Centrality Analysis in Vehicular Ad Hoc Networks

Technical Report

T-Labs/EPFL

August 28, 2008

Author : Yannick Do

Supervisors : Sonja Buchegger, Tansu Alpcan and Jean-Pierre Hubaux

Table of contents

1 Introduction **1**

1.1 Project Goals . . . 2

1.2 Contributions . . . 2

1.3 Outline . . . 2

2 Related Work **5**

2.1 Vanet Connectivity Analysis . . . 5

2.2 Centrality Measures in Spatial Networks of Urban Streets . . . 5

2.3 Social Network Analysis for Routing in Disconnected Delay-Tolerant MANETs . . . 6

3 System Model **7**

3.1 Network . . . 7

3.2 Mobility . . . 10

3.3 Vehicular Infrastructure . . . 11

3.4 Topology . . . 13

4 Graph Theory & Centrality Analysis **15**

4.1 Graph Theory . . . 15

4.2 Centrality Analysis . . . 16

4.2.1 Definition . . . 16

4.2.2 Measures . . . 17

5 Experiments **23**

5.1 Toolkit . . . 23

5.1.1 Datasets . . . 23

5.2 Density and Centrality Localization (DCL) . . . 24

5.2.1 GIS rural . . . 25

5.2.2 GIS urban . . . 25

5.2.3 GIS city . . . 25

5.2.4 others . . . 25

5.3 Multi-Hop Dissemination (MHD) . . . 27

5.4 Distance to Infrastructure Backbone (D2B) . . . 30

6 Conclusions and Future Work **31**

A DCL Results 33
A.1 Rural setting . . . 33
A.2 Urban setting . . . 37
A.3 City setting . . . 39

B MHD Results 41
B.1 Rural setting . . . 41
B.1.1 noCF-noTL . . . 41
B.1.2 CF-noTL . . . 46
B.1.3 CF-TL . . . 51
B.2 Urban setting . . . 56
B.2.1 noCF-noTL . . . 56
B.2.2 CF-noTL . . . 61
B.2.3 CF-TL . . . 66
B.3 City setting . . . 67
B.3.1 noCF-noTL . . . 67
B.3.2 CF-noTL . . . 68
B.3.3 CF-TL . . . 69

C D2B Results 71
C.1 Rural setting . . . 71
C.1.1 noCF-noTL . . . 71
C.1.2 CF-noTL . . . 73
C.1.3 CF-TL . . . 74
C.2 Urban setting . . . 75
C.2.1 noCF-noTL . . . 75
C.2.2 CF-noTL . . . 76
C.2.3 CF-TL . . . 77
C.3 City setting . . . 78
C.3.1 noCF-noTL . . . 78
C.3.2 CF-noTL . . . 79
C.3.3 CF-TL . . . 80

Bibliography 81

Chapter 1

Introduction

The number of casualties being in Europe or U.S. (40,000 deaths per year [1]) due to road traffic is still unacceptably high, even if it has reduced significantly over the years due to safer vehicles, infrastructure and policies. Car ownership and use have continued to grow steadily, and the resulting congestion in built-up areas and on main highways has become a significant overhead cost and burden for travelers, for the economy and for the environment. In Vehicular Ad Hoc networks (VANET), vehicles will be equipped with wireless short-range communication devices, allowing vehicles and roadside infrastructure to communicate and form an Ad Hoc network.
As it is envisioned, VANET raise both at the same time tremendous opportunities but also huge design challenges. VANET are thought as a way to enhance the use of vehicle transportation by providing many different kind of applications. For example safety and cooperative applications, by periodic dissemination of information (position, speed, direction...). As well traffic efficiency could be increased. Hence by using communication and cooperation between vehicles could significantly reduce the negative impacts of road traffic by creating additional effective road network capacity and a more efficient use by vehicles.
It remains that the big challenge comes in the deployment of this technology, specifically taking into account the penetration of vehicular communication that will grow larger over the year. A way to bootstrap smoothly the technology and making coexist VANET enabled and non-enabled vehicles must be found. In that order of idea, study of Vehicular Infrastructure Integration *VII*, where the road environment is enhanced with sensing and communicating devices, is a first step.

Because it is not yet possible to rely on an omnipresent infrastructure, the network will rely on an hybrid solution consisting of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. The latter should help enhancing the overall connectivity when V2V is not available and provide services among the network participants. Connectivity issues in VANET have already been investigated [23][24], but there is still no clear understanding and consensus on how the vehicular infrastructure should be deployed efficiently. In this study we'll focus on topology and centrality analysis in order to asses how deployment of roadside infrastructure, Roadside Units*RSUs*, can affect connectivity in the network and which area can be considered as *hotspots*.

What are the most efficient/hotspot points to deploy RSUs? Answers should take into account different level of connectivity requirements. Characteristics of Delay-Tolerant-Networks is that at, any time, the network cannot safely assumed to be fully connected, and isolation of nodes (vehicles) should be minimized.

Why is it important? Improve network connectivity, data dissemination and protection against attackers.

The originality of our approach is to use social networks metrics such as Centrality measures, both on traffic and on road topology. Social networks analysis approach focus on the idea that some places (streets, crossroads), actors (vehicles, roadside units) plays more important roles than others. By correlating Centrality both from a road and traffic topological point of view, we can have a new understanding of important regions in the network and use this knowledge to deploy roadside infrastructure. A further step, would be to detect most vulnerable spots for attacker jamming. This would result in setting a game theoretic framework between attacker and authorities for battle of road safety.

1.1 Project Goals

Due to cost and technology adoption, the deployment of VANET is slow and yet still quite experimental. For a few years a lot of effort has been done in developing some real life testbed for vehicular networks. But to our knowledge the deployment of the infrastructure has not always been the main point of interest. The infrastructure unit, RSU, can have many capabilities, such as sensing and broadcasting information. Up to now, it is a common understanding to deploy the RSU at major crossroads or at very dense area (such as highways). We believe that a characterization of the importance of a geographical region according to the road network and car traffic flows is an alternative. Even though such a deployment seems to make sense, we believe that at the beginning of the infrastructure deployment, a smart placement of RSU could perform as good as a dumb one and also have some advantages in economics terms (less RSU) or flow control terms. Goals of the project are the following:

- Summarize centrality measures and their application in VANET.
- Compute density and centrality values for a road network based on realistic vehicular traces.
- Define Road Side Units placement strategies.

1.2 Contributions

The quantification of some nodes importance is mainly a task in social network analysis. Here we try to adapt this research for Vehicular Networks thus providing a new approach in the field. Compared to classical Social networks graphs, Vehicular networks present some interesting aspects. First of all due to the moving nature of the cars, network graphs are changing frequently with the addition (or subtraction) of new relational ties between nodes thus we provide centrality measures data of interest.

1.3 Outline

This report is organized as follows:

Chapter 2 details the context where this project takes place and what relevant work has already been done.

Chapter 3 presents the system model and the assumptions of the project

Chapter 4 describes graph theory and centrality analysis by providing insight on a few metrics.

Chapter 5 details the different experiments performed.

Chapter 6 concludes the project and gives some future directions.

Chapter 2

Related Work

First part of the work at T-Labs involved a large literature review on the global subject of Vehicular Ad-Hoc Networks and then on more specific themes such as Connectivity, Vehicular Infrastructure Integration, Centrality and so on. Most of the papers read were summarized in a Google Notebook (ask author for access). In this chapter we present some of the work that showed to be the most relevant.

2.1 Vanet Connectivity Analysis

Kafsi et al. [24] is the result of the work of Mohamed Kafsi, a former colleague from EPFL, during his internship at T-Labs. In some way this project is the follow-up of his. *Vanet Connectivity Analysis* describe relation between VANET connectivity, vehicles density, traffic flow, transmission range and market penetration. The main focus was put on the use of percolation theory. Therefore it heavily relies on the use of the SUMO Traffic Simulator [5]. Unfortunately the topology and mobility model lacks real life element, with a $N \times N$ grid map and predefined traffic flows for different car densities. Even though it is a very simple and extensible setting, it probably cannot represent real life settings. That's why in our project we choose to use real traffic traces.
The paper show that vehicle density is related too arrival flow but also too different mobility regime, and that for high enough vehicle flows, density is stable in central parts and large in peripheral parts. The main contribution of this work is about the definition of connectivity with respect too cluster size and vehicles density. Also the consideration of market penetration showed that background traffic can sometime affect positively connectivity level and more precisely the number of cars in the so-called biggest cluster.

2.2 Centrality Measures in Spatial Networks of Urban Streets

Crucitti et al. [17] is in some way the basic inspiration of our work. They investigated centrality in urban street patterns and showed that spatial analysis allows an extended visualization and characterization of a city structure. They used a primal approach which maps crossroads to graph vertices and roads to graph edges. Dual approach is also possible, more details in [28]. They computed several centrality indices such as closeness, betweenness, straightness and information centrality and studied their distribution.

2.3 Social Network Analysis for Routing in Disconnected Delay-Tolerant MANETs

Even though we didn't use much of the contribution of Daly and Haahr [18], it is a very interesting paper that show maybe the most effective use of social network and centrality analysis in mobile networking that is for routing. They use similarity and betweenness computation to derive a routing algorithm. Basic idea is that when message destination node is unknown to source node, the message is forwarded to a more central node increasing the potential of finding a suitable carrier. Betweenness computation assuming reduction to *ego network analysis* (i.e. local centrality).

They come up with *SimBet routing* algorithm, which is close in performance with Epidemic routing in terms of "total number of messages delivered", "End-to-end delays" and "Average number of hops" and this without the overhead of redundantly forwarding messages. Epidemic routing is also outperformed when it comes to "total number of forward messages".

Chapter 3

System Model

In this chapter we discuss the system model adopted in this project. We first introduce VANET systems, describe their specificities and possible applications. As for any vehicular related project, we pay attention to the mobility models that are used. Then we speak about the vehicular roadside infrastructure and what functions they provide and finish with a focus on the project topology.

3.1 Network

Vehicular Networks can be seen as a specific, and maybe the principal, application of Multi-Hop Mobile Ad Hoc Network. Main components are:

- **Servers/Authorities**: public agencies or corporations with administrative powers in a specific field/region. They are responsible for instantiating procedures (e.g. registration, license issuance etc...) and managing security credentials.
- **Roadside Units**: act as base stations, can belong to governments or private service providers.
- **Public vehicle**: public transportation (e.g. buses, taxi), public services (e.g. police).
- **Private vehicle**: belonging to individuals or private companies.

However there are some significant differences that make research on ad hoc network very specific.

Network dynamics characterized by VANET is quite different of classical MANET or sensor networks. Quasi-permanent *mobility*, *high speeds*, and (in most cases) very *short connection* times between communicating entities. Vehicles *trajectories* are mostly well defined by roads, which incurs advantages (message dissemination) and disadvantages (privacy). VANET is definitely the largest real-world application of mobile networks (100s millions of nodes), but communication remains mostly local (geographical) which make it *partitionable* and *scalable*. As opposed to usual ad-hoc networks, vehicles are enabled with advanced capabilities in terms of *computing power*, *storage*, and *power management*. Among all it posses *secure positioning* systems. Similar to the "black box" of airplanes, vehicles will be equipped with *Event Data Recorder* for event reconstruction (e.g. in the case of accidents), front-end *radars* for detecting obstacles and environmental *sensors*.

Due to life-critical situations, *real-time constraints* and error tolerance can be very stringent. That's why attacks on such networks can cause irremediable damages, and thus the needs of strong security requirements. Deployment of such networks is not expected before 2014, and penetration of enabled-vehicles will be low at the beginning. Moreover Roadside infrastructure might not be globally available because of cost issues.

Communication

Vehicles to Vehicles (V2V), Vehicles to Infrastructure (V2I) happens over the wireless radio medium. Infrastructure to infrastructure happens via wired backbone network. In case of no direct connectivity , Multi-Hop communication is used, where data is forwarded from one node to another, potentially via infrastructure, until it reaches it's destination. When both are available, V2V and V2I might exhibit significant difference in terms of communication, e.g. packet delay, bandwidth consumption and packet loss [11].

For the sake of standardization, the Federal Communication Commission (FCC) has allocated a 75Mhz around the 5.9 GHz channel spectrum, the DSRC (Dedicated Short Range Communications) [2]. It is a short to medium range (up to 1000 meters) communications service that supports both Public Safety and Private operations in roadside to vehicle and vehicle to vehicle communication environments. DSRC is meant to be a complement to cellular communications by providing very high data transfer rates (6-27Mbps) in circumstances where minimizing latency in the communication link and isolating relatively small communication zones are important. Around the world other 802.11-like technologies are also expected to be standardize in this way. Beyond DSRC, vehicle networks can leverage on other wireless communication technologies, such as (licensed-frequency) existing 2.5/3G cellular networks, WiFi, broadband wireless (e.g. WiMax), infrared, or low-speed radio broadcast systems used today for traffic information [30].

Communication appends upon messages exchange between network actors. Messages can be application specifics but for safety and traffic applications we derive 2 important types of message:

- periodic message (beacons): obtain local traffic information, 1-hop broadcast.
- event-driven message (e.g. emergency message): information dissemination, possibly over Multi-Hop.

Those messages are mainly *broadcast* and *standalone* (i.e. there is no content dependency among them). Any safety and traffic related messages includes *time-stamp*, *position*, *speed*, *direction*, *acceleration*, and *data-specific* (e.g. congestion notification, accident). Upon reception of messages, application On-board unit (OBU) react accordingly (.e.g. if receive an accident message, reduce speed,and change lane). Protocol design should ensure that messages are unique (non-replayable) and lifetime limited (area, TTL ...).

DSCR specifications say that safety messages can be transmitted over a single hop with sufficient power to warn vehicles in a range of 10-15 seconds travel time thus reducing need for Multi-Hop.

As proposed in [35], a possible and realistic protocol design is:

- Each vehicle sends beacons over a single hop every 300ms within a range of 10s (min 110m max 300 m), other messages are sent upon triggered by event.

- Inter message interval drops to 100ms (and the range to 15m) if the vehicle is very slow or stopped (i.e. their speed is less than 10 miles=16kmh).

- Vehicles take decision on the received messages and may transmit new ones.

- Safety messages can be discarded if the difference between sender and receiver time-stamp is larger than a system-specific constant that accounts for the maximum clock drift and one-hop transmission, propagation and processing delays. Moreover messages can be discarder at the receiver if the coordinates of its sender/relay, as reported in the message, indicate that the receiver is out of maximum radio range (validation on a per-hop manner)

Applications

VANET and Cooperative vehicle applications can be divided in three main categories:

1. **Safety** applications like accident warnings, warnings on environmental (e.g. ice on the pavement, aquaplaning etc), cooperative driving and collision avoidance. Because of the life-critical situation, safety applications require strong *security* guarantees, very short *timing constraints*, and *minimal isolation*. The communication should mostly be *local* (a few km/ttl/hop at most). Require a very *high penetration rate* to be effective.

2. **Traffic monitoring and optimization**. Distributing the traffic as to minimize traffic jam and overall waiting time. For example, on apparition of traffic jam all incoming vehicles are rerouted to alternative shortest routes (avoid route mapping, see internet congestion). Communication availability should be global (hundreds km) but timing constraint are not life critical.

3. **Infotainment-services** applications like internet, video streaming, online payment and so on. Communication either local (payment at border for example) or global(internet access etc), but not time constrained. Business driven constraints could help deployment of infrastructure.

A list of detailed applications is listed in [1]:

Optimum Traffic management Based on expected travel times and vehicle/driver destination, it provide a personalized route planning to follow and to help the roadside manager to predict traffic congestion and delays.

Area routing Intersection controllers signal momentary disturbances in the traffic flow and give individual, destination-based and appropriate routing alternatives to approaching vehicle.

Local Traffic Control Intersection optimization.

Flexible Lane Allocation To increase the capacity of the road infrastructure, a dedicated bus lane is made available to "licensed" and CVIS-equipped vehicles, travelling in the same direction, allowing them to use the lane when and where it would not be a nuisance to public transport and the arguments of speed, punctuality and economy would not be compromised.

Enhanced Driver Awareness (EDA) It focuses on safety and inform vehicle drivers within 5 (CVIS) seconds by communication from the roadside or even nearby vehicle, about relevant aspects of the dynamic traffic situation, current speed and other regulations, road and weather conditions downstream, also offering the possibility to enhance the effectiveness of in car systems for driver assistance.

Cooperative Travelers Assistance (CTA) Assistance of the drivers. It increases the transparency of the evolving traffic situation downstream on the road network, personalizes the information to travelers, enables them to make optimal use of the road network and assists the traveler making the right choice navigating through the road network, based upon full cooperation between Roadside systems, in-vehicle sensors, Traffic managers and Service providers. This system will provide information to the driver within 15 seconds about a major congestion/accident/incident, and 15 seconds later they receive a recommendation about an alternative route.

Fleet and Freigth Management Increase efficiency, safety, security, environmental friendly of cargo movements (see SmartWay [6]). Monitoring and guidance of dangerous goods, parking zone management and access control to sensitive infrastructures.

In-Vehicle Map updates Goal to receive map updates and live traffic or road infrastructure reports, along with other relevant local views in cars.

In-Vehicle Internet/Mobile Office Goal top provide Internet services on board that can be used by the driver when the car is stopped or by the passengers with the car on the move.

Urban parking zones Allow booking of urban parking lots (to professional and individuals).

3.2 Mobility

Since real-world testbeds are sparsely available, research rely a lot on simulations because of fast, cheap and repeatable properties. The simulation of a mobile ad-hoc network require exact position information of all nodes throughout the simulation, hence the importance that nodes movement are modeled as close as the real-world. Real vehicular traces are rarely available, thus the design of mobility models. Being application specific, a large number of mobility models have been proposed and a large study of them is out of scope of this project.

Vehicular mobility models can be divided in two categories either *macroscopic*, considering aspects like road topology, speed limits, collective behavior or *microscopic*, focusing on individual behavior. The use of Traffic-simulator is also a trend in the research area. Such simulator like SUMO, used by [24] or MMTS.

GIS

This project make extensive use of the realistic mobility model for vehicular ad-hoc networks proposed by [32], because of their open source web access, but also for ease of processing in *Matlab* while being quality models based on realistic vehicular traces. It uses detailed street map from the Swiss Geographic Information System (GIS). For detailed informations, the reader is encouraged to look at [32]. This project used three different types of microscopic behavior defining exact speed and acceleration of vehicles in the simulation: entity model, car-following model, car-following with traffic light model.

Entity model The vehicle speed is imposed only by the road speed limit ignoring any other vehicles in proximity. Such a model is easily implemented but fails to reproduce realistic traffic effects such as congestion.

Car-following model This model is based on Intelligent-Driver Model (IDM) [33]. The speed at next simulation step is a function of the current speed, a desired speed (aka road speed limit), and distances to other vehicles.

Car-following model with traffic lights This is an extended version of the previous model taking into account intersections behavior. Upon arrival at intersections, foremost vehicle check if it is free to pass. In the case of traffic light, the vehicle decelerates and stops. Since GIS maps do not reveal existence of traffic lights, [32] assume a first-come first-served principle on less important intersections, and traffic lights on important intersections (round-robin algorithm).

MMTS

We also used vehicular traces from the Multi-Agent Microscopic Traffic Simulator (MMTS). These traces are realistic mobility traces for simulation of inter-vehicle networks obtained from a simulator that was developed by K. Nagel (at ETH Zurich, now at the Technical University in Berlin, Germany).

Nice properties of MMTS is the simulation of typical workday behavior. According to [10], individuals in the simulation are distributed over the cities and villages according to statistical data gathered by a census. Within the 24 hours of simulation, all individuals choose a time to travel and the mean of transportation according to their needs and environment. E.g., one individual might take a car and go to work in the early morning, another one wakes up later and goes shopping using public transportation, etc. Travel plans are made based on road congestion; congestion in turn depends on the travel plans. To resolve this situation a standard relaxation method is used.

The street network that is used in MMTS was originally developed for the Swiss regional planning authority (Bundesamt fur Raumentwicklung) and unfortunately the road detail level is smaller than the one of [32]. [10] generated a 24 hour detailed car traffic trace file. The file contains detailed simulation of the area in the canton of Zurich, this region includes the part where the main country highways connect to the city of Zurich, the largest city in Switzerland. Around 260'000 vehicles are involved in the simulation with more than 25'000'000 recorded vehicles direction/speed changes in an area of around $250km \times 260km$.

3.3 Vehicular Infrastructure

Roadside Units (RSU) aims at providing an increased connectivity between vehicles and service provider. For example, when V2V communication is not available, or at specific hotspots of network such as dense crossroads, dangerous curve etc... It is also a wide area gateway for CA/servers when they want for example to revoke some nodes credentials and/or make some information globally available (e.g. map update etc...).
There is still no precise idea, or standard, on the topological deployment of those RSUs. Upon

literature review only some real-world testbed deployments exists, mainly in the US and Europe [8] [9] [31], their goal is to assess the feasibility of a global Vehicular Infrastructure Integration.

The market penetration will be low in the first few years, so a scalable and economically viable deployment of RSU is preferable. We believe that without deploying a large amount of RSUs, efficiency would still be good.

In [24], a first step was to deploy RSU at *crossroads* mainly for cost motivations (traffic lights, electricity). It is also assumed a communication range identical as the one of a car. Still the finding is that the proportion of isolated cars (single node cluster) does not really change when introducing RSU at crossroads. This can be explain as such: when we have traffic lights, all cars at crossroad are in any case connected through each other (via Multi-Hop).

RSUs would help Safety applications by extending connectivity, but safety applications as designed should not be dependent of infrastructure presence because their scope is mainly local and safety messaging, as explained before, would be designed upon direct vehicle to vehicle communication. But in some case it can be useful, one example, is when a car has an accident it trigger an event-message (emergency warning), upon receiving of this message other vehicle adapts their behavior and also might want to store and forward the message to closest RSU for help (call ambulance, police etc...). It could also rely on other technologies (cellular...) to call for help. Problem with those safety application is that they require a high penetration rate.

In this project we want to compare scenarios with/without RSUs and different types of RSU deployment. For this we need to find metrics to asses performance of the placement. An interesting one, would be the size of the area reachable in a 1-3 hop distance after emission of a safety message for example. More generally, the shortest path lengths might be a good indicator. Clustering coefficients tells us how close to a clique (fully interconnected) a graph or subgraph is, so for high values of this coefficient, RSU would be of no use locally.

Goal of RSU:

- provide greater connectivity by minimizing isolated clusters (i.e. clusters that are not connected to the vehicle infrastructure).
- gather traffic information
- be able to reach as many vehicles as possible
- provide shorter paths for information dissemination and hence less Multi-Hop.

