On the Structure and Evolution of Vehicular Networks

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Presentation Outline

- Defining VANETs
- Key Questions
- Motivation - Contribution - Research Focus
- VANET Graph Analysis - Implications on Protocol Design
  - Metrics Examined
  - Network Analysis
  - Centrality Analysis
  - Cluster Analysis
- Summary

VANET: Definition

- **Vehicular Ad-Hoc Networks (VANETs)**
  - Sub-Class of Mobile Ad-Hoc Networks (MANETs)
  - **Characteristics**
    - High mobility (> 16 m/s).
    - Frequent topology changes and network fragmentation.
    - Ample power, process and storage capabilities.
  - **Communication paradigms:**
    - **IVC**: Inter-Vehicle Communication
    - **RVC**: Road-to-Vehicle Communication
    - **Hybrid**: IVC + RVC

Key Questions

- **Routing Protocol Design**
  - *"Which are the highest-quality vehicles to carry out the forwarding process?"*
  - *"Which are the bridge nodes so as to deliver messages when the network is fragmented?"*
- **Geo-casting (location multi-casting)**
  - *"How can we spread the message with the minimal number of rebroadcasts so as to reduce collisions and latency?"*
- **Road-Side Unit Placement**
  - *"What is the distribution of the position of vehicles?"*

Research Motivation

- Real-World networks follow some topological statistical features
  - Scale-free networks.
  - Small-world properties. **[Faloutsos et. al 1999 | Leskovec et. al TKDD 2007]**

- VANET is not static
  - Evolves over time by adding or removing nodes.
  - Little work has been done to study the VANET features.

- Important to study the properties and topological statistical features that characterize the structure of VANETs.

Research Contributions

- Thorough study of **visible** and **latent** structure of VANET communication graph.
- Study of clusters and sub graphs inside a VANET.
- Implications on infrastructure & routing protocol design.

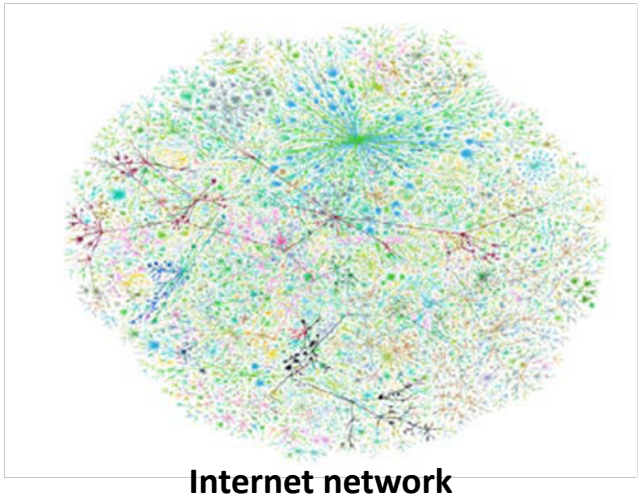
Research Focus

- Previous answers require knowledge of *the* ***topological characteristics*** of the VANET communication graph G(t).

- *G(t)* undirected graph of VANET at time *t*.
  - *V(t)={Ui}* -> set of vehicles.
  - *E(t)={Eij}* -> direct communication links among vehicles i and j.

What are the spatio-temporal characteristics of the VANET Communication Graph ?

Networks Studied in the Literature

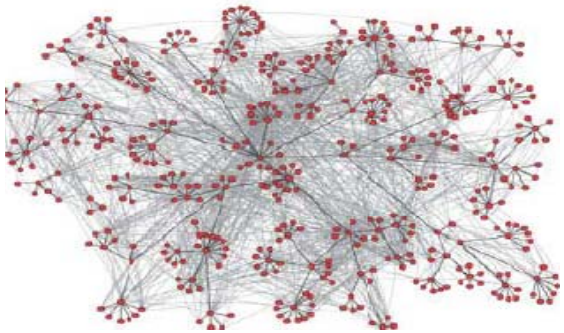


Internet network

(Faloutsos et. al., 1999)

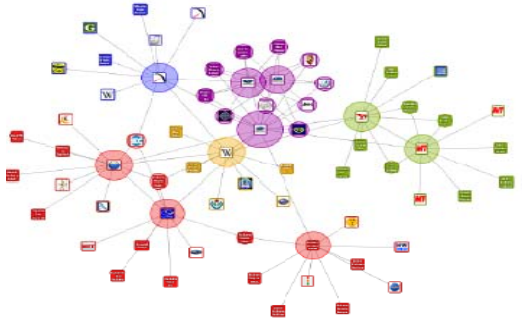
Social network

(Watts et. al., 2002)



MSN Communication network

(Leskovec et. al., 2008)



World Wide Web

(Raghavan, 2000)

Graph Metrics Examined

Localized Metrics

- Node Degree.
- Lobby Index.
- Link duration.

Network-Wide Metrics

- Network Diameter.
- Closeness Centrality.
- Betweenness Centrality.
- Bridging Centrality

Community Metrics

- Number of Clusters.
- Clustering Coefficient.
- Number of Communities.

