COST-EFFECTIVE ROUTING & COOPERATIVE FRAMEWORK FOR OPPORTUNISTIC NETWORKS

By

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Dedicated to

My Parents and Sisters

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Abstract

In Opportunistic Networks most of Internet's basic assumptions do not hold true. Due to sparse density of nodes and frequent changes in network topology, an end-to-end contemporaneous path may not exist. However, sporadic links emerging from coarse-grained mobility of nodes can be construed over a period of time, as presence of a complete path between a pair of nodes. Nodes hold a packet in permanent storage until an appropriate communication opportunity arises, which can help in further forwarding of the packet. In order to avoid packet loss, multiple copies of a single message are generally sent within the network, independently making their way to eventual destination. This design decision poses extra burden over network resources, and unnecessary utilization may result in degrading performance in resource-stringent environments. Hence, there is need to reduce this extra overhead, by determining effective next-hop utility of nodes, and to better utilize network capacity with real time comprehension of dynamic network characteristic. Heterogeneity of nodes, in terms of capabilities or mobility patterns poses several challenges in defining a utility function that fits all. Moreover, multi-hop routing protocols generally assume altruistic behavior of nodes. However, this assumption is not always true, as by agreeing to forward messages a node is contributing its resources such as memory, processing power, energy etc. Non-cooperative behavior may reduce effective node density and can be devastating in opportunistic environments, where intermediary hops are required to share custody of messages. We target these issues in this thesis.

In order to address first problem, we present a "Multi-Attribute Routing Scheme" (MARS) based on "Simple Multi-Attribute Rating Technique" (SMART) that collects samples of important information about a node's different characteristics. This stochastic picture of a node behavior is then effectively employed in calculating its next-hop fitness. We also devise a method based on learning rules of neural networks to dynamically determine relative importance of each dimension. Hence, estimations based on an optimized combination of multiple parameters help in taking wiser decisions in relay nodes selection with inherent advantage of efficient utilization of network capacity.

In second part of thesis, we analyze the aspect of nodes cooperation in challenged networks. We propose a novel framework to stimulate cooperation among nodes, which is deployed as an overlay to assist Destination-Dependent (DD) utility-based schemes. We envision that such an assistance mechanism to stimulate cooperation among nodes have the potential to help with practical deployments of DD utility schemes in real scenarios afflicted with selfish nodes.

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List of Acronyms

DTN	Delay/Disruption Tolerant Networks
ICNs	Intermittently Connected Networks
IPN	Inter-Planetry Network
CFDP	CSSDS File Delivery Protocol
CSSDS	Consultative Committee for Space Data Systems
BP	Bundle Layer
DP	Delivery Probability
OppNet	Opportunistic Network
SNC	Saami Nomadic Community
MARS	Multi-Attribute Routing Scheme
ONE	Opportunistic Network Environment simulator
SMART	Simple Multi-Attribute Rating Technique
DD	Destination Dependent
DI	Destination Independent
DSDV	Destination-Sequenced Distance-Vector
EBR	Encounter Based Routing
EV	Encounter Vector
SnW	Spray and Wait
PRoPHET	Probabilistic ROuting Protocol using History of Encounters and Transitivity

Chapter 1

Introduction

In sparse mobile ad-hoc networks, there may not exist a contemporaneous end-to-end path between a pair of nodes, which is due to high node mobility, sparse topologies or power-saving policies. This violates the assumption on which many ad-hoc routing protocols [3, 4] are based, thereby providing room for conducting research in identifying ways to provide connectivity in an environment that does not rely on basic assumptions of the Internet. Wildlife monitoring, disaster recovery networks, military applications etc. are some of the examples of such challenged environments, where most of the Internet's basic assumptions and rules need to be reconsidered. Intermittent connectivity, long or variable delays, frequent movements, and limited resources, are the characteristics due to which aforementioned environments can not be well served by traditional Internet protocols. Both the traditional reactive and proactive routing schemes fail in such kind of environments, reactive routing schemes may not discover a complete path before the communication could start. On the other hand, proactive routing protocols fail to converge due to rapidly changing network topologies, resulting in an increased overhead of topology update messages.

In challenged networks, which are highly prone to disruptions or frequent partitions and have high delays, concept of Delay Tolerant Networking [5] can be used to deliver data between a pair of nodes.

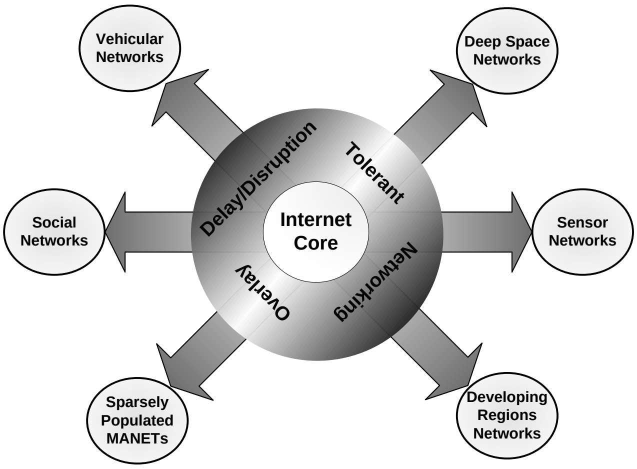

Fig. 1.1: Delay/Disruption Tolerant Networking Overlay (adapted from [1])

1.1 Delay/Disruption Tolerant Networks

In order to establish connectivity between nodes located on different solar system planets (e.g. Earth and Mars) Inter-Planetry Network (IPN) project [6] was launched in 1998. Later, research community started adapting some of the concepts of IPN to a broader class of challenged networks, also known as Intermittently Connected Networks (ICNs). The motivation for Delay/Disruption Tolerant networks (DTNs) is first presented in 2003 by K. Fall et al. [7]

DTN is capable of handling ICNs, and it is deployed as an overlay architecture on distinct ICNs' protocol stack to provide interoperability across various heterogeneous networks, as can be seen in Figure 1.1. The end-to-end message switching overlay is defined as "Bundle Layer" [8], which operates below application layer and above the existing protocol stacks in networks where it is hosted [5]. Every node that implements bundle layer is called a DTN node. The bundle layer handles network interruptions by store-carry-and-forward mechanism [5]. A node stores bundles/messages in persistent storage, when an immediate next hop is not available due to partitions or at DTN gateway to provide interchangeability across

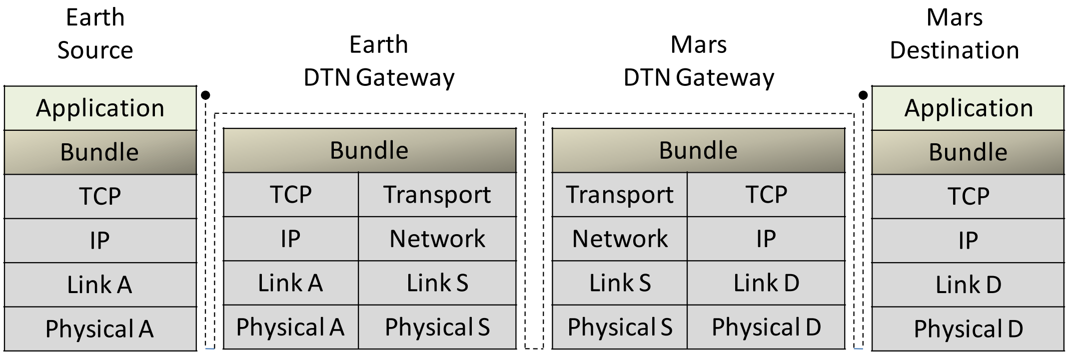

Fig. 1.2: Delay/Disruption Tolerant Networking Protocol Stack (adapted from [2])

heterogeneous networks. An exemplary scenario showing communication, between two nodes located on different solar planets, with DTN protocol stack is defined in Figure 1.2. Presence of other protocol layers indicate that bundle layer alone is not capable of carrying information within the network, instead it relies on specialized protocols for different networking environments [8]. For example, within an IPN scenario shown in Figure 1.2, it operates over TCP/IP within traditional Internet, then it provide gateway service to CFDP [9] in deep space networks [7] .

1.2 Opportunistic Networks

In DTNs, legacy-Internet protocols are typically used to compute routes within connected portions of the network. However, link unavailability, disconnection or interchangeability is handled by DTN gateways, which are often deployed at the edges of any network [7].

Legacy routing protocols require more structured networks in order to provide end-to-end connectivity. However, in many scenarios it is not possible nor advisable to build networks based on legacy approaches. Therefore, in order to provide connectivity in such environments, we require a network that can go beyond the capabilities of standard Internet protocols. For example, during a disaster when

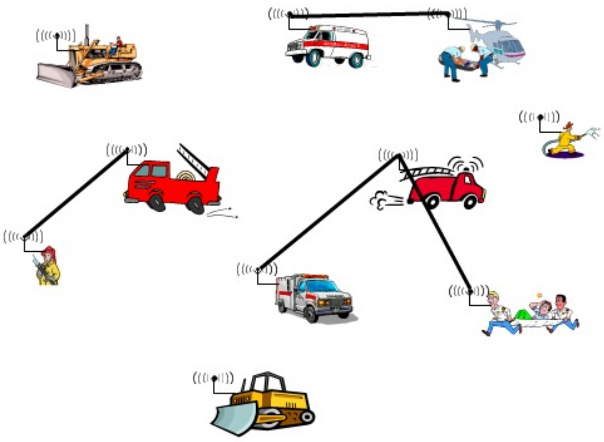

Fig. 1.3: Example Of An Opportunistic Network Envisioned To Facilitate Coordination During Disaster Recovery Operations

the existing communication infrastructure is destroyed, a fault and disconnection tolerant network, as envisioned in Figure 1.3, is required for a coordinated humanitarian rescue response. Frequent network partitions are common in such a sparse and highly mobile wireless network, as it is not feasible to keep the nodes remain connected at all times. In order to provide connectivity in such challenging environments, where we can not assume the presence of contemporaneous paths between nodes, a new type of communication paradigm called an Opportunistic Network (OppNet) has emerged.

Opportunistic Networks are kind of networks where every single node may act as a DTN node or gateway [10]. Therefore, opportunistic networking is often considered as a more flexible environment than DTNs, and promises unique opportunities for an emerging pervasive computing era. In an opportunistic network, nodes may store and carry a message in permanent storage, while waiting for any future contact opportunity that can bring it closer to eventual destination in a store-carry-and-forward manner [5], as shown in Figure 1.4. An OppNet is typically comprised of a heterogeneous set of mobile devices, and connection opportunities arising from node mobility are leveraged to disseminate information/data within the network.

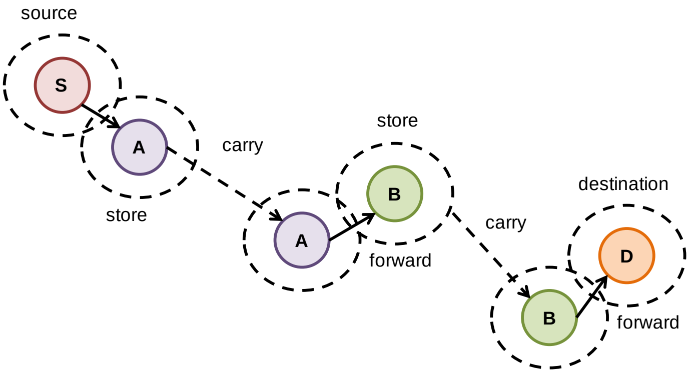

Fig. 1.4: Store-Carry-And-Forward Routing Paradigm

As a complete end-to-end path may not be available, data transfer between any pair of source and destination usually takes place with multiple discontinuous hops over a period of time [11], and usually infecting the network with redundant copies to combat with high loss ratios. As shown in Figure 1.5, a message m from source S can eventually be delivered to destination D at time 15, if previously S transfers m to R_1 at time 5 and R_1 transfers it to R_2 at time 9. Hence, DTN routing is about finding solutions to following problem.

> *How node S or R_1 knows that another node R_1 or R_2 is an appropriate next-hop for delivering message m to destination D. Moreover, how many copies of m should be present in the network in order to achieve high delivery ratios despite increased packet drop rate due to congestion or message lifetime expiry within opportunistic networks.*

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Opportunistic networking can also be used to provide cost-effective connectivity

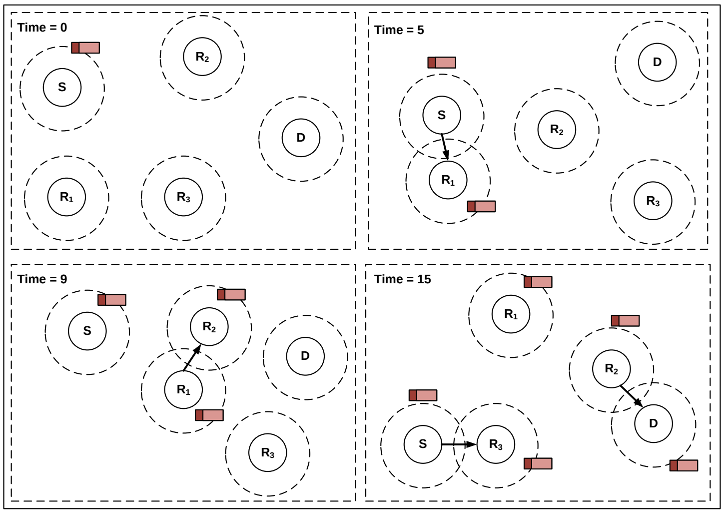


Fig. 1.5: Opportunistic Networking With Sporadically Emerging Links

to rural and developing areas e.g. DakNet [12] and SNC [13]. Moreover, wildlife monitoring (e.g. ZebraNet [14]) is an other application where opportunistic networking can help in limiting human intervention. In this case, tags with sensing capabilities are attached with animals and information is collected at base station from tags of nearby passing animals.

1.3 Problem Statement

Opportunistic networking makes use of transmission opportunities emerging from coarse-grained mobility of nodes within the network. Sporadic links appearing among nodes can be eventually construed over a period of time, as presence of a complete path between a source and destination pair, as shown in Figure 1.5.

Routing techniques for such networks generally infect the network with redundant copies of a single message. This may help to cope with high packet loss ratios and partial knowledge about network topology, but excessive duplication can also overload network resources. The problem becomes more appalling due to inadequate performance in resource-stringent networks. In order to control and efficiently distribute message replicas to ensure an increased probability of successful delivery, utility-based schemes choose relays based on next-hop fitness or utility of nodes.

Mostly, utility based protocols help prune the epidemic distribution tree by forwarding replicas of a message only to nodes presenting next-hop fitness greater than the current custodian of a message or a predefined threshold value. In this case, overhead of a protocol is directly proportional to the size of qualifying nodes. Therefore, a carefully defined utility function has the potential to reduce the unnecessary overhead resulting in increased overall performance of the network. However, in heterogeneous environments, where nodes are of very different capabilities, such as pedestrians, tiny sensors, and vehicles etc, defining a common utility function to determine next-hop fitness/utility of a node becomes more challenging.

With destination-independent utility-based schemes, nodes presenting special characteristics, such as, large memory, long battery life, or high social affiliation can be selected as next-hop relays. On the other hand, destination-dependent utility-based schemes forward packets only to nodes with some delivery probability to destination. This delivery probability is generally calculated based only on mobility behavior of a node within the network, while constraints over resources and other characteristics, such as, willingness to participate in forwarding, or congestion due to surged data, are often ignored.

Moreover, the intrinsic nature of utility-based schemes, makes it inevitable that the majority of the network traffic is carried by only the most suitable nodes. Concretely, this load imbalance and poor utilization of total network capacity may degrade performance in resource-stringent environments. Intuitively, the utility heuristics based on any single attribute are not sustainable, as the inefficiency of the algorithm to get itself cognizant of changing network characteristics can quickly deplete constraint resources in few better nodes, which are, ironically, vital for long term functioning of the network.

Therefore, DTN routing is a multi-attribute optimization problem, where it is prudent to define next-hop utility of a node based on mobility and resource related metrics. Moreover, determining relative importance of individual metrics in order to have an optimized combination is equally important to take intelligent decisions. Information derived from multiple metrics also enable real time comprehension of changing network dynamics, which can consequently be used for efficient utilization of network capacity with better load-balancing.

It is pertinent to mention here that in opportunistic environments, an intermediary node may be required to share custody of messages with source nodes. Nevertheless, in real world scenarios when we associate nodes with human beings, carrying wireless devices like PDAs or laptops to form an opportunistic network, egoistic behavior is not out of possibility. Moreover, the self-organizing nature of such networks, provides a node with the autonomy to decide on its own whether to participate in multi-hop communications as the epitome of underlying protocol rules or not. Hence, existing protocols may break down if a large portion of nodes do not participate in an altruistic manner, and rather, choose to enjoy services from the network as free-riders. Concretely, performance of a network afflicted with selfish nodes might be greatly impaired, unless the utility-based data forwarding scheme is not assisted with some incentive mechanism, which enforces penalty on not cooperating. Moreover, for an opportunistic multi-hop relaying scheme, to work upto its full potential in pragmatic settings, it is indispensable to safeguard interests of cooperative participants from being compromised by miscreant entities. However, these schemes do not enforce any mechanism to ensure cooperative participation, altruistic behavior is taken as an assumption, instead. Therefore, there is need to analyze the aspects of the willingness of a node to act as forwarder along with determining its next-hop fitness; and to propose a (distributive) mechanism in order to provide incentives for nodes who behave cooperatively and to isolate free-riders. Devising such a mechanism for opportunistic networks is challenging due to limited and sporadic communication opportunities and inadequate knowledge of network topology.

1.4 Research Objective

Research objectives of this study are twofold. First, we aim to develop a routing protocol, to increase performance within resource-stringent opportunistic networks. This hybrid routing protocol, takes advantage of both destination dependent and independent characteristics and defines one utility function that fits all, despite heterogeneity of nodes and scenarios. With significantly small overhead and load-balancing, the protocol is better able to utilize network capacity to achieve high delivery rates.

Second, we analyze effects of non-cooperative behavior of nodes within opportunistic networks. The outcome of this study is a model that provides a distributive mechanism to offer incentives for nodes that cooperate and to penalize the misbehaving nodes.

1.5 Research Contribution

Our contributions is this thesis are summarized below.

1. We propose a novel hybrid utility based routing scheme Multi-Attribute Routing Scheme (MARS) in this thesis that determines node's next hop fitness based on an optimized combination of a set of multiple parameters (metrics). These parameters can be selected based on destination indepen-

dent and dependent characteristics of nodes to represent changing network conditions and application requirements.

2. With the help of simulations, we show that routing overhead can be greatly reduced considering only those nodes as better relays which have high next-hop fitness to certain destination, based on combination of multiple parameters related with relay nodes characteristics. Moreover, we show that MARS can adapt to dynamic network characteristics and can better utilize network capacity through load-balancing resulting in optimal performance under different network scenarios.

3. We propose a novel cooperation enforcement framework which is deployed as an overlay to assist destination-dependent utility-based schemes. The proposed framework do not require any changes within the working of the protocol, neither it assume any additional entities to be deployed within the network.

4. We demonstrate the effectiveness of proposed framework through simulations with PRoPHET routing [15].

1.5.1 Publications

Journal Publications

Sadaf Yasmin, Rao Naveed Bin Rais and Amir Qayyum, "Resource Aware Routing in Heterogeneous Opportunistic Networks", accepted in International Journal Of Distributed sensor Networks (IF 0.665)

Sadaf Yasmin, Amir Qayyum, and Rao Naveed Bin Rais, "An Overlay Over Destination-Dependent Utility Schemes To Safeguard Altruism In Opportunistic

Environments", submitted for review in Arabian Journal of Science and Engineering

Conference Publications

Sadaf Yasmin, Rao Naveed Bin Rais and Amir Qayyum, "A Multi-Attribute Routing Protocol for Opportunistic Environments", in Proceedings of 23rd International Conference on Computer Communications and Networks ICCCN, WiMAN 2014

Peer Azmat Shah, Sadaf Yasmin, Sohail Asghar, Amir Qayyum, Halabi B Hasbullah, "A Fluid Flow Model for SCTP Traffic over the Internet", In proceedings of 8th IEEE International Conference on Emerging Technologies (ICET 2012), October 8-9, 2012, Islamabad, Pakistan

Sadaf Yasmin, Muhammad Yousaf, Amir Qayyum, "Security Issues Related with DNS Dynamic Updates: A Survey", in Proceedings of 7th ACM Frontiers of Information Technology, Islamabad, Pakistan 2010

1.6 Research Methodology

We have implemented our schemes with ONE [16] simulator and evaluations are performed with real and synthetic mobility models.

1.7 Thesis Organization

The rest of the thesis is organized as follows: in chapter 2 we present literature review of some existing routing protocols. Chapter 3 contains design details and elaborated description on our proposed routing scheme. Evaluation of MARS using variety of scenarios including synthetic and real heterogeneous mobility traces is explained in chapter 4. Cooperation enforcement framework is explained in chapter 5 and its evaluation and simulation results are presented in chapter 6. Conclusion and future work is presented in chapter 7 at the end.

Chapter 2

Literature Review

In this section, we discuss some of the proposed DTN routing schemes with focus on opportunistic routing approaches.

2.1 DTN Routing

A large number of DTN routing protocols are proposed that can be placed into many well-defined categories, shown in Figure 2.1, such as, 1)Deterministic Routing, 2) Enforced Routing, and 3) Opportunistic Routing.

Deterministic routing techniques assume that, dynamics of time varying connectivity within the network are known in advance in the form of *knowledge oracles* [17]. An *oracle* is defined as a notational entity, with encapsulated knowledge about the network, which is capable of answering any question required by an algorithm. A number of deterministic routing algorithms are also proposed by S. Jain [17], that are classified based upon the amount of knowledge they require to compute routes.

MV [18] , MORA [19], and work from W. Zhao et al. [20, 21] are examples of enforced routing techniques, where agents e.g. data mules or ferries are used to deliver information within the network. PMAR [22] is another example of enforced routing approaches, where node movements are intentionally altered to actively create new connections instead of waiting for any possible connection opportunity.

