Radar Aided Beam Alignment in MmWave V2I Communications Supporting Antenna Diversity

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***Abstract*—Millimeter wave (mmWave) communication is the only viable approach for high bandwidth connected vehicles exchanging raw sensor data. A main challenge for mmWave in connected vehicles, is that it requires frequent link reconfiguration in mobile environments, which is a source of high overhead. In this paper we introduce the concept of radar aided mmWave vehicular communication. Side information derived from radar mounted on the infrastructure operating in a given mmWave band is used to adapt the beams of the vehicular communication system operating in another millimeter wave band. We propose a set of algorithms to perform the beam alignment task in a vehicle-to-infrastructure (V2I) scenario, from extracting information from the radar signal to configuring the beams that illuminate the different antennas in the vehicle. Simulation results confirm that radar can be a useful source of side information that helps configure the mmWave V2I link.**

I. Introduction

Next generation vehicles are being equipped with more capable sensors to support higher levels of automated driving. Exchanging sensor data between vehicles would enlarge their sensing capabilities, with the subsequent enhancement of safety applications. Sensor data rates, however, are quite high with terabytes of data generated per hour. Dedicated short-range communication (DSRC) [1] permits vehicles to exchange messages (including basic sensor information) with a range up to 1000 meter (ideally), but the maximum data rate supported in practice is at most 2-6 Mbps [2]. Vehicle to vehicle (V2V) communication through D2D mode in LTE-A [3] supports higher data rates than DSRC (up to 1Gbps), but practical rates are limited to several Mbps by inaccurate channel state information (CSI) [4]. Therefore, current vehicular communication solutions do not support the required Gbps data rates.

To overcome this limitation, we propose to use millimeter wave spectrum for vehicular communication. The use of mmWave provides access to high bandwidth communication channels, leading to the potential for the required gigabit per second data rates [5]. One of the key drawbacks to develop mmWave V2X communication systems is the high overhead due to frequent beamtraining in high mobility scenarios. Most of beamtraining approaches are based on beam sweeping [6], [7], where pairs of transmit and receive beams are measured and used in the algorithm to search for the best beam pair. Discovering where to point the antennas, though, is challenging due to the narrow beamwidth, the potential high velocity of the transmitter and receiver, and the presence of frequent blockages of the propagation paths. This has lead to the general belief that beam training and therefore mmWave communication itself is infeasible in vehicular-to-everything (V2X) applications.

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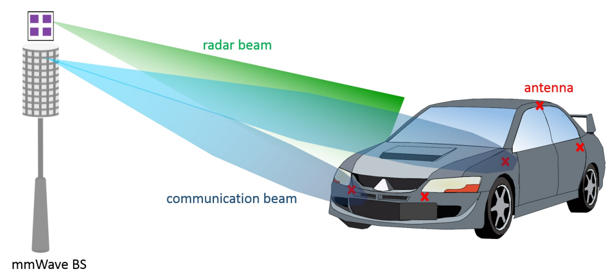


Fig. 1: V2I mmWave communication scenario with BS equipped with a radar to aid beam training.

To unlock the potential for mmWave in vehicular communication systems, we propose using a radar mounted at the road infrastructure to aid configuring the mmWave communication link in a V2I scenario. The concept of sensor aided mmWave beam alignment has been just proposed in [8], where sensors on vehicles are used to configure the mmWave V2V communication link. Our key idea is to use the information from the radar operating in a mmWave band to extract the channel information of another band (where communication happens). This goes beyond the downlink/uplink reciprocity that has been studied in the past for frequency division duplexing (FDD) communication systems [9], [10], [11], since the carrier frequencies may be very different and the environment, not the channel, is sensed.

We propose two protocols for beam alignmnet in a vehicle-to-infrastructure (V2I) scenario based on a blind design of the precoders/combiners which does not require channel state information, but only the covariance of the received signal. Radar signal operating in a different frequency band is used to estimate the covariance of the received signal. Simulation results confirm that the main DoAs for the radar and the communication signals are similar. The resulting spectral efficiency of the link shows that radar can help configuring the mmWave V2I link.

