# Full-Duplex Radios for Vehicular Communications

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**Abstract**

Recent significant advances in self-interference (SI) cancellation techniques pave the way for the deployment of full-duplex (FD) wireless transceivers capable of concurrent transmission and reception on the same channel. Despite the promise to theoretically double the spectrum efficiency, FD prototyping in off-the-shelf chips of mobile devices is still at its infancy, mainly because of the challenges in mitigating SI to a tolerable level and of the strict hardware constraints. In this article, we argue in favour of embedding FD radios in on-board units (OBUs) of future vehicles. Unlike the majority of mobile devices, vehicular OBUs are good candidates to host complex FD transceivers because of their virtually unlimited power supply and processing capacity. Taking into account the effect of imperfect SI cancellation, we investigate the design implications of FD devices at the higher-layer protocols of next-generation vehicular networks and highlight the benefits they could bring with respect to half-duplex devices in some representative use cases. Early results are also provided that give insight into the impact of SI cancellation on vehicle-to-roadside communications, and showcase the benefits of FD-enhanced medium access control protocols for vehicle-to-vehicle communications supporting crucial road safety applications.

**Index Terms**

VANETs, full-duplex, broadcasting, platooning, V2V, V2R, self-interference cancellation, 5G, C-ITS

## I. Introduction

Making vehicles more connected and autonomous puts unprecedented challenges in front of stakeholders in the automotive and communication fields to refine technologies that meet the ultra-low latency requirements while coping with the reliability and scalability issues of IEEE 802.11[1], the *de facto* standard for vehicular communications.

Lately, full duplex (FD) communication has gained attention in the context of advanced physical (PHY) layer design for fifth-generation (5G) and beyond networks with the promise of nearly doubling the system spectral

[1]The amendment for vehicular communications, formerly known as IEEE 802.11p, is now part of the IEEE 802.11-2012 standard.

efficiency [1], [2]. Although studies on the application of FD in classic infrastructured IEEE 802.11 networks have been conducted, the implications of FD adoption in future vehicles have not been fully investigated yet. On the one hand, there are concerns about the technical feasibility of FD technologies in the harsh channel propagation environment typical of vehicular ad hoc networks (VANETs). On the other hand, the availability of high-end transceivers that could be installed on-board the vehicles promise to overcome the hardware complexity limitations that delayed the practical realization of FD technologies in other wireless systems.

Very few preliminary works have focused on FD in cellular-based VANETs [3], [4]. While acknowledging the importance of these works, we believe that much more opportunities could be disclosed if FD solutions carefully consider *(i)* the IEEE 802.11 standard technology and *(ii)* the requirements and patterns of emerging vehicular applications such as cooperative and semi-autonomous driving. This is actually the aim and main contribution of this article, the organization of which can be summarized as follows. After introducing the FD concept from the perspective of the PHY and medium access control (MAC) layers, we discuss why the FD deployment in vehicular on-board units (OBUs) has fewer concerns than in other mobile devices like smartphones or laptops, and highlight the challenges for FD protocols design in VANETs. Then, we focus on the most representative vehicular use cases in which FD concepts could be successfully applied to improve their performance by rethinking the MAC and/or higher-layer data exchange protocols; and we complement our discussion by early simulation results. Finally, we debate open issues and future research perspectives to the deployment of FD technologies in VANETs.

## II. FD: AN OVERVIEW

**A PHY layer perspective.** In theory, in-band FD systems can double the system capacity by allowing simultaneous transmission and reception over the same center frequency. In practice, however, the increase in capacity is limited by the self-interference (SI) that is unavoidably generated when the transmitted signal couples back to the receiver in the in-band FD transceiver. Even though the transmitted signal is perfectly known in the digital baseband, eliminating the generated SI at the receiver has been considered for a long time as a difficult, if not impossible, task. The reasons essentially come from the considerable power difference between the transmitted and received signals[2], and the multiple causes of analog signal distortions (nonlinearities, I/Q imbalance, etc.) and estimation errors in the transceiver chain. If the latest advances on the subject of self-interference cancellation (SIC) techniques tend to nuance this negative belief, achieving a sufficient amount of SI attenuation calls for sophisticated multi-stage receiver architectures.

