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Access Layer Part**

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Keywords

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ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - NAF 742 C
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Contents

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Intelligent Transport System (ITS).

Introduction

It is essential to decrease the number of fatalities on our roads, not only because it causes much grief for individuals each year, but also because it costs enormous amounts of money for society. There are different ways of increasing the road traffic safety, which all contribute to a better and more efficient road traffic environment. One way is to build new highways with separated lanes as these are less prone to traffic accidents. However, this is only possible to some extent due to space limitations. Another way is to introduce wireless communications between vehicles which enable new applications for increasing road traffic safety such as wrong way warning, red light violation, intersection collision warning and emergency brake warnings. This is termed cooperative intelligent transport systems (ITS).

The impact of road traffic safety applications as well as road traffic efficiency applications is likely dependent of a considerably amount of vehicles being equipped with communication devices. The exact penetration of course depends on the application in question, but generally the more vehicles that are equipped the better. However, it is also at this stage the current technology chosen for cooperative ITS may encounter problems. When the number of ITS equipped vehicles increases, the standardized technology based on CSMA will face problems with scalability. The scalability of CSMA directly influences the reliability of the transmission, the channel access delay and thereby the fairness. When the number of nodes increases, the number of simultaneous transmissions will increase, resulting in lower reliability and decoding problems due to interference. One way to counteract the scalability issue of CSMA is to introduce decentralised congestion control methods (DCC) such that the amount of data traffic transmitted is restricted and transmit power levels adjusted. However, by decreasing the amount of data traffic transmitted the road traffic safety applications may suffer with performance degradation as a result.

Another way to counteract the scalability issue is to investigate the performance of other medium access control (MAC) protocols in terms of scalability, reliability, delay and fairness. Self-organizing time division multiple access (STDMA) and mobile slotted Aloha (MS-Aloha) are two time slotted MAC approaches designed for *ad hoc* networking (they are self-organizing and decentralized) and both can cope with a high and varying number of nodes without collapsing. When the number of nodes increases within radio range and all free resources are exhausted, both algorithms still admit transmissions through careful scheduling to maintain a high reliability for the nodes closest to the transmitter. This implies that the channel access delay has a maximum upper limit and the resulting network is fair and predictable.

In the present document, the performance of CSMA, STDMA and MS-Aloha are investigated through simulations with a varying number of vehicles, all equipped with cooperative ITS units. In particular, the performance measures *channel access delay* and *packet reception probability* are evaluated as these measures captures the reliability, the delay and the fairness of resulting system as well as how these depend on scalability.

1 Scope

The present document summarises the result from performance evaluations of CSMA and two time slotted MAC approaches through simulations. Two different time slotted MAC approaches, self-organizing time division multiple access (STDMA) and mobile slotted Aloha (MS-Aloha), have been considered in two different scenarios; highway and urban. CSMA, the MAC algorithm proposed for the current generation of vehicular *ad hoc* networks (VANETs) has been used as a benchmark. Packet reception probability at different distances from the transmitter together with the channel access delay has been used as performance measures. The purpose is first and foremost to evaluate the scalability of the resulting system, as initial results have shown that CSMA may degrade in performance when the number of vehicles equipped with cooperative ITS units increase.

NOTE 1: Håkan Lans holds a patent on STDMA [i.25], which expires in July 2012. The patent has been re-examined in the US cancelling all claims on March 30, 2011.

NOTE 2: A European patent procedure has been started by ISMB on MS-Aloha techniques (European patent request filed with number 10163964.9, May 26, 2010). They have received in September 2011 Communication Under Rule 71(3) EPC of the intention to grant a patent.

2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

Referenced documents which are not found to be publicly available in the expected location might be found at http://docbox.etsi.org/Reference.

NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

2.1 Normative references

Not applicable.

2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI TR 102 862: "Intelligent Transport Systems (ITS); Performance Evaluation of Self-Organizing TDMA as Medium Access Control Method Applied to ITS; Access Layer Part".

[i.2] IEEE 802.11p: 2010: "IEEE Standard of Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 6: Wireless Access in Vehicular Environments".

[i.3] M. Nakagami: "The m-distribution, a general formula of intensity distribution of the rapid fading", Oxford, England, Pergamon, 1960.

[i.4] V. Taliwal, D. Jiang, H. Mangold, C. Chen and R. Sengupta: "Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication," in Proc. ACM Workshop on Vehicular Ad Hoc Networks (VANET), Philadelphia, PA, USA, October 2004, pp. 88-88.

[i.5] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai and P. Mudalige: "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band," IEEE Journal on Selected Areas in Communications, vol. 25, no. 8, pp. 1501-1516, October 2007.

[i.6] R. Scopigno and H.A. Cozzetti: "Evaluation of time-space efficiency in CSMA/CA and slotted Vanets," in Proc of the IEEE 71st Vehicular Technology Conference (VTC Fall 2010), Ottawa, Canada, Sept. 2010.

[i.7] H.A. Cozzetti and R. Scopigno: "Scalability and QoS in slotted VANETs: forced slot re-use vs pre-emption," in Proc of the 14th Int. IEEE Conf. on Intelligent Transportation Systems (ITSC 2011), Washington, DC, USA, October 2011.

[i.8] ETSI ES 202 663: "Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.9] R. Scopigno, and H.A. Cozzetti: "Signal shadowing in simulation of urban vehicular communications", Proc. of the 6th Int. Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, Spain, September 2010.

[i.10] L. Pilosu, F. Fileppo and R. Scopigno: "RADII: a computationally affordable method to summarize urban ray-tracing data for VANETs" in Proc. of the 7th Int. Conf. on Wireless Communications, Networking and Mobile Computing (IEEE WiCOM 2011), Wuhan, China, September 2011.

[i.11] T. Jiang, H. H. Chen, H. C. Wu and Y. Yi: "Channel modeling and inter-carrier interference analysis for V2V communication systems in frequency-dispersive channels," in The Journal Mobile Networks and Applications, vol. 15, no. 1, pp. 4-12, 2010.

[i.12] The European Road Safety Observatory.

NOTE: http://erso.swov.nl/.

[i.13] "SUMO - Simulation of Urban MObility", developed by employees at the Institute of Transportation Systems at the German Aerospace Center June 2010.

NOTE: http://sumo.sourceforge.net.

[i.14] C. Campolo, A. Molinaro, H.A. Cozzetti and R. Scopigno: "Roadside and moving WAVE providers: effectiveness and potential of hybrid solutions in urban scenarios", in Proc. of the 11th IEEE Int. Conf. on ITS Telecommunications (ITST), St. Petersburg, Russia, August 2011.

[i.15] E.G. Ström: "On medium access and physical layer standards for cooperative intelligent transport systems in Europe", in Proceedings of the IEEE, vol. 99, no. 7, pp. 1183-1188, July 2011.

[i.16] E. Giordano, R. Frank, G. Pau and M. Gerla: "CORNER: A radio propagation model for VANETs in urban Scenarios", in Proceedings of the IEEE, vol. 99, no. 7, pp. 1280-1294, July 2011.

[i.17] D. Jiang, Q. Shen and L. Delgrossi: "Optimal data rate selection for vehicle safety communications," in Proc. of the 5th Int. Workshop on Vehicular Inter-Networking (VANET), San Francisco, CA, US, September 2008.

[i.18] K. Sjöberg, E. Uhlemann and E. G. Ström: "How severe is the hidden terminal problem in VANETs when using CSMA and STDMA?", in Proc. of the 4th IEEE Symposium on Wireless Vehicular Communications (WiVEC), San Francisco, CA, US, September 2011.

[i.19] Q. Chen, F. Schmidt-Eisenlohr, D. Jiang, M. Torrent-Moreno, L. Delgrossi and H. Hartenstein: "Overhaul of IEEE 802.11 modeling and simulation in NS-2," in Proc. of the 10th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2007), Chania, Crete island, Greece, October 2007, pp. 159-168.

[i.20] R. Meireles, M. Boban, P. Steenkiste, O. Tonguz and J. Barros: "Experimental study on the impact of vehicular obstructions in VANETs," in Proc. of the 2nd IEEE Vehicular Networking Conference (VNC 2010), Jersey City, New Jersey, USA, December 2010.

[i.21] E. Giordano, R. Frank, A. Ghosh, G. Pau and M. Gerla: "Two Ray or not Two Ray this is the price to pay", in Proc. of the 6th IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS 2009), Macau SAR, China, October 2009, pp. 603-608.

[i.22] C. Sommer, D. Eckhoff, R. German and F. Dressler: "A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments", in Proc. of the 2011 8th Int. Conf. on Wireless On-Demand Network Systems and Services (WONS 2011), Bardonecchia, Italy, January 2011, pp.84-90.

[i.23] M. Boban, T. T. V. Vinhoza, M. Ferreira, J. Barros, and O. Tonguz: "Impact of vehicles as obstacles in vehicular ad hoc networks" in IEEE Journal on Selected Areas in Communications, vol. 29, no. 1, pp. 15-28, January 2011.

[i.24] ETSI TS 102 687: "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part".

[i.25] H. Lans: "Position Indicating System," US patent 5,506,587, issued 1996.

[i.26] IEEE 802.11a-1999: "IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: High Speed Physical Layer in the 5 GHz band".

3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

broadcast: simplex point-to-multipoint mode of transmission

NOTE: This may contain additional information.

3.2 Symbols

For the purposes of the present document, the following symbols apply:

A	Symbol used to indicate a node in the examples
a	Sub-period of a period *c*, used for asynchronous MAC
AC_BE	Access Category Best Effort
AC_BK	Access Category Background
AC_VI	Access Category Video
AC_VO	Access Category Voice
B	Symbol used to indicate a node in the examples
b	Sub-period of a period *c*, used for synchronous MAC
c	Fixed period of time for the coexistence of two MAC methods
C	Symbol used to indicate a node in the examples
CW	Contention Window
CW_{max}	Maximum possible value of *CW*
CW_{min}	Minimum possible value of *CW*
D	Symbol used to indicate a node in the examples
E	Symbol used to indicate a node in the examples
F%	Percentage of slots perceived free by a node
F_1	Upper Threshold used by 2-SMtd to evaluate *F%* for the near-exhaustion condition
F_2	Lower Threshold used by 2-SMtd to evaluate *F%* for the unloaded condition
FI	Frame Indication
FI'	Extended Frame indication, including both *FI* and *STI*
FI_j	The j-th subfield of the *FI* field
j	Index used in the examples for the indication of slot number
J	The *j*-th slot in MS-Aloha's Frame
L1	Layer 1
L2	Layer 2
LA	Set of nodes receiving from node *A*
MB	Set of nodes receiving from node *B*

N	Number of slots in a period
PSF	Priority Status Field
SX	Equivalent number of slots required to transmit *X* Bytes
SLOT_n	Slot number n of MS-Aloha Frame structure
STATE	The field of each *FI_j* indicating the perceived state (*busy/free/collision/2-hop*)
STI	Short Temporary Identifier
T_{AIFS}	Arbitration interframe space period
T_{PLCP}	PLCP transmit period
T_{STI}	STI transmit period
T_{FI}	FI transmit period
T_{TX}	Time required to transmit *X* bytes
Tg	Guard Time
Thr	MS-Aloha threshold used for *2SMt* and *2SMtd* algorithms
T_{slot}	Duration of a slot
X	Generic number of bytes in a frame

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

2-SM	2-Hop Spatial Multiplexing
2-SMt	2-Hop Spatial Multiplexing with Threshold
2-SMtd	2-Hop Spatial Multiplexing with Dynamic Threshold
AC	Access Category
AIFS	Arbitration InterFrame Space
AIFSN	Arbitration InterFrame Space Number
AP	Access Point
ARQ	Automatic Repeat reQuest
CAM	Cooperative Awareness Message
CCA	Clear Channel Assessment
CCH	Control CHannel
CDF	Cumulative Distribution Function
CSMA	Carrier Sense Multiple Access
CW	Contention Window
DCC	Decentralized Congestion Control
DENM	Decentralised Environmental Notification Message
EA	Extra Attenuation
EPC	European Patent Convention
FI	Frame Indications
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HT	Hidden Terminal
IEEE	Institute of Electrical and Electronic Engineers
ISI	Inter Symbol Interference
ISMB	Istituto Superiore Mario Boella
ITS	Intelligent Transport Systems
LOS	Line of Sight
MAC	Medium Access Control
MAX	MAXimum
MS-Aloha	Mobile Slotted Aloha
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Density Function
PDR	Packet Delivery Ratio
PHY	Physical layer
PLCP	Physical Layer Convergence Procedure
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RADII	Ray-tracing Data Interpolation and Interfacing
RR	Report Rate
RX	Receiver

RX	Receiver
SI	Selection Interval
SINR	Signal-to-Interference-plus-Noise Ratio
SNIR	Signal to Noise and Interference Ratio
SNR	Signal-to-Noise Ratio
STDMA	Self-Organizing Time Division Multiple Access
STI	Short Temporary Identifier
SUMO	Simulation of Urban MObility
TCL	Tool Command Language
TDMA	Time Division Multiple Access
TX	Transmitter
TX	Transmitter
VANET	Vehicular *Ad Hoc* Networks
XML	eXtensible Markup Language

4 Introduction

Cooperative intelligent transport systems (ITS) applications are a promising approach in an effort to decrease road traffic accidents. Road traffic safety applications will mainly use broadcast communication in a vehicular *ad hoc* network (VANET), i.e. one sender and many receivers communication in a decentralized *ad hoc* network. All nodes will share a common frequency channel, commonly referred to as the control channel. The *ad hoc* topology together with broadcast will have a major impact on the requirements of the developed communication protocols. All communication systems use a communication stack consisting of several layers containing protocols, which are more or less complex depending on the developed system. The medium access control (MAC) algorithm, residing in the sublayer MAC of the data link layer, Figure 1, is one of the cornerstones in data communication because it determines when a node has the right to transmit.

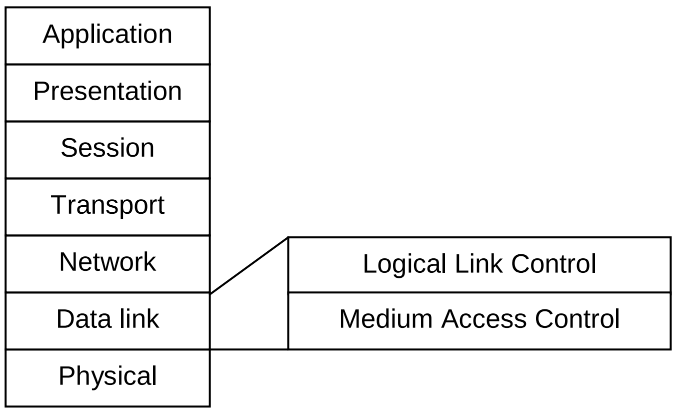


Figure 1: Generic protocol stack showing the logical position of the medium access control sublayer

Three MAC methods are examined through simulations in the present document; carrier sense multiple access (CSMA), self-organizing multiple access (STDMA) and mobile slotted Aloha (MS-Aloha). STDMA and MS-Aloha are two time slotted MAC approaches, where the available time is divided into time slots with fixed length. One transmission fits into one time slot and when all time slots are occupied, STDMA and MS-Aloha allow more than one transmission in each slot through careful scheduling (i.e. simultaneous transmissions can take place to cope with high network loads). CSMA, on the other hand, is a random access scheme, where nodes that want to transmit will start by sensing the channel for a predetermined sensing period and if the channel is sensed free the transmission can commence. If not, a random backoff procedure is invoked. Detailed descriptions of the MAC algorithms are found in [i.1].

In clause 4.2 in [i.1] requirements on the MAC algorithm applied in VANETs were detailed. It was concluded that road traffic safety applications have requirements on the MAC layer in terms of upper bounded channel access delay, reliability and fairness. The *ad hoc* topology calls for a decentralized, self-organizing and scalable MAC method. The scalability property is closely coupled to the requirements of road traffic safety applications. A lightly loaded network results in a lower channel access delay, a higher reliability and fairness. In other words it is generally no problem to fulfil the requirements of road traffic safety applications regardless of MAC method, if the network load is light enough.

However, when the network load increases all three requirements delay, reliability and fairness, are affected more or less severely depending on MAC method.

All three examined MAC protocols are self-organizing and do not have to rely on any access point or base station in order to schedule transmissions, i.e. they are decentralized. STDMA and MS-Aloha are scalable and always guarantee channel access regardless of the number of nodes within radio range and this makes them predictable as the maximum channel access delay is known. CSMA is scalable in terms of the number of nodes but not in number of transmissions.

Table 1, also found in clause 10 in [i.1], summarizes to what extent the three different MAC methods can fulfil the requirements of road traffic safety applications for light network load as well as heavy network load, respectively.

Table 1: An overview of the road traffic safety applications' requirements and the MAC methods ability to fulfil those

	Light network load			Heavy network load		
	STDMA	**MS-Aloha**	**CSMA**	**STDMA**	**MS-Aloha**	**CSMA**
Delay	Predictable	Predictable	Random	Predictable	Predictable	Random
Reliability	High	High	High	High	High	Low
Probability of fairness	High	High	High	High	High	Low

In the present document simulations have been carried out to evaluate the three MAC methods mentioned above in a VANET setting. All transmissions are in broadcast mode excluding traditional automatic repeat request (ARQ) mechanisms for increasing reliability. MS-Aloha has been simulated in an urban environment and STDMA has been simulated in a highway scenario. CSMA has been simulated and used as benchmark in both scenarios. Periodic cooperative awareness messages (CAMs) containing position, speed, heading etc., of each vehicle have been used as a data traffic model. Packet reception probability and channel access delay are the performance measures used for evaluating the performance. Decentralized congestion control (DCC) methods as outlined in [i.24] and required by ITS-G5 [i.8] to combat the scalability issue of CSMA have not been implemented in the simulators nor evaluated in the present document.

5 Simulation settings

5.1 Introduction

This clause describes the different settings of the simulators: STDMA simulations have been carried out using Matlab® whereas MS-Aloha simulations use the NS-2 environment with mobility traces from SUMO. The data traffic model is the same for both simulators: time-triggered position messages, i.e. CAMs, with two different packet lengths and update frequencies (2 Hz/800 bytes and 10 Hz/300 bytes). All MAC methods assume the same the physical (PHY) layer derived from 802.11p [i.2]. A transfer rate of 6 Mbit/s is used and 10 MHz frequency channel is adopted. Two different road traffic scenarios have been considered: urban and highway. STDMA has employed the latter whereas MS-Aloha has mainly been simulated for the urban scenario. The channel model for the highway scenario is a Nakagami *m* model with varying *m* values depending on distance between transmitter (TX) and receiver (RX). The urban channel model is partly based on ray tracing technique in order to get as realistic radio propagation environment as possible. The selected performance measures for evaluating the results are the same for both simulators: packet reception probability and channel access delay.

