THE CRITICAL MASS PROBLEM OF MOBILE AD-HOC NETWORKS

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ABSTRACT

Mobile ad-hoc networks have become increasingly popular in the last years and promise a huge potential for the future. Ad-hoc networks allow users to communicate without a fixed network infrastructure, thus are interesting for many mobile communication scenarios. Multi-hop ad-hoc networks extend the communication range of individual nodes with the help of ad-hoc routing protocols. Many researchers focused on lower communication layers and developed several protocols in the past. In this paper, we want to abstract from the physical layer, the data link layer and routing issues and want to measure the quality of an ad-hoc network independently from network and hardware issues. For this, we first introduce a formal network model and a set of metrics. With the help of a simulation tool, we then measure the quality of ad-hoc networks in specific scenarios. We especially want to discover the prerequisites for sufficient connectivity, stability and coverage. We call the number of nodes to form a reasonable network the *critical mass*. As a result of our simulations, we get a considerable high critical mass for realistic usage scenarios.

KEYWORDS

Mobile computing, wireless communication, ad hoc networks, evaluation metrics

1. INTRODUCTION

Mobile ad-hoc networks are self-organizing structures in which mobile nodes are temporarily connected without the aid of any fixed infrastructure or centralized administration. Mobile ad-hoc networks promise a high potential for mobile and ubiquitous computing scenarios. As they do not need any fixed infrastructure, they even work in environments where a pre-installed wired network is too cost-intensive or even impossible. Typical areas for ad-hoc networks are public places such as airports, fieldwork areas, disaster areas or military battlefields. In addition, ad-hoc networks may serve as access networks for commercial (e.g. cellular phone) networks.

As mobile devices and wireless networks get increasingly powerful, many researchers expect ad-hoc networks to play an important role for mobile users in the future. Many encouraging simulations affirm this view. Having a closer look however, these simulations are often based on idealistic assumptions. Often, a wide radio communication range (e.g., 250m) and a homogeneous distribution of nodes are assumed. In reality, we often have restricted communication ranges of 10 to 30m. As users usually walk on specific ways (e.g. streets or sidewalks) and assemble at interesting places, we have a strongly inhomogeneous distribution among the observed area.

In this paper, we want to investigate the prerequisites to form a reasonable ad-hoc network for a certain realistic environment. For this, we abstract from specific routing protocols, packet throughputs, network hardware etc. and measure the quality of a network with the help of a set of metrics. We applied our metrics to a realistic scenario - the *Minneapolis Skyways* with its shopping levels and ways for pedestrians. Simulating this scenario leads to a discouraging observation: we need more than 2000 nodes in an area of about 500m x 500m to establish a reasonable network. Compared to approx. 50 nodes under idealistic assumptions, this is a very high number, thus the whole idea of ad-hoc networks may be questionable.

2. RELATED WORK

In this paper, we follow the IETF definition of mobile ad-hoc networks (in the following called *MANETs*) [10]: MANETs are wireless multi-hop networks which organize themselves. Especially, the topology may change rapidly. To enable communication between nodes which are not directly connected via the wireless communication technology (e.g. Wireless LAN IEEE 802 or Bluetooth), networks use ad-hoc routing protocols such as LMR [5], Link Reversal [6], DSR [13], OLSR [11], DSDV [17], or TORA [16] to find routes to a receiver.

A number of approaches have been published in the last years, which deal with quality analysis of MANETs. Gupta and Kumar [8] assume n randomly located nodes, each capable to transmit with W bit/s over a wireless channel. Their analysis show that the throughput obtained by each node is $\Theta\left(W / \sqrt{n \cdot \log(n)}\right)$ bit/s, i.e., the throughput dramatically decreases with higher number of nodes. Jinyang et al. [12] examine the throughput of WLAN 802.11 networks. They find out that the capacity of long chain of nodes inside an ad-hoc network is 1/4 of the channel capacity obtainable from the radio connection. Glossglauser and Tse [7] show that inside an ad-hoc network the per-session throughput can increase when nodes are mobile rather than fixed. However, they made several idealistic assumptions und use loose delay constraints. Santi et al. [18] investigated, which wireless communication range ensures a strongly connected network. They assume an n-dimensional region with a homogeneous distribution of nodes. Their analysis focuses on a strong connected network, i.e. each node is connected to each other. This is a very hard requirement, usually not achieved in real ad-hoc network.

