22nd ITS World Congress, Bordeaux, France, 5–9 October 2015

Paper number ITS-1361

# Connected vehicles that use channel prediction will fully take advantage of 5G

**Dinh-Thuy Phan-Huy[1*], Tommy Svensson[2], Mikael Sternad[3], Wolfgang Zirwas[4], Bernadette Villeforceix[1], Fatima Karim[1], Berna Sayrac[1]**
1. Orange, France, 38 rue du Général Leclerc, 92794 Issy Les Moulineaux Cedex 9, France, +33 1 45 29 65 82, dinhthuy.phanhuy@orange.com
2. Chalmers University of Technology, Sweden
3. Uppsala University, Sweden
4. Nokia Networks, Germany

## Abstract

In the future, mobile networks will support masses of connected passengers. Successive generations of mobile networks have conveyed a rising traffic by increasingly exploiting the concept of channel state information at the transmitter. This information enables advanced signal processing techniques to lower the cost of a given data rate by orders of magnitude. Unfortunately, it is not robust to velocity. Beyond a limiting velocity, mobile networks fall back to less advanced techniques, with much higher costs. From a mobile network operator perspective, this cost gap is equivalent to a huge "wall of speed" to be climbed to connect the passengers. At high load, cost-effective connections may be prioritised. However, we believe that connected vehicles that are co-designed by vehicular and mobile networks manufacturers and use advanced features such as "channel prediction", will pass through the wall of speed and fully benefit from 5G.

**Keywords:** 5G, connected vehicles, channel prediction.

## I. Introduction

The 5th generation of mobile networks (5G) are currently at the research stage. We foresee that by the time these networks will be deployed (by the 2020's), masses of connected passengers will generate a huge demand for infotainment on-board. In this paper, we discuss whether the current research on 5G is taking the right direction to support these future masses of connected travellers and we issue a recommendation to vehicles manufacturers on their involvement on 5G design. This paper is organized as follows. Section II provides quantitative estimations of the upcoming data tsunami due to future masses of connected passengers. Then, section III analyzes how successive generations of mobile networks (2G, 3G, 4G and 5G) have managed (and will continue) to support the increase in wireless data traffic. Section IV shows that due to the way they are designed, mobile networks are much more cost efficient (in terms of energy and spectrum resource) when they serve a stationary or pedestrian user than when they serve a fast moving user. In this section, we also show how, from a mobile network operator perspective, this cost gap is equivalent to a huge “wall of speed” to be “climbed” for every connected passenger. Section V, presents an area of research in signal processing called “channel prediction”, which proposes solutions to reduce the cost gap. Finally, section VI concludes this paper with a recommendation to vehicle manufacturers on their involvement on 5G design.

## II. The upcoming masses of connected passengers

By 2020, mobile networks will have to face a data tsunami coming from a new kind of users: connected travelers. We expect infotainment on-board to be one of the main sources of this tsunami. Indeed, there is a daily period of time which still remains under-utilized today: the travel time. According to a worldwide study on urban mobility [1], the mean travel time to work is 30-40 minutes in urban areas and 64% of all travels made are within urban environments. According to [2], “video is the largest and fastest growing segment of mobile data traffic. It is expected to grow around 13 times by 2019, by which time it is forecasted to account for over 50 percent of all global mobile data traffic”. A lot of short videos (few minutes) are being watched. According to [3] 47% of mobile viewing time involves video content shorter than 30 minutes. In the future, we expect that masses of connected passengers will need a very high data rate connection during their travel time, partly because of these short videos.

Many different types of vehicles will transport connected passengers: connected cars, buses, trams or trains. However, we believe that the car industry is going to be a very active catalyst of the wireless data tsunami on-board. Indeed, in [4], it is assumed that in the future, every car will be connected to the outside world through a cellular network, thanks to a SIM card plus a communication system inside the car. The report [5] estimates a growth of the market for computers inside the car of around 8% annually (thanks to the lowering of the price of the connectivity) and an increase of the attach rates in the western world (due to infotainment) of about 20%. Many car manufacturers, for instance, are now including streaming music services as Spotify in their infotainment systems. Popular video streaming services, in particular Netflix, will soon be expected as service to be available on the move by consumers. We believe that a similar trend will be observed for the market of passengers of public transportation (trains, trams, buses). Finally, in the long term, connected trains and connected cars will be integrated together in an Intelligent Transport System (ITS), which requires a convergent technology. Cooperative awareness and other continuous ITS messaging (small messages with a high degree of repetition by a huge volume of vehicles) continuously disseminated in very dense vehicular networks, will be another source of exponential traffic load.

