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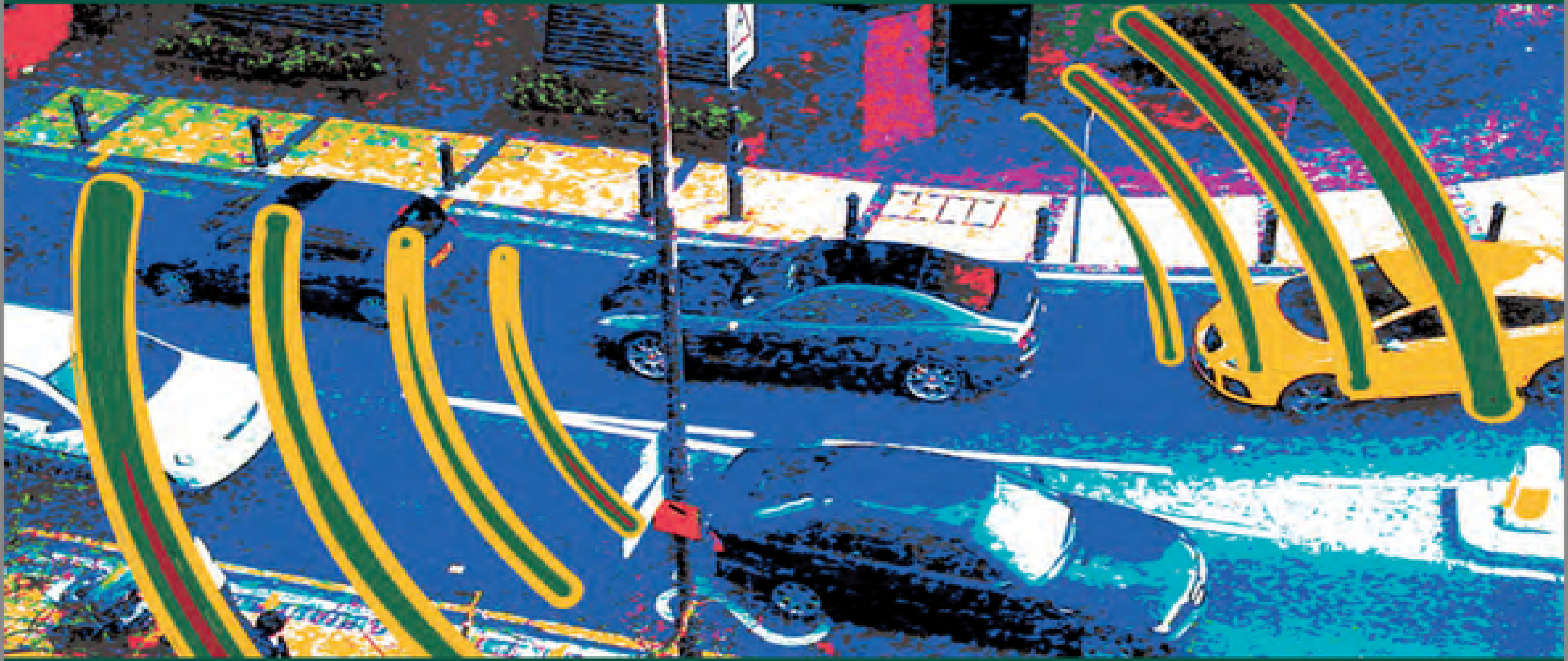

Vehicular Networks

Models and Algorithms

Edited by
André-Luc Beylot and Houda Labiod

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Contents

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Introduction

Due to the technical improvements implemented by car manufacturers, we have recently witnessed a significant decrease in road traffic accidents in developed countries. However, there is still considerable scope for improvement in the field of road safety. The advancement made in wireless communications provides numerous possibilities for offering drivers a large panoply of interesting services in the field of intelligent transport systems (ITS). The proposed solutions include the possibility to enable communication directly between vehicles or through a telecommunication infrastructure. The first solutions are thus related to infrastructureless communications and *ad hoc* networks; so we will discuss vehicular *ad hoc* networks (VANETs); in contrast, the second set of solutions comprises more conventional communications that can use infrastructures (general packet radio service (GPRS), universal mobile telecommunications system (UMTS), long-term evolution (LTE), etc.). Hybrid solutions could be involved in order to make the best use of available resources.

