# Simulation-Based Capacity Estimates for Local Broadcast Transmissions

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## ABSTRACT

The periodic transmission of status updates by all vehicles in a vehicular network represents a service primitive that forms the basis for a lot of envisioned applications, in particular safety related ones. Due to the limited resources that a wireless communication system like IEEE 802.11p is capable to provide, the question raises how much data each node may provide to the system such that the information can still be delivered with the quality of service required by the applications. In this work, *local broadcasts capacity* is introduced together with straight-forward upper and lower bounds, and estimated by extensive detailed simulations. We show that the *ratio* of simulation-based capacity estimates and the upper bound is similar for a wide range of system configurations and that the communication system may only be used up to 22% of its upper capacity bound such that service requirements can still be fulfilled.

## Categories and Subject Descriptors

C.2.1 [**Computer Systems Organization**]: Computer-Communication Networks—*Network Architecture and Design*[Wireless communication]

## General Terms

Performance

## Keywords

Broadcast, Capacity, Vehicular networks

## 1. INTRODUCTION

Wireless communication systems are currently seen as an important technology to improve vehicular systems in the future. A basic communication primitive that is required for many of the envisioned applications, in particular safety related ones, is the periodically repeated transmission of up-to-date status information by all vehicles and towards all vehicles positioned in a geographically local region. Such communication is implemented by transmitting periodic one-hop broadcast messages, also called beacons.

In this paper we discuss the challenge of the capacity that an IEEE 802.11p-based wireless communication system is capable to provide to the envisioned applications, assuming the underlying communication pattern of periodically transmitted one-hop broadcast messages. In order to achieve an awareness of how the nodes in the surrounding of each node behave, the status messages have to be received successfully with a certain maximum delay by all nodes positioned within a certain environment around each node. Given this requirement and given the restricted available communication resources we are faced with the question how much data each individual node may transmit within the communication system such that the requirements can still be fulfilled. In particular we are faced with the consequences of a CSMA-based medium access scheme given by IEEE 802.11p, i.e. packet collisions, and with the uncertainties of wireless communications, in particular when considering unacknowledged broadcast transmissions.

We tackle the capacity problem by providing a capacity definition dedicated to periodic broadcast transmissions, the *local broadcasts capacity*. We investigate on an upper bound under idealized assumptions and a lower bound under challenging ones. We then provide an extensive and detailed simulation study under realistic conditions with respect to environmental influences, radio propagation characteristics and the communication system behavior, that allows us to explore the capacity limitations that can be expected for a huge set of environmental influences and parameters. We show that the ratio of the capacity estimate derived by simulations and the derived upper bound remains nearly constant for almost all parameterizations and remains below an upper ratio for all examined configurations. The limited ratio gives the possibility to predict the load each node may provide to the communication system and thus forms a base for algorithms that control the load such that the service requirements can be fulfilled.

The paper is organized as follows: in Section 2 the local broadcasts capacity concept is motivated, introduced and defined. In Section 3 we provide an overview of related approaches while in Section 4 upper and lower capacity bounds are provided. In Section 5 we introduce the models and the simulation setup for the detailed simulation assessment, before we present the capacity estimates in Section 6 and finally conclude in Section 7.


*VANET'10,* September 24, 2010, Chicago, Illinois, USA.

## 2. LOCAL BROADCASTS CAPACITY

In this section we introduce the concept of local broadcasts capacity. We consider periodic one-hop broadcasts by all vehicles that are transmitted with the intent that a mutual awareness is achieved among all vehicles that currently are in near local distance to each other. Each vehicle provides its own status information (like position, speed, acceleration, direction of driving, etc.) to the vehicles in its surrounding by periodically transmitting the according information to a communication channel that all vehicles commonly share, i.e. to a multiple-access broadcast channel. If all vehicles periodically provide their status information, and if the communication system could guarantee the successful reception of the status information messages at all vehicles in a defined surrounding we call *awareness range*, the vehicles within this range would be capable to construct their local view on the current traffic situation.

The following basic questions should be answered: how reliable can multiple periodic broadcast messages be transmitted, being generated by all nodes in a scenario and containing information relevant at all nodes in a certain awareness range? What is the maximum capacity and data rate that a communication system can achieve when it is used for local broadcast communication? We develop an appropriate definition, *local broadcasts capacity*, that takes into account the aspects of *i)* the geographically local relevance of the information ("local"), *ii)* the multitude of broadcast messages ("broadcasts") and, *iii)* the limited communication resource ("capacity"). The definition allows us to decide under which configurations inter-vehicle communication is or is not able to provide the service that is required by applications. We discuss the question what amount of broadcast traffic can actually be transmitted over a constrained communication medium. Instead of looking at one transmitter-receiver pair, we investigate the situation of many transmitters, each of them having multiple receiving nodes all sharing a single communication channel.

We first specify the scenario that will be analyzed in the following. We assume that there is one common channel available for V2V communication, as it is foreseen in current projects and standardization activities. In the sense of a communication system specific analysis, we assume that the system is capable to transmit data with a maximum data rate $b$ expressed in [bits/s]. The achievable data rate is given by the communication system that is used, IEEE 802.11p [2] in this study. As we consider a distributed wireless communication system, the data rate may be used "in parallel" at locations spatially separated. In nearby locations, however, the communication system requires a coordinated and synchronized use of the available data rate by the different transmitters in the system. In consequence, the data rate $b$ reflects at each geographic location the maximum amount of data that all transmitters that have "influence" on the location may transmit jointly, given that they perfectly coordinate. The "influence" of a specific location raises the question how such influence may be determined and described. For the analytical considerations in the following we argue with fix ranges of influence, the simulations, however, underlie more realistic assumptions.

The definition of a maximum data rate yields some issues. In case that one single node is transmitting data to another node the definition resembles the theoretical maximum amount of data that can be transmitted. In practice, the achieved bandwidth typically is lower due to the overhead of a transmission. In case of broadcast transmissions, using the bandwidth does not explicitly mean that the bandwidth is successfully used. Exemplary, at one receiver a successful reception might be possible, while, at another receiver, the reception fails. It is also possible that more traffic is generated than can be handled at some position.

