# On the capacity of Vehicular ad hoc Networks

Muriel Mabiala, Anthony Busson and Véronique Vèque
Institut d'Eléctronique Fondamentale
Bat 220, Universite Paris-Sud, Centre Scientifique d'Orsay
91405 ORSAY cedex

***Abstract*— In this paper, we study the capacity of Vehicular Ad Hoc NETwork (VANET). Due to the particular topology of such a network, results on the capacity of two dimensionnal ad hoc networks are not convenient. Indeed, the nodes are ditributed on a line (the road or the highway), thus they form a chain of nodes. This particular topology reduces the spatial reuse with regard to two dimensionnal networks. The capacity is then smaller than in classical ad hoc networks. We propose a theoritical bound on the capacity that the VANET can offer to a inter-vehicle communication. We compare this bound to simulations results. We compare the capacity offers to a CBR flow when two routing protocols (GPSR and DSR) are used. These two routing protocols are representative of two kind of approaches (reactive and geographic) which have been shown efficient in VANET context.**

***Index Terms*— Vehicular Ad Hoc Network - Highly dynamic network - capacity estimation**

## I. INTRODUCTION

Vehicular Ad-Hoc Networks (VANETs) are a special kind of Mobile Ad-Hoc Network (MANET), where vehicles equipped with wireless devices constitute a network with no additional infrastructure. As not all vehicles are in the same radio range, some cars are required to relay packets on behalf of other nodes in order to insure network connectivity.

VANET networks can be used for two kind of applications: safety applications like alert diffusion, road foreseen, and user oriented applications like Internet access, VoIP, file transfers, advertising, etc. Both kinds of applications have different constraints as the required rate to support user oriented applications must be greater than for safety applications. Moreover, safety applications mainly use braodcasting or geocasting (broadcast in a given region) whereas user applications use unicast communication. For these unicast communications, a routing protocol is required. But, one of the properties of a VANET is its high dynamicity inducing frequent topology changes. It may involve an important control overhead with some routing protocols such as the proactive ones where a routing table is maintained for each node of the network. Particular routing techniques are thus studied for the VANET. Moreover, VANETs on a road or an highway generate a particular topology as cars are distributed in a line and the topology has only one dimension. As a consequence, network connectivity is greatly reduced as a small section of the road without any vehicle will break the network which is constituted of clusters without link among each other (see [10] for a study of connectivity in a VANET). Finally, this line topology also limits the spatial reuse since all the nodes located between a pair of communicating nodes will be on the path of both these nodes. Indeed, even nodes which are not forwarder for this communication, receive all the packets sent by the forwaders. The capacity is then reduced compared to classical ad hoc networks. In this paper, we evaluate the capacity of a VANET using realistic simulations. We combine a traffic simulator which generates realistic vehicle movements and a network simulator NS2. Next part focuses on the related works on VANET wireless capacity evaluation. In third part, we describe the analytical model we have developped. In fourth section, we introduce simulation scenario and the results we obtained.

### *A. Related works and contributions*

The study of the capacity of wireless ad hoc networks has received significant attention either for static ad hoc networks or mobile ad hoc networks. In a radio network, achievable capacity depends on time and spatial parameters. Time parameters come from traffic patterns whereas spatial parameters are function of network size, radio interactions and node mobility. In contrast with cellular networks, the capacity does not grow with network size because spatial reuse of the spectrum is limited by the forwarding property of ad hoc routing protocols in order to compute routes in the network or to relay traffic for other nodes. It means that the actual useful throughput per user pair has to be small.

For the static case and without assumptions on the MAC protocol, Gupta and Kumar [5] have considered a model in which n nodes are randomly located but fixed in a disk of unit area and each node has a random destination node. They showed that as the number of nodes n increases, the throughput per source and destination decreases to zero like $O(\frac{1}{\sqrt{n}})$ even allowing optimal scheduling and relaying of packets. When mobile nodes are considered, the previous analysis has been extended in [4], [11]. In [4], they use a random mobility model for user movements and they have showed that the throughput per S-D pair can actually be kept constant even as the number of nodes per unit area increases. As a result, most communication has to occur between nearest neighbours, at distance of order $\frac{1}{\sqrt{n}}$. The number of hops of a typical route is of order $\sqrt{n}$.

[11] extends this work as they consider more realistic mobility patterns (nodes move on great circles) and they show that the previous result holds when nodes moves in a limited manner.