Passive radio-frequency (RF) isolation comes first, with a twofold purpose: *(i)* to make certain that the SI signal power prior to entering the receiver chain is not too high for the low-noise amplifier (LNA) to prevent complete saturation, and *(ii)* to ensure that the dynamic range of the analog-to-digital converter (ADC) is high enough to capture the residual SI as well as the weak received signal of interest with sufficient precision. The most straightforward method uses separate transmit and receive antennas and exploits the natural electromagnetic

[2]The direct SI signal is typically 100 dB more powerful than the intended received signal in Wi-Fi systems.

isolation (path loss) between them, as well as polarization diversity. Passive isolation with a single shared antenna is another option and requires a hardware component, either a three-port circulator or an electrical balance duplexer. Most often, passive SI attenuation levels are insufficient to meet the above requirements.

The role of active analog SIC is to provide additional SI attenuation before the signal enters the receiver chain. An effective SI attenuation in the analog domain reduces the required range dynamic of the ADC. Classical time-domain trained-based methods subtracting a modified copy of the transmit signal from the overall received signal can be derived for both single- and multiple-antenna systems. The degree of freedom offered by the spatial dimension can be exploited in many ways (see, e.g., [5]). Similarly to passive techniques, claimed SI attenuation levels vary considerably depending on the considered use cases and contexts, ranging from 20 to 60 dB.

Active digital SIC is performed last, to attenuate the residual SI signal below the noise floor so that co-channel interference may start dominating. The principle is again to subtract from the overall received signal the original transmit signal modified according to the *effective* channel experienced by the SI signal. The effective channel includes the effects of the transmitter and receiver chains, active analog SI pre-cancellation, and multipath components reflected from antennas and surrounding environment. SI attenuation levels obtained with state-of-the-art algorithms typically vary between 20 and 30 dB.

Overall, recent experimentations have proved that the aforementioned techniques, when combined all at once, could achieve up to 70-110 dB SI attenuation levels (see, e.g., [1] and references therein).

**A MAC layer perspective**. FD communications can be broadly classified into *symmetric* and *asymmetric* [1]. In both cases, higher throughput is achieved compared to a half-duplex (HD) scenario. In symmetric FD links, a pair of nodes simultaneously transmit and receive each other's data. Capacity can be theoretically doubled, provided that the two links carry the same amount of data, but misalignments, e.g., packets that are offset in time and have different lengths, may limit the achievable capacity gains. The feedback delay reduction is a further beneficial side effect of symmetric FD communication at the MAC layer. Backward signaling, such as acknowledgement/negative acknowledgment, in fact, can be sent by the receiver while the sender is transmitting.

FD communications are called asymmetric when they involve more than one node in the network; a node targets a second one, which targets a third one, with the node in the middle acting as a *relay*, simultaneously receiving from the first node and transmitting to the third one. This would be the case of an infrastructured Wi-Fi network with the Access Point (AP) acting as the relay.

In general, FD techniques have the great potential to tackle the unsolved issues of distributed MAC protocols, like IEEE 802.11, relying on the carrier sense multiple access with collision avoidance (CSMA/CA) scheme. First, *collision detection becomes possible* since channel sensing is enabled while a signal is being transmitted, so that a FD node can realize whether other nodes are simultaneously transmitting. Second, in the case of asymmetric FD communication, *the hidden node problem can be counteracted* without the need for a handshaking procedure such as the 802.11 Request-to-Send/Clear-to-Send exchange.

In summary, FD techniques will inevitably ask for modifications to MAC protocols; the challenge is to account "by design" for the aforementioned symmetric and asymmetric patterns and efficiently schedule transmission opportunities, while not harming fairness among accessing nodes.

## III. FD FOR VANETS: BENEFITS AND CHALLENGES

The benefits of FD communications come at the price of a few serious constraints. Passive isolation necessitates advanced antenna design and, in case of separated antennas, sufficient space on the communicating devices. Along with this limitation, active analog and digital SI suppression require higher energy consumption and additional computational resources compared to HD communications. This is especially challenging if the purpose is to implement FD radios in low-cost battery-powered small mobile devices. Furthermore, low-cost analog components employed in mass-produced handheld devices, i.e., LNA, oscillators, and ADC, are prone to introduce severe nonlinearities and not insignificant levels of phase and quantization noise, the proper modelling of which is paramount in active digital SIC.