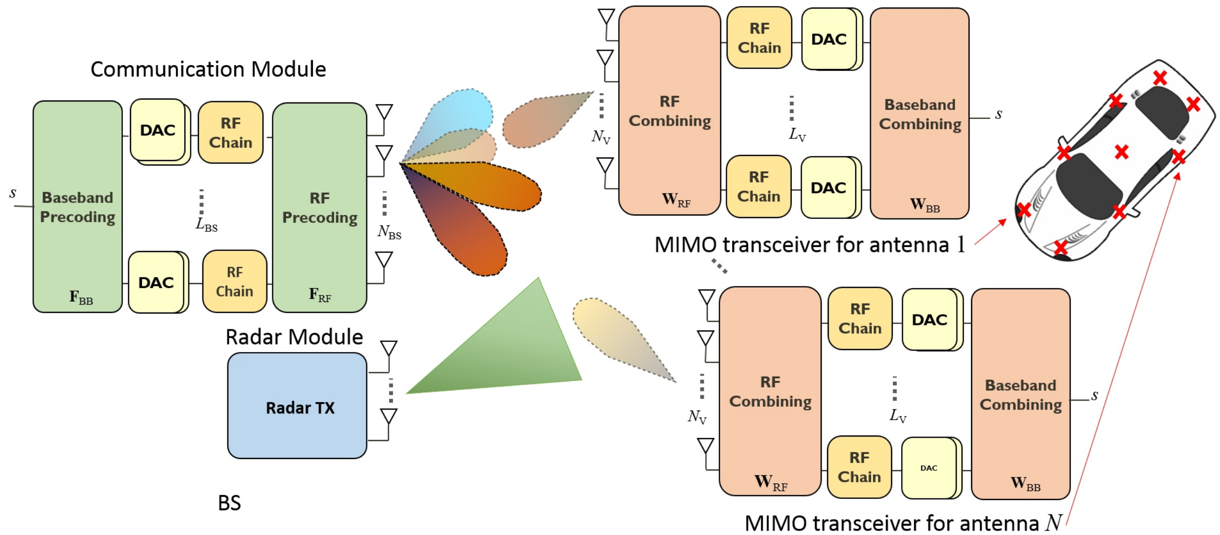


Fig. 2: Simplified block diagram of the radar aided mmWave MIMO system for V2I communication based on hybrid precoding.

II. System model

We consider a mmWave V2I communication system, e.g. supported through 5G cellular, where mmWave base stations serve as infrastructure for V2I communications. A radar operating in another mmWave band is mounted on the base station, as illustrated in Fig. 1. In real environments, depending on the beam width and the distance between the vehicle and the BS, the mmWave beam generated at the BS in a given direction could illuminate only a small fraction of the vehicle. To guarantee that the BS reaches the communication module at the vehicle, we propose using antenna diversity in the vehicle. Diversity can also be used to prevent dramatic effects of blockages in the communications with the car. Therefore, we assume that N phased arrays are placed at different points in the vehicle (shown as red crosses in the figure). This approach increases the probablility of that at least one path from the BS reaches one of the antenna arrays in the vehicle. The objective of the system we want to design is to steer the beams between some of the arrays in the vehicle and the BS relying on information extracted from the radar signal.

For the mmWave V2I communication system, we consider a hybrid MIMO (multiple input multiple output) architecture [12], [13], since a multi beam antenna pattern has to be designed to support the multiple receivers. The hybrid architecture splits the MIMO processing between the analog and digital domains to operate with a number of transceivers smaller than the number of antennas and reduce power consumption. An analog beamforming architecture allows beam steering only in one direction, while an all digital solution has too much power consumption [13], [14]. There are similarities with the multiuser communication problem in a mmWave cellular network when the different users (in our vehicular case the different antennas in the car) are located at nearby positions [15].