In our case, the nodes correspond to vehicles evolving on a highway. The width of the highway is widely greater than the radio range of the nodes. So, from a connectivity point of view, nodes are distributed on a line rather than a two dimensionnal space leading to a lower capacity value, compared to the refered papers. Estimation of the capacity of a network formed by such a chain of nodes have already be done in [9] and [2].

In [2], the authors study the throughput between two vehicles. They equipped two cars with 802.11 card configured in ad hoc mode. They varied the distance between the two vehicles which are moving in the same highway lane. A throughput of at least $1$ Mbit/s is measured when the distance between the two vehicles is less than $300$ meters. They also estimated the throughput and the lifetime of a data transmission between two vehicles circulating in opposite directions with different speed. In the fastest case, i.e. for a speed of $110$ km/h (a relative speed of $220$ km/h), they measure a data transmission of $800$ KB for a lifetime of $8$ seconds. They concluded that the 802.11 technology can be used for intervehicle communications. An evaluation of the packet delivery ratio and delay for a communication between vehicles in a convoy is also done. In this case, the vehicle are moving in the same direction and the distance between vehicles stays constant. They compare $5$ routing protocols in this context. But the fact to consider a convoy involves that the topology of the network is not very mobile. In this context, protocol which does not support very well mobility as OLSR shows good results.

In [9], the authors study the capacity of a MANET for two kinds of topology: a chain of nodes and a grid of nodes. For communication on a chain where the source is the first node and the destination is the last node of a chain of $8$ nodes, they find via simulations a throughput of $0.25$ Mbps for a 802.11 rate of $2$ Mbps. The loss of capacity has several causes. First, in a chain when a forwarder receives a packet, it has to send it to the next forwarder, then the next forwarder sends it to the next one. So, a forwarder of the chain receives the packet twice and sends it once. It decreases the utilization to $\frac{1}{3}$ of the capacity. Second, interferences range is greater than radio range. In their simulations, they consider an interference range of $550$ meters for a radio range of $250$ meters. This decreases the bandwidth utilization to approximately $\frac{1}{4}$. Lastly, the number of competing nodes (collision, retransmission, etc.) and the access protocols (RTS/CTS, etc.) also affect the overall performance leading to the poor observed utilization ($\frac{1}{8}$ of the global capacity). It is important to note that the throughput depends on the 802.11 rate and the size of the packets.

In this paper, we investigate the capacity offers in average by the VANET. As explained earlier, vehicles form a chain. But, the existing results cannot be used to estimate the throughput as both the routing protocol and the mobility have an impact on it. The goal of this paper is to evaluate the impact of the vehicle mobility and the routing protocol on the capacity. This allows us to evaluate the throughput that a VANET can offer and the kind of applications which can be supported. This throughput is compared to an analytical bound and to results found in [9] where neither mobility nor routing protocol have been considered.

# II. MODELS

In this Section we describe the model used for simulations and the analytical model used to express a theoritical upper bound on the capacity.

## A. Road traffic simulator

In order to obtain vehicle movements close to the reality we use a traffic simulator. In it, each vehicle has to emulate the driver behavior. On a highway, the driver behavior is confined to accelerate, brake and change lanes. We assume that there is no on-ramp on our section of the highway. A desired speed is associated to each vehicle. It corresponds to the speed that the driver would have reached if he had been alone in his lane. If the driver is alone, he adapts his acceleration to reach his desired speed (free flow regime). If he is not alone, he adapts his acceleration to the vehicles around (car following regime). He can also change lanes if the conditions of another lane seems better. All these decisions are functions of environment of the vehicles (speed and distance) and random variables used to introduce a different behavior for each car. This kind of simulation is called micro simulation and the model we use is presented in detail in [1]. We simulated a three lane segment of a highway, where the desired speed of vehicles is $120$ km/h. The density of vehicles i.e. the mean number of vehicles per kilometer is $24$. It corresponds to a situation where the vehicles are moving freely. With this density the probability that there exists a path between two vehicles distant of a few kilometers is high (according to [10], this probability is $0.95$, $0.89$ and $0.74$ for a distance of $1$, $2$ and $5$ kilometers and a radio range of $R = 0.25$ km). It allows us to partially abstract the computation of the capacity from the problem of connectivity.

## B. Network simulator

The realistic vehicle movements are injected in the network simulator NS2. In our experiments, the standard IEEE 802.11b radio interface is used with channel rate of 2Mbps. The transmission range is $250$ meters and the carrier sensing range is $550$ meters. The duration of each simulation run is $90$ seconds. For each set of parameters, the results shown in the different figures are the mean value of $xxx$ samples. These mean values are reported with a 95% confidence interval. For each connection, the source sends 512 bytes data packets.