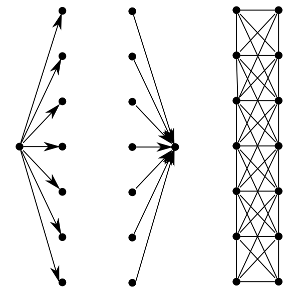


**Figure 1:** Sketch of different types of channels: broadcast channel, multiple access channel and multiple access broadcast channel. The arrows are not shown for the last channel as the connections exist in both directions.

From an abstract point of view what we actually consider is a combination of several challenges that have to be seen in combination:

- We have to handle a multiple receiver problem, i.e. a single transmission contains information for many receiving nodes, and cannot be optimized to be best for a single receiver. The type of channel is known as broadcast channel, see e.g. [20].

- We have to handle a multiple sender problem, i.e. a single channel is shared by multiple transmitters, and they have to follow procedures not to interfere each other. The type of channel is known as multiple access channel, also see [20].

The combined result of both problems is a multiple access, multiple receivers channel. Figure 1 shows the different variants visually. The vertices represent nodes in the network, whereas the edges represent connections between transmitters and receivers. It has to emphasized that all the edges share one single channel, i.e. although in the drawing they appear to be independent and partially separated from each other, they are actually not. Such type of model either assumes that communication is always possible between two nodes, or not, what clearly does not represent reality.

In order to give a technology-dependent capacity definition for a system with multiple access and locally restricted multiple receivers we make the following two assumptions on the underlying communication system:

- The system provides a wireless communication channel of specific bandwidth that, from the technical system specification, is capable to transport a specific amount of data bits per second at maximum, thus, that provides a maximum data bit rate $b$.
- We assume a system that is capable to handle one single successful packet reception at a time, as it is foreseen in the IEEE 802.11 standards [1]; multi-packet reception at one receiver in parallel is not considered.

The problem of local broadcasts is discussed from a receivers point of view. The density of nodes in a scenario is assumed to be homogeneous. In the one-dimensional case, the node density $d$ represents the number of nodes per kilometer. We now consider the requirements given by an application of the communication system: messages have to be received with probability $p$ at all nodes positioned within distance $r$. The derivation of values for $r$ and $p$ depends on the application, e.g. for the application *emergency electronic break light* [19] $r$=100 m and $p$ considerably high, e.g. 95 %, are appropriate values[1]. By a *Local Broadcasts Capacity* $C_{\mathrm{LB}}$ we identify the amount of data that each node in the network is allowed to transmit such that the requirements given by $r$ and $p$ are fulfilled:

DEFINITION 2.1. ***Local Broadcasts Capacity $C_{LB}$***
*Local Broadcasts Capacity $C_{LB}$ is defined as the amount of data that each node in a scenario with node density $d$ and available data bit rate of the channel $b$ may transmit per second such that at each receiver, $p$ percent of all messages transmitted from nodes within awareness range $r$ can be received successfully.*

The definition of local broadcasts capacity allows to compare the performance under different scenarios as well as the feasibility of a system configuration to achieve the expected requirements. We identify bounds on the local broadcasts capacity in Section 4 and derive simulation-based estimates of local broadcasts capacity in Section 6.

## 3. RELATED WORK

Before considering the multiple access multiple receivers capacity problem that will be further discussed, literature is reviewed and assessed with respect to capacity considerations. Most work that was done with respect to capacity considerations follows different goals and assesses other network and communication situations. Yet, some similarities of other approaches compared to ours are observed although, in particular, a network view in contrast to a connection-oriented view is not discussed frequently.

In information theory, broadcast channels were first described and analyzed in [6], and reviewed in [7]. The publications discuss different types of channels, particularly the problem of a single transmitter that simultaneously communicates information to several receivers. Without loss of generality, the problem is reduced to the situation of a single transmitter and two independent receivers. The papers discuss how the rates achievable by the two receivers depend on each other, under the assumption of different channel models. The most similar model to our scenario is the Gaussian broadcast channels, where the signal of each link is independently affected by white Gaussian noise. The general outcome of the paper is that alternatives like time-sharing (i.e. an individually adapted transmission to each receiver) or adapting to the worse of all individual channels are no optimal strategies as well. The approach used by inter-vehicle communication with broadcast transmissions that cannot be optimized for any individual receiver cannot be represented by any of the extremes mentioned.

In [9] the definition of capacity in wireless networks was introduced. Capacity is defined as the achievable throughput per node that a network is capable to transport. The work provided the basis for a whole field of research on the capacity of wireless networks. Yet, the work focused on unicast communication between pairs of nodes in the scenario and thus is not directly applicable to our case.

A broadcast capacity for wireless networks was defined in [17] and provided related boundaries. The per node capacity of a wireless network is bounded by $O(C/n)$ where $C$ is the channel capacity in bits per second and $n$ is the number of nodes. In the work, no spatial restriction of the broadcast is considered and the defined goal of broadcasting was to transmit the information to *all* other nodes in the network, if necessary by using multiple hops, which is not the intention in our work. A similar approach was taken by [11] and continued in [12].

The work of [13] derived analytic expressions for an optimal transmission range such that one-hop broadcast packets best cover a dense wireless network. Therefore assumptions with respect to the propagation of packets were made by defining a transmit circle and an interference torus around. The probability that an interfering node is positioned in a specific distance from the transmitter was derived and the number of affected nodes not receiving the original transmission estimated conservatively. The model of the radio channel was kept simple and represents a worst case analysis of failed packet receptions.

In [8] a problem similar to ours is discussed as an algorithmic problem and delivers asymptotic bounds of local broadcasting. The physical interference model defined in [9] is assumed. Interference is treated in two domains, from "close-in" and "far-away" nodes, i.e. the latter ones being nodes further away than a definable proximity range. The time is considered within which every of the nodes performs a successful local broadcast. Two different scheduling algorithms are presented, one assuming that the number of neighbors $\Delta_x^A$ in the proximity range $A_x$ is known, and one where it is not know. The algorithms allow a successful broadcast within poly-logarithmic time, i.e. after $O(\Delta_x^A \log n)$ resp. $O(\Delta_x^A \log^3 n)$ time slots. The paper provides asymptotic bounds, yet it mentions that, in practice, where "far-away" interference has to be considered as well, achievable performance might strongly differ from the bounds derived. Medium access strategies are not considered as well.

In [14] an analytical approach to derive the performance and reliability of broadcast transmissions for safety applications is presented. Yet, the study does not consider the capacity considerations presented in this paper.