However, opportunistic routing protocols work without complete knowledge of the network a priori; rather network behavior is assumed random. These schemes are

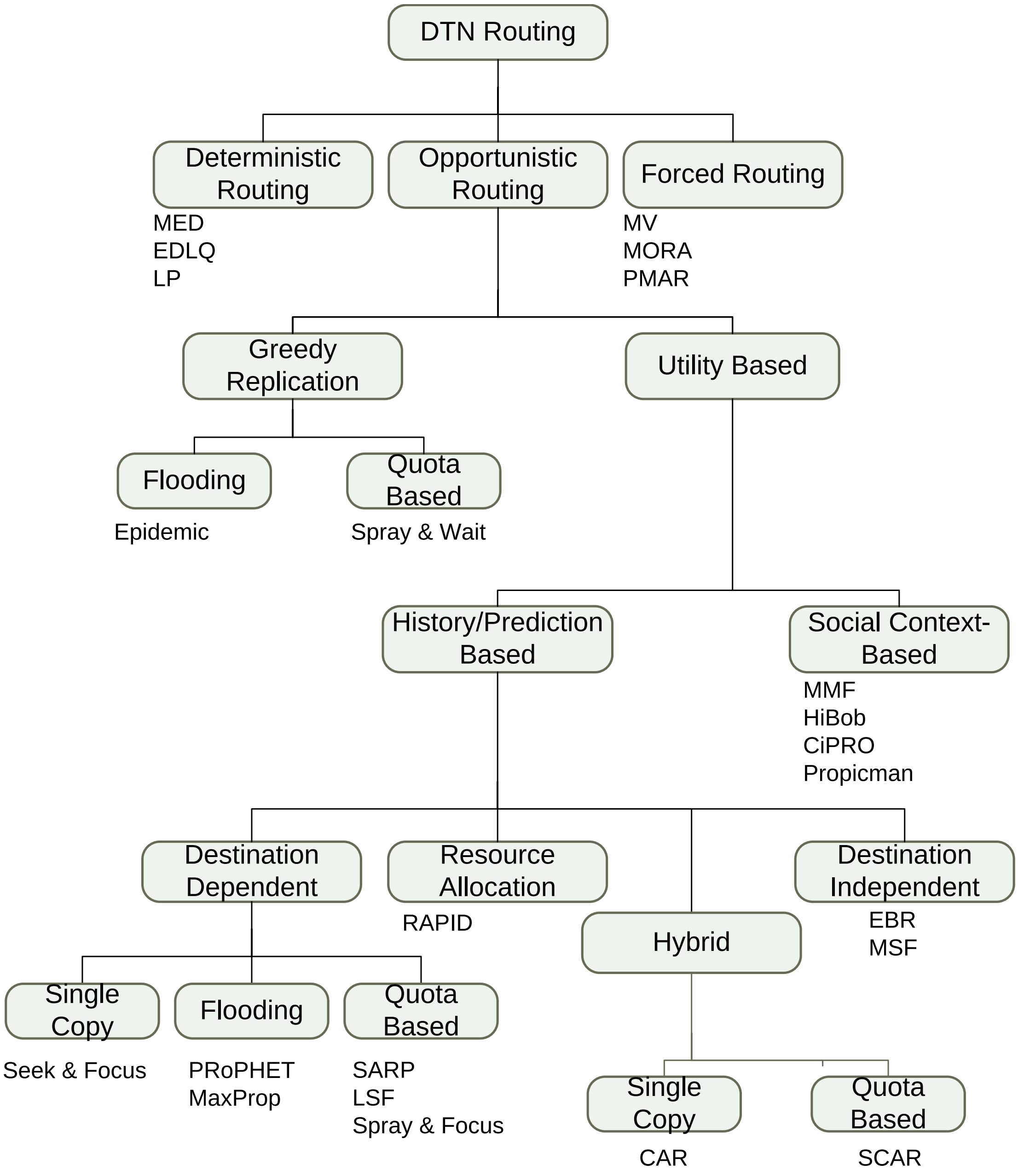


Fig. 2.1: DTN Routing Taxonomy

directed by making per hop forwarding decisions on sporadically emerging links among network nodes [23, 24]. Opportunistic routing can be further categorized into Utility-Based Schemes, and Greedy Replication.

2.1.1 Greedy Replication-Based Schemes

In greedy replication, nodes try to forward packets on every available transmission opportunity without considering suitability of nodes, as being able to contribute in delivering a packet to its intended destination. The governing principle behind these schemes is analogous to the spreading of an infectious disease; flood the network with excessive number of message replicas with the hope that at least one will eventually reach at its destination. The message replication is based on the assumption that challenged networks are prone to high packet loss ratios because of mobility of nodes, link failures, buffer constraints, and unavailability of a complete end-to-end path due to chronic network partitions or intermittent connectivity. Therefore, multiple redundant copies of a message should be transmitted, which are independently routed in the network to achieve robustness. Epidemic Routing [25] rigorously works on the above principle; on every encounter between two nodes, the nodes pass on a copy of those pending messages to each other that they do not have in common. In this way, message is spread to all nodes in the network, eventually being offloaded to its destination. In the presence of sufficient resources, epidemic routing offers minimum delivery delay, as shortest path is always selected when the packet is sent to every encountering node. However, performance degradation can be observed in case of epidemic routing with increasing message rate within the network [26].

Take Figure 2.2 as an example, we take message creation time as T, and future contacts occurring among nodes are represented as "T + time_units". Let us say,

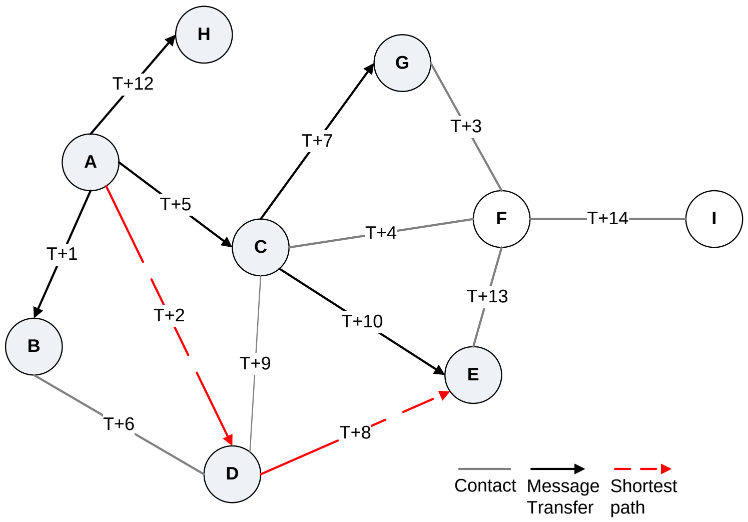


Fig. 2.2: Example Showing Message Transfer From Source A to Destination E With Epidemic Routing. Shortest Path From A to E is Shown With Dashed Arrow Lines.

at time T, a message is created at node A for destination E. Nodes which receive a copy of the message are shown with shaded color. We can see that with epidemic routing message copies are transferred on every contact. At time T+6, packet is not delivered to D by node B, because both the nodes have this packet in common at this time instant. Other nodes receiving the packet with epidemic routing are shown with solid arrows. With epidemic routing, first copy of the packet is delivered to E along the path (A-D-E) represented with dashed arrows.

In another study by T. Spyropoulos et al. [27], quota-based greedy replication scheme named as Spray & Wait, is proposed to avoid over utilization of network resources. This scheme consists of following two phases:

Spray Phase: In this phase, source spread limited number of copies (L) to first encountering nodes. In binary mode source sends L/2 copies on each transmission opportunity and decrements its replication counter by L-L/2 after every successful transmission. Intermediate relays receiving a copy of the message with number of forwarding tokens (L) $>$ 1, continues dissemination of the message according to

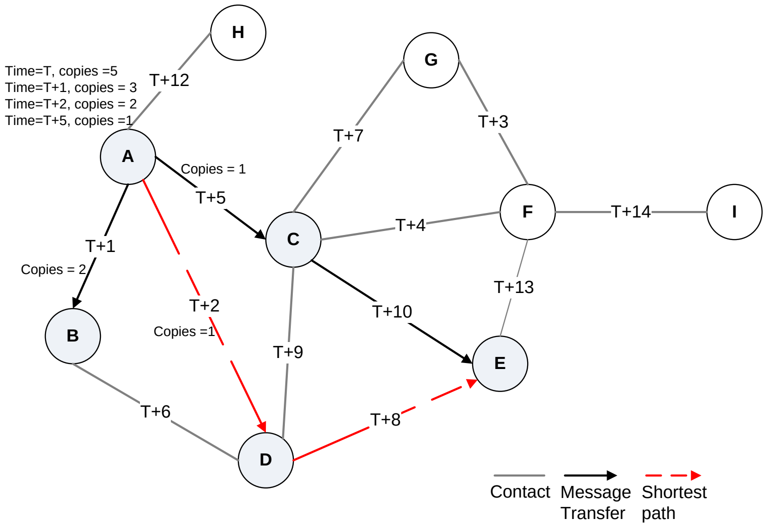


Fig. 2.3: Example Showing Message Transfer From Source A to Destination E With Spray and Wait Routing. Shortest Path From A to E is Shown With Dashed Arrow Lines.

above mentioned rule.

Wait Phase: When a node including source has only one copy (L = 1), it stops forwarding the message to any intermediate relay and waits for its direct contact with destination node.

Spray and Wait is aimed to use strengths of both naive replication and direct transmission schemes and is shown to have optimal performance in scenarios with independent and identically distributed inter-contact probabilities [27].

A binary spraying example is shown in Figure 2.3. We take message creation time as T, and future contacts occurring among nodes are represented as “T + time_units”, and nodes which receive a copy of the message are shown with shaded color. Let us say that at time T a message is generated at node *A* destined to *E* with 5 copies. Node *A* sends $\lfloor 5/2 \rfloor$ copies at T+1 to node *B*, and it is left with remaining 3 tokens. Next, during *A's* encounter with node *D* at T+2, $\lfloor 3/2 \rfloor$ copies are transferred, which eventually reaches destination at time T+8, as shown with dashed arrows in Figure 2.3. No more copies are sprayed when a node is left with only one copy of the message. Therefore, message is not transferred to G and H during their encounter with C and A respectively.

Instead of spraying all the L copies during single spray phase, E. Bulut et al. [28] propose to use multi-period spraying for distributing the required number (L) of copies. In this way, smaller number of tokens than the required L tokens are sprayed and then nodes wait for message delivery to destination through direct transmission. Each spray phase, accompanied by the associated wait phase, is defined as a period. If message is unable to be delivered to its destination, additional copies are sprayed during the next period. E. Bulut et al. [28] suggest that spraying L copies using multi-period spraying can reduce average number of copies used per message without effecting delivery rate.

The aforementioned naive replication techniques do not wisely select relay nodes, which can lead to wasteful replication, thereby degrading performance over resource stringent environments. In this thesis, we propose a utility-based opportunistic routing scheme, that gets itself cognizant of dynamic characteristics of nodes including mobility patterns present within the network. Utilities based on a set of encounter samples help in taking wiser decisions regarding relay nodes with the inherent advantage of efficient utilization of limited resources. A number of utility-based replication approaches exist in the literature that tends to characterize mobility of nodes for next hop selection. In following, we present a review of some well-known existing utility-based schemes.

2.1.2 Utility-Based Schemes

Forwarding on every available opportunity or controlled replication, like in Spray and Wait[27], can help in achieving promising delivery ratios in homogeneous network scenarios, where nodes can frequently move around the network. However, in heterogeneous scenarios, nodes may differ in terms of their capabilities and moving patterns. In this case, forwarding without considering node's candidacy to contribute in the delivery process may waste network resources with unnecessary overhead [23]. This arises the need to discover better relays, in terms of their ability or "utility" to help in delivering a message to its intended destination. Utility-based protocols are further divided into two categories 1) Social Context-Based protocols take into account social ties between nodes while taking forwarding decisions. In this, every node is assigned either a label like in MMF [29], and BubbleRap [30] or node profile e.g. name, address, occupation etc. like in HiBOp [31], Propicman [32], and CiPRO [33]. The utility of nodes is determined taking into account an increased match between the context of node and of destination, as an important parameter. 2) History/Prediction based approaches take decisions solely on exploiting mobility and other information regarding network resources and can be further divided into three more categories. In resource-based schemes utility of a packet is determine by allocating resources that are required to forward the packet towards its destination. PREP [34] and RAPID [35] are examples of resource allocation schemes where utility is assigned to packets instead of nodes. Prioritized Epidemic Routing (PREP) [34] alleviates the problem of performance degradation and accompanies epidemic dissemination of information along with arranging packets based on "transmit and drop" priority within message buffer. However, work from A. Balasubramanian [35] called RAPID routing, replicates messages depending on per-packet utility functions to minimize specific metrics such as average delay, maximum delay, and number of packets missing the deadline. In RAPID, the utility value assigned to packets is mostly based on intermeeting time between peer nodes. A packet is replicated only if it has a utility value higher than other packets within node's buffer while the fitness of relay node being able to contribute in the delivery process is ignored. To address this problem, a number of destination-dependent and destination-independent utility-based schemes are proposed in the literature.

Destination-Independent Utility-Based Schemes

In these utility-based schemes, the utility of a node is determined based on some special characteristics this node has, and it is defined independent of any destination [23]. In [36] S. Nelson et al. propose a destination-independent encounter-based routing (EBR) protocol. EBR is based on the assumption that nodes, who have frequent contacts with other nodes can be more suitable than other nodes within the network, as they are more likely to meet a destination. Therefore, transferring a message to a social node increases its possibility of successful delivery. EBR [36] is a quota-based scheme with L copies assigned to messages at source. Every node here, maintains an exponentially weighted moving-average called encounter vector (EV) that represents its past rate of encounters with other nodes. Source or any current custodian "A" of message "M", sends number of replicas of "M" to an encountering node "B" according to following weighted copy rule.

$$m_{send} = m_i \times \frac{EV_B}{EV_A + EV_B}$$

where m_i is the total number of replicas of "M" stored at node "A". Distribution of copies in EBR based on encounter vector (EV) of nodes is depicted in Figure 2.4. In another work, where "sociability" of a node is exploited as its utility to forward a packet is defined by T. Spyropoulos et al. [29]. Moreover, in [37] a modified spraying mechanism is proposed along with utility based message forwarding phase. During spray phase message copies are distributed in a way so that the

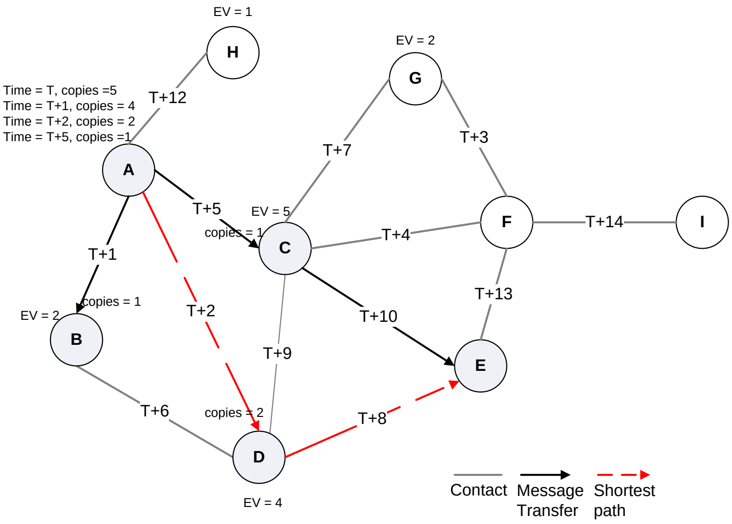


Fig. 2.4: Example Showing Message Transfer From Source A to Destination E With Encounter Based Routing. Shortest Path From A to E is Shown With Dashed Arrow Lines. Message Creation Time is Taken as T, and Future Contacts Occurring Among Nodes are Represented as “T + time_units”

node which is more popular among nodes should receive more copies of a message. A node’s contact count with other nodes is used to determine its popularity. If the message is unable to reach destination during spray phase, it enters into forwarding phase. During forwarding phase, the node stops replicating the message and forwards it to another node with higher utility value, based on contact duration with message’s destination.

With destination-independent utility based schemes, nodes presenting special characteristics i.e. large free buffer space, long battery life, or social affiliation can be selected as next hop relays. This can lead to sub-optimal performance in some scenarios; for instance, consider the case where different node groups are divided into different regions with only few nodes allowed to move across different regions. In this case, a node having high social behavior within the group or other regions but has never visited the region where destination node exists, can mislead routing decisions resulting in poor performance in highly heterogeneous environments.

Destination-Dependent Utility-Based Schemes

In these utility-based schemes, the utility of a node is defined taking into consideration its mobility behavior with reference to destination. hence, it is possible that a node may have high utility for a certain destination, but it may not be considered as a suitable candidate for another destination [23]. PRoPHET [38] is one of the first studies aimed to prune the epidemic distribution tree, based on a destination-dependent utility. A message is replicated only if a node presents higher delivery probability to message's destination than the current custodian of the message. This difference in forwarding strategy with epidemic routing, results in reduced overhead over network resources. Lindgren et al. [38] believe that movement of nodes within the network is not always random. A node visiting another node many times in the past is more likely to visit that location or node in future also. For this purpose, $P_{(a,b)}$ is calculated as shown below on every encounter between "a" and "b", where $P_{init} \in [0,1]$ is an initialization constant.

$$P_{(a,b)} = P_{(a,b)_{old}} + (1 - P_{(a,b)_{old}}) \times P_{init}$$

This way, nodes who encounter each other often will have high delivery probability for each other. Nodes calculate their transitive delivery probability for each other in following way, where β is transitivity constant.

$$P_{(a,c)} = P_{(a,c)_{old}} \times P_{(a,b)} \times P_{(b,c)} \times \beta$$

A simplistic example of PRoPHET is shown in Figure 2.5. A message is created at node *A* destined to node *E* at time T, and future contacts occurring among nodes are represented as "T + time_units". Here, for simplicity, we only consider direct encounters and represent delivery probability at nodes in terms of number of encounters with *E*. In the given network topology, *E* has direct contact with three nodes *C*, *D*, and *F*. Their delivery probability to *E* is shown next to them in Figure

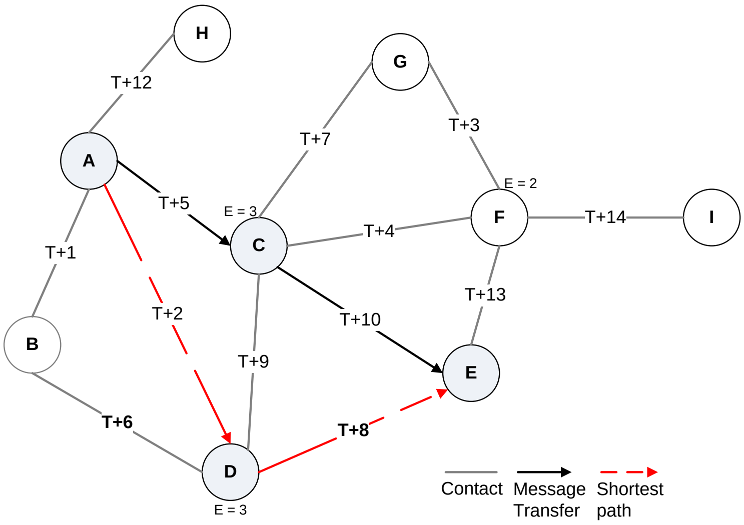


Fig. 2.5: Example Showing Message Transfer From Source A to Destination E With Encounter Based Routing. Shortest Path From A to E is Shown With Dashed Arrow Lines.

2.5. Nodes C and D have higher delivery probability to E than node A. Therefore, A transfers the message to both of them on respective transfer opportunities. First copy of the message is delivered to E along the path represented with dashed arrows.

Few amendments in the original PRoPHET routing scheme are proposed in [15] based on experiences from its implementation within N4C project [39]. These changes are part of IRTF Internet RFC [40] with well defined protocol specifications; this makes PRoPHET a better candidate for being used as a benchmark for evaluating new opportunistic routing schemes.

In MaxProp [41], every node maintains an estimate of probability of future contacts with other nodes and a cost (sum of probabilities of non-occurrence of a contact between peer nodes) associated with different paths. A packet is replicated onto a path presenting minimum cost towards destination node.

In another study [42], A. Elwhishi et al. argues that utility of a node defined on number of encounters may lead to long-term neighborhood problem. For example, consider two nodes that are in contact with each other for a long duration and make/break connections with other nodes, while moving with same velocity and in the same direction. Then, despite of the long contact duration, they will have low delivery probability to each other as they had only one encounter between them. On the other hand, delivery probability of a pair of nodes to each other will be high due to disrupted connection between them during a single contact. To address these problems, A. Elwhishi et al. [42] suggest to use inter encounter time rate to calculate utility of a node pair, as forwarders of messages to each other. Moreover, instead of allowing uncontrolled replication, SARP [42] assigns "L" forwarding tokens to every message like in quota-based schemes, and uses "weighted-copy-rule" to transfer more copies of a message to nodes having high utility value to message destination.

Some schemes use age-of-last-encounter timers [29] to spray limited message copies towards intended destinations. Every node maintains a timer $T_i(j)$ for every other node within the network. When a node "i" sees another node "j", $T_i(j)$ is set to 0. $T_i(j)$ is increased on every time unit until "i" is again encountered with "j". Utility of "i" for "j" is calculated as follows:

$$U_i(j) = \frac{1}{1+T_i(j)}$$

T. Spyropoulos et al. [43] [44] also use age-of-last-encounter timers with transitivity to forward a message to its destination during *"focus"* phase. In Spray and Focus [43], at first, L copies of a message are sprayed using Binary Spraying [27]. When a node (source or relay) is left with only one forwarding token, instead of waiting for its direct encounter with destination, it enters into focus phase. However, Seek and Focus [44] is based on single copy forwarding. *Seek phase* starts if the utility of current custodian of a message is less than the predefined threshold value. This way, a message is forwarded with probability p to any encountering node called randomized routing. When any node with utility value greater than the threshold receives the packet, it enters into focus phase. In networks with heterogeneous mobility patterns presenting large variations in inter-encounter times between different nodes, next hop decision on the basis of last encounter with destination alone might not be appropriate. In this way, it may be hard to make an intelligent guess of how long a message has to wait until it is finally delivered to its destination. Moreover, if two nodes rarely encounter each other, their recent encounter can mislead other nodes' next-hop selection decision. The other schemes which also make use of age-of-last-encounter timers for forwarding decisions include, Exponential Age Search (EASE) by M. Grossglauser et al. [45], and FResher Encounter Search (FRESH) by H. Dubois et al. [46].

Most utility-based schemes are generally aimed to characterize future probability of contacts by identifying mobility behavior of nodes within the network. Our proposed solution in this thesis is intrinsically different from these techniques as along with characterizing the mobility, we also consider other stochastic information related with network resources like available free buffer space at different node. We take into account a set of encounter samples, containing information about mobility and available resources, between pair of nodes and employ them in calculation of nodes' next-hop fitness to each other. We suggest determining node's fitness based on an optimized combination of multiple metrics, instead of deciding onto the utility of node based only on a single characteristic.

A utility model, where buffer and remaining energy at a node along with its social value, is proposed in [47]. This utility value is then used to select ferries among other network participants for message forwarding. However, in this work [47] a global information about present resources within the given network is required to describe the ranking of each node. Calculation of delivery probability based on multiple utility functions, applied on different context information of a node is explored in CAR [48, 49] and SCAR [50]. The composite utility function (delivery probability) is calculated using multi-attribute utility problem [51]. In both routing schemes, some connectivity is assumed among nodes to build routing tables, with limited mobility of nodes among different portions of the network. CAR is a forwarding technique based on DSDV [52], which is used to route packets within connected portions of the network. Along with information required to build routing tables with DSDV, nodes also advertise their delivery probability based on evaluation of different attributes i.e. rate of connectivity and colocation with destination. The packet is stored only if route to destination becomes unavailable due to partitions or mobility of nodes. Then, the packet is delivered to any node having delivery probability to destination higher than the current custodian of the message. However, SCAR [50] is a replication-based protocol proposed for sensor networks, where every sensor advertises its delivery probability to sink nodes based on multi-attribute utility theory [51] similar to CAR [48, 49]. These protocols only consider direct colocation or encounter of a carrier node with potential recipients, and require accurate prediction of future value of context information based on Kalman filters [53] and forecasting techniques proposed in [54]. However, accurate forecasting may not be possible in many mobile scenarios, and becomes more appealing in highly heterogeneous network environments where nodes differ greatly in terms of their capabilities, moving speed and mobility patterns. Moreover, in order to allow communication between two far apart nodes in heterogeneous opportunistic network scenarios, it is often useful to forward a message to a node which never had direct encounter with the destination, but can possibly contribute in message delivery by helping in transferring the message to other carriers having high encounter frequency with destination.

Our algorithm is not based on rigorous forecasting [53], instead we have devised a method to assign scores to different attributes, like it is done in “Simple Multi-Attribute Rating Technique” (SMART) [55], based on past history of encounters of a node with other nodes. Moreover, we consider DTN routing as multi-resource optimization problem in highly heterogeneous mobile opportunistic networks. A categorization of schemes is presented in table 2.1.