## C. Routing protocols

The two routing protocols we shall consider in the simulations are DSR and GPSR. They are briefly described in the two paragraphs below. They are representative of the two most efficient routing approaches in highly mobile ad hoc network: reactive and geographic. Indeed, proactive protocol where routing tables are updated in real time are inaccurate. The frequent change of topology involves a too important number of control messages to keep the routing tables up to date.

*a) DSR:* DSR (Dynamic Source Routing Protocol [7]) is a source-routed on demand routing protocol. The two major phases of the protocol are: route discovery and route maintenance. When a source node wants to send a packet to a destination node, it looks in the memory cache to determine if it has a route to the destination. The route record is the whole list of forwarders used to reach the destination. If the source has such a route, it send the packet containing the route record in the header to the next forwarder. If it does not have a route in the cache, it initiates the route discovery process by broadcasting a route request packet. The route request packet contains the address of the source and the destination, and a unique identification number. Each intermediate node checks if it has a route record to the destination. If it does not, it adds its own address in the route request header and broadcasts the route request packet to its neighbors. The route reply is generated when either the destination or an intermediate node with current information about the destination receives the route request packet. This route reply is unicast to the source and contains the route record to reach the destination. The benefits of such a protocol are that there is no routing tables, only sources have an entry corresponding to the destinations for which they are sending data. It greatly limits the protocol overhead. These entries are reactively up to date when a route failure is detected. The mechanism of route maintenance is sufficiently reactive to avoid massive losses when searching a new route. A performance evaluation of DSR in the context of VANET have been led in [10].

*b) GPSR:* GPSR (Greedy Perimeter Stateless Routing) [8], exploits the correspondence between geographic position and connectivity in a wireless network, by using the positions of nodes to make packet forwarding decisions. A node willing to forward a packet has to know the location of its neighbors (the nodes which are in the radio range of this node), it send the packet to the neighbor which is the closest in term of Euclidian distance to the destination. This greedy forwarding rule is used untill the destination is reached. If there is no node in the neighborhood which is closer to the destination than the current node, the forwarder is chosen according to the "Right hand rule". Roughly speaking, the next forwarder will be the first node on the right hand side of the current node. We use a modified version of GPSR. Indeed, with the first version of GPSR [8], Hello Packets are exchanged in order for each node to learn locations and adresses of its neighbors. But this approach leads to out of date list of neighbors. Indeed, Hello packets are emitted at regular interval (generally equals to a few seconds) and nodes may have moved since the last Hello. It is especially true in a highly dynamic network like a VANET. Several solutions have been proposed to solve this problem [3], [6]. We use the reactive GPSR proposed in [6]. It consists for a node which forwards a packet in first broadcasting a query in its neighborhood. All the neighbors unicast a response with their adresses and locations. With this mechanism, the forwarder has an up to date view of its neighborhood. It then chooses the next forwarder with the usual GPSR forwarding rule.

With GPSR, nodes do not have routing table to maintain, they just need to maintain a neighborhood table and for the reactive GPSR there is no table at all. Therefore, it is particularly adapted to highly dynamic networks. A performance evaluation of GPSR in the context of VANET has been led in [10].

### D. *Capacity per flow*

In this paper, our objective is not study the efficiency of these routing protocols to find the best path to the destination. We aim at evaluating the impact of both routing protocol and mobility on the capacity of the network. More precisely, the quantity we consider is the capacity that the network can offer to a source. We assume that there is a proportion of $p$ $(0 < p < 1)$ emitting nodes. We associate to each source a destination, randomly chosen among all the nodes. We initiate a CBR (Constant Bit Rate) flow from each source to its destination. The CBR flows consist in sending $N$ packets per second and are the same for all the sources. The packets size is fixed to $512$ bytes.