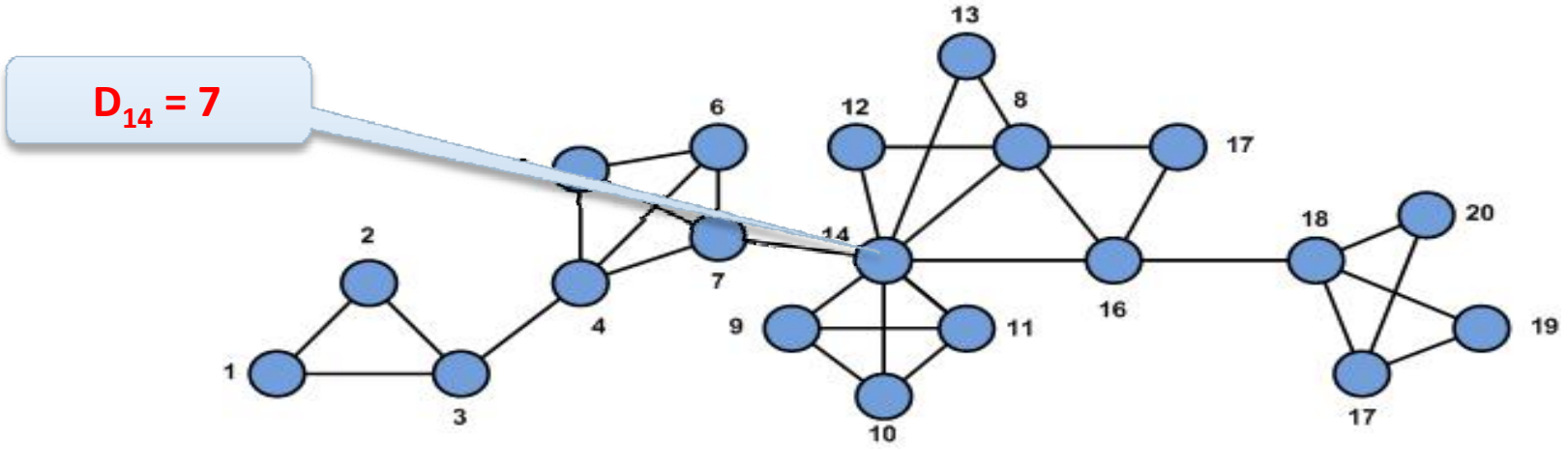
Traffic Data Studied

- **Realistic Vehicular Traces from city of Zurich**
  - Publicly available from http://www.lst.inf.ethz.ch/research/
  - Generated using the MMTS traffic simulator. **(V.Naumov et. al, MobiHoc 2006)**
  - MMTS simulates private and public traffic over regional maps.
  - Route choice of each vehicle is dynamic to react to time-dependent congestion effects.
  - Times studied: 6:00 a.m – 9:00 a.m
  - 200.000 distinct vehicle trajectories.

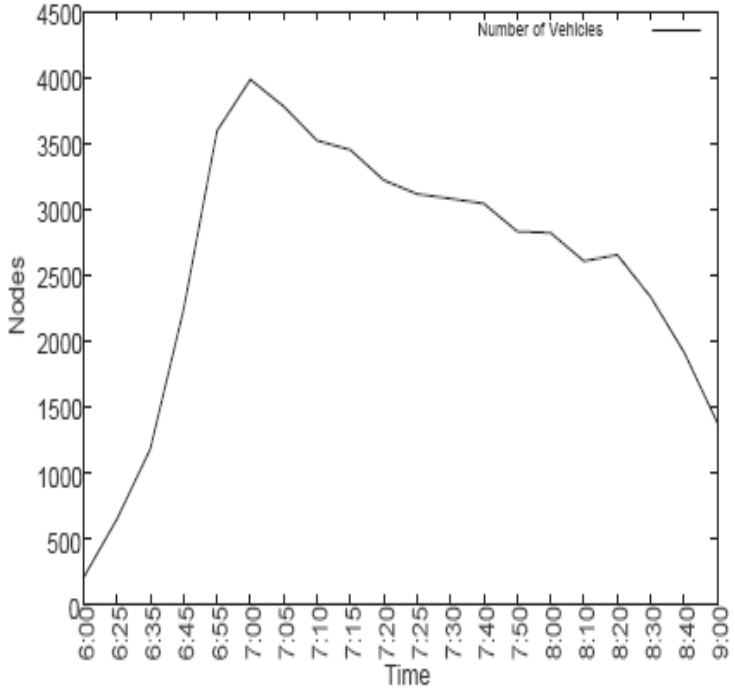
Network Analysis – Metrics

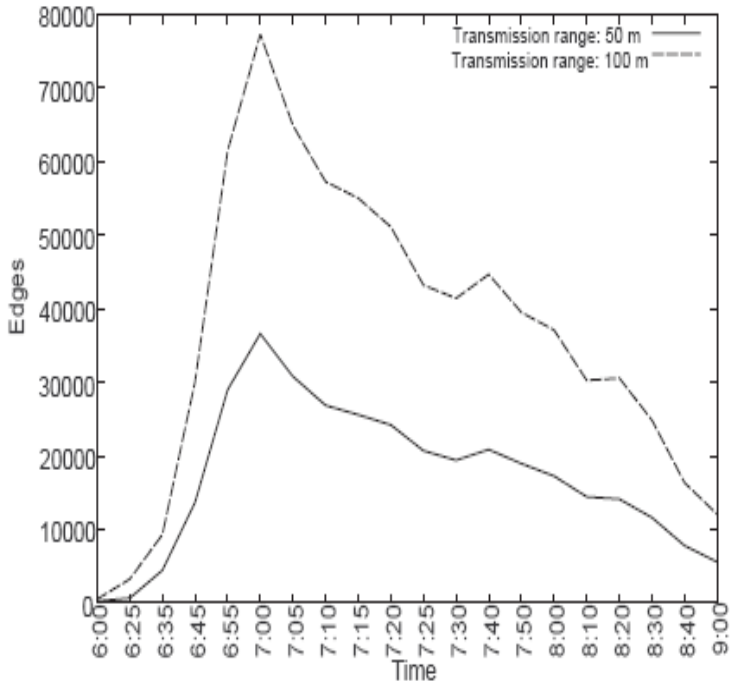
What are the laws that govern the temporal evolution of VANET graph properties ?

- **Node Degree (D_i)**
  - The number of vehicles in the transmission range of a node.
- **Network Diameter**
  - Longest distance between any two nodes in the network.