A simulation-based approach towards an assessment of local broadcasts and the comparability of different configurations is provided by the concept of *communication density* in [10]. In periodic one-hop broadcast scenarios communication density is the multiple of node density, communication range and message generation rate, while packet size is assumed to be constant. It is shown that scenarios with similar communication density and identical communication range behave similar. In contrast to our study, however, it is not discussed to what extent the capacity may be used; instead it is discussed which scenarios can be seen being comparable in performance.

[1] Ideally, $p$=100 % could be the "real" requirement of a safety application. Yet, a communication system cannot achieve such a guarantee. Instead, we set the requirement to an achievable value per transmission, here $p$=95 %. Note that by considering multiple transmissions in common, higher rates can be achieved, though with a possible longer delay until a successful reception occurs.

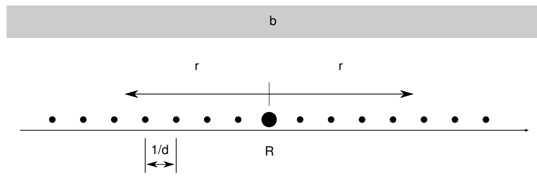



**Figure 2:** Sketch of the influencing factors of local broadcasts capacity. The perspective of receiver node $R$ is taken, which wants to achieve awareness over all nodes in its surrounding of size $r$, where nodes are distributed with a density $d$, i.e. an average distance of $d^{-1}$ between nodes in the one-dimensional case. The communication system uses a communication channel that can transport a data rate $b$ at maximum.

# 4. UPPER AND LOWER BOUNDS

In this section, we analytically identify an upper bound as well as a worst case of local broadcasts capacity under simplified assumptions. In order to illustrate the results we will apply the following parameterization example: we assume a communication system that provides a data rate $b = 3\,\text{Mbit/s}$ in a linear highway scenario with a node density of $d = 140\,\text{nodes/km} = 0.14\,\text{nodes/m}$ and a required awareness range of $r = 100\,\text{m}$ in which the reception probability $p$ should be higher than 0.95.

## 4.1 Maximum local broadcasts capacity

We first consider the maximum local broadcasts capacity $C_{\text{LB,max}}$ that a wireless communication system could theoretically provide over a limited resource, the communication channel. We therefore model the system under strongly idealized assumptions. Idealization is assumed with respect to radio propagation: a transmitted signal can be successfully decoded up to a specific distance, and, the signal does not have any influence at nodes positioned further away.

Idealization is also assumed with respect to node distribution: a homogeneous distribution of static nodes, i.e. equal distances between nodes aligned along one line, is assumed. Perfect coordination not causing any additional overhead is assumed with respect to medium access: all nodes follow a perfect time schedule such that two transmitted packets never overlap and thus never collide. It is further assumed in our considerations that a maximum of one packet reception at a node per time can be handled.

Figure 2 sketches the different factors of influence for a one-dimensional setup. We observe that each arbitrarily chosen receiver $R$ must be capable to receive messages from all the nodes positioned a maximum of $r$ away, thus, from nodes placed on a line of length $2r$. With a node density of $d$, the expected number of such nodes is $2rd$. As only one message per time interval can be received successfully, the available bit rate $b$ has to be shared by the $2rd$ nodes, and one node at maximum is allowed to transmit $\frac{b}{2rd}$ bits per second. Otherwise at least one packet from one of the nodes within the distance $r$ from $R$ would not be receivable successfully due to the insufficient amount of data rate, or in other words, a timely overlapping of at least two packets would not be avoidable.

Consequently, the derived ratio is an upper bound on the achievable bit rate per node when considering a fair distribution of available bandwidth. In consequence, we can define the maximum local broadcasts capacity $C_{\text{LB,max}}$:

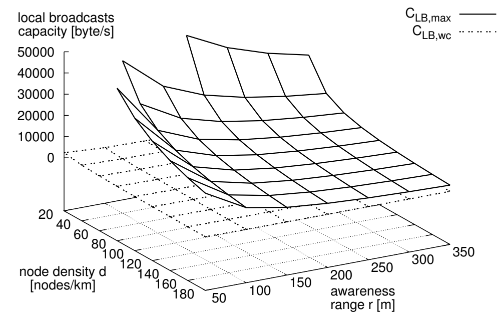



**Figure 3:** Comparison of maximum and worst case local broadcasts capacity, $C_{\text{LB,max}}$ and $C_{\text{LB,wc}}$.

Definition 4.1. ***Maximum Local Broadcasts Capacity $C_{LB,max}$***
*The Maximum Local Broadcasts Capacity $C_{LB,max}$ is calculated as:*

$$C_{LB,max}(b, d, r) = \frac{b}{2dr} \quad (1)$$

The variable $b$ denotes the data rate in [bits/s] that the communication system is able to provide at maximum, $d$ is the node density in [nodes/m] and $r$ is the awareness range in [m] within which each node requires to receive periodic status information updates. The parameter $p$ that represents the required probability of reception within the awareness range does not influence $C_{\text{LB,max}}$ and thus can be omitted for this considerations.

Maximum local broadcasts capacity $C_{\text{LB,max}}$ reflects the maximum amount of data per second that each node may deliver to the medium, assuming that all other nodes behave similar. Thus, the channel within the awareness range of each node will not be over-saturated. Figure 3 shows maximum local broadcasts capacity for a one-dimensional scenario in dependence of the parameters $r$ and $d$ for a fixed data rate $b = 3\,\text{Mbps}$. The worst case local broadcasts capacity that is shown as well is discussed in the next section.

In case of the example parameterization we achieve the following (rounded) result:

$$\begin{aligned} C_{\text{LB,max}}(b, d, r) &= C_{\text{LB,max}}(3 \cdot 10^6, 0.14, 100) \\ &= 107,142 \text{ bit/s} \\ &= 13,392 \text{ byte/s} \end{aligned}$$

The local broadcasts capacity thus expresses that for the given configuration each node may at maximum provide 13,392 byte/s to the medium, e.g. in form of 10 packets per second, each of maximum size 1,339 byte.