The aforementioned issues would be largely mitigated in vehicular devices. First, miniaturization is no more a concern: antennas can be kept separated on a vehicle rooftop at a distance that could even make passive isolation remarkably efficient. The only remaining constraint is related to cabling issues and wiring costs. Second, vehicular OBUs can host large processing and virtually unlimited power capabilities, hence they are capable to support complex transceivers. Third, cost constraints that directly impact the quality of analog components are less stringent for vehicles. Higher quality analog components are likely to create less signal distortions and imperfections. Last but not the least, vehicular technology is at an early stage and new vehicles could be easily equipped with FD radios. Such features would all facilitate and expedite an incremental deployment of FD technologies in VANETs.

On the other hand, a major concern for FD mobile devices is the time-dispersive nature of the SI channel, caused by the moving scatterers and reflectors in the surrounding environment and the mobility of the device itself. Although preliminary experimental results presented in [6] for handheld FD mobile devices with single shared antennas are encouraging, we expect the challenge of tracking the fluctuations of the SI channel in real-time to be exacerbated in vehicular scenarios, where the vehicle mobility can be much higher and the propagation conditions very harsh. The passive isolation stemming from distant antennas on the vehicle rooftop will not necessarily contribute to make the task easier.

Another feature of OBUs that could be impacted by FD is that they will likely be deployed as *dual-radio* devices to fully benefit from the multi-channel worldwide allocated spectrum in the 5.9 GHz band. The main reason of this choice is that it allows separation between safety messages exchanged on a dedicated channel, on which one radio is constantly tuned, and non-safety critical data exchanged on a different channel on the second radio [7]. In the multichannel allocated spectrum, however, *adjacent channel interference* (ACI) is an issue that may affect the parallel usage of adjacent channels. A target receiver can be disturbed by spurious emissions from adjacent channels, due to non ideal spectrum power mask[3] that increases the interference level and, eventually, cause errors

[3]The spectral mask losses at a frequency offset of $\pm$ 10 MHz from the center frequency, corresponding to the adjacent channel carriers, are around 40 dB.

in the received packet. For this reason, until now, the simultaneous use of adjacent channels has been discouraged in the same OBU. Now, instead, SIC techniques designed for FD devices open new possibilities to counteract ACI phenomena in VANETs, by allowing the simultaneous transmission and reception over adjacent channels in the same device and, hence, improving the multi-channel usage.

Despite the mentioned high potential, especially for what concerns transceiver deployment in OBUs, to the best of our knowledge, the peculiar implications of FD in VANETs at the MAC and higher layers have not been adequately addressed and will be analyzed in detail in the following:

- Unlike the majority of FD studies that consider unicast communications, in VANETs there is rationale for analyzing FD capabilities for *broadcasting*, due to its crucial role in the support of road-safety applications.
- Moreover, the fact that the majority of interactions in VANETs rely on 802.11 vehicle-to-vehicle (V2V) communications, is a further facet so far mostly unexplored in the FD literature.

Table I summarizes pros and cons of FD techniques for Wi-Fi mobile devices, in general, and for VANETs, more specifically, from the PHY[4] and MAC layer perspective, by also highlighting challenging issues.

## IV. FD IN RELEVANT VANET USE CASES

We are highly confident that FD capabilities can be successfully exploited in crucial vehicular scenarios involving: *(1)* vehicle-to-roadside (V2R) communications, and *(2)* V2V interactions, with focus on safety applications. For both of them, in the following, we will discuss the status quo, the relevant open issues and how and to which extent their performance can be improved by taking advantage of FD capabilities.

### A. PHY layer modelling

Before all else, we need to introduce a generic FD vehicle-to-everything (V2X) system model with $n$ nodes (vehicles, infrastructure nodes) and adequately justify our assumptions. Amongst the $n$ nodes, node $i$ is an in-band FD node with separated transmit and receive RF chains/antennas, transmitting its own signal and simultaneously receiving the signals of a distant node $j \neq i$, of interest, and other distant interfering nodes $k \neq \{i, j\}$. The transmission links between nodes are subject to large-scale path loss and shadowing effects, small-scale frequency non-selective fading, and zero-mean Additive White Gaussian Noise (AWGN). To understand/measure how the SI impacts the reception dynamics and, thus, the overall MAC layer performance, we define the Signal-to-Interference-plus Noise Ratio (SINR) at the receive antenna of node $i$ as

$$\gamma_i = \frac{\alpha_{i,j} P_j}{K_i P_i + \sum_{k \neq \{i,j\}} \alpha_{i,k} P_k + N_0}, \tag{1}$$

where $P_i$ is the transmit power of node $i$, $\forall i \in \{1, \ldots, n\}$, $\alpha_{i,j}$ is the attenuation of the received signal power from node $j \neq i$ accounting for distance-dependent path loss and fading phenomena, $N_0$ is the AWGN power, and $K_i$ is a specific factor used to model the attenuation level of SI by means of passive isolation and active cancellation