5.2 Data traffic model

All simulations are conducted using time-triggered position messages, i.e. CAMs. Two different heartbeats (CAM update rates) and packet lengths have been considered, based on the discussions in standardization within ETSI and IEEE, Table 2. The packet length excludes the preamble and signal fields of the physical layer (PHY). In clause 5.2.1 the packet structure is outlined.

Table 2: Data traffic settings

	Update rate [Hz]	Packet length [bytes]	Required bandwidth by each node [kbit/s]
ETSI setting	2	800	12,8
IEEE setting	10	300	24

5.2.1 Packet structure

The PHY parameters are derived from IEEE 802.11p [i.2]. All transmissions have been conducted using a transfer rate of 6 Mbit/s. This implies the modulation scheme quadrature phase shift keying (QPSK) with a code rate of 1/2 (r = 1/2). In Figure 2, the packet structure for the simulations is depicted. The PHY data field corresponds to the packet length found in Table 2.

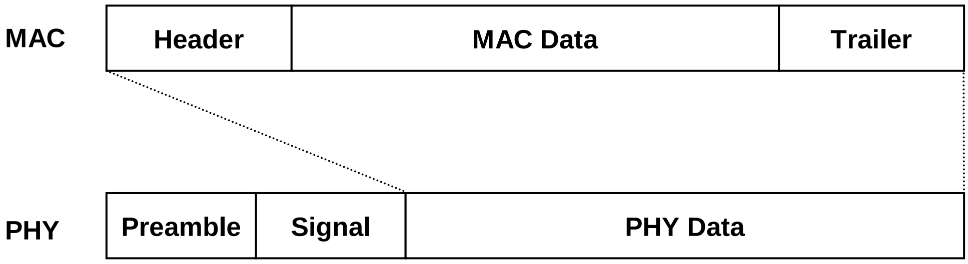


Figure 2: The packet structure for the simulations

The preamble field consists of 12 orthogonal frequency division multiplexing (OFDM) symbols, which has a total duration of 32 µs. The signal field is one OFDM symbol of duration 8 µs. In Table 3 the duration of a packet transmission for each of the two different packet lengths are tabulated.

Table 3: Packet duration

Packet length/ PHY data	Duration of packet transmission at 6 Mbit/s [µs]	Preamble [µs]	Signal [µs]	Total duration of packet in the air [µs]
300 bytes	400	32	8	440
800 bytes	1 067	32	8	1 107

5.2.2 Slot length, guard time and clock hold-on

Guard times are added in time slotted MAC approaches to avoid inter-slot interference. It accounts for propagation delay and synchronization jitter. The latter is due to drifting clocks when synchronization is lost. The synchronization method intended for the two time slotted MAC approaches evaluated herein is GNSS, such as GPS. If GPS synchronization is lost, the quality of the local oscillator determines how long a node can stay synchronized. This is called the clock hold-on property. A clock hold-on of 50 µs is considered in the simulations; clause 8 in [i.1], together with a propagation delay of 6 µs. In Table 4 the total duration of a slot for each of the two packet lengths are given.

Table 4: Slot duration

Packet length/ PHY data	Total duration of packet in the air [µs]	Propagation delay [µs]	Clock hold-on [µs]	Total duration of one slot [µs]
300 bytes	440	6	50	496
800 bytes	1 107	6	50	1 163

5.2.3 Frame length

5.2.3.1 STDMA

The frame length in STDMA is set to 1 s. The number of slots and the total duration of each slot for the two different packet lengths are tabulated in Table 5.

Table 5: Number of slots in the STDMA frame

Packet length/PHY data	Total duration of one slot [μs]	Number of slots in the frame
300 bytes	496	2 016
800 bytes	1 163	859

5.2.3.2 MS-Aloha

In MS-Aloha the following entities are mutually linked and jointly contribute to define the frame settings:

- number of slots in a MS-Aloha period
- number of bits used for the STI (typically 8 bits)
- slot length: it is connected to the length of the packets being transmitted; it has to account also for the signaling information carried within the FI (appended to the slots in the *signaling frames*)
- guard time
- number of *signaling* frames: it is possible to send the FI only in certain MS-Aloha frames (*signaling frames*). For instance, it can be chosen to append FI to the slots in one frame every 2 or 10

All the parameters together determine the frame duration. Considering that the FI contains as many subfields as the number of slots, the number of slots n_{slot} in a period P can be computed as the solution of an equation of power 2, whose solution is presented in clause 7.1.2.

Obviously, the equation should be called only initially, to make decisions on the settings. More details on the settings are discussed in clause 7.1.2. However, in Table 6 columns 2 to 5 the settings of the here presented MS-Aloha's simulations are tabulated. In this analysis, all MS-Aloha frames will be signaling frames (i.e. FI will be appended to all the slots), waiving the opportunity to improve the efficiency by less frequent FI transmissions. In Table 6 columns 6 to 7, also other possible settings are mentioned, for the non-continuous update of FIs (only once per second).

Table 6: Number of slots in the MS-Aloha frame for two possible setting: *k*=1 (columns 2 to 5), as used in the simulations; k≠1 (columns 6 to7)

(1) Packet length and PHY settings		(2) Slot duration excluding T_g [μs]	(3) Number of slots in the frame	(4) Number of the slots per second	(5) Settings	(6) Number of slots per second	(7) Settings
300 bytes	**6 Mbit/s**	707	131	1 310	*K*=1, *P*=0,1s	1 870	K=10, P=1s
800 bytes	**6 Mbit/s**	1 736	287	574	K=1, P=0,5s	668	K=2, P=1s
300 bytes	**12 Mbit/s**	444	200	2 000	K=1, P=0,1s	3 060	K=10, P=1s
800 bytes	**12 Mbit/s**	1 033	459	918	K=1, P=0,5s	1 104	K=2, P=1s

5.3 Vehicle traffic model

As many as 55 % of all fatal accidents occur in rural areas [i.12]. The majority of rural fatal accidents are due to head-on collisions. In rural areas the roads usually have one lane in each direction with occasional support for two lanes and thus the scalability of the MAC protocol is likely not to be a major issue. The lowest probability of fatal accidents has the highway environment with 10 % and the majority of those accidents are rear-end collisions and single collisions (only one vehicle involved). In urban environment 35 % of all fatal accidents occurs but here it is often vulnerable road users that get killed such as pedestrians and bicyclists, which collide with vehicles. Despite the practical relevance, very few theoretical studies address such scenarios, basically due to a lack of propagation models accounting also for the obstruction by buildings. Very recently, some models have been proposed and validated to account for obstruction by buildings ([i.9]). The results presented here exploit one of them ([i.9], the simplest but most general one): more details are provided in clause 5.3.2.

Three main scenarios are mentioned in literature for the study of VANETs: highway, urban, and rural. The selected scenarios for simulations are highway and urban as the highest vehicle densities are found here, which should stress the MAC protocols most. As mentioned earlier the scalability of the MAC protocol is closely connected to the channel access delay, reliability and fairness.

- In *a highway scenario*, the relative speed can be as high as almost 300 km/h. Although PHY layer phenomena are supposed to be counteracted by the underlying layers, network topology sometime changes too rapidly due to high relative speeds between the driving directions (whereas the topology is more stable within one direction). The density of vehicles can be high, especially during rush hour and when an accident occurs. This scenario can test how scalable a MAC protocol is.

NOTE: In IEEE 802.11p [i.2], the doubled symbol duration, with respect to IEEE 802.11a [i.26], is meant to counteract inter-symbol interference (ISI) [i.15]; the frequency displacement by Doppler's effect, according to Jake's model is about 2 kHz at almost 400 km/h mutual speed [i.11], which is below the guard-band of IEEE 802.11p [i.2] PHY.

- *In an urban environment*, the speeds are lower resulting in slower changes of the network topology. However, as buildings will obstruct the signal, vehicles can therefore suddenly disappear and reappear again. An example of this is when a vehicle travels through an intersection. The urban layout contributes to many nodes in certain areas being hidden to one another and this may have a major impact on the performance, i.e. due to the hidden terminal problem. The density of vehicles in large cities can be rather high so scalability is an important issue also in this scenario.

5.3.1 Highway scenario (STDMA)

Simulations of STDMA and CSMA have been carried out in a highway scenario with several lanes, where the vehicles appear Poisson distributed and receive a speed drawn from a Gaussian distribution with different mean values depending on lane. Once given, the speed is constant as long as the vehicle remains on the highway. No overtaking is considered. The purpose of the selected vehicle traffic model is to capture the mobility of nodes and evaluate different vehicle densities. In a highway scenario, the highest relative speeds are found, which results in the most rapidly changing network topology for the VANET and thereby likely the most stressful situation for the MAC method. Two different highway scenario settings have been used, reflecting a normal vehicle traffic density and a high vehicle traffic density. In Table 7 the two different settings are detailed together with the approximate vehicle density.

Table 7: Two different highway scenario settings for STDMA and CSMA

Highway scenario		Number of lanes	Poisson - mean inter-arrival time	Vehicle density for 100 m of highway
1	**Normal vehicle density**	6 (3 in each direction)	3 seconds	9 to 10 vehicles
2	**High vehicle density**	12 (6 in each direction)	1 second	25 to 26 vehicles

In Figure 3 the two highway scenarios with different number of lanes together with the Gaussian distributed mean values of the speed for the different lanes are depicted. The vehicle speeds are approximately between 70 km/h to 140 km/h.

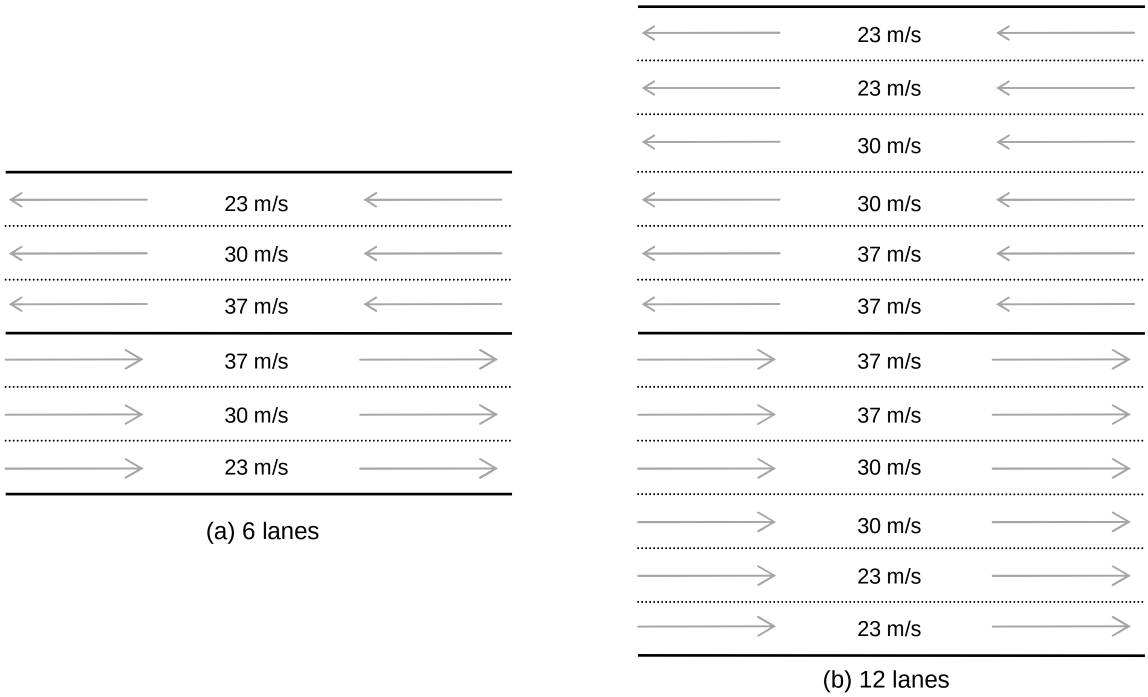


Figure 3: Two highway scenario settings with the Gaussian distributed mean values of vehicle speed depicted for each lane

The highway is 6 km and to avoid edge effects data is collected only from the middle part of the highway, Figure 4.

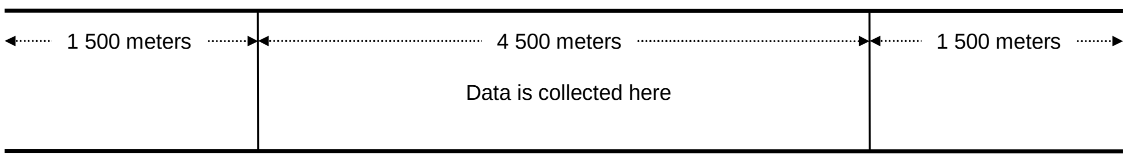


Figure 4: Showing where data in the simulation is collected to avoid edge effects

5.3.2 Urban scenario (MS-Aloha)

The urban scenario is set in a grid. It includes two subcases an *obstructed urban scenario* (with models accounting for effects of buildings on the propagation) and a *non-obstructed urban scenario*.

The urban scenario is set in a grid: it is shown in Figure 5, and includes 5 × 5 (double-lane) roads, 150 m far the one from the other (the area is wide 750 m). The mobility traces are generated by SUMO [i.13]: the nodes are 290 with a mean speed of 60 km/h (16,7 m/s). All the nodes are in the map from the beginning of the simulation: initially they are evenly distributed and, over time, they move in a random way along paths which include also turnings. XML-encoded mobility traces have been generated using the SUMO [i.13] and translated into TCL commands.

For simplicity, buildings are supposed to occupy all the areas not assigned to roads (hence with large 150 m × 150 m blocks). Given the channel model explained in clause 5.3.2, the scenario is meant to increase the sudden appearance of nodes and the number of hidden terminals: this is the case when, given three nodes A, B and C, node B can receive both by A and C but, conversely, A and C cannot hear each other.

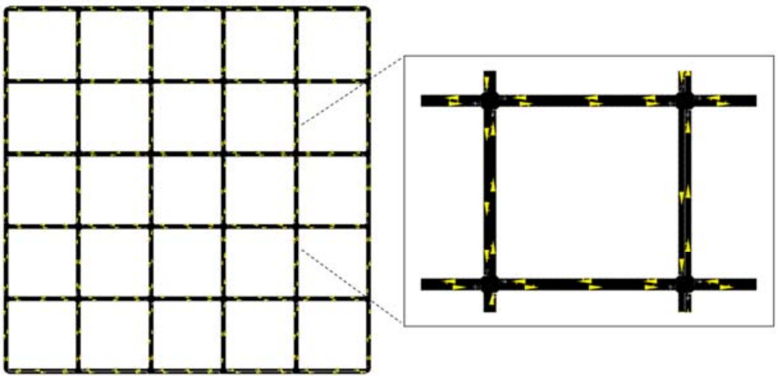


Figure 5: The urban scenario set in the 5 × 5 grid topology

Some considerations may help the understanding of the scenario and its rationale:

Thanks to the buildings which restrain propagation, vehicle traffic congestion is not the main issue, despite the number of nodes (290 in 750 m × 750 m). Consequently, all the decays in the reception rates can be imputed only to one of the following causes:

- Misbehaviors of the MAC protocol (for instance due to the sudden appearance of the node)
- Collisions due to hidden terminals

As discussed in clause 7.1.2, the effects could be even heavier including a higher number of crossroads (i.e. smaller blocks). Since MS-Aloha prevents hidden terminals, the chosen setting is beneficial to CSMA/CA.

In order to discuss the preferred parameter settings for scalability, a different Manhattan grid without obstructions is used in clause 7.2.3 (in the joint simulations by NS-2 and SUMO there are some scalability issues in a highway scenario). This scenario is called non-obstructed urban scenario and is set as follows: 8 × 8 (double-lane) roads 150 m far the one from the other (the area is wide 1 050 m); no obstructions (line-of-sight condition); 600 nodes moving in the map (with the same speed as in the obstructed case). The scenario is not realistic, but, for the sake of clarity, its goal is just the study of the recommended parameter settings for MS-Aloha, also for heavily congested scenarios.

The unobstructed urban scenario exploits the same channel model used in the highway (clause 5.4.1, Table 9), with a dual slope attenuation pattern and the same Nakagami settings. Border effects are prevented as follows: the packet delivery ratio (PDR) statistics are computed considering the transmissions by all the nodes, but receptions only by the nodes in the central area 4 × 4. In this way the full distance of the map can be covered but the nodes in the borders are excluded from the analysis on reception, being affected by lower interferences (less nodes in their radio range).

5.4 Channel model

5.4.1 Highway scenario

The Nakagami *m* model [i.3] serves as channel model in the highway scenario. It has previously been identified as a suitable probabilistic channel model for the VANET setting [i.4] and [i.5]. The small scale and the large-scale fading are both represented by the Nakagami *m* model. The probability density function (PDF) for the Nakagami *m* distribution is:

$$f\left(x;m,P_r(d)\right)=\frac{2m^m x^{2m-1}}{\left[P_r(d)\right]^m\,\Gamma(m)}e^{\frac{mx^2}{P_r(d)}}, \tag{1}$$

where m represents the fading intensity, $P_r\left(d\right)$ the average received power at a distance d, and $\Gamma\left(m\right)$ is the gamma function. Rayleigh fading conditions, i.e. no line-of-sight exists, can be obtained through Nakagami by setting $m=1$. Higher values of m can be used for approximating Rician distributed channel conditions where a line-of-sight path exists, while for $m<1$, the channel conditions are worse than the Rayleigh distribution. The values of m are distance dependent and presented in Table 8, i.e. the fading intensities are varied depending on distance between TX-RX.

Table 8: The different *m* values in the Nakagami model

Distance bin in meters	m
0 to 50	3
51 to 150	1,5
151 -	1

The averaged received power $P_r(d)$ is following a dual-slope model:

$$P_{r,dB}(d) = \begin{cases} P_{r,dB}(d_0) - 10\gamma_1 \log_{10}\dfrac{d}{d_0}, & d_0 \le d \le d_c \\ P_{r,dB}(d_0) - 10\gamma_2 \log_{10}\dfrac{d}{d_c} - 10\gamma_1 \log_{10}\dfrac{d_c}{d_0}, & d > d_c \end{cases} \quad (2)$$

where numerical values are presented in Table 9. The $P_{r,dB}(d_0)$ is calculated using the following free space path gain formula:

$$P_{r,dB}(d_0) = P_{t,dB} - 10\log\left(\frac{\lambda^2}{(4\pi)^2 d_0^{\,2}}\right), \quad (3)$$

where $d_0 = 10$ m and the wavelength, λ, is based on a carrier frequency of f = 5,9 GHz.

