

5G on Board: How Many Antennas Do We Need on Connected Cars?

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Abstract— Mobile networks will support increasing numbers of connected vehicles. Successive generations of mobile networks have reduced the cost of data rate, in terms of spectrum usage and power consumption at the base station, by increasingly exploiting the concept of channel state information at the transmitter. Unfortunately, beyond a limiting velocity (which depends on the carrier frequency), networks are no longer cost efficient, since such information is not usable. Recently, channel prediction techniques requiring several antennas on the car roof have been introduced to solve this problem. In this paper, for the first time, we determine the most cost efficient configurations, in terms of numbers of antennas on the car roof and carrier frequency, in various scenarios (highway and dense urban). Our studies show that with a simple prediction technique based on predictor antennas, the network can use twice less spectrum and around 20 dB less power, for cars with 3 antennas on their tops than for cars with the same number of antennas and not using prediction.

Keywords—5G; connected cars; predictor antenna; MIMO

I. INTRODUCTION

Future mobile networks will need to support a very large number of connected vehicles. Connected cars represent both a large opportunity and a challenge for future 5G network operators. The challenge arises from extra costs, that are related to the mobility in two ways. First, ubiquitous mobile use is challenging due to distance propagation and shadowing. This problem is present in all mobile systems but it becomes increasingly difficult at higher frequencies. Therefore, we believe that mobile users should be served primarily by systems working below 6 GHz. An interesting option here is to use a local network inside the vehicle and a wireless backhaul link below 6 GHz between the vehicle and the 5G network [1].

Second, the short-term fading will cause rapid time-variations of the propagation channel. We are forced to spend additional power and spectral resources for the transmission to a vehicular user, as compared to a stationary user with the same data rate and quality-of-service (QoS) requirements. These resources are used for coding, diversity transmission and power margins, which together assure that the QoS target is met. The extra cost in terms of transmission resources of serving connected cars represents a huge “cost of speed” from a mobile network operator perspective. This cost disadvantage is increasing in relative terms since successive generations of mobile networks have conveyed an increasing traffic partly by exploiting the concept of channel state information at the transmitter (CSIT), and techniques proposed for 5G strengthen this trend [2],[3]. With multi-antenna techniques, CSIT enables us to lower the cost, in terms of spectrum and power spent by

the network per transmitted bit, by orders of magnitude. However, these methods are degraded by the use of outdated channel estimates [4],[5]. Short-term fading cannot be predicted more than 0.3 wavelengths ahead in space by conventional means [6],[7] and is unpredictable at vehicular velocities in current systems. Beyond a limiting velocity (depending on the carrier frequency), mobile networks must therefore fall back to less advanced techniques, with much higher costs.

This paper analyzes a re-design at the connected car that has the potential to essentially eliminate the cost of speed: the introduction of multiple antennas placed on the vehicle roof for the wireless backhaul link, and a special way of using them. Already one single antenna on the vehicle roof will improve the signal-to-noise ratio (SNR), as compared to an antenna inside the vehicle. The use of multiple antennas on the roof can provide additional benefits in several ways. One possibility, which will be used as our reference case, is diversity reception (Rx Div) by maximum ratio combining [8]. It is robust, improves the average SNR and also reduces the variability of the received power. It reduces the cost of speed, but does not eliminate it. A novel powerful way to use multiple antennas on vehicles is to place them along the direction of travel, and let the first one act as “predictor antenna”: Pilot-based estimates of its channel can then be used to predict the fading radio channels that will be encountered later by other antennas, when they reach that position. This concept was proposed in [9] and has recently been verified on a large set of measurements in an urban environment to provide an order-of-magnitude increase in the useful prediction horizons [10]. It therefore enables the use of accurate CSIT at high vehicular velocities. As will be seen below, it could result in a large reduction of the cost of speed for connected vehicles.

For the first time, in this paper, we determine the most cost efficient configurations, in terms of numbers of antennas on the car top and carrier frequency, for various scenarios (highway and dense urban). To quantify the costs (in spectrum and power) of connected vehicles for future 5G network operators, we will here consider a wireless backhaul downlink between a base station (BS) and a moving connected car. The system is aiming at delivering a target data rate, with a given Modulation and Coding Scheme (MCS) with a target QoS. We compare a reference case with single antenna transmitter and Rx Div to two examples of 5G adaptive antennas techniques, that both would use massive antenna arrays at the BS side (up to 256 antenna elements) [3]:

- Maximum ratio transmission Multiple Input Single Output (MRT-MISO) beamforming, that has the advantage to save energy at the network side [3];
- Zero forcing Multiple Input Multiple Output (ZF-MIMO) beamforming, that has the advantage to save spectrum at the network side [3],[8].

We also discuss the size of the antenna array at the vehicle in the different considered scenarios, as this parameter affects the ease of integration on vehicles. The Tx-Div reference design could be improved by using space-frequency coding [11], and we discuss the gain that would thereby be attainable¹.

Section II presents our common system model. Section III details the studied schemes and Section IV our evaluation methodology. Section V presents a first study evaluating the cost of a connected car for speeds up to 150 km/h while Section VI considers “low speed cars” in a dense urban area. For both scenarios, the most cost efficient configuration in terms of carrier frequency and number of antennas on the car top is determined.