Table 2.1: Categorized List OF Representative Schemes

Scheme	**Forwarding**	**Replication**	**Destination-Independent**	**Destination-Dependent**	**Hybrid**	**Metric**
W. Huang et. al, 2011 [56]		√		√		Node location
L. Cheng et. al, 2013 [57]		√		√		Age of last encounter
CPTR, 2015 [58]		√		√		Probability of meeting
T. Kimura et. al, 2015 [59]		√		√		Probability of meeting, Location
ABCON, 2015 [60]	√			√		Percolation centrality
SK. Kim et. al, 2015 [61]	√			√		Common neighbor similarity
HBPR, 2015 [62]		√		√		Direction, Speed, Location
CAR, 2009 [49]	√				√	Colocation, Sociability
SCAR, 2006 [50]		√			√	Colocation, Battery
EBR, 2009 [36]		√	√			Sociability
G. Zheng et. al, 2013 [63]	√			√		contact periodicity, Inter-contact time

Chapter 3

Multi-Attribute Routing In Opportunistic Network Environments - Design Details

3.1 Introduction

Opportunistic networking makes use of transmission opportunities emerging from coarse-grained mobility within the network. Sporadic links appearing among nodes can be eventually construed over a period of time as presence of a complete path between any source and destination pair. Nodes hold a packet while they wait for any neighborhood node, providing a chance to forward packets – with some governing principle – so that it can eventually be offloaded to its destination. However, due to intrinsic nature of opportunistic networks, based on sporadic connectivity, high packet loss ratios are inevitable. Intuitively, many routing protocols[25, 43, 15, 41], for opportunistic environments, are accustomed to spread multiple redundant copies of a message in order to achieve throughput and efficiency in end-to-end latency. These replication based schemes can be categorized into greedy-based [25, 43] and utility-based approaches. Greedy-based replication assumes homogeneous set of nodes [29] and spread replicas on every proximity encounter to increase the probability of successful delivery. However, this assumption reveals itself unrealistic in many scenarios where nodes exhibit heterogeneous characteristics, in terms of their mobility patterns and available resources, that might be deterrent for their participation in the delivery process.

There has been a succession of utility-based routing schemes [15, 41] – choose intermediate relays based on next-hop fitness of nodes – to avoid unnecessary overhead incurred by greedy replication in heterogeneous environments. In this case, number of extra copies of a message is directly proportional to the number of nodes presenting next-hop fitness above than certain threshold value. Hence, inefficient determination of next-hop utility of nodes can ironically result in very high number of message replicas. Each copy consumes energy to transmit along with extra computational resources, thereby, leading to sub-optimal performance in resource-stringent networks. Number of forwarding tokens, however, can also be assigned to limit message replication [42, 36, 29]. In this case, first encountering nodes meeting the given utility criteria are selected for distribution of tokens at each hop. Hence, correct determination of next-hop fitness of a node becomes more apparent to achieve eventual delivery.

Next-hop utility/fitness of a node is generally calculated based on destination dependent or independent utility/fitness parameters [29]. With destination-independent utility based schemes, nodes presenting special characteristics i.e. large free buffer space, long battery life, or social affiliation can be selected as next-hop relays. This can lead to sub-optimal performance in some scenarios, where, due to heterogeneous mobility patterns, and disjoint communities, a resource rich node may never come in contact with certain destination. This way, selecting nodes only based on their availability of resources can mislead routing decisions resulting in poor performance in highly heterogeneous environments. On the other hand, some destination-dependent utility based routing schemes [38] tend to prune the epidemic distribution tree by forwarding packets only to nodes with some delivery probability to destination. This delivery probability is generally calculated based only on mobility behavior of nodes within the network [38, 42]. Nodes having high probability of a future encounter, with the destination, are selected as next-hop relays while constraints over different resources and other nodes' characteristics are often ignored. This can result in poor performance in many heterogeneous scenarios where nodes are of very different capabilities such as pedestrians, tiny sensors and vehicles etc. Sending message copies to nodes unable to contribute in the delivery process due to constraints over their resources like reduced free buffer space, limited remaining power, high packet drop rate due to congestion or limited bandwidth etc. can waste network resources.

Moreover, the intrinsic nature of utility based schemes, based on pruning the epidemic distribution tree, makes it inevitable that the majority of network traffic is carried by only the most suitable nodes resulting in unfair load distributions[64]. Intuitively, the utility heuristics based on any single mobility attribute are not sustainable as the inefficiency of the algorithm to get itself cognizant of changing network characteristics can quickly deplete constraint resources in few better nodes.

These problems illustrate the need of a routing protocol that can achieve high delivery rates in resource-stringent environments, along with better load-balancing, despite introducing limited redundancy within the network. With this in mind, in this chapter, we present a hybrid utility-based routing protocol called Multi-Attribute Routing Scheme (MARS) for opportunistic environments that determines a node's next-hop fitness through an optimized combination of a set of multiple parameters based on "Simple Multi-Attribute Rating Technique" (SMART) [55]. These parameters can be selected based on destination independent and dependent characteristics of a node to better reflect its suitably as next-hop relay. Moreover, MARS is not based on rigorous forecasting techniques [53, 54]. We devise a method to assign scores to different attributes, like it is done in "Simple

Multi-Attribute Rating Technique" (SMART) [55], based on past history of encounters of a node with other nodes. Further, with MARS, we can assign different number of forwarding tokens to limit number of replicas of a message along with uncontrolled replication.

Routing decisions based on multiple attributes is explored in many routing protocols [65, 66, 67] to provide QoS in MANETs. Rank Order [65] and Threshold [66, 67, 68] methods are generally used to select a best route when multiple metrics are involved. These techniques generally fail to provide a good compromise on available metrics because of not considering all objectives simultaneously. Moreover, these protocols only work in environments where all potential candidates i.e. routes are available at the time of making a decision. Analogously, many existing routing protocols for opportunistic networks, determine next-hop utility or fitness of a node based on multiple metrics that can be well placed in social-context based or prediction-based utility schemes. Social-context based protocols take into account social ties between nodes while determining next-hop fitness of a node. These schemes are applicable in environments where user profile including name, address, and occupation etc. is attached with every node [31, 32, 33] or they can be well divided into different communities [30, 69, 70]. The utility of a node is determined taking into account an increasing match between the context of the node and of destination, as an important parameter. Here, we are interested in prediction-based utility schemes where next-hop fitness of a node is calculated based on destination dependent or independent utility or fitness parameters [29]. Analogous to these schemes, MARS determines destination independent/dependent characteristics of nodes and employs them in calculating their next-hop fitness or utility.

Our contributions in this chapter can be summarized as follows:

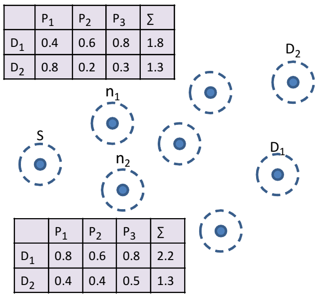
Table 3.1: List Of Symbols Frequently Used In Describing Multi-Attribute Routing Scheme

Symbols	
$F_{(p,q)}$	p's next-hop fitness to q
ΔT	Time Window
$\Omega_{p,q}$	Set of contact duration samples of node p with node q within time interval ΔT
$\hat{Y}(\Omega_{p,q})$	Exponential Moving Weighted Average of contact durations of node p with node q
$\hat{S}(\Omega_{p,q};\Delta T)$	Estimate of Contact Duration at p with node q
Θ_p	Occupied buffer space at node p
$\hat{S}(\Theta_p;\Delta T)$	Estimate Of Free Buffer Space
$\lambda_{p,q}$	Encounter count of node $p's$ encounters with node q
$\beta_{p,q}$	Encounter count of node $p's$ encounters with node q within time interval ΔT
$\hat{S}(\lambda_{p,q};\Delta T)$	Estimate Of Rate Of Encounter
$\mho_{p,q}$	Set of samples of inter-encounter times between nodes p & q within time interval ΔT
$\hat{Y}(\mho_{p,q})$	Exponential Moving Weighted Average of Inter-Encounter Times between nodes p & q
$\hat{S}(\mho_{p,q};\Delta T)$	Estimate of Meeting Time
L	Number of Tokens

- First, we propose a novel hybrid routing protocol (MARS) that determines destination independent/dependent characteristic of nodes and employs them in calculating their next-hop fitness or utility.
- Second, we devise a method based on error correction learning [71] technique of neural networks to dynamically determine relative importance (weights) of each dimension.

3.2 MARS Overview

Multi-Attribute Routing Scheme (MARS) is a hybrid utility-based replication and forwarding scheme for opportunistic networks. With MARS next hop selection is based on fitness value of a node to message destination. Every MARS node maintains a contact table which contains its next-hop fitness to so far known destinations. On sporadically emerging links within the network, every node shares its contact table with its peer node after aging its value. The aging mechanism used in MARS is similar to PRoPHET routing protocol [15], which helps in removing



	P_1	P_2	P_3	Σ
D_1	0.4	0.6	0.8	1.8
D_2	0.8	0.2	0.3	1.3

	P_1	P_2	P_3	Σ
D_1	0.8	0.6	0.8	2.2
D_2	0.4	0.4	0.5	1.3

Fig. 3.1: Next-Hop Fitness Based on Multiple Parameters

stale information about node's next-hop fitness to known destinations in order to avoid misled routing decisions. Message transfer is initiated if node has message "m" in its buffer with pending delivery, and decides onto forwarding based on next hop fitness value of peer node to m's destination (forwarding algorithm is discussed in Section 3.7). We calculate fitness of node based on multiple parameters such as encounter rate, contact duration, free buffer space etc. A simplistic exemplary scenario for calculating next-hop fitness based on multiple node attributes is shown in Fig. 3.1. The key points we want to highlight with the help of this example are: First, analogously, in MARS all parameters (represented as P_1, P_2, P_3 in Fig 3.1) are considered simultaneously for fitness calculation, and only the node which represent a better trade-off of all considered parameters is selected as next-hop relay. For example, both $n_1 \& n_2$ can be used as next-hop relays for destination D_2. Secondly, this helps in better load distribution over network resources as it helps in avoiding situations, where only few nodes may bear most of the forwarding overhead due to representing high values in any single attribute (such as number of encounters). Load-balancing with MARS is explained in detail in section 3.8. In MARS, parameter combination is consisted of destination independent (such as, free memory space) and dependent characteristics (such as, encounter rate, contact duration etc.) of nodes, it is therefore stated as hybrid utility-based scheme. We also propose an adaptive mechanism for assigning weights to determine relative importance of each parameter to form an optimized combination reflecting application and network requirements.

Moreover, In many scenarios it is often useful to limit the number of forwarding tokens to some required value as can been seen in work from T. Spyropoulos et al. [27]. Therefore, MARS exhibits this flexibility to reduce overhead by assigning number of forwarding tokens with messages. Even when no limit is defined on replication MARS can efficiently steward network resources by taking wise decisions while selecting next-hop nodes. Different symbols used in this paper are defined in Table 5.1.

3.3 Next-Hop Fitness Calculation

In MARS, every node calculates its fitness to serve as next-hop for other nodes within the network, as a function of different metrics based on "Simple Multi-Attribute Rating Technique" (SMART) [55]. These metrics are carefully selected to represent destination dependent and independent characteristics of a node. Moreover, every metric is assigned an associated weight to represent its relative importance within an optimized combination. Opportunistic network are characterized to have uncertain topologies with frequent partitions due to high mobility, and heterogeneous capabilities of nodes. Therefore, in order to achieve stability and correctness of opinion about utility of a node, it is important to consider variations in its behavior over a period of time. For this purpose, we introduce a *Time Window* (ΔT) to maintain a limited history of past information, that is, employed in calculating individual score of each attribute.

The generalized formula to calculate next-hop fitness at a node p for a destination node q is then represented as.

$$F_{(p,q)} = \sum_{i=1}^{n} (w_i \times \hat{S}(\mu_{(p,q)}; \Delta T)_i) \tag{3.1}$$

Weight w_i is defined as associated weight of i^{th} parameter and its value can vary within range [0,1]. Moreover, sum of all weights used for different parameters is always equal to 1. This tweaking of weights, help us fine tune different network parameters to better calculate next-hop fitness values helping in forwarding a message towards its destination. $\mu[1..n]$ are some given independent characteristics of a node p, such as, available free space or average residual energy, and attributes that are correlated with a destination, such as, encounter rate or contact duration with node q that are considered to calculate its fitness as next-hop relay for the latter node. We have shown a ˆ on S to represent change in score of each attribute with respect to time. Here, the *Time Window* ΔT is an important parameter to be defined, so as its width should involve a reasonable set of samples to help in making an educated guess about the dynamic behavior present within the network. Certainly, this can be defined keeping in mind a rough idea about inter-encounter times within the given network. In this paper, we have used empirically defined values of ΔT in different scenarios. However, many experimental studies [72, 73] intend to analyze properties of real and synthetic mobility models, whose findings can provide a better guideline to configure opportunistic forwarding algorithms.

In this thesis, the metrics which we consider for our calculations are 1)encounter rate $\hat{S}(\lambda_{p,q}; \Delta T)$, 2)contact duration ($\hat{S}(\Omega_{p,q}; \Delta T)$), 3)free buffer space ($\hat{S}(\Theta_p; \Delta T)$) and 4)meeting time ($\hat{S}(\Upsilon_{p,q}; \Delta T)$). Hence, Eq 3.1 can be rewritten as follows:

$$F_{(p,q)} = w_1 \times \hat{S}(\lambda_{p,q};\Delta T) + w_2 \times \hat{S}(\Omega_{p,q};\Delta T) + w_3 \times \hat{S}(\Theta_p;\Delta T) + w_4 \times \hat{S}(\mho_{p,q};\Delta T) \tag{3.2}$$

Attributes scores are real numbers within range [0,1]; their higher values represent a high probability that node p can be used as relay for destination q by other nodes in the network.

Destination-dependent attributes are normally defined to identify similarities in mobility patterns of the two nodes. In this regard, we believe that the encounter rate, contact duration and meeting likeliness (calculated in terms of inter-encounter times) can better predict the behavior and probability of any future interactions. Moreover, MARS does not involve any prediction mechanisms. Instead, we rely on a sample set of past information calculated within a given time window. Hence, the considered parameters lie within the scope of our scheme, and at the same time effectively defines the mutual behavior of two nodes. Further, many destination-independent attributes, such as, free buffer-space, residual energy, and sociability of a node help to select better candidates for next-hop selection among others. To involve the resource sufficiency at a node - required to forward messages- we have picked free buffer space. Buffer is an important parameter to determine the level of congestion, and effectively employing this with other destination-dependent attributes in determining the next-hop utility of a node can potentially avoid message drops.

In following, we explain in detail calculation of each value.

3.3.1 Estimate Of Contact Duration

We define $\hat{S}(\Omega_{p,q};\Delta T)$ as the estimate of time duration, the two nodes stay in each others vicinity. Intuitively, its high value results in high next-hop fitness of p to

q, as it allows large data exchanges between two nodes.

Mobile nodes in an opportunistic network may occasionally come close in each other's vicinity, remain connected for a period of time and then move apart in different directions. This connected period between the two corresponding nodes is called a contact duration. If we take t_1 as the time of contact between p and q, and t_2 as the time when the two nodes depart from each others transmission range; then *Contact Duration* (c) is defined as follows.

$$c = min\{\Delta T, t_2 - t_1\}$$

This maximum threshold on contact duration is defined to avoid long-term neighborhood problem [42]. In case a contact remain for an indefinitely large time, an update on contact duration information is made on every ΔT time, and the two nodes recalculate their next-hop fitness to each other.

Next, we define $\Omega_{p,q}$ as a set, which contains samples of contact durations within time window ΔT, between nodes p and q paired with time-stamps at which the contact occur, defined as follows:

$$\Omega_{p,q} = \{t \mapsto c \mid \text{t is time of contact } \mathit{AND} \text{ c is duration of the contact}\}$$

Then, on every contact between p & q

$$\Omega_{p,q} = \Omega_{p,q} \cup \{t \mapsto c\}$$

Next, we calculate an exponential moving weighted average ($\hat{Y}(\Omega_{p,q})$) of all contact duration samples within interval ΔT as follows:

$$\hat{Y}(\Omega_{p,q}) = \frac{\sum_{i=1}^{|\Omega_{p,q}|} dom((t \mapsto c)_i)^{*} \times ran((t \mapsto c)_i)^{\dagger}}{\sum_{i=1}^{|\Omega_{p,q}|} dom((t \mapsto c)_i)}$$

Where, $t \mapsto c \in \Omega_{p,q}$.

Taking weighted average this way helps recent behavior of nodes to have a higher influence while calculating estimate of contact duration, as high weights in terms of time are assigned to the latest activities.

Now, an estimate of contact duration between two nodes p & q can be calculated as follows:

$$\hat{S}(\Omega_{p,q};\Delta T) = \begin{cases} \frac{\hat{Y}(\Omega_{p,q}) \times |\Omega_{p,q}|}{\Delta T} & if\,(\hat{Y}(\Omega_{p,q}) \times |\Omega_{p,q}|) \geq \Delta T \\ 1 & Otherwise \end{cases} \tag{3.3}$$

if we consider a scenario, where two nodes have small inter-encounter time, and often meet each other for short duration, within time window ΔT. Then it is possible to have a small weighted average due to short individual contact periods, despite remaining connected with each other most of the time. In order to avoid such behavior, we multiply the calculated weighted average with the size of the set $\Omega_{p,q}$ before normalizing with the time window. Contact duration plays very important role while determining next-hop fitness of a node. A large estimate on contact durations between two nodes represent that, they stay in each others vicinity most of the time. Therefore, they can better be used as relays for each other.

---

[*] Domain of the i^{th} pair $t \mapsto c$ of set $\Omega_{p,q}$

[†] Range of the i^{th} pair $t \mapsto c$ of set $\Omega_{p,q}$

3.3.2 Estimate Of Free Buffer Space

$\hat{S}(\Theta_p;\Delta T)$ is defined as the estimate of time, free buffer space is available at relay node p. High value represents that node p has enough free space in its buffer to relay messages most of the time. Node p reads its occupied-buffer defined as Θ at regular intervals to calculate the time T it takes to get its buffer full.

$$T = \begin{cases} 0 & if\,\Theta \geq max\,for\Delta T\,time \\ \Delta T & if\,\Theta < max\,for\Delta T\,time \\ time\;(\Theta \geq max) - time\;(\Theta < max) & Otherwise \end{cases}$$

Here, $time(\Theta < max)$ is the initial time, occupied-buffer was observed less than the maximum buffer value. Then the average time it takes to fill the buffer at node p is calculated as:

$$AT_\Theta = \begin{cases} \frac{1}{N}\sum_{i=1}^{N} T_i & if\,i \geq 1 \\ \Delta T/2 & Otherwise \end{cases}$$

Here, N is the total number of calculated samples. A node might get congested due to sudden data flows for some time duration, while its buffer remain free most of the time. Moreover, filling of the buffer sometimes indicates node's willingness and a high feasibility to serve as a next-hop relay. Therefore, the time it takes to fill the buffer should be averaged over a large duration or by considering a reasonable amount of samples. For results in this paper we do not put any limit on number of samples, however, for real time networks supposed to be running for long duration a limit on sample size could be defined to better reflect recent activity at a node. Then estimate of time, free-buffer space is available at a node is normalized as follows:

$$\hat{S}_{buff}(\Theta_p;\Delta T) = \frac{AT_\Theta}{\Delta T} \tag{3.4}$$

3.3.3 Estimate of Meeting Time

$\hat{S}(\mho_{p,q};\Delta T)$ is defined as the probability of time duration in which a contact between two nodes p and q can occur. High value indicates larger time duration within which the two nodes can meet, thereby resulting in high next-hop fitness of node p to q. A rigorous definition of meeting times between two nodes can be found in [74]. For calculating an estimate of meeting time between p & q we first define a set $\mho_{p,q}$, similar to $\Omega_{p,q}$ described earlier in subsection 3.3.1, which contains samples of inter-encounter times between two nodes paired with contact time within time window ΔT as follows:

$$\mho_{p,q} = \{t \mapsto e \mid \text{t is time of contact } AND \text{ e is inter-encounter time}\}$$

Similarly, on every contact between p & q, $\mho_{p,q}$ is updated as follows:

$$\mho_{p,q} = \mho_{p,q} \cup \{t \mapsto e\}$$

Here, e is calculated as:

$$e = \begin{cases} min\{\Delta T, t\} & \text{if no. of encounters} = 1 \\ t - t_1 & \text{if no. of encounters} > 1 \end{cases}$$

where, t_1 is the last connection down time of node p & q, and t is current connection time.

Next, we define an exponential moving weighted average $\hat{Y}(\mho_{p,q})$ of all inter-encounter time samples present within the set $\mho_{p,q}$ as follows;

$$\hat{Y}(\mho_{p,q}) = \frac{\sum_{i=1}^{|\mho_{p,q}|} dom((t \mapsto e)_i)^{\ddagger} \times ran((t \mapsto e)_i)^{\S}}{\sum_{i=1}^{|\mho_{p,q}|} dom((t \mapsto e)_i)}$$

Where, $(t \mapsto e)_i \in \mho_{p,q}$. Now, an estimate of inter-encounter time between two nodes p, and q can be defined as:

$$\hat{S}_{int-enc}(\mho_{p,q};\Delta T) = \begin{cases} \frac{\hat{Y}(\mho_{p,q})}{\Delta T} & \text{if } \hat{Y}(\mho_{p,q}) \leq \Delta T \\ 1 & Otherwise \end{cases}$$

Average inter-encounter time is usually calculated by dividing the sum of inter-contact times by total number of encounters [75]. In this way, all inter-encounter times are assigned equal weights. However, we say that by taking a running weighted average, recent behavior of node movements can better be depicted. Next, we can calculate meeting time between two nodes p and q as:

$$\hat{S}(\mho_{p,q};\Delta T) = 1 - \hat{S}(\mho_{p,q};\Delta T) \tag{3.5}$$

3.3.4 Estimate Of Rate Of Encounter

Every node p maintains an encounter count $\beta_{p,q}$ of its encounters with node q within time interval ΔT. Along with this it also maintains an encounter counter $\lambda_{p,q}$ of all its encounters with node q. The difference between these two parameters is shown in Fig 3.2.

Next, if we take δ as size of the time window ΔT, we can calculate an estimate on

---

[‡] Domain of the i^{th} pair $t \mapsto e$ of set $\mho_{p,q}$

[§] Range of the i^{th} pair $t \mapsto e$ of set $\mho_{p,q}$

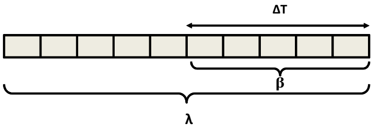


Fig. 3.2: Representation Of Encounter Window & Encounter Count

rate of encounter between two nodes p & q as follows:

$$\hat{S}(\lambda_{p,q};\Delta T) = 1 - (1 - (\frac{\lambda_{p,q} + \beta_{p,q}}{\lambda_{p,q} + \delta}))^{\lambda_{p,q}} \tag{3.6}$$

This way, an estimate on encounter rate of two nodes gradually increases over time. We can see that size of the time window should be reasonably large to represent moving behavior of two nodes. On the other hand, by including the encounter counter of previous contacts, we can have a smooth impact of rate of encounter on determining the overall utility of a node.

3.4 Weight Assignment

When we calculate next-hop fitness of a node based on multiple attributes, determining relative importance of each dimension becomes very important. By efficiently adjusting different weights assigned to different dimensions, an optimized combination can be formed to calculate next-hop fitness reflecting underlying network characteristics. For example, if there are large inter-encounter times among nodes within the network, high weight can be assigned to contact duration and available resources at nodes in order to have next-hop fitness of nodes be consistent with network conditions. Adaptive weight-assignment to different attributes can result in more educated calculation of next-hop fitness of nodes, which help to improve performance in terms of delivery-ratio and routing-overhead.