We consider the infrastructure-to-vehicle link shown in Fig. 2, with a single stream, a transmit array of size N_{BS} connected to L_{BS} RF chains at the BS, and N receive antenna arrays of size N_{V} connected to L_{V} transceivers at the vehicle.

A narrowband frequency-flat channel model as in [16], [17] is assumed, where the infrastructure-to-vehicle channel for the i-th array in the vehicle is

$$\mathbf{H}_{\mathrm{d},i} = \sqrt{\frac{N_{\mathrm{BS}} N_{\mathrm{V}}}{L_i}} \sum_{\ell=1}^{L_i} \alpha_{i,\ell} \mathbf{a}_{\mathrm{V}}(\theta^{\mathrm{V}}_{i,\ell}, \phi^{\mathrm{V}}_{i,\ell}) \mathbf{a}^*_{\mathrm{BS}}(\theta^{BS}_{i,\ell}, \phi^{BS}_{i,\ell}). \quad (1)$$

L_i is the number of paths with complex gain α. $\mathbf{a}_{\mathrm{V}}(\theta^{\mathrm{V}}, \phi^{\mathrm{V}}), \mathbf{a}_{\mathrm{BS}}(\theta^{\mathrm{BS}}, \phi^{\mathrm{BS}})$ are the receive and transmit array response vectors corresponding to the angles of arrival and departure (AoA/AoD) in azimuth and elevation. We use an equivalent model for the uplink channel $\mathbf{H}_{\mathrm{u},i}$.

The downlink and uplink channels can be approximated using the extended virtual channel model [13]

$$\mathbf{H}_{\mathrm{b},i} = \mathbf{A}_{\mathrm{BS}} \mathbf{H}_{\mathrm{v},i} \mathbf{A}^*_{\mathrm{V},i}. \quad (2)$$

The matrices $\mathbf{A}_{\mathrm{BS}} = [\mathbf{a}_{\mathrm{BS}}(\theta_1, \phi_1) \ldots \mathbf{a}_{\mathrm{BS}}(\theta_{N_{\mathrm{BS}}}, \phi_{N_{\mathrm{BS}}})]$ and $\mathbf{A}_{\mathrm{V},i} = [\mathbf{a}_{\mathrm{V}}(\theta_{1,i}, \phi_{1,i}) \ldots \mathbf{a}_{\mathrm{V}}(\theta_{N_{\mathrm{V}},i}, \phi_{N_{\mathrm{V}},i})]$ contain the BS and vehicle array response vectors evaluated on the grid of AoAs and AoDs. Given the sparse nature of the mmWave channel (a few paths exist), $\mathbf{H}_{\mathrm{v},i}$ is a sparse matrix with K non zero entries corresponding to path gains associated with AoAs and AoDs taken from a uniform grid of N_{BS} and N_{V} points.

On the infrastructure-to-vehicle link, the BS applies a hybrid precoder $\mathbf{f} = \mathbf{F}_{\mathrm{RF}} \mathbf{f}_{\mathrm{BB}}$, with the RF precoder $\mathbf{F}_{\mathrm{RF}} \in \mathbb{C}^{N_{\mathrm{BS}} \times L_{\mathrm{BS}}}$ and the baseband precoder $\mathbf{f}_{\mathrm{BB}} \in \mathbb{C}^{L_{\mathrm{BS}} \times 1}$. The received signal at time k at the i-th phased array in the vehicle is given by

$$\mathbf{x}_i[k] = \mathbf{H}_{\mathrm{d},i} \mathbf{f} s[k] + \mathbf{n}_{\mathrm{d},i}[k], \quad (3)$$