The following notations are used throughout the paper. If $h \in \mathbb{C}$, then $|h|$ is the module of h . If $L, K \in \mathbb{N}$ and $\mathbf{H} \in \mathbb{C}^{L \times K}$, then, \mathbf{H}_{lk} is the element lk , \mathbf{H}^\dagger is the conjugate-transpose of \mathbf{H} , and $\|\mathbf{H}\| = (\sum_{l=1}^L \sum_{k=1}^K |\mathbf{H}_{lk}|^2)^{1/2}$. If $x \in \mathbb{R}$, then $\lceil x \rceil \in \mathbb{N}$ is the nearest integer value of x .

II. COMMON SYSTEM MODEL

We consider a downlink (DL) of a wireless backhaul link between a BS and a moving connected car with a velocity vector \vec{v} and speed $v = \|\vec{v}\|$. The BS is equipped with K transmit antenna(s), each indexed by k , with $1 \leq k \leq K$. The connected car is equipped with L antenna(s), indexed by l , with $1 \leq l \leq L$. The antennas of the car are placed upon the roof aligned along the car direction with the front antenna numbered $l = 1$. These antennas are assumed separated by 0.5λ , where $\lambda = c/f_0$, is the wavelength, $c = 3 \times 10^8$ m/s is the speed of light and f_0 is the carrier frequency. The array is therefore distributed over the following length on the car roof:

$$\Delta = \frac{(L-1)c}{2f_0}. \quad (1)$$

We assume that an Orthogonal Frequency Division Multiplex (OFDM) waveform is used. The system can thus be mathematically described on a sub-carrier basis, using a matrix $\mathbf{H} \in \mathbb{C}^{L \times K}$ to model the MIMO propagation channel between the transmitter and the receiver.

The vehicle is assumed to be moving in a time-invariant and spatially correlated fading propagation channel. This means that \mathbf{H} depends only on the positions in space of the antennas. This assumption is not exactly valid, but it has been verified in [10] and [15] to be a very good approximation. The vehicle is also assumed to be moving forward with approximately constant velocity along a linear trajectory during

¹ As a simplification, we do not consider the use of space-time coding [12], since this either assumes time-invariant channels within code blocks [13] or would incur very large delays by interleaving over time. We also do not consider slow outer-loop block error rate control [14], which works on the time-scale of the shadow fading.

the required prediction horizon (which would be true in most real scenarios). With these assumptions, the trajectory of any antenna of the vehicle is aligned with the trajectory of the front antenna. We denote the position of the front antenna ($l = 1$) at the time t by a vector $\vec{\xi}(t) \in \mathbb{R}^{3 \times 1}$ in Cartesian coordinates. The position of any antenna $l \geq 1$ is then $\vec{\xi}(t) - l\vec{v}/v$. For a given velocity \vec{v} , the downlink MIMO channel at time t can then be regarded as a function of $\vec{\xi}(t)$. We denote the downlink MIMO channel matrix at time t by $\mathbf{H}(\vec{\xi}(t)) \in \mathbb{C}^{L \times K}$.

A Time Division Duplex (TDD) frame, with uplink and downlink periods $[-\tau^{UL}, 0]$ and $[0, \tau^{DL}]$, respectively, is considered. The channel reciprocity in TDD mode is exploited. Non-reciprocities of the uplink (UL) and DL RF chains are assumed to be ideally mitigated by calibration [3]. We will assume that the DL channel can be perfectly estimated based on UL pilots, without errors, when the vehicle is non-moving.

The system aims at delivering a desired data rate, using a given MCS at a target QoS. The target QoS corresponds to a target Signal to Noise Ratio (SNR) x_T and a corresponding target Block Error Rate (BLER). For this purpose, the transmission power $P_u(t)$ of a downlink OFDM symbol at time $t \in [0, \tau^{DL}]$ is adapted based on the measurement of $\mathbf{H}(\vec{\xi}(t'))$ performed at a previous OFDM symbol at time $t' \in [-\tau^{UL}, 0]$. For all studied schemes, the time lag $t - t' \geq t_0$, where t_0 is the value for the reference scheme (Rx Div). More precisely, the BS uses a prediction $\hat{x}(t)$ of the SNR as a function of three parameters: $P_u(t)$, $\mathbf{H}(\vec{\xi}(t'))$ and P_n , which is the receiver additive white Gaussian noise (AWGN) power. The transmit power $P_u(t)$ is then determined by the BS so that:

$$\hat{x}(t) = x_T. \quad (2)$$

When the vehicle moves (i.e. when $v > 0$), $\vec{\xi}(t) \neq \vec{\xi}(t')$, it is likely that $\mathbf{H}(\vec{\xi}(t)) \neq \mathbf{H}(\vec{\xi}(t'))$ so the actual SNR attained by the receiver, which we denote $x(t)$, differs from x_T :

$$x(t) \neq x_T \text{ for } v > 0. \quad (3)$$

III. STUDIED SCHEMES

We study the following types of schemes: Rx Div with 3 branches (1×3 Rx Div); two adaptive antenna techniques (MRT-MISO and ZF-MIMO), with and without prediction; and the same adaptive antenna techniques with fallback to 1×3 Rx Div to guarantee a BLER bounded by 10%.