## III. Building high speed internet access for low mobility users

The wireless internet traffic has been constantly increasing over the last twenty years. Three successive generations of mobile networks have been introduced to keep up with the increasing demand: 2G in the nineties, 3G in the years two thousands and 4G today. At the time when these systems where being standardized, the traffic demand coming from stationary or pedestrian users was far more important than the one coming from drivers of vehicles or passengers on board of these vehicles. The recommendation issued by the International Telecommunications Union (the worldwide telecommunication regulation body) [6], more than ten years ago, in order to set common targets on 4G to the global research community, well illustrates this gap. This document requested ten times less data rate (in Mbits/s) for users moving at 250 km/h than for stationary or pedestrian users (moving at 3 km/h). Following this injunction, the research community gave birth to advanced radio techniques that considerably boost the speed of the internet access, but only when the user is stationary or pedestrian. In other words, although our mobile networks have mobility programmed in their DNA, they were born with an “Achilles heel”: a lack of robustness at high velocity.

During the last decades, advances in signal processing for wireless communications have increasingly exploited a very powerful concept: the use of “channel state information at the transmitter” (CSIT). This concept was introduced by Claude Shannon in [7] as follows: “In certain communication systems where information is to be transmitted from one point to another, additional side information is available at the transmitting point. This side information relates to the state of the transmission channel and can be used to aid in the coding and transmission of information.”

This principle is quite general. It has been applied to the particular case of mobile networks, considering base stations (i.e. the nodes of the cellular network) communicating with mobile devices (phones, smartphones, dongles etc…). Let us first consider one base station transmitting data to one mobile device. In this configuration, the base station is the “transmitter”, and the mobile device is the “receiver”. Before transmitting any data to the receiver, the transmitter acquires the “channel state information at the transmitter”. This simply means that the transmitter gets informed about the way radio waves currently propagate from the transmitter to the receiver. The current number of echoes (due to scattering or multiple reflections on obstacles), the level of attenuation and the delay of each echo are examples of parameters that characterize the “channel state”. The availability of such information at the transmitter has far-reaching consequences. Thanks to this CSIT, the transmitter can adapt its transmission to the current radio propagation condition and thereby increase its data rate by orders of magnitudes. Interestingly, the use of CSIT increases the overall performance within a constant budget (in terms of energy and/or spectrum). The transmission can be better controlled to cause less interference to other ongoing transmissions, and in that way improve the overall system capacity. CSIT can also help to robustify the transmissions with respect to propagation channel fading and interference. This reduces packet losses for real-time services, stalling of streaming services and lowers the delay of internet services. Conversely, the use of CSIT reduces the overall resource budget required to deliver a constant data rate. Thanks to this property, the use of CSIT has contributed to lowering the overall cost of a given rate (Mbit/s). Of course, the use of CSIT also applies to the reverse configuration, i.e. when the mobile device is transmitting data to the base station. The mobile device and the base station are the ‘transmitter’ and the ‘receiver’, respectively.

In practice, the acquisition of the CSIT by the transmitter is rather simple, when the base stations and the mobile devices transmit over the same carrier frequency, but successively in time (time division duplex mode). The same radio propagation is then experienced whether the base station is transmitting and the mobile device is receiving or vice-versa. Therefore, the receiver simply needs to send a known pilot signal which propagates to the transmitter, and the transmitter uses the received pilot signal to determine the CSIT. When the base stations and the devices use different frequency bands for transmission (frequency division duplex mode), achieving CSIT is more complex. During a first step, the transmitter sends pilots. The receiver then determines the CSIT and compresses this information and places it in a signaling message. During a second step, the receiver sends the compressed CSIT to the transmitter in the signaling message. An optimum level of compression achieves a trade-off between high speed of internet access and low signaling overhead.