We should note that some area of the networks might not necessarily need RSU coverage, it is a tradeoff between the efficiency to the network and the coast of the device.

RSU placements will be conditioned by the following measures:

1. density
2. cluster size
3. centrality

We can imagine two kind of infrastructure road side unit. The standard one where each RSU is interconnected to the infrastructure backbone, or a more lightweight and hence local one, static RSU which is not connected to the backbone infrastructure and who only act as a replay hence providing connectivity in a R range. Such local RSU could be parked cars.

Placing RSUs in the network graph is just about adding new "nodes". If local RSUs, add new 1-hop link (relay) between out-of-range nodes. If Global RSUs, add new paths between any pairs of nodes in source RSU area and sink RSU area. On a centrality analysis viewpoint adding new paths can only shorten geodesics. For very distant pairs of nodes, it is likely that geodesics goes through the RSUs backbone. Nodes on the old paths don't belong to the geodesics anymore hence their centrality decreases. Nodes around the RSUs are part of more new geodesics hence their centrality increase. And of course RSU nodes get large centrality values.

Now it comes to define where to place those RSU. Let's try to develop some placement strategies and hypothesis:

Low Density Area (LD) + interconnect isolated cars (no more 1-cluster cars), + improve global connectivity (cars that could not communicate before can now), - impact useless because only very few cars benefit of the service,

High Density Area (HD) + interconnect many very dense cluster (a lot of new connections), - locally might be ineffective (cluster viewpoint) because since it is dense every car might already have a path to any other, - Geodesics between any two nodes in different clusters is likely to go through RSU, implying bottlenecks.

Low Centrality (LC) + balance centrality (low central get more central, high central get less central)

High Centrality (HC) - high central get more central

Normalized High Centrality (HC_N) Centrality/Density. Give more importance to area which have large centrality values, even for small time compared to area with relatively slow values for long time.

Random (RD) +- random

3.4 Topology

We can consider two kind of topology: the network topology and the road topology.

Road topology First taking only topology, no traffic data, we can compute centrality for a pice of map as done by [17]. We assume a road network map, represent crossroads as nodes and roads as edges. We could compute centrality measures for each node (even edge). Edges weight values could be either *geographical distance* (and thus looking for shortest distance path), *time-related* (smallest accumulated time), or any combination. In order to analyze road topology, we need a representation of the map such as with TIGER or even likely GIS (not sure). A parser might be necessary to transform those data into graphs for computation of centrality metrics (See Future Work).

Network topology Vehicles and RSU are nodes, edges are between those nodes that are within radio range. With moving nodes, graph is subject to change frequently. Working with network topology, and from the vehicular traffic traces of the mobility models in 3.2, we try to extract informations. Centrality values can be derived by the knowledge at any time of the simulation of the tuple <Node_ID, timestamp, X_coord, Y_coord> and a fixed, binary, radio range (default is $r = 300m$), and thus we can take topology snapshots at specified time intervals (default is $1s$). We end up with a sequence of network graph $\langle G_1, \ldots, G_T \rangle$ on which we can compute some centrality metrics. We can also the development of an individuals metric over time.

Because we are not really interested in individual node value, we try to map back those value to the road layer. Because of the knowledge of the `<Node_ID, timestamp, X_coord, Y_coord>` tuple, this is easily done. For that mapping we need to divide the road map into areas. We choose to divide the map into squared grid blocks (default block size is $b = 300m$), but depending on the situation other choices can be suitable (e.g. segment in highway etc). How the mapping is done is also suitable to questions. We choose to sum centrality metrics at each timestep into the corresponding grid block at first. It would be interesting to compare centrality metrics on road topology and network topology. Does it yield to same results?

Chapter 4

Graph Theory & Centrality Analysis

The use of Centrality Analysis in Mobile Ad-Hoc Networks has seen very little attention from the research community [14], and in particular applications to VANET. Here we introduce what we believe to be relevant measures that can be used in VANET. First we refresh some knowledge of graph theory and then introduce centrality analysis theory and present those measures.

4.1 Graph Theory

Representing wireless ad-hoc networks can be made through the use of graph theory. The following just aimed to present the definitions that will be used throughout the report.
The network is modeled as a graph $G =< V, E >$ with $V = \{1 \dots n\}$ the vertex set, and $E \subseteq V \times V$ the edge set. A *vertex* represent a vehicle or more generally a mobile node in the network terminology, any of those terms refer to the same meaning. An *edge* between two vertices represent a direct wireless link in the network analogy. We say that two nodes are *direct-neighbors*, or adjacent, if and only if there is a link between them. Two nodes which are not direct-neighbors can reach each other through, if and only if there exist one or more *paths* between them. A path in a graph is a sequence of vertices such that from each vertices there is an edge to the next vertex. An example graph is shown on Figure 4.1.

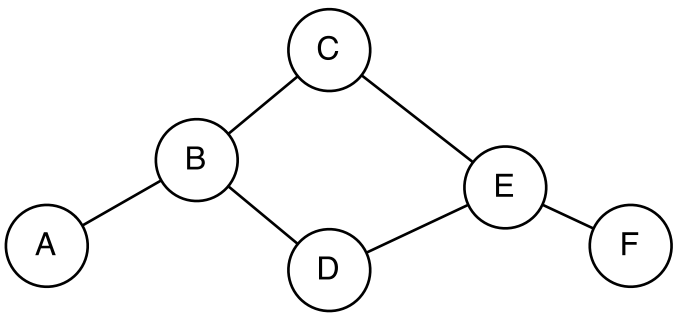


Figure 4.1: Network graph example

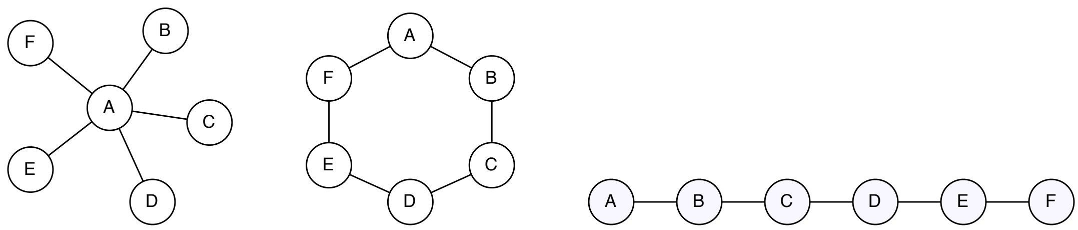
We usually represent graphs through an $n \times n$ *adjacency matrix* M. The graph is said to be *connected* if there is a path between any pair of nodes, otherwise it is *disconnected*. Graphs may be *undirected*, meaning that there is no distinction between the two vertices associated with each edge, or its edges may be *directed* from one vertex to another. The degree of a node n_i in a graph G is the number of edges in G that have n_i as endpoints. We speak about neighborhood or *k-neighborhood* set of a node n_i, as all nodes such that $d(n_i, n_j) \leq k$ *hops* .

4.2 Centrality Analysis

Social Networks Analysis is used to describe relation among individuals and groups. It make use of graph theory, mainly, in order to identify "most important" actors in a social network. This definition of importance has been a vast research field for more than 50 year and has yield to the definition of many different metrics that measure properties of an actor location in a social network. Interested readers about Social Networks Analysis should look towards [34].

This study focus on nondirectional relation (i.e. undirected graphs) for simplicity reason, assuming a two way directional communication between pair of nodes, but keeping in mind that extension to directional relation (i.e directed graphs) is possible. Among the centrality metrics discussed, one can always look at the *actor index* which attempt to quantify the importance of a single individual (node) in the network, or through aggregation of actors indices yielding a *group-level index* in the goal to summarize how variable or differentiated the whole set of actors is with respect to a given measure.

In Centrality Analysis it is common to refer to standard graphs shown on Figure 4.2 since the actors and group centrality greatly varies in those graphs. A quick look shows that in 4.2(b), all nodes are equally interchangeable and hence should be equally central, in 4.2(a) one node completely outranks the others (which are interchangeable), and in 4.2(c) centrality decrease for peripheral nodes.



(a) star (b) circle (c) line

Figure 4.2: Network graphs illustrating Centrality

4.2.1 Definition

The definition of "most important" actors is quite ambiguous, but the work of Freeman [19] is considered as the main definition. An actor is considered to be central, or equivalently prominent, if the ties it has make the actor especially more visible than the other actors in the networks . Hence in a nondirectional network of g actors, actor's i prominence is based on the pattern of the $g-1$ possible ties it has with the other actors. For directional relation, actor's i prominence is based on the pattern of the $2(g-1)$ possible ties. Nevertheless as we'll see later on some specific definitions, it will also take into account choices made by intermediaries in the centrality computation.

Actor Centrality Prominent actors are those that are extensively involved in relationships with other actors, being then more visible. Being the recipient or the source of the tie is not a concern, the actor being simply involved in the relation. So naturally the focus is first on nondirectional relations since there is no difference between source and recipient. Hence in nondirectional relation, a central actor is one that is involved in many ties.

The work of [19] yield to the use of the casual notation when it come to actor centrality measures. C is a particular centrality measure, which will be a function of n_i, where subscript index i range from 1 to g. As there is different version of centrality, C will be subscripted with an index for the particular measure under study. Then centrality measure A of node i is $C_A(n_i)$.

Group Centralization Combining actors index in one group-level measure allow us to compare networks between each other. The group-level quantity is an index of centralization, and identify how variable or heterogenous the actors centralities are. It can also be seen as a measure of how unequal the network is. For example, the larger the group index is, the more likely there is one single very central actor in the network whereas other actors are considerably less central (for example by being in the periphery of the network). Going back to the examples on Figure 4.2, star graph is maximally central because one central actor has ties with all other actors (which do not have any other ties). We define $C_A(n^*) = max_i C_A(n_i)$ as the largest value of index A among all actors in the network. The general group centralization index, called Freeman's index, is:

$$C_A = \frac{\sum_{i=1}^{g}[C_A(n^*) - C_A(n_i)]}{max\sum_{i=1}^{g}[C_A(n^*) - C_A(n_i)]}$$

where $max\sum_{i=1}^{g}[C_A(n^*) - C_A(n_i)]$ is the theoretical maximum possible sum of differences in actor centrality. This maximum being taken over all possible graphs of g actors. It can be demonstrated, that this maximum occurs for the star graph. This Freeman's index then leads to quantity between 0 and 1. C_A is 0 when all actors have equal centrality index, and is 1 if one actor completely dominate the others (as in star graph).

4.2.2 Measures

Here we list the main measures of interest that are widely that can be used in network analysis.

Degree Centrality

Simplest definition of centrality is that central actors are the one that have the most ties in the network graph, we say that there are the most active. Looking at the star graph, one node has $g - 1$ ties with all other actors, whereas the remaining have only 1 tie to the first actor. The first actor is the most active and hence maximally central. Circle graph has no actor more active than any other, so all have same centrality index. The Actor-degree centrality index is defined as:

Actor Degree index:

$$C_D(n_i) = d(n_i) = \sum_j x_{ij} = \sum_i x_{ji}$$

where $x_{ij} = 1$ if there is a link between nodes n_i and n_j. The measure is usually standardized with:

Standardized Actor Degree Index:

$$C'_D(n_i) = \frac{d(n_i)}{g-1}$$

Actors with high level of centrality, measured by degree, should be recognized as where the action is in the network. Thus this measure focus on the more visible actors in the network. According to the standard definition of group-level index, the group degree centralization index is then:

Group Degree Centralization Index:

$$C_D = \frac{\sum_{i=1}^{g}[C_D(n^*) - C_D(n_i)]}{max\sum_{i=1}^{g}[C_D(n^*) - C_D(n_i)]} = \frac{\sum_{i=1}^{g}[C_D(n^*) - C_D(n_i)]}{(g-1)(g-2)}$$

It is 1 for star graph, and zero in a circle graph. There is also other indices based on degree such as graph density or variance of degrees [34].

Closeness Centrality

Another view of actor centrality is based on closeness or distance. It focus on how close one actor is from the other. The idea is that an actor is central if it can quickly interact with all others. Actor closeness index is a function of the geodesic distances. As geodesics increases, so decrease the centrality. Note that this index does not only depend on direct ties but also on undirect ties. Define $d(n_i, n_j)$ be the number of links between n_i and n_j. Total distance for actor n_i to other actors in the network is $\sum_{j=1,j\neq i}^{g} d(n_i, n_j)$. Thus actor closeness index is:

Actor Closeness Index:

$$C_C(n_i) = [\sum_{j=1,j\neq i}^{g} d(n_i, n_j)]^{-1}$$

Standardized Actor Closeness Index:

$$C'_C(n_i) = \frac{g-1}{\sum_{j=1,j\neq i}^{g} d(n_i, n_j)} = (g-1)C_C(n_i)$$

It can be seen as the average distance between actor i and all others actors. It is 1 when i is adjacent to all others.

Group Closeness Centralization Index:

$$C_C = \frac{\sum_{i=1}^{g}[C'_C(n^*) - C'_C(n_i)]}{[(g-2)(g-1)/(2g-3)]}$$

The main drawback of this index is that it is only meaningful for a fully connected graph! In order to overcome this, [16] propose an interesting approach that circumvents the problem of disconnectedness. It offers the possibility to compute closeness centrality in both connected and disconnected symmetric networks, and is based on the original Freeman's index, but also includes information about how an actor is not connected to others.

Betweenness Centrality

Betweenness centrality, in which most central nodes are the ones that are on many shortest path of any nodes pair. It seems very suitable for investigation in VANET since wireless communication tends to opt for shortest path, this could give us information about where does the communication flows. A fundamental assumption is that all geodesics (i.e. shortest paths) are equally likely to be used. The following Actor index are used:

Actor Betweenness index:

$$C_B(n_i) = \sum_{n_s \neq n_t \neq n_i} \frac{g_{st}(i)}{g_{st}}$$

Standardized Actor Betweenness index:

$$C'_B(n_i) = \frac{C_B(n_i)}{(G-1)(G-2)}$$

with g_{st} number of geodesics linking node s and node t, $g_{st}(n_i)$ number of geodesics linking the two actors that contains actor i, and G being the total number of actors G. Actor Betweenness index is an unbounded number whereas Standardized Actor Betweenness index range in $[0, 1]$ with 1 when node is maximally central (e.g. middle node in a star graph) and 0 if it on no geodesics (e.g. edge node in star graph).
In order to measure the centrality on the whole graph, we introduce:

Group Betweenness Centralization index:

$$C_B = \sum_{i=1}^{G} \frac{[C'_B(n^*) - C'_B(n_i)]}{(G-1)}$$

with $C_B(n^*)$ largest realized Actor Betweenness index for the set of actors. Group Betweenness index allow to compare different networks with respect to the heterogeneity of the Betweenness centrality of the members of different networks. Maximum value, unity, is reached for a star graph. Minimum value, zero, occurs when all actors have the same actor betweenness index (e.g. a circle graph).

Others

Flow betweenness [26], as an alternative to classical betweenness, can also be another opportunity if we assume, that communication does not travel through geodesic paths only. This index can include non-geodesic path as well as geodesic paths. Path metrics can be in term of distance, time (speed limit, traffic free flow), or road segment utilization cost (e.g. toll).
Information Centrality which relates the node centrality to the ability of the network to respond to its deactivation. For example, when looking at attacker possibilities if we are able to build a network such that each node has as small as possible information centrality meaning that no nodes is essential to the well behavior of the network. And thus under a jamming attack, the global efficiency of the network is not affected. Global efficiency [17], as the inverse average shortest path length between any two nodes, is measure of how well the nodes communicates over the network

Dynamic Networks & Temporal Betweenness Centrality

[22] propose methods to measure betweenness in time ordered networks. Focus on timing aspects, introduction of betweenness with respect to temporal path, i.e.paths upon "aggregation" of snapshots. Importance of a node is not only on its position with respect to geodesics but also at which time it appear on the geodesics.

Dynamic Network: series $\langle G_1, \ldots, G_T \rangle$ of static networks with G_t snapshot at time t. $(G = (V, E), \lambda)$ is a dynamic network with λ time labeling function. Called multigraph.

Temporal paths: it is a *(strict) time respecting* path in the multigraph (i.e. time labels are increasing).

Geodesics: length of the shortest temporal path. If there is no delays then $d(u, v)$ is the number of edges on the path $p(u, v)$ otherwise it is the time difference of the first and last interaction $d(u, v) = \lambda(v_{n-1}, v_n = v) - \lambda(v_0 = u, v_1) + 1$.

Shortest Simple Temporal Path: $p_s(u, v)$ temporal paths with each individual present at most once and geodesics with delays.

Shortest Link path: $p_l(u, v) = min|p_s(u, v)|$.

Shortest Temporal Trails measure the ratio of time spent on an intermediate node to the total length of the path. Same as Shortest Simple Temporal Path, but same individual can appear multiple time.

Betweenness:

1. **Temporal Betweenness Centrality**: importance of individuals based on their position in the shortest temporal path of all other nodes.
   - g_{st} number of shortest temporal path between s and t
   - $g_{st}(v)$ number of shortest temporal path between s and t that pass through v.
   - TBC of v is

$$B_T(v) = \sum_{s \neq t \neq v} B_{T(st)}(v) = \sum_{s \neq t \neq v} \frac{g_{st}(v)}{g_{st}}$$

2. **Delay-Betweenness Centrality**:
   - nst_{st} number of shortest trails from s to t.
   - $nst_{st}(v)$ number of time steps of delay of v that all shortest trails from s to t.

- DBC of v is

$$B_D(v) = \sum_{s \neq t \neq v} B_{D(st)}(v) = \sum_{s \neq t \neq v} \frac{nst_{st}(v)}{nst_{st}}$$

Chapter 5

Experiments

Once we get hand on some vehicular traces of interest we aim at computing some centrality and connectivity related metrics

5.1 Toolkit

Being a follow up of the work of [24], we tried to push it too a more realistic analysis. Using SUMO [5] is nice to test some connectivity issues, and design experiments, our goal of computing centrality measures can only be relevant for a realistic behavior of vehicles. That's why we did not pursue working with SUMO and preferred realistic traces. Vehicular traces are generated in NS2 format, hence allowing them to be later incorporated in tools such as TraNS, and in order to treat them with *Matlab* they need to be processed and sampled in order to get a matrix of position for each time step.

We used *Matlab* as a tool of choice in this project for the analysis of any mobility traces. Computation of centrality measures is not straightforward into *Matlab*, but the use of specific social network analysis tools such as UCINET [7] is not appropriate since they do not handle well large sets (>500nodes), and we like to keep it simple into one single framework. Hopefully, the existence of *Matlab Boost Graph Library* [4], does a great job in helping to compute graph metrics and extend our toolkit with nice graph theoretic features. Moreover it provide the ability to compute betweenness centrality in a very efficient way.

If you are interested in the *Matlab* Toolkit or centrality data just ask me.

5.1.1 Datasets

GMSF

Generic Mobility Simulation Framework (GMSF) from [32] is a mobility traces online generator (`http://polar9.ethz.ch/gmsf/`).
The choice of the following parameters is possible:

- **Mobility Model**: GIS, MMTS, Manhattan (not used) and Random Waypoint (not used)
- **Scenario**: rural, urban, city
- **Number of Nodes**

- **Simulation Time**

The output traces generated can have different formats such as NS-2, NAM, Qualnet/Glomosim or a generic XML file format. We used only NS-2 output format for ease of processing with *Matlab*. GMSF data are from Zürich region area. All scenario map have a $3000m \times 3000m$ area and the following default number of nodes: `rural=100`, `urban=420`, `city=880`.

(a) rural (b) urban (c) city

Figure 5.1: GMSF maps

We choose to work with two different type of mobility models: the GIS-based[1] mobility model and the MMTS model. The GIS models implements a basic car-following mechanism using the Intelligent-Driver Model (IDM) [33]. Additionally, major road intersections are controlled by a simple traffic light model, so in the end we have:

- `GIS-noCF-noTL` GIS model without car-following module and without traffic lights module
- `GIS-CF-noTL` GIS with car-following module
- `GIS-CF-TL` GIS with car-following module and traffic lights module
- `MMTS` Multi-Agent Microscopic Traffic Simulator model

More details about them can be found in 3.2. In order to easily identify results, data files uses the following nomenclature:

`gis-rural-n100-r300-b300-noCF-noTL`
`=`
`<mobility_model> - <type_of_map> - <nb_of_nodes> - <node_communication_range> - <block_size> - <car_following_model> - <traffic_light_model>`

5.2 Density and Centrality Localization (DCL)

This first experiment is the starting point of our study, it aims at localize dense and central regions in a specific vehicular network of interest based on the traffic traces we could observe. The map is divided in grid blocks for the sake of simplicity but any other discrete form could

[1]Swiss geographic information system

be used (e.g. in a highway scenario, chunk road in segments). Whereas finding dense regions is almost straightforward as we only sum the number of cars that happens to be in a specific block, computations of central regions is more complex because we need first to compute centrality index for all actors at each time step and convert it logically to the block level (e.g. with a sum). For now on, we classified blocks according to the sum of Betweenness Centrality Actor Indices (see 4.2.2).
The experiments results for each combination of maps, mobility models, and vehicular networks settings in the GMSF framework can be found in appendices A to C.

Subfigures A.1(a) to **??** show nodes positions and wireless connectivity at a specific time step ($t = 500$). A *Matlab* animation would help to visualize the continuous flow of moving vehicles. Subfigures A.1(b) to **??** ranks blocks according to vehicle density averaged throughout whole simulation time. Subfigures A.1(c) to **??** ranks blocks according to the sum of Betweenness Centrality Actor Indices. Subfigures A.1(d) to **??** ranks blocks according to Betweenness Centrality Actor Index per vehicle averaged on the whole simulation time. Figure 5.2 represents the rural map scenario with car-following and traffic lights model disabled. Others graphs are in the appendix A.

5.2.1 GIS rural

Figures A.1 to A.3 represents the rural map scenario under the three different GIS-based mobility models. Due to a major intersection in the rural scenario at the middle of the map, with no surprise this intersection is the most dense but also the most central. It is to note that with the addition of the car following and the traffic light model, cars tend to group together toward the main intersection.