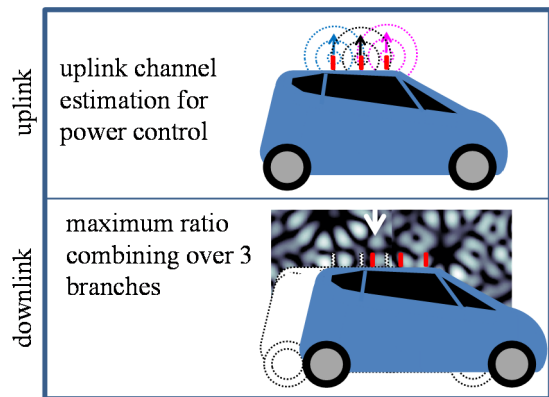


Fig. 1. Downlink 1 × 3 Rx Div.

A. 1×3 Rx Div

In this case, as illustrated by Fig. 1, a 1×3 Rx Div communication system is considered: We use only $K = 1$ antenna at the BS and $L = 3$ antennas on the roof of the car.

The duration of the TDD frame is here assumed fixed: $\tau^{UL} = \tau^{DL} = t_0 = 1\text{ms}$. At time $t' \in [-\tau^{UL}, 0[$, the antennas of the car send UL pilots to the BS. The BS estimates the MISO channel: $\mathbf{H}(\tilde{\mathbf{e}}(t')) \in \mathbb{C}^{3 \times 1}$. The channel is assumed to be perfectly known at the receiver. No prediction is used here: The SNR $\hat{x}(t)$ that the car will experience at time $t = t' + t_0$ is estimated as if the channel would be unchanged from t' and a receiver beamforming vector \mathbf{H}^\dagger (maximum ratio combining), is used, based on the measured channel at t' :

$$\hat{x}(t) = \frac{P_u(t)}{P_n} \mathbf{H}^\dagger(\tilde{\mathbf{e}}(t')) \mathbf{H}(\tilde{\mathbf{e}}(t)).$$

The BS could then ensure the condition (2), by setting:

$$P_u(t) = x_T P_n \left(\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t)) \mathbf{H}(\tilde{\mathbf{e}}(t)) \right)^{-1},$$

but this setting of $P_u(t)$ would result in an obtained SNR:

$$x(t) = x_T \frac{\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t)) \mathbf{H}(\tilde{\mathbf{e}}(t))}{\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t')) \mathbf{H}(\tilde{\mathbf{e}}(t'))} \neq x_T.$$

$$\Rightarrow x(t) \neq x_T.$$

To make sure that the attained BLER is upper bounded by 10%, we introduce a power boost factor $a_{boost} > 1$, and instead use the transmit power

$$P_u(t) = a_{boost} x_T P_n \left(\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t')) \mathbf{H}(\tilde{\mathbf{e}}(t')) \right)^{-1}.$$

The attained SNR then becomes:

$$x(t) = a_{boost} x_T \frac{\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t)) \mathbf{H}(\tilde{\mathbf{e}}(t))}{\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t')) \mathbf{H}(\tilde{\mathbf{e}}(t'))}. \quad (4)$$

The parameter a_{boost} is determined empirically, for different sets of transmission parameters. If we would also utilize space-frequency coding over K transmit antennas, such as the one proposed in [11], the power boost could be reduced to a factor a_{boost}^{opt} , with a resulting SNR:

$$x^{opt}(t) = a_{boost}^{opt} x_T \frac{\sum_{l=1}^L \sum_{k=1}^K |\mathbf{H}_{l,k}(\tilde{\mathbf{e}}(t))|^2 / K}{\sum_{l=1}^L \sum_{k=1}^K |\mathbf{H}_{l,k}(\tilde{\mathbf{e}}(t'))|^2 / K}, \quad (5)$$

where $a_{boost}^{opt} < a_{boost}$ is determined empirically.

B. MRT-MISO

1) Without prediction

In this case, as illustrated by Fig. 2, we consider a car with a single ($L = 1$) antenna. At the BS side, $K > 1$ antennas are used. The duration of the TDD frame is fixed: $\tau^{UL} = \tau^{DL} = t_0$. We consider a $K \times 1$ MRT-MISO beamforming system. At time $t' \in [-\tau^{UL}, 0[$, the car's antenna sends UL pilots to the BS. The BS then estimates the MISO channel: $\mathbf{H}(\tilde{\mathbf{e}}(t')) \in \mathbb{C}^{1 \times K}$ and uses it to build the MRT beamformer $\mathbf{P}(t)$:

$$\mathbf{P}(t) = \frac{\mathbf{H}^\dagger(\tilde{\mathbf{e}}(t))}{\|\mathbf{H}(\tilde{\mathbf{e}}(t))\|}$$

The normalization of the beamformer gives total transmit power $\|\mathbf{P}(t)\|^2 = 1$. The BS estimates the receiver SNR $\hat{x}(t)$ without prediction:

$$\hat{x}(t) = \frac{P_u(t)}{P_n} \|\mathbf{H}(\tilde{\mathbf{e}}(t)) \mathbf{P}(t)\|^2,$$

and ensures the condition (2), by setting:

$$P_u(t) = x_T P_n \frac{\|\mathbf{H}(\tilde{\mathbf{e}}(t'))\|^2}{\|\mathbf{H}(\tilde{\mathbf{e}}(t')) \mathbf{H}^\dagger(\tilde{\mathbf{e}}(t'))\|^2}. \quad (6)$$