Below is a non-exhaustive list of techniques that rely on the availability of the CSIT at the transmitter (listed by order of appearance in the history of cellular networks):

1. Fast link adaptation techniques. The transmitter adapts its transmission rate to the CSIT through the choice of modulation and coding schemes.
2. Fast channel-aware multi-user scheduling techniques. The base station preferably allocates radio resources to users in good radio propagation conditions.
3. Fast adaptive beamforming techniques. The transmitter generates a narrow beam by the use of several transmit antennas. The transmitter uses the CSIT to steer the beam towards a particular receiver. The transmitter can either save energy (the energy saving scales with the number of antennas) or improve its coverage.
4. Multiple input multiple output (MIMO) spatial multiplexing techniques [8]. Several antennas are utilized at both the transmitter and the receiver side. The transmitter uses the CSIT to generate multiple signals that will be non-interfering at the receiver. The data rate gain here scales with the number of antennas (the least of the numbers of antennas at the transmitter and the receiver side).
5. Coordinated multipoint (CoMP) techniques [9]: Several base stations use CSIT to transmit/receive in a coordinated manner, either to avoid interference to cell-edge users (and thereby increase their SINR) or to jointly/synchronously transmit/receive to/from cell edge users (and thus increase their throughputs).
6. Massive MIMO techniques [10]: The transmitter or the receiver is in this case equipped with hundreds of antennas. The performance (in terms of data rates and throughput) of the previously mentioned beamforming and MIMO spatial multiplexing techniques are then potentially multiplied by the large number of utilized antennas.

The literature is full of studies showing that these techniques improve the performance by orders of magnitude, especially in the case of 4G networks. Let us mention a few examples;

- Fast link adaptation multiplies the transmission rate by a factor of 4 when the CSIT indicates excellent radio conditions (thanks to the use of the 256 Quadrature Amplitude Modulation (QAM) instead of the Quadrature Phase Shift Keying (QPSK) modulation) [9].
- The throughput is improved by 17% to 38% and the coverage is improved by 30% to 86% thanks to fast channel-aware scheduling [11].
- The data rate of users at the ‘edge’ of the coverage is improved by 30% thanks to beamforming [12]. This improves the coverage.
- A link with MIMO spatial multiplexing, with 8 transmit and 8 receive antennas, can support up to 8 times more traffic than with a single antenna system [9].
- The data rates of users at the ‘cell edge’ can be improved by a factor of three by CoMP [13].

The exploitation of CSIT has been intensified and generalized when progressing from 3G to 4G towards 5G. Like fertilizers are used on plants to increase their growth, CSIT has been used to boost the performance of cellular networks in various ways. The gains foreseen due to the use of CSIT in 5G are even more spectacular than they are already in 4G. A base station could use 100 times less energy to cover the same area thanks to massive MIMO (assuming 100 antennas) [10]. A base station could serve a factor of 10 more users simultaneously and multiply its data rate by a factor of 10 thanks to massive MIMO [14]. Network densification is expected to help conveying 10 times more traffic [13]. Bandwidths on the order of 1 GHz (instead of 10-100 MHz in 4G [9]) are also expected to enable 10 times more traffic [15]. All the aforementioned techniques can and will be combined in future 5G system. Indeed, [13] shows that with an efficient combination of dense networks, CoMP and massive MIMO, 5G networks will deliver 1000 times more traffic than 4G networks do today, assuming that reliable CSIT can be made available.