Table 9: The path gain model's parameters

Parameter	Value
Path gain γ_1	1,9
Path gain γ_2	3,8
Cut off distance d_c [m]	80
Reference distance d_0 [m]	10
Wave length λ [m]	0,0508

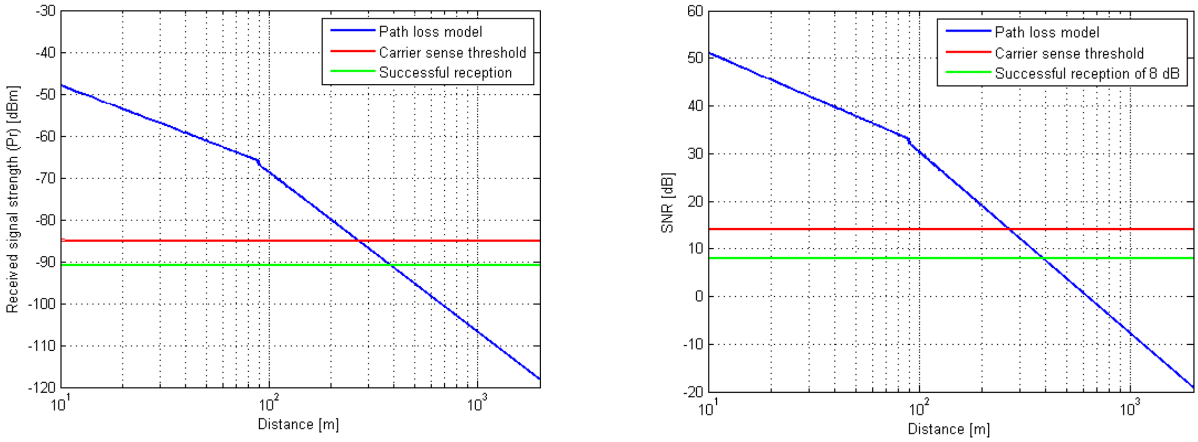
The resulting signal-to-interference-plus-noise (SINR) ratio at RX is calculated using the following formula:

$$SINR = \frac{P_r}{P_n + \sum_k P_{i,k}}, \quad (4)$$

where P_r is the power of the desired signal, $P_{i,k}$ is the power of the k-th interferer, and P_n the noise power. The noise power is set to -99 dBm. When there is no interference, the interference power in the denominator vanishes and the result is signal-to-noise (SNR) ratio:

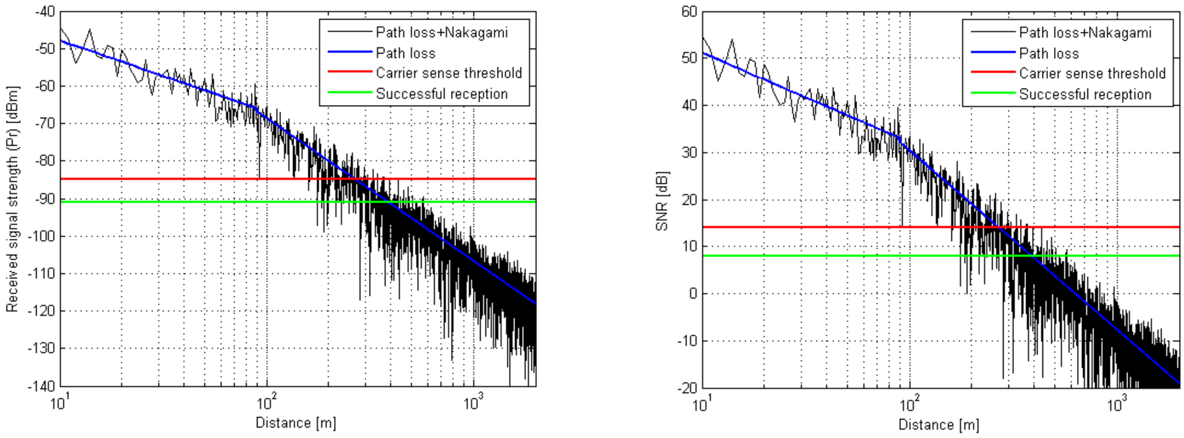
$$SNR = \frac{P_r}{P_n}. \quad (5)$$

The carrier sense threshold for CSMA is -85 dBm and for successful decoding of a packet a SINR/SNR value of 8 dB is required. Two different output powers are considered in the simulations; 20 dBm and 25 dBm. In Figure 6 and Figure 7 an output power of 20 dBm is used. In Figure 6(a) the path loss part of the channel model is depicted together with the carrier sense threshold and the received power of -91 dBm required for successful reception when no interference is present. In Figure 6(b) the noise power is added to the received signal strength, resulting in SNR on the x-axis for the path loss part. The resulting communication range will be approximately 400 m. In Figure 7, one realization of the Nakagami distribution has been added on top of the path loss part and again in Figure 7(a) the resulting received power is shown and in Figure 7(b) the resulting SNR. The increase of fading intensity with distance is clearly seen and successful reception varies from around 180 m up to 550 m.



(a) The received signal strength in dBm **(b) The SNR with a noise power of -99 dBm**

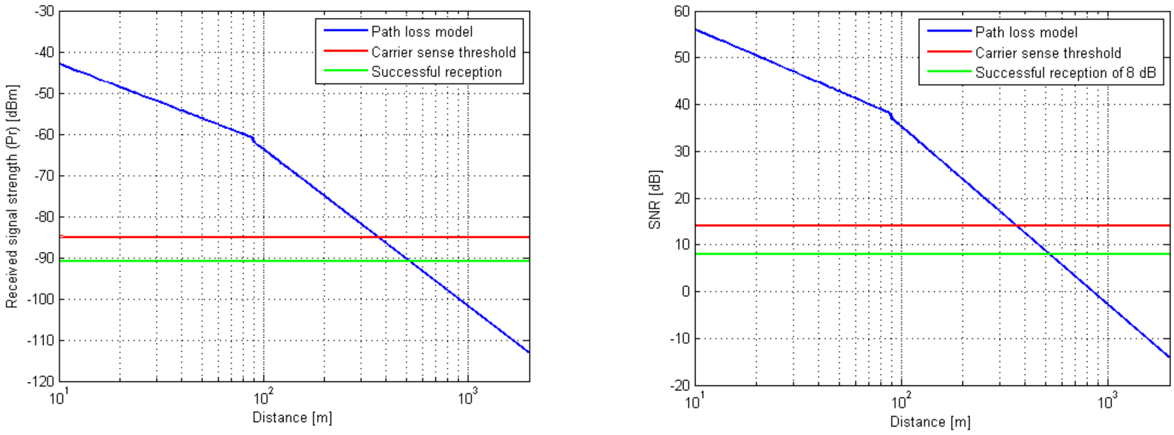
Figure 6: The path loss part of the channel model together with the carrier sense threshold and successful reception limit when using an output power of 20 dBm



(a) The received signal strength in dBm **(b) The SNR with a noise power of -99 dBm**

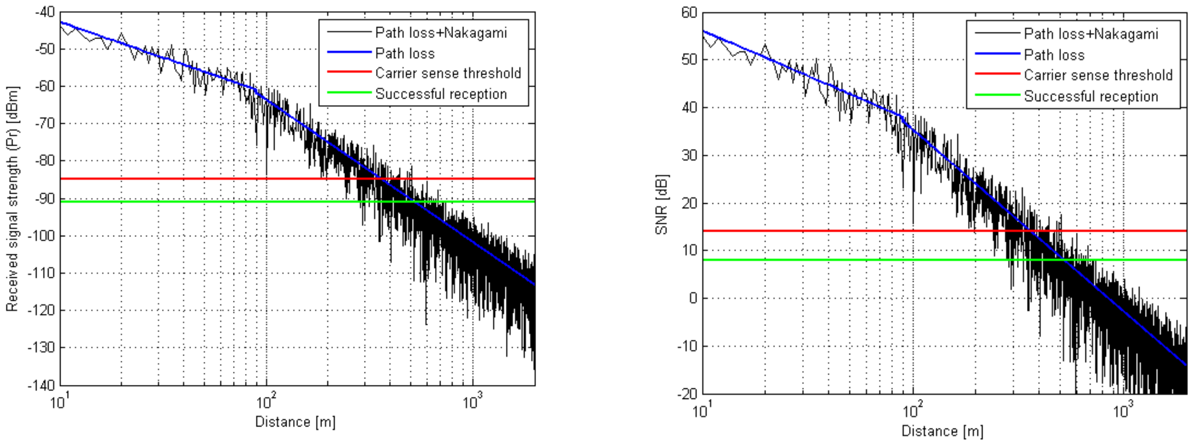
Figure 7: One realization of the channel model with Nakagami together with the carrier sense threshold and successful reception limit when using an output power of 20 dBm

In Figures 8 and 9 an output power of 25 dBm has been used to illustrate the channel model. By increasing the output power with 5 dBm the successful reception considering the path loss part has increased with 100 m from 400 m up to 500 m.



(a) The received signal strength in dBm **(b) The SNR with a noise power of -99 dBm**

Figure 8: The path loss part of the channel model together with the carrier sense threshold and successful reception limit when using an output power of 25 dBm



(a) The received signal strength in dBm **(b) The SNR with a noise power of -99 dBm**

Figure 9: One realization of the channel model with Nakagami together with the carrier sense threshold and successful reception limit when using an output power of 20 dBm

5.4.2 Urban obstructed and non-obstructed scenarios

At the time of this writing, the most general approach to urban network simulations has been proposed in [i.10],where, based on a real 3D urban map and a ray-tracing tool, an urban area is classified into segments. For each couple of segments it is possible to summarize propagation in terms of reachability, mean attenuation and fading spread, as a function of the position in the respective segments. This approach (RADII) requires a pre-processing and some simplifications in the propagation scenarios but makes the joint physical-and-network layers simulation feasible, preventing possible issues in the scalability of the simulations. Previous attempts, which tried to couple the network simulator and tray-tracer and launched a ray-tracing process at each transmission event by the network simulators.

However RADII represents more a methodology than a channel model: it is aimed to generate a channel model for any given urban topology. On the other hand it would be arbitrary the use of any specific urban map and it would be difficult to interpret the results in a general way.

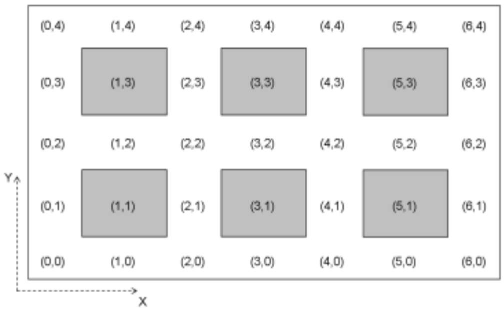


Figure 10: The Automatic classification of possible positions based on the distribution of buildings: an example of the automatically generated discrete coordinates *(x*, y*)*

For this reason it is here used a simplified, but validated, approach [i.9], which applies to grid topologies, as the one introduced in clause 5.3.2. In the simple case of a grid topology, positions can be classified with respect to blocks by simple arithmetic tools. If, along *x*-axis, obstructions are d_2^x-wide and d_1^x-far the one from the other, an automatic classification into the discrete variable x^* is carried out. If H() is the step function, then x^* can be defined following equations:

$$\begin{cases} a_1 &= x \operatorname{div} \left(d_1^x + d_2^x\right) \\ a_2 &= x \bmod \left(d_1^x + d_2^x\right) \\ x^* &= 2 * a_1 + H(a_2 - d_1^x) \end{cases} \quad (6)$$

The new discrete variables, permit to easily classify the position into Line-of-Sight (LOS), Near Line of Sight (NLOS) and non Line of Sight (nLOS). For each of the above cases a respective extra-attenuation (EA) can be associated.

$$\alpha_{TOT} = \alpha + EA$$

$$EA = \begin{cases} 0 & \text{if} \quad ((x_1^* = x_2^*) \wedge (x_1^*, x_2^* \text{ even})) \vee \\ & \quad\;\; ((y_1^* = y_2^*) \wedge (x_1^*, x_2^* \text{ even})) \\ & \quad\;\; \textit{i.e.}, \text{ same street -- LOS} \\ EA_{\text{NLOS}} & \text{if} \quad (|x_1^* - x_2^*| = 1) \wedge \\ & \quad\;\; (|y_1^* - y_2^*| = 1) \\ & \quad\;\; \textit{i.e.}, \text{ turning -- NLOS} \\ EA_{\text{nLOS}} & \quad\;\; \text{otherwise -- nLOS.} \end{cases} \quad (7)$$

The following extra-attenuation parameters are used in the simulations.

Table 10: The extra-attenuation for urban model

Parameter EA	Value
EA_{LOS}	0
EA_{NLOS}	-13 dB
EA_{nLOS}	-30 dB

Actually, the main rationale of the extra-attenuation parameter is not to provide a precise description of the attenuation, but rather to:

- Have no effects on LOS mutual position.
- Almost completely block transmissions in nLOS.
- Qualitatively match experimental and theoretical data for NLOS, in terms of reception probability.

For this reason, the most important parameter can be considered EA_{NLOS} which, effectively, has already been demonstrated both to match experimental data [i.9] and to reflect theoretical analyses based on ray-tracing [i.14]. In particular, in [i.14] it has been demonstrated that, for different mutual positions in NLOS, distance where a frame can be received reflects the proposed simplified channel model. In other papers more severe attenuation parameters have been proposed (in [i.16] the authors an attenuation of 20 dB for corners and much higher for non-line-of-sight). A similar, but more refined, approach based on extra-attenuation is found also in [i.22].

NOTE: The urban attenuation model has been validated in [i.14] by means of a ray-tracing software, called Wireless InSite®. The tool permits to select also materials, and the brick is selected as the main component of buildings. Half-wave dipole antennas with vertical polarization are configured in the frequency of 5,9 GHz and 10 MHz of channel bandwidth, compliantly with 802.11p [i.2] specifications. The urban canyon propagation model is used to simulate the real environment. Ray-spacing, number of reflections and number of diffractions are some settable parameters that influence the power transferred from any active transmitter to all active receivers.

Finally, also the attenuation (as from α in Equation 7) and Nakagami fading (as discussed in clause 5.4.1) have been set as from the suggested settings available from literature.

The parameter of Nakagami fading adopted for the urban model are the same used for the highway (as from Table 8); instead the attenuation is set differently in the obstructed and non-obstructed scenarios: in the former case the attenuation is fixed to power 2 (which simplifies the dual slope path-loss model from Equation 2 and Table 9), while, in the latter, the same dual-slope used in highway is adopted. While the suggested models are straightforward, they adhere to and are qualitatively validated by existing measurements on packet reception [i.16].

Given the different signal attenuations and interference, the resulting SINR at RX is calculated using Equation 4.

5.4.2.1 Receiver model used for the urban scenarios

Simulations set in the urban scenarios adopt the build NS-2.34 of the simulator NS-2; this advanced version - released by Mercedes Benz® [i.19] - introduces two new modules: Mac802.11Ext and WirelessPhy-Ext. The two extensions modify previous NS-2 WiFi model so to account for IEEE 802.11p [i.2] specific features and, what is more, to compute the cumulative interference coming from all the nodes. Thus, also in the urban simulations, given the signal attenuations, the interference is computed and the resulting SINR at RX is calculated using Equation 4.

However, unlike simulations set in the highways (clause 6), the urban simulations (results presented in clause 7) use sensitivity thresholds both for CSMA/CA and for the synchronous protocol - not only for CSMA. More explicitly, in these simulations also in MS-Aloha a frame can be received only if, simultaneously:

(i) its received power exceeds the carrier sensitivity threshold; and

(ii) the SINR exceeds the threshold for correct reception.

The reasons why the model of the receiver includes the carrier-sensing threshold are twofold:

- First of all MS-Aloha is built on the top of IEEE 802.11p [i.2] physical layer and PLCP and is being developed so to be, as much as possible, backward compatible to IEEE 802.11p [i.2].
- Moreover, conceptually, carrier sense is still required to detect and decode an incoming signal preamble. In fact, despite the synchronization, and due to time of flight, the exact time of arrival of frames cannot be exactly foreseen: thus, transmissions are synchronous but receptions are supposed to require carrier-sensing.

NOTE: The sensitivity of a receiver (or other detection device) is the minimum magnitude of input signal required to produce a specified output signal. It accounts also for the internal *noise figure* of the receiver.

- If a more efficient sensing solution were available for MS-Aloha with respect to CSMA/CA, the analysis proposed in clause 7 could be considered a worst case analysis.

The proposed model applies both to urban obstructed and urban non-obstructed scenario in clause 7. This may help to explain some different PDR graphs, especially in the upper bounds (ideal cases) of clause 6 and clause 7, despite the same attenuation model. Qualitatively, the introduction of the sensitivity threshold reduces PDR so that a given value can be reached, without carrier sensing some hundreds meters farther.

5.5 CSMA specific parameters

The clear channel assessment (CCA) sensitivity, also known as the carrier sense threshold popularly, for CSMA has been set to -85 dBm according to [i.2]. The listening period, i.e. the arbitration interframe space (AIFS) is set to 58 µs, which is the listening period of the highest priority found in 802.11p [i.2]. IEEE 802.11p [i.2] supports 4 different priorities or access categories (AC), where each has its own AIFS and contention window (CW). The AIFS is calculated using the following formula:

$$\mathrm{AIFS}[\mathrm{AC}]=\mathrm{AIFSN}[\mathrm{AC}]\times \mathrm{aSlotTime}+\mathrm{aSIFSTime} \qquad (8)$$

where, aSlotTime and aSIFSTime are derived from the PHY layer in use. The AIFSN[AC] is the AIFS number (AIFSN) for each AC, i.e. the priority of the data traffic. In Table 11 the default values for the different ACs are provided [i.2]. The aCWmin and aCWmax parameters are also fetched from the PHY layer in use.

Table 11: Default values for the ACs in 802.11p [i.2]

AC	CWmin	Cwmax	AIFSN	Description
AC_VO	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2	AC_VO refers to voice traffic. Highest priority.
AC_VI	(aCWmin+1)/2-1	aCWmin	3	AC_VI refers to video traffic.
AC_BE	aCWmin	aCWmax	6	AC_BE refers to best effort traffic.
AC_BK	aCWmin	aCWmax	9	AC_BK refers to background traffic. Lowest priority.

In Table 12 the values for the different parameters in 802.11p [i.2] PHY layer is tabulated assuming 10 MHz channel.

Table 12: The PHY layer values

Parameter	Value
aSlotTime	13 µs
aSIFSTime	32 µs
aCWmin	15
aCWmax	1023

In Table 13 the resulting AIFS and CW sizes are shown for 802.11p [i.2].