With this transmit power, the SNR $x(t)$ attained at t will be:

$$x(t) = \frac{P_u(t)}{P_n} \|\mathbf{H}(\tilde{\mathbf{e}}(t)) \mathbf{P}(t)\|^2,$$

$$\Rightarrow x(t) = x_T \frac{\|\mathbf{H}(\tilde{\mathbf{e}}(t)) \mathbf{H}^\dagger(\tilde{\mathbf{e}}(t'))\|^2}{\|\mathbf{H}(\tilde{\mathbf{e}}(t')) \mathbf{H}^\dagger(\tilde{\mathbf{e}}(t'))\|^2}. \quad (7)$$

When the car is moving, $\tilde{\mathbf{e}}(t) \neq \tilde{\mathbf{e}}(t')$ and $x(t) \neq x_T$, this is the beamforming mis-pointing effect illustrated by Fig. 2.

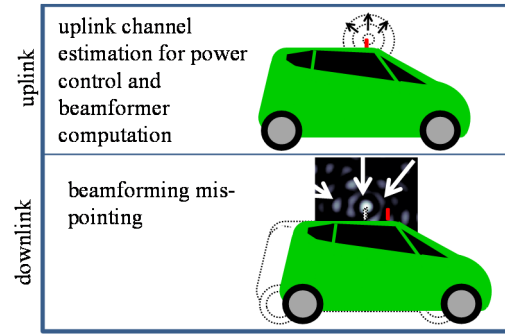


Fig. 2. DL MRT-MISO without channel prediction.

2) With Separate Receive and Training Antenna (SRTA) prediction, using the predictor antenna

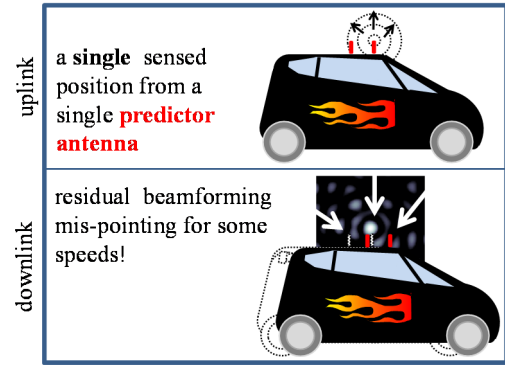


Fig. 3. MRT-MISO, with SRTA channel prediction.

This scheme has been fully described in [16]. We here consider a car with $L = 2$ antennas, as illustrated by Fig. 3. The front antenna is the “predictor antenna” [9]. At the BS side, $K > 1$ antennas are used. We still consider a $K \times 1$ MRT-MISO beamforming system, but in this case, the front antenna sends UL pilots whereas the back antenna receives DL data.

The duration of the TDD frame is here assumed to be elastic and lower-bounded by t_0 : $\tau^{UL} = \tau^{DL} \geq t_0$. The frame duration is adapted to the vehicle velocity, here quantized in steps of t_0 . The velocity is assumed to be measured by the

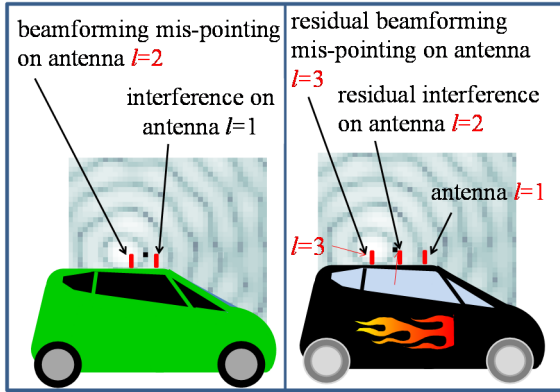
vehicle (using e.g. Global Positioning System or correlation of the antenna signals) and is reported to the BS. The frame duration τ^{UL} is then chosen equal to the time (quantized in steps of length t_0) necessary for the back antenna to replace (at best) the position of the front antenna:

$$\tau^{UL} = t_0 \left\lfloor \frac{\lambda}{2vt_0} \right\rfloor. \quad (8)$$

(When this expression equals 0, then τ^{UL} is set to the default value t_0 .) The SNR is then estimated at the base station based on the predicted channel for the second antenna.

C. ZF-MIMO

1) Without prediction



a) Without channel prediction
b) With SRTA prediction: antenna 1 is predicting for antenna 2, and antenna 2 is predicting for antenna 3

Fig. 4. ZF-MIMO (2 data streams), the signal intended to the back antenna is represented, it has a null (black spot) intended to the front antenna.