In contrast to the approaches above, we do not have the assumption of homogeneously distributed users among the observed area. As we do not have a simple model to describe the movement of mobile nodes (e.g. the random waypoint model), a closed analytical or probabilistic approach is very difficult to achieve. In this paper, we thus specify the metrics and restrict the analysis on simulations.

Compared to other approaches, we introduce a number of new metrics that measure the quality of a MANET; especially the combination of *reachability*, *vulnerability* and *coverage* is new and reflects the end-user's demand of a stable network with a high degree of connectivity.

3. MEASURING MANET'S PROPERTIES

In the following, we introduce a network model, which does not deal with physical aspects. We assume that two nodes, which are in communication range, are linked together with a maximum throughput without any errors. Beyond a certain distance, the communication breaks down immediately, i.e. the communication quality does not smoothly decrease when the distance between two nodes gets larger.

We observe a specific MANET in a time interval $[t_1, t_2]$ in an area *A*. Let $N = \{N_1, ..., N_n\}$ denote the set of all network nodes, which have been active at least once in the area *A*. Every node $N_i \in N$ has a position, denoted by $p_i(t)$.

Let $O(t) \subseteq N$ denote the set of network nodes, which are active (i.e. online) at a certain time $t \in [t_1, t_2]$. Active nodes can send, receive and route packets. We introduce *O* for two reasons: first, nodes may participate in the MANET, but are temporarily switched off. Second, nodes may only pass through the MANET, i.e. only participate for a short time and then disappear. *N* does not change over time, thus we use *O* to model the behaviour of such nodes. For every node $N_i \in O(t)$, we introduce the sets $c_i(t)$ and $r_i(t)$:

- $c_i(t)$ denotes the set of *directly* connected nodes. Only active nodes can be connected, i.e. $c_i(t) \subseteq O(t)$. We only consider bi-directional connections, thus $N_i \in c_j(t) \Leftrightarrow N_j \in c_i(t)$.
- $r_i(t)$ denotes the set of nodes reachable by *multiple hops*. $N_j \in r_i(t)$ if either $N_j = N_i$ or $N_j \in c_i(t)$ or N_i and N_j can communicate with the help of directly connected intermediate nodes.

This model implies an important simplification of real MANETs: after a topologic change, both $c_i(t)$ and $r_i(t)$ *immediately* contain the correct sets of communicating nodes. In reality, changes have to be propagated via the network with a finite speed and inactive or unreachable nodes could be falsely viewed as reachable.

Based on this network model, we introduce a number of metrics. Our metrics should not be confused with metrics used to find optimal routes from sender to receiver in routing protocols (e.g. hop counts). Our metrics measure particular characteristics of the entire network. We asked ourselves following questions:

- When a new node enters the area of a MANET, how high is the probability to be instantly connected?
- Once a node is connected to the MANET, how many nodes can it access, or in turn, how many nodes can access the new node?
- Once a node accessed another node, how stable is the communication link?

If we knew the surface or volume covered by the MANET, the first question could be answered, using p_i and the communication range. Examining the sets r_i leads to an answer to the second question. The third question is more difficult to answer: moving specific nodes may disable an ongoing communication where other nodes are less important to existing communication links. We measure this effect by introducing so-called *important* nodes later.

Segmentation

The first metric is called the *Segmentation*, which is used as a basis for further metrics. The Segmentation S denotes the number of segments in the MANET. Nodes inside a segment can only communicate to nodes inside the same segment. Equation (1) shows how S is related to r_i.

$$S = \sum_{N_i \in O} \frac{1}{|r_i|} \qquad \textbf{(1)}$$

To get a measurement, which is independent from the current number of nodes, we introduce the *Normalized Segmentation SN*:

$$SN = \begin{cases} \dfrac{S-1}{|O|-1}, & \text{if } |O| > 1 \\ 0, & \text{otherwise} \end{cases} \qquad \textbf{(2)}$$

SN has values between 0 and 1 where *SN* = 0 means *no segmentation* and *SN* = 1 means *maximum segmentation* (all nodes are separated).