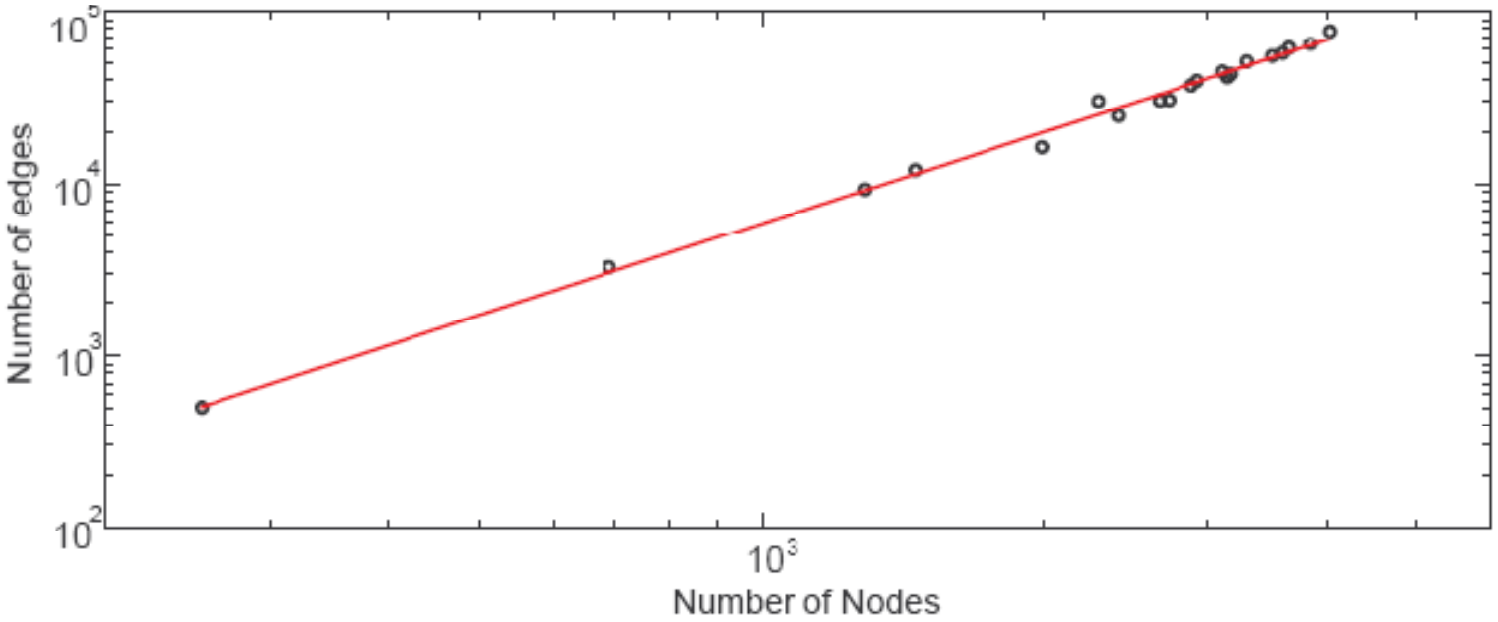
What are the laws that govern the temporal evolution of VANET graph properties ?





- VANET graph grows with the number of vehicles injected in the map and transmission range increases.

What are the laws that govern the temporal evolution of VANET graph properties ?

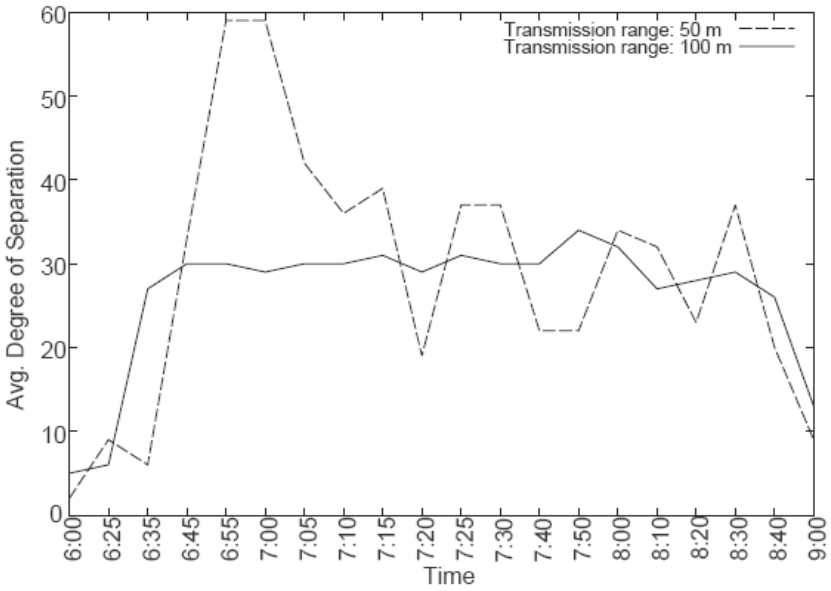


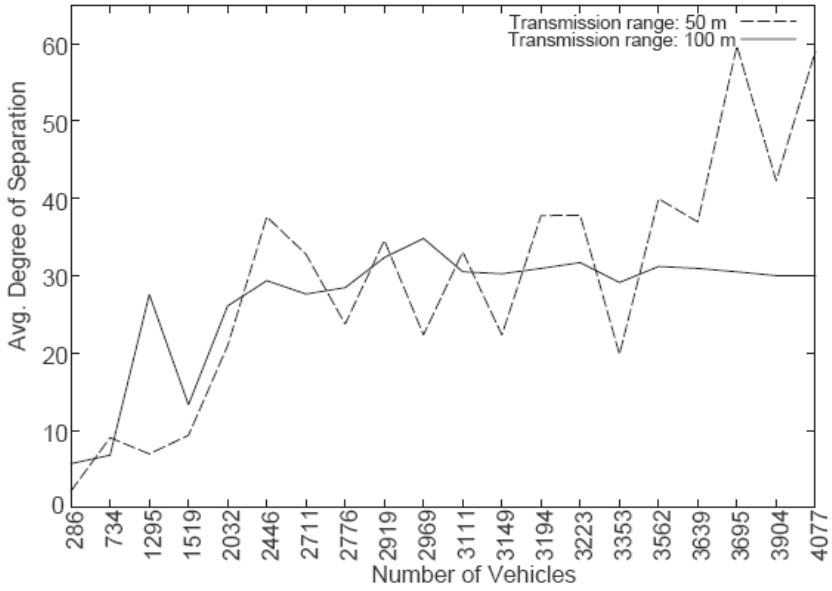
- VANET graphs obey a **power-law** with a consistently good fit.

$$E(t) \propto V(t)^{\alpha}, \text{ where } \alpha \simeq 1.77$$

- The VANET graph is **dense** (α=2 extremely dense graph).
- We can estimate the number of communication links in the network.