Therefore, from a network point of view, we see that new, specific problems are emerging. These problems are related not only to the particular applications implemented but also to the heterogeneous aspect of the types of networks used. For example, in the given context, we cannot simply apply the proposed solutions to *ad hoc* networks (such as mobile *ad hoc* network (MANET)). The tackled themes can be found at the crossroads of several research communities: the telecommunications research community and the research community of transport systems.

In this book, we discuss several interesting and relevant research topics related to vehicular networks, such as congestion control, routing, clustering, interconnection between vehicular networks and LTE/LTE advanced networks, signal traffic control, simulation tools and mobility trace generation.

The main objective of this book is to present the contributions brought by each research community in their respective fields. Finally, we have chosen a descriptive approach to draw up exhaustive reports, to globally present the individual author contributions, to illustrate clearly their advantages and limitations, and to pave the way for future research. Readers wishing to broaden their knowledge of the technical concepts will find at the end of each chapter a set of references and the recent publications of various authors.

Considering the diversity of the fields discussed in various chapters, this book is structured into seven chapters.

Following the Introduction written by Houda Labiod and André-Luc Beylot, Chapter 1 written by Razvan Stanica, Emmanuel Chaput and André-Luc Beylot presents a state of the art of the congestion control protocols in VANET networks. This problem is very critical. A tendency toward decentralized congestion control is emerging at the level of academic research, as well as at the level of standardization, more particularly within the European Telecommunications Standards Institute (ETSI) where several technical specifications have been published on this subject. Five approaches are discussed in this chapter: the first approach based on the adaptation of the sending frequency of beacons, the second approach based on the increase in data transmission flow rate (due to the use of complex modulations), the third approach based on the transmission power control in order to increase the channel capacity, the fourth approach based on the reduction of the contention window size and, finally, the fifth approach based on carrier sensing. A performance assessment of several adaptive mechanisms involved is presented by comparing them to the IEEE 802.11p standard mechanism.

Chapter 2, written by Xunxing Diao, Jian-Jin Li, Kun-Mean Mou and Haiying Zhou, focuses on the geographical routing techniques in a pure VANET. The routing is, of course, a basic, indispensable feature that must be supported by every *ad hoc* network, including VANETs. The routing in vehicular networks – which is different from classic IP routing and from MANET routing – is, in particular, a challenging problem due to the high mobility of vehicles on the one hand and the frailty of wireless connections on the other hand, and due to the strong constraints of the applications as well. The chapter presents a summary of various ITS projects related to intervehicular communications. Wireless technologies, which are indispensable in the design of all routing techniques, are made available, developed and experimented by these ITS projects, and described in detail before addressing the key problem, that is geographical routing dedicated to VANET. In the conclusion of this chapter, the authors sketch a list of open questions such as security, location management, transport layer contextual techniques and, finally, the support of the Quality-of-Service in order to increase the reliability and efficiency of the applications.

Chapter 3, written by Véronique Vèque, Florent Kaisser, Colette Johnen and Anthony Busson, analyzes the forming of clusters in vehicular networks. The authors start out from the assumption that the VANETs by themselves cannot implement all the applications correctly, primarily because of their intermittent connection. They can only function in conjunction with an infrastructure. However, if we observe road traffic, we notice that natural groups of vehicles are formed and the main objective then becomes to take advantage of these geographical characteristics in order to form clusters. The aim of clustering is to facilitate the organization of communications and minimize their cost. The authors then propose a hierarchical protocol called a “convoy”, which allows the construction of stable clusters as well as providing scalability.

Chapter 4, written by Guillaume Rémy, Sidi-Mohammed Senouci, François Jan and Yvon Gourhant, sheds more light on the previous chapter by focusing on the complementarity between infrastructureless vehicular networks and LTE networks. The idea is thus to fill in the gaps of the infrastructure-based network coverage by using intervehicle communications. The solution is called LTE for vehicle-to-X communications (LTE4V2X) and has several characteristics. A first protocol allows us to collect information and organize the network in a centralized manner. Depending on the total or partial coverage by the LTE network, several scenarios are considered. A second protocol deals with the dissemination of data toward the vehicles, uniquely either in LTE or in multihop networks. Giving specific examples, the authors show that their solution is powerful and it allows us to fix, quite effectively, the gaps in coverage due to the presence of tunnels, for example.