5.2.2 GIS urban

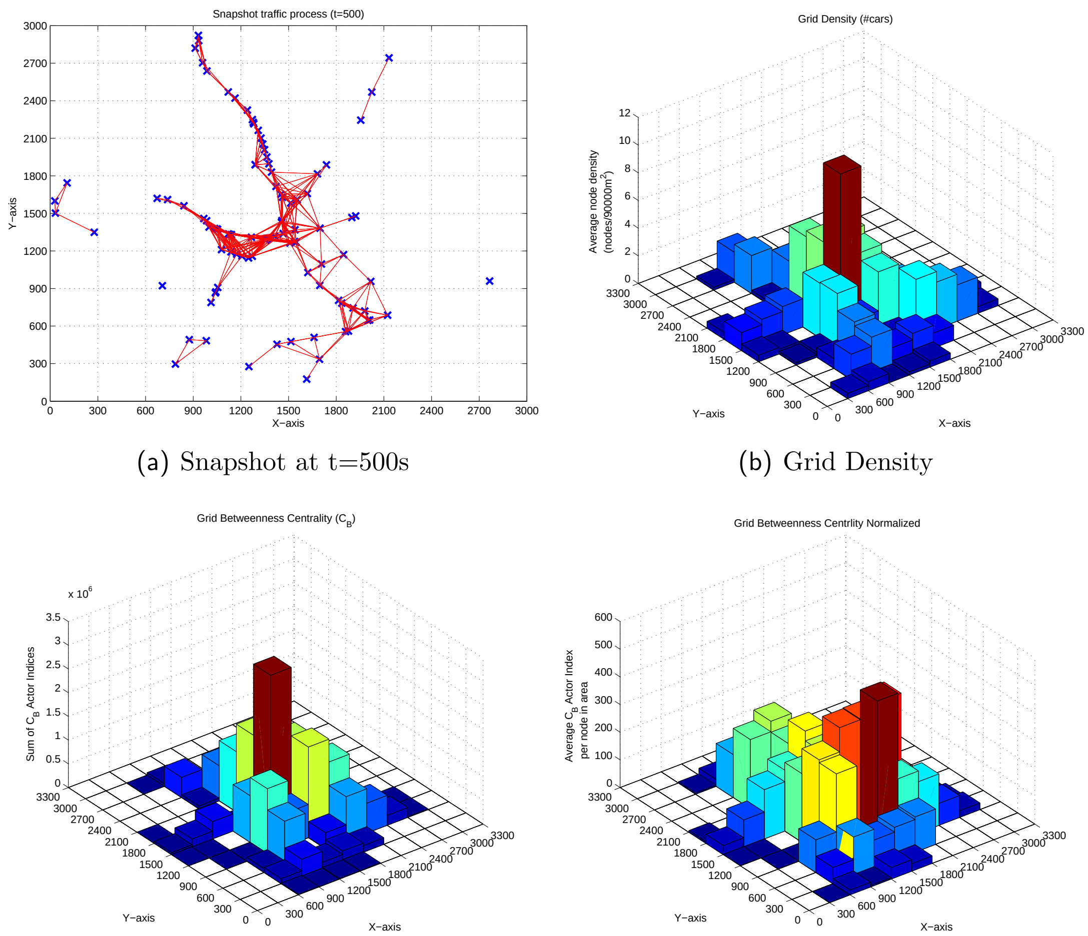
In the urban scenario (Figures A.4-**??**), the previous observation still holds, nodes are regrouped towards major intersections with addition of the car following and traffic light models. Contrary to rural scenario, where there was one main intersection, here the diversity of paths is much bigger and central blocks are more uniformly distributed on the map.

5.2.3 GIS city

In city scenario (Figures **??**-**??**), there is a strong congestion effect with car following and traffic light model.

5.2.4 others

Relation between density and centrality is not very clear. For example, two grid blocks having the same amount of centrality but one with high density and the other with low density have completely different meaning. We should favor the second one if we are strictly looking at centrality, because in that case we would have a very small amount of car each heaving large actor index. Also very dense area are likely to have limited betweenness centrality (at least on a node basis) since most of those nodes are directly connected. This is confirmed by looking at the plots, in all case top dense area is different than the top central (normalized betweenness).



(a) Snapshot at t=500s

(b) Grid Density

(c) Grid Betweenness

(d) Grid Betweenness Normalized

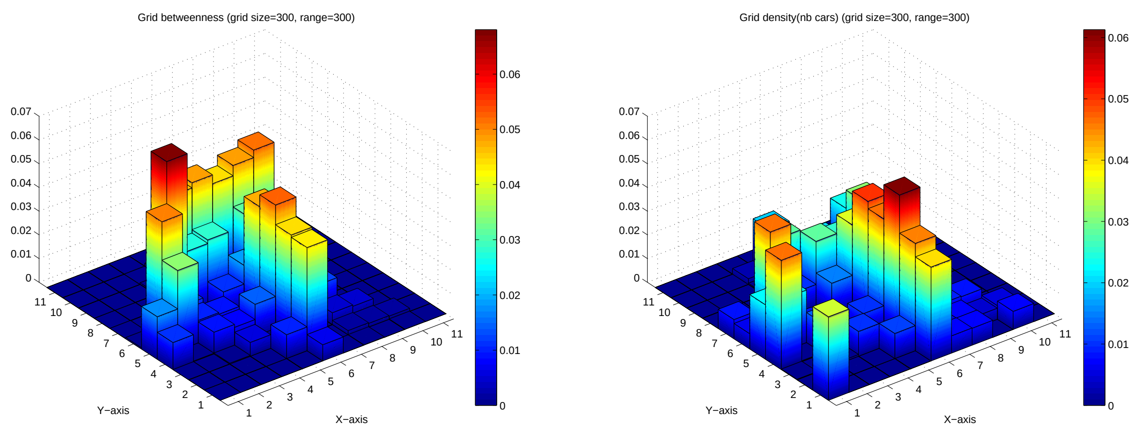
Figure 5.2: GIS-rural-n100-r300-b300-noCF-noTL

If we look at the Normalized Betweenness subfigures (A.1(d)-A.3(d) and A.4(d)-**??**), in both rural and urban scenario, the behavior is interesting. The centrality per vehicle is also more uniformly distributed on the whole map.

The GIS models used restricts node movements along the exact course of roads. The car-following model and the traffic light model do not influence the area covered by node movements but introduce hotspot regions with higher node densities in the center and in the proximity of traffic lights. As done by [32], we can also observed, for a reduced block size ($50m \times 50m$ instead of $300m \times 300m$) that enabling the car-following model has no large effect on the number of nodes per unit square. Yet, traffic lights in the GIS model increase the clustering of nodes and lead to a similar node density as can be found with MMTS model.

So centrality and density are not necessarily related. In the case of Betweenness centrality and to describe what explained at the previous paragraph let's look at the following example. As in figure 5.3 a few connected cars on a rural road might be in "between" (hence the term) large clusters of cars (highways), communication flows would thereof go through those rural cars. If those cars would be replaced by RSU, then information flows would be permanent and hence connectivity could be enhanced.

Figures 5.4 and 5.5 represents the total mean betweenness centrality actor index value over the simulation time.

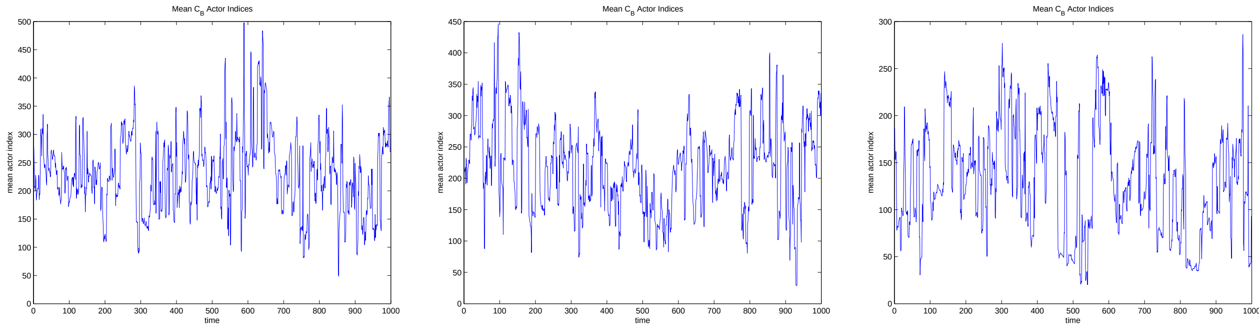


(a) Grid Betweenness (b) Grid Density

Figure 5.3: MMTS-unterstrass-n7797-t736-r300-b300

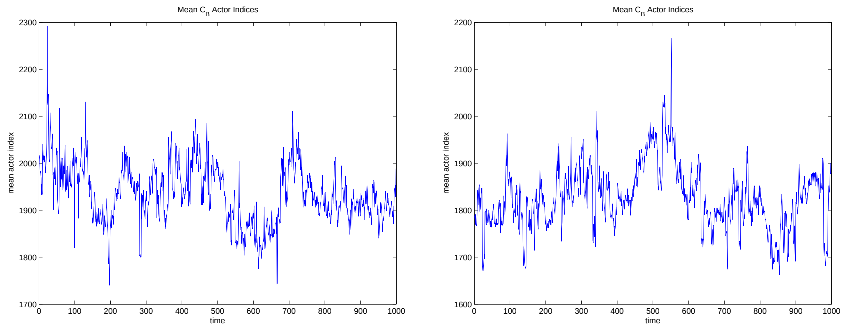
5.3 Multi-Hop Dissemination (MHD)

We set up the Multi-Hop Dissemination (MHD) experiment with the following idea in mind. Assuming a safety situation, such as an accident, where some node would have to broadcast a safety message advertising other nodes to change trajectory or slow down. How far could the communication go? That is to how much nodes can the message be disseminated. The goal is not to flood the network so we restrict the message time-to-live to 1 to 3 hops (too much Multi-Hop is not desirable in VANET), hence considering 1-3 hop neighborhood.



(a) noCF-noTL (b) CF-noTL (c) CF-TL

Figure 5.4: Rural setting: Mean Betweenness Centrality Actor Index



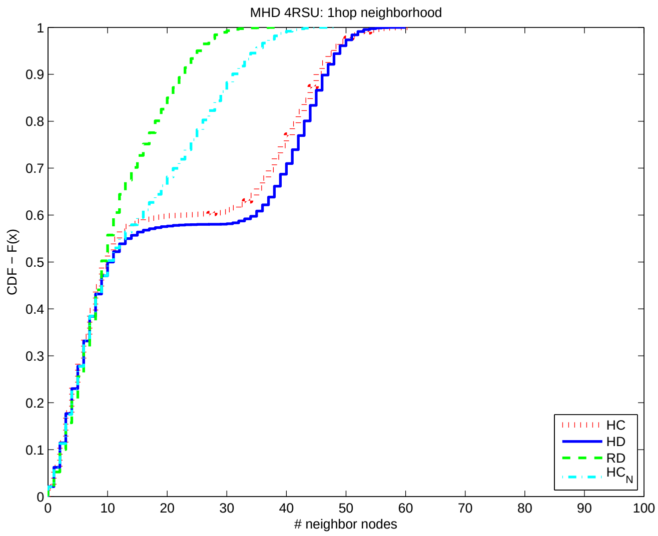
(a) noCF-noTL (b) CF-noTL

Figure 5.5: Urban setting: Mean Betweenness Centrality Actor Index

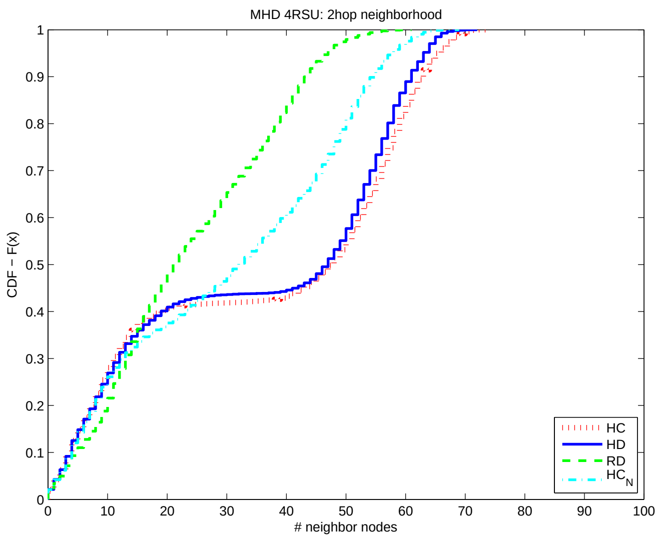
Then using information from the previous experiment where we found top dense/central blocks for a map, does having road side unit nearby help in the dissemination? We used simple strategies described in 3.3 for the placement of RSUs. A common hypothesis is to place road side units at very dense places. We argue that central places might also be interesting since by definition those are the place that do "see" a lot of communication flow.

In appendix B we shows the distribution of the dissemination for all scenarios (rural, urban, city), all mobility models(noCF-noTL, CF-noTL, CF-TL) and for different RSUs number (4 to 10). Cumulative Distribution Function (CDF) is on the Y-axis and the number of spread neighbors on the X-axis.

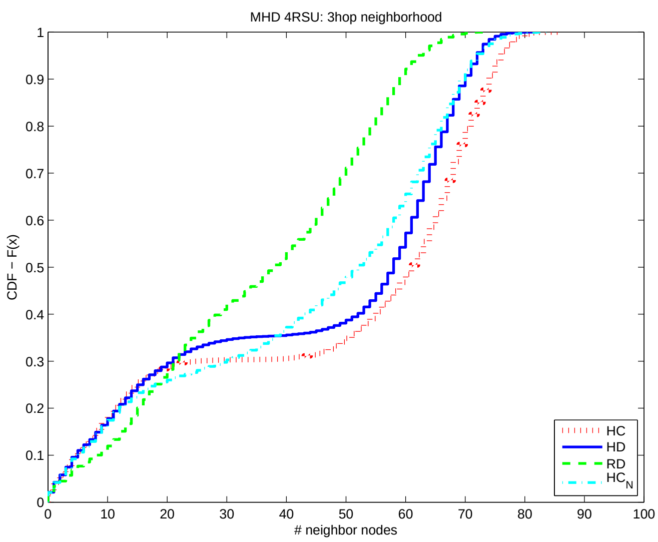
Figure 5.6 shows Rural-noCF-noTL scenario with 4 RSUs. Other figures are in appendix B. With increasing neighborhood HC does as well as HD and even better in the 3hop-neighborhood. But the difference is very small if not negligible, for example, 90% of the nodes in HD have a neighborhood of 70 nodes or less whereas 90% of the nodes in HC strategy have a neighborhood of 75 nodes or less. With the addition of more RSUs, the difference is even reduced, and all strategies seems to have a similar distribution. This is due, too the fact that the set of dense blocks and central ones (in both HC and HC_N) become similar as we increase the number of RSU we want to place, and also that with more and more RSUs of quite large transmission



(a) MHD with RSU: 1hop neighborhood



(b) MHD with RSU: 2hop neighborhood



(c) MHD with RSU: 3hop neighborhood

Figure 5.6: 4RSUs MHD-gmsf-rural-n100-r300-b300-noCF-noTL

range ($300m$) a good part of the map is covered.

HC_N to add more value to those blocks that have a large centrality contribution even for a small time, and we see that with increasing neighborhood it does very fast as well as HD and HC.

Those observation are also valid for Rural-CF-noTL scenarios (Figures B.5-B.8) and Rural-CF-TL scenarios (Figures B.9-B.12).

In the 3 Urban scenarios, difference between HD and all others is much more stronger, and curve show some more "wild" behavior. Also in all case the neighborhood is much more uniformly distributed.

We can think that for small density maps such as rural or country side areas, Centrality strategies can perform as well as Density whereas for large density maps such as a city/downtown it does not. Moreover using Centrality related strategies definitely offers advantage with respect to communication flows.

5.4 Distance to Infrastructure Backbone (D2B)

It is desirable that communication does not rely too much on Multi-Hop. Therefore a placement of Road Side Unit would be one such that the distance of each vehicle to the infrastructure is minimal. In this experiment we want to see "how far" from infrastructure backbone are the nodes. For this we measure the shortest distance in hops to any RSUs.

Appendix C contains histograms of distances to the infrastructure for all scenarios. Again by placing RSU at dense areas, the minimal distance of one hop is obtained for a majority of nodes, centrality is also close.

Chapter 6

Conclusions and Future Work

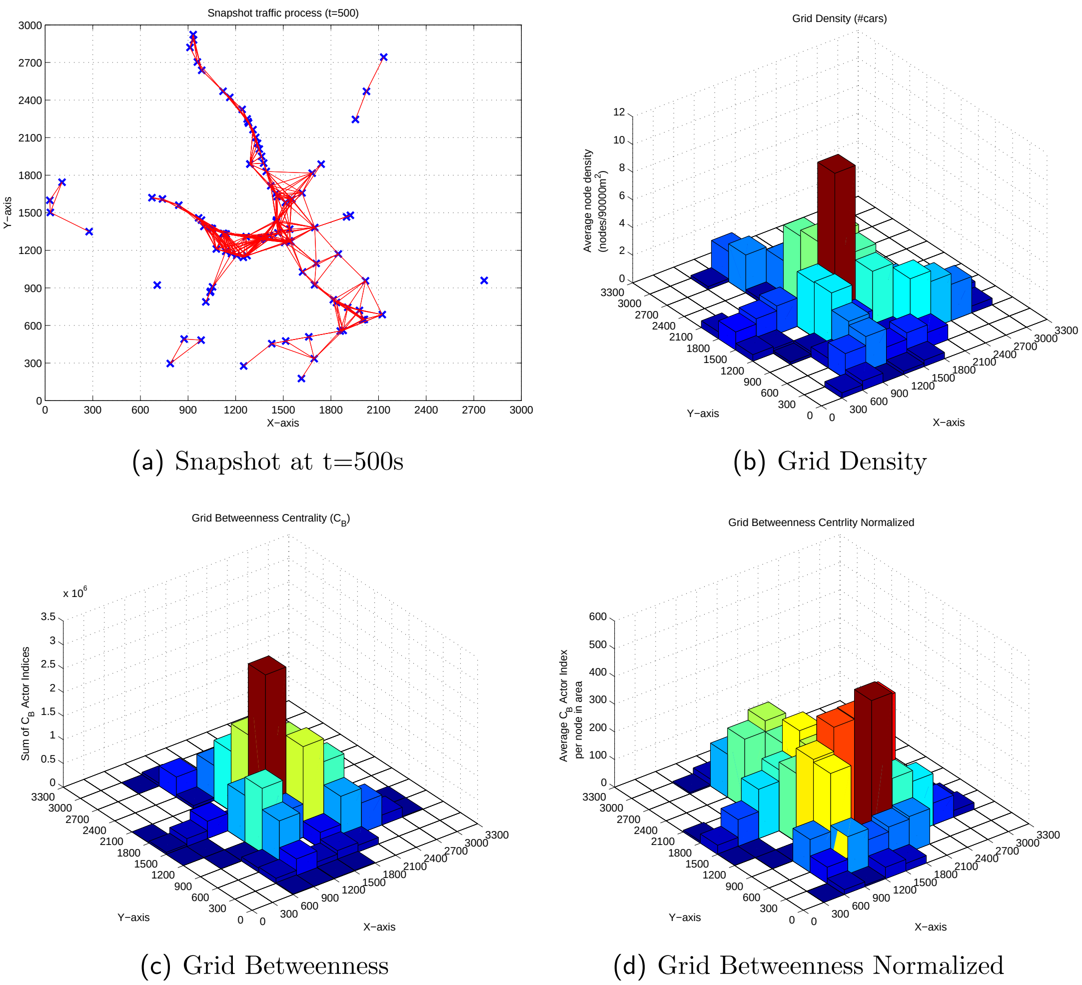
In this project we showed how the theory of social network analysis and mainly centrality analysis could be use in Vehicular Ad Hoc Networks. From the literature review, even though centrality analysis was a hot topic for many years, very few have used it for mobile networking purpose. In order to find the gap, we focused on the integration of centrality analysis in VANET and related topics such as connectivity analysis. We proposed to analyze centrality in VANET from different perspective being a network topology layer or a road topology layer. For this we took care of having relevant traffic data and also analyzed different kind of mobility models. The computation of different centrality measures (betweenness, closeness, degree...) allowed to us to design Road Side Units placement strategies.
In the end it turned out that centrality metrics would not perform much better than strategies based on density, meanwhile it can also offers acceptable performance while also offering interesting characteristics. For example, communication flow monitoring based on betweenness centrality.

We still want to see in the future a game theoretic approach between attackers (jammers...) and law enforcement organization. In the mean time a lot can still be done. First of all, we only looked at high central or high dense places, but it would be interesting also to have a look at lower places or any combination thereof and see what effect it could have.
New Strategies could be derived by the use of other centrality measures, especially the closeness one. Not restricting to [32] data, it would also be interesting to have a look at the traces from MMTS model (the P.Sommer ones and the [10] original ones). Finally we miss the comparison between centrality of the network topology layer and the road topology layer. For the latter we would need to have graph representations of maps. Since it is based on GIS data, it is likely possible to design such a tool that would convert the map into a graph in order to perform centrality analysis.