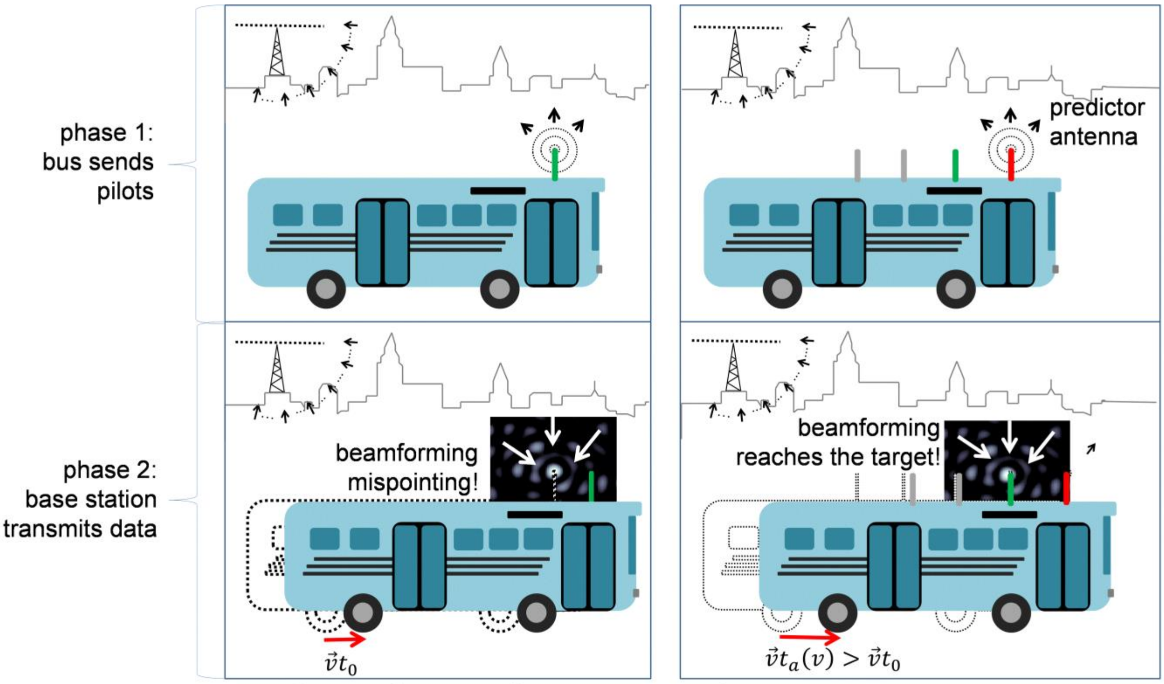
To conclude, CSIT is one of the pillars of current mobile networks and will continue to be an essential ingredient of 5G networks [16]. It improves the speed of the internet access by orders of magnitude, for a given spectral bandwidth and a given energy budget. This has a direct consequence on the cost of any service (voice, video, web browsing, chat etc…). Thanks to CSIT, a network can deliver a better service to a larger number of users, with the same amount of spectrum and energy.

Unfortunately, CSIT is only reliable for stationary or pedestrian users, as we will explain it further in the next section. In other words, the high speed and cost effective wireless internet access has been designed behind what we call in this paper a “wall of speed”. The next section will further elaborate on this “wall of speed”.

## IV. High speed wireless internet is more costly beyond the « wall of speed »

There is an effect that prevents any system to exploit the CSIT for fast moving users: “channel aging” [17]. The basic problem is that there is a delay between the time when the channel state is measured and the time when it is made available at the transmitter and used to adapt the transmission of data. During this delay, a fast mobile device moves by a fraction of a wavelength or even several wavelengths (depending on its velocity and the utilized radio frequency). As a consequence, when the data propagates from the transmitter to the receiver, it experiences a radio propagation (reflections, scattering, echoes, attenuations, delays, etc..) which can be radically different from the one that has been measured earlier. In other words, due to this delay, the CSIT related to a user moving with a high velocity is always outdated. For fast moving users, this “channel aging” effect renders the CSIT useless. Any attempt to adapt the transmission to the radio propagation would then fail.

Let us illustrate the “channel aging” effect with a very simple example represented in Figure 1-a). The impact of channel aging has been studied recently for some particular 5G techniques: massive MIMO beamforming [17-19] and CoMP [20]. In [18], passengers of a vehicle (a bus, a car or a train) get internet access through an access point located inside the vehicle. This access point is connected to the cellular network via an on-board communication router. The antenna of the router is placed on the external roof of the vehicle to get a better coverage. At the cellular network side, a base station equipped with a massive array of antennas is considered. The base station transmits data to the antenna upon the roof of the moving vehicle.



a) Reference System (RS). $t_0$ is the delay between phase 1 and 2. $\vec{v}$ is the bus velocity vector.

b) Separate Receive and Training Antenna system (SRTA). $t_a(v)$ is the delay between phase 1 and 2. $\vec{v}$ is the bus velocity vector, $v$ is the norm of $\vec{v}$.

**Figure 1- Massive MIMO beamforming with beam mispointing due to the vehicle motion**

The time division duplex mode, with two phases of transmission, is considered. During the first phase, the antenna on the bus sends pilots and the base station uses the received pilots to determine the current CSIT. During the second phase, the base station uses the CSIT to steer a beam into the direction of the vehicle. An urban environment with multi-path propagation is considered. In such environment, strong and fast variations of the propagation channel, every 7.5 cm on average (for a carrier frequency of 2GHz) render the beam extremely narrow (as illustrated by Figure 1-a). Due to the delay $t_0$ between the first phase and the second phase, and due to the velocity $v$ of the vehicle, beam mispointing occurs. The signal is received with such a bad quality that the target rate and quality of service is not met (the video would be frozen or the web browsing is not working).