Table 13: The resulting AIFS and CW sizes for 802.11p [i.2]

AC	CWmin	Cwmax	AIFS
AC_VO	3	7	58 µs
AC_VI	7	15	71 µs
AC_BE	15	1 023	110 µs
AC_BK	15	1 023	149 µs

The choice of the highest priority is mainly due to keep the AIFS as short as possible and thereby more data traffic can be squeezed into the channel, i.e. the channel utilization is increased because nodes listen shorter before transmission. The drawback is the CW size for the highest priority, there is few number to select from when performing the backoff procedure implying an increased probability of simultaneous channel accesses during high network utilization periods, i.e. nodes reach a backoff value of 0 at the same time.

5.6 Performance metrics

5.6.1 Introduction

The selected performance measures are *channel access delay* and *packet reception probability*. Throughput has been omitted for several reasons. First and foremost, in the majority of all road traffic situations it is not interesting to transmit packets that have old and outdated information. Consequently, CAM and DENM have deadlines to meet. There is no use transmitting an old CAM when a newer one has been generated by the application (the deadline was missed for the previous packet). A DENM is triggered in an event of hazard and also contains a deadline (no use transmitting if the event that triggered the hazard warning is no longer active). Therefore, road traffic safety applications can be classified as real-time systems since the packets generated by the applications are perishables. In real-time communication systems throughput, which is a measure of average behavior, is of no importance. Instead the worst case behavior is the main issue as the real-time system will never be better than the worst case behavior. A system can have a high throughput and still there are nodes that are not allowed to transmit (the channel access delay extends beyond the deadline of the packet and packets are dropped at receiver before transmitted). Further, throughput is difficult to define for broadcast communication because all packets have multiple receivers. For example, all correctly received packets do not have to be of interest to a specific node (information from nodes in the opposite direction on a highway moving away from the node for example). Moreover, if half of the nodes intended to receive a DENM actually receives it, it is difficult to determine if it is best to define the throughput locally within each node, or globally for each packet.

Throughput is of greater interest in unicast transmissions, where one TX-RX pair wants to achieve as efficient communication as possible. The *ad hoc* topology and mobility of nodes contributes even more to the definition problem of throughput for VANETs (the set of intended receivers change rapidly). Note that the aggregated throughput can never be higher than the bandwidth offered by the communication channel. The selected transfer rate for the simulations in clauses 6 and 7 is set to 6 Mbit/s, which is the maximum that can be achieved. However, it is not possible to achieve this maximum due to overhead in the protocols, such as carrier sensing and backoff procedures in CSMA and clock hold-on times in time slotted MAC approaches. However, a hint of the maximum performance in terms of the number of supported vehicles can be made. The theoretical number of supported vehicles within radio range of each other, considering the two different data traffic models in clause 5.2 using 6 Mbit/s, is presented in Table 14.

Table 14: Number of theoretically supported nodes within radio range

Data traffic model	Required bandwidth by each node	Required bandwidth including carrier sensing/clock hold-on and preamble plus signal field at PHY	Number of supported vehicles within radio range
2 Hz and 800 bytes	12,8 kbit/s	14 kbit/s	428 vehicles
10 Hz and 300 bytes	24 kbit/s	30 kbit/s	200 vehicles

The data in Table 14 is theoretical and serves as an upper limit. To achieve this upper limit would require, e.g., for CSMA that all transmissions are perfectly scheduled and arrives at the MAC layer one after the other. For time-slotted MAC approach it is easier to come closer to the maximum since the transmissions already are scheduled and synchronized such that the randomness with carrier sensing and backoff do not exist.

5.6.2 Channel access delay

The channel access delay is defined as the time elapsing from the channel access request until the actual channel access takes place. As the name suggests, the parameter states the average and worst case channel access delay and therefore it can also be used to evaluate the fairness between nodes. Fairness implies that all nodes, having the same type of data traffic, should have equal opportunity to access the channel within each specific time span. The fairness between nodes can be found by examining the channel access delay of each node. If there is a major difference between one node having long channel access delays and another node having short channel access delays, the MAC protocol is unfair. In Figure 11 the delays encountered at TX and RX together with the channel are depicted. At t_0 a channel access request at TX is done, and the time elapsing from t_0 to t_{TX} is denoted channel access delay, τ_{ca}. The propagation delay is denoted τ_p and the decoding delay is τ_{dec}. The deadline for the packet is denoted t_{dl}. In the simulations conducted in clauses 6 and 7 the deadline is proportional to the periodicity of the message rate, i.e. the update frequency, f_p. If $\tau_{ca} > t_{dl}$ the packet is dropped at TX since the deadline is missed. The MAC-to-MAC delay, τ_{MM}, includes all latencies found from the TX MAC layer to the RX MAC layer.

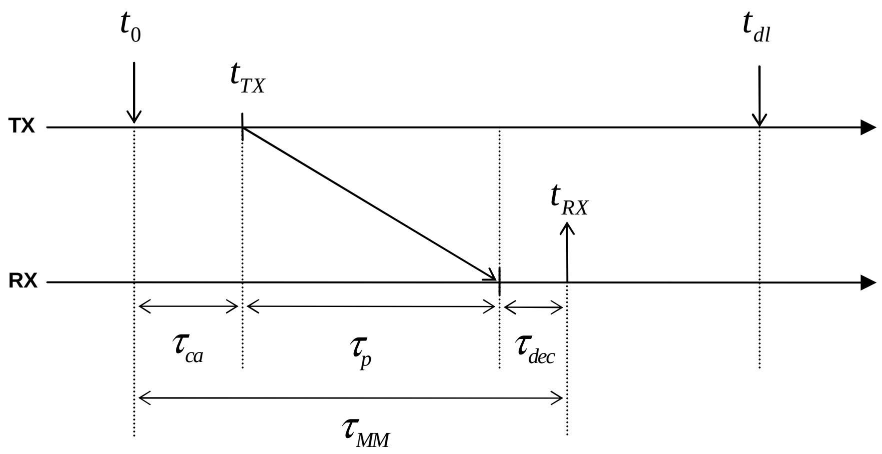


Figure 11: The channel access delay, τ_{ca}, is depicted

5.6.3 Packet reception probability

The packet reception probability is calculated at different distances from TX and is a measure of the reliability of the transmissions. The packet reception probability will decrease for RXs further away from TX due to signal path loss. Reliability is used as a performance measure on several layers in the protocol stack. Herein the reliability refers to the received signals strength which is affected by the wireless channel due to fading and path loss. The interference from other ongoing transmissions also contributes to the received signal strength and thereby affects reliability. Successful reception of a packet implies a SINR ≥ 8 dB, [i.17]. This is based on the requirement of the chosen transfer rate of 6 Mbit/s using the modulation scheme QPSK with a code rate of 1/2 (r = 1/2). Figure 12 shows an example of a transmission from one TX and twenty RX. Fifteen of the twenty RX receives the packet within a specific distance from TX, i.e. the packet reception probability is 75 % in this example.

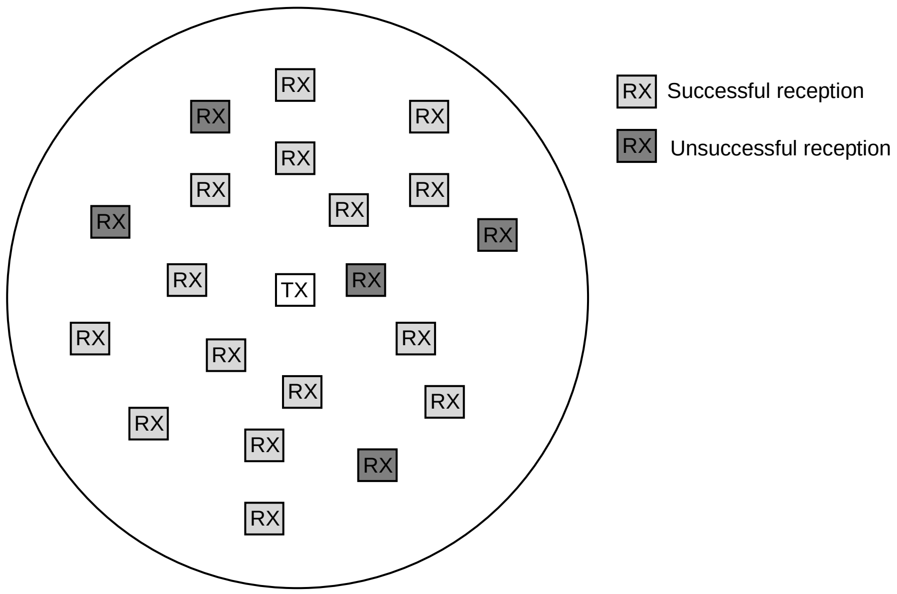


Figure 12: An illustration of packet reception probability

6 Simulation results of STDMA

6.1 Introduction

This clause describes the simulation results and findings when comparing STDMA and CSMA in a highway scenario using packet reception probability and channel access delay as performance metrics. The vehicle traffic model is described in detail in clause 5.3.1 and the channel model is described in clause 5.4.1. Two different vehicle densities have been evaluated, Table 15. In the normal vehicle density case the TX will have approximately 15 nodes within a radius, *R*, of 100 m. In the high vehicle density case, the TX will have approximately 52 nodes within a radius of 100 m.

Table 15: Number of RX within TX at different distances

Scenario	*R* < 100 m	*R* < 200 m	R < 300 m	*R* < 400 m	*R* < 500 m	*R* < *600 m*	Description
Normal vehicle density	~15	~30	~45	~60	~75	~90	6-lane highway and an inter-arrival time of vehicles of 3 s using Poisson.
High vehicle density	~52	~104	~156	~208	~264	~316	12-lane highway and an inter-arrival time of vehicles of 1 s using Poisson.

6.2 Parameter settings

In Table 16 all parameters that are the same throughout all simulations conducted in this clause are presented. The backoff window in CSMA is never increased since broadcast data traffic is considered and therefore the backoff procedure is only invoked once due to a busy carrier sensing.

Table 16: Parameters that are the same throughout all simulations in this clause

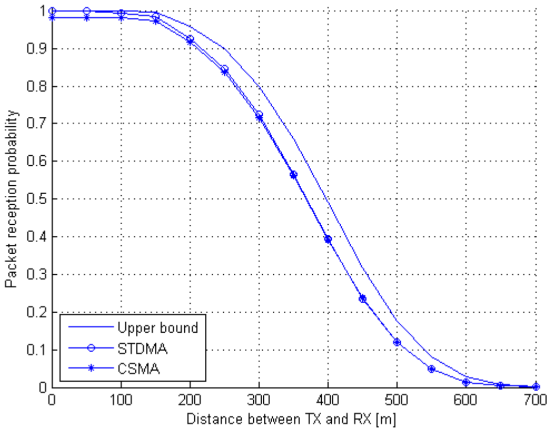
Parameter	Value	Description
CCA sensitivity	-85 dBm	The CCA sensitivity/carrier sense threshold for 10 MHz channels found in [i.2].
Listening period/carrier sensing (AIFS)	58 µs	Listening period (AIFS) for the highest priority supported in 802.11p [i.2].
Backoff window size	[0, 3]	The backoff window size for the highest priority supported in 802.11p [i.2].
Backoff times	[0, 13 µs, 26 µs, 39 µs]	The number of different backoff times that are eligible.
Successful reception threshold	8 dB	All packets having an SNR/SINR of 8 dB and above are received successfully.

6.3 Simulation results: highway scenario

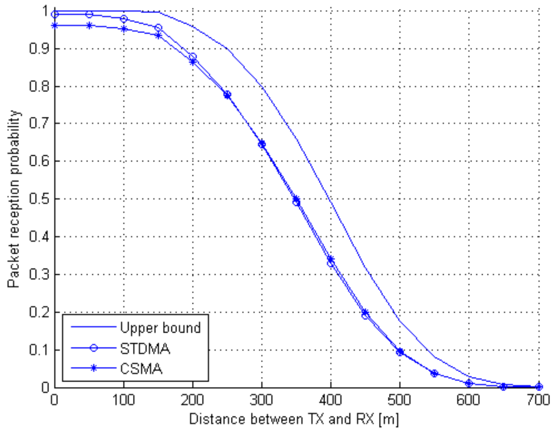
6.3.1 Packet reception probability

6.3.1.1 Normal vehicle density

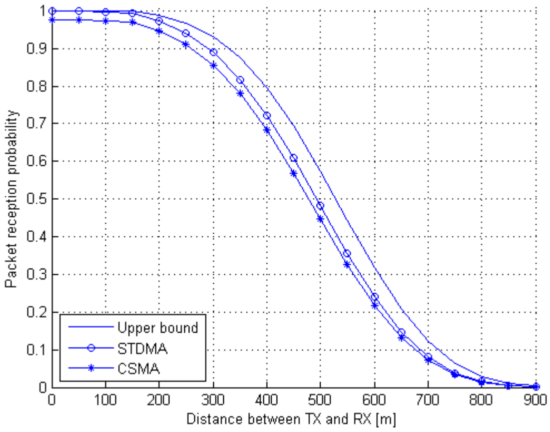
For all figures presented in this clause, the simulation results are based on 100 000 transmissions. The packet reception probability for the normal vehicle density setting described in clause 5.3.1, Table 6.1 is presented in Figure 13 for both 2 Hz/800 bytes and 10 Hz/300 bytes. The output power is set to 20 dBm and 25 dBm respectively. On the x-axis the distance between TX and RX is depicted. The upper bound found in Figure 13 is the best packet reception probability that can be achieved with the current channel model when no interference is present, i.e. there is no other node transmitting simultaneously anywhere in the system. The nodes using the data traffic setting 10 Hz/300 bytes inject twice as much data traffic as the 2 Hz/800 bytes setting. Therefore, the packet reception probability is slightly lower in Figure 13 (b) as compared to Figure 13 (a). The lower packet reception probability in Figure 13 (b) for both MAC algorithms is due to the higher channel load but CSMA has a slightly lower packet reception probability compared to STDMA within 100 m from TX. The reason why the two MAC algorithms are not closer to the upper bound is due to the general interference present in the system caused by simultaneous transmissions.



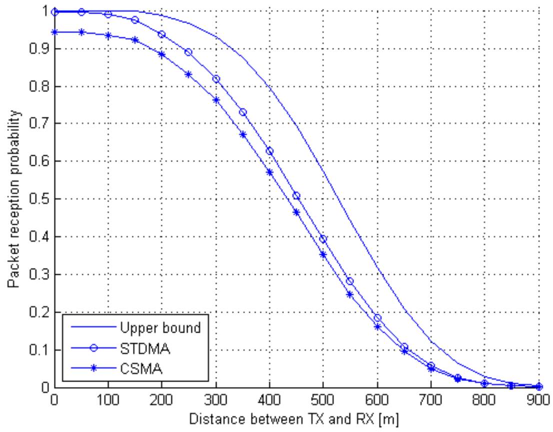
(a) 2 Hz/800 bytes and 20 dBm output power



(b) 10 Hz/300 bytes and 20 dBm output power



(c) 2 Hz/800 bytes and 25 dBm output power



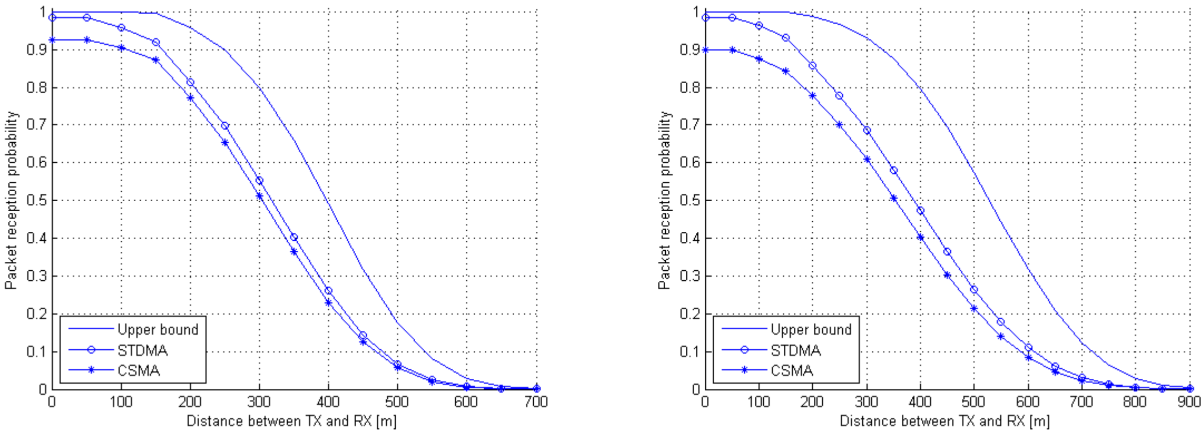
(d) 10 Hz/300 bytes and 25 dBm output power

Figure 13: Packet reception probability for distances of up to 700 m and 900 m from TX, respectively

Figure 13 (c) and Figure 13 (d) show the packet reception probability when the output power is increased to 25 dBm. In Figure 13 (c) the 2 Hz/800 bytes setting is found and in Figure 13 (d) the 10 Hz/300 bytes setting is found. It can be seen that the higher output power results in an increase in the communication distance for all settings compared to the results in Figure 13 (a) and Figure 13(b), i.e. up to 900 m. STDMA benefits more from the higher output power, while CSMA loses in performance compared to STDMA especially in the 10 Hz/300 bytes case (Figure 13 (d)). Note that the system is not overloaded and the performance difference is due to STDMA employing synchronized transmissions, i.e. if two nodes transmit at the same time the packets overlap completely, whereas in CSMA, nodes can have partial overlap of several simultaneous transmissions.

6.3.1.2 High vehicle density

The packet reception probability for the high vehicle density case is depicted in Figure 14 with a data traffic setting of 2 Hz/800 bytes, where 14 (a) has an output power of 20 dBm and 14 (b) has an output power of 25 dBm. We note that for the high vehicle density case the interference level is higher and therefore both STDMA and CSMA are further away from the upper bound. STDMA still benefits more from the higher output power than CSMA does and within 100 m from TX STDMA maintains a packet reception probability of more than 95 %. Also note that STDMA achieves almost 10 % higher within 100 m compared to CSMA within 100 m for an output power of 25 dBm.



(a) 20 dBm output power **(b) 25 dBm output power**

Figure 14: Packet reception probability for distances of up to 700 m and 900 m from TX, respectively, in a high vehicle density scenario with data traffic setting 2 Hz/800 bytes

CSMA as employed within ITS-G5 [i.8] have to implement DCC [i.24]. The current proposal is to load the control channel (CCH) to 25 %, i.e. when a node receives more data traffic than 25 % of the time it has to react and adjust its transmit power level as well as restrict its data traffic injected into the network. This is not considered in the simulations results presented herein, i.e. DCC is not implemented. The channel load in the high vehicle density case is up to 90 %.