The next-hop fitness equation of MARS can be roughly mapped to a neural net-

ALGORITHM-1: Weight Adaptation at Node p

```
$AdjustWeights(\xi(F_p))\{$
    $\forall i \in \{1..n\}$
        $\Delta w_i = c * \xi(F_p) * X_i$
        $w_{i(new)} = \eta * w_{i(old)} + \Delta w_i$
To normalize weights for their sum equal to 1
we use [76]:
    $\forall i \in \{1..n\}$
        $w_{i(new)} = \frac{w_{i(new)}}{\sum_{j=1}^{n} w_{j(new)}}$
$\}$
```

work architecture. If we consider that the desired output i.e. next-hop fitness of a node is 1. Then, we can use error correction learning [71] to adjust weights at a node in order to maximize its next-hop fitness for known destinations. Let F_p be the set of fitness values of a node p for known destinations with whom p had a direct encounter. We then calculate our error function $\xi(F_p)$ defined as average deviation of fitness values of node p from desired output, that is, 1 as follows:

$$\xi(F_p) = \frac{\sum_{i=1}^{|F_p|}(1-f_i)}{|F_p|} \qquad where,\ f_i \in F_p$$

This average deviation from desired fitness value of a node is back-propagated to adjust individual weights. Next, we define our input parameters at any given node p as follows: For example, if one of the parameters to calculate fitness of node p is *Estimate Of Contact Duration*, then, A is taken as the sorted list of all *Estimates Of Contact Durations* of p with nodes to whom p has a direct fitness value (directly encountered nodes). We can then define our n input parameters as follows:

$$X_i = Median(A_i) \quad \forall i \in \{1..n\}$$

Before taking mean, we first, age all values within set A_i with Eq 3.7. Now we can define weight adaptation at node p in Algorithm-1.

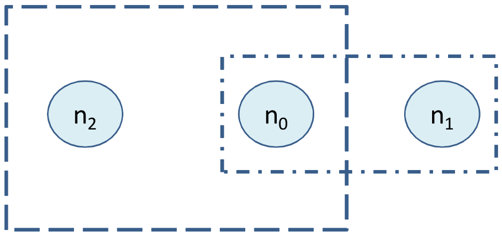
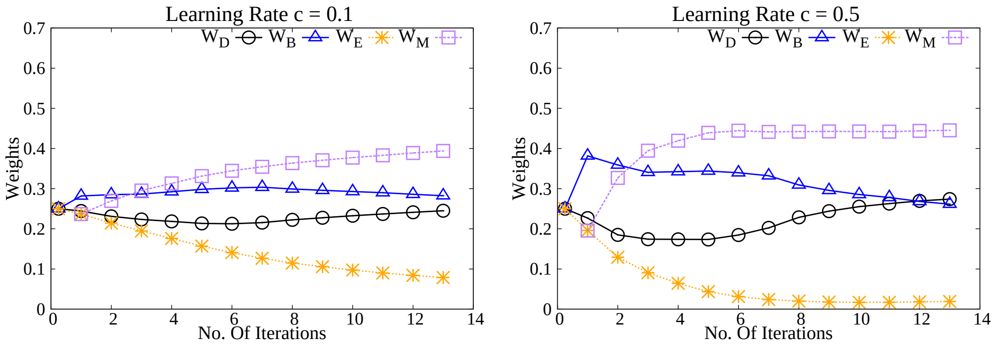
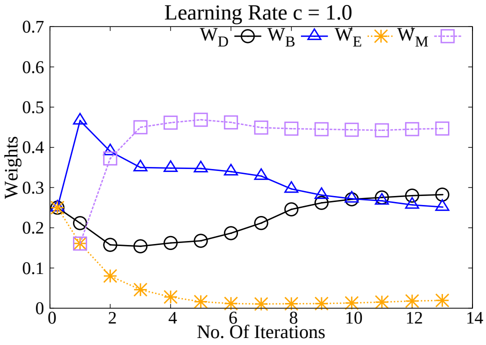


Fig. 3.3: Mobility Scenario for Weight Adaptation at node n_0



(a) c = 0.1 (b) c = 0.5



(c) c = 1

Fig. 3.4: Effect Of Changing Learning Rate "c" On Weight Adaptation at Node n_0

c (line 3) is the learning rate and η (line 4) is the momentum parameter [71]. The momentum parameter helps to improve convergence time of the algorithm and it is usually set to 0.9, as described in [77], by default. The delta change in weight of the i^{th} attribute is first derived by multiplying the corresponding value with the *error* and *learning rate* (line 3). Then the new weight is calculated by adding this delta change into old weight value at line 4 as defined in [71]. We have first described in section that in our case the sum of all the corresponding weights must be equal to 1. Therefore, after every update, weights are again normalized to limit the values within the 0-1 range (line 6).

In order to show how learning rate effects weight adaptation at a node, let us take the example of a scenario shown in Fig. 3.3. The two boxes show that n_0 has different kind of mobility patterns with n_1 and n_2. In Fig. 3.4 weight adaptation for different attributes at n_0 is shown against taking different learning rate values. Here, W_D, W_B, W_E, and W_M are corresponding weights of Estimate of Contact Duration, Estimate of Free Buffer Space, Estimate of Rate of Encounter, and Estimate of Meeting Time respectively at node n_0. We can see that when learning rate is small, their is little variation from the original value at each iteration, and the weights are slowly adapted. Here, it is pertinent to mention that by considering the median value among the available information avoids a sudden significant change in weights. However, the weights will be slowly adapted to reflect towards new environment around the node. As, a node obsoletes information older than the given time window, thereby, we can safely opine that weight adaptation can take no longer than ΔT to reflect to changing network dynamics.

The weighting mechanism introduced in this section can dynamically adapt itself to determine the relative importance of each considered parameter within any given scenario. For example, in a network with high frequency of encounters and long contact durations, resource limitations would be given less preference. Inevitably, the ability of the MARS to get itself cognizant of underlying network characteristics can potentially provide good performance in many scenarios.

3.5 Aging Mechanism

We use the same aging mechanism as used in [15] for eliminating stale information from the network. Therefore,

$$hF_{nxt(a,b)new} = hF_{nxt(a,b)old} \times \gamma^{k} \tag{3.7}$$

Where γ is the aging constant having value between [0,1] and k is the time units elapsed since last aging of the fitness value is done.

3.6 Transitive Next-Hop Fitness Calculation

S. Grasic et al. [15] suggest the effectiveness of transitive property of a routing scheme for opportunistic networks. In many scenarios it is possible that some nodes may never had a direct encounter, one of the examples of such a network can be presence of multiple disjoint communities with only few nodes visiting different regions [15]. In such scenarios, transitive calculation of next-hop fitness help in forwarding packets towards destination through multiple intermediate hops. However, we believe that transitive next hop fitness of a node should be comparatively low as compared to direct next hop fitness values. Next, we define transitive next-hop fitness calculation in MARS with the help of following example scenario.

$$S \rightarrow B \rightarrow M \rightarrow D$$

Here B calculates its fitness to D through M as follows:

$$F_{(B,D)new} = \begin{cases} [\frac{min\{F_{(B,M)},F_{(M,D)}\}}{2}] & \text{If previously calculated through M} \\ max\{F_{(B,D)old},[\frac{min\{F_{(B,M)},F_{(M,D)}\}}{2}]\} & Otherwise \end{cases}$$

The value is divided by 2 at each hop in order to incorporate the effect of uncertainty in opportunistic networks and presence of multiple intermediate forwarding nodes. The node that is multiple hops away from destination will have small fitness value due to division at each hop.

3.7 Forwarding Policy

We associate a forwarding threshold with every message on a relay node including source, which is initially set to next-hop fitness value of the current custodian to message's destination. Whenever a copy of the message is forwarded, its associated threshold is updated to next-hop fitness of peer. The forwarding threshold of a message ensures that redundant copies should only be sent to nodes having greater next-hop fitness to destination than the nodes to whom it is previously sent. In this way, we can reduce overhead over the network by restricting message replication only to nodes, presenting themselves as better candidates than the previously selected relays. Moreover, a message threshold is aged using the same mechanism as defined in Eq. 3.7 before comparing with peer's utility value. Further, if a node is connected to two or more nodes at a time, a message is only sent to a node which presents highest next-hop fitness to destination among currently connected peers.

Moreover, with MARS, we can assign different number of forwarding tokens (L) in order to limit number of replicas of a message. When no limit is defined, it keeps on replicating the packet to nodes presenting next-hop fitness to destination until, 1) message lifetime is expired, 2) it is dropped due to buffer overflow, or 3) it is offloaded to destination node. In following we define behavior of MARS with different number of forwarding tokens.

Single-Copy Forwarding

MARS turns into forwarding scheme when only single token is assigned. In this way, every MARS node relinquishes the custody of the message – and removes it from its buffer – on forwarding it to first encountering node, presenting next-hop fitness to destination higher than the node itself. In this way, only a single copy of the message exists within the network. Although this approach effects performance but simulations show that MARS is able to achieve comparable delivery rates with single copy forwarding as compared to existing routing scheme.

L-Copy Forwarding

When $L > 1$, every node sends $\lceil L/2 \rceil$ copies of a message to peer whose next-hop fitness is greater than the node itself and corresponding forwarding threshold of the message; this is analogous to how L copies are forwarded in Spray and Wait binary mode [27]. However, here, message transferring is based on utility of a node. When a node is left with only one copy of a message it is forwarded according to single copy forwarding.

3.8 Load-Balancing and Choosing Number of Copies (L) with MARS

Destination-Dependent utility-based schemes imply that messages might be forwarded towards destination through few “better” nodes presenting high next-hop fitness to it based on given utility criteria. Intuitively, it can lead to significant load imbalance in opportunistic networks which can degrade performance in resource-stringent environments. The uneven load distribution results in poorer utilization of total network capacity, secondly, it can quickly deplete resources (e.g battery drainage) in heavily utilized nodes, which are, ironically, the most vital for long term functioning of the network.

We can extrapolate the effectiveness of using multiple parameters with MARS through the simplistic scenario shown in Figure 3.5. Consider a network of five nodes with two sources and one destination node. Both sources and destination nodes are stationary while n_1 and n_2 move between source and destination locations. If we consider the case where source decides next hop nodes based only on number of encounters with destination, then both S_1 and S_2 will send all their packets to D through n_1, shown with solid lines in Figure 3.5, because of high encounter rate between n_1 and D. In this way, n_1 can get congested over some time resulting in message drop due to buffer overflows, while resources available at n_2 are never used. Considering the given scenario, if fitness of a node is based on two parameters such as, encounter rate, and free space instead of considering only a single attribute, then n_2 node can also be used as intermediate relay by S_1, due to available free buffer space when n_1 get congested, shown with dotted line in Figure 3.5. Some studies such as [29, 64] address the issue of load-balancing in opportunistic networks. However, the clear distinction we intend to make here is that the intrinsic nature of MARS, based on using multiple parameters for calculating next-hop fitness of nodes, secondly, dynamic determination of relative importance of each parameter with adaptive weights, helps in effective utilization of network capacity with better load-balancing.

Moreover, the flexibility of allocating number of copies (L) for a message to be used with MARS can substantially reduce unnecessary transmissions within the network in many scenarios. From this, we get the epiphany that selecting L to achieve acceptable delivery ratios (network performance) inevitably impact re-

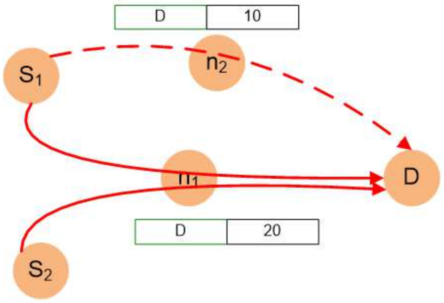


Fig. 3.5: Example Scenario Showing Effectiveness of Using Multiple Parameters in Path Selection

source utilization. It reminiscent that minimizing required copies (L) may induce traffic loads, a given network is capable of handling without impacting its performance.

MARS is utility-based scheme that spread L copies analogous to binary Spray and Wait routing [43]. Nevertheless, when a node is left with only one copy of a message it is forwarded according to single copy forwarding as discussed in section 3.7. Therefore, every custodian of a copy is leveraged to make an educated decision, based on next-hop fitness of nodes, to bring forward the packet to destination. Inevitably, in destination-dependent utility-based schemes, every extra copy serve to cope with high packet loss ratios and possibility of wrongly selecting a next-hop relay due to limitations in the given utility-function.

Assume R is the delivery ratio that can be achieved through single-copy forwarding with MARS, and R_{min} is the minimum delivery ratio required by an application. Let η is the ratio of error in calculating next-hop fitness of nodes. Let ℓ is the packet loss ratio of the network due to congestion at nodes. Then optimization of L with MARS is expressed in Eq 3.8.

$$1-(1-R)^{L} \geq R_{min} \tag{3.8}$$

We adopt the model presented in eq 3.8 from [23]. Here, in our case R can effectively represent magnitude of η and ℓ within the network. R might be close to R_{min} if η and ℓ are significantly low. From here, we can imply that:

$$L \propto (\eta \times \ell) \tag{3.9}$$

Here, we argue that η and ℓ significantly depend on the utility protocol that is in use to route messages. Effective load-balancing to prevent message drops out of overloading available resource, secondly, intelligent calculation of next-hop utility of nodes can substantially reduce these ratios. Hence, delivery cost (L) to achieve certain delivery ratio is also reduced. We defer the question of selecting optimal copies (L) with MARS for future work, nevertheless, copies at intermediate hops can be dynamically adapted base on a recent study [75] where is selected based on remaining life-time of a message. However, here we assume that the number of copies are set by the application. We have done simulations taking a low value of L i.e 5 and simulation results greatly help to elucidate our point that next-hop utility in opportunistic networks is a multi-objective function. Moreover, intrinsic benefits of defining a multi-attribute utility function along with dynamic adjustment of corresponding weights are twofold, first, it result in educated decisions regarding message carriers, second, effective load-balancing to prevent overloading of network resources.

3.9 Conclusion

We present a hybrid utility protocol MARS, in this Chapter, to support communication in opportunistic networks. MARS considers both destination dependent and destination independent attributes of a node and employs them in calculating its next-hop fitness. MARS is based on SMART as in sparse heterogeneous environments accurate forecasting of future behavior of a node might not be possible. Likewise, we devise a general mechanism to calculate relative score of each dimension considering samples collected over a finite time interval ΔT. We also demonstrate that error correction techniques from neural networks can be effectively applied to determine relative importance of each dimension when we simultaneously consider multiple attributes of a node to calculate delivery probabilities within different networking environments. Moreover, in order to avoid arbitrarily large overhead, number of forwarding tokens can also be assigned with MARS. Due to considering multiple dimensions and real time determination of each dimension's score, MARS can better distribute its overhead which can effectively utilize total network capacity.

In MARS calculating next-hop fitness is based on the principle of mutual interest. A node based on its availability of resources along with mobility information calculates its next-hop utility for other network participants, and vice-versa. This utility of nodes is then used to derive data towards intended receivers in a multi-hop fashion. Hence, only the utility value for a destination node is shared with peer in order to help with forwarding messages, while information regarding resources and mobility etc. remain encapsulated. This helps in keeping the processing overhead to a significantly lower limit for facilitating cooperation among nodes. Moreover, to calculate next-hop fitness for peer a node calculates estimates of its own resources, and mobility related information, that is, common to both nodes, such as, their encounter rates, and inter-encounter times etc. Further, to calculate transitive fitness through peer, nodes only share their next-hop utility tables, which are also used in taking forwarding decisions, as discussed earlier. Thereby, a node's mobility details with other network participants remain hidden from peer. Therefore, the exchange of information is not affected with increase in the number of nodes within the neighborhood of a node.

Chapter 4

Multi-Attribute Routing in Opportunistic Network Environments - Evaluation and Results

4.1 Simulation Setup

For the evaluation of the protocol we use ONE simulator [16]. We compare MARS with well known routing protocols such as PRoPHET [15], RAPID [35], EBR [36], SCAR [50]. For PRoPHET and EBR we use suggested settings in [15] [36] respectively. In PRoPHET, and MARS time unit for aging fitness values is set to 30 seconds that is default value suggested in [15]. We assume full battery at all nodes. Therefore, we set battery level to 1 in SCAR for all the scenarios. In SCAR exchange threshold is set to 0.1 as used in default settings of the simulator.

We set ΔT equal to 1hr in scenario-1 and scenario-3, while it is set to 6hrs in scenario3 to cope with high expected delays in real environments. Learning rate c is set to 1 considering heterogeneous mobility patterns in all scenarios. All parameters are initially assigned equal weights by default, that is 0.25, as there are four attributes which we consider in this thesis.

Performance metrics we use to compare MARS with other schemes are defined below. Here M is total number of delivered messages and M' is total number of undelivered messages.

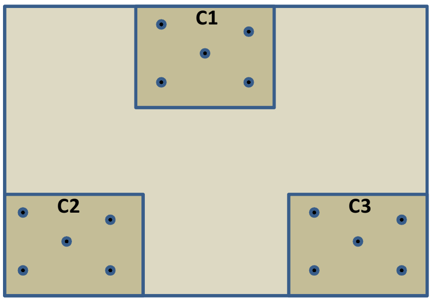


Fig. 4.1: Scenario-1: Community Based Mobility Model

$$Delivery\,Ratio = \frac{msgs\_delivered}{msgs\_created}$$

$$Overhead\,Ratio = \frac{msgs\_relayed - msgs\_delivered}{msgs\_delivered}$$

$$Average\,Latency = \frac{M\_latency + M'\_latency}{msgs\_created}$$

$$Where,$$

$$M\_latency = \sum_{i=1}^{M} receive\_time_i - creation\_time_i$$

$$M'\_latency = (msgs\_created - M) \times largest\_msgTTL$$

Adaptive weight assignment along with dynamically calculating individual score of each attribute results in better load-balancing. This helps to increase delivery ratio, as it can prevent message drops at intermediate relays. At the same time dynamically defined effective estimates of next-hop utility of nodes keeping in mind the stochastic picture of resource availability in opportunistic networks also helps in reducing the overhead incurred by the protocol. Hence, we can safely opine that the considered performance parameters that are delivery ratio and overhead ratio can potentially provide a good estimate on the effects and significance of weight assignment.

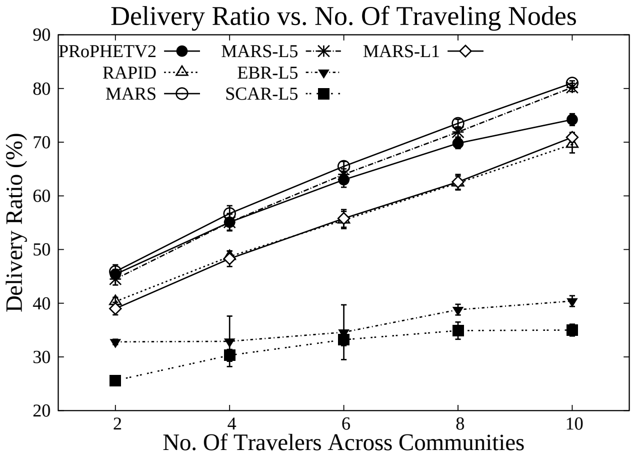
4.2 Scenario-1: Simulations with Community-Based Mobility Model

In this we take 3 communities within 800m × 400m area. In each community 10 nodes are placed which move with RandomWaypoint mobility model, around 5 attraction points. The mobility model is shown in figure 4.1. We assume Bluetooth devices with 10m range and 250Kbps bandwidth. Buffer size of nodes within the communities is set to 50MB while buffer size of traveling nodes is set to 100MB. Simulation time is set to one day with message ttl of two hours. We run simulations 10 times, each time using different seeds for nodes in each community and traveling nodes. Traffic load is set to 40 msgs/hr with random source, and destination pairs unless it is stated. Similarly, six traveling nodes move across different communities unless where it is stated.

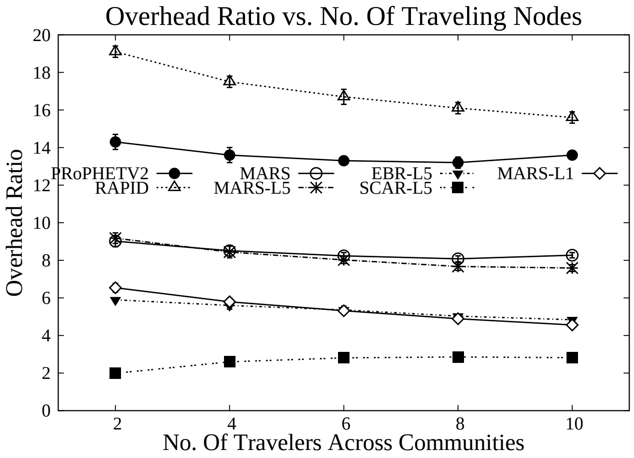
The residual energy at network nodes heavily depends on the introduced overhead by the underlying routing schemes. Therefore, for fairly making the comparison with different kinds of schemes including controlled-replication based approaches, we assume that the nodes are never out of energy to perform network operations. Consequently, node battery level is not considered as a primary metric.

4.2.1 Effect of Number of Traveling Nodes

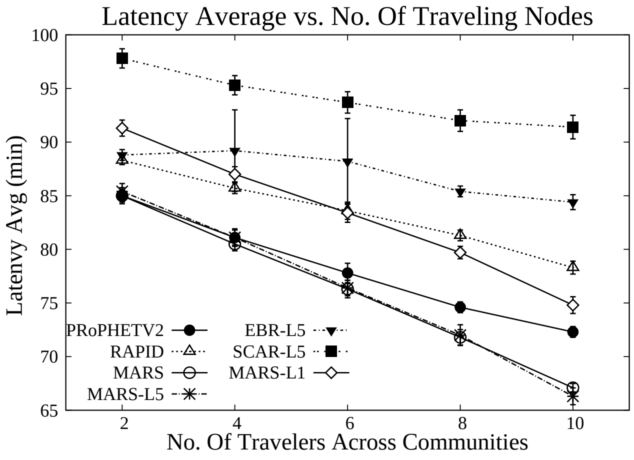
In Figure 4.2, we investigate the effect of number of traveling nodes across different communities. It is somehow correlated to the level of connectivity within the network. By increasing number of nodes that can travel across communities, the possibility of successful communication between two nodes residing in two different communities also increases. Traffic load is set to 40 msgs/hr. We can see that MARS clearly outperforms other protocols in terms of delivery ratio (Figure 4.2(a)) and average latency (Figure 4.2(c)). Careful selection of next-hop nodes in MARS also help in maintaining reasonable overhead, which is significantly smaller than PRoPHET and Rapid routing as can be seen in Figure 4.2(b). Overhead of MARS-L1 and MARS-L5 is higher than SCAR-L5 and EBR-L5 due to increased number of intermediate hops, between a source destination pair, used by the pro-



(a) Delivery Ratio vs Traveling Nodes



(b) Overhead Ratio vs Traveling Nodes



(c) Latency vs Traveling Nodes

Fig. 4.2: Scenario-1a: Comparison of MARS with different Number of Forwarding Tokens, PRoPHET, RAPID, EBR, and SCAR Routing against varying Traveling Nodes across Communities in Community Based Mobility Scenario

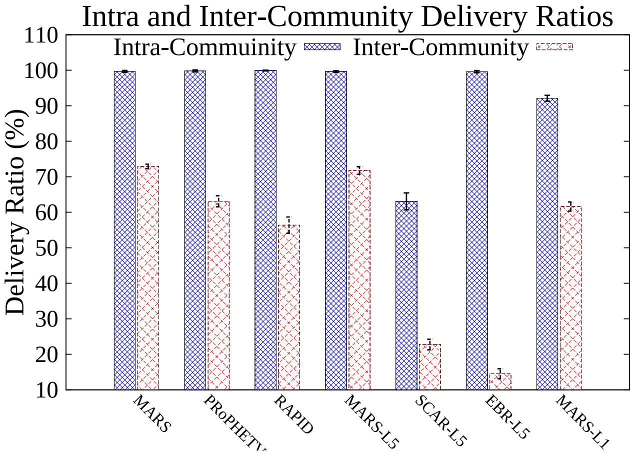
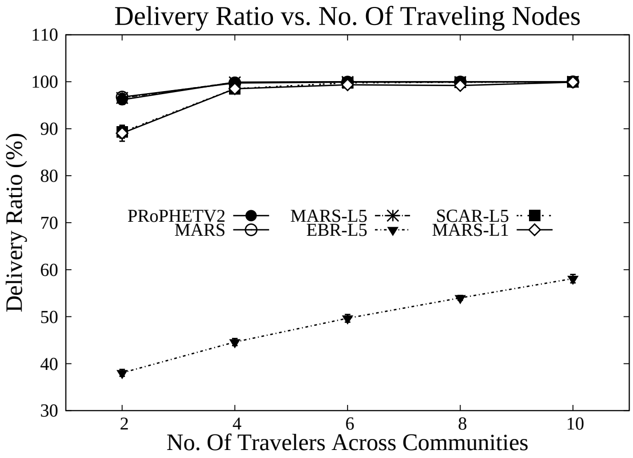


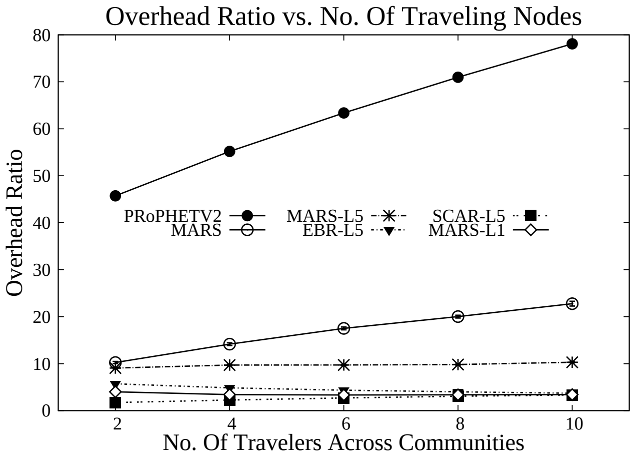
Fig. 4.3: Scenario-1b: Comparision of Inter-Community & Intra-Community Delivery Ratios

tocol. However, it keeps on decreasing with increased connectivity within the network. Analogously, as expected, average latency of protocols (Figure 4.2(c)) also decreases with increased connectivity. SCAR+L5 introduces very small routing overhead and also have almost asymptotic behavior of delivery ratio curve on increasing traveling nodes. From here, we can deduce the effectiveness of calculating transitive next-hop fitness of nodes, by MARS and PRoPHET, in highly heterogeneous mobility scenarios. MARS-L1 is able to achieve comparable delivery rates than PRoPHET routing. Hence, the gap between delivery ratios of MARS and its variants MARS-L5 and MARS-L1 represent that replication introduced by the protocol effectively contributes in increasing performance of the network. Hence, MARS, with the ability to calculate utility based on multiple-attributes along with adaptive weighting mechanism, is better able to adapt itself with changing mobility patterns to improve network performance.