What are the laws that govern the temporal evolution of VANET graph properties ?





- Network diameter and the average node degree increase in most cases as the VANET grows in size.
- The VANET **does not** exhibit small world properties.
- Graph diameter follows avg. degree of separation and gets large values.

Protocol Design Implications

- *Dense VANET* :
  - Flooding is prohibitive → tremendous number of collisions.
  - Need for clustering protocols.
  - Transmission power adjustment is mandatory.

Centrality Analysis – Metrics

Do the centrality metrics identify "quality" nodes and what is the spatial distribution thereof?

Closeness Centrality

Betweeness Centrality

Bridging Centrality

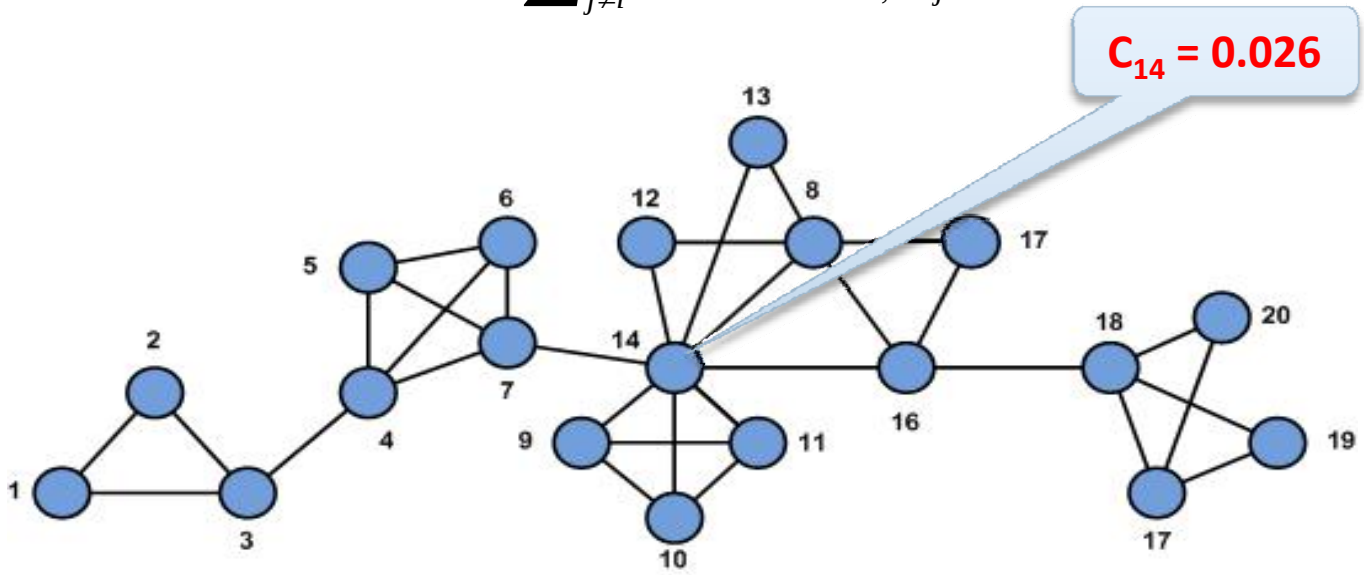
Lobby Index

Centrality Analysis – Metrics

Closeness Centrality

- *Measures how long it will take information to spread from a given vehicle to other vehicles in the network.*

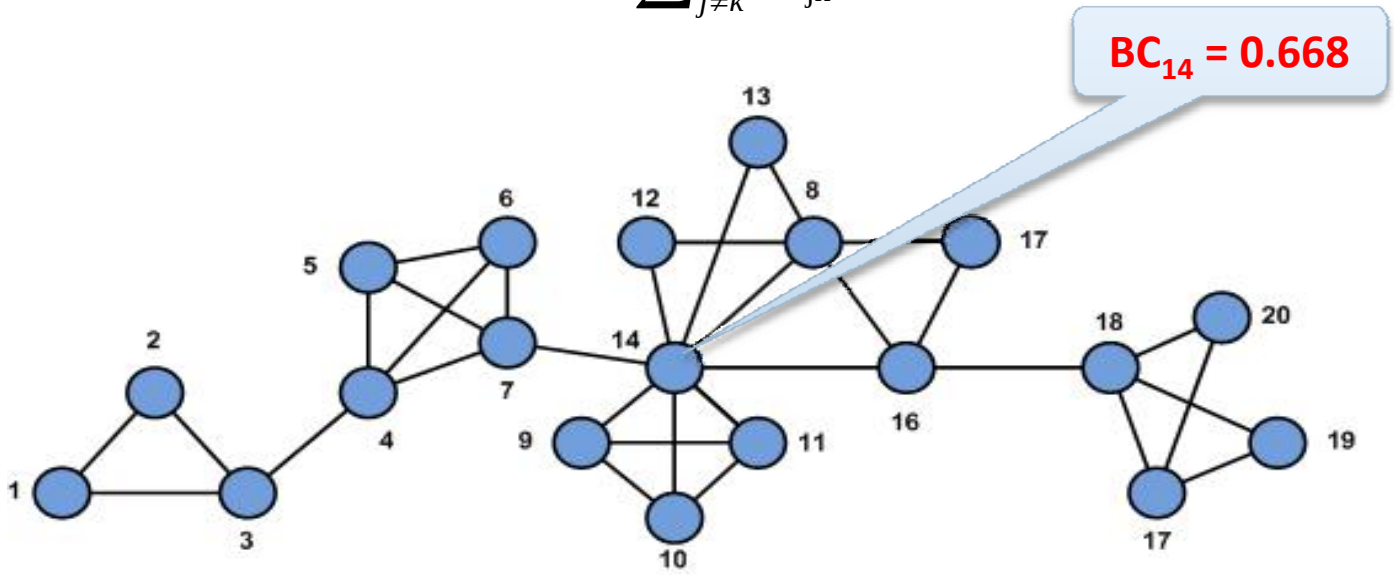
$$C_i(t) = \frac{1}{\sum_{j \neq i} \text{distance}(U_i, U_j)}$$