Chapter 5, written by Ghayet El Mouna Zhioua, Houda Labiod, Nabil Tabbane and Sami Tabbane, discusses the integration of VANET networks into fourth-generation mobile networks. The association between a mobile network and a VANET network aims to improve the coverage of the mobile network and the Quality-of-Service, while having the possibility to resort to alternative traffic routes in case there are any problems on the usual connections. In the first stage, the authors give an overview of the state of the art of clustering algorithms proposed in the relevant literature. The gateway selection problem for the vehicle-to-infrastructure (V2I) connection is discussed in the case of traffic transport from the VANET network toward the infrastructure. The authors study the proposed algorithms in a clustered and non-clustered VANET architecture. Then, the authors look into the problem of gateway selection from the VANET network toward the LTE advanced network.

Chapter 6, written by Jérôme Härri, Sandesh Uppoor and Marco Fiore, deals with the simulation of vehicular networks. The authors present an exhaustive report on the simulation tools used, including microscopic, macroscopic and mesoscopic traffic simulators, as well as on the interactions between these different simulators. The chapter details the trace generation/mobility models used by the network simulators aimed for the assessment of different vehicular networks' mechanisms; it also provides the reader with the basic elements for successfully carrying out simulations for these type of networks.

Chapter 7 describes the signal traffic control systems. The authors provide a classification of the different existing systems and a fine comparison between them. A special emphasis is placed on the dynamic systems whose objective is to reduce traffic jams and improve traffic flow. A new original approach via vehicle-to-vehicle communications is presented. The proposed control system adjusts the duration of traffic lights by using the density information provided by the dissemination protocols, which, in turn, use geographic and directional clustering.

Besides presenting several relevant and very interesting areas of research, we hope that this book will contribute to bring a realistic global view of the evolution of VANETs. As all the authors in this book have already pointed out, there still remain numerous research topics to be explored.

We warmly thank the authors for their very relevant contributions and the quality of their work, as well as the proofreaders who had the difficult task of helping us deliver a final version of this book.

Houda LABIOD and André-Luc BEYLOT
April 2013

Chapter 1

Congestion Control for Safety Vehicular *Ad Hoc* Networks

1.1. Introduction

In the highly dynamic vehicular environment, congestion control is essential, especially with regard to safety messages. Although a dedicated spectrum has been allocated for vehicular communications, the European 30 MHz Intelligent Transportation System (ITS) band (with a possible extension to 50 MHz) or the US 75 MHz Direct Short Range Communication (DSRC) band still represent a scarce resource and need efficient mechanisms in order to be optimally used under high vehicular density. In both Europe and the US, the allocated spectrum has been divided into 10 MHz channels. From these channels, one is known as the control channel (CCH) and it is used solely by road safety applications. The rest of the channels, called service channels (SCH), can be used by both safety and non-safety applications.

The number of proposed vehicular safety applications that could use direct vehicle to vehicle (V2V) communication is impressive [PAP 09]. However, at a close inspection, it can be noted that all these applications practically use the same information, coming from onboard sensors of neighboring vehicles: speed, acceleration, steering angle and location.

Considering this, the standardization bodies decided to add a supplementary layer between the applications and the transport protocol. The role of this layer, called *message sublayer* in the IEEE Wireless Access in Vehicular Environments (WAVE) architecture and *facilities layer* in the ETSI ITS terminology, is to keep an accurate image of the surrounding environment inside every vehicle and to provide applications with the desired information.

The facilities layer only needs two types of messages in order to achieve these objectives, called (in the ETSI ITS architecture) cooperative awareness message (CAM) and decentralized environmental notification message (DENM). CAMs are regular beacons, transmitted by every vehicle with a predetermined frequency, and containing details about the vehicle that might be relevant to its neighbors from a safety point of view. In addition, if a vehicle detects a potential hazard (e.g. a sudden brake) and considers that this information needs to be quickly disseminated to the other traffic participants, it transmits a DENM.

However, regardless of the scenario and message type, these safety messages are always transmitted in broadcast mode at the medium access control (MAC) layer. Even in the case when the transmitted information targets a certain geographical area (e.g. an electronic brake alarm is only of interest to vehicles traveling in the same direction as the transmitter and situated behind it), the message is still broadcast and the filtering happens at the facilities layer, as described by the ETSI framework [EUR 10].