6.3.2 Simultaneous transmissions

A hidden terminal situation occurs when two terminals are out of radio range of each other (and thereby out of control for the MAC protocol) but still close enough to have a common set of receivers such that simultaneous transmissions can create decoding problems at these receivers due to a higher interference level. In particular, in an access point (AP) based network using CSMA, the hidden terminal situation can cause major performance degradation to one or both of the TX involved in the hidden terminal situation. The distinguishing feature of a broadcast scenario is that there is more than one receiver interested in receiving each transmitted packet, as opposed to in the unicast case when two TX compete for access to one RX, typically the AP. The hidden terminal situation encountered in a VANET with broadcast communication has been defined in [i.18]. The definition is based on an intended communication range, which is derived from the application requirements of successful packet reception. When the intended communication range of two transmitters overlap, there is potentially a common set of intended receivers and a hidden terminal situation may occur. If two TX do not have overlapping intended communication range, they are no longer defined as hidden to one another as no common set of intended receivers exists, but rather interferers as they contribute to the SINR at receivers located in between them. This definition based on intended communication range is required as a VANET may cover an entire country and at some distance terminals are no longer hidden according to the original definition from the AP-based network, but simply distant. In Figure 15, a hidden terminal situation is depicted, i.e. two TX having overlapping intended communication ranges and thereby a common set of RX, in this case three RX.

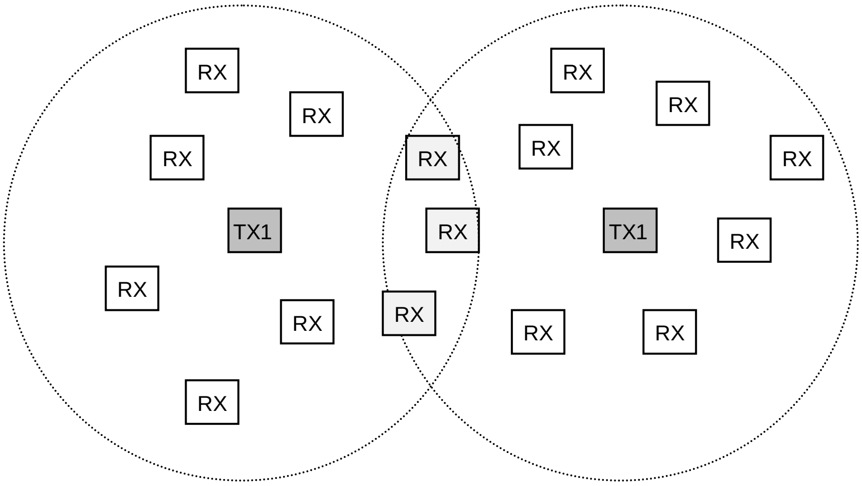


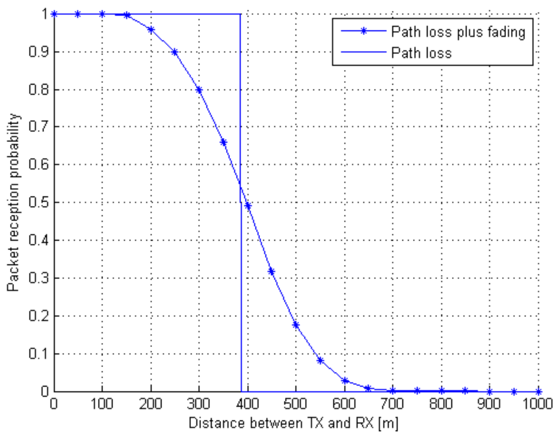
Figure 15: An illustration of the hidden terminal problem in VANETs with broadcast communication

To define the intended communication range in our case, the path loss part of the channel model served as a base line. In Figure 16, the packet reception probability when considering:

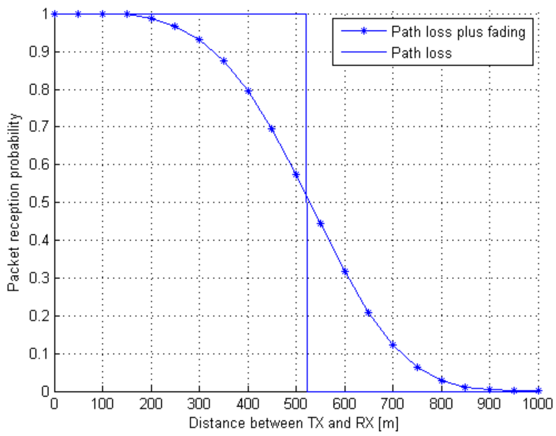
(i) the path loss part; and

(ii) the path loss part plus the Nakagami fading is depicted for the two different output powers, i.e. 20 dBm and 25 dBm.

The path loss part is deterministic and therefore the packet reception probability is 1 until the SNR falls below 8 dB, recall Figures 6 to 9 in clause 5.4.1. The path loss plus Nakagami fading is the same as the upper bound in previous figures. The range of the deterministic part (the path loss part) for the two different output powers has been used as the intended communications range of our scenarios. For 20 dBm the intended communication range was set 500 m and for the 25 dBm it was set to 600 m. Note that for a particular use case, the intended communication range required by that application should be used.



(a) 20 dBm



(b) 25 dBm

Figure 16: Packet reception probability for the path loss solely and the path loss plus the Nakagami fading when using an output power of 20 dBm and 25 dBm

First we need to evaluate the number of nodes located within the intended communication range of any of the two simultaneously transmitting nodes. Given the intended communication range of 500 m and 600 m respectively, it makes sense to group simultaneous transmissions into three different groups: the simultaneous transmitters are within the intended communication range of each other, the simultaneous transmitters are beyond communication range but close enough to have overlapping communication ranges (and thereby potentially a common set of receivers) and finally the transmitters are too far apart to have overlapping communication ranges, Table 17.

Table 17: Classification of transmissions in different groups based on distance between simultaneous transmitters

	Distance TX-TX Output power 20 dBm	Distance TX-TX Output power 25 dBm	Description
Group 1	0 m to 500 m	0m to 600 m	The two TX are within range of each other, i.e. not hidden. The MAC protocol should be able to handle this.
Group 2	500 m to 1 000 m	600 m to 1 200 m	The two TX are not within communication range but will have overlapping ranges and may therefore have a common set of receivers. These TXs could be defined as hidden terminals.
Group 3	> 1 000 m	> 1 200 m	The two TX are not within communication range, nor do they have overlapping ranges. They are simply distant interferers.

In Tables 18 and 19 the number of transmissions carried out in each group is tabulated. Table 18 considers an output power of 20 dBm and Table 19 an output power of 25 dBm. Groups 1 to 3 for every setting is based on 100 000 transmissions. As can be seen in both tables, the high vehicle density case suffers most from simultaneous transmissions within communication range (which is intuitive as the number of nodes within communication range has tripled). Simultaneous transmissions in group 1 are due to nodes reaching a backoff value of zero at the same time for CSMA (few backoff values to select from) and for STDMA it is due to the possibility to change to the same, previously empty, slot.

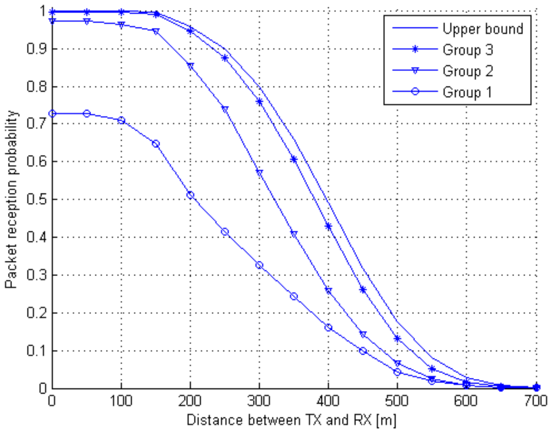
Table 18: Number of transmissions carried out in the different groups when considering an output power of 20 dBm

		CSMA		STDMA	
		2 Hz/800 bytes	10 Hz/300 bytes	2 Hz/800 bytes	10 Hz/300 bytes
Low vehicle density	Group 1	3,5 %	8,4 %	3,7 %	10,6 %
	Group 2	16,2 %	24,6 %	11,2 %	20,2 %
	Group 3	80,3 %	67,0 %	85,1 %	69,2 %
High vehicle density	Group 1	16,0 %	N/A	18,4 %	N/A
	Group 2	40,7 %	N/A	26,6 %	N/A
	Group 3	43,3 %	N/A	55,0 %	N/A

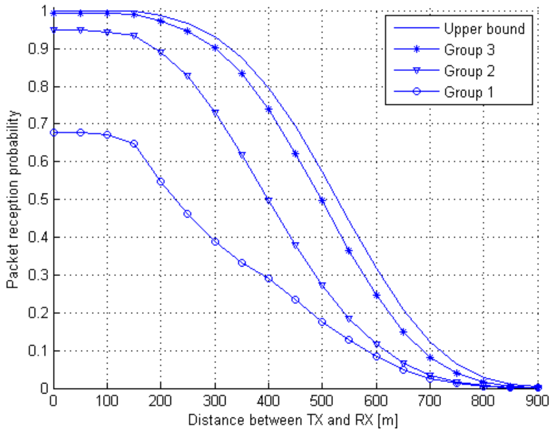
Table 19: Number of transmissions carried out in the different groups when considering an output power of 25 dBm

		CSMA		STDMA	
		2 Hz/800 bytes	10 Hz/300 bytes	2 Hz/800 bytes	10 Hz/300 bytes
Low vehicle density	Group 1	3,4 %	9,3 %	2,4 %	8,6 %
	Group 2	17,6 %	31,7 %	8,5 %	19,0 %
	Group 3	79,0 %	59,0 %	89,1 %	72,4 %
High vehicle density	Group 1	18,5 %	N/A	20,3 %	N/A
	Group 2	43,4 %	N/A	27,6 %	N/A
	Group 3	38,1 %	N/A	52,1 %	N/A

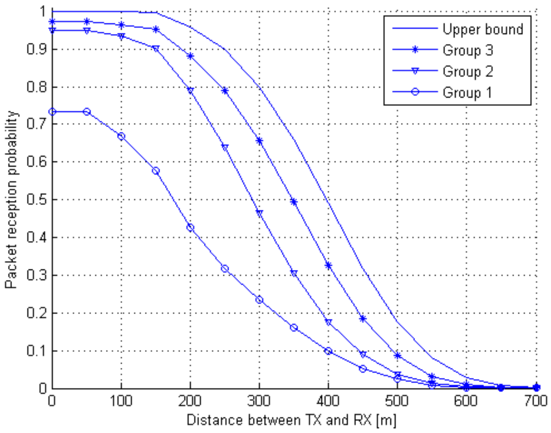
Next, we can evaluate the packet reception probability of nodes subject to simultaneous transmissions. In Figure 17 the packet reception for the individual groups considering CSMA when using 2 Hz/800 bytes data traffic is depicted. In Figure 17 (a) and (b) a low vehicle density is shown for the two different output powers, 20 dBm and 25 dBm, respectively. Figure 17 (c) and (d) show the high vehicle density case for the two different output powers. As can be seen, the packet reception probability for Group 1 packets is very low, whereas Group 2 has a better packet reception probability than Group 1 despite the presence of so called hidden terminals. In the low vehicle density case, Group 3 performs close to the upper bound as the interference level is closer to the upper bound than to the situation in the high vehicle density case. Group 1 has the same shape for all settings and as nodes can reach a backoff value of zero in CSMA, simultaneous transmissions can occur between two very closely located nodes. However, it should be noted that the occurrence of situations found in Group 1 is very small for the low vehicle density (Figure 17 (a) and (b)) compared to the high vehicle density (Figure17 (c) and (d)). Therefore it is important to note that the corrected weighted average of all these transmission is presented in Figures 13 and 14.



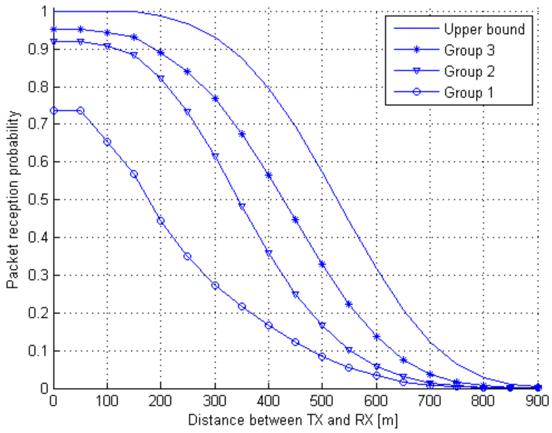
(a) Low vehicle density and output power of 20 dBm



(b) Low vehicle density and output power of 25 dBm



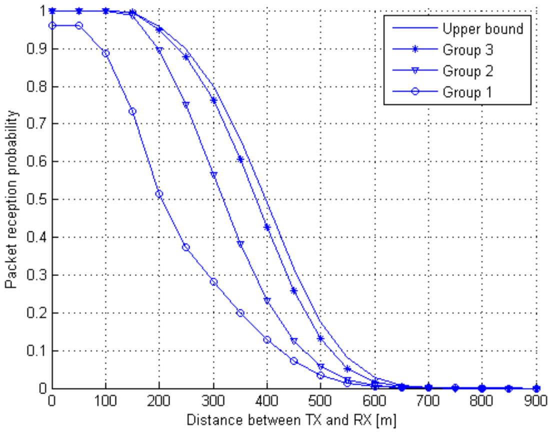
(c) High vehicle density and output power of 20 dBm



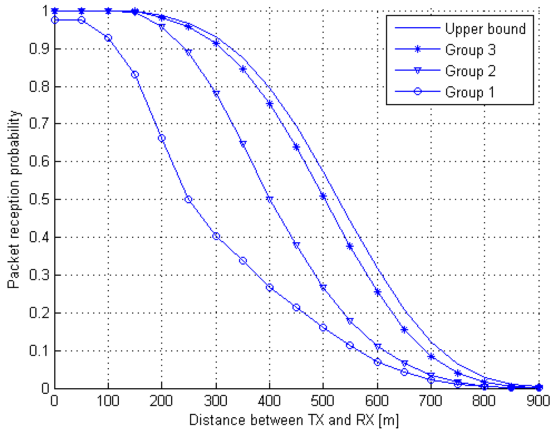
(d) High vehicle density and output power of 25 dBm

Figure 17: Packet reception probability for the different groups in CSMA with 2 Hz/800 bytes

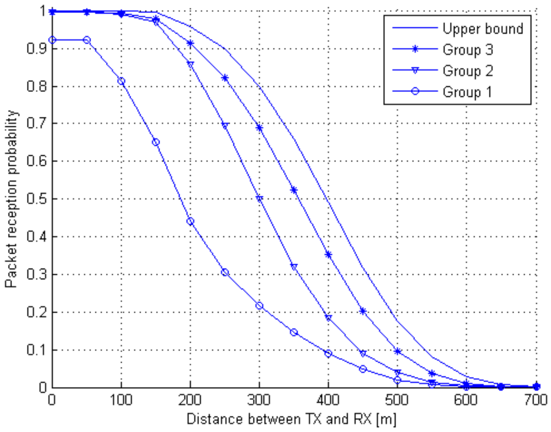
In Figure 18 the packet reception probability for the different groups considering STDMA when using a 2 Hz/800 bytes is depicted. In Figures 18 (a) and (b), a low vehicle density is shown for the two different output powers, 20 dBm and 25 dBm, respectively. Figures 18 (c) and (d) show the high vehicle density for the two different output powers. It can be seen that with STDMA there is no difference in the packet reception probability for Group 2 and Group 3 within 150 m from the TX. We also note that the packet reception probability for Group 1 is much better for STDMA compared to CSMA, especially in the close proximity to the TX. The *occurrence* of simultaneous transmissions in Group 1 of STDMA is actually slightly higher than for CSMA, but the *effects* are smaller resulting in a better performance. This is due to nodes in Group 1 of STDMA typically being located closer to a distance of 500 m because of the position aware scheduling of transmissions in space, whereas in the CSMA case, the distance between two TX are random.



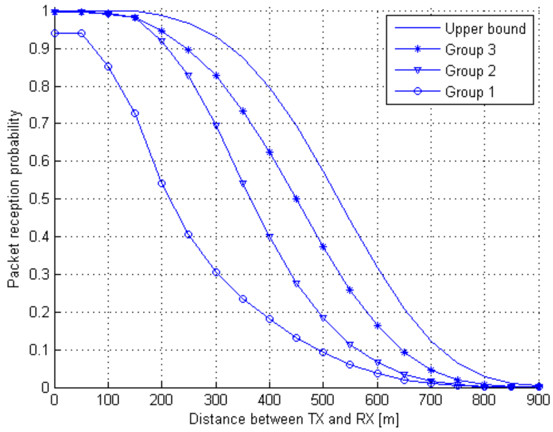
(a) Low vehicle density and output power of 20 dBm



(b) Low vehicle density and output power of 25 dBm



(c) High vehicle density and output power of 20 dBm



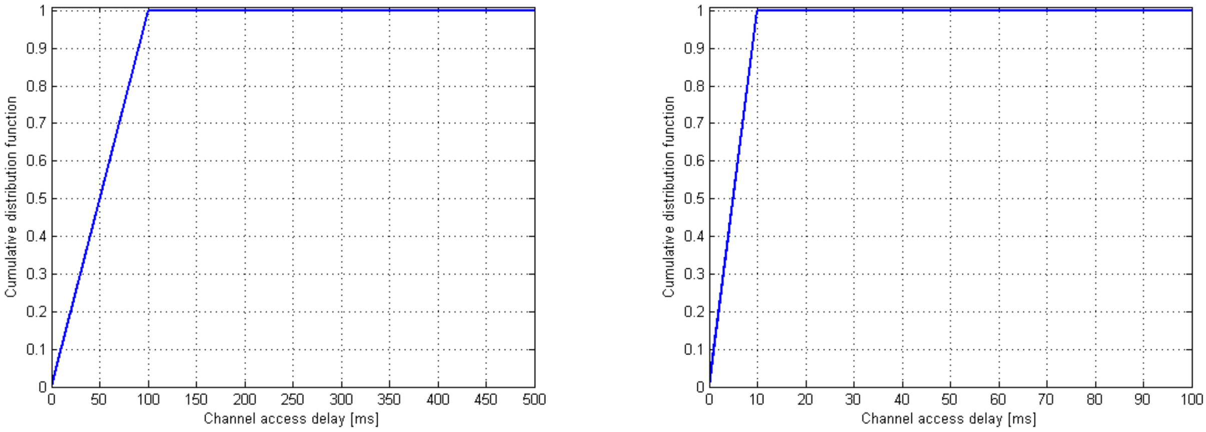
(d) High vehicle density and output power of 25 dBm

Figure 18: Packet reception probability for the different groups in STDMA with 2 Hz/800 bytes

6.3.3 Channel access delay

In STDMA, the channel access delay is upper bounded since a node is always allowed to transmit regardless of the number of nodes in the system. When all slots are occupied, a node will transmit at the same time as another node but it selects the one situated furthest away from itself. A node is eligible to select a transmission slot within the selection interval (SI) which is 20 % of all the slots in the frame, i.e. a 2 Hz update rate gives a period of 500 ms and hence the slots contained within an interval of 200 ms is eligible for transmission. Details around STDMA are found in [i.1].