where $\mathbf{n}^{\mathrm{f}}_i$ is the additive white Gaussian noise vector at the i-th phased array with covariance $\mathcal{N}(0, \sigma^2_{\mathrm{f}} \mathbf{I})$. $s[k]$ is the transmit symbol with unit variance. The combined signal vector at the output of the i-th array in the vehicle is given by $y_i[k] = \mathbf{w}_i^* \mathbf{x}_i[k]$, where $\mathbf{w}_i = \mathbf{W}_{\rm RF}^i \mathbf{w}_{\rm BB}^i \in \mathbb{C}^{N_{\rm V}\times 1}$ is the hybrid combiner vector with $\mathbf{W}_{\rm RF}^i \in \mathbb{C}^{N_{\rm V}\times L_{\rm V}}$ and $\mathbf{w}_{\rm BB}^i \in \mathbb{C}^{L_{\rm V}\times 1}$.

We consider now the vehicle-to-infrastructure link. The i-th transceiver in the car applies a hybrid precoder $\mathbf{f}_i = \mathbf{F}_{\rm RF}^i \mathbf{f}_{\rm BB}^i \in \mathbb{C}^{N_{\rm V}\times 1}$ to the transmit signal. Only L out of N phased arrays in the vehicle transmit a signal that reach the BS. The received signal at the BS is given by

$$\mathbf{x}[k] = \sum_{i=1}^{L} \mathbf{H}_{{\rm u},i} \mathbf{f}_i s_{\rm V}[k] + \mathbf{n}_{\rm u}[k]. \tag{4}$$

$\mathbf{H}_{{\rm u},i} \in \mathbb{C}^{N_{\rm BS}\times N_{\rm V}}$ is the channel matrix corresponding to the link between the i-th phased array in the vehicle and the BS; $\mathbf{n}_{\rm u}$ is the additive white Gaussian noise vector at the BS phased array with covariance $\mathcal{N}(0, \sigma_{\rm b}^2 \mathbf{I})$. All the antenna arrays in the vehicle transmit the same signal $s_{\rm V}[k]$. The BS applies a hybrid combiner $\mathbf{w} = \mathbf{W}_{\rm RF}\mathbf{w}_{\rm BB}$ to the received signal. The combined signal at the BS can be written as $y[k] = \mathbf{w}^* \mathbf{x}[k]$, with $\mathbf{W}_{\rm RF} \in \mathbb{C}^{N_{\rm BS}\times L_{\rm BS}}$ and $\mathbf{w}_{\rm BB} \in \mathbb{C}^{L_{\rm BS}\times 1}$.

We assume that the radar mounted at the BS has an antenna array of size N_{BS} operating in a mmWave band not used by the communication system. We model the vehicle as a multipoint target represented by L virtual scattering points used to define the electromagnetic behavior of the vehicle [18]. We also assume that all the reflected radar signals from the vehicle reach the radar receive antenna at the same time. With this assumption the signal at the receive radar antenna can be written as

$$\mathbf{x}_{\rm R,BS}[k] = \sum_{i=1}^{L} \mathbf{H}_{{\rm R,u},i} \mathbf{e}_i[k] + \mathbf{n}_{\rm R,BS}[k]. \tag{5}$$

with $\mathbf{e}_i$ the radar echo signal coming from the i-th virtual scattering point and $\mathbf{H}_{{\rm R,u},i}$ denotes the $N_{\rm BS} \times N_{\rm V}$ channel matrix between the i-th array in the vehicle and the radar at the infrastructure.

The antenna array at the radar and the phased array at the BS are closely separated and vertically aligned. We also assume that the radar signal from the BS reaches some of the antenna arrays in the vehicle at the same time. With this assumption the radar signal at the i-th phased array in the vehicle can be wriiten as

$$\mathbf{x}_{{\rm R},i}[k] = \mathbf{H}_{{\rm R,d},i} s_{\rm R}[k] + \mathbf{n}_{{\rm R},i}[k]. \tag{6}$$

$\mathbf{H}_{{\rm R,d},i}$ denotes the $N_{\rm V} \times N_{\rm BS}$ channel matrix between the radar at the infrastructure and the i-th array in the vehicle. $\mathbf{n}_{{\rm R},i}$ is the additive white Gaussian noise with covariance $\mathcal{N}(0, \sigma_{{\rm R},i}^2 \mathbf{I})$.