Centrality Analysis – Metrics

- **Betweeness Centrality**
  - *Measures the extend to which a vehicle has control over information flowing from others.*

$$BC_i(t) = \frac{sp_{j,k}(u_i, t)}{\sum_{j \neq k} \mathrm{sp}_{\mathrm{jk}}(t)}$$

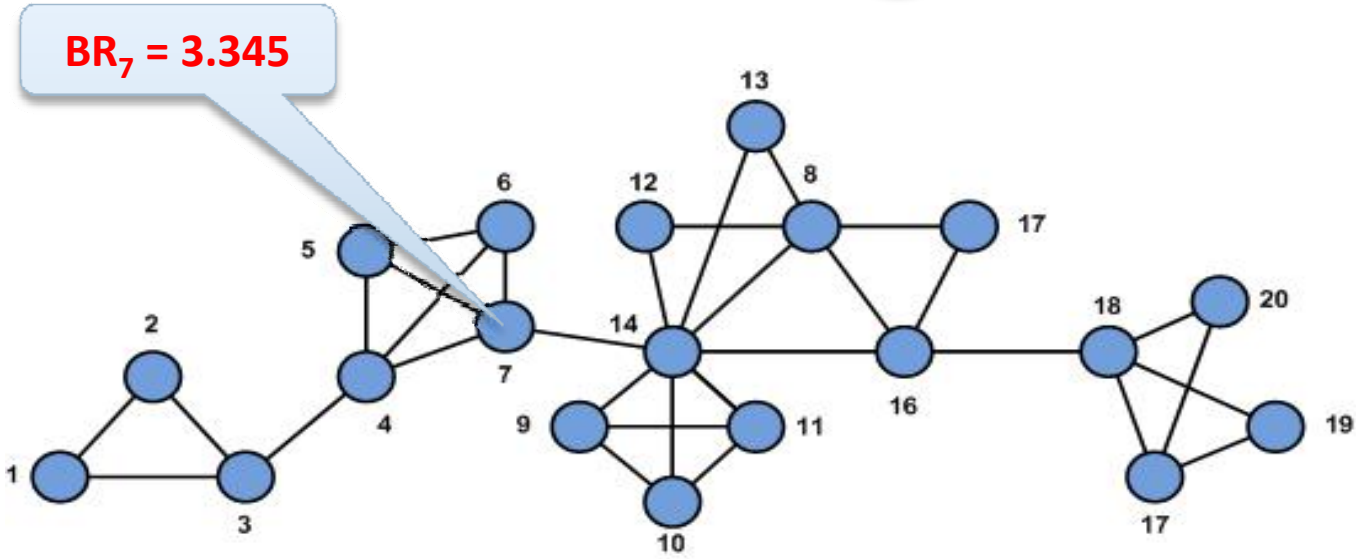


Centrality Analysis – Metrics

Bridging Centrality

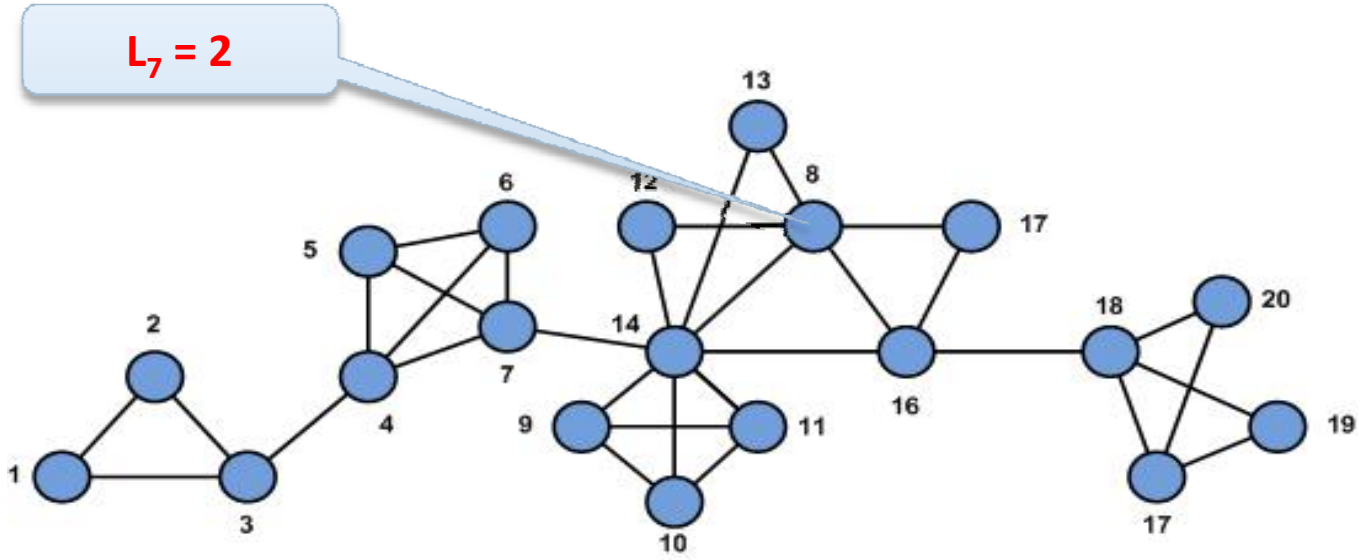
- *Attempts to find nodes that are central to the graph, but also have a low number of direct connections relative to their neighbours connections.*