[4]Identified items for the PHY layer of Wi-Fi-equipped devices are quite general and may hold also for other mobile devices.

techniques[5]. As a first approximation, we can assume a *reliable* communication from node $j$ to node $i$ if $\gamma_i \geq \gamma_{\min}$ with $\gamma_{\min}$ the SINR threshold defined as a function of the modulation and coding scheme, the targeted residual bit or block error rate, and decoding capabilities of node $i$.

### *B. V2R communications*

**Status quo.** Road-side units (RSUs) deployed along the road supply connectivity to passing-by vehicles that can exchange environmental/traffic/diagnostics data, access traditional Internet services and emerging cloud services and social networks. Short-term and intermittent V2R connectivity are the main issues, due to the vehicle speed, the short-range RSU coverage, and the non-ubiquitous roadside infrastructure deployment. Tackling these issues has implied so far improving the channel access mechanism, for example by leveraging time-division multiple access (TDMA) on top of the CSMA/CA scheme [9]; or by using relays to enlarge the V2R coverage range [10]. Nonetheless, such techniques provide only partial solutions, either incurring additional signaling overhead (as for TDMA solutions) or limiting the capacity (in case of relay-based V2R communications).

**FD benefits.** V2R communications (both direct and relayed), Figure 1, could experience capacity enhancements by leveraging FD radios. As a result, the exchanged amount of data between a vehicle and the RSU in a given time can be doubled w.r.t. the HD case, by enabling novel bandwidth-hungry infotainment applications. Alternatively, massive transmissions by several vehicles can be accommodated so coping with scalability issues which characterize VANETs due to the very limited allocated spectrum. However, such benefits highly depend on the vehicle-to-RSU distance.

**Impact of SI**. To get insights into the achievable transmission ranges for FD-based V2R communications, 802.11 link-layer simulations have been conducted in Matlab to measure the SINR at in-band FD node(s) under different transmitter-to-receiver distances as reported in Figure 2. The solid and dashed curves, labeled as *same CH* and *adjacent CH*, report the SINR value measured at a target FD node transmitting while receiving, respectively on the same or on an adjacent channel. For discussion, we consider 6 Mbps (corresponding to $\gamma_{min} = 8$ dB) that is the most robust data rate for vehicular communications. The effectiveness of the SIC techniques is captured through the aggregate attenuation parameter $K$[6], which varies in the range 70-110 dB [1]. The curve labeled as $HD$ refers to the benchmark case of HD communications accounting only for the received power of the useful signal, without SI and for which successful decoding at 6 Mbps is possible within a distance of around 350 m.

Although FD techniques promise to improve the vehicular spectrum utilization, provided results clearly demonstrate that SI, if not completely cancelled, may limit the communication ranges, with a different impact either if the same or adjacent channels are used in an OBU:

[5]Only the power of the direct SI, i.e., the line-of-sight component of the signal transmitted by node $i$, is taken into account in this simplified model. The effect of the reflected SI consisting of the superposition of the non-line-of-sight components of the signal transmitted by node $i$, modeled as a Ricean distribution in [8], can be neglected if the other nodes in the system are at a distance lower or equal than potential reflectors, and if all nodes transmit with similar power levels.

[6]Here, $K$ refers to the attenuation factor $K_i$ in (1). The subscript has been removed for easiness of notation.

- In OBUs using *the same channel* for simultaneous transmission and reception, FD interactions can be allowed only for short distances between communicating nodes (around 50 m for $K = 90$ dB and 225 m for $K = 110$ dB). When considering data rates higher than 6 Mbps, requiring higher target SINR values, such conditions are even more difficult to be met. Whereas, successful decoding at 6 Mbps is not possible for $K = 70$ dB. Achieved trends are reasonably in line with the expectations, since higher distances imply lower received useful signal and higher detrimental effect of SI in comparison.
- In OBUs resorting to *adjacent channels*, compared to the previous case, successful decoding can occur at larger distance from the sender, e.g., approximately 350 m (for $K = 90, 110$ dB[7]). Moreover, in case of adjacent channels, communication ranges are large (around 225 m) even when less accurate cancellation techniques (e.g., due to the time-varying SI channel) are considered ($K = 70$ dB).