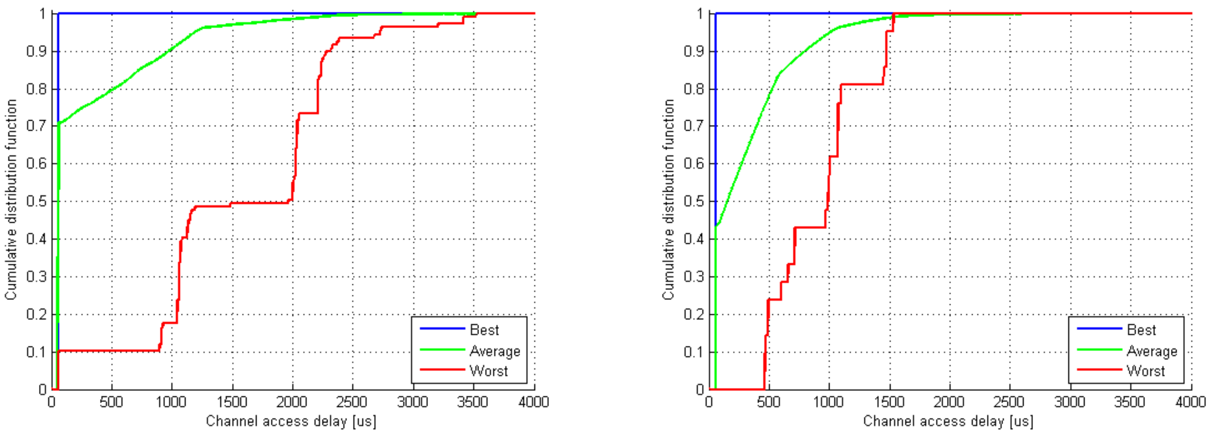
The cumulative distribution function (CDF) for the channel access delay in STDMA is shown in Figure 19 for both the 10 Hz/300 bytes setting and the 2 Hz/800 bytes setting. It has the same shape as the CDF for a uniform distribution because all the slots in SI are equally likely to be selected for transmission.



(a) 2 Hz/800 bytes **(b) 10 Hz/300 bytes**

Figure 19: Cumulative distribution function for the channel access delay for STDMA

In Figure 20 the CDF for the channel access delay of CSMA is depicted for the two different data traffic settings. As the channel access delay in CSMA is random, the figures are based on the simulations conducted in the high vehicle density case. Since the channel access delay is not upper bounded with CSMA, it is not guaranteed that all nodes will have the same delay or even a delay close to the average delay. It is therefore interesting to find the node which experiences the longest channel access delay on average as well as the node that experiences the shortest average delay. The "worst" case curve shows the node experiencing the worst case channel access delay in the system, the "average" curve is the channel access delay averaged over all nodes in the system, whereas the "best" curve represents the node experiencing the best channel access delay. Figure 20 (a) shows the CDF for 2 Hz/800 bytes and (b) shows the CDF for 10 Hz/300 bytes. There is generally longer channel access delays for the 2 Hz/800 bytes setting because of the longer packets used. It can be seen that there is major difference between the two nodes experiencing the worst case and the best case delay in the CSMA system, revealing an unfairness problem when the number of nodes increases in the system.



(a) 2 Hz/800 bytes **(b) 10 Hz/300 bytes**

Figure 20: Cumulative distribution function for the channel access delay for CSMA

6.4 Conclusions

The packet reception probability:

- Low density: STDMA benefits more from the higher output power, while CSMA loses in performance compared to STDMA especially in the 10 Hz/300 bytes case (Figure 13 (d)). Note that the system is not overloaded and the performance difference is due to STDMA employing synchronized transmissions, i.e. if two nodes transmit at the same time the packets overlap completely, whereas in CSMA, nodes can have partial overlap of several simultaneous transmissions.

- High density: We note that for the high vehicle density case the interference level is higher and therefore both STDMA and CSMA are further away from the upper bound. STDMA still benefits more from the higher output power than CSMA does and within 100 m from TX. STDMA maintains a packet reception probability of more than 95 %. Also note that STDMA achieves almost 10 % higher within 100 m compared to CSMA within 100 m for an output power of 25 dBm.
- Simultaneous transmissions: It can be seen that the hidden terminal transmissions are not contributing to a major performance degradation in the high vehicle density case instead the simultaneous transmissions within application range that contribute to the most performance degradation especially for CSMA.

Channel access delay:

- STDMA: deterministic depends on SI.
- CSMA: random, there is generally longer channel access delays for the 2 Hz/800 bytes setting because of the longer packets used. It can be seen that there is major difference between the two nodes experiencing the worst case and the best case delay in the CSMA system, revealing an unfairness problem when the number of nodes increases in the system.

STDMA performs better than CSMA because of the synchronized transmissions, scheduling of transmissions in space and nodes avoid using allocated slots when there still is available resources in the system. Due to the scheduling of transmissions the packet reception probability for STDMA is always better then CSMA regardless of setting. Interesting to note is that STDMA for all setting has over 96 % packet reception probability within 100 m from the TX and there is no difference between the Group 2 (hidden terminals) and Group 3 transmissions for up to 150 m from TX.

7 Simulation results of MS-Aloha

7.1 Guide to the Interpretation of Results from Simulations

Conceptually, the difference between CSMA/CA and MS-Aloha lies in their different philosophies: the former provides a statistical channel access; the latter a deterministic and connection-oriented approach.

Before entering the analysis of results (clause 7.2), next clauses shortly introduce some topics which are meant to support the study: spatial multiplexing (by slot-use and slot-reuse), hidden terminal and configuration rules (especially framing rules).

7.1.1 Rational and Effects of Spatial Multiplexing

The main idea behind slotted protocols is to make order in resource distribution. In CSMA/CA distributes channel access evenly and in a random way: hence it may happen that two nodes, despite being very close the one to the other, pick-up the same waiting time and happen to transmit simultaneously; this leads to a strong interference and worsens PDR. Conversely, synchronous protocols, in particular, connection-oriented ones, aim to distribute transmitting resources so that a transmitting time is never accessed by two nodes, unless far enough. For this reason slotted approaches are often referred to as time-space multiplexing algorithms.

MS-Aloha, in particular, is meant to prevent as much as possible interference and hidden terminals, hence introduces the concept of 2-Hop Spatial Multiplexing (2-SM). The idea of 2-SM is that:

- Nodes 1-hop-far from the transmitting node *A*, directly receive it and do not re-use the same slot (say slot *n*).
- Nodes 2-hop-far from the transmitting node *A*, indirectly know about node *A* and do not re-use slot *n*, but still announce it as busy.
- Nodes 3-hop-far from the transmitting node *A*, indirectly know about node *A* and neither re-use slot *n* nor announce it as busy.
- Nodes 4-hop-far can re-use slot *n*.

This way possible interference may come only from nodes which are two-hop far. Hence interference is supposed not to affect nodes in the neighborhood of the transmitter. On the other hand slot re-use is not prevented, since the announcements on slot allotments are not forwarded indefinitely, but span only 2 hops.

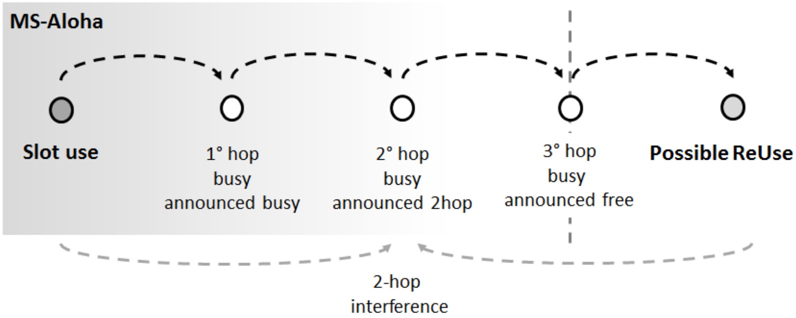


Figure 21: Image depicting the rationale subtended by the hidden terminal analysis

In principle MS-Aloha could work also without forwarding the information, just communicating the information at 1-hop but this would lead to a poorer coordination: nodes could not select a free slot based on the information at two-hop distance and this would increase the number of collisions. In practice:

(i) the first hop represents carrier sensing;

(ii) the second hop carries out hidden terminal prevention;

(iii) the third hop puts into practice a mechanisms for collision prevention and more effective coordination (if a slot was reused at third-hop it would result in a collision, which would be anyway detected but would lower the medium efficiency).

Thus, the information of the different hops has a different criticality.

On the other hand, it may still happen that the forwarding of information over multiple hops is still too rigid and cannot face the heavily congested scenarios, due to a poor slot re-use. For this reason MS-Aloha leverages a threshold mechanism so that only certain announcements - the ones coming from the closest nodes - are considered for channel state analysis. The mechanism, called 2-SMt [i.1] and [i.6] is provided also with dynamical reactivity so that the threshold is set based on channel congestion (2-SMtd) [i.1] and [i.7]. In practice, the effect of 2-SMtd is to shrink one or more hops, so that re-use can take place at a shorter distance. While this slightly worsens interference, the worsening is not perceived by the closest nodes, unless the congestion is dramatically high [i.7]. As a result, the reception probability of MS-Aloha is expected to be higher especially at shorter distances. However, the way in which the 2-SMtd mechanism is optimally used falls in the area of optimal parameter setting and is discussed in clause 7.1.2.

7.1.2 Configuration Rules

MS-Aloha presents several parameters and its performance can be optimised based on the chosen settings. In particular, the framing structure can be optimized based on the expected payload and transmission rate; the 2-SMtd algorithm can be trimmed depending on the transmitted power; the pre-emption should be configured according to the services being carried on the protocol. Some insight into the configuration rules is then required. In the following clauses the three configurations are shortly discussed. In particular:

- Framing rules are explained, so to explain how the settings of Table 6 have been achieved.
- The possible configurations of *2-SMtd* algorithm are explained, so to facilitate the understanding of the results presented in clause 7.2.3.
- Configuration of pre-emption is just shortly introduced.

7.1.2.1 Framing rules

In MS-Aloha, slots house both the 802.11p-like frame and the protocol information required by the signalling; additionally the FI information can be sent in all the frames or only in some of them. As a result, the overall framing is a function where the following parameters are mutually linked:

- number of slots in a MS-Aloha period;
- number of bits used for the STI (8 bits in our study);
- slot duration; this is connected to the length of the packets being transmitted and has to account also for the signaling information carried within the FI and appended to the slots during the *signaling frames* (hence it is a function also of the number of slots);
- the chosen guard-time (basically following the rules mentioned in [i.1] (clause 8);
- number of the signaling frames: it is possible to send the FI only in certain MS-Aloha frames (*signaling frames*). For instance it can be chosen to append FI to the slots in one frame, all the times or, alternatively every 2 or 10 MS-Aloha frames.

Considering that the FI contains as many subfields as the number of slots, the number of slots n_{slot} in a period P can be computed as the solution of an equation of power 2, whose solution is presented in clause 7.1.2.

$$n_{slot} = -\frac{k(T_g + T_{PLCP} + T_{TX}) + T_{STI}}{2 \cdot T_{FI}} + \sqrt{\left(\frac{k(T_g + T_{PLCP} + T_{TX}) + T_{STI}}{2 \cdot T_{FI}}\right)^2 + \frac{P}{T_{FI}}} \tag{9}$$

In the Equation 9, T_{PLCP}, T_{TX}, T_{STI}, T_{FI} and T_g, are respectively the time required to transmit PLCP, the time required to transmit the frame (excluding the PLCP, the STI and the FI), the time required to transmit an STI, the time required to transmit an FI subfield (not the full FI). STI is always supposed to be 8-bit long (more details in [i.1]). k is the number of MS-Aloha frames elapsing between two consecutive signaling frames (k=1 means that the FI are appended to all the frames; k=2 appended alternatively). P is the duration of the overall period (including 1 signaling period and $k-1$ non-signaling ones). Obviously, the equation should be called only initially, to make decisions on the settings.

As in all the slotted protocols, the slot length should be enough to avoid the fragmentation and, at the same time, not excessive, not to lose efficiency; in case a frame length is particularly frequent, its length should drive the selection of slot length. This is the case of the present analysis, where slot can house respectively 300 bytes or 800 bytes, so to optimize the framing depending on the given CAM. Other solutions could be proposed, such as an intermediate length (*e.g.* 400 bytes) so that 300 bytes packets can be easily housed with a reduced waste, while 800 bytes packets can be fragmented.

The FI could be sent every time or only in some frames. The only important rule seems to send *FI* at least once per second: at 400 km/h relative speeds it corresponds to a distance of about 100 m. Given the radio range (both at 10 dBm and 25 dBm transmitted power), 1 second is sufficient to promptly update the varying topology. For the sake of simplicity, in the proposed analysis the FI is always sent (k=1).

Finally, the following alternative rules can be used for the decisions on the periodicity:

(i) period equal to 1s (accordingly with the required FI update);

(ii) period equal to the maximum transmission rate;

(iii) period equal to a minimum transmission rate (but allowing the reservation of multiple slots).

For simplicity, the rule (ii) is here used. A more general perspective is provided in the conclusions drawn is clause 7.3.

7.1.2.2 Re-Use and Threshold Algorithm

The rationale of 2-SMtd algorithm is to have a power-threshold to accept or discard signaling information (by the FI) and to use congestion level to raise or lower the threshold. The algorithm is distributed.

For this purpose the following parameters are required by the algorithm:

- percentage of free slots required to lower the threshold; this is usually set around 20 % to 25 % of the overall number;
- percentage of free slots required to raise the threshold; this is can be set around 50 %; as a result, a number of slots in [25 %, 50 %] can be always supposed to be free;
- predefined steps Δ for the variation (increment or decrement) of the reception threshold;
- time required between two consecutive variations (this is meant to increment stability): this is typically 5 periods, so to let the FI information propagate over 4 hops.

Notably, given the interpretation of 2SMtd provided in clause 7.1.2, the parameter Δ can be used in a flexible way (the three hops have very different practical meanings). Accordingly with the different meaning of the three hops covered by 2-SM (respectively sensing, hidden terminal prevention and better coordination) 2-SMtd has been studied with different settings. In clause 7.2, two algorithms have been used for the simulations:

- with algorithm n°1, Δ is constant for all the hops and equal to 3 dBm;
- with algorithm n°2, Δ is differentiated by number of hops:
  - Δ = 10 dBm for information of third hop;
  - Δ = 1 dBm for information of second hop;
  - Δ = 0,1 dBm for information of first hop.

The rationale of algorithm n°2 is to renounce third hop coordination rather than worsening sensing. However the algorithms lead to very similar results, basically due to the multihop forwarding.

Finally, it may be worth mentioning another opportunity enabled by MS-Aloha: the same 2-SMtd mechanism can be coupled with a mechanism for transmit power control (as the decentralized congestion control mechanism introduced in [i.8]). In other words it would be possible to act decongestion by alternating, step by step, a 2-SMtd threshold raising and a DCC transmit power reduction. This, however, is out of the scope of the present document.

7.1.2.3 Pre-emption

Pre-emption, at this stage, is just an opportunity, because it has not been extensively studied yet. Some promising results are available in [i.7]. The following possible policies are currently envisioned:

- Priority for pre-emption based on services or node type (*e.g.* emergency *vs.* entertainment).
- Priority based on a node policy (a predefined number of slots which each node can claim for each priority type).
- Priority configuration to facilitate migration and coexistence between CSMA/CA and MS-Aloha (more details available in [i.1]).

7.1.3 Hidden terminals in an urban environment

One possible problem hindering wireless communications are ***hidden terminals***. Hidden terminals occur when all the nodes do not perceive the same collision domain. For example, given three nodes, *A*, *B* and *C*, a hidden terminal situation takes place when *B* can receive from (or at least sense) both *A* and *C*, but *A* and *C* cannot hear each other and, consequently, transmissions by *A* and *C* cannot be coordinated and can potentially collide.
This introduces the concept of *collisions by hidden terminals* or ***hidden collisions***. While hidden terminals are potentially harmful, their actual effects can be evaluated only by the statistics of collisions: depending on the available resources, the traffic load and the topology, collisions by hidden terminals can be more or less frequent; depending on the distance of the colliding nodes, collisions can be more or less harmful.

All in all, the number of hidden terminals depends on the number and location of the nodes, the communication environment, and the transmit power level; the number of collisions by hidden terminals depends also on the amount of data traffic of ITS-G5 stations. The last two parameters, transmit power level and amount of data traffic, will be controlled by DCC and regulated depending on the vehicle density. Therefore, the DCC algorithms will to some extent also combat the effects of hidden terminals.

Hidden terminals are supposed to worsen PDR especially in urban areas.

1) In *highways*, in fact, hidden terminals are met only due to attenuation at long distances, supposing a purely line-of-sight condition. As a consequence, hidden collisions are not expected to be critical, because they cause weak interference and worsen PDR only at longer distances.

2) In *urban areas*, instead, due to obstruction by buildings, hidden terminals may be more dangerous: for instance in crossroads, nodes will receive by nodes in the legs of the crossroad; conversely, nodes in the legs of the crossroad can basically receive and transmit only inside the straight road [i.16] and [i.20]. For this reason nodes in the centre of the crossroads are exposed to strong interference by hidden terminals in the crossroad.

3) An even worse case is that of *obstructions by vehicles* (trucks). As demonstrated by real measurements in [i.20] and [i.23], the obstruction by a single vehicle causes a non-line-of-sight condition with an attenuation which is as high as 20 dB in static conditions (in parking lot, with obstruction by a large car); this grows to 30 dB when a truck is involved (or in other measurements at 10 m by the same authors [i.23]), Similar results are achieved under mobility. The attenuation is worse in proximity of the obstacle and drops at higher distances (about 400 m). A larger number of vehicular obstacles are expected to worsen dramatically the attenuation and, consequently, to increase the number of hidden terminals both in the urban and highway scenarios.

In clause 7.3 only case 2 (buildings) will be evaluated and, in addition, in a scenario which is not particularly severe: however, even in this case, the hidden collisions will be demonstrated to be harmful also at short distances.

To support the analysis of results in clause 7.3 (about hidden collisions), the same urban scenario has been simulated (exploiting the model for obstruction by buildings presented in clause 5.4.2) to evaluate the occurrence of hidden terminals. The urban topology is the same presented in clause 5.3.2: a 5 × 5 grid (6 × 6 roads) with perpendicular roads 10 m-wide,each including 4 lanes (2 per direction), and an overall map which is 750 m-wide.