### E. *Theoritical bound on the capacity*

| $L$ | $2$ | $4$ | $6$ | $8$ | $10$ |
|---|---|---|---|---|---|
| $alpha$ | $0.65$ | $0.1875$ | $0.125$ | $0.12$ | $0.12$ |

TABLE I

BANDWIDTH UTILIZATION IN 802.11 WITH A CHAIN OF $L$ NODES (PACKET SIZE= $512$ BYTES AND $802.11$ RATE=2 MBIT/S)

In order to estimate the mean capacity offers to a given flow we make the following assumption: we assume that the capacity offers to a flow is proportional to the global capacity divided by the number of concurrent flows. The throughput for a flow is thus proportional to $\frac{B}{M}$ where $B$ is the technology bandwidth (equals to $2Mbit/s$ in our simulations) and $M$ is the mean number of communications passing through a node. The number of concurrent flows in a part of the network depends on the spatial reuse thus the topology of the network. Since the nodes form a chain and assuming that $\lambda$ is the mean number of nodes per kilometer, $R$ is the radio range, $p$ is the proportion of emitting nodes and $L$ is the mean number of hops for a communication, we have:

$$\frac{B}{M} = \frac{B}{\lambda pRL}$$

The throughput for a given communication is thus less than $\alpha\frac{B}{\lambda pRL}$. The coefficient $\alpha$ is a coefficient which takes into account the utilization of the bandwidth. As explained in Section I-A, the throughput measure in a chain of nodes decreases with the size of the chain. The throughput for a single communication through a chain of nodes has been measured in [9]. We use this approximation to compute our theoritical bound. In Table I, we give the parameter $\alpha$ according to [9] as a function of the mean size of the chain (it will correspond to the mean number of hops in our simulations). But, as long as this bound is not reached, the throughput per flow is equal to the emission rate denoted $c$ (if $N$ is the mean number of packets generated per second, the emission rate is $c = N * 512 * 8$ bits/s):

$$\text{throughput} \leq \min\left(c, \frac{B}{\lambda pRL}\right)$$

## III. Capacity per node

In this Section we present the results of the simulations and compare them with the theoritical bound result. At least two reasons can cause the difference we remark between the theorical bound and simulations results. First, a route to the destination does not always exist. Second, the capacity depends on the efficiency of the routing protocols: ability to find the route when it exists, amount of bandwidth used by control packets, reactivity of the routing protocol to update the route due to nodes mobility. The capacity per flow (also named throughput in the following) shown in the different figures is the average on all the flows of a simulation. To obtain the capacity for a given flow, the total number of bits received by the destination is divided by the lifetime of the CBR flow.

### A. Capacity for a single communication

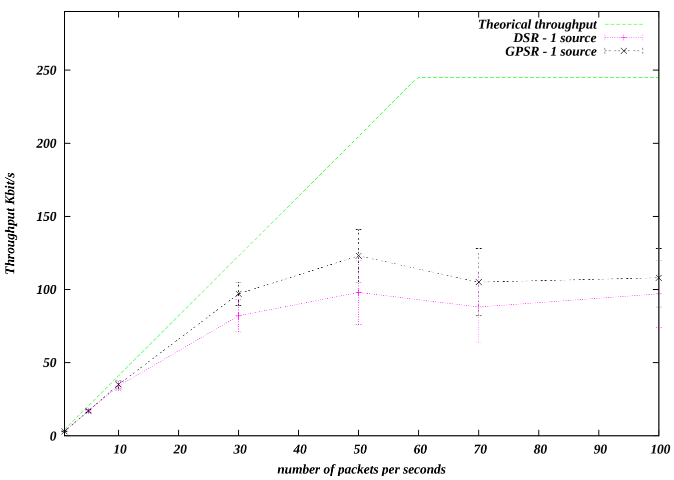


Fig. 1. Capacity for one communication as a function of the emission rate

First, we estimate the capacity when there is only one CBR flow in the network. In this case, all the available bandwidth on the path between the source and the destination is dedicated to this communication. It allows us to estimate the maximum available throughput and to compare it to the theorical bound. Since we consider only one flow, the theoritical throughput is in this case:

$$throughput \leq \min\left(c, \alpha B\right)$$

where $\alpha$ is given in Table I (the number of hops is approximately $6$ in these simulations leading to $\alpha = 0.125$). In Figure 1 we plot this capacity as the number of packets sent per second $N$ which increases from $1$ to $100$ (the emission rate varies from $4$ to $400$ Kbit/s). As long as $N < 20$ (the emission rate is less than $82$ KBit/s), there is no loss and all the packets are received at the destination. When $20 < N < 50$, some packets are lost because of congestion whereas GPSR and DSR give similar results. When $N > 50$, the throughput is kept constant (approximately $90 Kbit/s$) with DSR, whereas GPSR collapses. The poor performances of GPSR are explained by the fact that we use the reactive GPSR release where several control packets are transmitted each time a node forwards a packet of data. The throughput with DSR does not vary because the overhead does not depend on the traffic rate.