## 4.2 Worst case local broadcasts capacity

The worst case local broadcasts capacity $C_{\text{LB,wc}}$ requires more effort with respect to its definition and derivation. Trivially, the lowest achievable rate that a node may provide is 0 bit/s. Yet, with this rate, any requirement from applications that requests communication between the nodes would not be fulfilled, and consequently the “zero rate” would not provide any feasible solution. Instead, we assume non-ideal and uncoordinated conditions in the following, to a degree that cannot be worse from a communications point of view. Non-ideal conditions are considered with respect to radio propagation: we assume that a transmission affects nodes in a large range. An even worse assumption would be that any node is affected by every single transmission. Yet, that would make any worst case consideration meaningless and lead to infeasibility of any system configuration as the number of affected nodes could not be derived. Uncoordinated conditions are considered with respect to medium access behavior: we assume that nodes do not coordinate at all, but transmit their packets randomly, without respecting the behavior of other nodes; the only worse strategy would be "forced collisions" of packets, i.e. transmission of packets when collisions on the channel are the unavoidable consequence. Thus, we actually consider the "most uncoordinated" but "still meaningful" situation.

As mentioned before, we consider a system model in which we assume that medium access is done randomly without sensing whether a transmission from another node is currently ongoing. This random access scheme is known as the ALOHA strategy, first discussed in [3]. We further assume that a transmitted message can, under best conditions, i.e. without being interfered, be received by all nodes in a radius $r'$ (reception range) around the transmitter. A reception is considered being successful if there was no other timely overlapping transmission within a radius $r''$ (interference range) around each receiver. For an arbitrary transmitter $T$ in a linear scenario the transmission range would have an absolute size $2r'$, and a receiver $R$ would be exposed to interferences from an area of absolute size $2r''$. In our considerations we ignore propagation delays, thus, we assume that the moment of transmission is equal to the moment of reception at all nodes. Note that we still argue with deterministic and fixed radio ranges here.

We now discuss $\mathrm{C_{LB,wc}}$, the data rate that each node may use under the described uncoordinated conditions. We assume that the maximum data rate $b$, the node density $d$ and the expected awareness range $r$ are provided similar to the definition for maximum capacity. Additionally, we derive the following relations. The load $l$ of each node is the multiple of the size $s$ of each data packet and the rate $f$ with which packets are transmitted, thus $l = sf$. As $b$ is the effective data rate that can be provided by the communication system we can determine the duration $\tau$ that a data packet needs to be transmitted: $\tau = \frac{s}{b}$.

We identify the number of nodes $g$ that are possible receivers of a message transmission as $g = 2dr'$. As broadcast messages should be transmitted to all nodes within distance $r$ a broadcast is considered as successful if none of the intended receivers is interfered by another node's transmission. A broadcast is considered being failed if one or more nodes are interfered by another transmission. All nodes within the awareness range $r$ may possibly be interfered. Particularly the nodes positioned at the edge of the awareness range, thus in distances close to $r$, may be affected by any other transmission from nodes within distance $r''$ away from them. Thus, in order to perform a successful broadcast, no other transmission from nodes within distance $r + r''$ from the transmitter may overlap in time. In consequence, taking the two directions of the one-dimensional scenario, the range $h$ in which possibly interfering nodes for broadcast transmission are positioned is $h = 2(r + r'')$.

If one packet is transmitted we observe a collision at a specific receiver if any other packet from a node within $r''$ overlaps in time. If transmission starts at time $t$ and lasts for duration $\tau$, then an overlap occurs for messages transmitted within the time interval $[t - \tau, t + \tau]$, i.e. a duration of $2\tau$. Thus, in order to determine the success probability of a packet transmission at all intended receivers of a broadcast transmission, we have to derive the probability that no node in range $h$ transmits for a duration of $2\tau$. We now assume that the start times of message transmissions of nodes are independent of each other and exponentially distributed[2] with the average transmission rate $f$. Then, the probability $p$ that there will be no transmissions for a duration $\delta$ (here $\delta = 2\tau$) and for a number of expected transmissions per time unit $\omega$ (here $\omega = fdh$) is $\mathrm{e}^{-\delta\omega}$, see [3]. Applied to the scenario we achieve:

$$p = \mathrm{e}^{-\delta\omega} = \mathrm{e}^{-2\tau\cdot fdh} = \mathrm{e}^{-4fd\tau(r+r'')}. \qquad (2)$$

From Equation 2 we observe that the probability of a successful broadcast reception depends on several factors. Under the simplifying assumption that $r$ and $r''$ are equal, i.e. the required reception range and the interference range are identical, we achieve the probability of a successful broadcast as:

$$p = \mathrm{e}^{-8df\tau r}. \qquad (3)$$

By substitutions and transformations we can derive $\mathrm{C_{LB,wc}}$, the data rate with which the requirements can be fulfilled. Respecting the relations $\tau = \frac{s}{b}$, $l = sf$ and Equation 1 we derive:

$$\begin{aligned} \ln p &= -8df\tau r = -\frac{8dfrs}{b} = -\frac{8drl}{b} && (4)\\ l &= -\frac{b\ln p}{8dr} && (5)\\ &= \frac{b}{2dr}\cdot\left(-\frac{\ln p}{4}\right) && (6)\\ &= \mathrm{C_{LB,max}}(b,d,r)\cdot\left(-\frac{\ln p}{4}\right) && (7) \end{aligned}$$

As $l$ is the maximum achievable data rate under the given conditions we can now define:

Definition 4.2. ***Worst Case Local Broadcasts Capacity $C_{LB,wc}$***

*The Worst Case Broadcasts Capacity $C_{LB,wc}$ is calculated as:*

$$C_{LB,wc}(b,d,r,p) = C_{LB,max}(b,d,r)\cdot\left(-\frac{\ln p}{4}\right) \qquad (8)$$

As we can see from Equation 8, $\mathrm{C_{LB,wc}}$ is a fraction of $\mathrm{C_{LB,max}}$ and depends on $p$, the required probability that the reception is successful within the awareness range. For $p \to 1$ yet, $l \to 0$, thus, there is not any achievable data rate with which successful reception at all nodes can be reliably achieved. In consequence, values can be identified only for success probabilities $p$ smaller than 1. Exemplary a factor of 0.0025 is achieved when $p = 0.99$, and 0.026 for $p = 0.90$. In Figure 4 the ratio between $\mathrm{C_{LB,max}}$ to $\mathrm{C_{LB,wc}}$ is shown for varying reception probabilities $p$.