The nodes are a large number (2 530), fixed and evenly distributed, in order to achieve statistics which are meaningful and immune from the effects due to a too high granularity - if the nodes were not dense enough, some positions around the corner (where the signal is still received) could not be populated enough. On the other hand, this hypothesis is not critical because:

(i) the presence of hidden terminals is finally given by percentages (not absolute numbers);

(ii) the scenario is very crowded but not congested: in fact the analysis is purely topological and nodes do not transmit simultaneously.

Two propagation models (Free-Space, Two-Ray-Ground) and Nakagami fading have been combined as basis for the extra-attenuation model of obstructions published in clause 5.4.2. The nodes in the borders of the map are excluded from the computation, in order to prevent border effects.

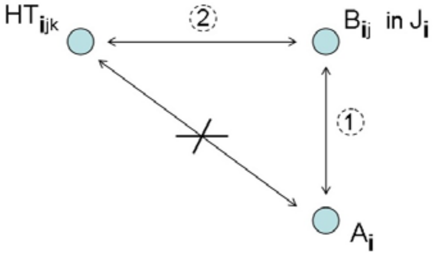


Figure 22: Image depicting the rationale of the hidden terminal analysis

If *I* is the set of all the nodes (excluding those in the borders), for each node ***Ai*** in *I*, the set ***Ji*** is first computed as the set of all the nodes ***Bij*** receiving from ***Ai***. Afterwards the number of hidden terminals ***#HTi*** (hidden to ***Ai*** with respect to one or more nodes ***Bij*** in ***Ji***), is computed as the union of all the sets respectively including the nodes ***HTijk*** receiving from some ***Bij*** but not from ***Ai***. The resulting number is averaged across all the nodes ***Ai***. The final figure is referred to as HT^*.

If the channel settings are those mentioned in clause 5.4.2, then all the nodes 300 m far and along a straight street are reachable. Roughly, two main cases are possible:

- If ***Ai*** is in the centre of a crossroad, all the stations are hidden terminals with exception of those along the two legs of the same crossroad. Then hidden terminals are about 50 %.
- If ***Ai*** is in the middle, between two crossroad, the hidden terminals are about half as the previous case.

One could object that a lower transmitted power could be used, as suggested for DCC [i.8]: while it is not clear how DCC could be enabled without congestion, just to prevent hidden terminals, however an analytical evaluation was carried out involving a lower transmitted power (10 dBm).

Figures in Table 20 show that, despite the lower transmitted power, the hidden station are still non negligible (these results have been simulated, are not qualitative). Notably, if the blocks/buildings become smaller and the number of crossroads grows, then the percentage of hidden terminals grows as well, and with a square-power.

Table 20: Hidden Terminal computation. Case of 150 m-large blocks

	HT per pivot *mean HT per Bij*	**min HT** *min HT per Ai*	**MAX HT** *MAX HT per Ai (in the crossroads)*	**HT*** *mean HT per Ai*	**HT**** *mean HT per Ai without crossroads*
2-Ray-Ground +"*Urban*"	72	116 **4,6 %**	236 **9,3 %**	144 **5,7 %**	132 **5,2 %**
2-Ray-Ground with Nakagami+"*Urban*"	87	108 **4,3 %**	219 **8,7 %**	133 **5,2 %**	123 **4,8 %**

The hidden collisions caused by hidden terminals are supposed to grow with the number of hidden terminals and with the congestion state of the medium, with different effects on CSMA/CA and on the slotted protocols.

- In CSMA/CA, due to hidden terminals, a node *HT**ijk*** can start a transmission while node *A**i*** is already transmitting (because *HT**ijk*** cannot sense *A**i***). As a result nodes *B**ij*** would meet a heavy interference, leading to a poor reception rate also in proximity to the transmitting node [i.21].
- If MS-Aloha did not have the *FI* as the mechanism against hidden terminals, nodes *HT**ijk*** and *A**i*** could select the same slot and continue to collide with no opportunity to have it detected and signalled.

7.2 Simulation Results: Urban Scenario

7.2.1 Analysis of Results: Urban Obstructed

In the case of urban scenarios, the propagation is so confined by buildings that, despite the high transmitted power (20 dBm), the medium is not congested. This effect is well reflected by the transmission statistics: both CSMA/CA and MS-Aloha can handle the transmission of all the traffic.

In the urban scenario it is instead interesting to analyze the effects of hidden terminals in terms of hidden collisions. In clause 7.2.1 the likelihood of hidden terminal occurrence has already been discussed; however it remains unclear how much this may affect reception. For this purpose Figures 23 to 25 show some relevant results under different settings. All the results here shown are obtained for 20 dBm of transmitted power; due to the effect of obstructions, the partial results obtained by 25 dBm do not differ significantly. In all the cases MS-Aloha always transmits it FIs (it does not benefit from a higher number of slots). The figures display the reception rate at three different settings of SNIR threshold required for correct reception (respectively of -82 dBm, -85 dBm and -88 dBm).
The first behavior, which can be abstracted by the PDR both for CSMA/CA and MS-Aloha (and is common to all the graphs), is that buildings markedly affect the PDR. In fact:

- All the curves are irregular with down steps around 150 m and 300 m. This is interpreted as a clear effect of obstacles with the drops corresponding to the chosen grid topology (150 m is the distance between parallel roads). Practically at that given distance a lot of nodes are in parallel roads and, consequently, they are not likely to receive a packet (they fall in the nLOS category).

- The slope of the PDR at short distances is higher than for free-space, basically because, for each Euclidean distance *d*, the number of nodes which are not in LOS but at the given *d* mutual distance, grows with *d*. This, obviously has a detrimental effect on the PDR.

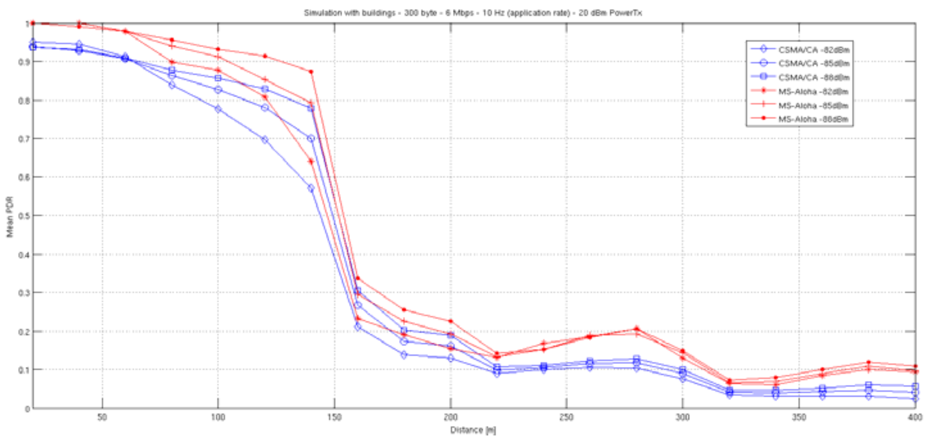
NOTE: If the model with extra-attenuation is accepted, the interference by hidden terminals can grow to values greater than the sum of the sensitivity threshold and the extra attenuation. In fact, due to extra attenuation by obstructions, such power would fall under the sensitivity and would not be received by a hidden terminal.

The medium is not congested and the effects of buildings on PDR affect both CSMA/CA and MS-Aloha. Altogether, given that MS-Aloha has a solution against hidden terminals and CSMA/CA does not have it, the differences between the PDR of the two protocols can be basically ascribed to the effects of hidden terminals.

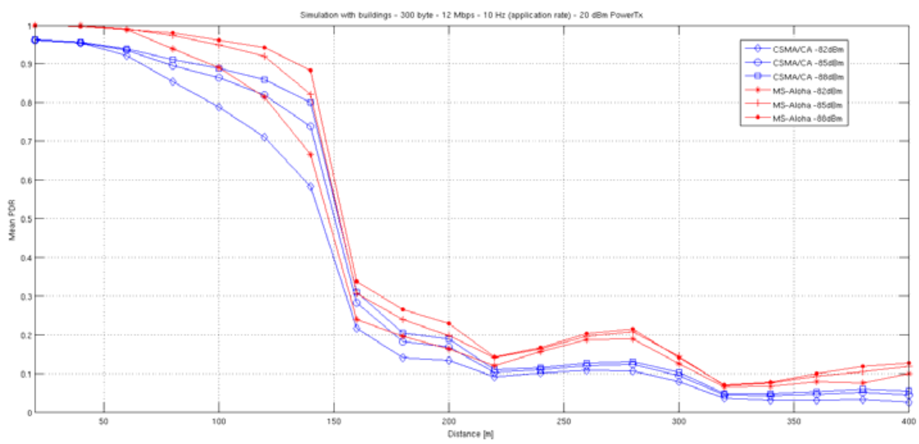
MS-Aloha can perfectly coordinate transmissions in close proximity to the transmitter: its packet delivery rate is almost ideal (100 %) in the first meters while, in CSMA/CA, the PDR graphs start with a lower value due to the unintentional simultaneous transmissions from hidden terminals. This result qualitatively agrees with literature [i.21].

Additionally, there is an interesting gain at higher distances. While the practical importance of this effect is a subject which can be disputed about- reception is more critical at shorter distances - it demonstrates the multi-hop coordination by MS-Aloha. In fact, at higher distances, the interferences also by farther hidden terminals become prominent and can critically worsen the SNIR ratio.

Concerning instead the different reception thresholds, they affect both CSMA/CA and MS-Aloha's statistics but, in most cases, it is kept constant the difference between the PDRs achieved by the two protocols, almost independently of the given threshold (-82 dBm, -85 dBm and -88 dBm).



(a) Line-rate 6 Mbit/s

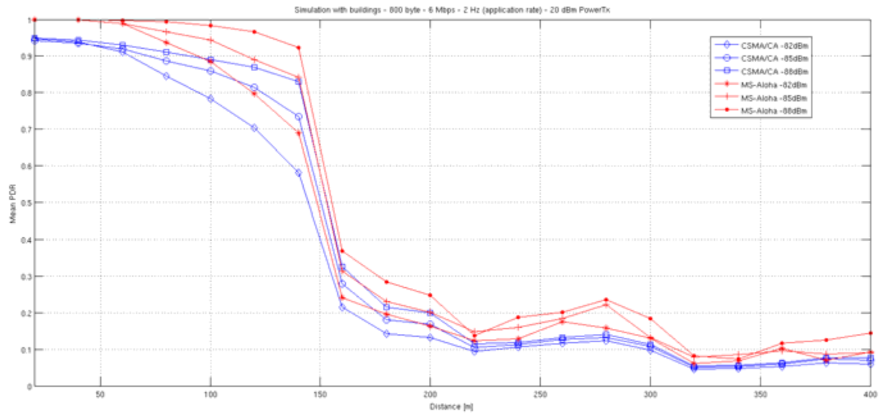


(b) Transfer rate 12 Mbit/s

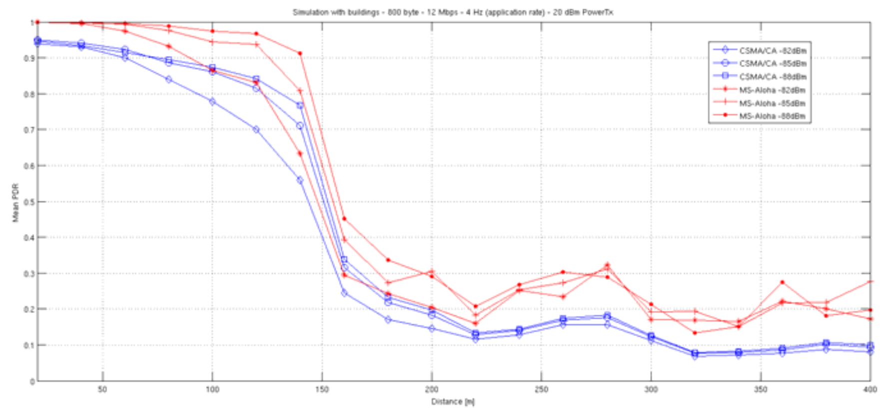
Figure 23: Packet reception probability for distances of up to 400 m from TX: 10 Hz and 300 bytes

Interestingly, the case of 300 bytes -10 Hz (Figures 23(a) and 23(b)) does not change much if the transfer rate gets doubled (from 6 Mbit/s to 12 Mbit/s), until the higher (SNIR and sensitivity) reception thresholds of the higher transfer rate become to play a role. This qualitatively confirms that the hidden collisions are not due to a congestion state and, with such a channel load they are something more related to topology than to traffic.

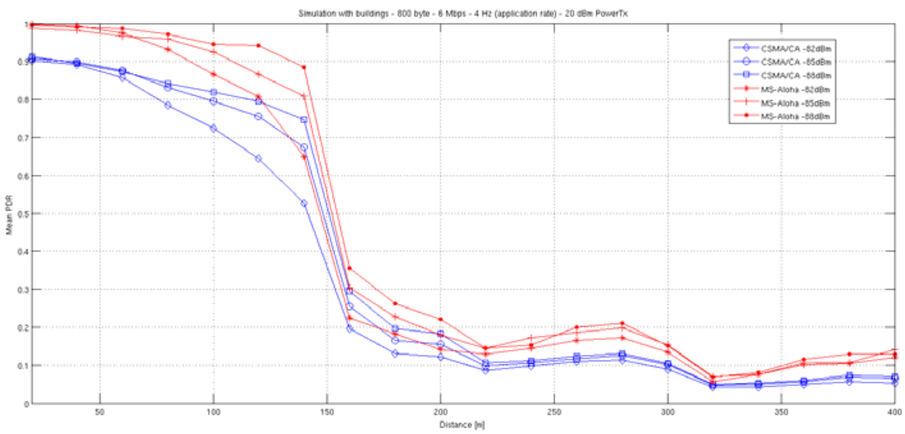
The PDR of CSMA/CA is a little worse in the case of 800 bytes rather than 300 bytes payload (respectively Figures 23 (a) and 24 (a)): this may seem contradictory because the medium is more congested in the latter case (as shown if Table 5.6.1, it is almost twice). Due to the urban channel model, the medium is still far from congestion: hence it is not so likely that two nodes pinch the same collision avoidance time. However the interference by two hidden terminals (say *A* and *B*) onto a third node *C* is more likely to happen when a transmission takes a longer time.



(a) 2 Hz application rate and 6 Mbit/s of transfer rate



(b) 4 Hz application rate and 12 Mbit/s of transfer rate



(c) 4 Hz application rate and 6 Mbit/s of transfer rate

Figure 24: Packet reception probability for distances of up to 400 m from TX: 800 bytes

The other way to highlight the difference between CSMA/CA and MS-Aloha is to increase the transmission rate or the number of nodes. The application rate has been hence doubled from 2 Hz to 4 Hz (which is however lower than the highest rate foreseen by CAM messages). The channel load is now comparable to that of 300 bytes, 10 Hz (Table 2). Here the results (Figures 24 (a) and (b)) show that when the traffic grows, the difference between CSMA/CA and MS-Aloha starts with a value of 10 % and reaches 15 %. This confirms also the role packet length in the occurrence of collisions by hidden terminals (longer transmission times mean higher probability of occurrence of simultaneous transmissions).

Finally, if the extra-attenuation due to corners is increased to 25 dB (results not shown here) the two scenarios of 800 Bytes/4 Hz and 300 Bytes/10 Hz behave almost in the same way, with MS-Aloha at 100 % in proximity of the transmitter (and CSMA/CA at 90 %); the difference between the two protocols can be as high as almost 20 % (at about 100 m).

For the sake of precision, the urban propagation is characterized by strong differences between nodes in the centres and in the legs of a crossroad: in fact, nodes situated in intersections can receive from all the legs and are exposed to multiple transmissions at the same time. However, even considering PDR for the only nodes in the centres of the crossroads, results do not differ for MS-Aloha, while CSMA/CA experiences a further worsening of up to 10 %: for instance, the CSMA/CA PDR shown in Figure 24 (c) drops to 0,82 at 20 m, when accounting only for the nodes in the centres (the ones more exposed to hidden terminals). This is a very interesting result and will be further investigated , especially to assess CSMA/CA weaknesses.

Considering all the results, the difference between MS-Aloha and CSMA/CA's is always between 5 % to 10 % in the first 100 m and, with longer frames (or heavier traffic), the difference further grows. The initial 5 % to 10 % is mainly ascribed to topological reasons. Depending on the extra attenuation due to the obstruction, the percentages can further grow. Similarly the difference between the two rises to almost 20 % in some scenarios considering the nodes which are in the centres of the crossroads (the ones more exposed to hidden terminals).

Summing up the following conclusions can be drawn:

- Hidden terminals cannot be always considered negligible.
- The number of hidden terminals depends on the topology and on the load of transmitted traffic: the number grows with the traffic and/or transmission-power. Notably collisions by hidden terminal take place also in conditions far from congestion, when CSMA/CA is not expected to make use of DCC techniques.
- Similar effects are expected also by obstructions by vehicular nodes (clause 7.1.3, [i.20] and [i.23]).
- The difference in the PDR achieved by CSMA/CA and MS-Aloha has been measured in the interval 5 % to 20 % and could certainly be worse, due to the previous reasons.
- Unlike CSMA/CA, with MS-Aloha the PDR is always very high (about 100 %) in the neighbourhood of the transmitter.

7.2.2 Analysis of Results: Urban Non-Obstructed

7.2.2.1 Motivation of the Analysis in Non-Obstructed Scenarios

It has already been demonstrated that slotted protocols can improve reception probability in highway congested scenarios and in urban scenarios. In this clause some additional results in scenarios with line-of-sight conditions and under congestion are outlined. The purpose of this clause is twofold:

(i) to qualitatively demonstrate that scalability applies also to MS-Aloha; and

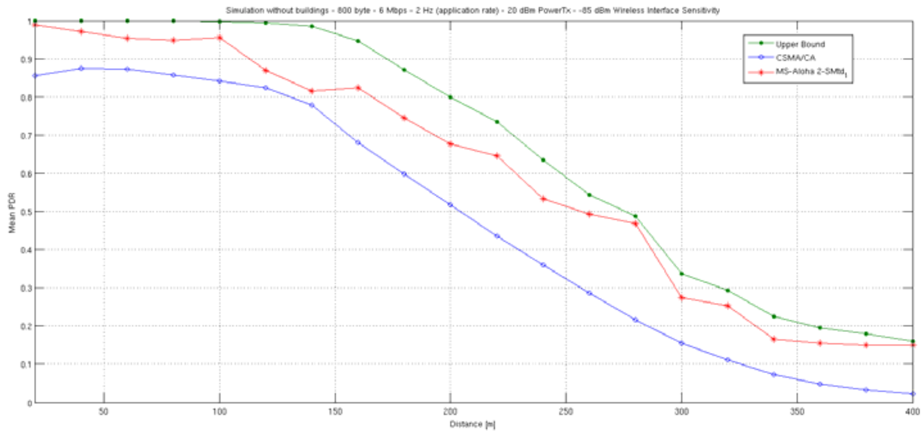
(ii) to identify the recommended parameter.