Appendix A

DCL Results

A.1 Rural setting



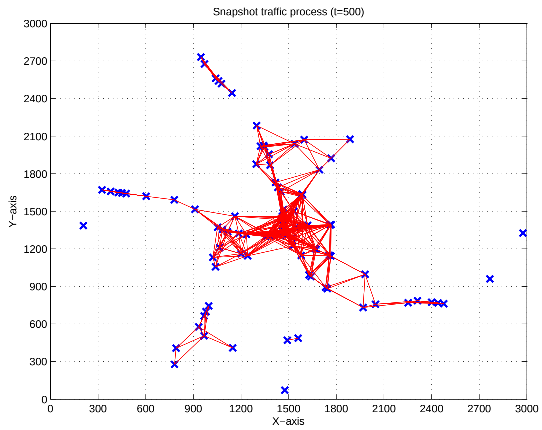
(a) Snapshot at t=500s

(b) Grid Density

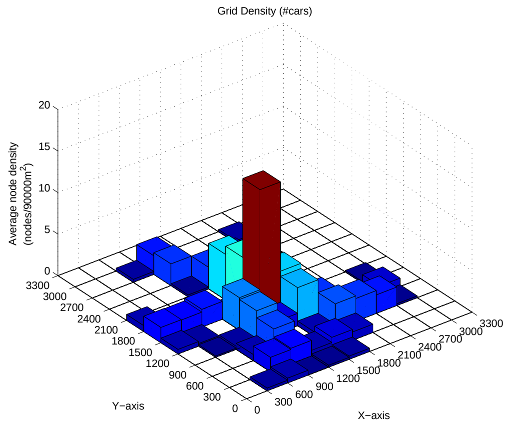
(c) Grid Betweenness

(d) Grid Betweenness Normalized

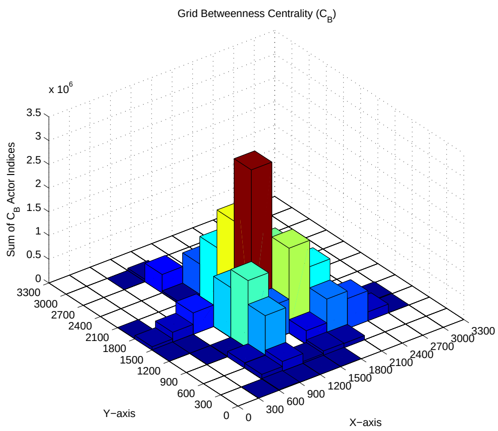
Figure A.1: GIS-rural-n100-r300-b300-noCF-noTL



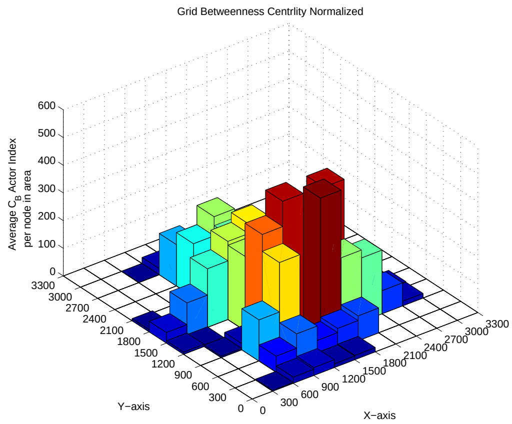
(a) Snapshot at t=500s



(b) Grid Density

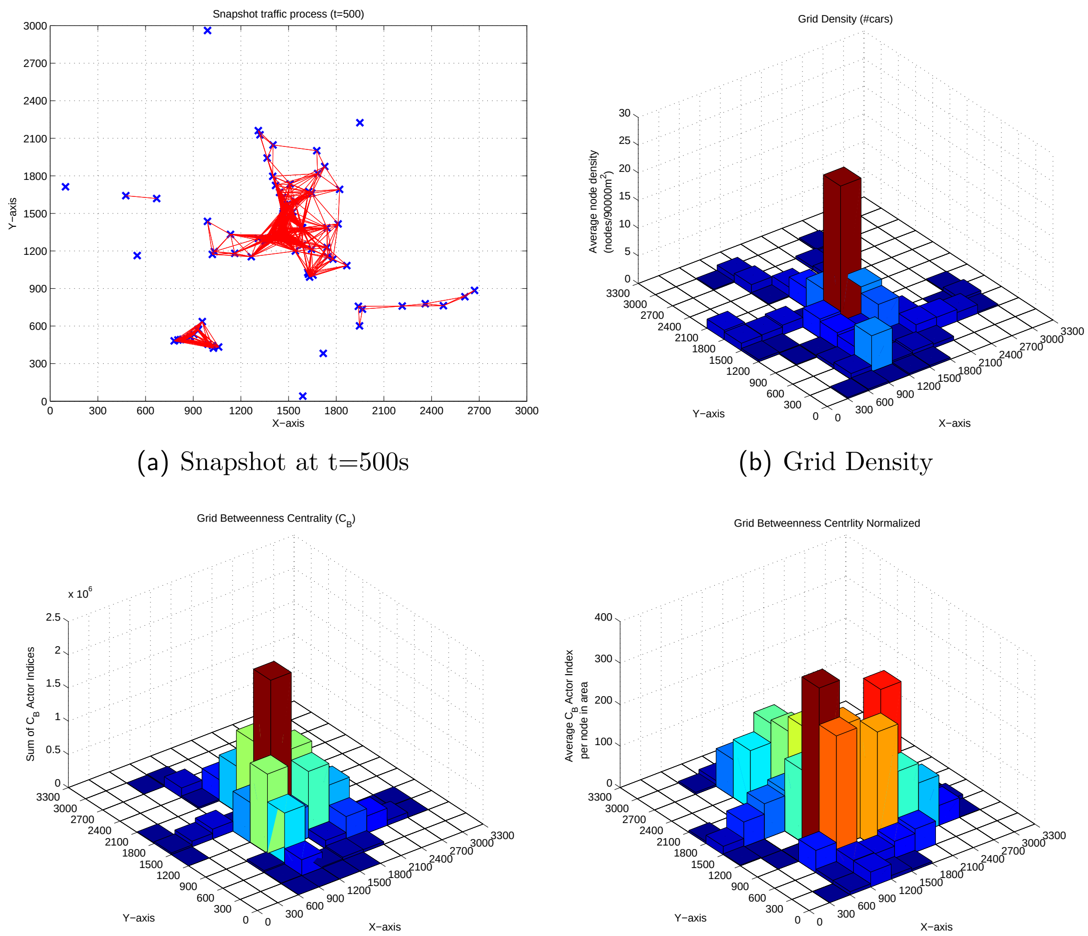


(c) Grid Betweenness



(d) Grid Betweenness Normalized

Figure A.2: GIS-rural-n100-r300-b300-CF-noTL

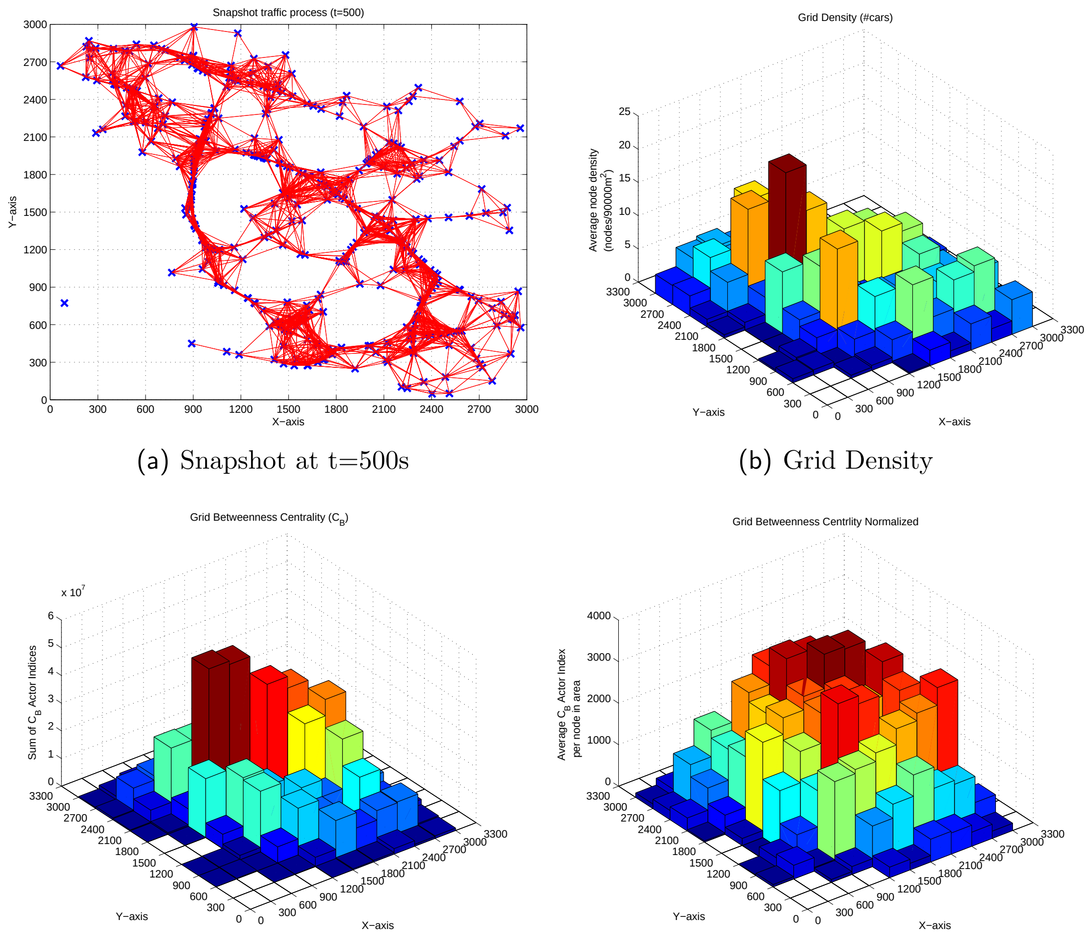


(a) Snapshot at t=500s (b) Grid Density

(c) Grid Betweenness (d) Grid Betweenness Normalized

Figure A.3: GIS-rural-n100-r300-b300-CF-TL

A.2 Urban setting



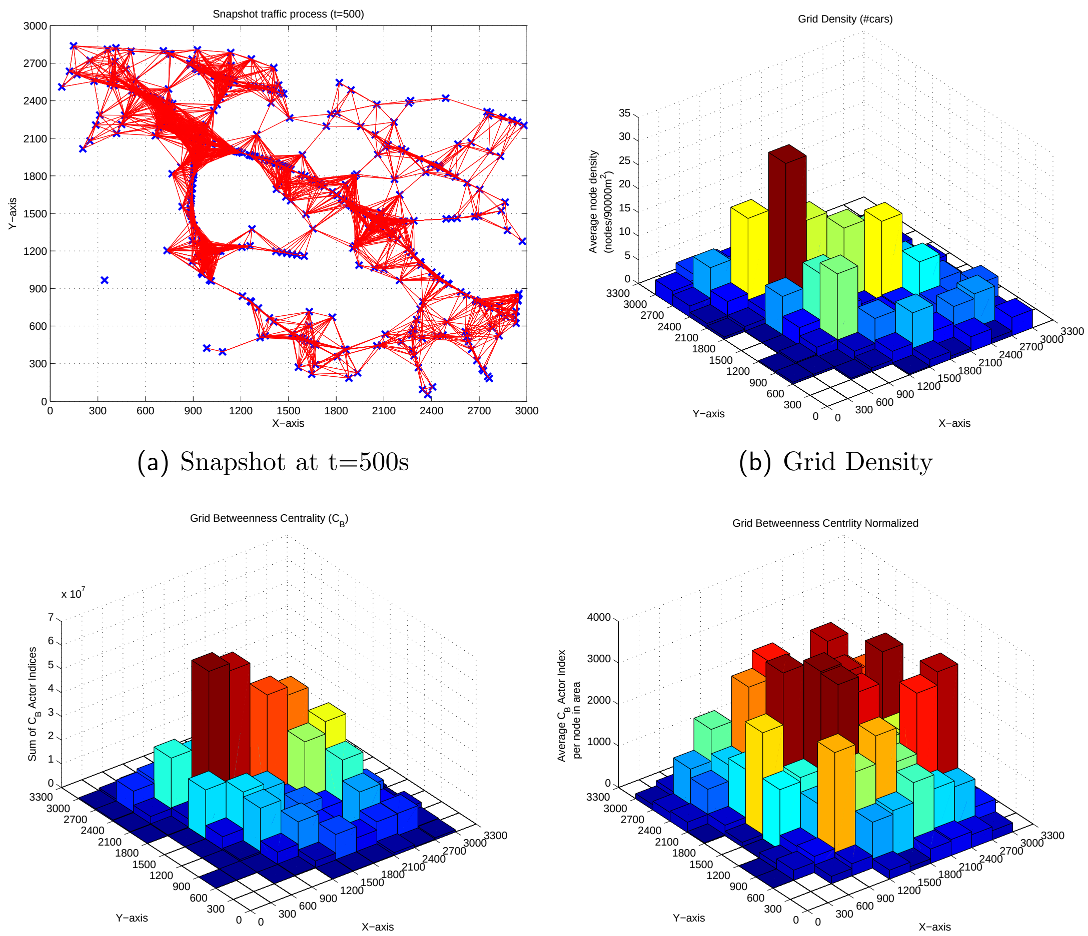
(a) Snapshot at t=500s

(b) Grid Density

(c) Grid Betweenness

(d) Grid Betweenness Normalized

Figure A.4: GIS-urban-n420-r300-b300-noCF-noTL



(a) Snapshot at t=500s

(b) Grid Density

(c) Grid Betweenness

(d) Grid Betweenness Normalized

Figure A.5: GIS-urban-n420-r300-b300-CF-noTL

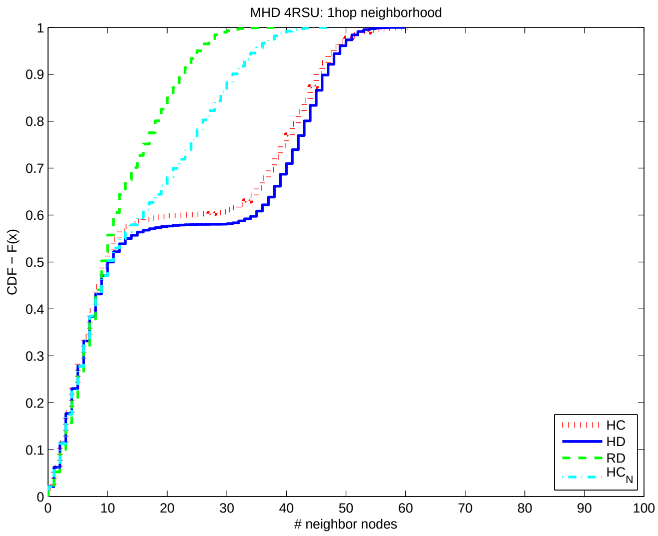
A.3 City setting

Appendix B

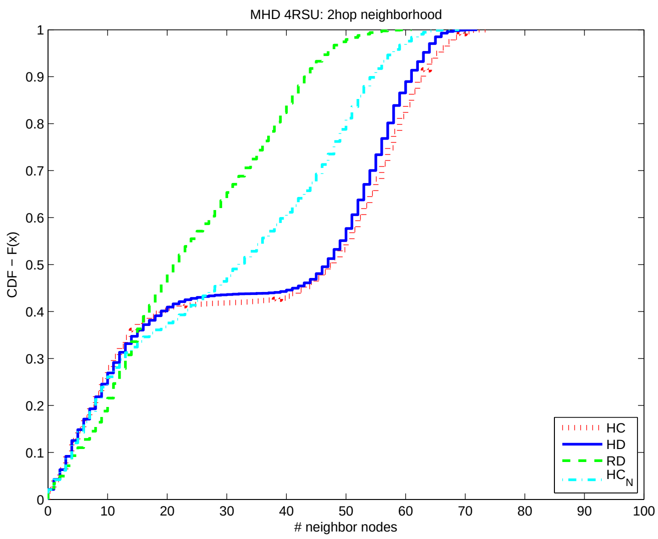
MHD Results

B.1 Rural setting

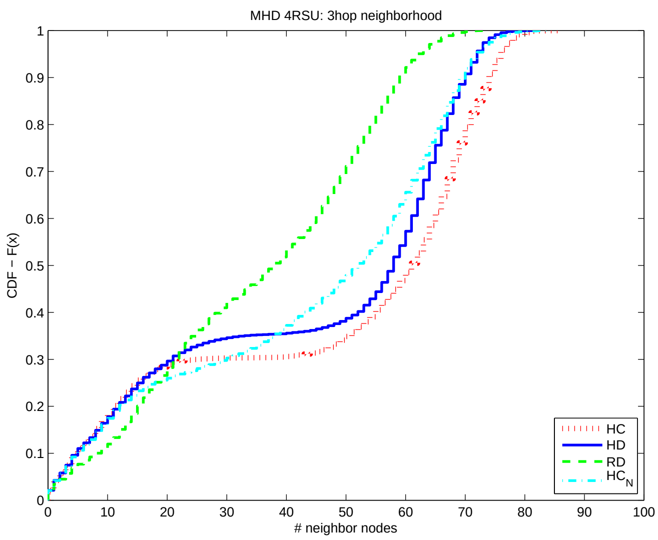
B.1.1 noCF-noTL



(a) MHD with RSU: 1hop neighborhood

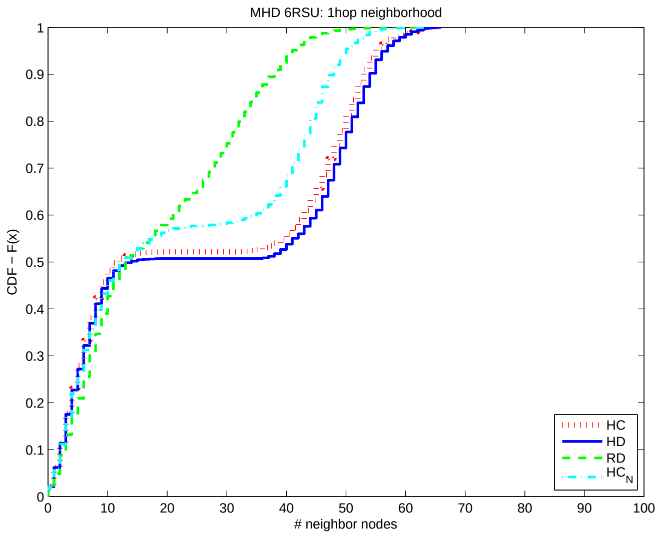


(b) MHD with RSU: 2hop neighborhood

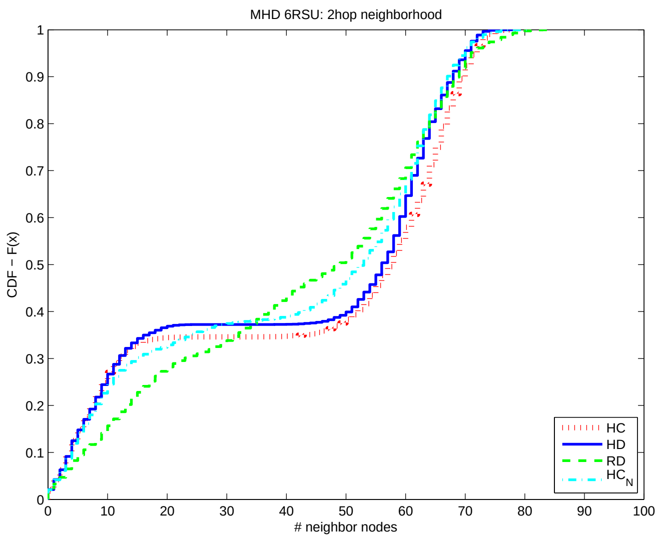


(c) MHD with RSU: 3hop neighborhood

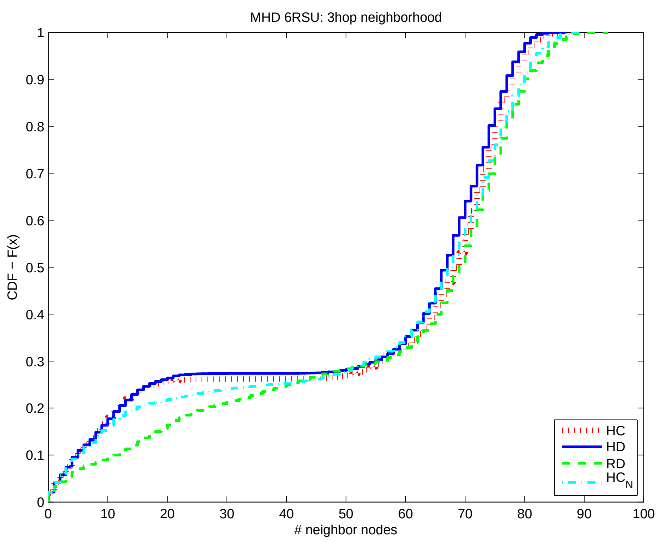
Figure B.1: 4RSUs MHD-GIS-rural-n100-r300-b300-noCF-noTL



(a) MHD with RSU: 1hop neighborhood

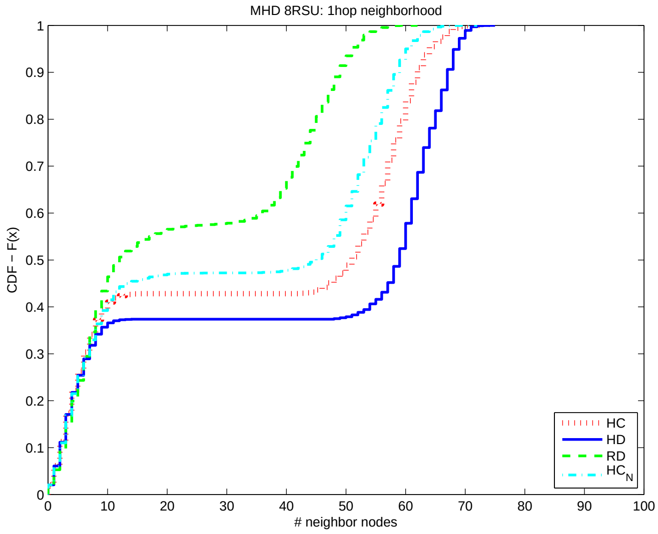


(b) MHD with RSU: 2hop neighborhood

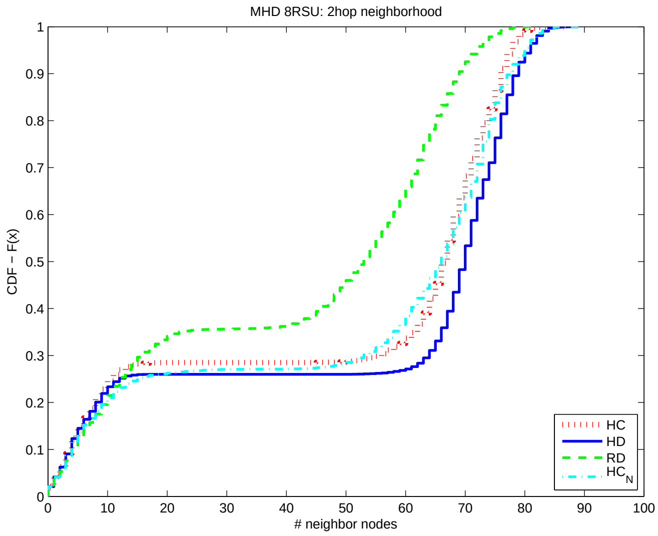


(c) MHD with RSU: 3hop neighborhood

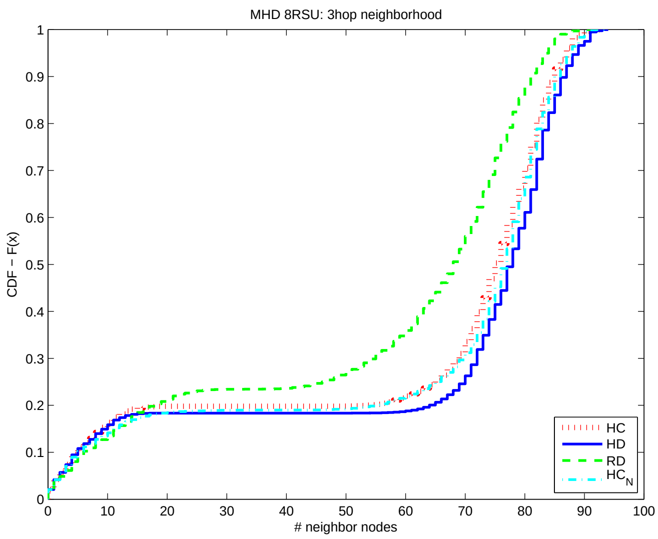
Figure B.2: 6RSUs MHD-GIS-rural-n100-r300-b300-noCF-noTL