The broadcast nature of the CCH in vehicular *ad hoc* networks (VANET) is an essential property that distinguishes it from other IEEE 802.11-based networks. As a matter of fact, the numerous studies on the distributed coordination function (DCF) implementing MAC mechanisms in IEEE 802.11 usually focus on unicast traffic, and broadcast messages are only considered for control purposes. Oliveira et al. [OLI 09] quantify the influence of broadcast traffic on the performance of IEEE 802.11 networks, and they find out that the effect of broadcast messages becomes significant when the proportion of broadcast traffic is higher than 50%. In this scenario, the behavior of the network largely deviates from what is predicted by classic DCF models. However, the authors consider this situation *quite unreal* and they do not investigate the issue further.

Another important characteristic of safety messages comes from the limited lifetime of CAMs. As these beacons are produced periodically by the facilities layer, there is a certain probability that they can expire before the MAC layer has the opportunity to transmit them. When a CAM is waiting for the IEEE 802.11 back-off timer to expire, and the next beacon also arrives in the transmission queue, the first message has to be dropped, as its transmission would only disseminate outdated information to its neighbors. This property, rarely taken into consideration in VANET studies, has a significant effect on the optimal value of different MAC layer parameters.

The IEEE 802.11p amendment [THE 10] is the preferred MAC technology in both the IEEE WAVE and the ETSI ITS architectures. IEEE 802.11p radios can communicate at a distance of 1 km. In a simple scenario, with a two-lane road in both directions and an average inter-vehicular distance of 50 m (a medium density highway), the number of one-hop neighbors reaches 160 vehicles. This is clearly a more challenging environment than the classic Wireless Local Area Network (WLAN), with a central access point and no more than 10–20 nodes. The MAC layer protocol, therefore, needs solutions for this congested environment to achieve scalability.

Congestion control mechanisms received a lot of attention from the VANET research community and the most relevant studies in this area are summarized later. The standardization bodies also recognized the importance of a decentralized congestion control framework for V2V safety communications, and ETSI published a series of technical specifications in this area in July 2011 [EUR 11]. In the US, the Society of Automotive Engineers (SAE) is also developing a standard with similar objectives, SAE J2945.1, currently in a draft phase. SAE J2945.1 is expected to be integrated into the WAVE architecture as a complement for the different IEEE standards.

In this chapter, five different approaches for MAC layer congestion control are discussed. In section 1.2, beaconing frequency adaptation is presented that reduces the number of transmitted safety messages in a dense network, speculating the relationship between high density and reduced speed in vehicular traffic. In section 1.3, increased data rates can be achieved by using more complex modulations and result in a lower occupancy of the CCH. Other proposals form the object of section 1.4, which are based on the fact that transmission power control has an important impact on the number of hidden nodes, and can increase the spatial reuse and hence the channel capacity, in a congested network. In section 1.5, the fourth element, the minimum contention window (CWmin), is analyzed, a parameter with a major importance for collision probability in an IEEE 802.11 network. Finally, the role of the physical carrier sense in congestion control is highlighted in section 1.6.

1.2. Beaconing frequency

The most obvious solution for controlling the channel load in a congested environment is to reduce the number of transmitted messages. This can be achieved in a straightforward manner in vehicular networks by adapting the frequency of the safety beaconing. However, such an adaptive mechanism should be designed carefully because sending less messages can easily have the effect of damaging the performance of safety applications instead of improving it.

In this context, Fukui *et al.* [FUK 02] proposed transmitting a CAM every time the vehicle travels a certain distance instead of using a regular time interval. According to a fundamental relationship from traffic theory, the mean speed decreases when the vehicular density increases, thus the consequence of this approach would be that nodes would reduce the beaconing frequency in a dense network where they would travel at low speeds. However, a basic example for which this solution fails is that of a vehicle waiting to make a left turn in normal traffic. Because the vehicle would need to stop, the adaptive mechanism would practically turn off the beaconing transmission, making an application like the left turn assistant practically unusable. Therefore, as stationary vehicles or low speeds are not always the consequences of high vehicular densities, such an approach cannot be efficiently used in a real scenario.

As a part of the California PATH program, Rezaei *et al.* [REZ 07] take a more complex approach, where vehicles run an estimator to calculate the position of each one-hop neighbor based on the already received messages. The same estimator is used by the node to predict its own position, as it would be calculated by its neighbors. When the difference between the prediction and the actual location becomes larger than a predefined threshold, the node transmits a safety beacon. The problem with this solution is that it is efficient in the predictable free-flow traffic, but not in a congested scenario where the acceleration is highly variable. Moreover, this self-estimator approach does not take into account that the error at some of the neighbors might be considerably different because some of the transmitted beacons could be lost. To solve this problem, Huang *et al.* [HUA 10] further develop this idea using the packet error ratio (PER) measured by a node to predict the losses encountered by its neighbors. Still, measuring a PER in a vehicular network without being able to detect collisions or use feedback from the receivers is not a straightforward task.