Because the antenna array at the radar and the phased array at the BS are closely separated, we assume that the MIMO channels between the antena array at the radar and any array at the vehicle share the same dominant paths with the channels between the BS phased array and any antenna in the vehicle

$$\mathrm{supp}(\mathbf{H}_{{\rm R,d},i,v}) \sim \mathrm{supp}(\mathbf{H}_{{\rm d},i,v}), \tag{7}$$

where $\mathbf{H}_{{\rm R,d},i,v}$ is the virtual channel matrix representing $\mathbf{H}_{{\rm R,d},i}$ using the extended virtual channel model as in (2), $\mathbf{H}_{{\rm d},i,v}$ is the virtual channel matrix representing $\mathbf{H}_{{\rm d},i}$ and $supp$ stands for the support of a sparse matrix, i.e., the indices of the matrix corresponding to the non-zero coefficients. In the same way, $\mathrm{supp}(\mathbf{H}_{{\rm R,u},i,v}) \sim \mathrm{supp}(\mathbf{H}_{{\rm u},i,v})$.

We also assume channel reciprocity of time division duplex (TDD) systems with perfect circuit calibration, so that the precoder is designed as the transpose conjugate of the combiner.

In this paper, we want to design the precoders and combiners at the vehicle and the infrastructure sides using information extracted from the radar signal. The key idea is to use the estimation of the covariance obtained from the radar signal (or its reflected echo) to design the intial precoders/combiners, either at the BS or at the different phased arrays in the vehicle. The assumptions behind this idea are the following: i) at the vehicle side, the L strongest directions of arrival (DoAs) obtained from the covariance of $\mathbf{x}_{{\rm R},i}[k]$ are approximately equal to those obtained from the covariance of $\mathbf{x}_i[k]$; ii) at the BS side, the strongest directions of arrival extracted from the radar echos after background substraction come from the virtual scattering points in the vehicle, located approximately at the same places as the antenna arrays used for communications. Due to the complexity of the theoretical validation of these assumptions, we verify the hypothesis by ray tracing simulations, as described in Section IV.

III. Processing for radar aided beam alignment

In this section, we design two iterative strategies between the BS and the vehicle to configure the hybrid precoders and combiners. We propose to use a power criterion to design the hybrid precoders and combiners, since it does not require explicit channel knowledge but only covariance information. To estimate the covariance from the radar signal we propose to use a compressive approach as in [15], which leverages the sparse nature of mmWave channels. For the preliminary designs proposed in this paper we will use the covariance estimate obtained at the radar band as an estimation of the covariance of the comunication signal in another frequency band.

PROTOCOL 1 (BS starts establishing the link)

The adaptive protocol we propose is an adaptation to the vehicular scenario of the multi-user scheme described in [15]. The key idea is to assume that the strongest echos from the radar can be used to identify the DoA of the signals coming from the antennas in the vehicle. It includes the following steps:

1) When a moving target is detected by the radar the raw echo signal is sent to the communication module at the BS. The BS applies conventional radar processing for background substraction and estimates the spatial correlation of the received echo using the sample covariance

$$\hat{\mathbf{R}}_{\mathbf{x}_{\text{BS,R}}\mathbf{x}_{\text{BS,R}}} = \frac{1}{P}\sum_{k=1}^{P} \mathbf{x}_{\text{BS,R}}[k]\mathbf{x}^*_{\text{BS,R}}[k]. \tag{8}$$

The estimated correlation of the radar echo is used as an estimation of the covariance of the communication signal

$$\hat{\mathbf{R}}_{\mathbf{xx}} = \hat{\mathbf{R}}_{\mathbf{x}_{\text{BS,R}}\mathbf{x}_{\text{BS,R}}}. \tag{9}$$

The BS designs the hybrid combiner using a power criterion based on the covariance information (see Section III-A) and the precoder as it transpose conjugate exploiting downlink and uplink reciprocity.. Using the designed precoder the BS transmits a training signal to the vehicle.