[2]The assumption of exponentially distributed average transmission rates is simplified and relates to ALOHA where random start times of transmissions are assumed.

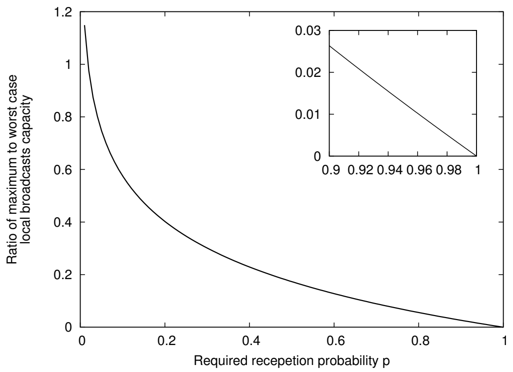



**Figure 4:** Ratio of $C_{LB,max}$ and $C_{LB,wc}$ with respect to $p$, the required reception probability within the awareness range $r$.

We observe that under worst case conditions only a very small amount of the theoretically available maximum capacity can be used. In Figure 3 already presented before $C_{LB,max}$ and $C_{LB,wc}$ are shown in comparison, thus, the achievable data rate under perfectly coordinated and completely uncoordinated conditions.

For the example parameterization provided at the beginning of this section we achieve the following result:

$$\begin{aligned} C_{LB,wc}(b,d,r,p) &= C_{LB,wc}(3\cdot 10^6, 0.14, 100, 0.95) \\ &= 1,373 \text{ bit/s} \\ &= 171 \text{ byte/s} \end{aligned}$$

The local broadcasts capacity thus expresses that for the given configuration each node may at maximum provide 171 byte/s to the medium, e.g. in form of 10 packets per second, each of maximum size 17 byte. It is obvious that the worst case values reflect very low performance.

From the derivation of maximum and worst case local broadcasts capacity we observe that there is an enormous difference when comparing the capacity results. The theoretical derivation covers the two extremes of perfect coordination and complete in-coordination, realistically achievable capacities are expected to be positioned between these extremes. In the following sections we will identify the range in which capacities can actually be expected. The next Section 5 provides the models and simulation tools necessary for such an empirical study.

# 5. SIMULATION APPROACH

Tackling the capacity problem by a simulation approach requires the availability of detailed and precise models that represent the different parts of the communication system. As our considerations concentrate on the capacity of the wireless channel in vehicular networks under periodic broadcast traffic a detailed modeling is particularly necessary with respect to *i)* the layout of the scenario investigated, *ii)* the characteristics of the data traffic exchanged, *iii)* the physical layer and medium access characteristics of the participating nodes and, *iv)* the behavior of the wireless channel. The models are all implemented in the network simulator NS-2 [15], version NS-2.34. We used the extended and adapted version of the simulator that we described in [4] to appropriately realistically reflect the aspects briefly discussed in the following.

The road scenario layout taken for the evaluation represents different snapshots of vehicle positions on a 5.0 km long extract of a highway. The HWGui tool [18] provides realistic node distribution and node movement patterns for several densities and traffic situations. However, we want to discuss the results over a wider range of densities, and neither node movement nor precise node positions are a primary issue when regarding single-hop broadcast transmissions. Consequently, we created our own scenarios, covering the major features known from the HWGui tool, but abstracting from the ones not relevant for broadcast studies. We assume static nodes that are randomly distributed along a linear highway scenario and consider node densities of 20 to 180 nodes/km in increasing steps of 20 nodes/km. For each density, several independent node distributions were created and then used for the simulations. All evaluations are restricted to the nodes being positioned within the inner 3.0 km of the scenario, i.e. skipping all statistics contributed by nodes positioned closer than 1.0 km to the scenario border to avoid any border effects.

Each node of a scenario is equipped with an application agent that periodically generates messages that are given down the stack to the communication layers to finally being transmitted. The *periodic broadcast agent* is configured with respect to the packet size and the packet transmission rate, thus, in each simulation run, *all* nodes are identically configured and generate the same amount of data. The duration of the interval between the generation of two subsequent message includes a random jitter of 10 % of the duration of the interval. If new messages are generated while previously generated messages were still not transmitted, the new messages are stored in an interface queue that is capable to store up to 10 packets at maximum.

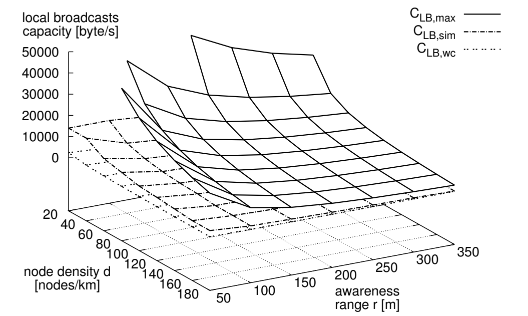
All possible combinations of the following parameters are simulated for all node densities in the empirical capacity study: packet sizes $s$ are set from 100 to 1000 byte in 100 byte steps, the message generation rate is configured from 2 to 14 packets per second and node in steps of 2 packets per second, transmission powers are selected from -6 to 20 dBm, corresponding to idealized transmission ranges of 100 to 1000 meters in 100 meter steps[3] and the contention window parameter of the MAC layer is set to 7, 31 and 127 to derive the optimum between medium access delay and packet collision avoidance.

The communication stack is configured with respect to the parameters defined in the standard draft of IEEE 802.11p [2] and with respect to conversations with chip manufacturers for values that are not publicly available, see Table 1 for the configuration parameters used. An important feature of wireless chipsets is the capture capability, i.e. the possibility to synchronize on newly arriving packets with strong reception power, although another packet is currently been received. We investigate different variations of this feature: deactivated, active only during the preamble and header reception, and active all time of a reception. We consider data rates of 3 and 6 Mbps that use BPSK resp. QPSK modulation schemes and 1/2 coding rate. These comparably slow rates are chosen due to the fact that in broadcast transmissions more advanced schemes reduce the amount of successful receptions at nodes further away due to the necessity of