### *C. V2V communications*

V2V communications are crucial for vehicular safety applications, especially in the following two representative use cases: cooperative driving and semi-autonomous driving (a.k.a. platooning).

*1) Cooperative driving:* **Status quo.** Cooperative Awareness Messages (CAMs), carrying position and kinematics parameters, are periodically exchanged in broadcast among nearby vehicles for collision warning/traffic efficiency purposes. CAM losses cannot be detected (no feedback from the receivers is allowed in 802.11 for broadcast packets) and then lost packets will not be retransmitted. CAM failures are either due to channel errors or collisions. In the latter case, the reason of the loss can be either the interference from hidden transmitting nodes or the simultaneous expiring of backoff timers by nodes in reciprocal visibility (*direct collisions*).

**FD benefits.** The FD capability of sensing the channel while transmitting can be leveraged to improve the reliability and timeliness of CAMs. To counteract direct collisions, we propose a simple 802.11 MAC enhancement that lets FD OBUs detecting a collision abort transmission and promptly retransmit the collided packet. The time a FD node requires to detect a collision (i.e., the collision detection time) highly depends on the accuracy and complexity of the implemented SIC techniques [11]. Clearly, the longer the collision detection time, the higher the collision detection accuracy, but the recovery from CAM losses is slower. A collision detection time equals to the MAC header duration is for example assumed in [12]. Imperfect channel sensing may cause: *false alarms* when a node wrongly labels as a collision a successful transmitted packet, and *missing detections* if a collision cannot be detected [11]. As soon as a potential collision is detected, the node aborts the packet transmission by not wasting radio resources for transmitting a packet that would end up to a failure. Then, the detecting device retransmits the packet by triggering the backoff procedure immediately. The CAM will be retransmitted, on the backoff expiry, until a success or a maximum retry limit, $M$, is achieved[8]. CAM replicas are transmitted as separate packets following the 802.11 MAC rules, and doubling the contention window (CW) at every retry to reduce the collision probability.

[7]In both cases the SI signal, received 40 dB-attenuated due to the spectral mask loss, is pushed down to the noise floor thanks to effective cancellation. Thus, both curves coincide with the curve for HD, no accounting for any source of interference.

[8]The same CAM is retransmitted until it is replaced by fresher information generated by the upper layer and queued in the MAC buffer.

**Early results.** To showcase the potential of the proposed FD broadcasting scheme we compare it against the HD (legacy) 802.11 broadcast, according to which a failed CAM cannot be either detected or retransmitted. The behaviour of the mentioned MAC schemes have been simulated in Matlab, with settings closely following the 802.11 standard specifications for a variable number of vehicles transmitting CAMs. To focus on the MAC-layer performance and ease the interpretation of results, channel-induced losses and imperfect sensing are not simulated. Packet losses only occur due to direct collisions (no hidden terminals are considered). The CAM reliability and timeliness have been evaluated, respectively, through the following metrics: *(i)* the fraction of successfully delivered CAMs in the coverage area of a transmitter, and *(ii)* the average update delay, i.e., the time difference between two consecutive successful CAMs received by a vehicle. Figure 3 reports the two metrics when varying the repetition parameter $M$ for the FD broadcasting scheme. The latter one significantly outperforms the legacy scheme: e.g., for 30 vehicles CAM delivery fraction passes from 0.2 of HD to more than 0.5 for FD broadcasting when $M = 2$ and up to 0.8 when $M = 3$.

The Figure also shows longer update delay values, for HD w.r.t. FD broadcasting. With the legacy scheme, values are close to 400 ms with 30 transmitters, which is unacceptable for safety applications; whereas update delays are slightly above 100 ms for the FD broadcasting scheme with $M = 3$. Overall, such encouraging early results prove the FD advantages in safety data broadcasting.

*2) Semi-autonomous driving:* **Status quo.** Platooning is the first step towards fully autonomous driving. It reduces fuel consumption and gas emissions by making vehicles that follow the same path in a platoon, drive very close to each other (with inter-vehicle distances in the order of 10 m). The platoon stability is ensured by updating regularly the control algorithm with new CAM information by neighboring vehicles, possibly with a frequency higher than 10 Hz (hence, higher than in the previous case of cooperative driving). For instance, in the *predecessor-following* strategy each vehicle gets information from its preceding vehicle only at each CAM update, and in the *bidirectional* strategy, the control action at each CAM update depends equally on the information from both the immediate front and back neighbors [13]. The 802.11 CSMA/CA is known to be quite unsatisfactory in supporting the strict delivery demands of platooning applications and enhancements have been proposed relying on collision-free protocols. For instance, a TDMA scheme is proposed in [14], where vehicles in the platoon transmit *sequentially* in different time slots, according to their position in the platoon, so to avoid interference within the platoon and with other ongoing transmissions sharing the same channel. Such an approach well suits the rather stationary platoon chain structure.