$$BR_i(t) = BC_{u_i}(t) \bullet \beta(u_i)$$

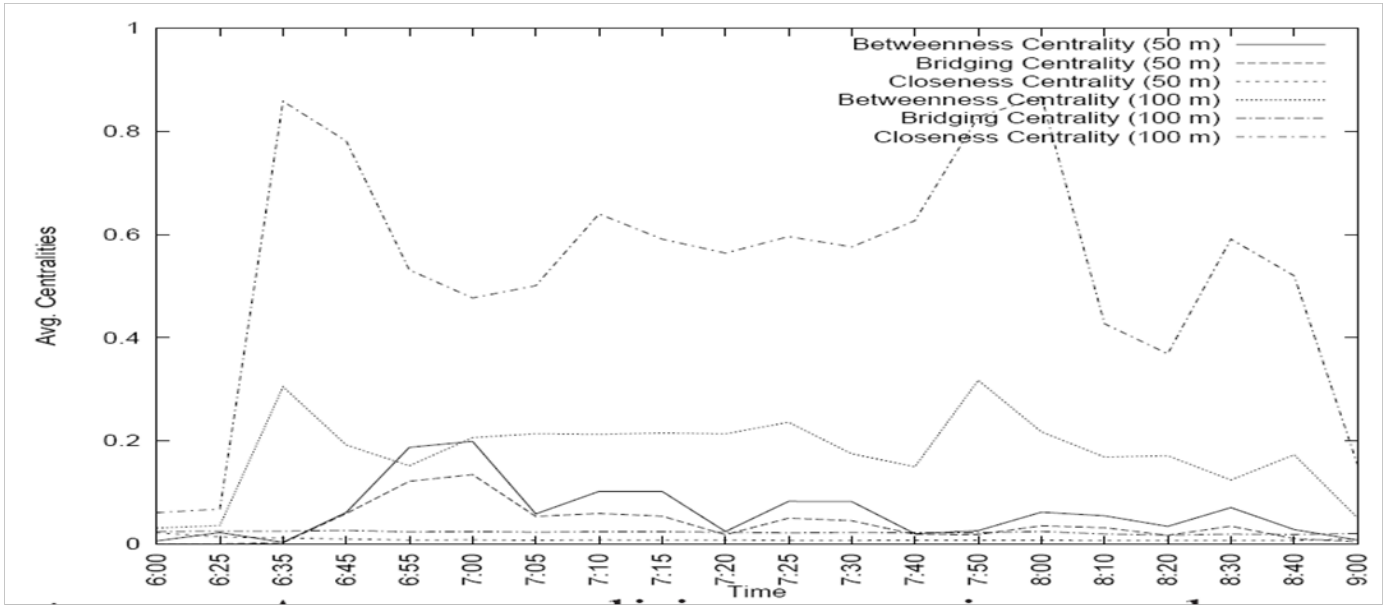


Centrality Analysis – Metrics

- **Lobby Index**
  - *The largest integer k such that the number of 1-hop neighbours of node U_i with degree k equals k.*

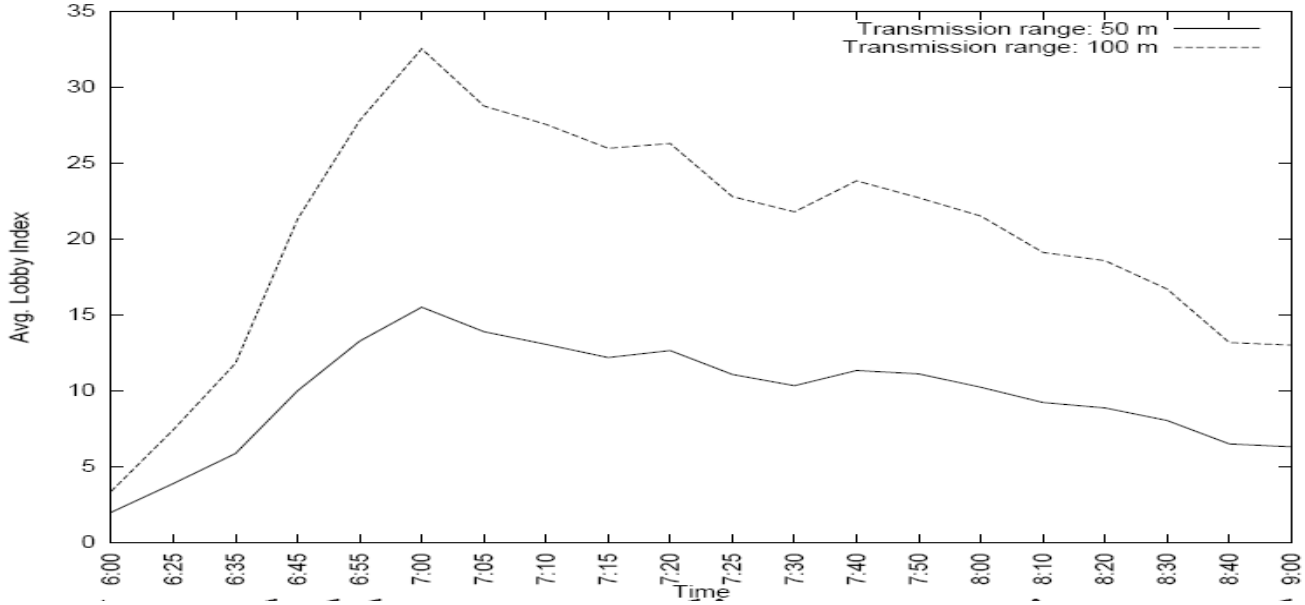


Do the centrality metrics identify "quality" nodes and what is the spatial distribution thereof?



- Distribution of central nodes **is not** affected by transmission range (similar shapes for T=50m & T=100m).
- Centrality is an indication of the "*latent*" behaviour of vehicles
  - Road Network
  - Driver Intentions

Do the centrality metrics identify "quality" nodes and what is the spatial distribution thereof?