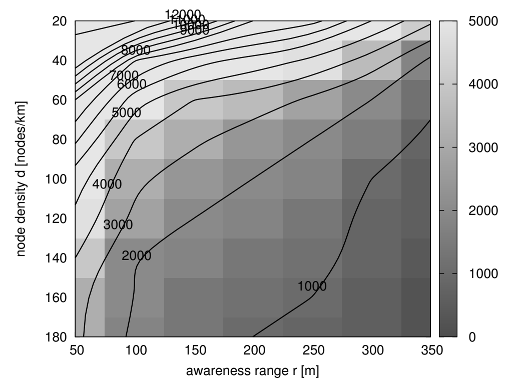
[3]Note that the ideal ranges could only be reached under idealized deterministic channel conditions; we, in contrast assume more realistic probabilistic models for the wireless channel.

| Layer | Parameter | Value |
|---|---|---|
| MAC | Slot time | 13 $\mu$s |
| | SIFS time | 32 $\mu$s |
| PHY | Carrier frequency | 5.890 GHz |
| | Channel bandwidth | 10 MHz |
| | Preamble length | 32 $\mu$s |
| | PLCP header length | 8 $\mu$s |
| | OFDM symbol duration | 8 $\mu$s |
| | Carrier sense threshold | -94 dBm |
| | Noise floor | -99 dBm |
| | SINR thresh. preamble cap. | 5 dB |
| | SINR thresh. frame body cap. | 10 dB |
| Antenna | Antenna height | 1.5 m |
| | Antenna gain | 0.0 dBm |

**Table 1:** IEEE 802.11p MAC and PHY configuration parameters used in the simulation study.




(a) Three dimensional view on $C_{LB,max}$, $C_{LB,sim}$ and $C_{LB,wc}$.




(b) Contours lines plot of $C_{LB,sim}$. The underlying color identifies $C_{LB,sim}$ in the range from 0 byte/s colored black to 5,000 byte/s colored light-gray. Higher values are colored with light-gray color as well.

**Figure 5:** Comparison of maximum, empirically simulated and worst case $C_{LB}$ for $b$=3 Mbps and $p$=0.95.

better reception conditions (with respect to the SINR) and due to the unavailability of any acknowledgment schemes.

The wireless channel and radio propagation behavior is modeled by the use of probabilistic radio propagation models. The *Nakagami-m* radio model is used and parameterized such that it covers the adverse channel conditions observed in vehicular networks due to the mobility of nodes and the strong influence of the environment. The model can be configured to represent different intensities of fading by varying the $m$-parameter of the model; a small value of $m$ representing intensive fading. The reception power is derived statistically on a per-packet basis for each individual reception at each receiver. The applicability of the used radio models was e.g. shown in [5].

Each individual simulation is run for 10 seconds, the first second being skipped from evaluation to exclude the startup phase and achieve results in steady state. The number of random seeds each scenario is run with was set to ten to achieve statistical confidence. The enormous number of possible parameter combinations and studied configurations required the use of a high performance computing cluster used for an overall time of 8200 days of single-core CPU time.

# 6. CAPACITY ESTIMATES

The simulation-based capacity estimates of local broadcasts capacity are achieved by the procedure described in the following. In order to explore the simulation-based estimate of local broadcasts capacity $C_{\text{LB,sim}}(b, d, r, p)$ the global input parameters channel data rate $b$, node density $d$, expected awareness range $r$ and the required probability of reception within the awareness range $p$ have to be given.

The data rate $b$ is given by the modulation scheme and coding rate of the simulation study. Simulations are run for all node densities $d$ being considered. Several awareness ranges $r$ and required probabilities $p$ are covered by a simulation study, as the influence of $r$ and $p$ is considered during the evaluation, and not during the simulation phase.

The resulting statistics files are then evaluated. For each awareness range and its related required reception probability tuple of interest, each simulation configuration is evaluated and it is checked whether the achieved *Successful packet reception ratio* (SRRo) at all distances smaller or equal to $r$ exceeds the required reception probability $p$. If the condition is fulfilled, the average load that is contributed to the medium by nodes within the particular parameter configuration is calculated as the configured packet size in byte multiplied by the packet transmission rate that is achieved in the scenario. The parameter configuration and the load value are added to list of candidates for $C_{\text{LB,sim}}(b, d, r, p)$.

After the evaluation of all simulated configurations the highest load value from the list of candidates is selected and $C_{\text{LB,sim}}(b, d, r, p)$ is assigned the according value. If several configurations achieve the same load the configuration that achieves the highest SRRo in distance $r$ is selected as the representative configuration that is capable to provide $C_{\text{LB,sim}}$. If the list of candidates is empty, $C_{\text{LB,sim}}(b, d, r, p)$ is set to 0 as there is no configuration that is capable to fulfill the requirements. The procedure guarantees that the highest load under which the requirements are still fulfilled is selected. The capacity derived by simulations can only take into account values from simulation configurations that have actually been run, thus, there remains the possibility that for other configurations a higher $C_{\text{LB,sim}}$ can be achieved. Yet, we perform the analysis for a broad variety of configuration parameters, to cover the whole spectrum of configurations and consequently provide a good estimate for $C_{\text{LB,sim}}$.

In Figure 5 the local broadcasts capacity as it derived from simulations and by the theoretical models presented in Section 4 is shown. The data used for the figure is taken from simulations that are run with a data rate of 3 Mbps, capture capabilities are fully activated, and the Nakagami-3 model is assumed as radio propagation model. In Figure 5(a) the local broadcasts capacities under theoretical maximum ($C_{\text{LB,max}}$), under theoretical worst case assumptions ($C_{\text{LB,wc}}$) and under the results obtained by the simulation approach ($C_{\text{LB,sim}}$) are shown over different awareness ranges $r$ on the x axis and for different node densities $d$ on the y axis. The required reception probability $p$ is set to 0.95. On the z axis the maximum load that may be provided to the medium by each node is shown. The z axis is skipped at 50,000 byte/s such that higher achieved values of $C_{\text{LB,max}}$ are not shown. Further, the curves cover each other and not all data points can be seen in the figure.