The illustrated lack of robustness of MIMO and beamforming transmission at high velocities happens already in 4G where fewer antennas are used. The study in [18] simply shows that this problem persists and grows for 5G (with massive arrays). In other words, at high velocity, it becomes worse to try to use CSIT than not to use it.

In practice, when the velocity is high, i.e. for speeds beyond a limiting velocity $v_{limit}$, 3G and 4G networks today fall back on techniques that do not exploit the CSIT at the transmitter side [9]. This ensures that the service being used by the user (whether it is video, web browsing or another service), is provided with the target quality (i.e. the target delay and throughput) instead of being interrupted. Techniques without CSIT are more robust to high velocity. However, they consume more spectrum and/or energy to deliver the same service (in terms of bits/s) than CSIT-aided techniques do. In other words, a given service (in terms of bits/s) costs more spectrum and/or energy to a mobile operator when it is provided to a connected passenger than when it is delivered to a stationary user. Depending on the business scenario, this cost gap (for a fixed data rate) can be transformed into a data rate gap (for a fixed cost).

One can estimate roughly the cost gap due to the “non-usage” of a CSIT based technique, as follows. Let us consider a CSIT based technique bringing a gain of a factor of X in data rate, for a given spectrum and energy budget. Without CSIT, the same system needs X times more spectrum to deliver the same service. Therefore the following simple rule of thumb can be used: any CSIT technique that improves the data rate by a factor of X (for a given spectrum and energy budget), implies a cost gap in terms of spectrum (for a fixed data rate) of X. Here are two examples of cost gap computation associated to two techniques presented in section III:

- The energy saving at the base station obtained thanks to massive MIMO beamforming with N antennas, scales with N and is only achievable for a stationary user. Therefore, a connected passenger costs N times more radio frequency (RF) transmit energy (in linear scale, i.e. in Joules) than a stationary user; the cost gap X in terms of RF energy is equal to N, and for 5G, N is typically expected to be on the order of 100; this is equivalent to having a radiated power saving (in logarithmic scale) of 3dB for each doubling of the number of antennas;
- The data rate obtained thanks to MIMO spatial multiplexing with M streams is improved by a factor of up to M. Therefore, a connected traveller, who cannot be served by spatial multiplexing, costs up to M times more spectrum than a stationary user. The cost gap X in terms of spectrum is here equal to up to M, and for 5G, M is typically in the order of 10.

One can also roughly estimate the aforementioned speed limit $v_{limit}$ above which the system should fall back to a non CSIT based technique. Based on the results from [18], one can deduce that $v_{limit}$ is equal to 5 km/h (this corresponds to a walking person) for the massive MIMO beamforming technique considered in [18], assuming a delay $t_0$ of 2 milliseconds and a carrier frequency of 2 GHz. Other values of $v_{limit}$, can be derived for other values of the carrier frequency and the delay from the above result using the relationship: $t_0$ x (carrier frequency $f$) x $v_{limit}$ =2 milliseconds x 2 GHz x 5 km/h:

- $v_{limit}$ = 6.7 km/h for $t_0$ =1.0 ms and $f$ = 3.0 GHz;
- $v_{limit}$ = 6.7 km/h for $t_0$ =0.10 ms and $f$ = 30 GHz;
- $v_{limit}$ = 3.3 km/h for $t_0$ =0.10 ms and $f$ = 60 GHz.

Instead of supporting the burden of a cost gap to deliver a fixed data rate, an operator can decide to keep the cost fixed and accept a resulting data rate gap. A mobile operator spending the same spectrum and energy budget, whatever the kind of users it may serve, cannot deliver the same data rates when all users in the cell are vehicular instead of pedestrian. For instance, the first release of 4G can delivers 17 Mbits/s per cell in average, when the cell is loaded with pedestrian users moving at 3 km/h [21][11]. When the same users move at 120km/h instead of 3km/h, the throughput goes down to 12 Mbits/s per cell on average. Hence, the average data rate drops by 30%. This performance gap might seem rather low, however it is evaluated for an early version of 4G, where CSIT use is not as intense as for the last versions of 4G.