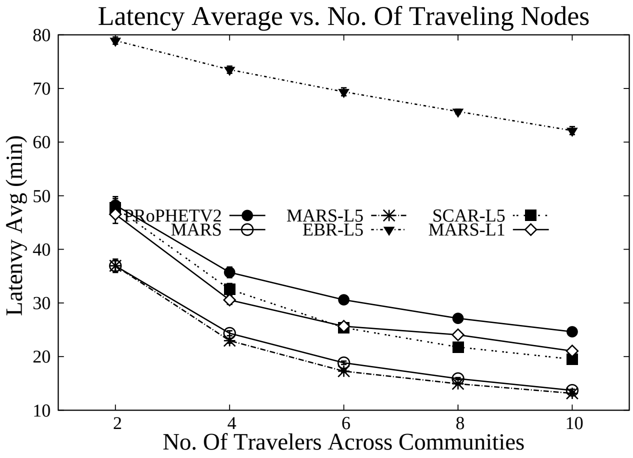
Figure 4.3 shows comparision of inter-community and intra-community delivery ratios achieved by different protocols when there are 10 number of traveling nodes across communities. Here, its clear that MARS and MARS-L5 have highest inter-community delivery rates despite smaller overhead as can be seen in Figure 4.2(b).



(a) Delivery Ratio vs Traveling Nodes

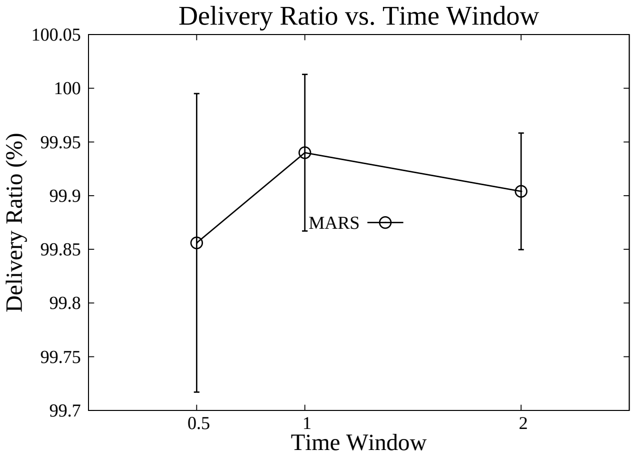


(b) Overhead Ratio vs Traveling Nodes

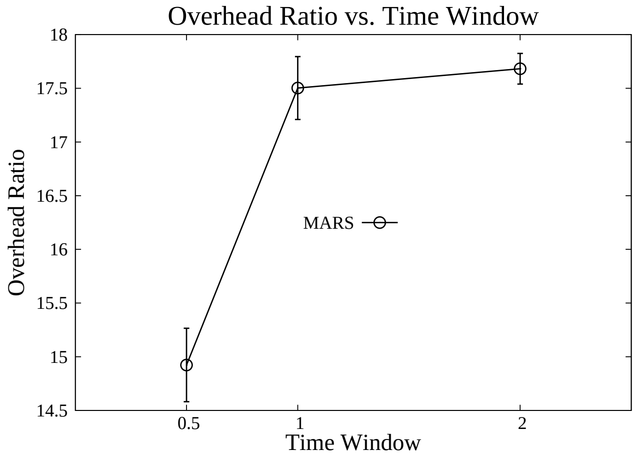


(c) Latency vs Traveling Nodes

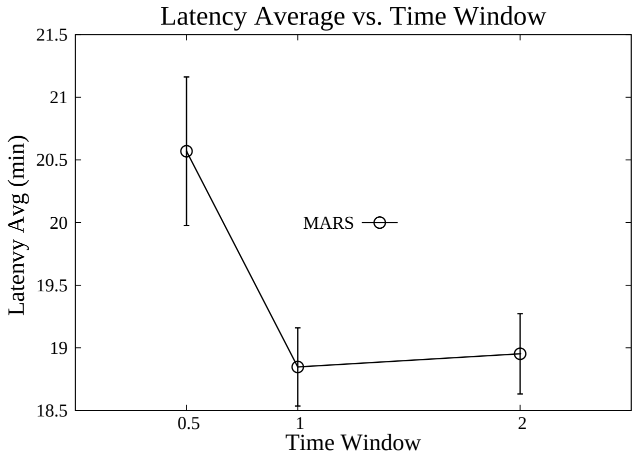
Fig. 4.4: Scenario-1c: Comparison of MARS with different Number of Forwarding Tokens, PRoPHET, EBR, and SCAR Routing against varying Traveling Nodes across Communities in Community Based Mobility Scenario with small message size



(a) Delivery Ratio vs Time Window

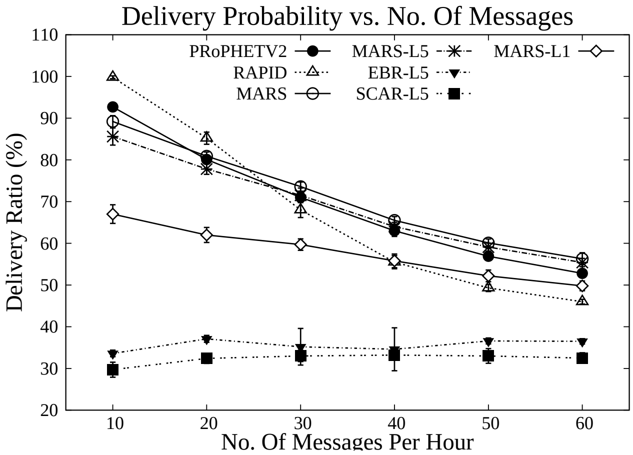


(b) Overhead Ratio vs Time Window

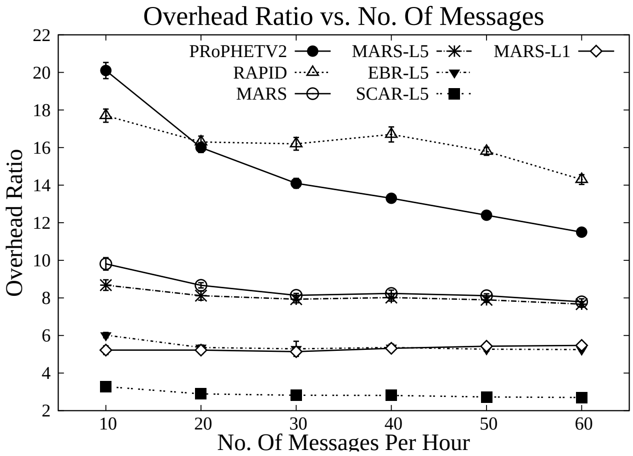


(c) Latency vs Time Window

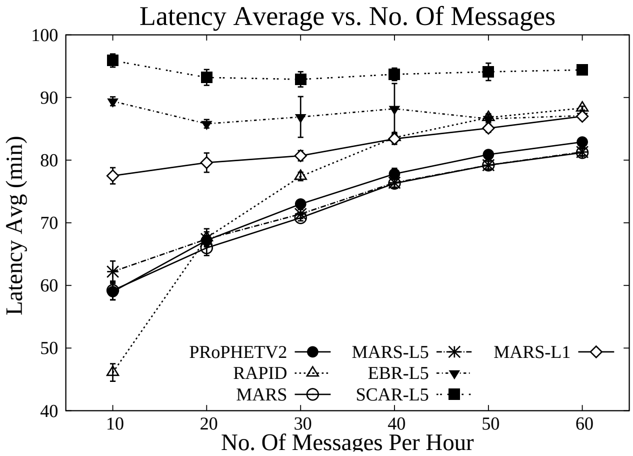
Fig. 4.5: Scenario-1d: Comparison of MARS against Time Window ΔT in Community Based Mobility Scenario



(a) Delivery Ratio vs Traffic Load



(b) Overhead Ratio vs Traffic Load



(c) Latency vs Traffic Load

Fig. 4.6: Scenario-1e: Comparison of MARS with different Number of Forwarding Tokens, PRoPHET, RAPID, EBR, and SCAR Routing against varying Traffic Loads in Community Based Mobility Scenario

Hence, we can deduce that MARS is better able to identify heterogeneous mobility patterns within the network.

A comparison of MARS with small packet sizes and taking different ΔT values is shown in Figures 4.4, and 4.5 We can see that by taking small packet sizes that is 500k, packet capacity at nodes increases which results in decreasing message drops. Due to this delivery ratio of all the schemes increases. Rapid has better performance in terms of delivery ratio at 2 traveling nodes with 16 overhead, however results of rapid are not included here due to high computational complexity. we can see that MARS performance is better in terms of routing overhead. In Figure 4.5 a MARS performance is shown against taking different ΔT values with 6 traveling nodes.

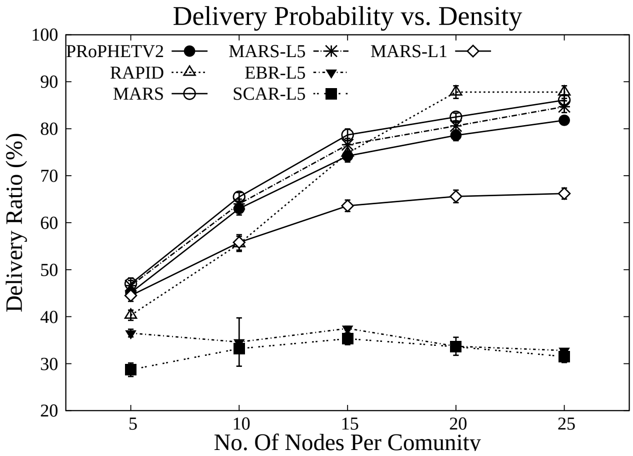
4.2.2 Effect of Traffic Load

It is evident in Figure 4.6 that MARS is able to sustain high delivery rates (Figure 4.6(a)) with increasing traffic loads with small overhead than PRoPHET and RAPID routing (Figure 4.6(b)). RAPID has slightly high delivery ratio than MARS at low data rates but the protocol is unable to cope with high traffic demands due to large overhead. Introducing limited redundancy in case of MARS and MARS-L5 help in avoiding large message drops resulting in increased performance in terms of delivery ratio and end-to-end latency (Figure 4.6(c)) in resource-stringent environments. EBR-L5 and SCAR-L5 also introduce small overhead as shown in Figure 4.6(b) but at the cost of high end-to-end latency (Figure 4.6(c)) and smaller delivery rates as compared to MARS-L5. Here, we can see that even if the number of forwarding tokens is not associated with messages, MARS does not overload network resources due to careful selection of next-hop relays. The effectiveness of next-hop fitness calculation of MARS is more evident at high data rates as MARS-L1 has similar delivery ratio as compared to PRoPHET, while its delivery rate is significantly higher than RAPID routing. In Figure 4.6(b) high overhead of MARS-L1 than SCAR-L5 and EBR-L5 is due to increased number of intermediate hops between a source destination pair.

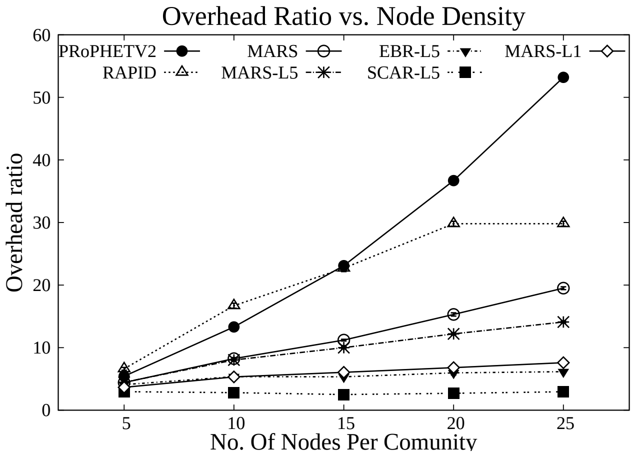
4.2.3 Effect of Node Density

In this scenario, there are six traveling nodes, while we increase number of nodes within each community. When we increase number of nodes, the amount of connectivity or chances of frequent encounters between two nodes also increases within the community. With increased density overhead of unlimited replication schemes, that is, PRoPHET and MARS also increases proportional to number of nodes presenting next-hop fitness to potential destinations. It also increases in case of RAPID routing due to increased number of contact opportunities within the network as can be seen in Fig 4.7(b). However, we can see that MARS does not greedily occupy increasing network resources, while it still maintains high delivery ratios shown in Figure 4.7(a). Overhead also increases due to messages traveling through increased number of intermediate hops before they are finally delivered at eventual destination as can be seen in case of MARS-L5 and MARS-L1. Decrease in end-to-end latency can also be observed in Figure 4.7(c) due to increasing delivery rates and because of chances of somewhat stable paths in dense environments.

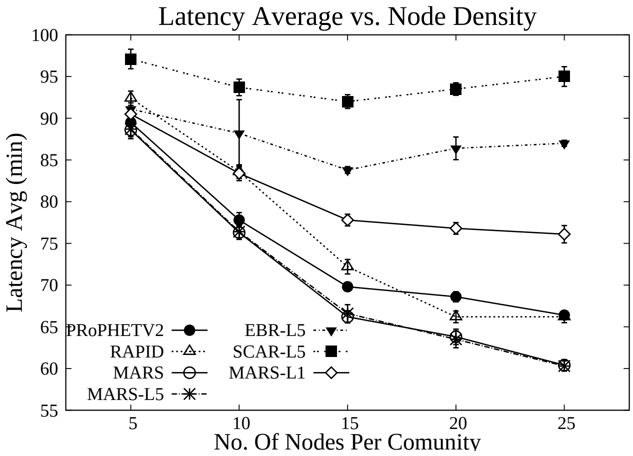
Results with RAPID routing at 25 nodes/community are not included due to very large computational time required by the protocol. As we can see that MARS-L5 shows consistent delivery rates as compared to MARS, hence, a trade-off can be achieved between acceptable delivery ratios and introduced routing overhead with our scheme, when there are limited resources within the network.



(a) Delivery Ratio vs Node Density

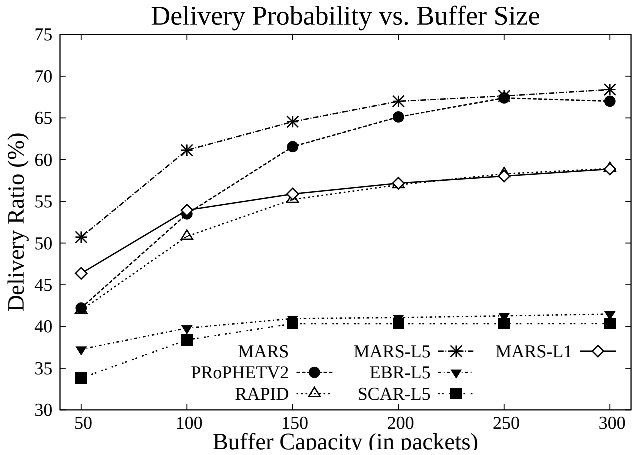


(b) Overhead Ratio vs Node Density

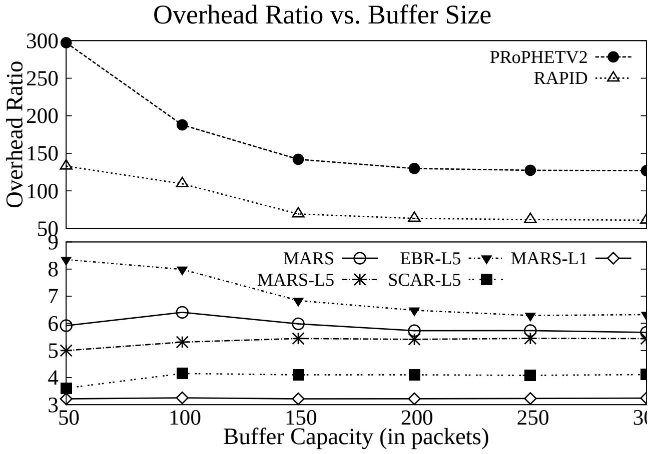


(c) Latency vs Node Density

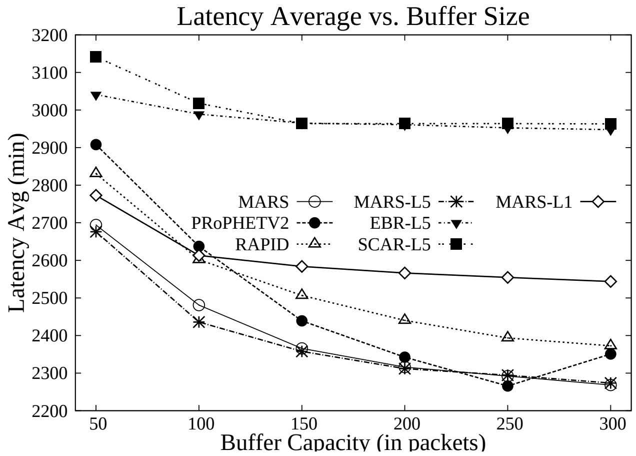
Fig. 4.7: Scenario-1f: Comparison of MARS with different Number of Forwarding Tokens, PRoPHET, RAPID, EBR, and SCAR Routing against varying Node Density in different Communities in Community Based Mobility Scenario



(a) Delivery Ratio vs Buffer Size



(b) Overhead Ratio vs Buffer Size



(c) Latency vs Buffer Size

Fig. 4.8: Scenario-2: Comparison of MARS with different Number of Forwarding Tokens, PRoPHET, RAPID, EBR, and SCAR Routing against varying Buffer Sizes in N4C Real Traces

4.3 Scenario-2: Simulation with Real Traces

To evaluate the performance of our scheme on real test-bed traces we used connectivity and traffic traces of N4C deployments in 2010. We thank S. Grasic et al [15] for sharing these traces with us. The N4C project was aimed to deploy DTN systems for providing Internet connectivity to remote areas in Swedish, details about the project can be seen at [39]. These traces are collected from 18 DTN nodes and time duration of these traces is 56 days. One helicopter flight with data mules is scheduled every day and message lifetime is set to 3 days.

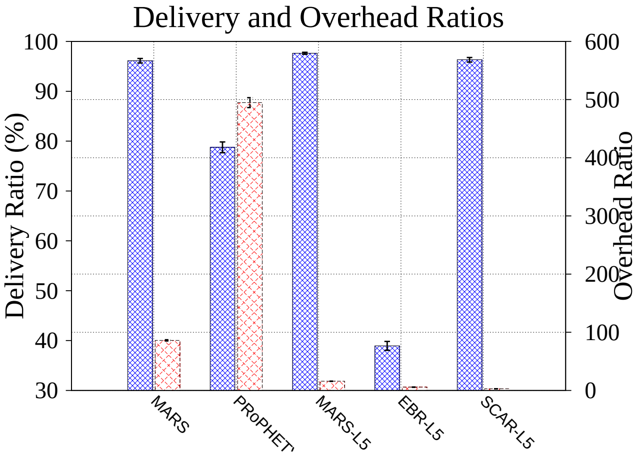
4.3.1 Effect of Buffer Capacity

In Figure 4.8 our scheme is compared with other routing schemes against varying buffer sizes with message size fixed to 2MB. By avoiding congestion due to small routing overhead and intelligent selection of next hop nodes, delivery ratio of our scheme (MARS and MARS-L5) is higher than all other schemes at small buffer sizes (Figure 4.8(a) 4.8(b)). With increase in buffer size at nodes, capacity of the network to store extra redundant copies is also increased. Therefore, we can observe an increase in delivery ratio, in Figure 4.8(a), in case of PRoPHET routing, but at the cost of significantly large routing overhead as can be seen in Figure 4.8(b). Overhead of PRoPHET and RAPID routing in Figure 4.8(b) keeps on decreasing with increase in buffer size due to less number of message drops but, it is still very high than MARS routing. Delivery rate of EBR and SCAR with 5 tokens almost remains constant at large buffer sizes while, in MARS-L5, due to the ability of scheme to learn changing network behavior, it keeps on increasing with increase in buffer size of network nodes. Despite introducing limited redundancy within the network MARS and MARS-L5 have smaller end-to-end latency as compared to other protocols in Figure 4.8(c). Chances of congestion at intermediate nodes can be avoided by keeping the overhead at a constant rate. From here, we can infer that better performance can be achieved by introducing limited redundancy into the network, which can survive message drops due to buffer overflows. This is the reason we can observe higher delivery ratio in case of MARS-L5 as compared to MARS at low buffer sizes.

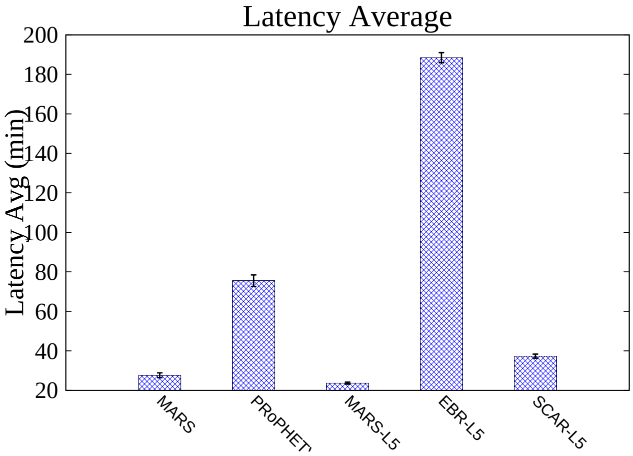
4.4 Scenario-3: Simulations with Cluster-Based Movement

In scenario-3 we use ClusterMovemnet Model [16] defined in ONE simulator for evaluating MARS with other schemes. This is the well known scenario available in ONE with defined settings. Simulation time is set to 12hrs and there are 160 nodes divided into 4 different groups within the network. There are three clusters of nodes and 40 ferries move around these clusters to carry data traffic. We run simulations against five different seed values. Messages of size within range 50k, and 150k are generated after every 25 to 35 seconds randomly choosing source destination pairs. Message lifetime is set to 5 hours. Results against this movement model are shown in Figure 4.9. Results with RAPID routing are not included in this scenario due to indefinite computational time required by ONE implementation of the protocol. Here, we have used completely different settings in terms of packet size and other characteristics. We believe that the variety in taking the scenarios can better reflect the adaptation measures defined in MARS.