### B. Throughput as a function of the communication rate

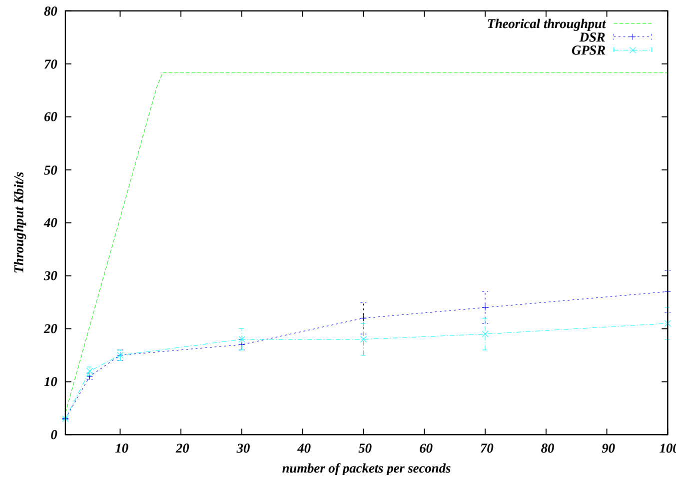


Fig. 2. Capacity when there are several communications as a function of the emission rate $N$

In Figure 2, we vary the emission rate of the CBR flows, but we consider that $10\%$ of the nodes have initiated a CBR flow to a randomly chosen destination. The capacity of the network is then divided by all the communications. The throughputs achieved by the two routing protocols are quite close to the maximum expressed by the theoritical bound when the rate is less than $5$ packets per second. After this point, the packet delivery ratio decreases less faster than the emission rate leading to an increasing throughput. Beyond a threshold ($30$ for GPSR and $40$ for DSR), the packet delivery ratio decreases faster than the emission rate and the throughput decreases. An analysis of the trace files of the simulations shows that the losses are mainly due to congestion. DSR offers better performances than GPSR: as in the previous case, the overhead in GPSR increases with the traffic in contrast of DSR.

### C. Throughput as a function of the number of flows

In Figure 3, we vary the proportion of sources from $1\%$ to $30\%$ of the nodes. Since the mean number of hops is approximately $6$, the mean number of communications which crosses through a node (equals to $\lambda LRp$ in average) varies from $1$ to $11$. The ratio between the theoritical bound and the observed throughput is more or less $\frac{1}{2}$. In this case, the performances of DSR and GPSR are equivalent. Indeed, the overhead of DSR increases with the number of flows and in this case, DSR is experienced the same routing overhead as GPSR.

### D. Capacity as a function of the number of hops

In order to increase the mean number of hops of the flows, we choose a vehicle in a longer section of the highway.

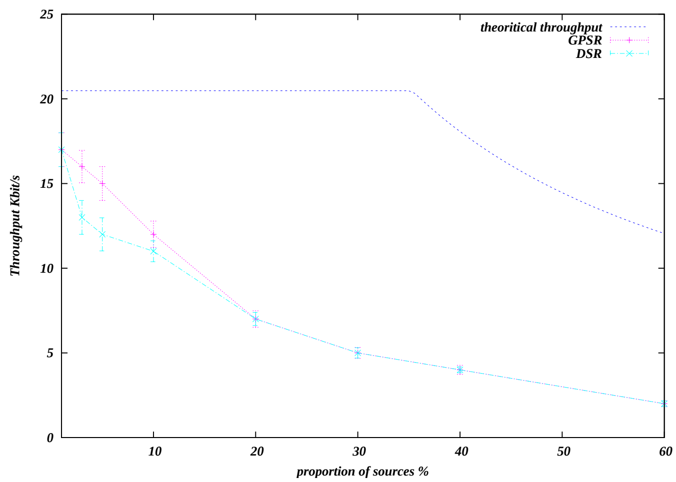


Fig. 3. Throughput as a function of the number of CBR flows ($N = 5$)