In this case, as illustrated by Fig. 4-a), we consider a car with $L = 2$ antennas. At the BS side, $K > 1$ antennas are used. A $K \times 2$ ZF-MIMO beamforming system is considered, with 2 data streams being multiplexed in the spatial domain. The duration of the TDD frame is here fixed: $\tau^{UL} = \tau^{DL} = t_0$. At time $t' \in [-\tau^{UL}, 0]$, the car's antennas send UL pilots to the BS. The BS then estimates the DL MIMO channel: $\mathbf{H}(\vec{\xi}(t')) \in \mathbb{C}^{2 \times K}$. Assuming the channel to be invertible, the BS uses this estimate to build the ZF beamformer $\mathbf{P}(t)$:

$$\mathbf{P}(t) = \frac{\mathbf{H}^\dagger(\vec{\xi}(t))(\mathbf{H}(\vec{\xi}(t))\mathbf{H}^\dagger(\vec{\xi}(t)))^{-1}}{\|\mathbf{H}^\dagger(\vec{\xi}(t))(\mathbf{H}(\vec{\xi}(t))\mathbf{H}^\dagger(\vec{\xi}(t)))^{-1}\|}.$$

Note that the introduction of the precoder leaves the sum of transmit powers of the BS unchanged as $\|\mathbf{P}(t)\|^2 = 1$. Each data stream is allocated the same transmit power $P_u(t)$. The BS estimate $\hat{x}^{(l)}(t)$ of the signal to noise and interference ratio (SINR) of the antenna l at time t is

$$\hat{x}^{(l)}(t) = \frac{\|\hat{\mathbf{G}}_{l,l}(t)\|^2}{\|\hat{\mathbf{G}}_{l,m \neq l}(t)\|^2 + P_n},$$

where $\hat{\mathbf{G}}(t)$ is the channel gain matrix estimated by the BS as:

$$\hat{\mathbf{G}}(t) = \mathbf{H}(\vec{\xi}(t'))\mathbf{P}(t)\sqrt{P_u(t)}.$$

$$\Rightarrow \hat{\mathbf{G}}(t) = \frac{\sqrt{P_u(t)}}{\|\mathbf{H}^\dagger(\vec{\xi}(t'))(\mathbf{H}(\vec{\xi}(t'))\mathbf{H}^\dagger(\vec{\xi}(t')))^{-1}\|} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

The BS then sets $P_u(t)$ so that $\hat{x}^{(l=1)}(t) = \hat{x}^{(l=2)}(t) = x_T$:

$$P_u(t) = x_T P_n \left\| \mathbf{H}^\dagger(\vec{\xi}(t'))(\mathbf{H}(\vec{\xi}(t'))\mathbf{H}^\dagger(\vec{\xi}(t')))^{-1} \right\|^2. \quad (9)$$

We denote by $\mathbf{G}(t)$ the actual attained channel matrix:

$$\mathbf{G}(t) = \mathbf{H}(\vec{\xi}(t))\mathbf{P}(t)\sqrt{P_u(t)}.$$

$$\Rightarrow \mathbf{G}(t) = x_T P_n \mathbf{H}(\vec{\xi}(t))\mathbf{H}^\dagger(\vec{\xi}(t')) \left(\mathbf{H}(\vec{\xi}(t'))\mathbf{H}^\dagger(\vec{\xi}(t')) \right)^{-1}.$$

The actual SINR $x^{(l)}(t)$ attained at time t by antenna l is then

$$x^{(l)}(t) = \frac{\|\mathbf{G}_{l,l}(t)\|^2}{\|\mathbf{G}_{l,m \neq l}(t)\|^2 + P_n}. \quad (10)$$

When the car is moving, $\vec{\xi}(t) \neq \vec{\xi}(t')$, $\mathbf{G}_{l,l}(t) \neq x_T P_n$ and $\mathbf{G}_{l,m \neq l}(t) \neq 0$. As illustrated by Fig. 4, the data stream number l , (intended to the antenna number l) will then be mispointed and is interfering with the antenna $m \neq l$, and vice and versa.

2) With SRTA prediction

In this case, as illustrated by Fig. 4-b), we consider a car with $L = 3$ antennas. At the BS side, $K > 1$ antennas are used. A $K \times 2$ ZF-MIMO beamforming system is still considered, with two streams being multiplexed in the spatial domain. However, this time, the antennas number 1 and 2 are sending UL pilots, whereas the antennas number 2 and 3 are receiving the data. The same elastic frame as for the MRT-MISO system with SRTA prediction is used. The same expressions of the SINR as for the ZF-MIMO without prediction are valid. They will take different values, due to the different value of the frame duration.

D. Adaptive antenna techniques with fall back to 1×3 Rx Div to bound BLER by 10%

In these cases, we consider a vehicle with $L = 3$ antennas. At the BS side, $K > 1$ antennas are used. Either MRT-MISO or ZF-MIMO is used (with or without prediction), as described in previous sub-sections. When the attained BLER exceeds a threshold of 10%, the system falls back to 1×3 Rx Div.

IV. EVALUATION METHODOLOGY

A. Simulation methodology

We set $t_0 = 1$ ms. This corresponds to the shortest value standardized for 4G networks today [17]. Values of the carrier frequency f_0 below 6 GHz, envisioned for 5G future networks, are tested. The corresponding antenna array occupancy on the roof of the car is computed using (1) and plotted in Fig. 5. We consider an MCS using 64QAM with a coding rate of $\frac{3}{4}$. x_T is chosen equal to 15.5 dB, which corresponds to a BLER value of around 0.01, see Table I.