(a) MHD with RSU: 1hop neighborhood

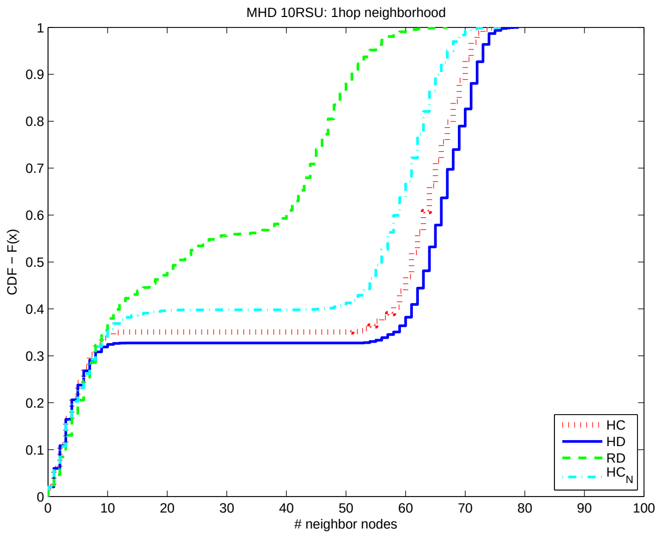


(b) MHD with RSU: 2hop neighborhood

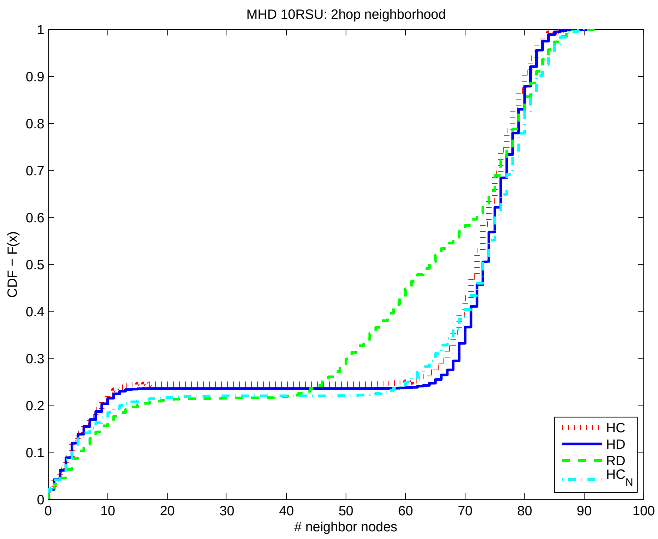


(c) MHD with RSU: 3hop neighborhood

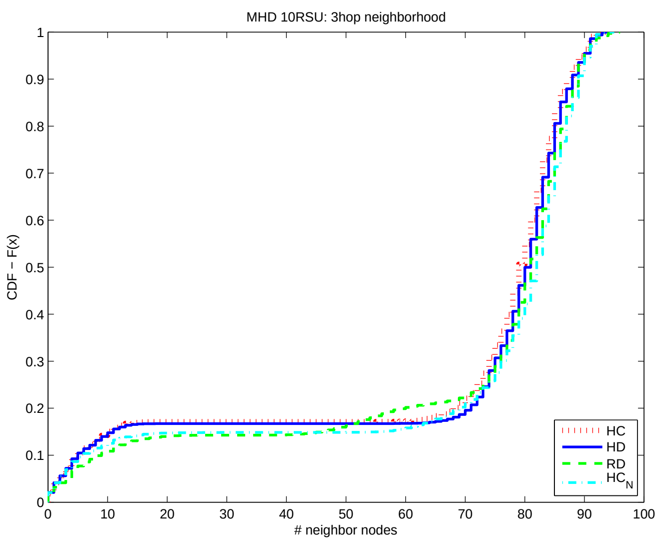
Figure B.3: 8RSUs MHD-GIS-rural-n100-r300-b300-noCF-noTL



(a) MHD with RSU: 1hop neighborhood



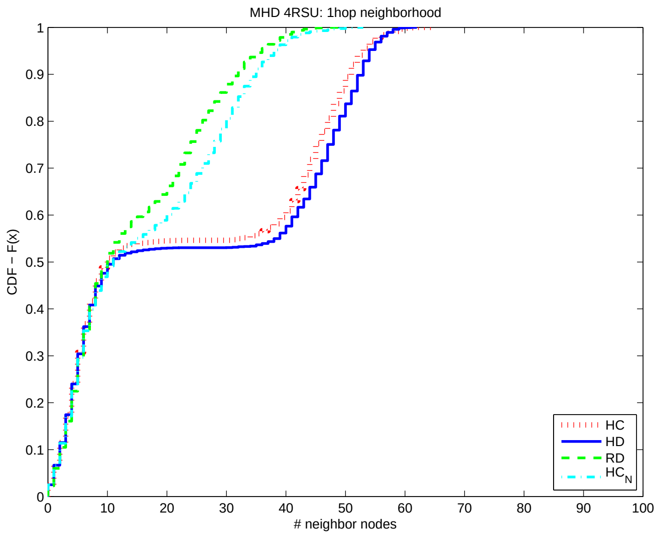
(b) MHD with RSU: 2hop neighborhood



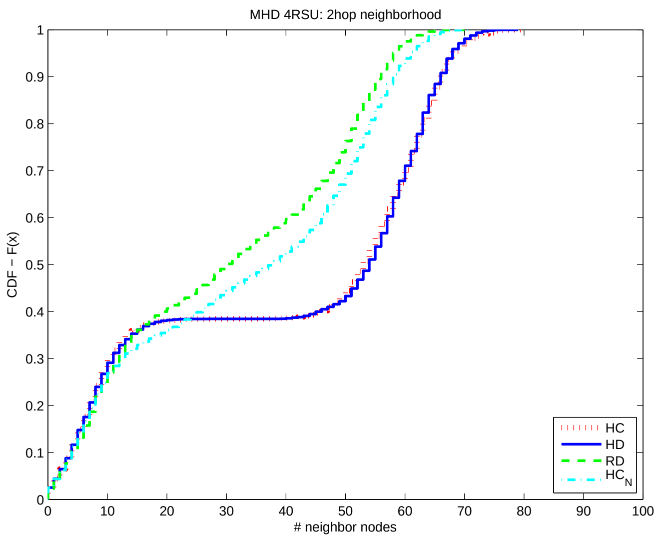
(c) MHD with RSU: 3hop neighborhood

Figure B.4: 10RSUs MHD-GIS-rural-n100-r300-b300-noCF-noTL

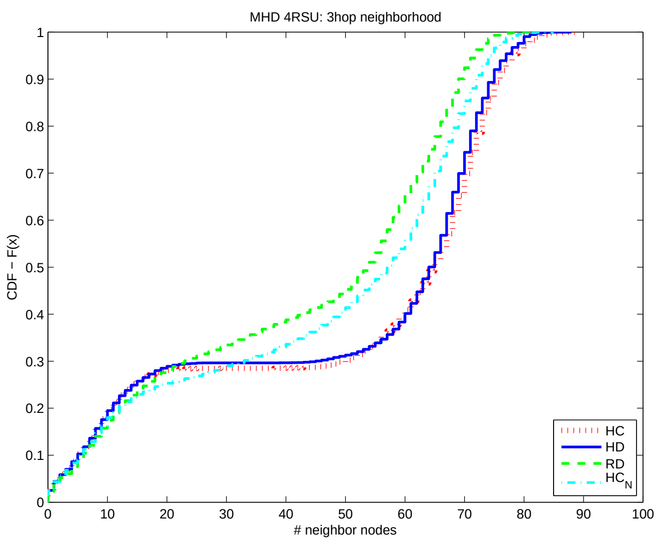
B.1.2 CF-noTL



(a) MHD with RSU: 1hop neighborhood

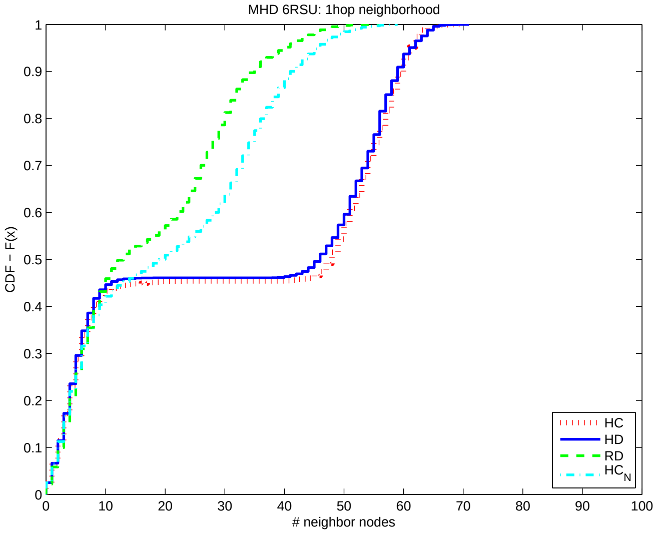


(b) MHD with RSU: 2hop neighborhood

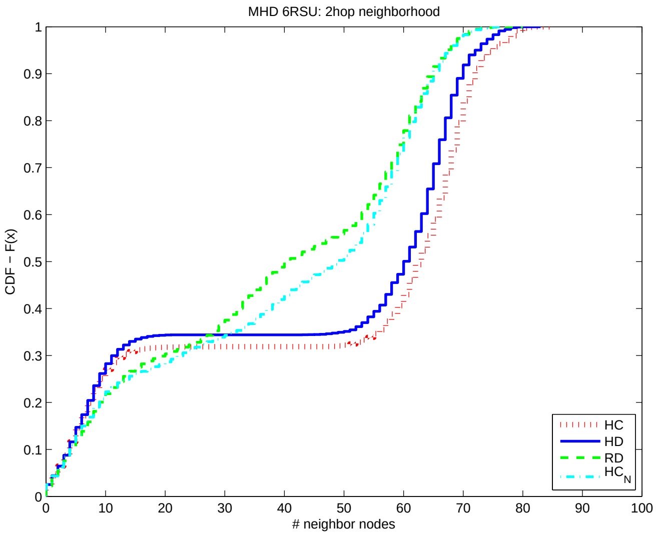


(c) MHD with RSU: 3hop neighborhood

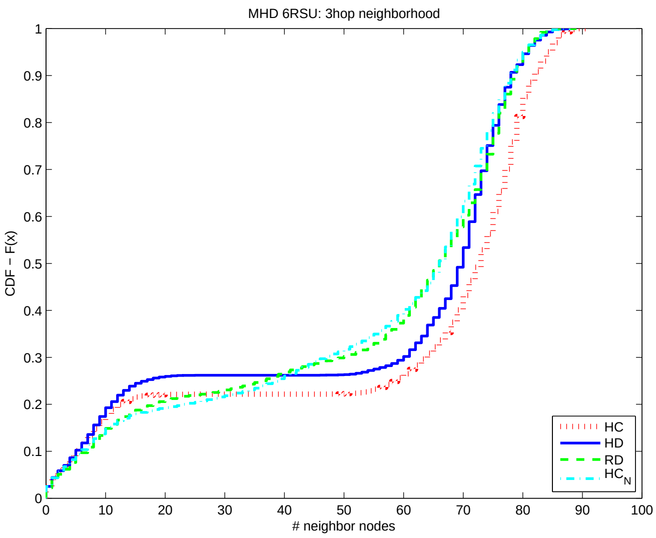
Figure B.5: 4RSUs MHD-GIS-rural-n100-r300-b300-CF-noTL



(a) MHD with RSU: 1hop neighborhood

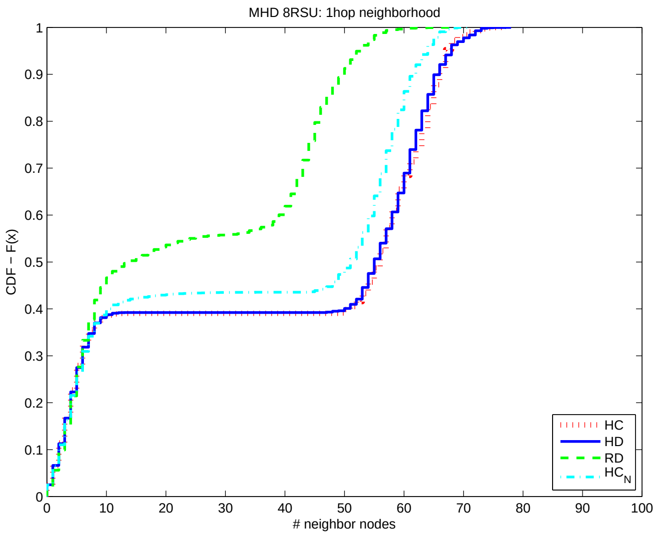


(b) MHD with RSU: 2hop neighborhood

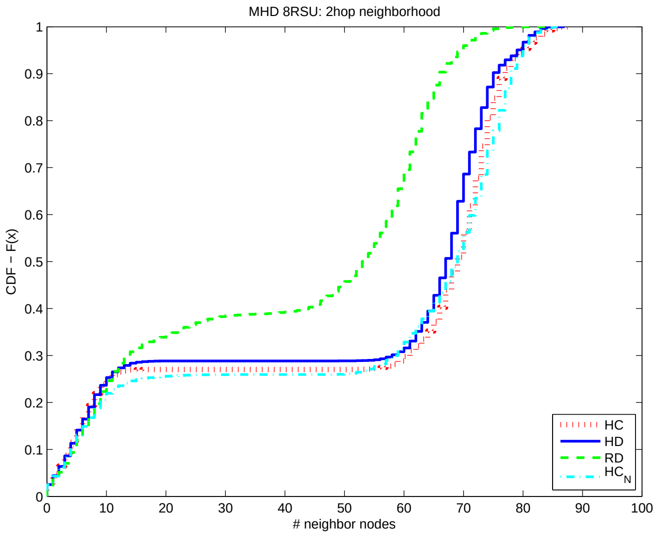


(c) MHD with RSU: 3hop neighborhood

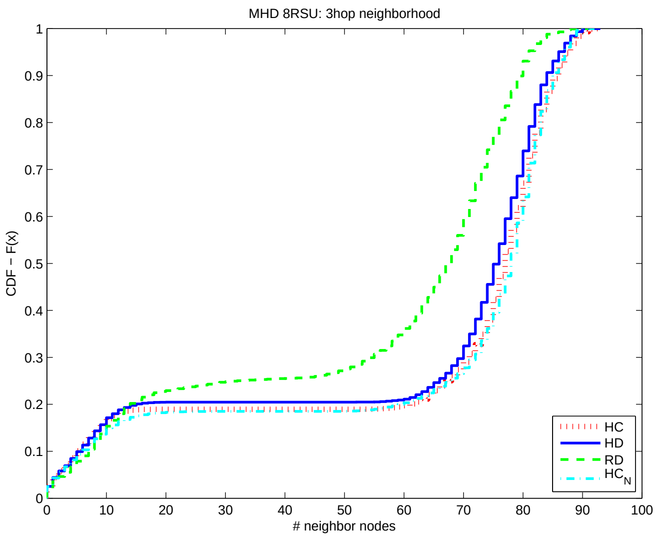
Figure B.6: 6RSUs MHD-GIS-rural-n100-r300-b300-CF-noTL



(a) MHD with RSU: 1hop neighborhood

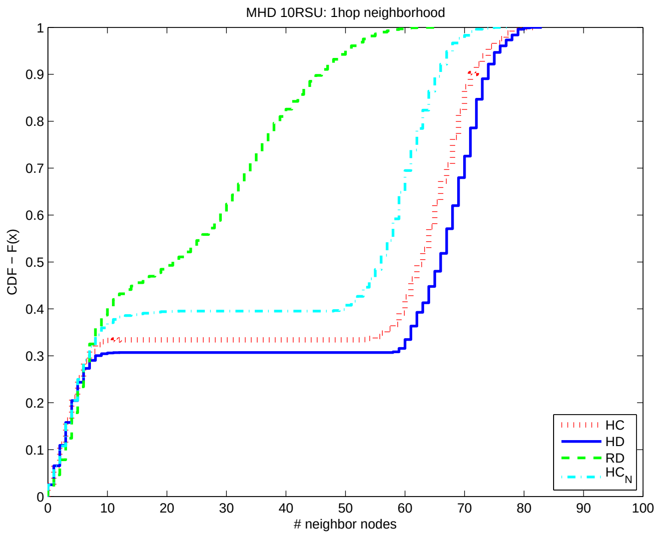


(b) MHD with RSU: 2hop neighborhood

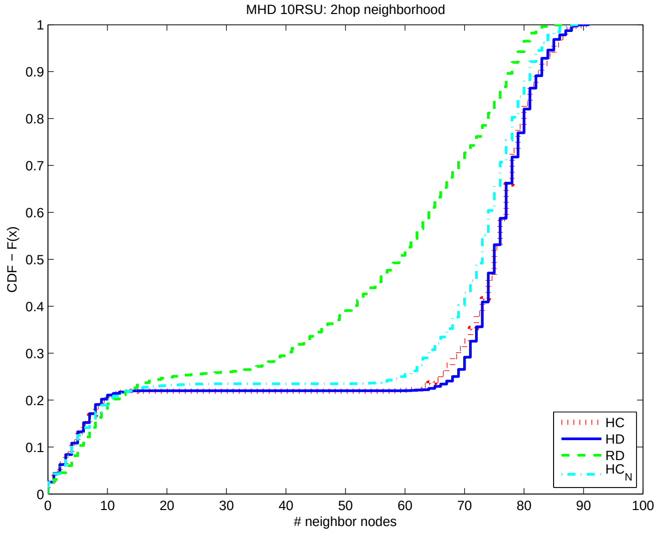


(c) MHD with RSU: 3hop neighborhood

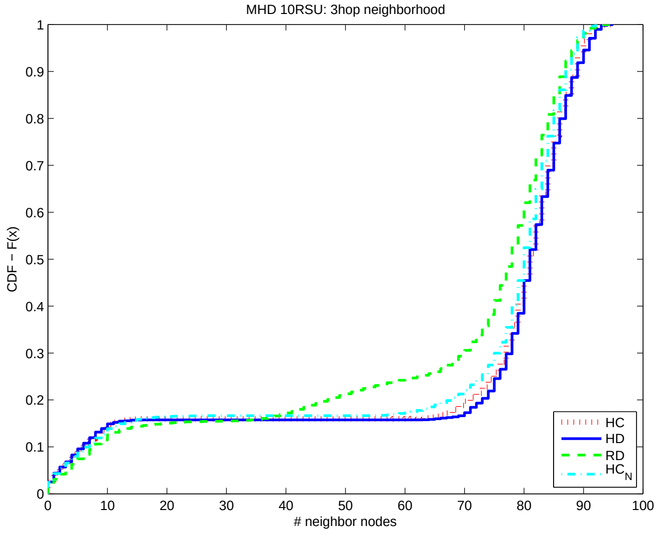
Figure B.7: 8RSUs MHD-GIS-rural-n100-r300-b300-CF-noTL