Based on these observations on the “channel aging” effect, we can conclude that for speeds beyond $v_{limit}$, the operator must spend X times more resources in energy and/or spectrum to provide the same service (depending on the CSIT based technique that is considered). From a mobile network operator perspective, this is equivalent to a “wall of speed” (or a barrier, or a hurdle) to be “climbed” each time a passenger must be connected with high speed internet access. This wall is positioned at the speed $v_{limit}$ and has a height of X which is greater for 5G CSIT-based techniques than it is for 4G. Figure 2 illustrates this “wall of speed”.

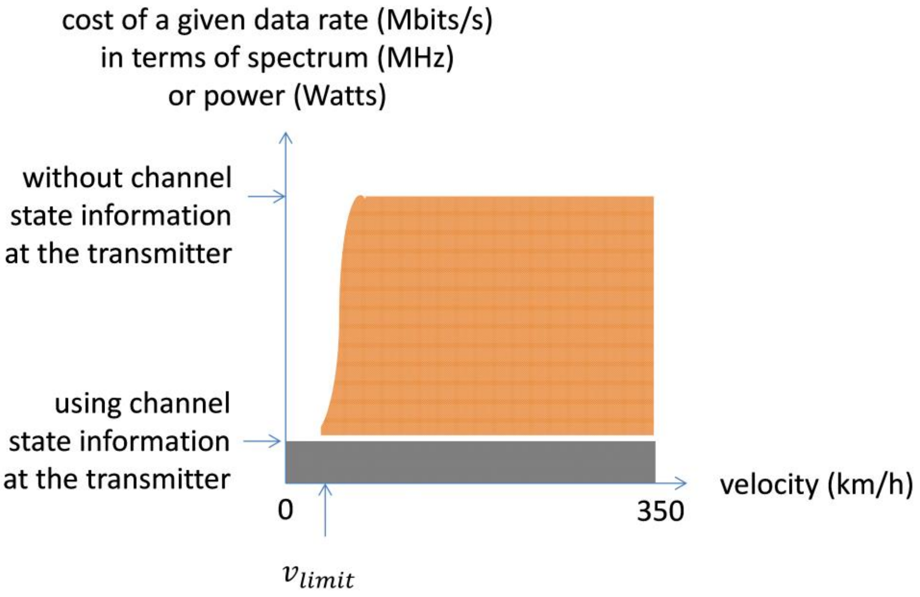


**Figure 2: the wall of speed raises the cost of high speed internet on-board**

This “wall of speed” is getting higher with each generation of mobile networks. It is acceptable until now, as a very small part of the traffic is due to connected passengers and as its height is reasonable. However, with the future masses of connected passengers and the future improvements in 5G, will this still be reasonable in ten years from now?

## V. The use of channel prediction makes transmission to vehicles pass through the “wall of speed”

Channel prediction techniques have been proposed and experimentally investigated to counteract the “channel aging” effect. These techniques aim at providing up-to-date CSIT at the transmitter side. They therefore extend the benefits of 5G techniques designed for stationary users to connected passengers.

A first example of channel prediction technique exploits the fact that the channel is in fact more predictable when one considers a vehicle. Indeed a vehicle is moving along (locally) linear trajectories. In a first approximation, one can consider that the electromagnetic field forms a standing wave pattern and that the vehicle moves through this fixed pattern. Therefore, if one places a receive antenna on the roof of the vehicle and another antenna (called the ‘predictor antenna’ [22]) in front of the receive antenna, the receive antenna experiences exactly the same channel state as the predictor antenna, but simply a little bit later. The channel state determined by the predictor antenna can be used as a prediction for the channel state to be experienced by the receive antenna when the receive antenna reaches this position. In preliminary measurements, the use of predictor antennas have provided at least an order-of-magnitude increase in the attainable channel prediction horizon in time, as compared to using statistical signal processing based on previous channel samples [22]. One can illustrate the use of predictor antennas with the same very simple example as for section III. We consider again the example of a base station using a CSIT based MIMO beamforming in TDD mode, as illustrated by Figure 1-b). In [18], the predictor antenna sends pilots whereas the data is demodulated by the receive antenna behind the predictor antenna. The beamforming mispointing is reduced or completely canceled (as illustrated by Figure 1-b, where $t_a(v)$ is the delay between channel estimation and beamforming). In [19], thanks to further improvements, beamforming mispointing is perfectly cancelled. This enables the network keep on saving energy (thanks to massive MIMO beamforming) even at high velocity.