Seo *et al.* [SEO 10] make an analogy between the safety beaconing and the coupon collector problem. The mechanism they design relies upon nodes piggybacking acknowledgments (ACKs) for the received beacons in their own safety message. Every received ACK would further delay the transmission of the next CAM, reducing the beaconing frequency. However, the introduced overhead would be significant, especially in a dense network (a 4 byte ACK for 50 one-hop neighbors would result in 200 extra bytes for every safety message). It is also unclear if this approach would be compatible with a security framework based on changing pseudonyms, like the approach currently proposed by the ETSI ITS architecture [PAP 08], because the ACK would need to include the identifier of the sender and most probably a sequence number for the acknowledged message.

Adaptive Traffic Beacon (ATB) is a solution/mechanism/approach proposed by Sommer *et al.* [SOM 11], where the beaconing frequency is calculated based on two metrics: the channel quality and the message utility. The idea is to transmit only the most important messages in a congested network, reducing the offered load. Nevertheless, the channel quality is very sensitive to the number of collisions, which implies that the nodes are somehow supposed to detect such events, clearly a difficult task in a broadcast environment [STA 12]. Moreover, while different utility factors could help differentiate between CAMs and DENs, safety beacons would be difficult to prioritise, as they belong to the same message class. Finally, ATB increases the beaconing period to a mean of 3.6 s, clearly a value that does not comply with the delay requirements of most safety applications, which vary between 100 ms and 500 ms [PAP 09].

For more details on adaptive beaconing solutions, the reader is referred to the very comprehensive review paper by Schmidt *et al.* [SCH 10]. To conclude, while reducing the beaconing frequency is a powerful tool in congestion control, the consequences of this adjustment on every safety application should be taken into account. However, road safety applications will most likely not be standardized, and addressing the constraints imposed by proprietary solutions is a difficult task.

1.3. Data rate

The standards from the IEEE 802.11 family provide multi-rate capability at the physical layer, but without specifying a particular approach for data rate adaptation. In wireless communications, a more complex modulation results in a higher data rate, but it also requires a higher signal-to-noise ratio (SNR) at the receiver in order to be correctly decoded. In the continuous fight for increased bandwidth, the search for an efficient data rate control solution in the very lucrative WLAN industry stimulated the research in this area, and two main classes of mechanisms have been designed.

The solutions in the first class are based on their choice for a certain modulation and coding rate on the success or failure of previously sent messages. For example, the Robust Rate Adaptation Algorithm (RRAA), proposed by Wong *et al.* [WON 06], calculates the frame loss ratio in a short time window and compares this value with two predefined thresholds. Too many losses determine a reduction in data rate, while a high percentage of successful transmissions results in the choice of a more complex modulation. The second type of mechanisms are based on feedback from the receiver regarding signal quality. A representative example in this class is receiver-based auto rate (RBAR), described by Holland *et al.* [HOL 01]. RBAR relies upon the idea of receivers measuring the channel quality by analyzing the Request To Send (RTS) message and calculating the highest achievable data rate based on the channel conditions. This information reaches the transmitter through the Clear To Send (CTS) message and the best modulation is set for the data frame.

The applicability of mechanisms from the two classes discussed above in a unicast vehicular network is studied experimentally by Camp and Knightly [CAM 08]. They show that, because of the highly variable vehicular channel, decisions based on historical data are not accurate in this environment, while the SNR-based mechanisms need to be trained in the target geographical region in order to cope with the short coherence time (around 300 μs when other vehicles are also present on the road).

In broadcast safety communications, solutions using feedback from the receivers are clearly unsuitable, therefore the data rate adaptation mechanisms proposed for vehicular safety messages follow the classic path of algorithms based on historical data. Mertens *et al.* [MER 08] use RRAA in their simulation study, showing a significant improvement in performance when compared with regular IEEE 802.11p. Nevertheless, they do not address the problem of computing the frame loss ratio in a VANET. A more innovative approach is proposed by Ruffini and Reumerman [RUF 05], building on the correctly received CAMs to create a map of the average path loss at different receivers and use this map to estimate the highest data rate that could be successfully used.