Coverage

To measure the surface or volume a MANET covers, we first introduce the *Coverage Area*. The Coverage Area *CA* is the area inside *A* where an inactive node can become active without increasing the number of segments. Note that activating a node inside the Coverage Area does not necessarily mean to be connected to *all* nodes in the MANET. We define the *Coverage C* to get a value, which is independent from the size of the area *A*:

$$C = \frac{vol(CA)}{vol(A)} \qquad \textbf{(3)}$$

Here, *vol* denotes the size of a volume or surface.

Reachability

We now define how reachable nodes are inside a network. Let $R(N_i)$ for $N_i \in O$ (called *Reachability* of N_i) denote the ratio of active nodes which N_i can access:

$$R(N_i) = \begin{cases} \dfrac{|r_i| - 1}{|O| - 1}, & \text{if } |O| > 1 \\ 0, & \text{otherwise} \end{cases} \quad \textbf{(4)}$$

We use $|O| - 1$ as denominator, since we do not count the node N_i itself as reachable. To measure the reachability of all nodes, we define the *Average Reachability AR*:

$$AR = \frac{\sum_{N_i \in O} R(N_i)}{|O|} \quad \textbf{(5)}$$

AR is only defined, if $O \neq \{\}$, i.e. we have at least one active node in the MANET.

Importance and Vulnerability

Inside a MANET, some nodes are more important for communication than others are. Some nodes in the 'centre' of a MANET may disable an ongoing communication when they are moved or switched off, as they may separate nodes from each other. On the other hand, some 'peripheral' nodes can be turned off without affecting the rest of the network. We want to formalize this issue.

Let $I(N_i)$ denote the *Importance* of $N_i \in O$. The Importance returns, how many new segments are caused by a turning off N_i:

$$I(N_i) = \begin{cases} S'(N_i) - S, & \text{if } S'(N_i) > S \\ 0, & \text{otherwise} \end{cases} \quad \textbf{(6)}$$

$S'(N_i)$ denotes the number of segments, if we remove N_i from O. To measure the entire network, we define the *Vulnerability V*, which returns how the network reacts on average to deactivating nodes:

$$V = \begin{cases} \dfrac{\sum_{N_i \in O} I(N_i)}{|O| - 2}, & \text{if } |O| > 2 \\ 0, & \text{otherwise} \end{cases} \quad \textbf{(7)}$$

We can easily proof that the maximum value of the numerator is $|O| - 2$, thus the value of V is in the interval [0,1]. Our list of metrics is now complete.

4. EVALUATIONS

The metrics provide a tool to measure the quality of a specific MANET, i.e. a network where nodes reside at specific positions at a specific time. We now want to abstract from a specific MANET and want to examine general prerequisites for 'good' MANETs, which offer a sufficient connectivity for end-users and applications.

In principle, we could use physical nodes in real environments for this. The *Ad hoc Protocol Evaluation* (*APE*) test-bed [14], e.g., follows this approach. To evaluate MANETs with APE, users with mobile nodes have to move in real environments. Initial experiments were carried out with only 37 nodes.

Since real experiments are very cost-intensive and time-consuming, we use a simulator in our approach to evaluate a reasonable number of nodes (e.g. some hundreds). There exist a huge number of network simulators (e.g. NS-2 [20]). Broch et al. extend NS-2 to address mobility issues [2]. *Adhocsim* [1] is especially designed to simulate ad-hoc networks. These tools, however, focus on MAC or network level. They can simulate packet delays or errors, which is too fine-grained for our intended goals. To measure our metrics, we developed a new simulation tool.

The tool easily allows a user to specific the number of nodes, the communication ranges and the observed area. Running a simulation, the nodes move randomly across the area. The tool presents current and average metric values.

In principle, the tool is able to simulate three-dimensional networks. Nevertheless, even in buildings, where a three-dimensional network could be formed in principle, ceilings are often impenetrable; thus, MANETs fall apart to independent, two-dimensional MANETs. The following simulations are thus only two-dimensional.