TABLE I. BLER FOR 64 QAM, TURBO CODE $\frac{3}{4}$, WITH BLOCK OF 6000 BITS

SNR	14.5	15.0	15.5	15.7	16.0
BLER	1.0	0.8205	0.0125	0.0028	0.000001

For each simulation run, the channel matrices $\mathbf{H}(\vec{\xi}(t'))$ and $\mathbf{H}(\vec{\xi}(t))$ are generated using a random spatially correlated

Rayleigh fading channel model. 20 rays with random angles of departure and arrival are used to model multiple scattering. The following variables are calculated and stored for each run: the transmit power, the attained SNR or SINR, and the utilized spectrum. The expressions for $P_u(t)$, $P_u^{(l)}$, $x(t)$ and $x^{(l)}(t)$ given in Section III are used at this stage. For the considered run, the attained BLER corresponding to the attained SNR or SINR is derived using the look-up table given in Table I, and stored. 1000 independent simulations are run and the attained BLER is averaged over runs.

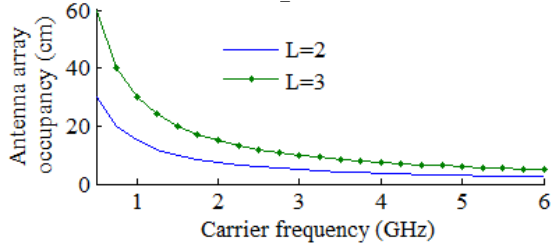


Fig. 5. Antenna array occupancy (Δ) as a function of the carrier frequency f_0 for various numbers L of car's antennas, for a uniform linear array with $\lambda/2$ antenna spacing.

B. Cost metrics: RF power consumption and spectrum usage

The performance for receive diversity with a single transmit antenna (1×3 Rx Div) is taken as the reference for power use and spectrum cost.

Regarding MRT-MISO, the ratio $\rho^{power}(t)$ between the RF power spent for the considered scheme over the RF power spent for 1×3 Rx Div is computed. The spent power is evaluated using the expressions of $P_u(t)$ given in Section III. Except when falling back to 1×3 Rx Div, MRT-MISO schemes are expected to be more energy efficient (for the network) than 1×3 Rx Div, i.e. we expect that $\rho^{power}(t) < 1$.

Regarding ZF-MIMO, the ratio $\rho^{spectrum}(t)$ of the spectrum spent for the considered scheme over the spectrum spent for 1×3 Rx Div, under the same transmit data rate constraint, is computed. Except for the fallback to 1×3 Rx Div, ZF-MIMO schemes with two data streams are expected to use half of the spectrum compared to 1×3 Rx Div, i.e. we expect that $\rho^{spectrum}(t) = 0.5 < 1$. (When $K > 2$, we can in addition also have a transmit power gain relative to 1×3 Rx Div.)

For one given simulation run, $\rho^{power}(t)$ and $\rho^{spectrum}(t)$ are derived based on the computed amounts of spent power and spectrum, and stored. We denote r^{power} and $r^{spectrum}$ as the averages over runs, of $\rho^{power}(t)$ and $\rho^{spectrum}(t)$.

V. STUDY 1: POWER AND SPECTRUM USED BY THE NETWORK, FOR ONE CAR ON A HIGHWAY (UP TO 150KM/H)

A. The worst case: 6 GHz frequency and fallback to Rx Div

In this study, we consider the worst case in terms of Doppler. With a carrier frequency $f_0 = 6$ GHz, the Doppler effect is the strongest in the considered frequency range.

We first study 256×1 MRT-MISO with fall back to 1×3 Rx Div. Such a system needs $L = 3$ antennas on the car. Cases with no prediction and with SRTA prediction are both tested. In Fig. 6, we observe that without prediction, MRT saves

energy (compared to Rx Div) for speeds up to $v^{limit,6GHz} = 30$ km/h. Beyond this speed, the system falls back to Rx Div. With SRTA prediction, MRT saves energy (compared to Rx Div) for speeds up to $v^{limit,6GHz} = 120$ km/h. Note that there is more than 20 dB difference in required RF energy, between MRT and Rx Div. Based on our empirical evaluation of a_{boost} (see equation (4)) and a_{boost}^{opt} (see equation (5)), the difference would still exceed 10 dB even with an optimum and complex S-F coding scheme.

We then study 256×2 ZF-MISO with fall back to 1×3 Rx Div. Such a system needs $L = 3$ antennas on the car. In Fig. 7, we observe that without prediction, ZF saves spectrum until $v^{limit,6GHz} = 10$ km/h. It stops saving spectrum beyond this speed, by being forced to fall back to Rx Div. With SRTA prediction, 256×2 ZF saves spectrum for speeds up to $v^{limit,6GHz} = 30$ km/h, and for some values of the speed between 30 and 100 km/h (the ups and down of SRTA predictions are explained in [16]).

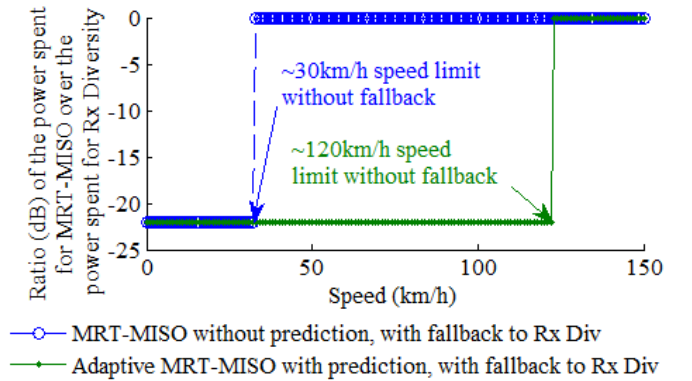


Fig. 6. r^{power} for a carrier frequency of 6 GHz.