For this reason the results are not extensively presented in all the possible permutations of settings but rather selected to support the two goals. For the same reason same scenarios particularly critical for MS-Aloha are presented, with the aim of showing how they could be improved.

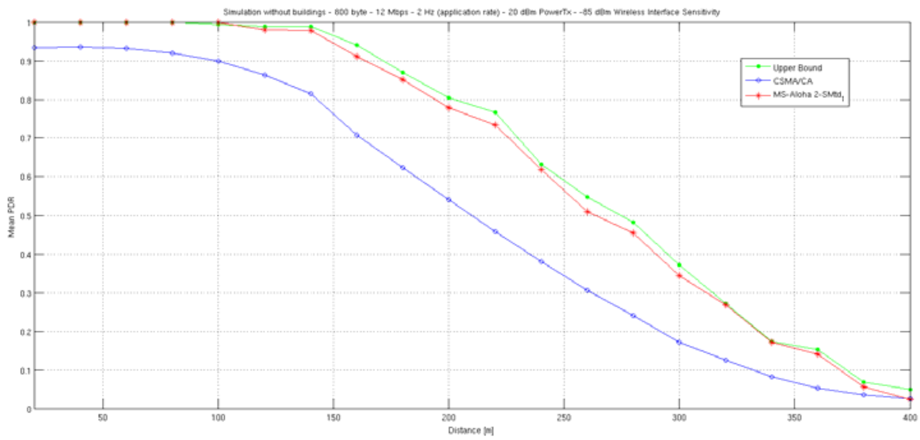
In all the figures displaying the resulting PDRs, the graphs in *green* refer to the ideal PDR (due just to attenuation and fading but no interference); the ones in *red* are those achieved by MS-Aloha (including obviously interferences by simultaneous transmissions); the ones in *blue* refer to CSMA/CA. It is worth reminding that both the PDR of the ideal case and the results of the slotted approach, are affected by carrier-sensitivity threshold in the same way as CSMA/CA is, unlike the results presented in clause 6. This is important to justify some differences in the results of the respective simulations. The motivations substantiating for this hypothesis have been stated in clause 5.4.2.1. The scenario is the urban non-obstructed scenario explained in clauses 5.3.2 and 5.4.2 (with 600 nodes in a 1 050 m-wide Manhattan grid under line-of-sight).

7.2.2.2 Analysis of Results

Most of the results which will be discussed here refer to scenarios involving a traffic of 300 bytes and 10 Hz. The reason is that such settings are the most challenging conditions become more critical. Instead, the settings adopted for 800 bytes 2 Hz are easily managed by MS-Aloha, as shown in Figure 25. In particular, even with continuous transmission of *FI*s, the performance is almost ideal and is even better when 12 Mbit/s close to the transmitter.



(a) 6 Mbit/s



(b) 12 Mbit/s

Figure 25: Packet reception probability for distances of up to 400 m from TX: 800 bytes, 2 Hz and 6 Mbit/s or 12 Mbit/s line-rates

Next results focus on the case involving a traffic of 300 bytes and 10 Hz. The first case refers to a sensitivity threshold of -85 dBm and a transmitted power of 20 dBm (Figure 26). This result shows that:

(i) also when the FIs are transmitted in all the frames MS-Aloha performs better than or equal to CSMA/CA, with notable differences in the vicinity of the transmitter - where the PDR of MS-Aloha is beyond 90 % - and far from the transmitter (where MS-Aloha is almost ideal).

(ii) Results slightly improve when the FIs are sent only once per second, basically due the gain in terms of number of slots.

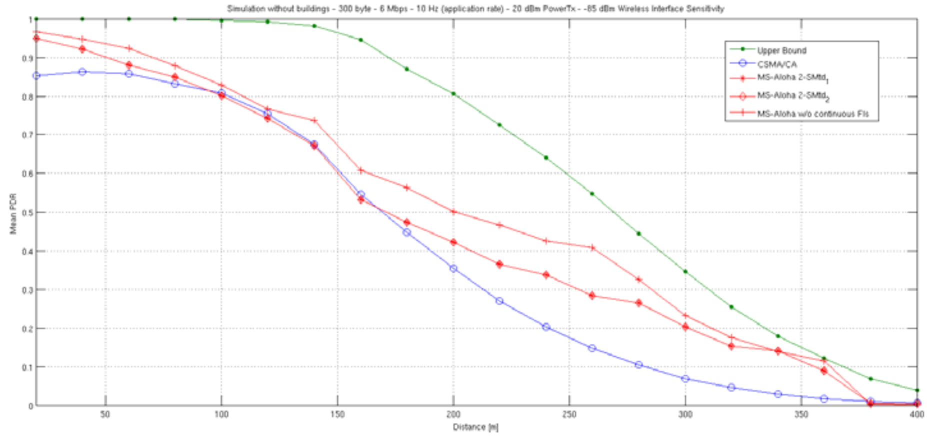


Figure 26: Packet reception probability for distances of up to 400 m from TX: 10 Hz and 300 bytes, 6 Mbit/s, 20 dBm transmitted power and -85 dBm sensitivity

Figure 27 displays the results for the same scenario of Figure 26 but with a different sensitivity threshold at the receiver (-82 dBm instead of -85 dBm). In addition, these simulations have explored also the 2-SMtd algorithms mentioned in clause 7.1.2.2. Here the benefits of MS-Aloha are slightly more marked in proximity of the transmitter, while results worsen at higher distances. No meaningful differences are seen between the two 2-SMtd algorithms. Comparing the results for the two sensitivity thresholds, it is argued that the PDR is here higher because more slots are free; while the 2-SMtd algorithm is aimed at this goal, the parameter F_1 should be set more aggressively (higher than 20 %, as it is here). Such approach, as demonstrated in [i.7], leads to almost ideal PDR but only in the first 50 m to 100 m and with marked reduction farther.

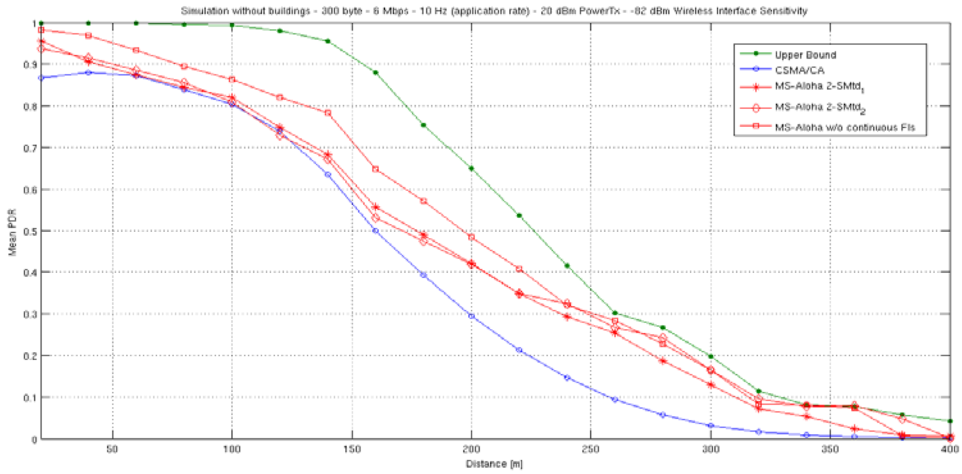


Figure 27: Packet reception probability for distances of up to 400 m from TX: 10 Hz and 300 bytes, 6 Mbit/s, 20 dBm transmitted power and -82 dBm sensitivity

This is qualitatively demonstrated by the simulation run at 10 dBm of transmitted power (Figure 28). Here MS-Aloha, especially the one with non-continuous transmission of *FI*s is almost ideal and, the one with continuous *FI*s, only slightly worse. Moreover, in the first 100 m the PDR of MS-Aloha is around 95 % and in the first 140 m, MS-Aloha with 10 dBm of transmitted power behaves better than MS-Aloha at 20 dBm and better than any setting of CSMA/CA. Interestingly this demonstrates that slotted approaches, more than CSMA/CA, can benefits from a DCC policy based on the lowering of transmitted power. Also the intermediate transmit power of 15 dBm shows a 95 % PDR at 100 m and, at 200 m achieves also the same values of CSMA/CA with 20 dBm.

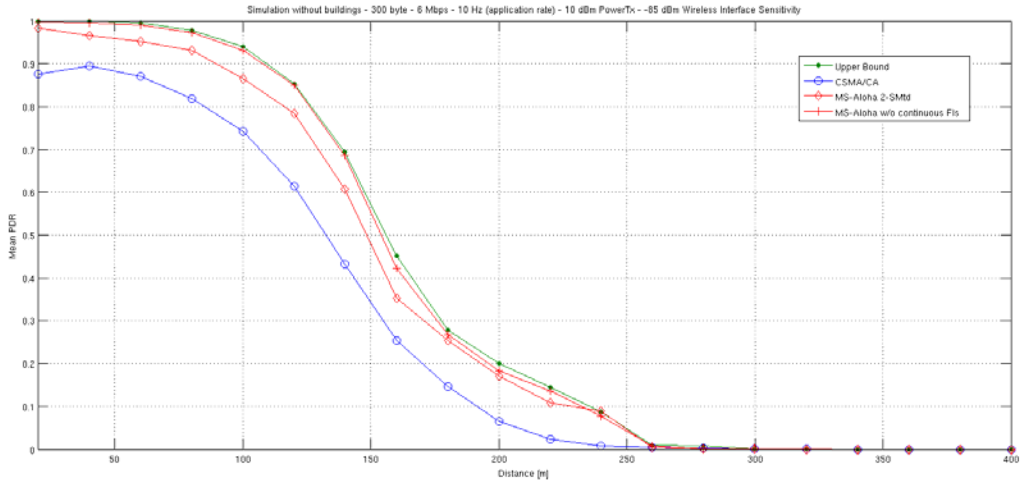


Figure 28: Packet reception probability for distances of up to 400 m from TX: 10 Hz and 300 bytes, 6 Mbit/s, 10 dBm transmitted power and -85 dBm sensitivity

7.3 Conclusions: Recommended Parameter Settings

The main benefits which MS-Aloha shows are related to determinism and can be summarized by the following points:

- The protocol is self-organized and non-blocking in a self-adaptive way (a configurable number of slots are always free); pre-emption is available and can be re-used for coexistence with CSMA/CA [i.1]).
- All the frames are always sent within a period-time - latency is upper-bounded.
- MS-Aloha achieves a higher PDR than CSMA/CA, very close to 100 % in proximity to the transmitter, also in case of harsh congestion.
- Hidden collisions are completely prevented, in case of obstructions both by buildings and by vehicles. Hidden collisions have been demonstrated to affect significantly CSMA/CA, also in conditions far from congestion - where DCC mechanisms are not supposed to be active.

MS-Aloha has been demonstrated to manage spatial multiplexing also in very heavily congested scenarios at 6 Mbit/s. However the setting at 12 Mbit/s seems even more promising for the protocol. In fact, while it is generally accepted that the default choice is 6 Mbit/s, this assumption is not rooted in strong technical foundations and a higher transfer rate can be preferred also for CSMA/CA.

- In [i.19] they demonstrate that 6 Mbit/s in not the best choice also for CSMA/CA when congestion grows (in particular when messages become longer).
- Moreover slotted protocols carry out a better time-space multiplexing by slot assignments. Thus, despite the higher SNIR required by the faster modulation (12 Mbit/s), in the first 150 m to 200 m (where delivery is more important), they achieve a higher PDR than CSMA/CA with a lower line rate (6 Mbit/s), even if not heavily congested.
- Since slotted protocols should select a rate (the coexistence of two rates would be difficult), probably 12 Mbit/s could be more suitable to face heavy congestions.

Based on the previous statements the following settings of MS-Aloha are shortly discussed as the preferred ones.

- With a transfer rate of 12 Mbit/s and an application rate of 10 Hz the following settings could be used: for 800 byte packets (European standard) 130 slots (continuous *FI* transmission) or 150 slots per 0,1 s (*FI* transmitted one period per second); if the packets are 300 byte-long (USA setting) the slots are respectively 200 and 306.

- A possible alternative could be to have *FI* transmitted once per second and 155 slots. This setting is adequate to house 800 byte-long packets at 12 Mbit/s for and 300 byte-long packets at 6 Mbit/s (385 bytes actually available). Other similar solutions could be possible, to permit coexistence between different settings (USA/Europe) and to permit, at some extent, the coexistence of different rates (or different packet length without fragmentation).

- Given the protocol scalability and the connection-oriented approach, the stations could be always connected, the 10Hz application rate natively supported and the latency of 100 ms guaranteed.

- Given the number of slots, the 2-SMtd algorithm should be configured so to have more than 30 % free slots (a lower number tends to result into collisions to be resolved).

- The transmitted power could be lower than 20 dBm:

  - For instance, 15 dBm the same PDR of MS-Aloha is higher than the one achieved by CSMA/CA with 20 dBm.

  - As an alternative the same 20 dBm transmitted power could be used as default but lowered based on the number of free slots. In other words, the transmitted power could be a parameter to be regulated within the 2-SMtd algorithm.

8 Executive summary

Road traffic safety applications have requirements on *delay, reliability*, and *fairness* for messages broadcasted using an *ad hoc* network topology. To meet these requirements, the MAC method should have a maximum delay which is upper bounded, implying that the maximum time from channel access request to actual channel access is known beforehand, i.e. the MAC method is predictable. The reliability should be as high as possible given the current status of the wireless channel, especially for the closest neighbours to a transmitter. Further, when considering the same data traffic class, all nodes in a VANET should have equal opportunity of channel access during each period of time, regardless of the number of nodes, i.e. the MAC method should be fair. In addition, the MAC method should be decentralized and allow nodes to self-organize, which is an inherent requirement from the *ad hoc* topology. The ability of the MAC method used in a VANET to meet these requirements is affected by how many nodes that currently is within radio range of each other. In VANETs the number of participating nodes cannot be restricted. Therefore, the one feature of the *ad hoc* topology that affects performance most is the scalability of the MAC method.

CSMA of ETSI ITS-G5 has some of the desired properties, i.e. it is decentralized, self-organizing and aims at minimizing interference between any transmitters. However, it does not necessarily maximize the packet reception probability for the closest neighbouring nodes or provide fair and predictable channel access for broadcast. This becomes particularly apparent when the number of ITS equipped vehicles increases: the number of simultaneous transmissions will increase, resulting in lower reliability and decoding problems due to interference. Further, the channel access delay is affected when the number of nodes increases and thereby the fairness is compromised. Therefore, DCC mechanisms are required to combat the scalability issue of CSMA. Another way to counteract the known scalability issues of CSMA is to investigate the performance of other MAC protocols in terms of scalability, reliability, delay and fairness. STDMA and MS-Aloha are two time-slotted MAC approaches designed for *ad hoc* networking (they are self-organizing and decentralized). When the number of nodes increases within radio range to the point where all resources are exhausted, STDMA and MS-Aloha still admit additional transmissions through slot reuse with careful scheduling to maintain a high reliability for the nodes closest to the transmitter. This implies that the channel access delay has a maximum upper bound and the resulting network is fair and predictable. Further, it implies that both MAC methods can cope with a high and varying number of nodes and transmissions without collapsing. In the present document simulations have been conducted to evaluate the performance of CSMA, STDMA and MS-Aloha in two different scenarios; highway and urban. *Channel access* delay and *packet reception probability* have been used as performance measures as they capture the reliability, delay and fairness of the resulting system as well as how these parameters depend on scalability. The DCC mechanisms for CSMA have not been implemented nor evaluated in these simulations.

STDMA has a higher packet reception probability for all settings compared to CSMA in the highway scenario and thereby a better reliability. The packet reception probability never falls below 95 % in close proximity of TX (< 100 m) in the highway scenario. For a low vehicle density case, CSMA performs well and the difference between STDMA and CSMA is relatively small. On average, STDMA has a somewhat longer channel access delay but it is upper bounded and a node knows when to transmit, i.e. STDMA shows predictability and fairness.

MS-Aloha simulations also confirm that slotted protocols have a strong potential. In particular, in the urban simulations, including obstructions, MS-Aloha demonstrates that it can completely prevent the problem of hidden terminals, due to its multi-hop coordination of transmissions. Thanks to spatial multiplexing, MS-Aloha results also confirm that in congested conditions, slotted protocols perform better than CSMA. In the simulated scenarios, MS-Aloha guarantees a very high packet reception probability in close proximity of the transmitter (over 95 % in the first 100 m). In the urban scenario selected for simulation, due to obstructions, propagation is confined and channel congestion is prevented naturally. Therefore, if the DCC mechanisms had been present for CSMA, the urban simulations results presented in clause 7.2.1 would not have been expected to be influenced by DCC.

Altogether, the conclusion is that synchronous MAC solutions (e.g. STDMA and MS-Aloha) perform better than CSMA in all investigated scenarios and for all given performance measures. STDMA or MS-Aloha would therefore represent a viable solution for a future upgrade of the current asynchronous MAC method based on CSMA. Note that a synchronous and an asynchronous MAC method could coexist since the asynchronous method can be a fall-back solution in absence of a GPS signal and a synchronous MAC method solves the open issues of scalability and reduced reliability due to e.g. hidden terminals. This way we can guarantee a future usability to preserve investments. This perspective should not be neglected, but rather further investigated.

NOTE: STDMA and MS-Aloha do not need DCC to function properly. They are inherently scalable. Consequently, the channel load limit of 25 % for the CCH is not necessary for these, implying that both time slotted MAC algorithms support four times the data traffic compared to a CSMA based system due to scheduling in time and space.

Annex A: Bibliography

H. Hartenstein and K. Labertaux: "VANET: Vehicular Applications and Inter-Networking Technologies", Wiley 2010.

T. S. Rappaport: "Wireless Communications - Principles and Practice", Prentice-Hall, Second ed., 2002.

H.A. Cozzetti and R. Scopigno: "RR-Aloha+: a slotted and distributed MAC protocol for vehicular communications" in Proc. of the 1st IEEE Vehicular Networking Conference (VNC 2009), Tokyo, Japan, October 2009.

R. Scopigno and H.A. Cozzetti: "Mobile Slotted Aloha for VANETs" in Proc. of the IEEE 70th Vehicular Technology Conference (VTC Fall 2009), Anchorage, Alaska, USA, September 2009.

H.A. Cozzetti, R. Scopigno, L. Casone and G. Barba: "Comparative analysis of IEEE 802.11p and MS-Aloha in VANETs scenarios" in Proc. of the 2nd IEEE Int. Workshop on Vehicular Networking (VON 2009), Biopolis, Singapore, December 2009.

History

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