Correlation Coefficient* defined in [add-reference]. This metric basically computes the proportion of nodes shared between two sets.

Each node keeps a list of *combined groups*, that keeps track of groups with multiple encounters along the time. For each local group detected in the previous process, we check if there is a combined group with Group Correlation Coefficient greater or equals 0.5. If there is, the local group is combined into the combined group adding its members to it and registering a new encounter. If there isn't, a new combined group is initialized with the local group data.

The combined groups generated in this process are used by neighborhood inspection to compose the final groups considered in the forwarding algorithm.

4.2.2 Neighborhood Inspection

Besides inspecting its current neighborhood, at each considered time interval each node also collects its neighbors combined groups. The collected groups are combined with the groups generated by the local group combination process using the same approach described previously. Groups that have correlation coefficient greater or equals 0.5 are merged. This step is used to expand a node local vision with its neighbor network knowledge. So, in the end the local combined groups are updated with neighbors detected group information.

4.2.2.1 Group Graph Creation

In this step we build the graph of groups using the combined groups created by the neighborhood inspection process. The graph is created using the approach described in [Nunes et al., 2016a]

Chapter 5

Conclusion

Put some text here

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