Another example of channel prediction scheme has been proposed in [23]. Luckily expected features for future 5G radio systems provide options to improve the prediction performance. For example, massive MIMO allows for very narrow beamforming, thereby simplifying the channel state information (reducing the number of perceived echoes). This simplifies the prediction implementation and also improves its performance. Also, for vehicles that traverse repetitive routes regularly, maps of the radio propagation patterns can be built up gradually by collecting measurements from a large number of vehicles.

One can notice that these channel prediction techniques require a special design of the connected vehicle. This impacts either the hardware (“predictor antenna”) or the software. In any case, only connected vehicles with the right features and channel prediction will pass through “the wall of speed”. Such features have been studied within the EU FP7 project METIS and will be studied during the 5G Public Private Partnership (5GPPP) project FANTASTIC 5G [24].

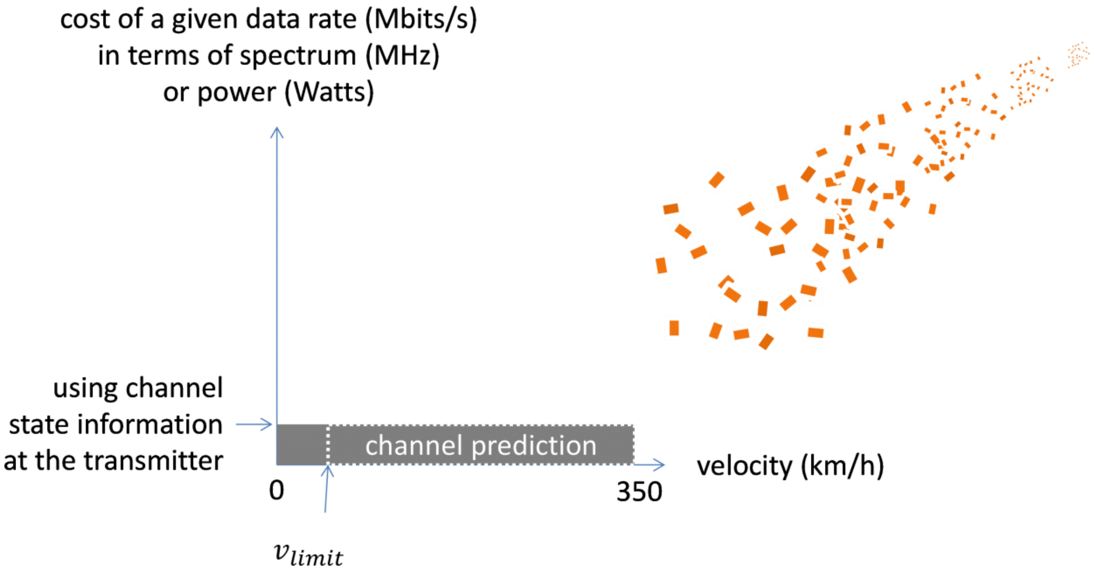


**Figure 3: channel prediction breaks the wall of speed**

## VI. Conclusions and recommendations

“Channel state information at the transmitter” contributes to lowering the cost (in terms of energy and spectrum) of high speed wireless internet access. By being informed of the current state of the radio propagation channel, a transmitter can adapt its transmission and improve its performance by orders of magnitude. However, this approach is not robust to high velocities. In practice, beyond a certain speed limit, the network falls back to less advanced techniques. This causes an increase in the cost (in terms of spectrum and energy) of the high speed internet access. In high load situation, cost-effective connections may therefore be prioritized and vehicular users down-prioritized. Nevertheless, channel prediction potentially provides reliable channel state information at the transmitter even at high mobility. This approach may impact the design of connected vehicles. We therefore believe that connected vehicles (cars, buses, trams, trains or even planes, ships and drones) co-designed by vehicular and mobile networks manufacturers to support channel prediction will fully benefit from the best of 5G.

## Acknowledgements

Most part of this work has been performed in the framework of the FP7 project ICT-317669 METIS, which is partly funded by the EU. This paper has also been partially performed in the framework of the H2020-ICT-2014-2 project FANTASTIC-5G (grant 671660).

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