SCAR-L5 has negligible overhead but with high end-to-end latency and delivery ratio slightly less than MARS and MARS-L5 in this case as shown in Figure 4.9(b) and 4.9(b) respectively. Overhead of unlimited replication schemes i.e PRoPHET and MARS is high due to high connectivity within the network as a large number of nodes present higher next-hop fitness to potential destinations. However, MARS is still able to limit its overhead to a significantly lower value than PRoPHET



(a) Delivery & Overhead Ratio



(b) Latency Average

Fig. 4.9: Scenario-3: Comparison of MARS with different Number of Forwarding Tokens, PRoPHET, EBR, and SCAR Routing in ClusterMovement Based Mobility Model

routing.

MARS-L5 outperform MARS in this case. It has slightly higher delivery ratio than MARS despite introducing limited redundancy, and it still has end-to-end latency comparable to MARS. Hence, it further strengthens our point, rather introducing limited redundancy into the network by taking wiser decisions helps in achieving better performance than trying to occupy network resources through greedy replication.

Although, only 5 replications of each message are allowed with MARS-L5, but as we have stated that when only single copy is left with a node, MARS turns into forwarding scheme. Hence, some copies may keep on moving within the network until their lifetime is expired. Each transmission contributes in increasing routing overhead. Therefore, overhead of MARS-L5 is higher than 5 in Figure 4.9(a), although, there are only 5 replicas for each message present within the network.

4.5 Conclusion

A thorough evaluation of MARS against variety of parameters in heterogeneous synthetic and real mobility traces is presented in this Chapter. We show, with simulations that fitness value based on multiple attributes can help in taking wiser decisions regarding forwarding of a message towards its eventual destination. Moreover, comparison against well known destination-dependent, destination-independent, and hybrid utility-based schemes is included to depict a more realistic picture on performance gain achieved through MARS.

Evaluations in variety of heterogeneous environments, show that MARS exhibits very small overhead and still achieves better delivery ratios and end-to-end latency as compared to other protocols taken into consideration. Hence, it can achieve better performance in resource-stringent environments characterized with sparse connectivity.

Chapter 5

An Overlay Cooperation Framework For Destination-Dependent Utility Schemes - Design Details

5.1 Introduction

Opportunistic routing [15, 36, 27, 35] has received increased attention in last decade, since the basic epidemic routing protocol [25] is proposed to enable communication in challenging environments. Contrary to mobile ad-hoc networks, in DTNs, a contemporaneous end-to-end path may not exist. In this case, mobility of nodes is characterized as the main communication mean within the network. Hence, a node is required to lend its memory resources for a considerably long duration to perform store-carry-and-forward routing [5]. Moreover, to deal with uncertainty of a future path due to partially known network topology, many protocols [25, 15, 36, 35] send multiple redundant copies of a message, in the hope that one will finally make its way to eventual destination.

Given these features, altruistic behavior of intermediate nodes is the fundamental assumption on which these protocols [25, 15, 36, 35] are based. However, in real world scenarios when we associate nodes with human beings, carrying wireless devices like PDAs or laptops to form an opportunistic network, egoistic behavior is not out of possibility. Moreover, the self-organizing nature of such networks, provides a node with the autonomy to decide on its own whether to participate or not in multi-hop communications as the epitome of underlying protocol rules. Hence, existing protocols may break down if a large portion of nodes do not participate in an altruistic manner, and rather, choose to enjoy services from the network as free-riders. Concretely, performance of a network afflicted with selfish nodes might be greatly impaired, unless the utility-based data forwarding scheme is not assisted with some incentive mechanism, which enforces penalty on not relaying. Moreover, for an opportunistic multi-hop relaying scheme, to work upto its full potential in pragmatic settings, it is indispensable to safeguard interests of cooperative participants from being compromised by miscreant entities.

Many credit-based and reputation-based mechanisms are proposed in literature to stimulate cooperation among nodes. However, in this thesis, we propose an overlay framework to enforce cooperation, specifically, in destination-dependent utility-based schemes [15, 35, 78]. In these techniques, data forwarding is stimulated when a node presents next-hop fitness/utility to destination higher than the current custodian of a message. Hence, node's participation plays a vital role in successful functioning of the protocol. However, many protocols [15] [42] [78] do not enforce any mechanism to ensure cooperative participation, instead, altruistic behavior is taken as an assumption. The framework is provided with a service differentiation mechanism working independently on top of the utility-based scheme to distinguish between egoistic and benign behaviors, while a node meets with other nodes within the network. When a contact occur, involved parties calculate a selfish metric based on past behavior of the peer. Each node then employs this metric in calculating its final next-hop utility for the peer node. The framework works on the principle that if a node is detected as selfish, relays reduce their next-hop fitness/utility for former node, which ultimately affects the level of service it might be able to receive from the network as a free-rider.

Our Contributions in this part of thesis, can be summarized as follows:

- We propose a novel cooperation enforcement framework which is deployed as an overlay to assist destination-dependent utility-based schemes.
- The proposed framework do not require any changes within the working of the protocol, neither it assume any additional entities to be deployed within the network.
- We demonstrate the effectiveness of proposed framework through simulations with PRoPHET routing [15] in Chapter 6.

Rest of the chapter is organized as follows. Working of proposed framework is explained in detail in Section 5.3. In Section 5.4, we discuss parameters settings of the framework. In Section 5.5, we show that the proposed framework is a Nash Equilibrium followed by conclusion in Section 5.6.

5.2 Background

Many DTN routing protocols assume altruistic behavior from nodes to accept, store and forward messages allowing multi-hop communication between a pair of nodes. This assumption is not always true in real world scenarios, as by agreeing to forward messages, a node is contributing its resources such as memory, processing power, and energy etc. Nodes not willing to expand their resources for others can reduce effective node density, that may impact overall network performance [79]. The node cooperation issue has been extensively studied in mobile ad-hoc networks, and the schemes can generally be classified into reputation-based schemes and virtual currency-based schemes [80]. Virtual currency based schemes enforce node cooperation by giving incentives to nodes for participating in network operations. Nodes use these incentives to get service from the network. This can avoid

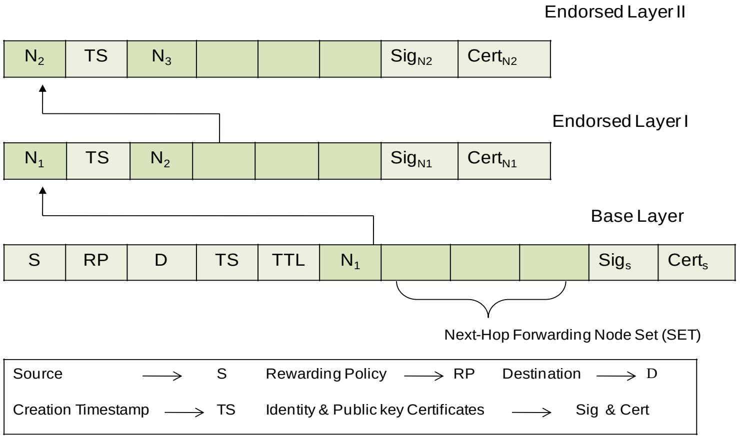


Fig. 5.1: SMART: Example Of A Layered Coin For A Single Forwarding Path. An Endorsed Layer Is Added At Each Next-Hop.

selfish behavior of nodes who refuse to forward packets on behalf of others in order to conserve their resources. However, reputation-based schemes are normally used to avoid threats from misbehaving nodes [80], and to isolate non-cooperating entities [81]. Many of the schemes for opportunistic networks try to mitigate the effect of non-cooperation by borrowing above ideas from mobile ad-hoc networks.

5.2.1 Credit-Based Schemes

In this category, network operations are performed through a credit-based system, in which credits are paid to participating nodes, helping as intermediate relays, by the communicating parties. In other words, available credits at a node are basically its tokens to get any service from the network. Hence, a node agrees to carry packets for others, in order to earn credits for its potential future activities, as non-cooperation will result in less or zero credits that will eventually lead to deprivation from network services.

A layered coin mechanism is introduced in SMART [82] to keep track of participating nodes on forwarding path from source to destination. As shown in Figure 5.1, each intermediate node inserts an endorsed layer into the packet accompanying base layer inserted from source node. These layers are concatenated by adding information about the generator of the next layer in previous layers as shown in Figure 5.1. In this way, each hop cooperatively contributing on successful delivery path can be easily tracked. After that, for clearance, the last forwarding node submits the generated layered coins to a virtual bank (VB), which then equally distributes the credits, to contributing nodes, paid by the message source. MobiCent [83] is one of the representative credit-based schemes, as it introduces compatibility with replication-based DTN routing protocols. In this technique, offline payment adjustments are performed by a trusted third party (TTP). Credits are paid to helper nodes, on the eligible delivery path from source, by mobile clients who initiate downloading. A MobiCent framework consisting of TTP, data sources, clients and helper nodes is shown in Fig. 5.2. In another incentive scheme [84], instead of utilizing the concept of TTP or VB, every node is assigned with an initial set of available credits. A node can then rent a neighbor, by paying credits, to help itself in fetching messages, it is interested in, from AP. In contrast to MobiCent, here, instead of, helping as relays, nodes only carry and share messages they are interested in, until a node rents some of its neighbors by paying credits. To resist certain attacks a secure credit-based schemes is proposed in a recent study [] to provide incentives to cooperative nodes. In [85] a node cooperation mechanism is proposed to deliver vedio packets over opportunistic networks. based on quality of vedio every packet is assigned a utility gain value. The encountering nodes exchange packets and then collectively calculate utility gain of packet exchange that is divided among themselves. The information is then reported to virtual bank for payment clearance.

Cryptographic techniques are required in credit-based mechanisms for basic validity checks. Moreover, in order to regulate payments, a number of trusted central

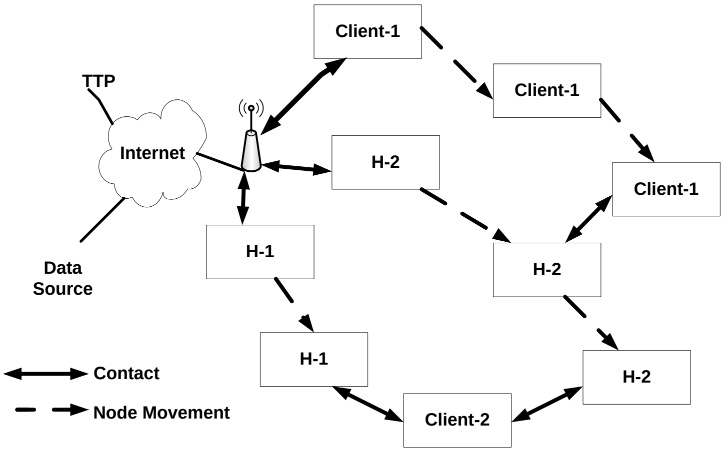


Fig. 5.2: MobiCent Framework

entities are assumed which limits our options regarding network topology. Further, DTNs are characterized with high packet loss ratios and sparse connectivity. For this reason, routing is usually performed by sending multiple redundant copies of a message by source or other intermediate relays, which travel through multiple paths towards destination. In this case, rewarding nodes involved in extra transmissions would be costly, and it might overburden the paying party. On the other hand, it will be unfair to reward only nodes involved in the path from whom the packet is first received by the destination.

Instead, in this thesis, our focus is to have an incentive mechanism which does not require additional entities in existing networks. Moreover, every single packet a node forwards, should contribute in crediting a node for behaving fairly.

5.2.2 Reputation-Based Schemes

In reputation-based schemes, reputation of nodes is used as a measure to evaluate their trustfulness. Pi [86] is a hybrid incentive scheme, for single copy routing, in which source attaches an incentive with every message it forwards. If the message is able to reach destination, then credits are charged from source node. However, even if it fails, the faithful participants can still earn good reputation from a trusted authority. As high reputation of a node contributes in building other relays confidence in helping the former with forwarding messages, this fairness introduced by the protocol further stimulates cooperation within the network. Analogously, in Give2Get epidemic forwarding [87], a node is forced to show "proof-of-relay" to previous relays or source node. A "proof-of-misbehavior" is sent to a central authority if it fails to do so, which affects reputation of a node. An observer-based reputation technique is proposed in [], where special nodes named observers are deployed to assess the reputation of different nodes in a disaster scenario. Reputation of a node is periodically announced to help cooperative nodes for avoiding selfish nodes while forwarding data.

In order to avoid the need for a trusted authority, many reputation schemes [88] [89] are coupled with some service differentiation mechanisms. In MobiID [90], similar to Give2Get forwarding, every node maintains reputation tickets it has received on successfully forwarding a message to a next-hop relay. These tickets are then shown, on demand, to source node on any future encounter. Based on these tickets, reputation of a node is established through self and community checks. In IRONMAN [91], nodes maintain a reputation value for other nodes within the network. If a node is found selfish, its rating is decremented by a factor x; however, it is incremented on showing cooperative behavior.

In many reputation-based schemes for opportunistic networks, generally a watchdog analogous to S. Marti et al. study [92], is associated with every node, which observes the behavior of other participants. Further, Beta-Distribution mechanisms are commonly used [93] [88] to assess cooperative and selfish actions taken by different nodes. The calculated reputation of a node is then used in deciding whether to forward a packet to it or not. This way performance of opportunistic routing protocols can be improved by avoiding sending of packets to nodes who drop them in spite of sending forward [88] [89] [94] [95].

Above reputation-based schemes generally depend on identifying nodes 1) which maliciously attract packets and then drop them, or 2) selfish nodes which, due to protocols or network settings, are compelled to receive packets, but later drop them to avoid forwarding overhead to themselves. However, in destination-dependent utility-based schemes, nodes independently calculate their next-hop utility for each other. Hence, it is rational for a node to falsely present zero or very small next-hop utility in order to avoid its participation in forwarding bundles.

5.2.3 Barter-Based Schemes

In barter-based schemes, encountering nodes trade same amount of messages, in the sense, to fully cooperate with the peer, only if, altruism is presented by the latter. In [96], a message value is assigned to every bundle based on users' interests. A node sends a message of primary or secondary interest to peer, in reciprocal to receive messages, it is interested in. Nodes generally accept secondary messages in order to trade for primary messages in future. Another Tit-For-Tat scheme is proposed by U. Shevade et al. in [97], in which, path selection from source to destination is constrained to have same number of packets on any link $i \longrightarrow j$ within the path, as of traffic in opposite direction (i.e. $j \longrightarrow i$). Moreover, in [?] a Tit-For-Tat strategy is also adapted to share contents in opportunistic networks in publish/subscribe manner to avoid selfish behavior. In another recent study [?] node interactions are modeled as a game, where a node behave cooperatively or selfishly. Based on the information collected over a number of past interactions nodes are classified into selfish and cooperative individuals.

We can see that barter-based schemes put strong constraints on flow of traffic based on users' interests. However, in utility-based protocols, traffic exchange among intermediate relays is usually driven based on their next-hop utility/fitness.

Hence, in this thesis, we suggest the need to have a cooperative framework to couple with existing destination-dependent utility-based approaches.

5.3 Proposed Technique

Many destination-dependent utility-based routing protocols are proposed in literature to enable communication despite sparse and intermittent connectivity within an opportunistic network. Connection opportunities arising through mobility of nodes are utilized to share and exchange information among involved parties, and messages are generally replicated towards intended destinations traveling through multiple paths. Intermediate nodes without having direct interest in information they relay, consume their resources for the benefit of others. Therefore, a rational node may choose to behave selfishly at the expense of performance received by cooperative nodes. This behavior give rise to free-riders that are able to receive information, they are interested in, from the network, without participating for others benefit. These selfishly behaving nodes do not forward messages for other nodes at any time.

Our proposed framework, in this Chapter, works as an overlay over any destination-dependent utility-based scheme to stimulate cooperation among nodes. The framework does not require any changes within the network, in the form of additional entities, or in functioning of the underlying data forwarding schemes. The objective is to ensure a fair performance achieved out of the utility-based scheme, in use, within pragmatic settings afflicted with selfish nodes. The cooperative framework is shown in Figure 5.3, and in succeeding discussion we explain each module in detail, where the meanings of notations are listed in Table 5.1.

Table 5.1: List Of Symbols Frequently Used In Describing Cooperation Overlay Framework

Notations	
U_{BA}	B's next-hop utility/fitness to A
α	Altruistic behavior count
β	Egoistic behavior count
ρ_A	Number of node A's own messages
ϑ_A	Number of messages node A forwards as intermediate relay
w	Aging constant
f_{Bi}	familiarity value of B for node *i*
b_{BA}	Node B's belief in node A
d_{BA}	Node B's disbelief in node A
u_{BA}	Uncertainty at node B for measured behavior of node A
Θ_{BA}	Selfishness of node A to node B
λ	Network Tolerance

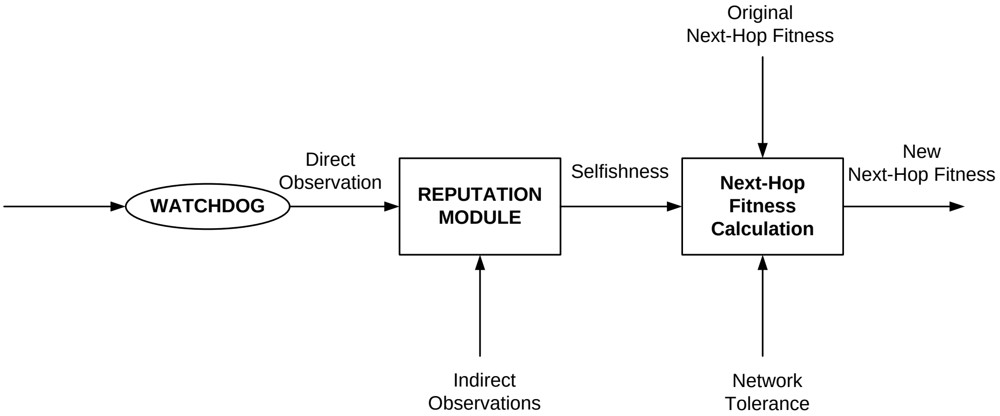


Fig. 5.3: Framework for Calculating Next-Hop Utility/Fitness Based on Reputation of a Node

5.3.1 Reputation Module

We use Beta Distribution mechanisms (i.e. Beta(α,β)) as in [93], to measure altruistic and egoistic behavior of a node in terms of α & β respectively. As shown in Figure 5.3, a watchdog is associated with every node, which observe behavior of its peer during every encounter, labeled as "*Direct Observation*" in the given Figure 5.3. Along with this, every node also collects information about a node from other nodes it encounter. Keeping in mind, stochastic characteristics of opportunistic networks, this indirect information can leverage prediction of accurate behavior of

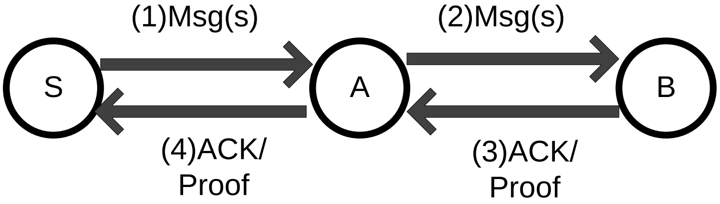


Fig. 5.4: Proof of A, Forwarding Message Of Source S to B

a node [88]. Further, based on available information, “Reputation Module” calculates selfishness of a node, which serve as input to “Next-Hop Fitness Calculation” module. In following we present each of these steps in detail.

DIRECT-OBSERVATION

A selfish node may falsely present small utility values to avoid receiving messages destined to other nodes. Hence, it can easily circumvent observation techniques [88, 89] that are based on showing proof of forwarding to previously cooperating relays or sender of a message. These techniques also assume presence of encryption methods to validate proofs. A simplistic scenario is shown in Figure 5.4. Here, we emphasize on calculating direct-observations, regarding behavior of a node, only based on direct encounters with that node. For example, in scenario shown in Figure 5.4, node B, instead of sending back the proof of forwarding, based on forwarding behavior of node A, updates its positive/negative ratings for the latter node. Let an encounter occur between two nodes A and B. A’s interaction with B can be categorized into three possible ways, first, it sends its own messages to B for forwarding towards corresponding destinations (defined as ρ_A), second, it forwards messages of other nodes (defined as ϑ_A), third, no message exchange is done. Further, let us consider the sets $\vartheta_{A_{srs-ids}}$, and $\vartheta_{A_{dst-ids}}$, which contain the corresponding source and destination Ids of relayed messages, and a set $\rho_{A_{dst-ids}}$ containing the destination Ids of messages for which A is the source node. Then, B updates its α_{BA} and β_{BA} for peer node A as follows:

$$\alpha^{dir}_{BA_{new}} = w \times \alpha^{dir}_{BA_{new}} + \frac{\vartheta_A \times |\vartheta_{A_{srs-ids}}| \times |\vartheta_{A_{dst-ids}}|}{\vartheta_A + \rho_A + 1} \tag{5.1}$$

$$\beta^{dir}_{BA_{new}} = w \times \beta^{dir}_{BA_{new}} + \frac{((\rho_A \times |\rho_{A_{dst-ids}}|) + 1)}{\vartheta_A + 1} \tag{5.2}$$

Here, ϑ_A in Eq. 5.1 is multiplied with corresponding number of unique source and destination Ids to encourage nodes to help in forwarding messages for a diverse set of nodes. It also helps to avoid a small group of nodes that collude to avoid negative ratings. Similarly, while calculating β in Eq. 5.2 a node multiplies ρ messages received from its peer to corresponding number of unique destination Ids. Moreover, In Eq. 5.1, the division is done with total number of messages received from node A. Therefore, if the node is only offering its services to a small group of nodes or the number of its own messages, that is, ρ_A is high, it will result in a small increase in $\alpha^{dir}_{BA_{new}}$ value. Similarly, a high value of ϑ_A will help in decreasing the node's negative rankings in Eq. 5.2. We add aging constant w in above equations to avoid stale information. This helps in keeping updated information about the behavior of a node to cope with dynamic topology intrinsic to opportunistic networking environments.

INDIRECT-OBSERVATIONS

Along with direct observations, a node also collects indirect observations from experiences of other nodes. In our case, node present next-hop utility for different destinations. A node forwards a packet only if the peer has high next-hop fitness to destination than the node itself. In example scenario shown in Figure 5.5, although, node j is carrying packets for other nodes but it does not forward them to i, as the latter node does not present any next-hop utility to those destinations.

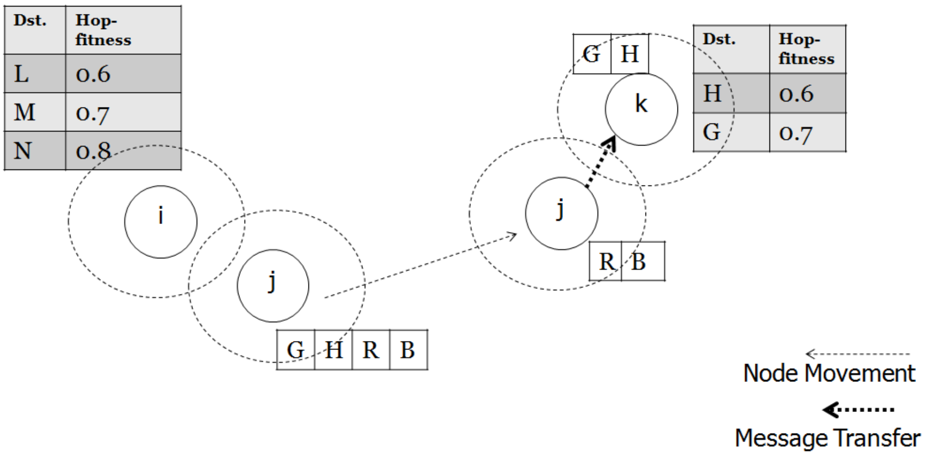


Fig. 5.5: Node k presents next-hop fitness to G and H. Therefore, j forwards packets destined to Node G and H to k instead of i

Therefore, from i's perspective j is acting selfishly within the network. However, this is not true according to observations collected by node k about node j. Keeping in mind this intrinsic nature of the network at hand, we emphasize on sharing only the positive information about a node.