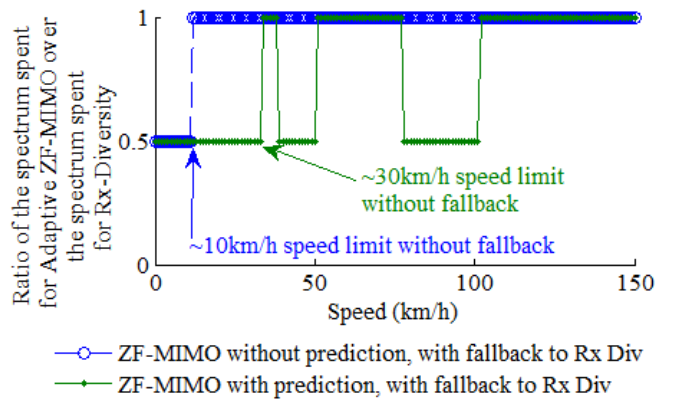


Fig. 7. $r^{spectrum}$ for a carrier frequency of 6 GHz.

If a car has $L = 3$ antennas occupying only 5 cm on its roof, and if these antennas are used for SRTA prediction instead of only diversity reception (Rx Div) this will enable the network to spend less energy at speeds up to 120 km/h, and less spectrum at speeds up to 30 km/h. With only $L = 2$ antennas occupying 2.5 cm, a connected car with SRTA prediction is still energy efficient for the network at speeds below 120 km/h, but it is spectrally efficient only at speeds below 10 km/h.

According to our simulations (not shown here due to a lack of space) with $K=8$ to 256 antennas, using less antennas at the network side does not extend the speed limit. Whatever the number K , the attained BLER exceeds 10% at the same speeds.

In conclusion, at such a high carrier frequency, even with SRTA prediction, it is not possible to save power and spectrum for all speeds. However, connected cars with 2 or 3 antennas that are used for SRTA prediction can be more cost efficient (in terms of spectrum usage and power consumption at the network side) than connected cars that use the same numbers of antennas but without prediction.

B. The best configuration

In this study, we consider a carrier frequency f_0 between 500 MHz and 6 GHz. We study several schemes (256x1 MRT-MISO and 256x2 ZF-MIMO with and without prediction). This time, these schemes are used without fallback to 1x3 Rx Div. We compute the speed limit v^{limit} beyond which the BLER is no longer bounded by 10%, as a function of the carrier frequency f_0 . The limit v^{limit} is simply given by $v^{limit} = v^{limit,6GHz} \times 6GHz/f_0$, where $v^{limit,6GHz}$ is the value which has been determined in the sub-section V-A.

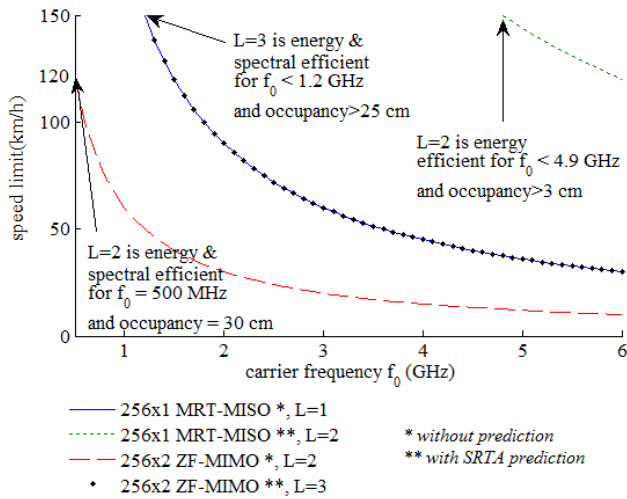


Fig. 8. Carrier frequency limit without fallback to 1x3 Rx Div.

The result is illustrated by Fig. 8. With $L=2$ antennas only, a connected car using SRTA prediction enables the network to save energy for all speeds (as long as $f_0 < 4.9$ GHz) but not spectrum. This corresponds to $\Delta = 3$ cm. With $L=2$ antennas only, a connected car enables the network to save energy and spectrum for speeds up to 120 km/h only (if $f_0 = 500$ MHz). This corresponds to $\Delta = 30$ cm. This study, shows that there is a trade-off between energy and spectrum cost at the network side and the antenna array occupancy Δ at the car side. With $L=3$ antennas, a connected car with SRTA prediction, enables the network to save energy (with MRT) and spectrum (with ZF) for all speeds, as long as $f_0 < 1.2$ GHz. This best configuration corresponds to $\Delta = 25$ cm.

VI. STUDY 2: POWER AND SPECTRUM USED BY THE NETWORK, FOR CARS IN A DENSE URBAN ENVIRONMENT

One can focus on “low speed cars” used only in dense urban environments, (like electrical rental cars in big cities). For such cars, as v is limited, the constraints identified in section V, on Δ can be a bit relaxed. In this study, we use a mobility model from the METIS 2020 project [18]. In this model, 420 cars move in a dense urban area during 3600 seconds. Their speed v is limited to 50 km/h. We analyze two different strategies for the operator. Both target that all cars attain a BLER bounded by 10%.