However, the data rate adaptation problem is not exactly equivalent in WLAN and in safety vehicular networks. In the first case, the goal is to maximize throughput by choosing the corresponding modulation. While the problem is, of course, difficult to solve, the existence of a solution cannot be questioned. In a VANET, the goal, as described in the different congestion control architectures, is to reduce the transmission time of a message when the vehicular density increases to give more stations the chance to access the channel during a beacon period. The choice of the modulation is not dictated in this case by the quality of the channel, but by the number of one-hop neighbors, and there is currently no proof that the assignment of a data rate based solely on the local node density could increase the beaconing reception ratio. Moreover, an experimental study led by General Motors R&D and presented by Bai *et al.* [BAI 10] argues that using Quadrature Phase-Shift Keying (QPSK) and a data rate of 6 Mb/s) is the only reasonable choice for V2V communications. In their tests, only two communicating vehicles have been used, ignoring therefore the impact of message collision or interference. Even in these idealistic conditions, any modulation resulting in a higher data rate drastically reduces the reception probability, even at small distances from the transmitter (less than 50% received beacons at 50 m using 18 Mb/s). Furthermore, even the more robust 3 Mb/s Binary Phase-Shift Keying (BPSK) modulation shows lower performance, because, in this case, the transmission time is larger than the coherence time (found to be around 300 μs, just like in [CAM 08]).

Considering these results, data rate adaptation mechanisms need to be better evaluated, especially using real hardware during field tests, before a decision relative to their usefulness in VANET congestion control can be taken.

1.4. Transmission power

Transmission power control is one of the most studied topics in the area of VANET congestion control. However, most of the proposed mechanisms are just variants of solutions previously proposed in a mobile *ad hoc* network (MANET) context, where the objective of adjusting the transmission power is to minimize energy consumption while keeping a connected network. For example, Chigan and Li [CHI 07] use a directional antenna approach originally designed for topology control in MANETs to obtain the minimal power needed to transmit messages only to the closest vehicle on each direction. Similarly, Yoon and Kim [YOO 11] adapt transmission power with the objective of keeping a constant number of one-hop neighbors.

Nevertheless, these solutions are not appropriate for a safety VANET, where messages need to cover a minimal distance, not a certain number of neighbors. With these requirements in mind, Guan *et al.* [GUA 07] define a *target range* for safety messages. When a node receives a message, it calculates the distance from the sender and verifies if it is positioned inside the target range. Vehicles receiving a beacon despite being outside the target range include the identifier of the transmitter in a special feedback field in their own beacon. Using the information in this field, a station can calculate how many nodes outside the target range were reached by its transmission and the goal of the power control mechanism is to keep this number between certain limits.

Another proposal using special feedback piggybacked in the CAMs is the distributed fair power adjustment for vehicular environments (D-FPAV) strategy described by Torrent-Moreno *et al.* [TOR 09]. D-FPAV defines a maximum beaconing load (MBL) that can be accommodated by the CCH while still having spare bandwidth in the eventuality of a special notification. A distributed algorithm ensures an optimal power level assignment, where vehicles use the maximal possible power that still respects the MBL constraint. However, this optimality is achieved only when the power levels used by all the two-hop neighbors are known.

Because the overhead introduced by D-FPAV is significant, especially under high node density when saving bandwidth is the most important, Mittag el al. [MIT 08] designed segment-based power adjustment for vehicular environments (SPAV). SPAV on the one hand does not achieve an optimal assignment like D-FPAV, but on the other hand it does not require full knowledge about the power levels used by different neighbors, but only an estimate of the local density that can be obtained in a much more inexpensive manner.

The local node density (estimated, for example, from the received beacons) is also used in the computation of the transmission power by Rawat *et al.* [RAW 09], but in this case the transmission range is calculated using results from traffic flow theory. Artimy [ART 07] manages to entirely eliminate the overhead for transmission power control, using only data from the onboard speedometer to estimate the local density, again using fundamental relationships from traffic flow theory.

While calculating local density based on the CAMs received from the other vehicles is considered a natural property of the safety beaconing, this task might be complicated by the use of changing pseudonyms. Huang *et al.* [HUA 10] propose a solution that can cope with the VANET security requirements. In their framework, a node simply measures the channel occupancy from the information provided by the clear channel assignment (CCA) function. If the percentage of time the medium is sensed as busy in the last beaconing period is under a certain threshold U_{min}, the node uses the highest power level, otherwise a linear mapping between the channel occupancy and transmission power is used.