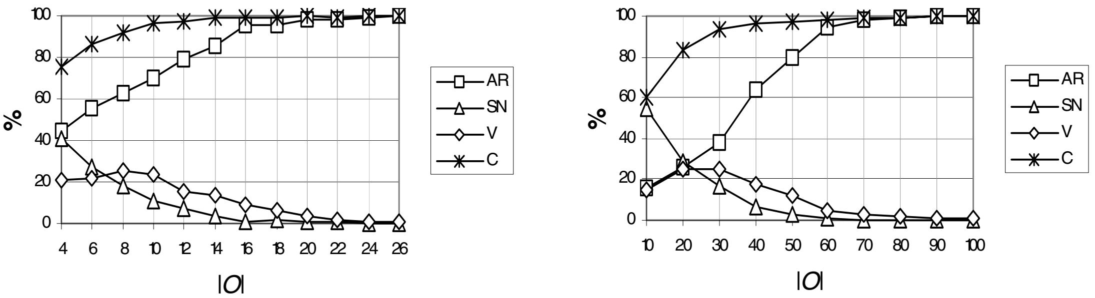
Often, smaller locations such as aircrafts, busses or apartments are considered as locations for MANETs. In these scenarios however, it is more sensible to install a low number of access points connected via a fix network, rather than using a MANET. Thus, the following simulations examine larger areas. We carried out two types of simulations: the first type simulates moving nodes in an unstructured plain area. In the second, more realistic example, we simulate a shopping centre.

4.1 Simple Areas

In the first scenario, we put a number of mobile nodes in a square area. The nodes choose a random direction and speed and move straight forward until they reach the border. They then choose a new direction and move again. All nodes are active all the observed time.

Although this scenario is very artificial, it is a first step towards a more realistic example in a later section. We use this simple scenario to derive first results. It especially leads to a definition of the *critical mass* – the number of nodes that form a reasonable MANET.

a) 250m x 250m, *CM* = 16 b) 500m x 500m, *CM* = 56



c) 750m x 750m, *CM* = 120 d) 1000m x 1000m, *CM* =211

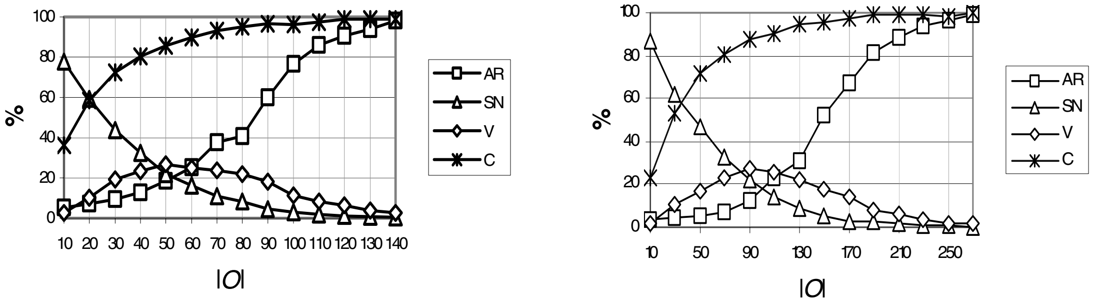


Fig. 1. Evaluation of MANETs in simple areas

We chose 100m as the transmission range. The range of *Wireless LAN IEEE 802b*, e.g., is between 30m and 300m, where the latter only occurs under ideal conditions [9]. Low power Wireless LAN adapters for handhelds often only reach 90m even in open environments [22].

We carried out the simulations for a number of areas: 250m x 250m, e.g. a yard of a small company; 500m x 500m, e.g. a university campus; 750m x 750m, e.g. a pedestrian zone; 1000m x 1000m, e.g. a city centre. We simulate the MANETs for different number of nodes. Fig. 1 presents the results. Not surprisingly, *C* and *AR* are monotonic increasing and converge to 100% for increasing $|O|$. *SN* is monotonic decreasing and converges to 0% with nearly the same speed as *C*.

V starts at 0%, reaches a maximum of approx. 30% and then converges to 0% for higher number of nodes. *V* has values of about 0% for low number of nodes, since we have a high segmentation, thus there is no multi-hop routing in the network. Values of more than 30% are rare in real networks, as only very specific constellations cause nodes with high importances *I*.