2) The different transceivers in the vehicle estimate the spatial correlation of the received signal using the compressive approach described in Section III-B. The hybrid combiner and the conjugate hybrid precoder are then designed using the power criterion described in Section III-A. The transceivers in the vehicle transmit applying this hybrid precoder.
3) The BS estimates now the spatial correlation of the received communication signal using the same compressive approach and updates the precoder and combiner using the same critrerion as in step 1.

Notice that no feedback between the vehicle and the BS is needed because reciprocity is exploited.

PROTOCOL 2 (Vehicle starts establishing the link)

We propose an adaptive protocol where the vehicle leverages the received radar signal to establish the communication link with the BS. It includes the following steps:

1) All of the transceivers in the vehicle which receive the radar signal estimate its spatial correlation $\mathbf{R}_{\mathbf{x}_{\text{R},i}\mathbf{x}_{\text{R},i}}$ using the compressive approach described in Section III-B. The estimated correlation of the radar signal is used as an estimate of the covariance of the communication signal

$$\hat{\mathbf{R}}_{\mathbf{x}_i\mathbf{x}_i} = \hat{\mathbf{R}}_{\mathbf{x}_{\text{R},i}\mathbf{x}_{\text{R},i}}. \tag{10}$$

The combiners are designed using a power criterion based on the covariance information corresponding to the radar band (see Section III-A). The precoders are designed as their transpose conjugate. Every transceiver in the car sends to the BS a training signal (there is no need of sending incorrelated signals, since a single stream has to be transmitted by all the active transceivers in the vehicle).
2) The BS estimates the covariance from the training signal received in the communication band using a compressive approach. The combiner is designed again using the power criterion described in Section III-A. The precoder is designed as its transpose conjugate.

No feedback between the BS and the vehicle is needed.

A. Precoder and combiner design for multibeam V2I communications

The final aim in this setting is not to maximize the sumrate of the system as in a classical mult-user scenario, but using diversity to overcome a possible blockage to some of the antennas in the car. This way the combiner, either at the BS or at the vehicle side, should be designed maximizing the combined output signal power, to steer the beams on the directions of arrival of the radar signal and its strongest reflections. This criterion leads to a blind approach, which does not require any a priori knowledge about the received signal. It is equivalent to maximizing the SNR of the combined signal when the additive white Gaussian noise powers $\mathbf{n}_{\text{R},i}$ are equivalent [19]. Using this criterion, the optimum combiner is the dominant eigenvector of the covariance matrix of the received signal.

The optimum combiner at the BS is given by $\mathbf{w}^{opt} \in \mathbb{C}^{N_{\text{BS}}\times 1}$. In a hybrid MIMO architecture $\mathbf{w}^{opt} = \mathbf{W}_{\text{RF}}\mathbf{w}_{\text{BB}}$, that is, the optimum combiner is decomposed into a RF combiner subject to the specific hardware constraints (unit norm entries when using a phased array) and a digital combiner. The greedy method in [20] can be applied to find a near optimal decomposition of the designed combiner into the BB and RF components.

B. Compressive covariance estimation

The maximum combined output power design for the precoders and combiners relies on the estimation of the spatial covariance matrix. The receivers in the vehicle have to estimate $\mathbf{R}_{\mathbf{x}_{\text{R},i}\mathbf{x}_{\text{R},i}}$ At the BS side, it is necessary to estimate the covariance $\mathbf{R}_{\mathbf{xx}}$. Estimate $\hat{\mathbf{R}}_{\mathbf{xx}}$ could be obtained from the sample covariance matrix using P observations. $\mathbf{R}_{\mathbf{x}_{\text{R},i}\mathbf{x}_{\text{R},i}}$. A MIMO system based on the hybrid architecture described in Section II can not however compute these sample estimates, since the signal at the receive antennas is not accesible. Using the same approach as in [15], we can find an equation that relates the covariance of the received signal to the covariance of the signal at the output of the combiner. The solution to this equation provides an estimation of $\mathbf{R}_{\mathbf{xx}}$ (or $\mathbf{R}_{\mathbf{x}_{\text{R},i}\mathbf{x}_{\text{R},i}}$ at the vehicle side).