We can derive the following observations. First, we observe that

$$C_{\text{LB,max}}(b, d, r) > C_{\text{LB,sim}}(b, d, r, p) > C_{\text{LB,wc}}(b, d, r, p)$$

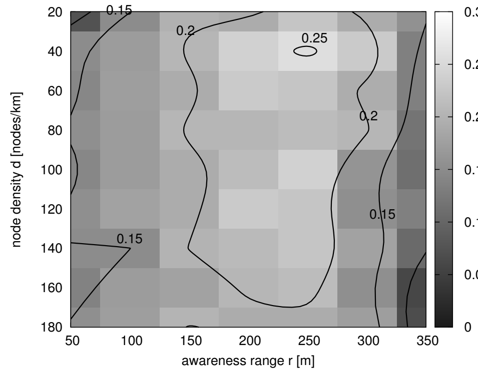
for $b$=3 Mbps, for $d \in \{20, 40, 60, 80, 100, 120, 140, 160, 180\}$ vehicles/km, for $r \in \{50, 100, 150, 200, 250, 300, 350\}$ m and for $p = 0.95$. Thus, we show that results by simulations fit in the range between the theoretically derived maximum and worst case capacity. The result confirms that the results observed by simulations that take into account the real mechanism and making more realistic assumptions with respect to the whole communication system and its components match neither of the theoretically derived extreme cases.

Second, we see that a principal trend is common to all local broadcast capacities: values achieved become lower when increasing awareness range as well as when increasing node density, leading to the arched shape of the plots. We also observe significantly higher absolute values under $C_{\text{LB,max}}$ than under $C_{\text{LB,sim}}$. In consequence, we derive that the interferences of realistic propagation behavior and the decentralized coordination of medium access does not allow to make use of all available capacity systems applied in reality.

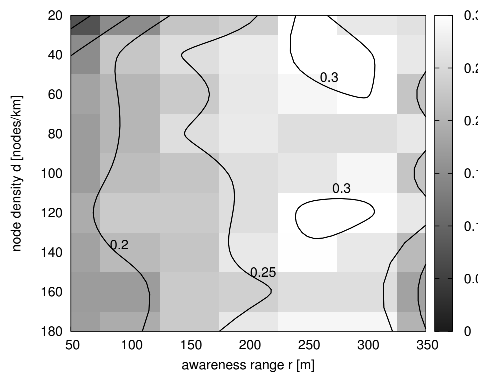
In Figure 5(b) the values obtained for $C_{\text{LB,sim}}$ are visualized as a colored contour map. The x and y axis are identical to Figure 5(a) shown above, but the values of the z axis are shown as colors where black represents 0 byte/s, light-gray 5,000 byte/s and interpolated gray levels the different data rates in between. Values higher than 5,000 byte/s are also shown in light-gray color. The values shown are discretely derived by simulation for the values of $d$ and $r$ listed before. In order to improve the readability of the plot contour lines are shown as well in equal distances of 1000 byte/s. Each line is an isoline connecting the points with same value. As values are only available for discrete points, values in between are interpolated. Additionally the contour lines are plotted as B-splines, the respective function of the *gnuplot* tool is used for the calculation.

The figure allows to easily derive the local broadcasts capacity that is achievable for combinations of awareness range and node density and thus allows a better analysis is possible whether the achievable rate is still acceptable. For example, if each node provides a load of 5,000 byte/s to the system and wants to cover an awareness range of 100 m, the system is capable to achieve that rate only up to a node density of approximately 70 nodes per kilometer. We further see that for a lot of combinations of $r$ and $d$ only very low capacities are achieved, showing the borders of system applicability.

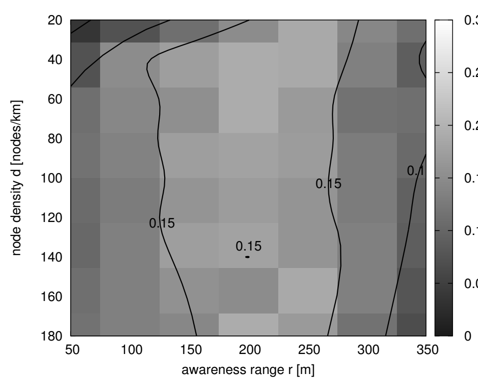
Next, the effectiveness of using the available capacity is explored. We compare for each combination of $r$ and $d$ the capacity achieved in the simulations with the theoretically upper bound. For a fixed data rate $b$ and a fixed required reception probability $p$ the effectiveness ratio $e(d, r)$ at node density $d$ and awareness range $r$ is calculated as:




(a) $b = 3$ Mbps (BPSK modulation), $p = 0.95$.




(b) $b = 3$ Mbps (BPSK modulation), $p = 0.90$.




(c) $b = 6$ Mbps (QPSK modulation), $p = 0.95$.

**Figure 6:** Contour maps of effectiveness $e(d, r)$ of capacity usage.

$$e(d, r) = \frac{C_{\text{LB,sim}}(b, d, r, p)}{C_{\text{LB,max}}(b, d, r)} \quad (9)$$

$$= C_{\text{LB,sim}}(b, d, r, p) \frac{2dr}{b}. \quad (10)$$

The achieved ratios are shown in Figure 6 as contour plots for simulations studies with 3 Mbps and 6 Mbps respectively, and for required reception probabilities $p = 0.95$ and $p = 0.90$. Again, the Nakagami-3 model is taken and capture capabilities are fully activated. The black colored regions now represent configurations where 0 % of the maximum capacity is used, and light-gray colored regions represent a usage of at least 30 %, the contour lines are drawn in equal distance of 5 %-steps.

First, we see in all figures that large homogeneous regions arise. The areas particularly cover awareness ranges of medium size and spread over the complete set of node densities investigated. Thus, the maximum available capacity can only be used up to a certain ratio. In consequence, an approximate ratio of effective usage of theoretical maximum capacity can be derived for each simulated combination. For 3 Mbps with capture fully activated and Nakagami-3 radio propagation an average effectiveness ratio of 17.5±4.22 % is achieved for $p = 0.95$, averaged over all combinations of density and awareness ranges. As we see from the standard deviation there are derivations for some data points, yet, we have considerably low variations when respecting the broad range of variations that are covered by the average. If we only consider the "center" combinations, i.e. not taking into account the ratios of the highest two and the lowest two densities and awareness ranges, the average effectiveness ratio increases to 21.3±1.48 %. As we can also see visually effectiveness remains more homogeneous in this "center part", what is confirmed by the lower standard deviation achieved.