Because of its excellent properties and its feasibility using existing hardware, transmission power control is considered as a central mechanism for congestion control in VANETs and it has been included in the ETSI ITS decentralized congestion control framework [EUR 11].

1.5. Minimum contention window

The minimum contention window (CW_{min}) is one of the most important parameters of the IEEE 802.11 MAC layer. CW_{min} represents the initial value of the *CW*, the superior limit of the interval from which the back-off mechanism draws the number of idle slots the station has to wait before attempting a transmission. For unicast communication, the value of *CW* is doubled every time an expected ACK message is not received within a predefined delay and it is reset to CW_{min} for every acknowledged reception, leading to the so-called *binary exponential back-off* (BEB) mechanism.

Even before the release of the first version of the IEEE 802.11 standard, Bianchi *et al*. [BIA 96] showed that the optimal value for CW_{min} depends on the number of contending stations. More exactly, their analysis shows that, in a saturated WLAN, the throughput is maximized when:

$$CW_{\min} \approx n_c\sqrt{2T_t}, \quad [1.1]$$

where n_c is the number of nodes in the network and T_t is the time needed to transmit the message (acknowledgment included). Building on these results, Cali *et al.* [CAL 00] determined that the protocol’s performance peaks when the time the channel is idle due to the back-off mechanism equals the time the channel is occupied by collisions ($T_{\text{idle}} = T_{\text{col}}$).

Despite this well-known property, the IEEE 802.11 standard does not include any mechanism for the adjustment of CW_{min} when the number of contending stations grows. The main reason for this was that the protocol was designed for WLANs, with a central access point and a limited number of client stations (usually no more than 20) in mind. A second argument came from the use of the RTS/CTS handshake. In this case, collisions are limited to the short RTS and CTS messages, and therefore the time the channel is busy due to collisions is decreased. This implies that, for an optimal functioning, T_{idle} also needs to be reduced, which requires a lower *CW*. Moreover, with the massive success of multimedia services, and with the introduction of the IEEE 802.11e standard, the minimum *CW* has been reduced even more, in order to minimize the delay experienced by sensitive video and voice applications. The idea, in this case, was that most users, especially residential users, connect only a reduced number of devices to their access points, and generally use only one or two of them simultaneously. A reduced *CW* improves the MAC layer performance in this case, while the BEB mechanism is there as a back up for the cases when the number of contending stations increases.

An impressive number of modified back-off mechanisms have been designed in different WLAN scenarios, and Razafindralambo and Valois [RAZ 06] compare the performance of the most significant of these proposals. Most of the solutions considered in this unicast context still require a fixed value for CW_{min} and only modify the back-off mechanism. For example, Wang *et al.* [WAN 04] argue that when a transmission succeeds after a number of failures it is not correct to reset the *CW* to its minimal value, because the congestion will continue to exist on the channel. They propose a slower decrease of *CW*, and only after several acknowledged transmissions in a row. However, Medepalli and Tobagi [MED 06] proved analytically that the impact of CW_{min} on the throughput of a network is much more significant than the influence of the back-off mechanism.

For more than a decade, all the IEEE 802.11 enhancements related to CW_{min} adaptation in MANETs belonged to one of the two categories. The methods in the first class (e.g. [KIM 05]) estimate the number of contending stations in the two-hop neighborhood and use equation [1.1] or some variants to calculate the optimal *CW*. The second type of mechanisms consider the overhead introduced by the local density estimation as prohibitive, and the amount of time the channel is sensed as idle and the number of collisions are measured instead. The *CW* is adjusted, in this case, in order to keep the equality $T_{\text{idle}} = T_{\text{col}}$ valid: when there are too many collisions on the channel, the back-off time (and with it the idle time) is increased, while when the channel is idle for long time durations, the *CW* is reduced. A notable example from this second class is IdleSense, proposed by Heusse *et al*. [HEU 05].

Nevertheless, in 2008, Jiang and Walrand [JIA 10] took a completely different approach concerning the back-off mechanism in carrier sense multiple access (CSMA) networks, proposing *optimal CSMA* (oCSMA). The idea behind this new protocol is to adapt the *CW* of a node as a function of its queue length. In oCSMA, a node begins with an initial value for *contention aggressiveness* (which can be easily translated into a certain CW_{min}) and, when the number of messages in a link queue increases, the transmitter becomes more aggressive in the competition for channel access. Despite having very low complexity and requiring only local information, oCSMA has been proven to achieve throughput optimality under both continuous-time and discrete-time back-off duration [KIM 11], and was implemented using off-the-shelf IEEE 802.11 hardware [NAR 11].