**FD benefits.** Augmenting a TDMA-based protocol with FD capabilities could further reduce the latency in exchanging information feeding the control algorithm at each platoon vehicle. First, a predecessor-following strategy has similarities with the illustrated case of asymmetric FD communications. A vehicle can transmit a CAM to the following vehicle while simultaneously receiving a CAM from the preceding one. Second, with a bidirectional strategy, FD symmetric communications occur between a pair of nearby platoon vehicles.

**Early results.** We compare the performance of the HD and FD versions of the TDMA-based protocol in [14] when both the predecessor-following and the bidirectional control strategies are implemented. Performance analysis has been conducted under ideal channel settings, when varying the platoon size, to preliminarily show to which extent platooning can benefit from FD capabilities. In particular, Figure 4 reports the *minimum CAM update delay* which can be assured by accommodating all the CAM transmissions within a platoon so to feed the individual control algorithm in each vehicle when the control action needs to be taken. It clearly emerges that for both control strategies by leveraging FD, the metrics is almost halved w.r.t. the case where a single vehicle can transmit at a given time. A network-level positive side-effect of FD is that channel resources can be saved and the update of the control algorithm can be more frequent, thus allowing high-density platooning with very closely-spaced vehicles.

## V. Future research perspectives

The analysis in the previous Section investigated the potential of FD in vehicular use cases and the relevant open issues, which are summarized in Table II. Some challenges are inherited (more or less exacerbated) from FD research in the field of cellular and Wi-Fi networks. Others, instead, specifically emerge in the context of VANETs.

**Advanced SIC techniques.** With specific reference to VANETs, the major issue will come from the harsh rapidly time-varying nature of the propagation environment. It is mandatory to design agile SIC algorithms in both analog and digital domains. In the analog domain, the adaptive filtering-based approach presented in [6] with a closed-loop option to obtain and control the tap weights appears well suited to track the SI waveform in real-time. In the digital domain, the task is to model and estimate the residual effective SI channel taking into account amplifier distorsions, mixer nonlinearities, I/Q imbalance, etc. The parallel Hammerstein model used in [6] seems fairly accurate, even though it ignores some other source of impairements, like phase noise. As regards parameter estimation, it is unclear whether simple LMS algorithms will suffice under high mobility.

More sophisticated adaptive algorithms may be needed. Moreover, the overall receiver performance will improve if advanced model-based signal processing algorithms able to perform SIC jointly with the signal of interest's decoding are employed (see e.g., [15] and the references therein). Another challenge is to explore the potential of FD with multiple transmit and receive antennas in the context of VANETs.

**FD-based MAC design.** In the previous sections we provide preliminary results about possible improvements of the 802.11 MAC protocol to exploit FD capabilities. Suggestions were customized to different types of interactions, V2V and V2R, and also to different applications such as cooperative and semi-autonomous driving. Research efforts are further encouraged to be focused on *(i)* understanding the effect of imperfect channel sensing on MAC layer dynamics; *(ii)* combining FD collision detection capabilities with other techniques (e.g., adapting the transmission power and frequency) to improve broadcasting performance and cope with packet losses due to hidden terminals and channel-induced errors; *(iii)* designing wiser channel access mechanisms (e.g., aware of queue sizes and V2R data traffic patterns, of trajectory and distance from the RSU, of platooning CAM update requirements) to better schedule transmission opportunities and take full advantage of FD capabilities.

**Backward compatibility.** FD-based solutions are needed which are backward-compatible with HD protocols to facilitate the co-existence of FD and HD devices. Such an issue is less dramatic for VANETs than for other more mature wireless network technologies; the current deployment is far from being large-scale and is still limited to a few equipped vehicles and RSUs, mainly for field-trials purposes. There is room for paving the way for a complete

FD vehicular deployment.

**Deployment.** To successfully embed the FD capability in vehicular devices what is highly required is a close cooperation among stakeholders in the automotive and telecommunication industries and standardization bodies to push forward a better performing and harmonized technology.