A. Strategy 1: Minimising the network energy consumption

In this deployment strategy, the operator minimizes the costs by finding the f_0 range for which MRT-MISO and ZF-MIMO can be used without fallback to Rx-Div. A car is in outage if its attained BLER is larger than 10%. We compute the outage probability as the ratio of cars in outage. The results plotted in Fig. 9, show that without prediction, adaptive antennas work without problems for $f_0 < 1$ GHz. At such frequency, the car needs $L=2$ antennas occupying $\Delta = 15$ cm. With SRTA prediction, adaptive antennas work fine for $f_0 < 3.5$ GHz. At such carrier frequency, the car needs $L=3$ antennas occupying $\Delta = 8.5$ cm.

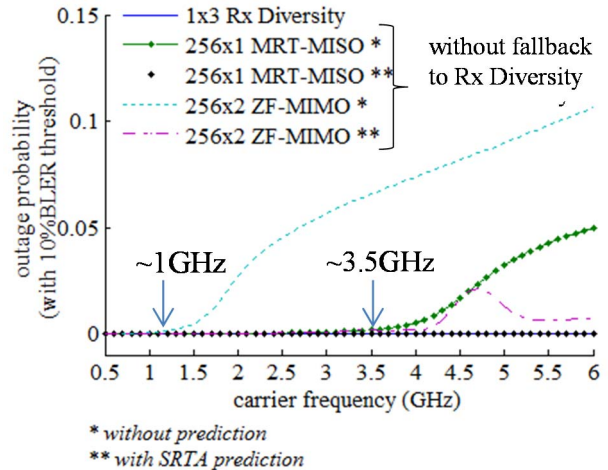


Fig. 9. Outage probability (with 10% BLER threshold).

In conclusion, in this scenario, the two aforementioned configurations are cost-efficient. However, even though it uses more antennas, the configuration with 3 antennas at higher carrier frequencies is more compact.

B. Strategy 2: Spending power or spectrum to guarantee QoS

In this deployment strategy, the operator spends the required power and spectrum to guarantee the QoS, regardless of the utilized antenna array size on the vehicle and for any utilized carrier frequency. It falls back to Rx Div, when adaptive antennas fail to keep the BLER bounded by 10%. In this scenario, we will use $L=3$ antennas. We measure r^{power} and $r^{spectrum}$ as functions of the carrier frequency. We observe that without prediction, the cost of the support of the connected cars increases fast with the carrier frequency. To achieve low antenna array occupancies (i.e. high carrier

frequencies) the network must spend more power and spectrum. SRTA prediction enables us to reduce these costs.

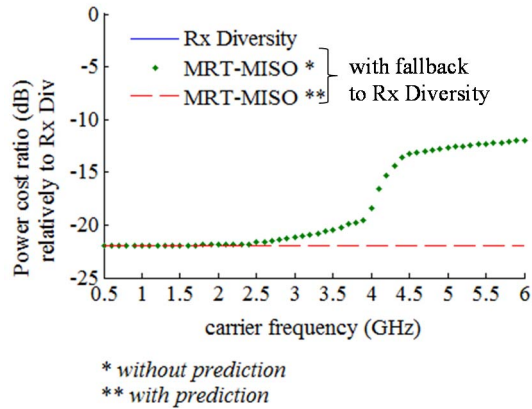


Fig. 10. Average per vehicle, of the spent power (normalised by the power spent for 1x3 Rx Div).

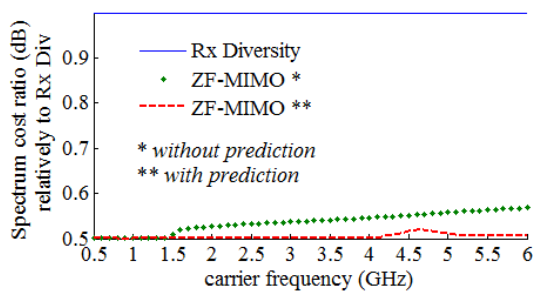


Fig. 11. Average per vehicle, of the spent spectrum (normalised by the spectrum spent for 1x3 Rx Div).

VII. CONCLUSIONS

We have studied 5G adaptive antennas for connected cars with and without a simple channel prediction scheme based on predictor antennas. We have considered 256 antennas at the network side to perform either maximum ratio transmission and save energy at the network or zero forcing (with two streams) to save spectrum at the network. For the first time, we have determined the numbers of antennas on the car top and carrier frequency which are the most cost efficient (in terms of power and spectrum usage at the network side). Our studies show that the network uses twice less spectrum and around 20 dB less power, for cars with 3 antennas on their tops and using prediction, than for cars with the same number of antennas and not using prediction. However, this cost efficiency is limited to frequencies below 1.2 GHz and 3.5 GHz, for cars on the highway and cars in dense urban areas, respectively. In the future, we will investigate an alternative more computationally demanding interpolation-based prediction scheme, which provides higher accuracy and potentially remains efficient at higher velocities and frequencies [16]. With such improvements, our solution would not only provide powerful 5G mobile radio links to moving cars with similar performance as to nomadic users, especially for the lower RF frequency bands providing good coverage, it should also be used for future Intelligent Transportation System applications and infotainment at higher frequencies [20].

ACKNOWLEDGMENTS

This work has been partially funded by the 5G PPP project Fantastic-5G [19] under grant ICT-671660 and the METIS 2020 project under grant ICT-317669 [18].

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