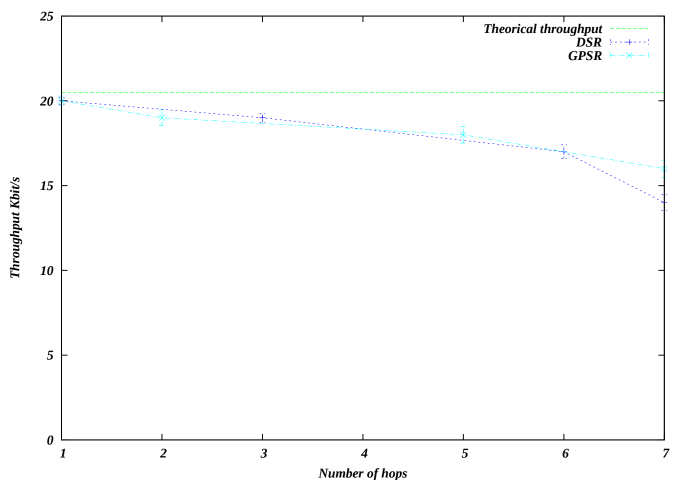


Fig. 4. Throughput as a function of the distance between sources and destination

In Figure 4, we plot the capacity per flow when the mean number of hops varies from $3$ to $10$. The throughput is kept quite constant until the number of hops reaches $8$. After this value, the throughputs for GSPR and DSR are decreasing. It is difficult to estimate throughput for higher numbers of hops because, for $L > 10$, the probability that the path does not exists to the destination does not become neglictible.

DSR has a better behavior in term of throughput than GPSR for all the cases except when the number of sources increases. In this study, we have neglected the overhead of a location protocol service which allows a node to learn the location of the destination. This information is required in every geographical routing protocols. The performance of GPSR presented here is thus optimistic. But even for DSR, the throughput measurement is very small. We knew that a chain of nodes greatly reduces the capacity of the network, but combining routing protocols with mobility of a VANET has lead to divide this capacity by two.

## IV. Conclusion

In this paper, we have studied the capacity offered by a VANET while using either geographical routing or reactive protocols. We have compared it to the theoritical capacity of a chain of fixed nodes which matches to an upper bound on the achievable throughput since it was computed when neither mobility nor routing control overhead are taken into account. It appears that the capacity of the VANET is very lower than this bound. Even for DSR which is characterised by few routing overhead, the observed throughput is very low. We consider this low rate is not a drawback for safety applications which do not require an important capacity. In the contrary, user-oriented applications like file transfer or Voice over IP will be penalized by this throughput and will not perform as well. We think that the best way to increase the throughput in VANET is to use an hybrid network where dedicated base stations are deployed along the road. Hybrid network has the advantage to greatly decrease the number of wireless hops used to reach the destination, increasing the spatial reuse and thus the capacity. An estimation of the capacity of an hybrid network in the context of a VANET will be studied in a future work.

## References

[1] Kazi I. Ahmed. *Modeling Drivers'Acceleration and Lane Changing Behavior*. Doctor of science in transportation systems, Massachusetts Institute of Technology, Boston (MA), 1999.

[2] Y. Khaled B. Ducourthial and M. Shawky. Conditional transmissions, a strategy for highly dynamic vehicular ad hoc networks. In *8th IEEE Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2007)*, June 2007.

[3] Bhaskar Krishnamachari Dongkin Son, Ahmed Helmy. The effect of mobility induced location errors on geographic routing in mobile ad hoc and sensor networks: analysis and improvement using mobility prediction. *IEEE Transactions on mobile computing*, 3(3):233 – 245, 2004.

[4] Matthias Grossglauser and David N. C. Tse. Mobility increases the capacity of ad-hoc wireless networks. In *INFOCOM*, pages 1360–1369, 2001.

[5] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Trans. on Information Theory*, 46(2):388–400, March 2000.

[6] M. Mauve H. Fler J.Widmer. Beaconless position-based routing for mobile ad-hoc networks. Technical Report TR-03-001, Department of Computer Science, University of Mannheim, 2003.

[7] David B. Johnson, David A. Maltz, and Yih-Chun Hu. The Dynamic Source Routing protocol for mobile ad hoc networks (DSR), July 2004. Internet-Draft, `draft-ietf-manet-dsr-10.txt`.

[8] B. Karp and H. T. Kung. GPSR: Greedy Perimeter Stateless Routing for wireless networks. In *Proc. of 6th ACM/IEEE Int. Conf. on Mobile Computing and Networking (MobiCom 2000)*, pages 243–254, 2000.

[9] Jinyang Li, Charles Blake, Douglas S.J. De Couto, Hu Imm Lee, and Robert Morris. Capacity of ad hoc wireless networks. In *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 61–69, New York, NY, USA, 2001. ACM Press.

[10] A. Busson M. Mabiala and Véronique Vèque. Inside vanet: hybrid network dimensionning and routing protocol comparison. In *IEEE 65th Vehicular Technology Conference VTC2007-Spring*, April 2007.

[11] D. Tse S. Diggavi, M. Grossglauser. Even one-dimensional mobility increases ad hoc wireless capacity. In *ISIT 02, Lausanne, Switzerland*, June 2002.