(a) MHD with RSU: 1hop neighborhood



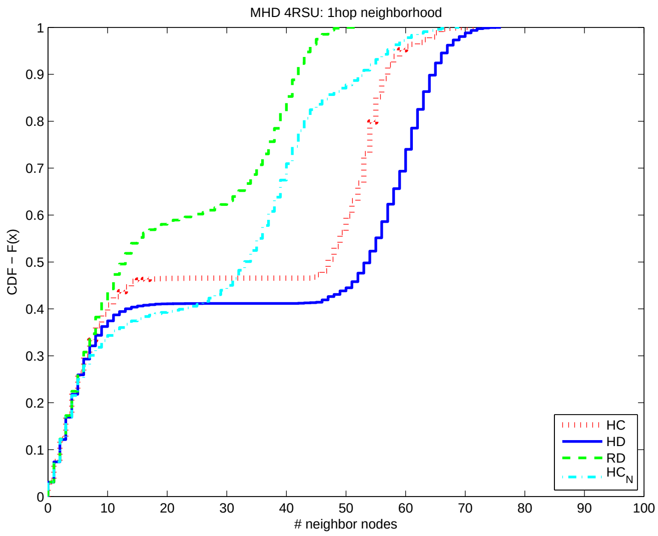
(b) MHD with RSU: 2hop neighborhood



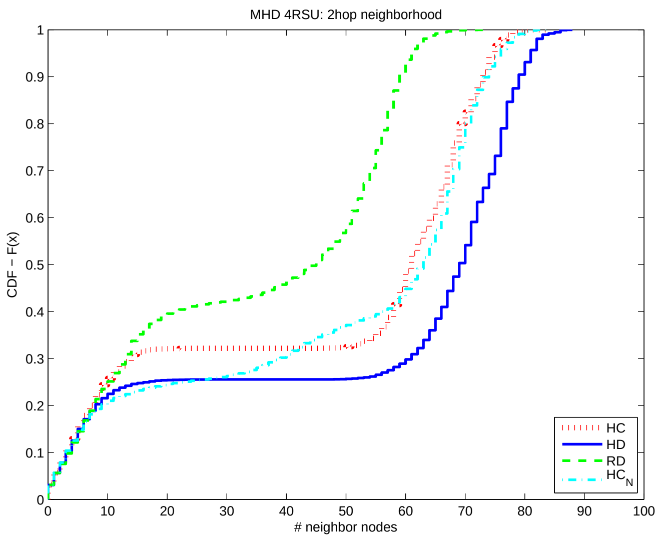
(c) MHD with RSU: 3hop neighborhood

Figure B.8: 10RSUs MHD-GIS-rural-n100-r300-b300-CF-noTL

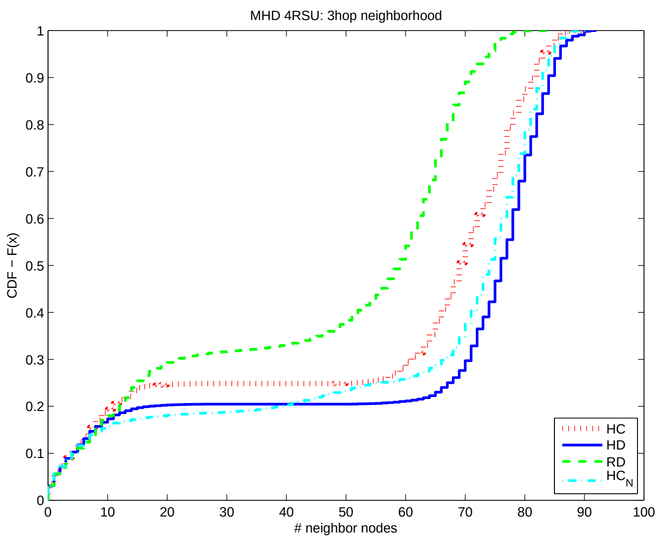
B.1.3 CF-TL



(a) MHD with RSU: 1hop neighborhood

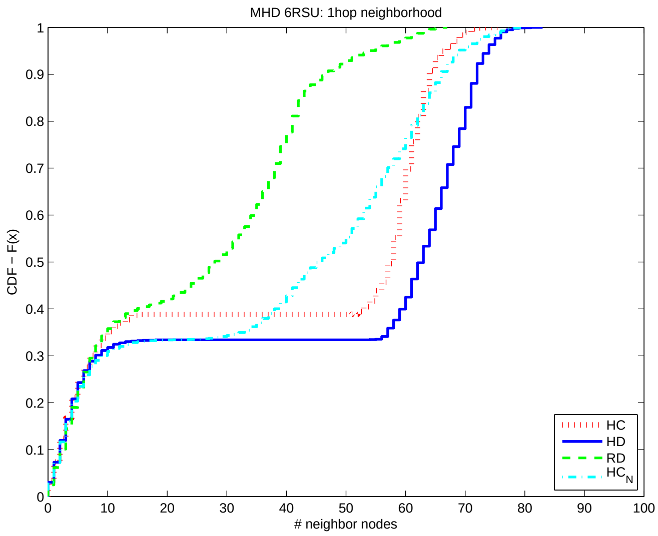


(b) MHD with RSU: 2hop neighborhood

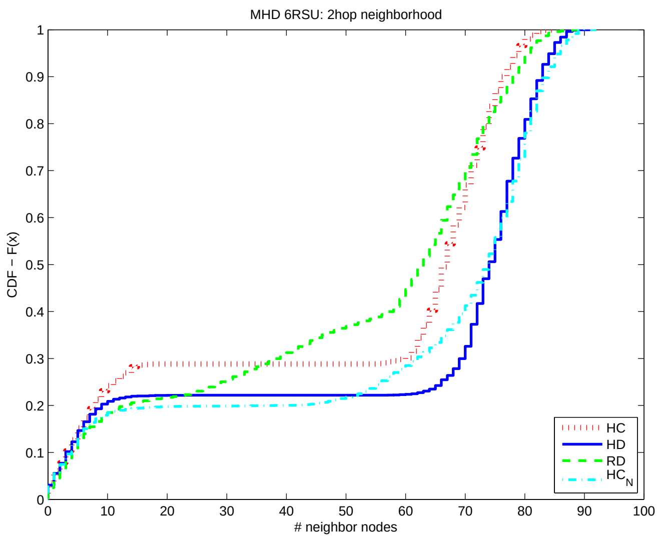


(c) MHD with RSU: 3hop neighborhood

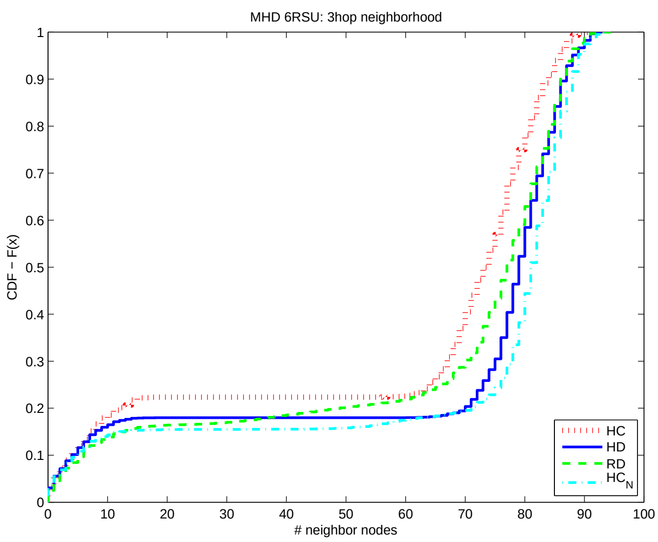
Figure B.9: 4RSUs MHD-GIS-rural-n100-r300-b300-CF-TL



(a) MHD with RSU: 1hop neighborhood

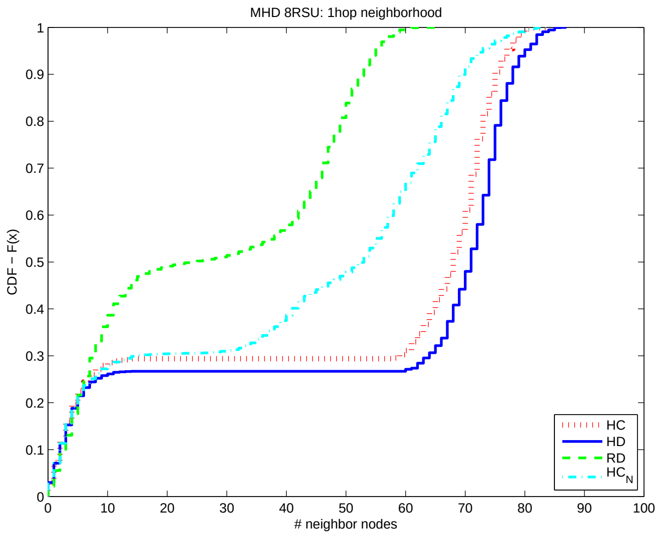


(b) MHD with RSU: 2hop neighborhood

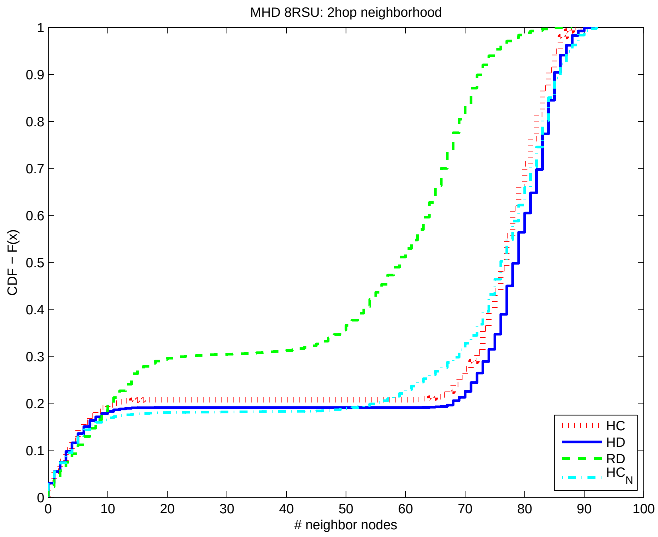


(c) MHD with RSU: 3hop neighborhood

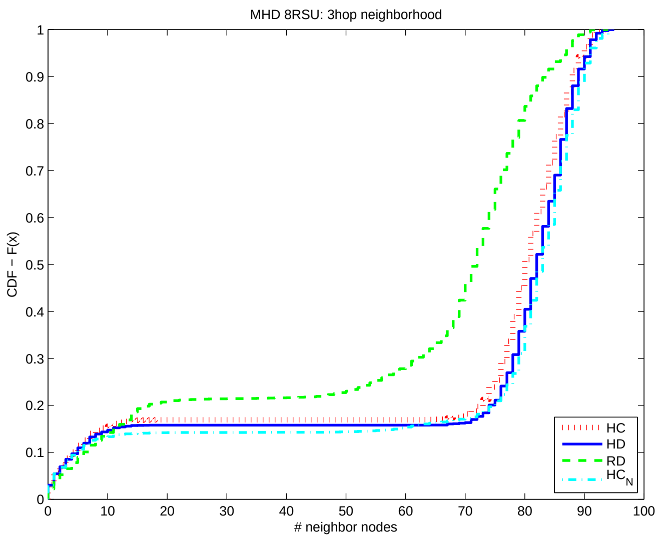
Figure B.10: 6RSUs MHD-GIS-rural-n100-r300-b300-CF-TL



(a) MHD with RSU: 1hop neighborhood

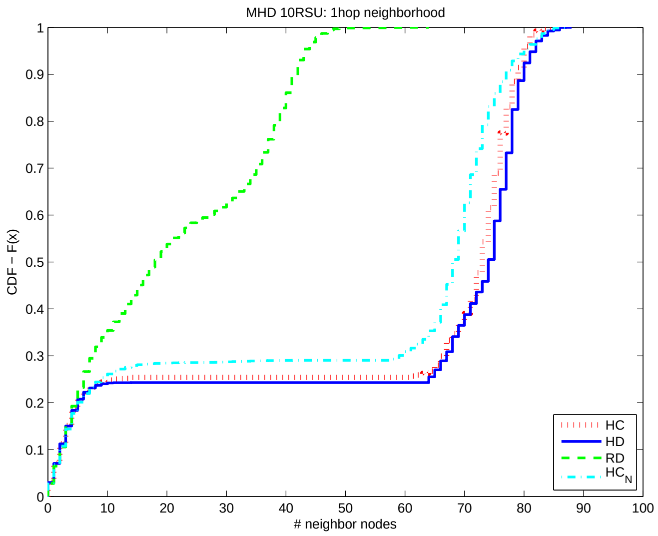


(b) MHD with RSU: 2hop neighborhood

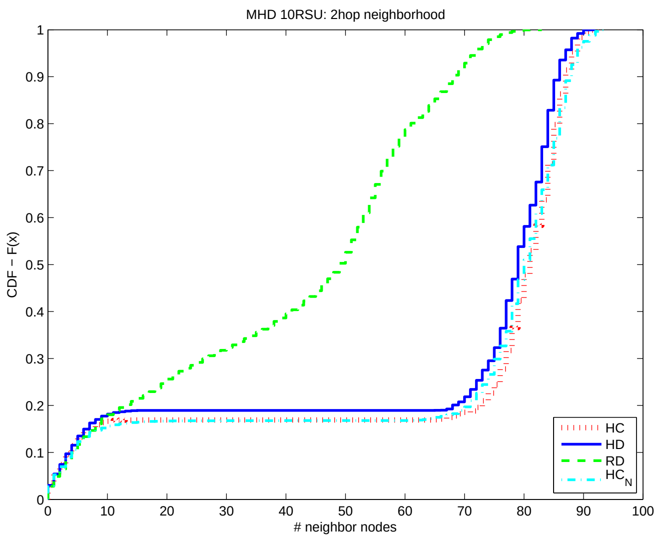


(c) MHD with RSU: 3hop neighborhood

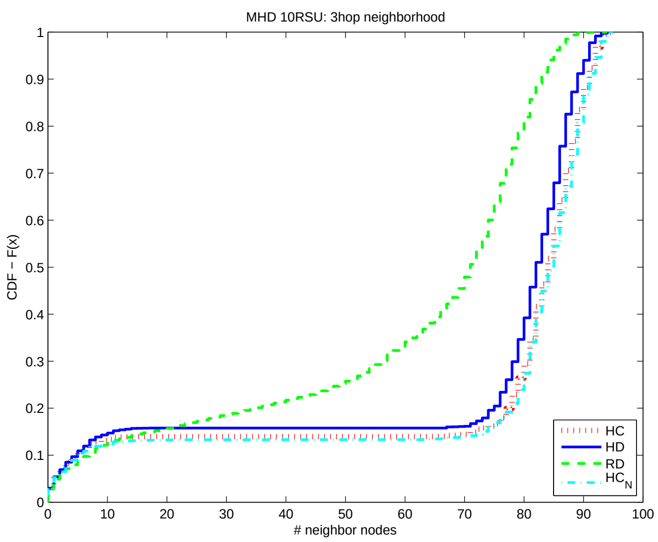
Figure B.11: 6RSUs MHD-GIS-rural-n100-r300-b300-CF-TL



(a) MHD with RSU: 1hop neighborhood



(b) MHD with RSU: 2hop neighborhood

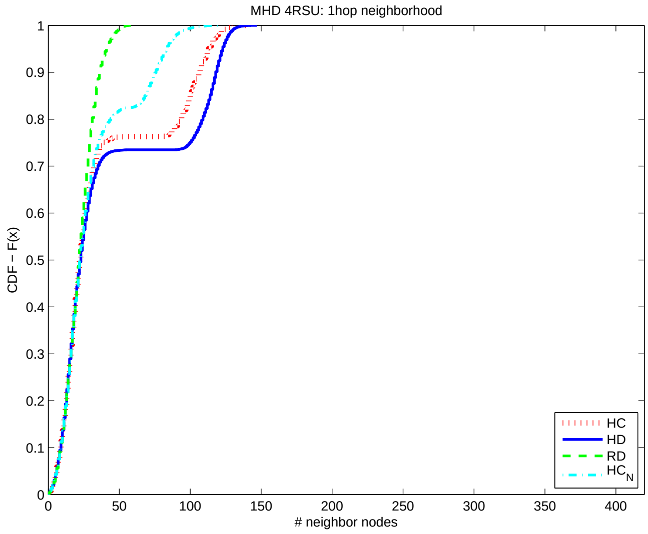


(c) MHD with RSU: 3hop neighborhood

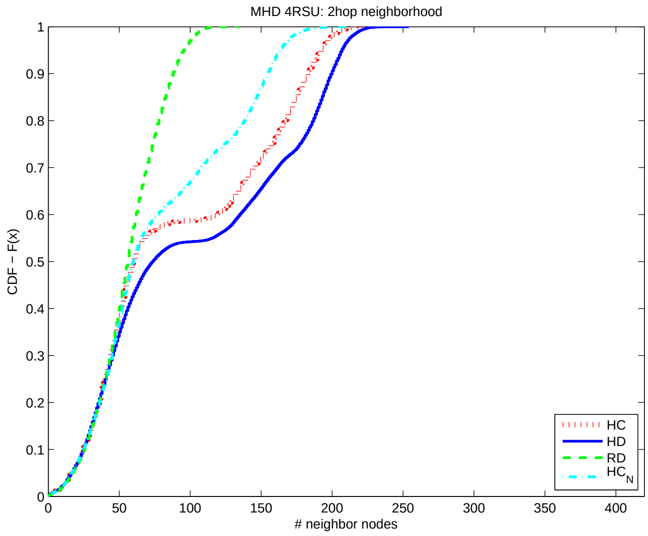
Figure B.12: 10RSUs MHD-GIS-rural-n100-r300-b300-CF-TL

B.2 Urban setting

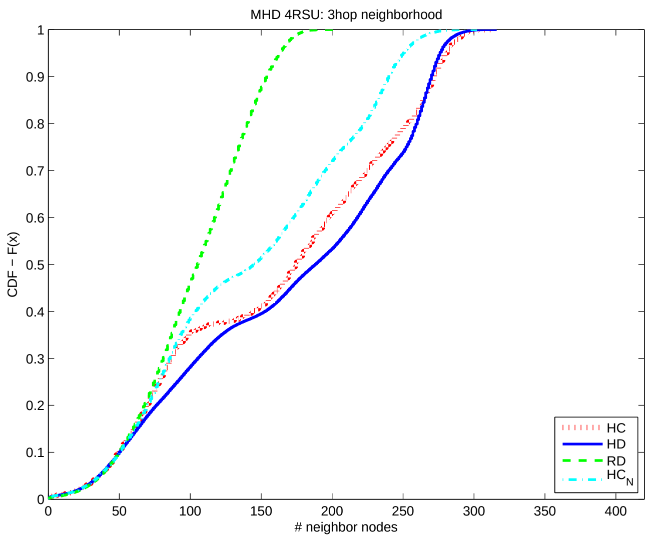
B.2.1 noCF-noTL



(a) MHD with RSU: 1hop neighborhood

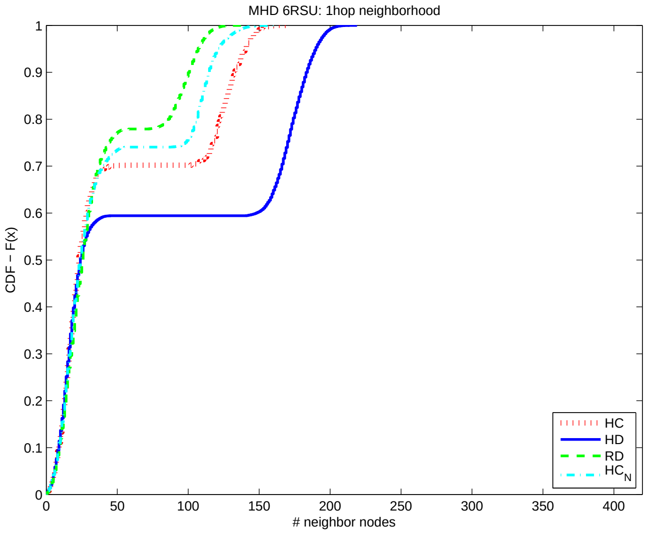


(b) MHD with RSU: 2hop neighborhood

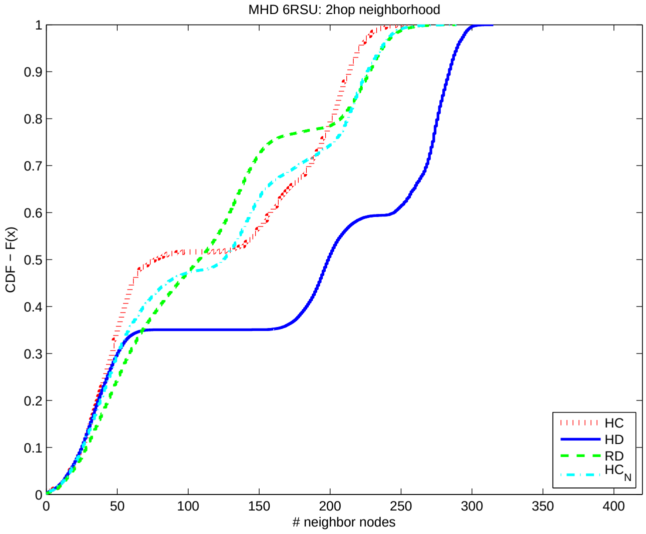


(c) MHD with RSU: 3hop neighborhood

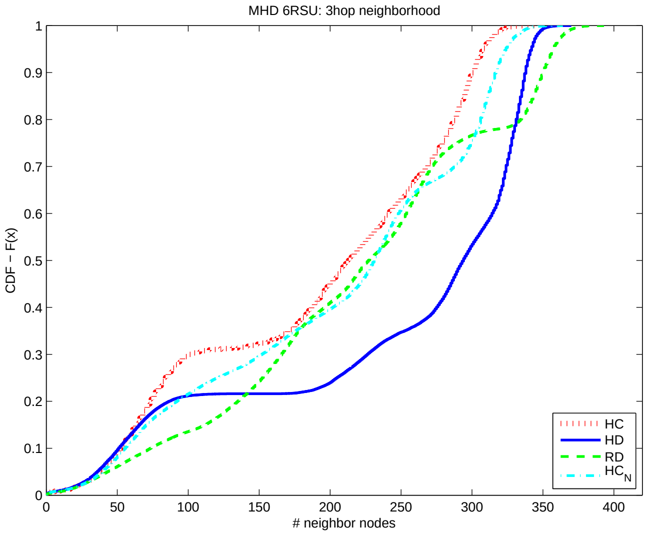
Figure B.13: 4RSUs MHD-GIS-urban-n420-r300-b300-noCF-noTL



(a) MHD with RSU: 1hop neighborhood

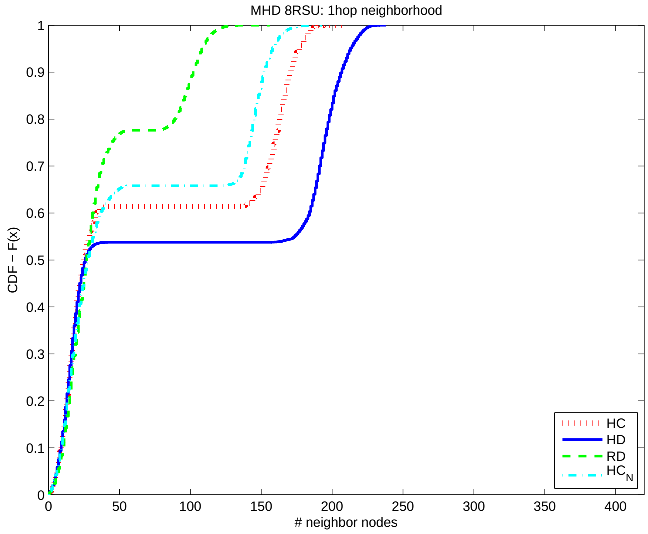


(b) MHD with RSU: 2hop neighborhood

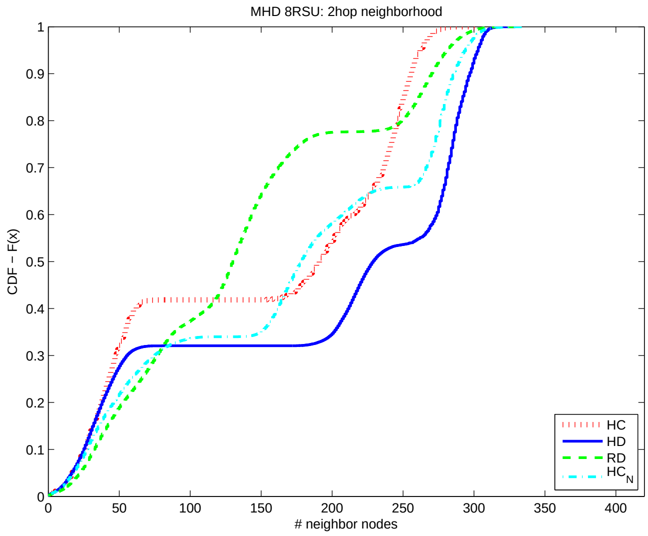


(c) MHD with RSU: 3hop neighborhood

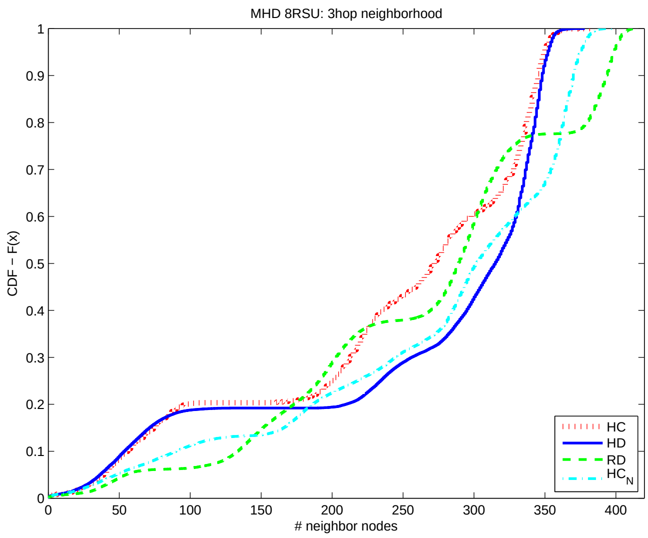
Figure B.14: 6RSUs MHD-GIS-urban-n420-r300-b300-noCF-noTL