- Lobby Index follows the general pattern of Betweenness.
- Several nodes with high Lobby Index value, few nodes with high BC value.
- **Betweeeness centrality** and **lobby index** are sufficient for capturing the structural properties of the VANET graph.

Do the centrality metrics identify "quality" nodes and what is the spatial distribution thereof?

- Are high-degree nodes also high-quality nodes?
- Use Pearson correlation coefficient (significance at 0.1).

	Betweenness	Bridging	Closeness	Lobby
Degree	0.044	-0.008	0.36	0.106

- High-degree nodes **are not** correlated with betweenness and bridging centralities.
- Node degree **is not able** to identify "*quality*" nodes in VANET.

Protocol Design Implications

- *Which nodes will be cluster-heads?* : Not necessarily those with high degree.
- *Which nodes will be cluster-heads?* Those with large betweenness centrality, if we need a few clusters.
- *Which nodes will be the forwarders in routing?*: Use any centrality metric to identify them.
- *How to spread a message to many nodes with few rebroadcasts? :* Use nodes with large lobby index.

Which are the link duration statistics in VANET when the vehicles are moving in urban areas ?

Transmission range	50 m	100 m
Time	6:00 – 9:00	6:00 – 9:00
Total links	21922350	23705232
Min	1 sec	1 sec
Max	978 sec	1105 sec
Mean	6.7531 sec	13.2038 sec
Median	3 sec	7 sec
Standard deviation	21.2401 sec	34.2413 sec

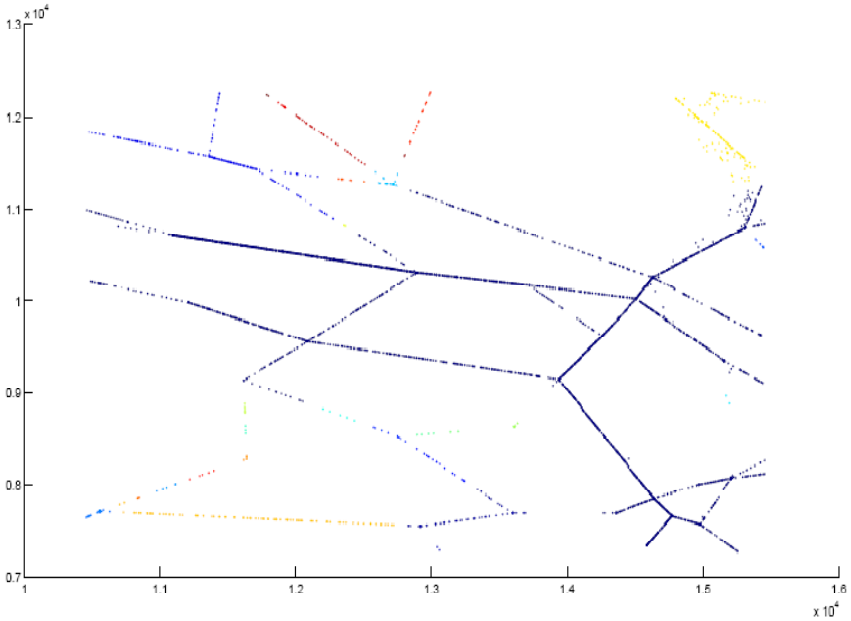
- Mean and Median indicate *high variability* in link duration.
- Most vehicles have low link duration but measured values can accommodate time requirements for VANET services (other studies showed successful transaction is 0.1 sec).
- Vehicles with high degree values have longer link duration times in comparison to those with low degree values.

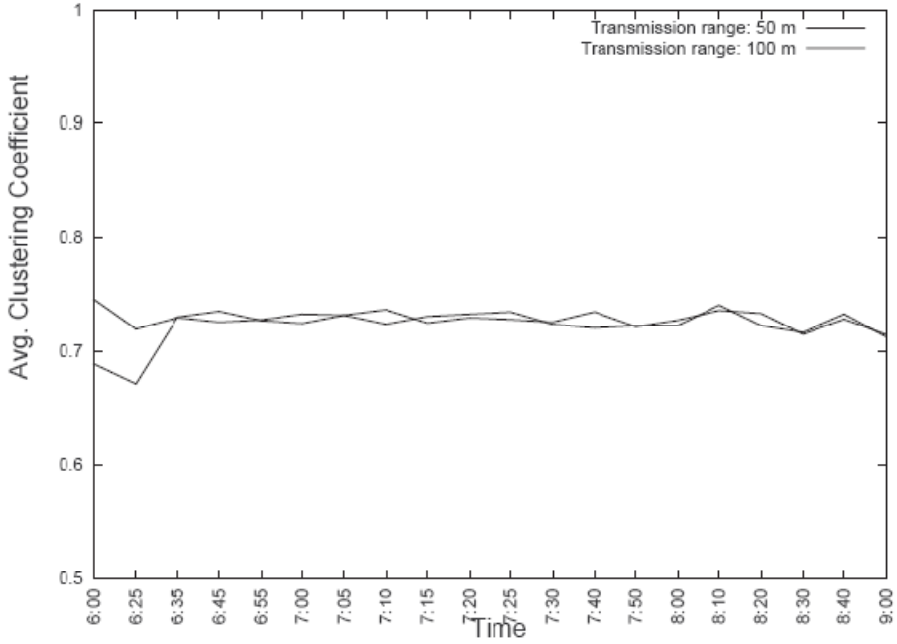
Cluster Analysis - Metrics

Does the VANET consist of a single connected component ? Are there any sub graphs inside VANET ?

- **Number of Clusters**
- **Clustering Coefficient**
  - *Measures the cliquishness of a network (Value =1 if network is clique).*
- **Number of Communities**
  - *Communities are sub-graphs where:*
    - *intra-community edges > inter-community edges*

Does the VANET consist of a single connected component?