Let us categorize nodes within any given network into two sets. Let S is the set of selfish nodes while C is the set of cooperative nodes. For simplicity let us define some rules, first, j $\in$ S if j is selfish to all nodes in the network, second, j $\in$ C if j is cooperative to any node in the network. Initially, we assume every node in the network is a cooperative node i.e. it atleast is cooperative to one of the nodes in the network, and α, β are probabilities that represent positive negative ratings of a node respectively. Now, we define two events, let D be the event "j is in set S" and B the event "j is selfish to node i". The probability that j is selfish based on event B $P_B(D)$ is given by the Bayes theorem:

$$P_B(D) = \frac{P(B)P(D|B)}{P(B|D)}$$

Here, P(B) = β_{ij} and $P(B|D) = 1$, because, a node is only considered selfish if it is selfish to every node within the network. Initially, every node is assumed cooperative, hence, probability of j being categorized as selfish node only based on i's observation is negligible. It is only significant if the observer node has equal probability to encounter all nodes within the network to collect observations on j's behavior. Intuitively, this condition does not holds true in real life networks with heterogeneous mobility patterns. Hence,

$$P_B(D) = 0$$

Therefore, we opine that collecting negative ratings about a node's behavior for integrating indirect observation may lead to misleading decisions. A node's fair share of the network is directly affected based on estimation of its behavior, thereby, we collect only positive ratings about a node's behavior from other nodes.

Indirect observations are calculated using Dempster-Shafer Belief Theory as proposed in [98] [99]. Following Eq. 5.3 represent A's reputation collected by node B through node C. This integration is known to handle bad-mouthing and ballot-stuffing attacks. We refer the reader to [98] for detail discussion on these attacks.

$$\alpha_{BA}^{C} = \frac{2 \times \alpha_{BC}^{dir}}{\beta_{BC}^{dir}} \tag{5.3}$$

If we assume that C is a set of cooperative nodes from whom B is collecting information about A, while node A is egoistically behaving within the network so that

$$\alpha_{CA} \ll \alpha_{BC} \quad OR \quad \alpha_{CA} \approx 0$$

Then, positive rating of A at B can incorrectly increase after different encounters with other cooperative nodes according to Eq. 5.3. Therefore, we also need to consider C's observation on A's behavior i.e. α_{CA} as well, in order to correctly determine reputation of the latter node. At the same time, C's positive rating of A should not exceed B's positive rating of the former node. Hence, for any n recommenders providing their opinion on A's behavior, B calculates its indirect rating of A as follows:

$$\alpha_{BA}^{ind} = \sum_{i=1}^{n} w \times \left(\frac{2 * \alpha_{Bi}^{dir} \times \alpha_{iA}^{dir}}{\beta_{Bi}^{dir}}\right) \times f_{Bi} \tag{5.4}$$

Here, $w \in \{0..1\}$ is aging/forgetting constant to prevent stale observations. Moreover, $f_{Bi} \in \{0..1\}$ is the familiarity value of B for i^{th} node [100]. In an opportunistic network environment with sparse connectivity it is important to determine familiarity degree among two nodes over a period of time to weight peer's opinions about other nodes. Nodes with high familiarity degree are better trusted for their opinions than the nodes with small familiarity degree. In this way, we can control the impact of a node opinion while calculating indirect reputations.

We opine that in opportunistic networks, next-hop fitness of a node for any other node/destination - calculated through utility-based protocols - can better reflect familiarity of a node calculated over a significant period of time. Hence, f_i is calculated through dividing B's next-hop fitness to i (U_{Bi}) by sum of all utility values of the former node.

$$f_{Bi} = \frac{U_{Bi}}{\sum_{j=1}^{N} U_{Bj}} \tag{5.5}$$

This helps in reducing uncertainty present within given information. Intuitively, convergence time also becomes small with increased confidence on available information [100].

Combining Direct and Indirect Observations

We combine direct and indirect observations using weighted average, and take η = 0.5 by default to equally favor both observations.

$$\alpha_{BA} = \eta \times \alpha_{BA}^{dir} + (1 - \eta) \times \alpha_{BA}^{ind} \tag{5.6}$$

Selfishness

It is difficult to exactly measure the forwarding behavior of a node due to long delays and frequent network partitions in OppNet. Packets at a node may drop out of lifetime expiry or buffer overflow, before being forwarded to corresponding destinations. Intuitively, this uncertainty about the measured behavior of a node need to be considered while evaluating its reputation [88]. Fortunately, Dempster-Shafer belief theory has the leverage to deal with such issues. For this, every node behavior is defined in terms of a tuple (b_{BA}, d_{BA}, u_{BA}), where b_{BA} is B's belief that A has behaved in altruistic manner, while d_{BA} is defined as disbelief of former node in A. u_{BA} represents uncertainty of B in measured behavior, thereby, $b_{BA} + d_{BA} + u_{BA} = 1$ is satisfied. Mapping of α_{BA} and β_{BA} to tuple (b_{BA}, d_{BA}, u_{BA}) is defined in Eqs. 5.7-5.9.

$$b_{BA} = \frac{\alpha_{BA}}{\beta_{BA} + \alpha_{BA}} \times (1 - u_{BA}) \tag{5.7}$$

$$d_{BA} = \frac{\beta_{BA}}{\beta_{BA} + \alpha_{BA}} \times (1 - u_{BA}) \tag{5.8}$$

$$u_{BA} = \frac{12 \times \alpha_{BA} \times \beta_{BA}}{(\alpha_{BA} + \beta_{BA})^2 \times (1 + \alpha_{BA} + \beta_{BA})} \tag{5.9}$$

Then, trust value of a node is calculated as in [88]:

$$trust_{BA} = b_{BA} + \sigma \times u_{BA}$$

Next, selfishness Θ_{BA} of a node can be quantified as follows:

$$\Theta_{BA} = 1 - trust_{BA} \tag{5.10}$$

Here, σ is relative atomicity based on the principle of insufficient reasoning, which is set as $\sigma = 0.5$ by default to have an unbiased view as in [88].

5.3.2 Next-Hop Fitness Calculation Module

Next-hop fitness is the measure of ability of a node for delivering data to other nodes. Many destination-dependent DTN routing protocols [15], [78], [49], [42], [41] determine next-hop utility or fitness of a node based on number of encounters or other common mobility and resource characteristics with the destination. This destination-dependent next-hop utility coming from any existing routing protocol in OppNets is taken as input to our Next-Hop Fitness Calculation Module.

Intuitively, our framework can be applied to any destination-dependent utility protocol that takes its forwarding decisions based on next-hop fitness of nodes. Another benefit of our framework is that it does not require any changes within the network, e.g introducing central entities to enforce cooperation, and working of underlying utility protocols. Therefore, our framework can generally be used as an overlay to enforce cooperation in OppNets with any existing utility driven data forwarding scheme. However, here we only exemplify working of the framework with one of the classic and widely deployed protocols in OppNets, PRoPHET [15]. In the following, we will first explain brief details of PRoPHET before introducing its application to our framework.

Overview Of PRoPHET

PRoPHET is a well known and simplistic data forwarding protocol designed for OppNets. In PRoPHET next-hop utility of a node for a destination is calculated based on number of encounters between two nodes. It works on the principle that if two nodes have high encountering history, there is strong possibility that the two will have an encounter in future. Therefore, frequently encountering nodess will get a high next-hop fitness or delivery probability to each other.

PRoPHET depends on following Eqs. 5.11-5.13 to update next-hop fitness values. Node B whenever it meets node A, updates its fitness to latter node in terms of

$$U_{(B,A)} = U_{(B,A)_{(old)}} + (1 - U_{(B,A)_{(old)}}) \times U_{enc} \tag{5.11}$$

where, U_{enc} is calculated as follows:

$$U_{enc} = \begin{cases} U_{max} \times (Intvl_A / I_{typ}) & if 0 \leq Intvl_A \leq I_{typ} \\ U_{max} & otherwise \end{cases}$$

I_{typ} is defined as expected inter-connection time, and $Intvl_A$ is the time interval since last encounter with node A. We refer the reader to [15] for more details.

To avoid stale information present within the network a node (B) age its next-hop fitness to other nodes (e.g. A) as in Eq. 5.12 with a constant time unit, in case, the two nodes do not have an encounter for a long time.

$$U_{(B,A)} = U_{(B,A)_{(old)}} \times \xi^k \tag{5.12}$$

Where, ξ is the aging constant, and k represents number of time units since last age update was done.

PRoPHET also supports transitive utility of a node defined in Eq. 5.13. If node A meets node C, and then meets node B, in this case, B can calculate its transitive next-hop fitness to latter through former node as.

$$U_{(B,C)} = max\{U_{(B,C)_{(old)}}, U_{(B,A)} \times U_{(B,C)} \times \zeta\} \tag{5.13}$$

Here, ζ is defined as scaling constant and its default value is set to 0.9 in our experiments as per configurations defined in [15]. In this work, we do not take into account transitive next-hop fitness of nodes, hence, forwarding is done only on the basis of direct next-hop fitness within the network..

Apparently, in PRoPHET, a selfish node who want to avoid forwarding messages for other nodes will announce small utility values ($U \to 0$). Hence, it will appear unattractive to be selected as intermediary node. We assume selfish nodes do not collude in announcing small next-hop fitness values only to a specific set of nodes. This assumption is quite realistic, as selfish nodes do not intend to harm the network. They only want to get benefit of network services without contributing their resources towards that service [101].

Next-Hop Fitness Calculation

Next-hop fitness of a node to a certain destination can be termed as its willingness to contribute in delivering a message to latter node in a store-carry-and-forward manner [7]. In OppNets an end-to-end connected path is unavailable between any source and destination. Thereby, a message is forwarded to intermediary nodes presenting high next-hop utility to destination until the latter is eventually reached. Otherwise, messages can only be delivered when the source would come in direct contact with the destination.

Intuitively, a node is more likely to receive messages addressed towards itself, if other nodes express their willingness in terms of high next-hop utility to former node. On the other hand, small next-hop utility or low willingness of intermediary nodes to a destination will affect the performance, latter node can get from the network in terms of delivery ratio. It will also prolong end-to-end latency, even if messages are eventually delivered, due to increased waiting time in source's buffer while striving for finding appropriate next hop candidates.

Selfish nodes may wish to avoid cost to themselves incurred by forwarding messages for other nodes; while still be able to get services from the network through cooperative intermediaries. Hence, it is indispensable to curb every entity for acting as epitome of deployed protocol's principles to achieve a win-win situation within the network.

Here, we suggest to have an overlay mechanism on top of any utility data forwarding protocol within the network in which a node's (e.g. A) cooperation level affect other nodes' (e.g. B) next-hop utility towards the former. In this case, no cooperation will eventually lead to small or zero next-hop fitness from relays to selfish nodes, which will affect relaying of packets destined to latter nodes. Our approach is formulated in following Eq. 5.14.

$$U_{(B,A)_{new}} = \Theta_{BA}\lambda U_{(B,A)_{old}} + (1-\Theta_{BA})U_{(B,A)_{old}} \tag{5.14}$$

Here, $U_{(B,A)_{old}}$ is next-hop utility of B to A calculated with underlying protocol, PRoPHET. Θ_{BA} is selfishness of node A within range [0,1] coming from "Reputation Module", and λ is a constant representing network tolerance for selfish behavior.

Here, it is clear that by penalizing selfish nodes, we can somehow increase share of cooperative nodes within the network. It can act as the motivating force for the nodes to cooperate resulting in increased performance of the network.

5.4 Setting Framework Parameters

5.4.1 Aging Constant w

Aging helps in avoiding selfish burst, where a node initially behave altruistically to avoid being detected as guilty in order to avoid punishment. It also help cooperative nodes to recover from their past uncooperative behavior, if they had stop receiving messages for some time period, due to insufficient energy or other resources and now started behaving cooperatively.

5.4.2 Network Tolerance

Network Tolerance (λ) is a constant within range [0,1] that represent how much a network is resistant to selfish behavior. In case, there are enough resources with cooperative nodes to accommodate free riders, λ can be set to greater than zero. Otherwise, it is set to zero to completely isolate selfish nodes from the network as can be seen in Figure 5.6. Here, in Figure 5.6, 50% nodes are selfish and we refer to our framework as C-PRoPHET. Concluding what we see in this Figure, we can say that when we increase tolerance under moderate data rates and sufficient resources, the percentage share of selfish nodes, in terms of delivery-ratio, also increases without affecting fair share of cooperative nodes. At λ equal to 1, the next-hop fitness to selfish nodes, despite behaving selfishly within the network, is not affected by other cooperative relays. Therefore, former nodes are able to achieve services from the network equivalent to latter nodes, as, in PRoPHET

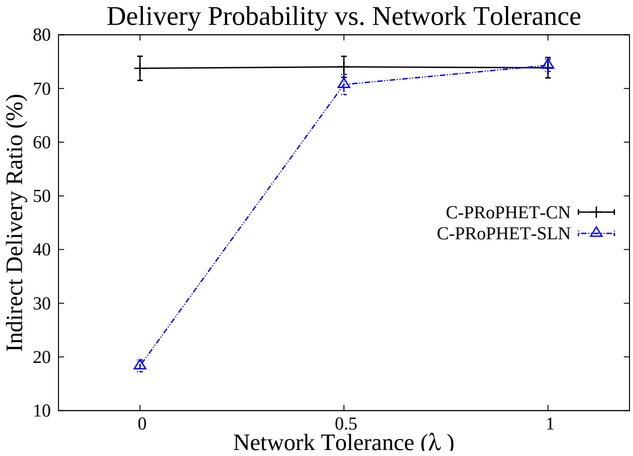


Fig. 5.6: Delivery Ratio vs Network Tolerance λ, CN refers to Cooperative Nodes and SLN stands for Selfish Nodes within the given Network Scenario

messages are not prioritized based on source-destination Ids.

However, we can clearly see the affect of isolating free-riders by setting λ equal to zero in a network with stringent resources in Figure 5.7. Here, cooperative nodes are able to maintain high delivery-ratios at small buffer sizes, as the resources are only spared for messages destined to these nodes. Hence, It can act as the motivating force for the nodes to behave altruistically, and abide by the rules of the underlying data forwarding protocol, for continuation of services they want to receive from the network.

5.4.3 Security Considerations

In our cooperative framework, during a contact each node directly calculates no. of messages peer sends as source or as an intermediate relay. Hence, it is possible for a node to create multiple fake identities (Sybils), and pretend to act as an intermediate relay, for one of them as source of the message, to avoid being detected as selfish.

Introducing timestamps and Signatures of message creator can help in reducing

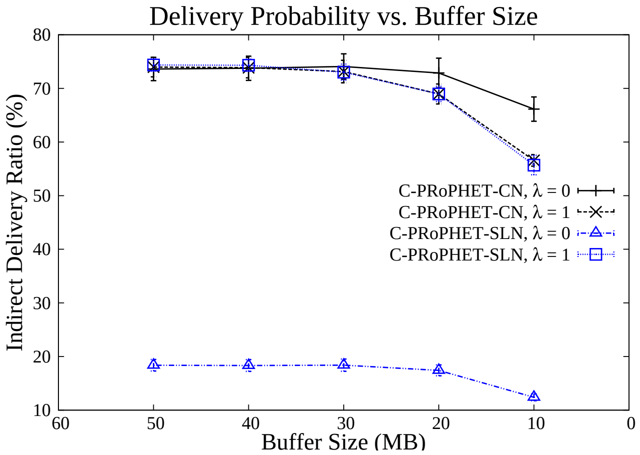


Fig. 5.7: Protocol Behavior at Different Network Tolerance (λ) against Buffer Sizes, CN refers to Cooperative Nodes and SLN stands for Selfish Nodes within the given Network Scenario

this effect. However, in this Thesis, we assume to deal with nodes who do not possess any malicious intentions. They show selfish behavior and do not obely protocol rules in order to save their own resources such as, memory and power consumption. Moreover, as in Eq 5.1, the number of source and destinations an intermediate relay helps in forwarding their messages directly adds towards its positive ratings. Hence, a malicious node is required to present a large set of fake identities in order to have positive rankings comparable with a benign node.

5.5 Nash Equilibrium

In this section, we show that our cooperative framework over any utility based protocol is a Nash Equilibrium. Let us first define a set of players P, a set of possible strategies S and a payoff function. Here, players are the nodes which form an opportunistic network, and S contains destination-dependent utility protocols deployed to enable communication within the network. Let π is our cooperative framework running as an overlay on the data forwarding utility scheme. Then, we can define payoff of a node i as follows:

$$f_i : \pi_s \longrightarrow \delta_i$$

Here, δ_i are the services or delivery rates achieved by node i from the network, following the protocol s from strategy set S, when the network applies the cooperative framework π.

As we know, the driving force behind a benign node to become part of the network is receiving services in the form of data or information addressed towards itself. Moreover, the basic functionality of any utility protocol in an OppNet is to enable communication in the form of data or information sharing among involved parties despite frequent partitions and intermittent connectivity within the network. Therefore, delivery ratio is the critical metric used to evaluate utility protocols in literature. However, here we consider delivery ratio from a single node's perspective. That is, how much delivery rate a node i is able to attain by following the protocol, if the cooperative framework π is implemented as an overlay on all other network participants.

Our goal is to show that if π is used as an overlay on any strategy s, then the resulting strategy profile π_s is a Nash Equilibrium. We show that if a player i unilaterally deviates by presenting low utility values ($U \to 0$) contrary to protocol s, that is, $s' \neq s$, then $f_i(\pi_{s'}) \leq f_i(\pi_s)$. Thereby, a node's fair share of network services decreases if it behaves selfishly. Therefore, nodes do not have any incentive in manipulating their utility to avoid forwarding, or to deviate from the protocol.

For simplicity we assume a network in which there are only two mobile nodes, and a fixed access point (AP). Messages from outside the network destined to these nodes arrive at AP, where they are stored until recipient itself or any other node

		Player B	
		Cooperate	Not Cooperate
Player A	Cooperate	1 (A) , 1(B)	0 (A) , 1(B)
	Not Cooperate	1 (A) , 0(B)	0 (A) , 0(B)

(a) Nodes' Payoff with Strategy s

		Player B	
		Cooperate	Not Cooperate
Player A	Cooperate	1 (A) , 1(B)	0 (A) , 0(B)
	Not Cooperate	0 (A) , 0(B)	0 (A) , 0(B)

(b) Nodes' Payoff with Cooperative Overlay π_s

Fig. 5.8: Nodes within the Network Represented as a Two Players Game. Each Player's Payoff is Shown Against its Own and Other Player's adapted Actions with s & π_s

having high utility for destination moves within AP's vicinity. We assume that in accordance with strategy s, next-hop utility of nodes for each other is always higher than AP's utility to both nodes. Therefore, both nodes are expected to relay messages for each other. However, a node e.g. A can cheat by showing 0 utility for second node B to avoid relaying messages for saving its memory and energy resource.

This network is modeled in the form of two players game in Figure 5.8. We assume a player's payoff is 1, if it receives messages from AP through an intermediate node, that is, second player. Otherwise, if it is only able to receive messages through direct encounter with AP, it's payoff is 0. Destination-dependent utility protocols [41] [42] [15] [78], do not employ nodes' behavior in determining their next-hop utility for each other. Therefore, if we consider the case where player A chooses not to cooperate, for saving its memory and energy resources, it has no affect on its payoff as long as player B chooses to cooperate, as per strategy s shown in Figure 5.8(a). However, latter player's payoff is 0 despite behaving cooperatively, as it is only able to receive messages through direct encounter with AP. Same is the case with player A while it cooperates when player B chooses not to cooperate.

Figure 5.8(b), shows payoff of players when our cooperative overlay over strategy s, that is, π_s is employed. With cooperative overlay a player silently observe other participants forwarding behavior to distinguish between selfish and cooperative ones. When the other player is not cooperating or behaving selfishly, the former will show zero next-hop utility towards it as per Eq. 5.14, even if, it does not possess any selfish intentions. Hence, behaving selfishly results in zero payoff with cooperative overlay π_s over strategy s due to other cooperative participants not willing to forward messages for the selfish player. Inevitably, if a player i chooses not to cooperate deviating from strategy s it gets less payoff than following the strategy cooperatively, that is, $f_i(s') \leqslant f_i(s)$. It is clear from Figure 5.8(b) that if players want to get highest payoff the only option left with them is to participate cooperatively in network functioning. Hence, our cooperative framework over any destination-dependent utility-based strategy is a Nash Equilibrium.

5.6 Conclusion

In this Chapter, a novel framework is proposed, which act as an overlay over destination-dependent utility-based schemes. Destination-dependent forwarding schemes are well-known to provide communication in opportunistic networks characterized with intermittent connectivity and frequent partitions. However, in existing schemes node cooperation is taken as an assumption, which may not hold true in many realistic settings when nodes are associated with human beings carrying wireless devices. The proposed framework intend to assist any destination-dependent scheme with stimulating cooperation among nodes, vital to functioning of the network. Moreover, we do not require any changes in working of these protocols, nevertheless, the framework is provided with a service differentiation mechanism which quietly work on top of the protocol to identify miscreant entities. If a node is detected as selfish, relays low down their willingness in the form of next-hop utility to former, which affects the level of service a node is able to receive from the network.

Chapter 6

An Overlay Cooperation Framework For Destination-Dependent Utility Schemes - Evaluation & Results

6.1 Simulation Setup

In this we have taken an area 300 × 300 m, where 100 nodes are moving with Random WayPoint mobility model. Selfish nodes in order to avoid relaying packets for other nodes falsely disseminate very small value of next-hop utility ($U \longrightarrow 0$) for potential destinations. We have omitted direct deliveries to destination nodes while calculating average delivery ratios of cooperative and selfish nodes with our framework (referred as C-PRoPHET) for clarity of results. Results are taken on 5 seed values and warm-up time for C-PRoPHET is set to 2 hrs of a 20 hrs simulation time. A message of size 1M, with lifetime expiry of 1 hr is generated after every 15 seconds interval randomly choosing source and destination pairs in all scenarios unless it is mentioned otherwise. We consider Bluetooth devices of 2Mbps transmission speed with 10m transmission range, and buffer size in terms of number of packets is set to 20.

We take network tolerance for C-PRoPHET as zero for isolating free-riders from the network. Aging constant w is set to 0.7 for gradually eliminating stale information present within the network.

6.2 Performance Metrics

6.2.1 Indirect Delivery Ratio

Here, we only consider messages which are first delivered traveling through one or more hops. Hence, we termed it as indirect delivery ratio.

6.2.2 Residual Energy

In order to present the impact of energy, we assume that x units of energy are available with every node at the start of the network. One unit of energy is consumed on each sending or receiving event of a message occurring at node. The formula to calculate collective percentage of residual energy at cooperative and selfish nodes is as follows: On every sending or receiving event at a node i

$$ConsumedEnergy_i++$$

Then, $\%ResidualEnergy$ of the given set at any given time in network is as follows:

$$\%ResidualEnergy = \frac{\sum_{i=1}^{N}(EnergyUnits_i - ConsumedEnergy_i)}{\sum_{j=1}^{N} EnergyUnits_j}$$

where, N is total number of nodes within any given group or set whether it is of selfish or cooperative nodes.