Overall, we believe that the interplay between the design of lower-layer solutions (e.g., multi-radio transceivers, transmission power control algorithms) and applications able to achieve the full potential of FD communications would highly improve the performance of next-generation vehicular networks.

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TABLE I

FD TECHNIQUES: FROM MOBILE DEVICES TO VANETS

| Views for FD Wi-Fi mobile devices | | |
|---|---|---|
| | **PHY layer** | **MAC layer** |
| **Pros** | 1) Theoretically doubled spectrum efficiency under perfect SI | 1) Simultaneous channel sensing and packet transmission (collision detection)<br>2) Reduced feedback (ACK) delay<br>3) Counteract hidden terminal problem for asymmetric communications |
| **Cons** | 1) Small device size precluding passive isolation between transmitter and receiver by means of separate antennas<br>2) Low computational capabilities and battery-powered devices hindering to perform analog and digital SIC<br>3) Stringent cost constraints translated into low-quality analog components responsible for RF distortions and imperfections<br>4) Slowly time-varying propagation environment complicating SI channel estimation | Misalignments in packet length and transmission instants |
| **Open issues** | 1) Provide a reasonable amount of passive isolation between transmitter and receiver sharing a single antenna<br>2) Prove the cost-effectiveness of state of the art self-adaptive analog and digital SIC algorithms | Define efficient and fair transmission scheduling policies at the AP |
| **VANETs perspective** | | |
| | **PHY layer** | **MAC layer** |
| **Pros** | 1) Same as for generic Wi-Fi mobile devices<br>2) Enough space on vehicle rooftop to provide good isolation between transmitter and receiver by means of separate antennas<br>3) Powerful CPUs to perform advanced signal processing<br>4) Unlimited power supply to run complex transceivers<br>5) Transceiver expenses written off by the high cost of the vehicle<br>6) ACI mitigation in the same OBU thanks to SIC techniques | 1) Same as for generic Wi-Fi mobile devices<br>2) Improved multi-channel usage<br>3) Higher chance to make the best of short-lived connectivity in V2X interactions |
| **Cons** | 1) Additional cabling and wiring required on the rooftop<br>2) Harsh highly dynamic propagation environment making SI channel estimation especially difficult | Misalignments in packet length and transmission instants |
| **Open issues** | Design ultra-agile analog and digital SIC algorithms able to track the rapid fluctuations of the effective SI channel | 1) Define efficient and fair transmission scheduling policies at the RSU<br>2) Conceive protocols able to support broadcast communications and distributed V2V interactions |

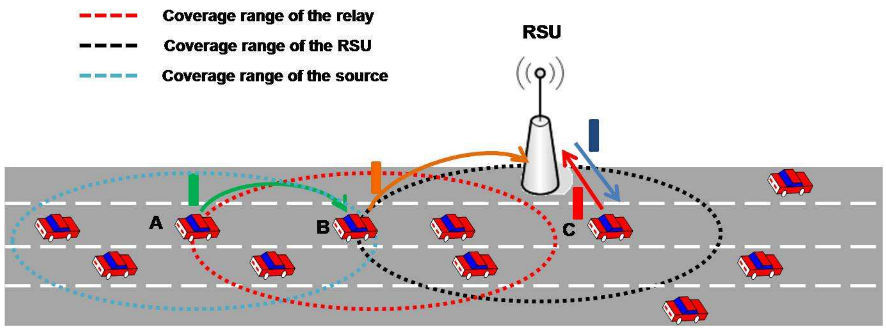


Fig. 1. V2R scenarios: direct vehicle-to-RSU symmetric (vehicle C-RSU) and relay-based vehicle-to-RSU asymmetric communications (vehicle A-vehicle B-RSU).