(a) MHD with RSU: 1hop neighborhood

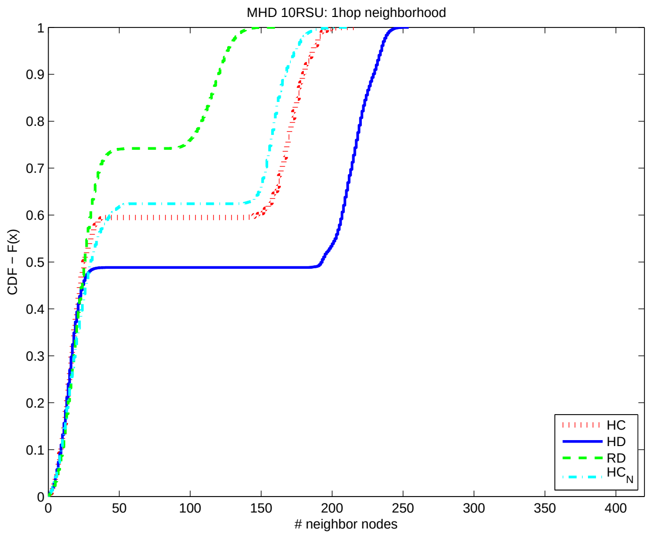


(b) MHD with RSU: 2hop neighborhood

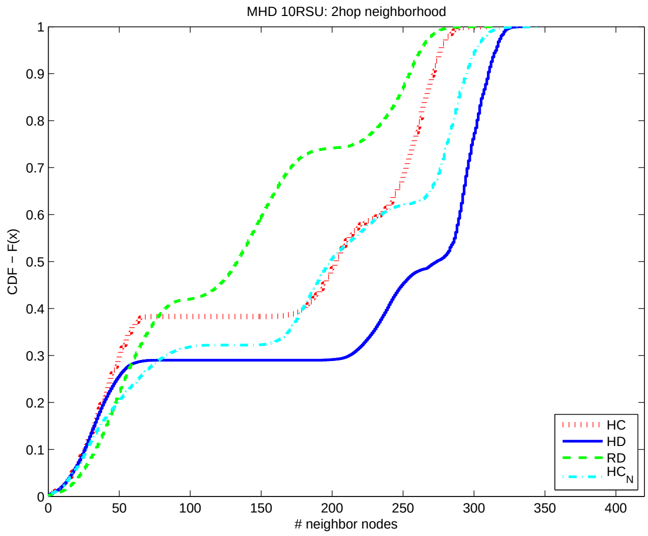


(c) MHD with RSU: 3hop neighborhood

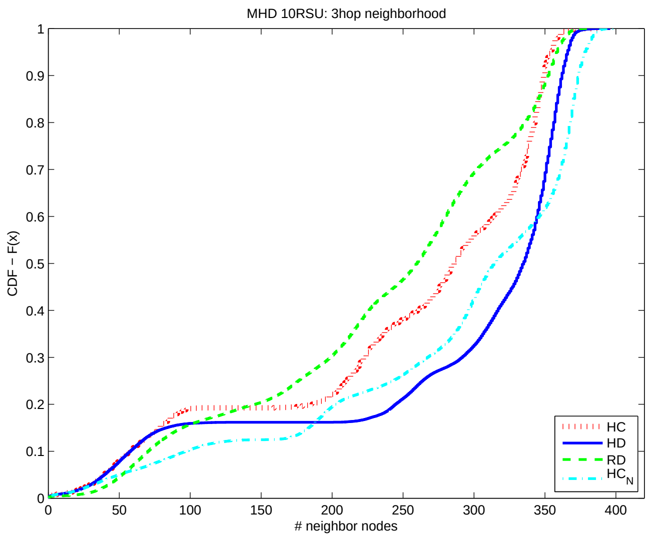
Figure B.15: 8RSUs MHD-GIS-urban-n420-r300-b300-noCF-noTL



(a) MHD with RSU: 1hop neighborhood



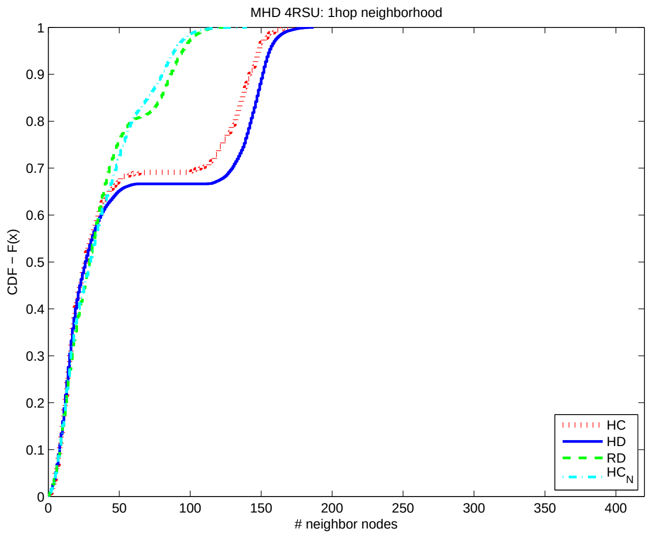
(b) MHD with RSU: 2hop neighborhood



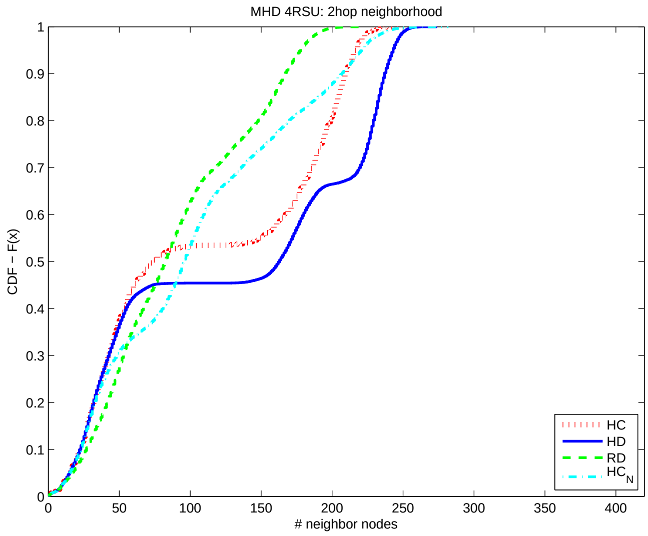
(c) MHD with RSU: 3hop neighborhood

Figure B.16: 10RSUs MHD-gmsf-urban-n420-r300-b300-noCF-noTL

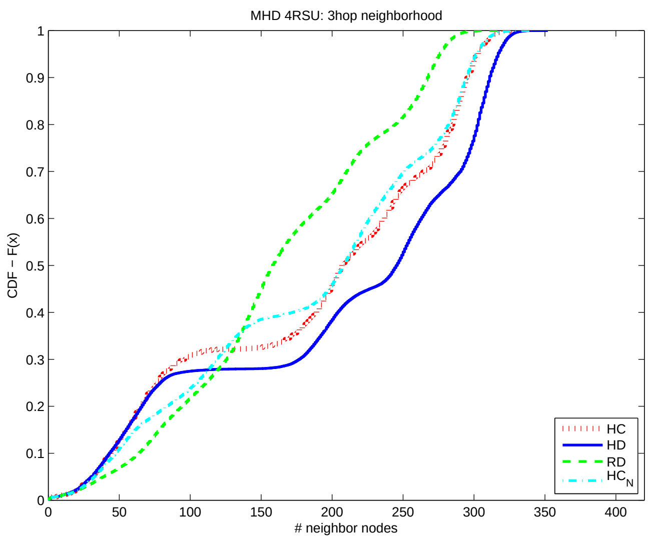
B.2.2 CF-noTL



(a) MHD with RSU: 1hop neighborhood

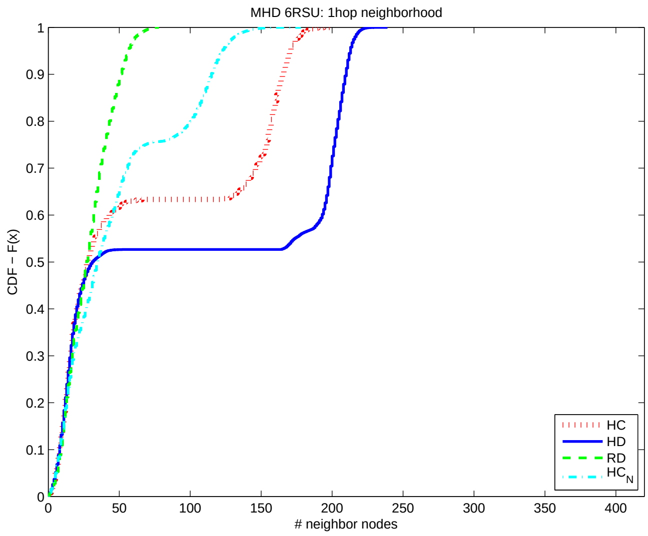


(b) MHD with RSU: 2hop neighborhood

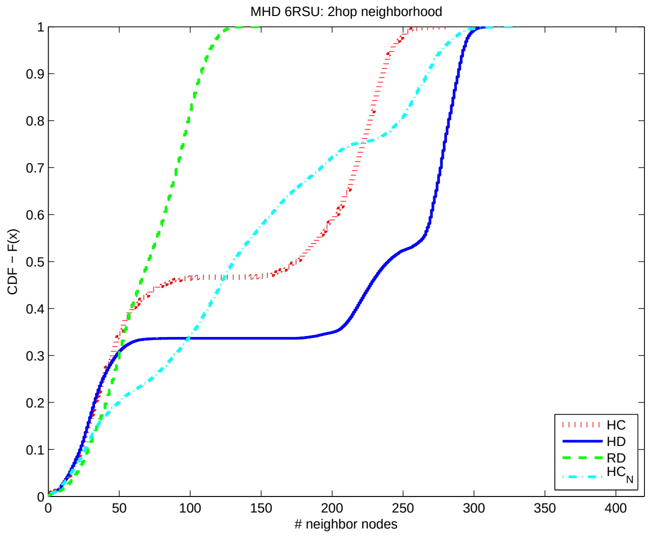


(c) MHD with RSU: 3hop neighborhood

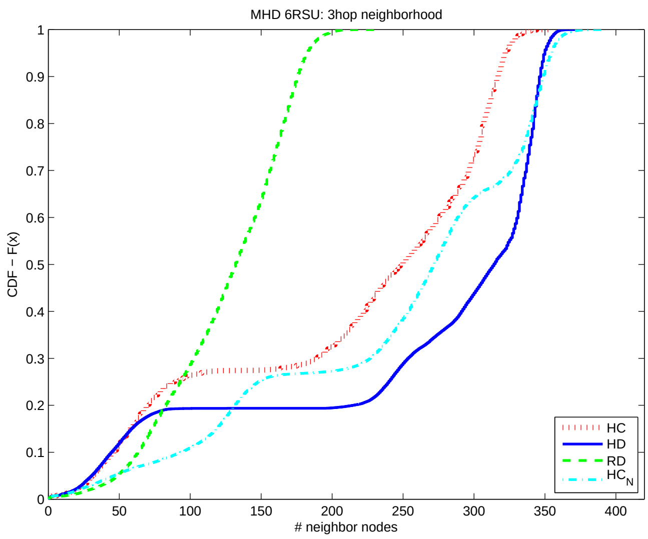
Figure B.17: 4RSUs MHD-GIS-urban-n420-r300-b300-CF-noTL



(a) MHD with RSU: 1hop neighborhood

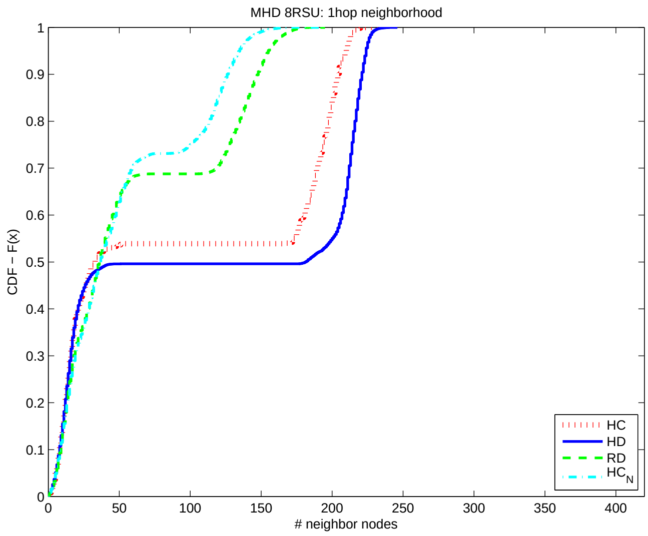


(b) MHD with RSU: 2hop neighborhood

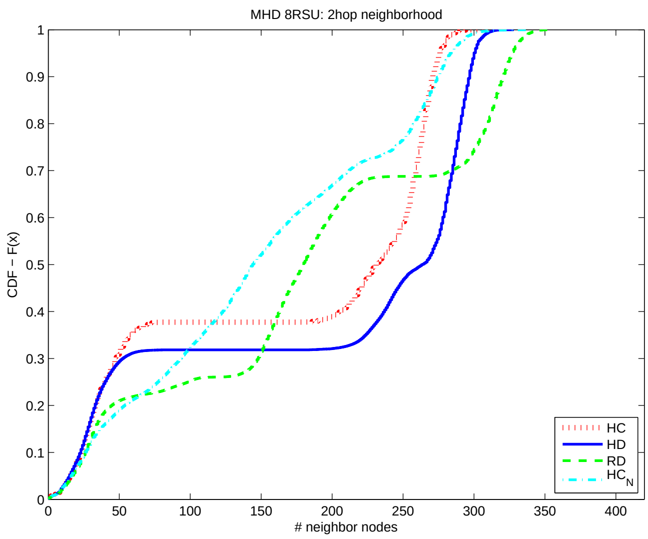


(c) MHD with RSU: 3hop neighborhood

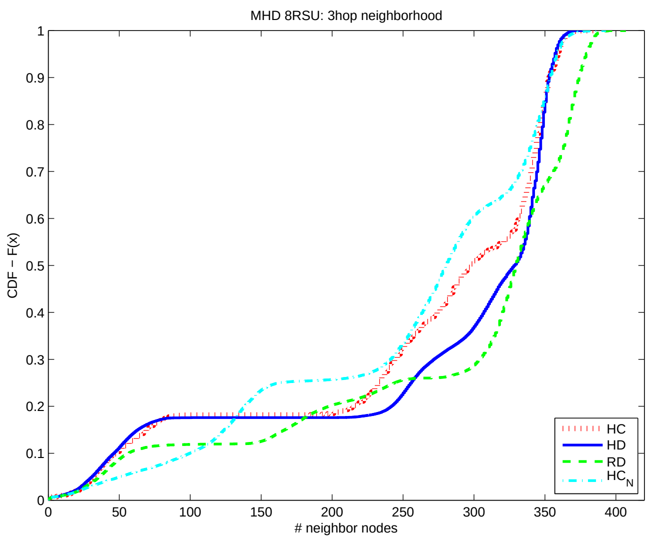
Figure B.18: 6RSUs MHD-GIS-urban-n420-r300-b300-CF-noTL



(a) MHD with RSU: 1hop neighborhood

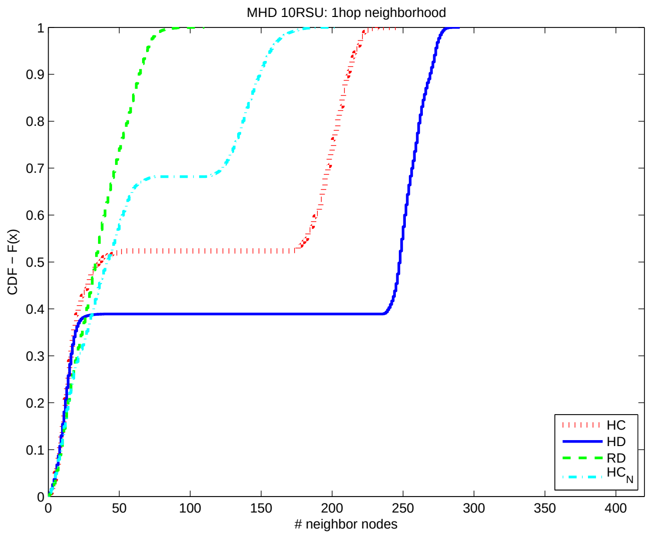


(b) MHD with RSU: 2hop neighborhood

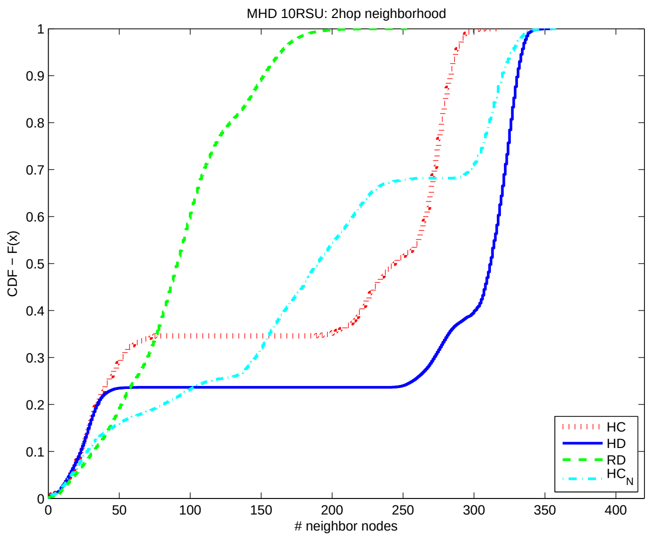


(c) MHD with RSU: 3hop neighborhood

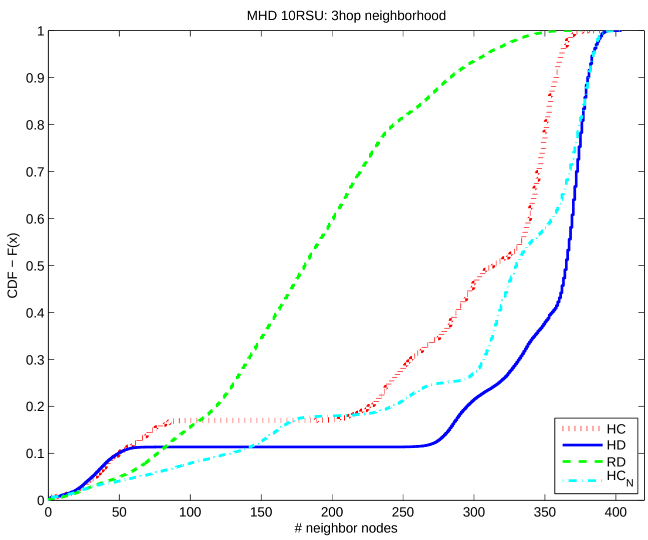
Figure B.19: 8RSUs MHD-GIS-urban-n420-r300-b300-CF-noTL