6.3 Comparison against Selfish Percentage

Performance degrade with increasing percentage of selfish nodes within the network as can be seen in Figure 6.1. We have divided nodes into two sets of selfish and cooperative individuals, and separately calculate their attained delivery ratios. In PRoPHET, selfish nodes are able to attain equivalent delivery rates as

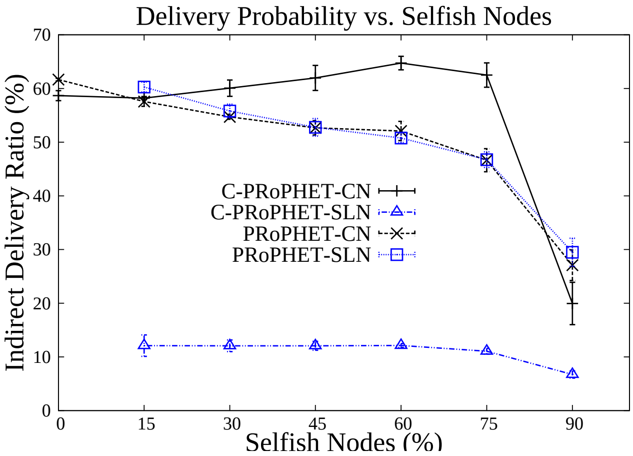


Fig. 6.1: Comparision of Delivery Ratios of cooperative and selfish nodes received by C-PRoPHET, and PRoPHET Routing against different percentage of Selfish Nodes within the Network. CN refers to Cooperative Nodes and SLN stands for Selfish Nodes within the given Network Scenario

achieved by cooperative nodes without lending their resources for servicing others. Although, PRoPHET is able to sustain its delivery rates despite selfish behavior present within the network, due to sufficient resources and capability of a node to move around different parts of the network. However, it is unfair with cooperative relays to carry all the burden, while there are free riders present within network who avoid forwarding costs to themselves, and are still able to get equal share of services. Moreover, cooperative forwarding incurs a cost in terms of energy (battery power), which is a constraint resource in mobile devices forming an opportunistic network environment. Further, PRoPHET, like other utility-based protocols, allows distributing multiple redundant copies of a messages to cope with high loss ratios. Hence, apparently, one message delivery requires additional storage at different intermediate relays resulting in quick depletion of resources at few cooperative nodes.

C-PRoPHET, on the other hand, adapts a fairer policy to nodes who present altruistic behavior as the epitome of the underlying protocol within the network.

We can see in Figure 6.1 that selfish nodes are completely isolated by limiting their delivery rates (services, they are able to receive from the network) to a significantly low limit. Resources that are spared due to not forwarding messages for selfish individuals are effectively utilized to provide services to other cooperative individuals. Hence, we can see an increase in performance received by latter nodes at increased selfish percentage present within the network.

However, when selfish percentage cross a certain limit within the network, multi-hop communication is highly affected. Moreover, as limited useful resource is available for functioning of the network in form of number of cooperative nodes, message drop due to congestion also increases. In C-PRoPHET during warm-up period messages for all node are equally treated. Thereby, chances may increase for wrongly determining a node as selfish who do not posses bad intentions, but was unable to deliver packets due to congestion or other possible reasons. Therefore, delivery rate to that node is affected for certain amount of time until it regain other nodes' confidence. This affect is also apparent at zero selfishness where delivery ratio achieved through C-PRoPHET with $\boldsymbol{\lambda} = \mathbf{0}$ is slightly lower than PRoPHET routing.

6.4 Delivery Ratio against Different Transfer Percentage of Nodes

In Figure 6.2, a comparison is shown of delivery rates or services received by nodes against their participation in multi-hop communications. In this scenario, 50% of nodes are selfish, who do not participate in forwarding messages, and message size is taken as 500kB with 10MB buffer at each node. Transfer Ratio on x-axis in Figure 6.2, refer to percentage of messages, transferred by a node, out of total messages that are transferred within the network. Here, we group nodes according to their transfer percentage, e.g. upto 1, 2 or 3 percent messages relayed

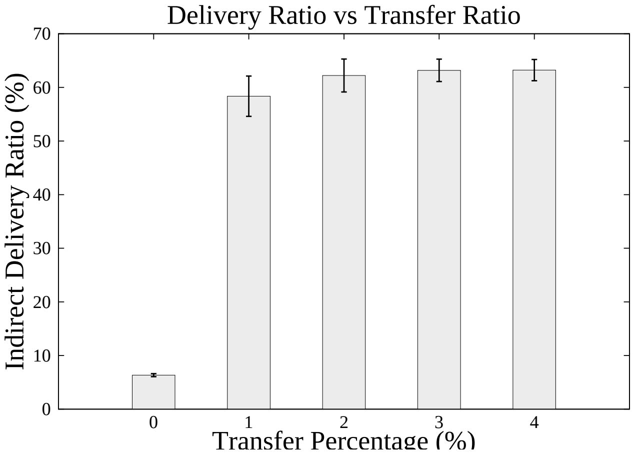


Fig. 6.2: Comparision of Delivery Ratios received by nodes against their participation in forwading messages as intermediate relays by C-PRoPHET

by different nodes.

We can clearly see that nodes, which participate in functioning of the network based on principles of underlying protocol, are able to receive more messages from the network that are addressed towards themselves. However, selfish behavior results in very low delivery rates, almost isolating the nodes from receiving services. In PRoPHET, data forwarding to a node through intermediate relays is driven by presenting high next-hop utility to former than the source of a message by latter nodes. As, in C-PRoPHET forwarding behavior of a node in a network affects relays next-hop fitness to it. Thereby, behaving selfishly will result in zero or very low next-hop fitness to a node from other participants. Intuitively, the low willingness of relays to forward data to a selfish individual will cut down the share of latter in receiving network services. On the other hand, the cooperative node will enjoy high willingness in forwarding data to itself from other cooperative relays as an incentive for showing altruistic behavior.

The castigating affect on selfish behavior imposed by C-PRoPHET plays fairly with cooperative individuals. Inevitably, it is indispensable for a node to present its next-hop fitness in a manner defined by the utility protocol. On the contrary, no or less participation in servicing the network will result in isolation.

6.5 Residual Energy Compared against Network Time & Traffic Loads

Despite storage available at a node for network operations, energy is also a constrained resource in opportunistic environments. Each transmission consumes energy at both receiving and sending nodes. Hence, if a node participates in forwarding data in an altruistic manner, a high cost is incurred to its energy resource. Low battery power can affect mobility of a node, and it may result in isolating the node from the network, as it might become unable to receive its own messages until it is recharged. Therefore, it is unfair to a cooperative node carrying the burden of forwarding messages for selfish nodes at the expense of performance it receives from the network. On the other hand, free riders are able to save their resources, which help them stay part of the network for long duration.

Moreover, when a large percentage of selfish nodes do not play their part, well behaved nodes presenting their next-hop fitness as per utility protocol tend to attract more data. This way, the few better nodes can become heavily utilized. This may result in quick depletion of energy at few cooperative nodes, which are, ironically, the most essential resource of a network and are vital for its long term functioning.

In Figure 6.3, a comparison of available energy resource with selfish and cooperative nodes against network time is shown. In this scenario, we have taken 50% nodes as selfish.

We can see in Figure 6.3 that selfish nodes are able to reserve a higher percentage

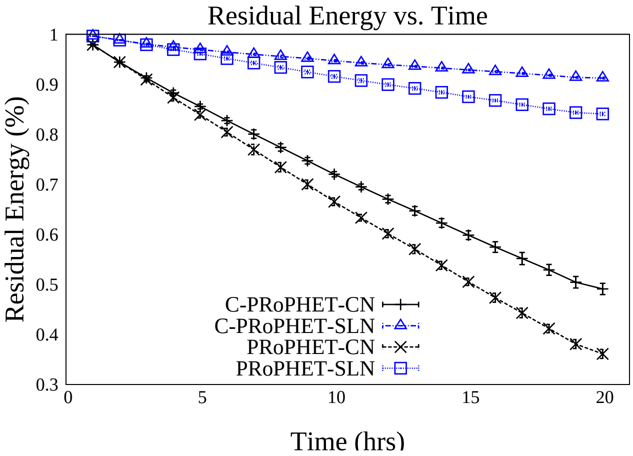


Fig. 6.3: Comparision of Available Percentage of Residual Energy with cooperative and selfish nodes against Network Time by C-PRoPHET, and PRoPHET. CN refers to Cooperative Nodes and SLN stands for Selfish Nodes within the given Network Scenario.

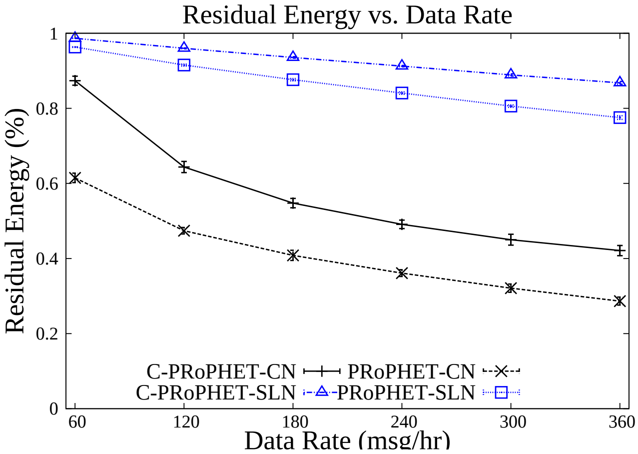


Fig. 6.4: Comparision of Available Percentage of Residual Energy with cooperative and selfish nodes against Different Traffic Loads by C-PRoPHET, and PRoPHET. CN refers to Cooperative Nodes and SLN stands for Selfish Nodes within the given Network Scenario.

of energy than cooperative participants of a network. However, energy at cooperative nodes gradually decreases over time, as they participate in network functions. Further, comparison of residual energy against increasing traffic loads is presented in Figure 6.4, where we can see significant decrease in energy at high traffic loads. In this scenario we also consider 50% nodes as selfish. C-PRoPHET tends to protect energy at cooperative nodes, which is a vital resource of a network. Therefore, we can see small decrease in energy percentage available with cooperative relays as compare to PRoPHET, because of refusing to carry messages destined to selfish nodes by showing small or zero utility for latter nodes. Hence, if a node utilize its energy resource for relaying messages, only then, in return, other nodes will help in forwarding messages destined to former node.

Selfish nodes are left with high energy with C-PRoPHET than of PRoPHET, as they experience small delivery ratios highlighted in Figure 6.5. They are only left to receive a message destined to themselves, if an opportunity arises to have direct encounter with source of the message, due to low willingness of cooperative relays. Thereby, despite saving a large percentage of energy, a selfish node is isolated in a network to receive messages through multi-hop communication. Inevitably, selfish nodes experience large end-to-end latency even if a message is somehow received from the network. We opine that selfish behavior may be discouraged due to this affect of C-PRoPHET on performance received by selfish nodes.

6.6 Comparison against Time & Framework Stabilization

In Figure 6.5, delivery ratios received by selfish and cooperative nodes is shown against simulation time. In this scenario 50% nodes are taken as selfish. In PRoPHET, multiple copies of a message are sent within the network that are forwarded independently towards the destination. This is usually done in utility

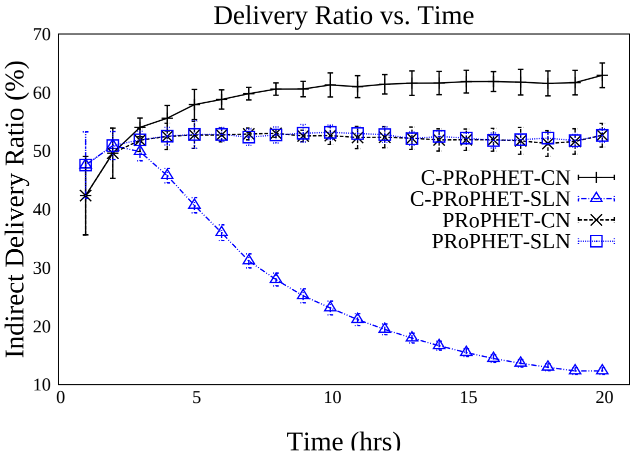


Fig. 6.5: Comparision of Delivery Ratios against Network Time by C-PRoPHET, and PRoPHET. CN refers to Cooperative Nodes and SLN stands for Selfish Nodes within the given Network Scenario.

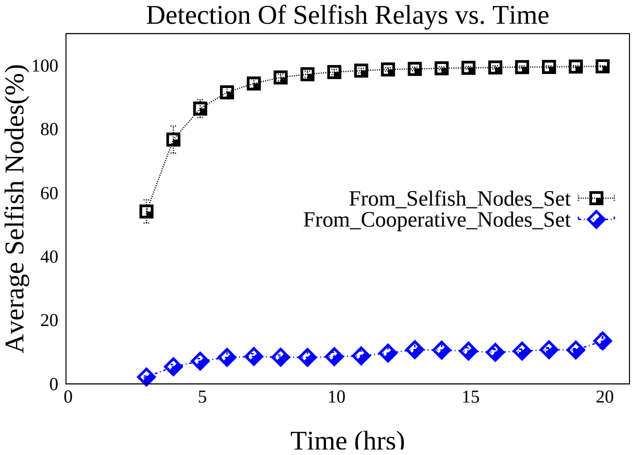


Fig. 6.6: Average Percentage Of Nodes Determined as Selfish by Cooperative Relays Against Simulation Time. 50% Nodes are Programmed to Behave Selfishly in this Scenario, and On-Line Detection with our Framework is shown separately against the two Sets of Nodes, i.e., Selfish, and Cooperative Nodes Sets.

protocols to avoid packet loss, but this trend also helps in overcoming selfish behavior that may affect forwarding of any copy from source to destination. Thereby, with PRoPHET, selfish and benign nodes receive almost equivalent delivery rates, as messages are not distinguished based on destination behavior. However, this equal treatment of the network to provide, analogous to best effort, services for all nodes discourage altruistic behavior expected from relays within the network.

We can see delivery rates tend to decrease for selfish nodes with C-PRoPHET, as the framework stabilizes over time. Low willingness to relay messages for selfish nodes results in sparing network resources that are utilized to provide better services to cooperative nodes. Thereby, latter nodes experience increased performance over time as a reward for showing altruistic behavior.

During warmup time a node relays messages as the epitome of PRoPHET routing, and silently collect observations during its interaction with companion nodes in the network. Therefore, we can see same delivery rates with C-PRoPHET and PRoPHET routing within this period. Here, This time period is taken as convergence time of our framework, and we opine that it is essential for a node to have enough number of observations before making an opinion about any other node in the network. Otherwise, if a node wrongly determine a large set of nodes as selfish, and deny relaying messages to latter based on Eq. 5.14, it's own credibility might get affected by other cooperative relays. Hence, this parameter needs to be carefully selected based on mobility patterns of nodes.

It is pertinent to mention here that nodes continuously refine their opinion about a node by collecting observations on each future interaction based on Eqs. 5.1, 5.2, even after warmup time. Inevitably, corrections are imposed over time, if a node is wrongly determined as selfish or a selfish node behave in a benign way in order to mislead opinions during warmup time. The behavior can be visualized in

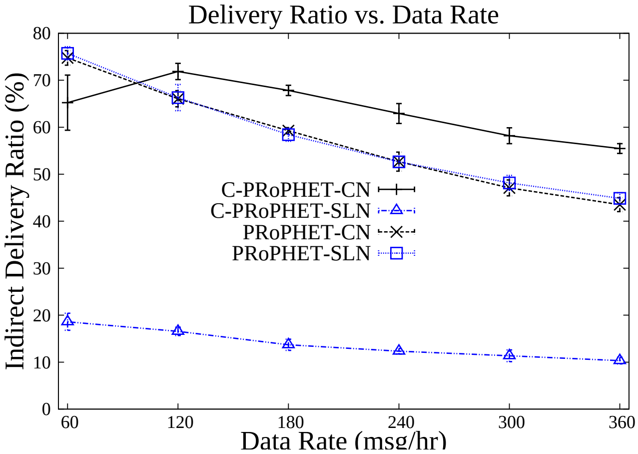


Fig. 6.7: Comparision of Delivery Ratio with cooperative and selfish nodes against Traffic Loads by C-PRoPHET, and PRoPHET

Figure 6.6, where average percentage of nodes detected as selfish at cooperative relays is shown against simulation time. We can see, as the time goes by, detection accuracy at a node is improved due to increased interactions with other nodes at different parts of the network. Detection accuracy soon goes upto near 100% within the network, which indicates that the damage resulting from selfish nodes in under control.

In Figure 6.6, we can see that a small percentage of nodes from cooperative relays set are also ironically detected as selfish. A message is only forwarded to another intermediate relay, if next-hop utility of the latter to the message's destination is greater than the utility of the current custodian. Moreover, due to following different mobility paths, it is unrealistic to expect from a node for showing next-hop utility to most of the nodes in the network. Hence, from this and the scenario explained in Figure 5.5 in section 5.3.1 of chapter 5, we can safely conclude that in a utility based protocol it is realistic for a node to wrongly determine a relay as selfish; which is ironically, playing its part in functioning of the network in an altruistic manner with other nodes. However, we can overcome this trend by adapting reputation techniques specially designed for opportunistic environments.

We aim to consider this issue as future work. In order to further explain this issue, a comparison of delivery ratio against different data rates is shown in Figure 6.7 when 50% nodes are taken as selfish. We can see with C-PRoPHET cooperative nodes experience small delivery rates as compare to PRoPHET at low data rates. The reason behind is similar as discussed above: at low data rates nodes have small number of messages to forward to other nodes within the network, which increase the chances to wrongly determine a benign node as selfish.

6.7 Conclusion

In this chapter, we evaluate our proposed framework with PRoPHET routing. We can see that when the framework is applied as an overlay to enforce cooperation it completely isolates selfish nodes from getting network services. The compulsion on nodes to behave in an altruistic manner in functioning of the network in order to avoid isolation serve as an incentive to encourage cooperation among nodes. We can also see that the resources that are spared by not forwarding messages for selfish individuals help to increase performance gained by cooperative nodes.

Chapter 7

Conclusion and Future Work

Opportunistic networking has emerged as a more flexible environment than Delay/Disruption Tolerant Networks (DTN), where every node may act as a DTN node. These networks are characterized with sporadic connectivity based on time-variant proximity of mobile devices, hence, it is termed as an opportunistically formed network (OppNet). Inevitably, end-to-end communication in OppNets is made possible with nodes that are equipped to store a message, they receive, in permanent storage, and carry it while moving, around different regions, unless further forwarding of the message is initiated that might bring it closer to eventual destination. This innovative communication paradigm is known as store-carry-and-forward routing. The ability, intrinsic to opportunistic networking, that, rather than counteracting, take mobility within the network as leverage to form time-variant connections promises unique opportunities for an emerging set of challenging environments. Pervasive computing, wildlife monitoring, disaster recovery networks, military applications etc. are some of the examples of such challenged networks, where most of the Internet's basic assumptions and rules need to be reconsidered. Intermittent connectivity, long or variable delays, frequent movements, non-contemporaneous paths, and limited resources, are the characteristics due to which aforementioned environments can not be well served by traditional networking approaches.

The extreme characteristics which violate assumptions on which ad-hoc routing protocols are based, poses several challenges on the way routing is performed in opportunistic environments. Moreover, in order to make efficient use of sparse density and sporadic connectivity, it is indispensable to engage nodes in cooperative communications. Hence, routing protocols that aim to increase delivery rates despite time varying nature of the environment, and nodes' willingness to spare resources for network benefit are two essential, and at the same time challenging parts of opportunistic networking, which we target in this thesis.

In the first part of this thesis, we describe a Multi-Attribute Routing Scheme (MARS) that determine next-hop utility/fitness of a node based on multiple destination dependent and independent characteristics.

Opportunistic routing makes use of transmission opportunities emerging from coarse-grained mobility within the network. Sporadic links appearing among nodes can be eventually construed over a period of time as presence of a complete path between any source and destination pair. Hence, a message travelling through multiple discontinuous hops might finally reach at its eventual destination. In order to make per-hop decisions more effective a class of opportunistic routing protocols, termed as utility-based schemes, maintain a utility or fitness function to decide on feasibility of a node as a next-hop relay. In this case, a message is only forwarded if utility of a node is greater than the current custodian of a message to avoid unnecessary overhead introduced by greedy-replication schemes. As data is driven towards destination based on next-hop fitness of nodes, thereby an efficient and accurate utility function is most essential to ensure a high percentage of delivery ratios within the network.

MARS is a hybrid utility-based routing protocol for opportunistic environments that determines a node's next-hop fitness based on an optimized combination of a set of multiple parameters (metrics). These parameters can be selected based on destination independent and dependent characteristics of a node to better reflect its suitably as next-hop relay. We also devise a method based on learning rules of neural networks to dynamically determine relative importance of each dimension. We also show that taking multiple dimensions into consideration has the inherent advantage of effective utilization of total network capacity along with introducing considerably small overhead over available resources. We evaluate MARS against well-known routing schemes using a variety of performance metrics, and in heterogeneous network environments. The advantages of MARS can be summarized as follows:

1. MARS is a novel hybrid routing protocol that determines destination independent/dependent characteristic of nodes and employs them in calculating their next-hop fitness or utility.
2. MARS use error correction learning [71] technique of neural networks to dynamically determine relative importance (weights) of each dimension.
3. MARS exhibits higher delivery rates as compared to other routing protocols, without overloading network constraints, which makes it suitable for resource-stringent environments.
4. In order to avoid arbitrarily large overhead, number of forwarding tokens can also be assigned with MARS.
5. Due to considering multiple dimensions and real time determination of each dimension's score, MARS can better distribute its overhead to effectively utilize total network capacity

In second part of thesis, we propose an overlay framework for destination-dependent utility-based schemes to stimulate cooperation among nodes. In these schemes, data forwarding is stimulated when a node presents next-hop fitness to destination higher than the current custodian of a message. Hence, node's fairly announcing their next-hop utility to get themselves engaged in cooperative forwarding is essential for accurate functioning of the protocol. However, these schemes do not enforce any mechanism to ensure cooperative participation, altruistic behavior is taken as an assumption, instead. Therefore, a wide range of existing schemes known to provide effective performance, may fail in pragmatic settings afflicted with selfish participants. Moreover, for an opportunistic multi-hop relaying scheme, to work upto its full potential in pragmatic settings, it is indispensable to safeguard interests of cooperative participants from being compromised by miscreant entities. We envision that an assistance mechanism to stimulate cooperation, associated with existing work (utility-based schemes), have the potential to help with practical deployments in real scenarios. Our framework is provided with a service differentiation mechanism working independently on top of the utility-based scheme to distinguish between egoistic and benign behaviors, while a node meets with other nodes within the network. When a contact occur, involved parties calculate a selfish metric based on past behavior of the peer. Each node then employs this metric in calculating its final next-hop utility for the peer node. The framework works on the principle that if a node is detected as selfish, relays reduce their next-hop fitness/utility for former node, which ultimately affects the level of service it might be able to receive from the network as a free-rider. We use Beta Distribution to calculate positive/negative behaviors of a node collected by its peers. Further, to cope with uncertainty present within opportunistic networks we determine selfishness of nodes through Dempster-Shafer belief theory.

We only consider individual selfishness and assume that nodes do not collude within the network. Nevertheless, in many scenarios nodes may posses social selfishness, that is, they show cooperative behavior with whom they have social ties and are non-cooperative for rest of the network. We aim to consider this issue as future work. Moreover, we assume that nodes only calculate direct next-hop utility with PRoPHET, as while calculating transitive fitness it is not necessary for nodes to have an encounter to directly observe the forwarding behavior of a node. As transitive next-hop utility is an important characteristic of PRoPHET and destination-dependent utility-based schemes, in future our cooperation framework could be extended to consider this. The framework can be extended to enforce cooperation in destination-independent utility-based schemes. Moreover, with MARS, we have used empirically defined values of ΔT. However, as future work this value can also be dynamically adjusted to configure MARS. In this way, based on learning the contact patterns present within any given network any initially defined value of ΔT can be updated accordingly. Moreover, we have used defined parameters to be used with MARS in this work. In future MARS can be accompanied with a self learning mechanism to dynamically select attributes according to network characteristics.

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