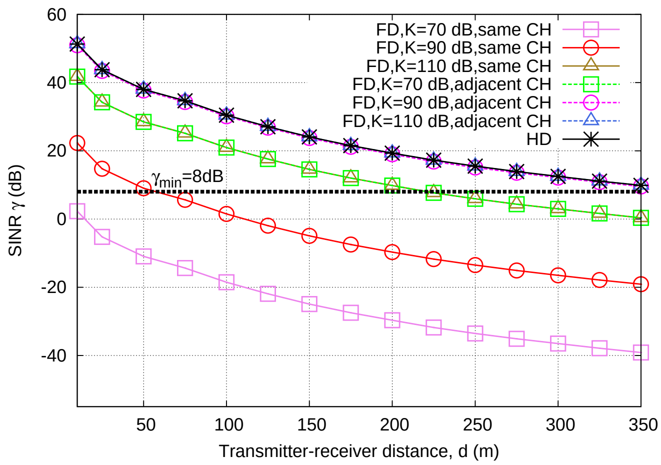


Fig. 2. Measured SINR values, averaged over 30 runs, when varying the transmitter-receiver distance, affecting the path-loss attenuation under $m = 3$ Nakagami fading, and transmission power ($P_i$=$P_j$) set to 20 dBm, $N_0$ =-99 dBm, in absence of interference ($P_k = 0$ [W], $k \neq \{i, j\}$).

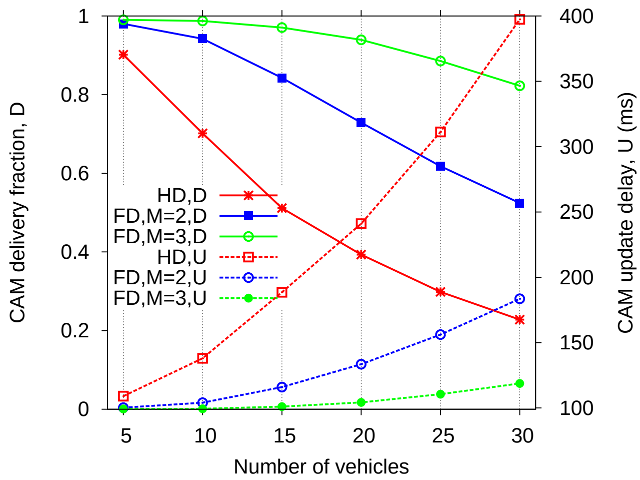


Fig. 3. Metrics vs. the number of vehicles for the two compared schemes (CW=15, slot time=13$\mu$s, SIFS=32$\mu$s, AIFSN=6, CAM frequency=10 Hz, CAM size=300 bytes, data rate=6 Mbps). Results are averaged over 30 runs.

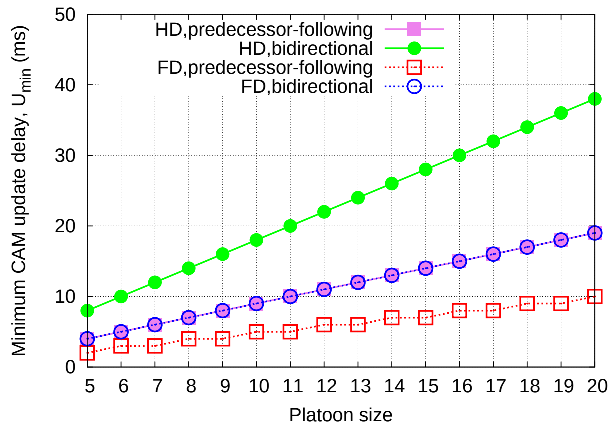


Fig. 4. Minimum CAM update delay for different platoon sizes (TDMA time slot length=1ms).

TABLE II

FD IN INVESTIGATED VANETS USE CASES

| **Use case** | **V2R communications** | **Cooperative driving** | **Semi-autonomous driving** |
|---|---|---|---|
| **Status quo** | Solutions improving channel access [9] and V2R coverage range [10] | Unacknowledged 802.11 broadcast with no packet recovery | TDMA-based solutions to disseminate messages feeding the platoon control algorithm [14] |
| **FD benefits** | Theoretically doubled capacity thanks to simultaneous transmission and reception resulting in higher throughput/larger scalability | Direct collision detection and prompt packet loss recovery for CAMs | Simultaneous transmission/reception among adjacent platoon vehicles |
| **Main findings** | Successful packet decoding over shorter ranges in presence of SI w.r.t. HD, unless to consider FD over adjacent channels | Improved CAM reliability and timeliness | Shorter latency for platoon control update saving resources and enabling high-density platooning with vehicles driving very close to each other |
| **Open issues** | 1) Design of effective SIC techniques with large values of $K$; 2) Identification of nodes to be engaged in symmetric/asymmetric communications | 1) Imperfect channel sensing and hidden terminals detection; 2) Coupling with existing congestion control techniques | 1) Imperfect channel sensing; 2) Design of scheduling schemes to effectively coordinate FD transmissions by platoon members |

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