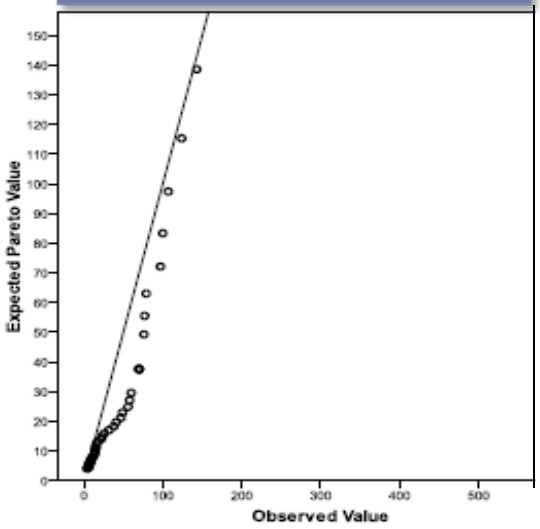




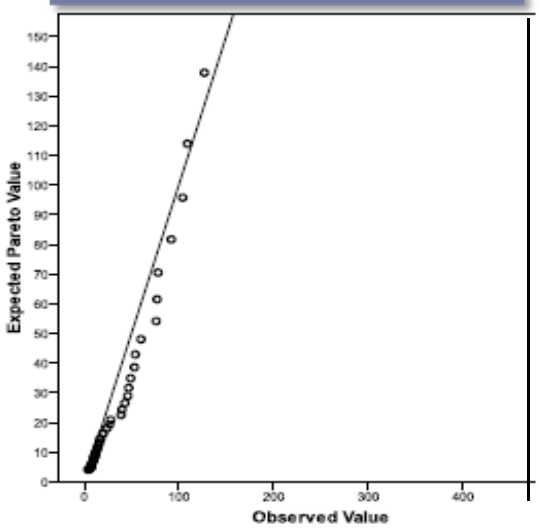
- The VANET graph includes a giant cluster.
- Clustering co-efficient stable (~0.73). No influence by density and transmission range.
- Existence of clusters → VANET ***graph is not connected***.
- Connectivity within a cluster remains stable over time.

Giant Cluster Analysis - Properties

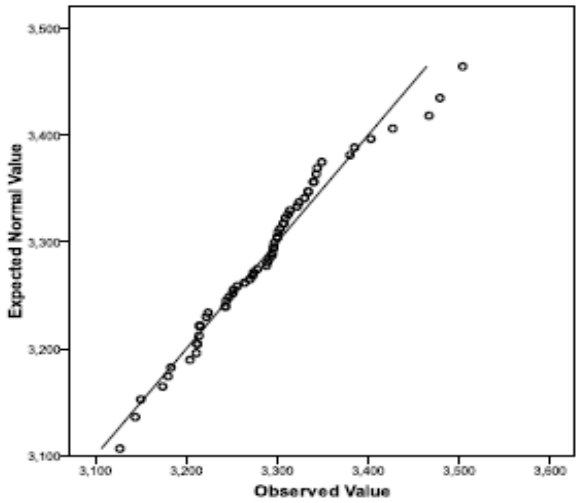
Distribution of Arrival Nodes



Distribution of Departing Nodes



Distribution of Static Nodes



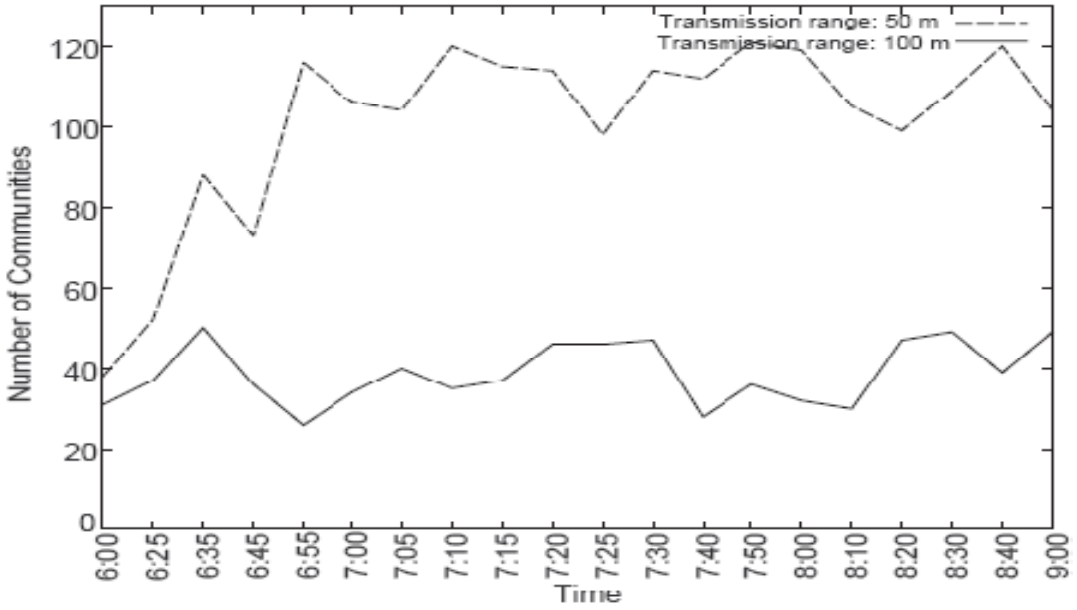
- Vehicle inter-arrival and inter-departures follow **Pareto distribution**

→ Burstiness is exhibited on several time scales.

- Static Nodes follow **Normal Distribution**.

- Cluster evolution over time can be predicted.

Do dense sub-graphs exists inside the VANET graph?



- Significant number of overlapping communities identified.
- Number of communities influenced by transmission range.
  - High transmission range →More edges → Longer and fewer communities.

Protocol Design Implications

- *Node with low localized clustering coefficient :* sparse network around it →Might consider forwarding the packets to roadside units to carry out the routing process.

- *Stable communities (clusters) exist?* : Run the solution for optimal placing of gateways to these communities

Thank you

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