With all these interesting studies coming from related research fields, we might believe that it should be rather straightforward to study and understand the impact of the *CW* in V2V communications. However, the particularities of the vehicular network translate once again into unique properties that modify the problem entirely. In a VANET, the node density is highly variable and a station can go, within a few minutes, from a vary sparse environment to several hundred contending neighbors. In addition to the fact that the RTS/CTS handshake cannot be implemented and the BEB mechanism is deactivated by the lack of ACK messages, none of the properties that allowed the use of a small *CW* in IEEE 802.11 WLANs hold in this scenario.

An adaptive mechanism is therefore needed, but a rapid analysis of the compatibility between the solutions described above and the safety VANET shows that the design of this mechanism is not exactly a simple formality. The Bianchi relationship is true for a unicast saturated one-hop WLAN cell, while a safety vehicular network is neither saturated nor fully connected. In addition, collisions remain difficult to detect in V2V communication, therefore IdleSense and other similar approaches cannot be directly transposed in a vehicular environment. Finally, because expired beacons are dropped, the MAC layer always has at most one safety message to transmit [STA 12], and the queue length cannot determine the *CW* as proposed in oCSMA. Moreover, the goal of all these mechanisms is to maximize throughput, an objective that is not shared by a safety vehicular network.

The few proposals for *CW* adaptation issued from the VANET research community failed to consider these important differences. Rawat *et al.* [RAW 09] propose a heuristic based on the number of detected collisions, where the *CW* is increased if the number of collided messages is higher than a predefined threshold. However, the threshold does not depend on the local node density and the technique used for collision detection is not described. The same critique applies to Mertens *et al.* [MER 08], who, in a first phase, estimate the local node density and directly use this result in equation [1.1]. Then, they further refine the value of the *CW* by increasing CW_{min} when the percentage of lost beacons becomes higher than a target PER. Balon and Guo [BAL 06] address this issue of measuring the percentage of lost beacons by using the sequence numbers inside the safety messages, which might not be compatible with a privacy framework based on pseudonyms.

In a similar manner, Wang *et al.* [WAN 08] design a heuristic relying upon the channel busy time measured by the CCA function during a predefined time period. In their solution, if the channel busy time increases between two consecutive measures, the *CW* grows linearly with the observed difference. In the opposite case, *CW* is reduced, also using a linear relationship. Although the efficiency of this mechanism depends on the initial value of the *CW*, the authors do not provide any guidelines for the choice of this parameter.

Meanwhile, Jang and Feng [JAN 10] establish a relationship between the number of contending stations and the optimal back-off time in a vehicular network, but their study is focused on unicast communication using RTS and CTS control messages. Finally, Alapati *et al*. [ALA 10] try to maximize throughput using a type of probing mechanism, where the node tests different values for CW_{min} until an optimum is reached. The problem comes from the fact that this optimum depends on the local density that might vary faster than the convergence speed of the algorithm.

On the basis of these observations, five different mechanisms for *CW* control in a vehicular environment have been adapted from solutions proposed in the research literature, but not necessarily related to CW_{min} adjustment. The properties and feasibility of these mechanisms are characterized below, followed by the results of a simulation study using the Java in simulation time/scalable wireless *ad hoc* network simulator (JiST/SWANS) framework [JAV] and the street random waypoint (STRAW) mobility model [CHO 05].

- *Beacon-based neighbor estimation:* Beaconing represents a native method for estimating the number of local neighbors in a VANET. Mertens *et al.* [MER 08] propose to calculate the number of surrounding vehicles by counting the different sources from which at least a beacon has been received in the last T_{update} seconds. However, as discussed above, the number of neighbors from which a beacon was received, $\tilde{n}_c$, determined this way, cannot be directly applied in Bianchi's equation, even though T_{t} would be very easy to calculate for fixed-size CAMs. In this case, not only does the VANET not correspond to the original assumptions of a full connected saturated network, but also the accuracy of the estimation $\tilde{n}_c$ depends on the beaconing reception ration.

Therefore, instead of using equation [1.1] directly, the first studied mechanism keeps this linear dependency, but uses a more general formula to calculate the *CW*:

$$CW = \lambda \tilde{n}_c,$$

where λ is a parameter depending on the size of the beacon, and whose optimal value was explored through simulation.