After the metrics reach a specific value, we can increase the number of nodes without a significant change. Basing on this observation, we define what we mean by a 'good' MANET:

- values of *C* and *AR* have to be greater than 90%,
- values of *SN* and *V* have to be lower than 10%.

We now define the *Critical Mass CM* of a specific scenario: *CM* is the minimum number of nodes, which are necessary to reach values of *C* and *AR* greater than 90% and *SN* and *V* lower than 10%.

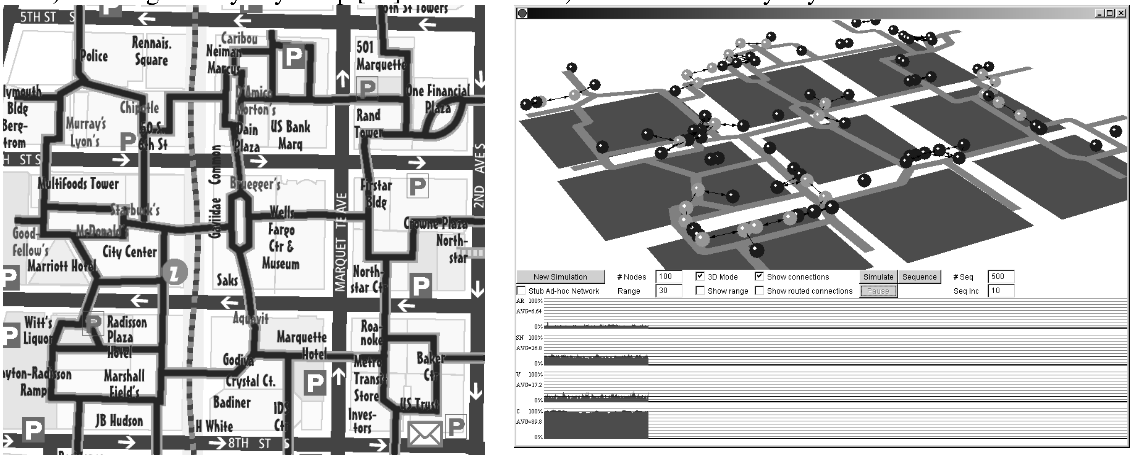
Note that at this point, we assume that each node is continuously active. In reality, nodes often are switched off, which significantly increases the critical mass. We discuss this issue in a later section.

4.2 Minneapolis Skyways

The simple area scenario gives a rough impression of the capabilities of MANETs. Thus, we conducted a more realistic simulation: the shopping centre in the downtown of Minneapolis. Towers in the centre of Minneapolis are connected via so-called *Skyways* in the first floor. Skyways and shopping levels form a network of ways for pedestrians. This scenario has several advantages:

- We have an exact map of all skyways (fig. 2a) and can easily put this map into the simulator (fig. 2b).
- Users and the corresponding ad-hoc nodes follow simple paths, thus it is easy to simulate a realistic behaviour of users going from one shop to another.

From all skyways, which have a total length of some kilometres, we chose a part of nine towers. These nine towers cover an area of 440m x 408m. From this area, only the ways, which are open for the public, are used to compute *C*. Other areas, e.g., offices, hotels and museums, are not taken into account. In addition, we restrict the area to the first floors of each tower.


a) The original skyways map [15]

b) The simulated skyways

New Simulation | # Nodes 100 | ☑ 3D Mode | ☑ Show connections | Simulate | Sequence | # Seq 500

☐ Stub Ad-hoc Network | Range 30 | ☐ Show range | ☐ Show routed connections | Pause | Seq Inc 10

Fig. 2. The Minneapolis Skyways

All nodes are indoors, thus we assume a communication range of 30m (which is the communication range of Wireless LAN IEEE 802b inside buildings). In our first simulation, we further assume that all nodes are continuously active. Fig. 3a shows the results. In this scenario *CM* = 510.