Further, we observe that for both the lowest and the highest awareness ranges the ratio that is achieved decreases. Although the observation is the same the reason for the decrease differs for both extremes. For low awareness ranges the ratio decreases due to the reason that the communication system is not yet saturated and is capable to transport more data. Yet, in the simulations these high data rates were not generated by any of the configured scenarios. An extension of the simulation studies with configuration possibilities that provide a higher load is possible, but not done due the reason that for periodic broadcasts the spectrum covered with the used configuration parameters already is quite broad. For high awareness ranges, however, the opposite situation is the case. The wireless medium of the communication channel is strongly saturated and in order to provide the required reception probability at all nodes up the distance $r$ the required performance is only achieved by the transmission of small packets with high transmission power. The resulting rate thus is considerably small and leads to a decrease of the effectiveness ratio.

In Figure 6(b) the required reception probability $p$ is set to 0.90. The effectiveness of using the medium increases due to the fact that a higher number of packets not being received successfully is accepted. We observe the average effectiveness ratio of 23.7 %.

We also see in Figure 6(c) that the ratio observed when evaluating the scenarios with a data rate of 6 Mbps is principally lower than the one observed with a data rate of 3 Mbps, thus, the effectiveness of using the medium is worse for the higher rate scenarios. As it was derived in Equation 10 the data rate $b$ is considered in the calculation of the ratio, being in the denominator. In consequence, the absolute values achieved can still be higher for higher data rates, what actually is the case here. However, a higher data rate does not necessarily use the communication channel more effective in case of broadcast transmissions.

In Table 2 we provide for different combinations of configurations, the achieved average effectiveness ratios as well as the according ratios from the inner combinations as described before. We see that the effectiveness is very low in case that the Nakagami-1 model is used as radio propagation model, an effectiveness of 4.5 % at maximum is achieved only. We also observe that the application of extended capture capabilities increases the effectiveness of the capacity usage, e.g. for Nakagami-3 and 3 Mbps the ratio increases from 9.7 % to 17.5 % when activating the capture capabilities. We see that the ratio from selected nodes is always higher than the one observed by all nodes. The trend that usage of maximum capacity is worse when using higher data rates, i.e. more advanced modulation schemes, is also present for all configurations.

| Configuration | | | Average ratio | |
|---|---|---|---|---|
| Propagation | Capture | Data rate | total | selected |
| Nakagami-3 | Disabled | 3 Mbps | 9.7 | 10.2 |
| Nakagami-3 | Full | 3 Mbps | 17.5 | 21.3 |
| Nakagami-3 | Disabled | 6 Mbps | 7.6 | 9.2 |
| Nakagami-3 | Full | 6 Mbps | 13.5 | 16.9 |
| Nakagami-1 | Disabled | 3 Mbps | 1.9 | 1.8 |
| Nakagami-1 | Full | 3 Mbps | 4.5 | 5.2 |
| Nakagami-1 | Disabled | 6 Mbps | 1.2 | 1.4 |
| Nakagami-1 | Full | 6 Mbps | 2.9 | 2.7 |

**Table 2:** Effectiveness of capacity usage for different combinations of radio propagation models and data rates.

| Scenario | | Best configuration | | |
|---|---|---|---|---|
| Density $d$ | Awareness range $r$ | Packet size | Idealized transm. range | Message gen. rate |
| 40 | 50 | 1000 | 300 | 14 |
| 80 | 150 | 800 | 800 | 4 |
| 120 | 250 | 700 | 1000 | 2 |
| 160 | 350 | 100 | 900 | 2 |

**Table 3:** Configuration examples for $b = 3$ Mbps and $p = 0.95$.

Table 3 provides some exemplary simulation configurations that provided the best performance for selected combinations of $d$ and $r$. It can be seen that there are principal trends observable, yet a detailed analysis of functional dependence of the parameters providing best capacity use is still in progress. We provide the full set of data for all parameters on our website *http://dsn.tm.kit.edu/english/misc.php* such that every interested reader can execute his individual analysis of local broadcasts capacity. More details and further results can also be found in [16].

Overall, we observe the following general trends with respect to the configurations:

- Propagation model: Models that include stronger fading are directly related to a less effective use of the available channel capacity.
- Capture capability: Activated capture capabilities lead to a significant increase of effective channel usage.
- Data rate / modulation scheme: A data rate of 6 Mbps compared to 3 Mbps leads to less effective use in terms of relative ratio, but better usage with respect to absolute values[4].

Finally, we conclude that, for tested combinations of fundamental factors that take into account fading and configu-

[4]Note that the result is currently limited to the two data rates presented. An evaluation of additional data rates and modulation schemes is left to future work.

ration parameters, the effectiveness of using the capacity of the wireless channel with communication techniques based on IEEE 802.11p never exceeds 22 % of the maximum achievable capacity for $p = 0.95$. It is an open discussion now whether other techniques could make use of the channel more effectively or whether a technology improvement would provide better performance. It has to be kept in mind that techniques to optimize a single or a set of wireless links do not help when considering local broadcast communications.

# 7. CONCLUSIONS

In this paper, we analyzed local broadcast communication from a system-wide perspective and analyzed the local broadcasts capacity that was derived by simulation studies. We observed the achieved capacity for varying node densities and awareness ranges and identified several regularities. Obviously the results derived by simulation perfectly fit between the theoretically derived results on maximum and worst case capacity. We also identified, as one would expect, that the achievable capacity is reduced when awareness ranges are increased and when the node density is higher.

The ratio of the capacity achieved by simulations and the theoretical maximum capacity, thus, the effectiveness with which the available capacity of the medium is used remains essentially constant over a wide range of awareness ranges and densities. The maximum ratio achieved over all simulated configurations is 22 % for a required reception probability of 95 % within the awareness range. The availability of such fundamental and general dependencies provides the possibility to develop adaptive algorithms that, by extracting information from ongoing communication, may control communication in such a way that the data rates provided by each node do not saturate the communication system and by that allows to determine feasible performance levels.

The contributions of this work allow predicting the system performance to be expected when, in the future, most vehicles will be equipped with communication technology and provide fundamental insights that have strong relevance and impact for further developing vehicular communication systems and algorithms that enable the efficient use of the communication channel. We hope that the work is taken up by the information-theory community to provide an accurate theoretical derivation of local broadcasts capacity.

**Acknowledgments**: We like to thank the anonymous reviewers for their valuable comments. We thankfully acknowledge the intensive use of the HP XC4000 high performance computing system of the State of Baden-Württemberg, Germany, operated at the Steinbuch Centre for Computing (SCC), Karlsruhe Institute of Technology (KIT), Germany, for the simulations presented in this paper.

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