(a) MHD with RSU: 1hop neighborhood



(b) MHD with RSU: 2hop neighborhood



(c) MHD with RSU: 3hop neighborhood

Figure B.20: 10RSUs MHD-GIS-urban-n420-r300-b300-CF-noTL

B.2.3 CF-TL

B.3 City setting

B.3.1 noCF-noTL

B.3.2 CF-noTL

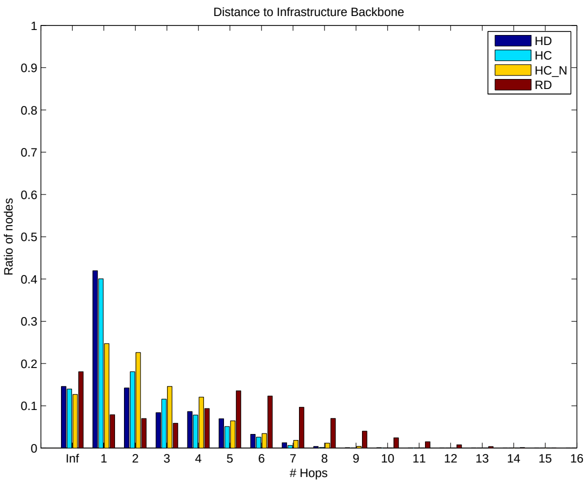
B.3.3 CF-TL

Appendix C

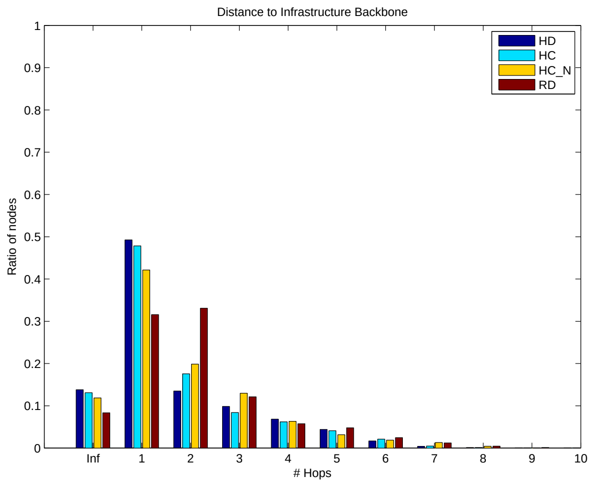
D2B Results

C.1 Rural setting

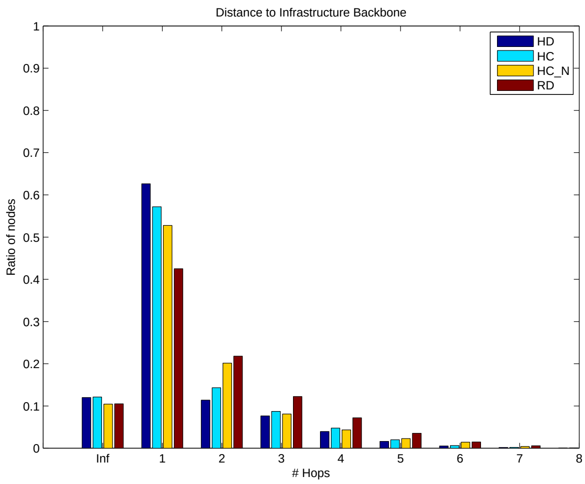
C.1.1 noCF-noTL



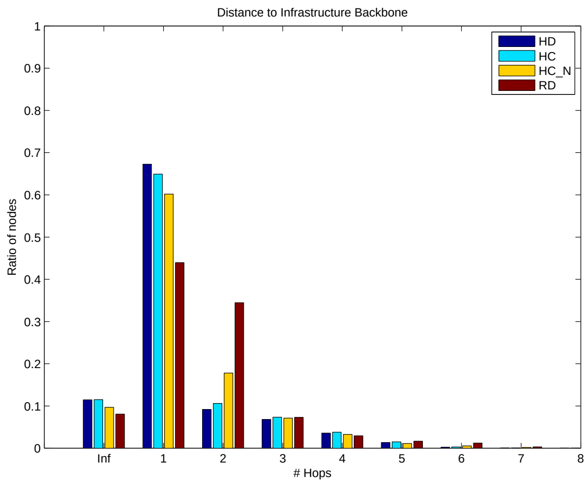
(a) D2B 4RSUs



(b) D2B 6RSUs



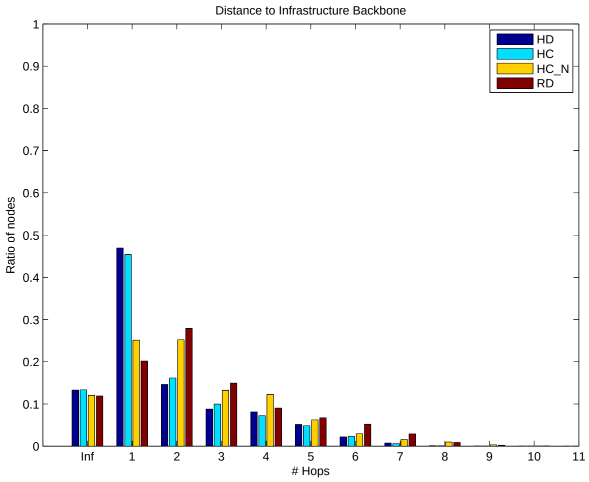
(c) D2B 8RSUs



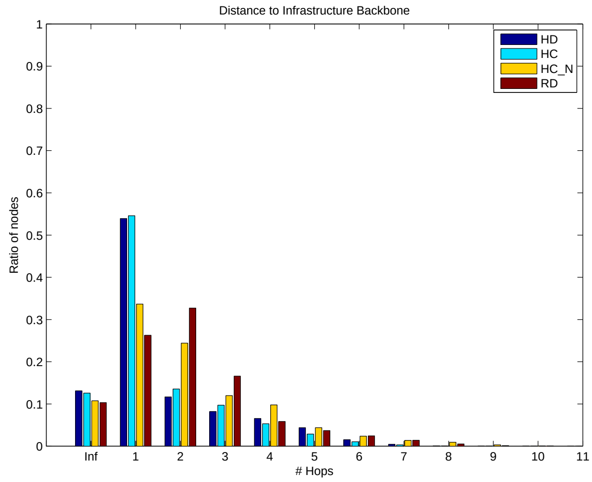
(d) D2B 10RSUs

Figure C.1: D2B-GIS-rural-n100-r300-b300-noCF-noTL

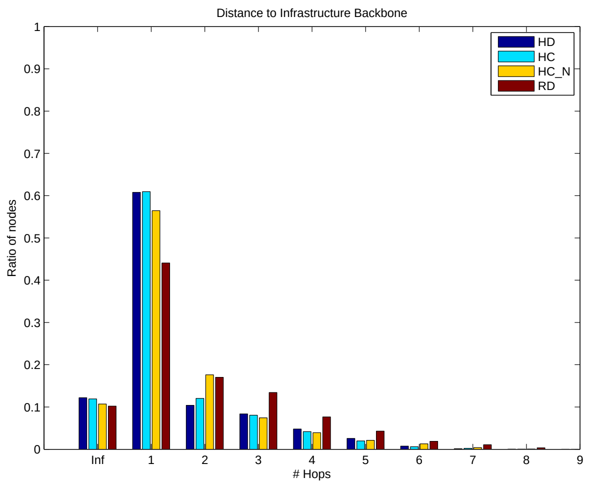
C.1.2 CF-noTL



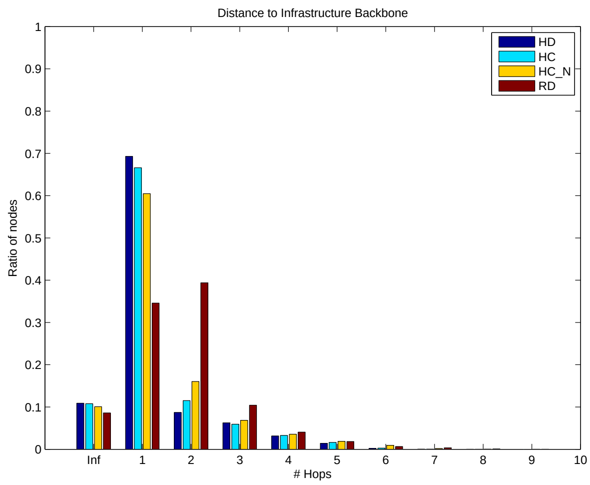
(a) D2B 4RSUs



(b) D2B 6RSUs



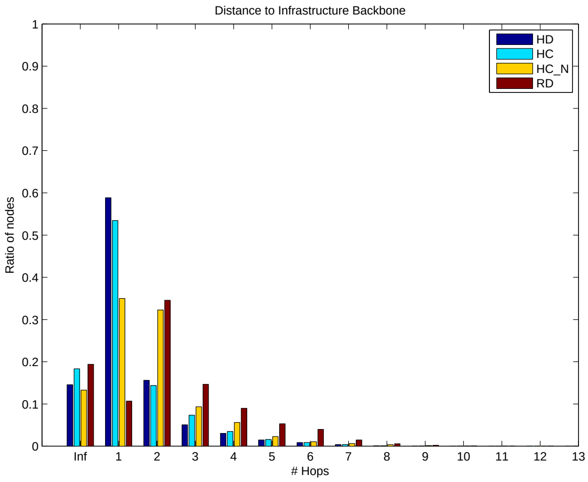
(c) D2B 8RSUs



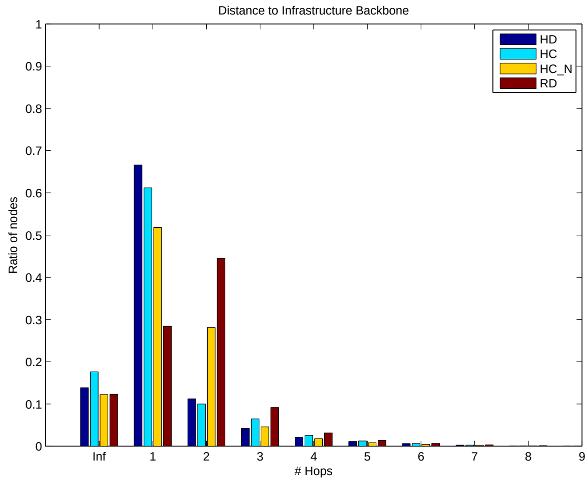
(d) D2B 10RSUs

Figure C.2: D2B-GIS-rural-n100-r300-b300-CF-noTL

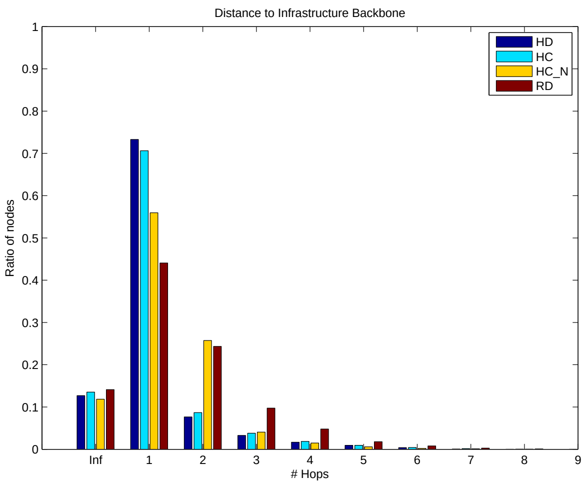
C.1.3 CF-TL



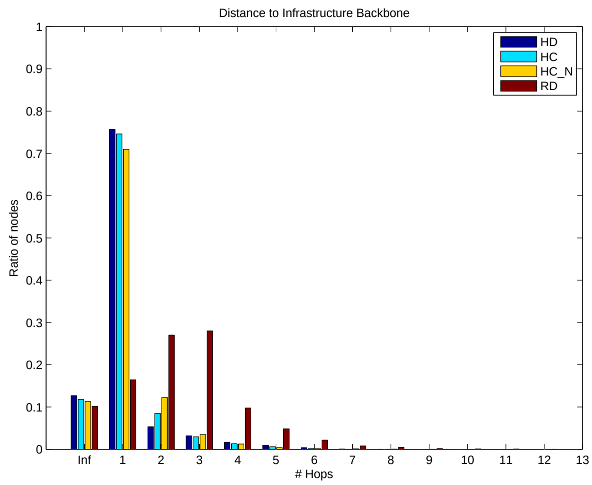
(a) D2B 4RSUs



(b) D2B 6RSUs



(c) D2B 8RSUs

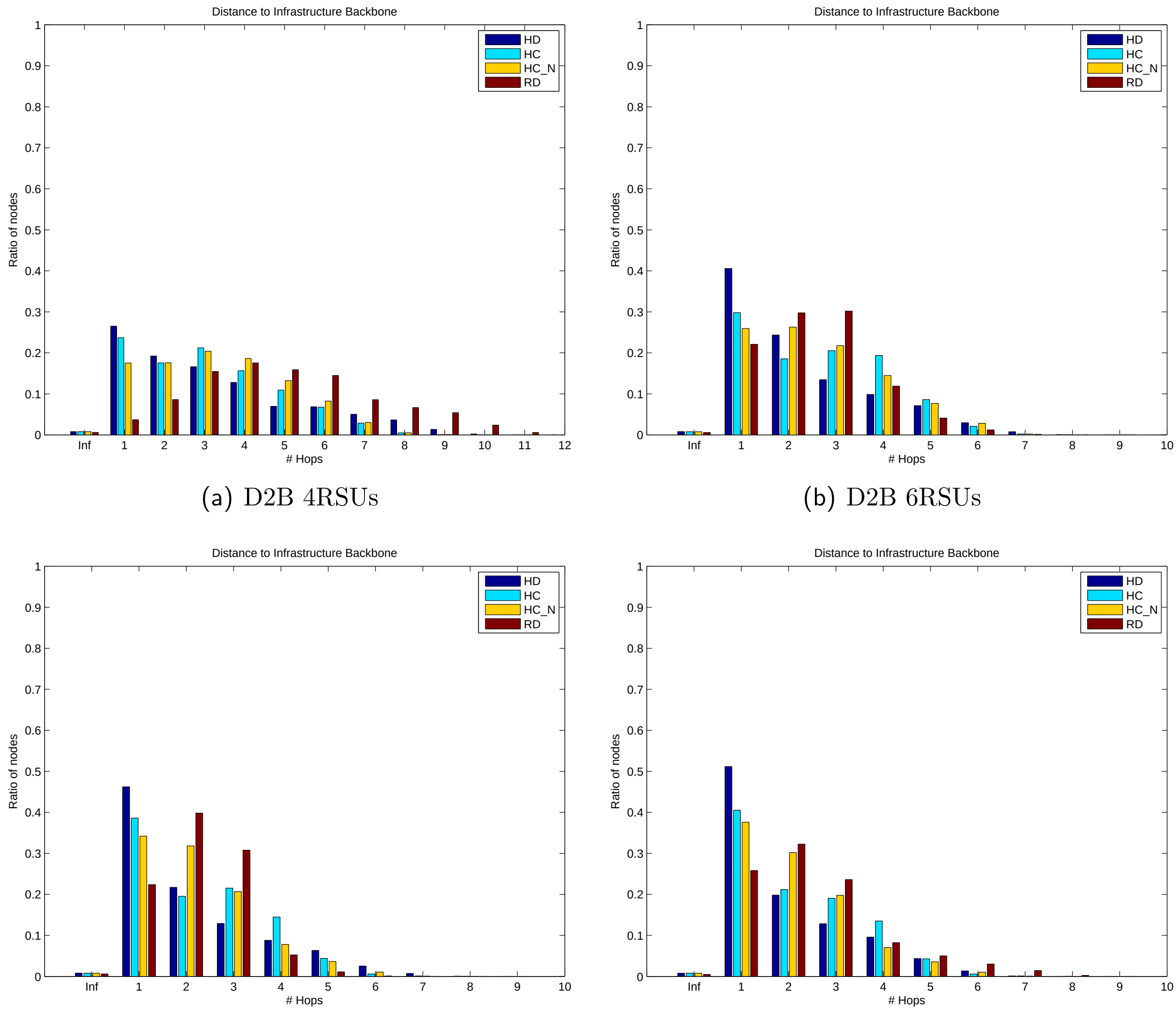


(d) D2B 10RSUs

Figure C.3: D2B-GIS-rural-n100-r300-b300-CF-TL

C.2 Urban setting

C.2.1 noCF-noTL



(a) D2B 4RSUs

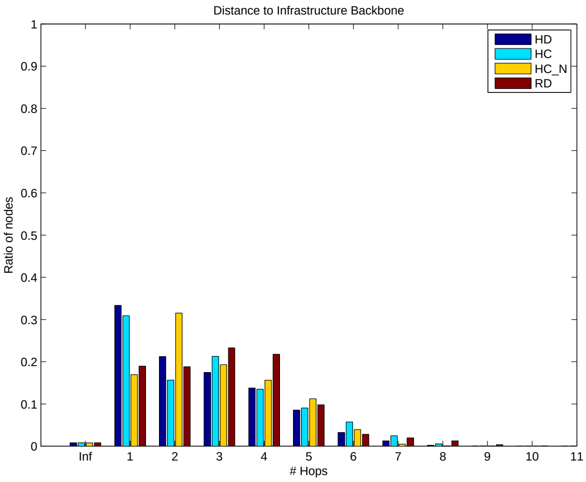
(b) D2B 6RSUs

(c) D2B 8RSUs

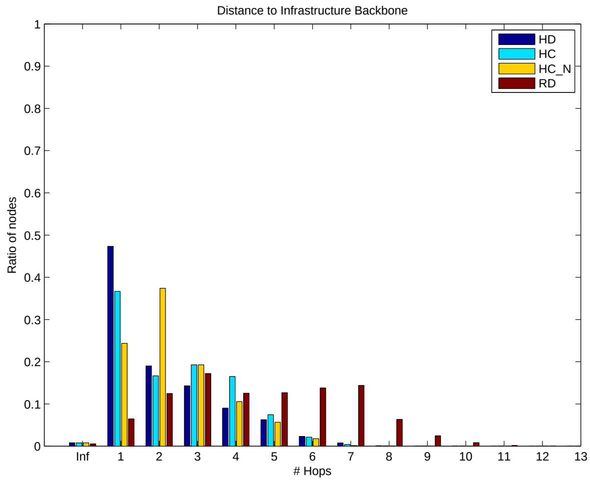
(d) D2B 10RSUs

Figure C.4: D2B-GIS-urban-n420-r300-b300-noCF-noTL

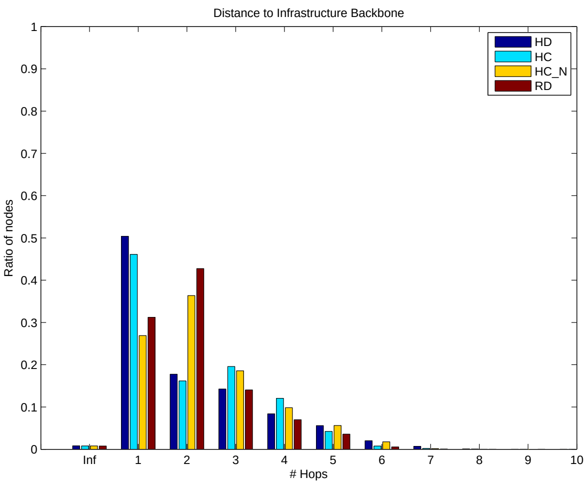
C.2.2 CF-noTL



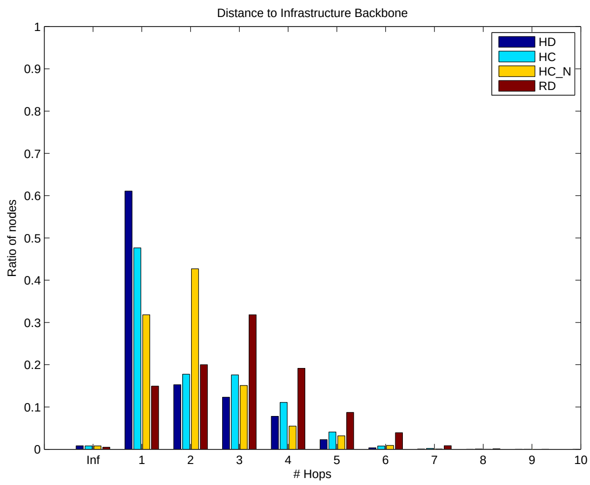
(a) D2B 4RSUs



(b) D2B 6RSUs



(c) D2B 8RSUs



(d) D2B 10RSUs

Figure C.5: D2B-GIS-urban-n420-r300-b300-CF-noTL

C.2.3 CF-TL

C.3 City setting

C.3.1 noCF-noTL

C.3.2 CF-noTL

C.3.3 CF-TL

Bibliography

[1] Cooperative Vehicle-Infrastructure Systems. URL http://www.cvisproject.org/.

[2] Dedicated Short Range Communications. URL http://www.leearmstrong.com/DSRC/DSRCHomeset.htm.

[3] Generic Mobility Simulation Framework. URL http://polar9.ethz.ch/gmsf/.

[4] URL http://www.stanford.edu/~dgleich/programs/matlab_bgl/.

[5] URL http://sumo.sourceforge.net/index.shtml.

[6] SmartWay. URL http://www.epa.gov/smartway/.

[7] URL http://www.analytictech.com/ucinet/ucinet.htm.

[8] . URL http://www.vehicle-infrastructure.org/.

[9] . URL http://www.viicalifornia.org/.

[10] Realistic vehicular traces. URL http://lst.inf.ethz.ch/ad-hoc/car-traces/.

[11] R. Baldessari, A. Festag, A. Matos, J. Santos, and R. Aguiar. Flexible Connectivity Management in Vehicular Communication Networks. In *Workshop on Intelligent Transportation (WIT 2006)*, pages 211–216, 2006.

[12] U. Brandes. On variants of shortest-path betweenness centrality and their generic computation. *Social Networks*, 2008.

[13] G. Calandriello, P. Papadimitratos, A. Lioy, and J.-P. Hubaux. Efficient and Robust Pseudonymous Authentication in VANET. In *VANET 2007*, Montreal, 2007. ACM.

[14] I. Carreras, D. Miorandi, G. Canright, and K. Engo-Monsen. *Eigenvector Centrality in Highly Partitioned Mobile Networks: Principles and Applications*. Springer, 2007.

[15] M. Cops. VII Strategy for Safety and Mobility, 2007.

[16] B. Cornwell. A Complement-Derived Centrality Index for Disconnected Graphs. *INSNA*, pages 70–81, 2005.

[17] P. Crucitti, V. Latora, and S. Porta. Centrality Measures in Spatial Networks of Urban Streets. *Physical Review E (Statistical, Nonlinear, and Soft Matter Physics)*, 73(3):036125, 2006. doi: 10.1103/PhysRevE.73.036125.

[18] E.M. Daly and M. Haahr. Social network analysis for routing in disconnected delay-tolerant manets. In *MobiHoc '07: Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing*, 2007.

[19] L. C. Freeman. Centrality in social networks: Conceptual clarification. *Social Networks*, 1979.

[20] J. Freudiger, M. Raya, M. Felegyhazi, P. Papadimitratos, and J.-P. Hubaux. Mix-Zones for Location Privacy in Vehicular Networks. In *ACM Workshop on Wireless Networking for Intelligent Transportation Systems (WiN-ITS)*, Vancouver, 2007.

[21] H. Habiba and T. Y. Berger-Wolf. Maximizing the extent of spread in dynamic network. Technical report, DIMACS, 2007.

[22] H. Habiba, C. Tantipathananandh, and T. Y. Berger-Wolf. Betweenness Centrality Measure in Dynamic Networks. Technical report, DIMACS, 2007.

[23] I. W. H. Ho, K. K. Leung, J. W. Polak, and R. Mangharam. Node Connectivity in Vehicular Ad Hoc Networks with Structured Mobility. In *LCN '07: Proceedings of the 32nd IEEE Conference on Local Computer Networks*, pages 635–642, Washington, DC, USA, 2007. IEEE Computer Society.

[24] M. Kafsi, O. Dousse, P. Papadimitratos, T. Alpcan, and J.-P. Hubaux. VANET Connectivity Analysis. Technical report, EPFL/T-Labs, 2008.

[25] V. Naumov, R. Baumann, and T. Gross. An Evaluation of Inter-Vehicle Ad Hoc Networks Based on Realistic Vehicular Traces. In *In Proceedings of The Seventh ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'06)*, 2006.

[26] M.E.J. Newman. A measure of betweenness centrality based on random walks. *Social Networks*, 2005.

[27] P. Papadimitratos, V. Gligor, and J.-P. Hubaux. Securing Vehicular Communications - Assumptions, Requirements, and Principles. In *Workshop on Embedded Security in Cars (ESCAR) 2006*, 2006.

[28] S. Porta, P. Crucitti, and V. Latora. The Network Analysis of Urban Streets: A Primal Approach. *ArXiv Condensed Matter e-prints*, 2005.

[29] M. Raya and J.-P. Hubaux. The Security of Vehicular Ad Hoc Networks. In *SASN 2005*, pages 11–21, 2005.

[30] M. Raya, A. Aziz, and J. P. Hubaux. Efficient Secure Aggregation in VANETs. In *VANET 2006*, pages 67–75, 2006.

[31] B. Smith, B. Park, H. Tanikella, and G. Zhang. Preparing to use vehicle infrastructure integration in transportation operations: phase i. Technical report, Virgina Transportation Research Council, 2008.

[32] P. Sommer. Design and Analysis of Realistic Mobility Model for Wireless Mesh Networks. Master's thesis, ETH Zürich, 2007.

[33] M. Treiber, A. Hennecke, and D. Helbing. Congested Traffic States in Empirical Observations and Microscopic Simulations. *Physical Review E*, 62:1805, 2000.

[34] S. Wasserman and K. Faust. *Social Network Analysis: Methods and Applications.* Cambridge University Press, 1994.

[35] X. Yang, J. Liue, F. Zhao, and N. H. Vaidya. A Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning. *First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services (MobiQuitous'04)*, pages 114–123, 2004.