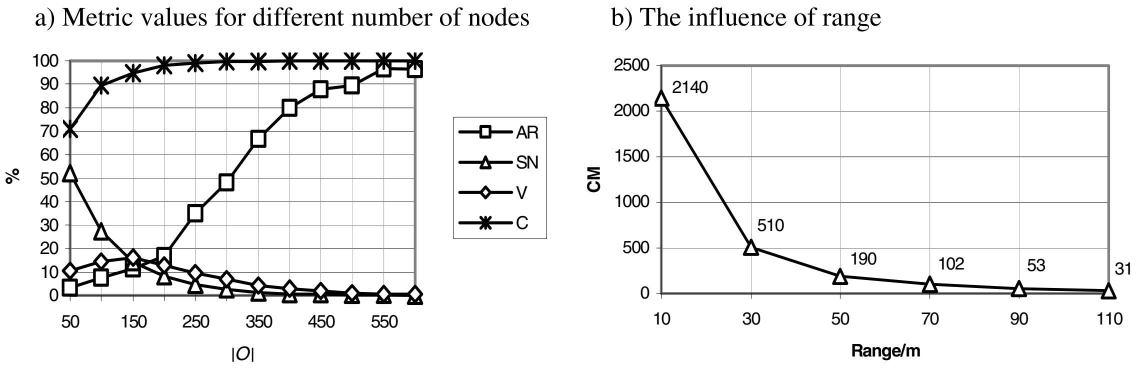


Fig. 3. Results of the skyway simulation

4.3 The Role of the Online Time

Until now, all nodes in our simulations are continuously active. In reality, power consumption is a limiting factor of mobile nodes, thus the operating system or the user often switches a mobile node off to safe valuable battery power. This problem becomes even worse, if battery is drained by wireless network connections used to transfer foreign packets.

Batteries of current PDAs have capacities of 2Wh (PalmOS device) to 10Wh (Windows CE device). Wireless LAN adapters consume about 2W when transmitting packets. In addition, the Wireless LAN hardware, CPU and memory consume power to perform the ad-hoc routing protocol. Some Wireless LAN adapters have separate batteries to safe power of the PDA's battery, however they typically have power for 2 hours network activity [22]. Notebooks have battery capacities of about 50Wh, but have to supply much more power-consuming parts. Typically, notebooks can be active for 2-3 hours. Assuming an online time of two hours in an observation time of 10 hours, we have a five times greater value of *CM*. In our skyway example, we have a *CM* value of 2550.

During the last few decades, mobile battery technology has made only moderate improvements in terms of higher capacity and smaller size [3]. There exist approaches addressing the battery problem especially in MANETs (e.g. [21]). However, if the battery technology does not significantly improve in the future, it will be a high barrier to introduce MANETs into a wider community.

4.4 The Role of the Communication Range

To examine the influence of the communication range, we carried out a number of simulations with different ranges in the skyways scenario and measure *CM*. Fig. 3b shows the results.

We start the simulation with a range of 10m, which is the range of Bluetooth transmitters [19]. One observation is that the communication range has a very high influence on the critical mass. Using, e.g., Bluetooth instead of Wireless LAN, we have a four times greater value of *CM*.

As an important output, the communication range plays an important role for ad-hoc networks. Assuming unrealistic communication ranges, we can easily form a reasonable MANET. However, as we can see in our simulation, the critical mass dramatically increases when the communication range goes below a certain value. One could argue that the communication range for radio transmitters will increase in the future. Having a larger communication range however, more nodes use the same radio resources (e.g. frequencies), thus the number of unwanted collisions increases. As a result, the communication range cannot go beyond a certain value, depending on the potential number of communicating nodes.

5. CONCLUSION AND FUTURE WORK

In this paper, we introduced a number of metrics to measure the quality of MANETs. These metrics can be used as a tool to answer questions such as *'How many nodes are necessary in a specific area to obtain a reasonable MANET?'* or *'What communication range is required if we have a specific number of nodes?'*. These metrics together with the simulation tool could help people who plan to form a MANET to investigate the effects of relevant parameters.

We carried out a number of simulations in different scenarios. One observation is that a relative high number of nodes is required to get a useful connectivity among the users. This number is even higher, if we take into account that mobile nodes may not be active all the time or that we have smaller communication ranges (e.g. with Bluetooth). As a general result, the whole idea of ad-hoc networks may be questionable for many scenarios. The work has currently an analytical character. We can find out, if a specific network scenario leads to an acceptable MANET or not. This is a starting point to explore alternatives and variations of MANETs.

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