Let $\mathbf{y}$ be the output of the RF combiner at the BS,

$$\mathbf{y}[k] = \mathbf{T}^*[k]\mathbf{x}[k], \tag{11}$$

where $\mathbf{T}[k] \in \mathbb{C}^{N_{\text{BS}}\times L_{\text{BS}}}$ is a combining matrix that contains the phases for the RF combiners (columns in $\mathbf{T}[k]$) applied at a given time slot. We consider a sequence of training combiners $\mathbf{T}_1, \ldots, \mathbf{T}_M$ applied in M consecutive time slots. During the m-th time slot the output of the combiner is given by $\mathbf{y}_m(t) = \mathbf{T}_m\mathbf{x}(t)$. The outputs $\mathbf{y}_m(t)$ are uniformly sampled obtaining S samples in each time slot. We define $\mathbf{Y}_m = [\mathbf{y}[k_1^m] \ldots \mathbf{y}[k_S^m]] \in \mathbb{C}^{L_{\text{BS}}\times S}$.

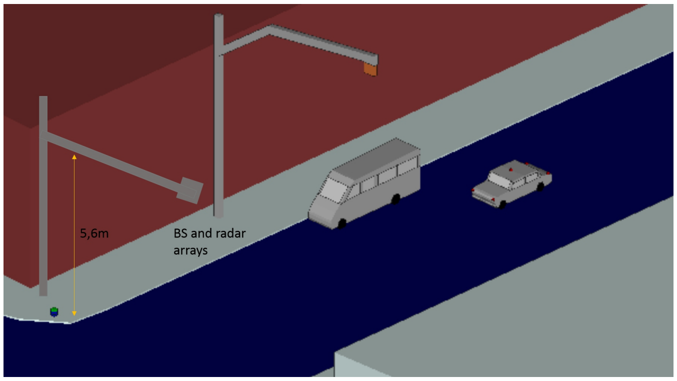


Fig. 3: Vehicular to infrastructure communication link with a radar at the BS simulated by ray tracing.

Following the steps described in [15], we can obtain the equation

$$\begin{bmatrix} \mathrm{vec}(\mathbf{R_{yy}}^1) \\ \vdots \\ \mathrm{vec}(\mathbf{R_{yy}}^M) \end{bmatrix} = \begin{bmatrix} (\mathbf{T}_1 \otimes \mathbf{T}_1) \\ \vdots \\ (\mathbf{T}_M \otimes \mathbf{T}_M) \end{bmatrix} \mathrm{vec}(\mathbf{R_{xx}}) \tag{12}$$

$$\Leftrightarrow \mathbf{r_y} = \mathbf{T}_S \mathbf{r_x} \tag{13}$$

where $\mathbf{R_{yy}}^m = \mathbf{T}_m \mathbf{R_{xx}} \mathbf{T}_m^*$ is the covariance of the m-th time slot that can be estimated using the sampled covariance matrix $\hat{\mathbf{R}}^p_{\mathbf{yy}} = \mathbf{Y}_p \mathbf{Y}_p^*/S$. Different possibilities to solve this equation with their corresponding conditions can be found in [15]. One approach is to exploit the sparsity of the mmWave channel to formulate a compressed sensing problem. If the phases in $\mathbf{T}_m$ are randomly chosen, an estimate of $\mathbf{R_{xx}}$ can be obtained using standard sparse recovery algorithms.

IV. Simulations

Ray tracing simulations have been used to predict the propagation phenomena in different settings, including the vehicular scenario [21]. Fig. 3 shows the V2I setting which has been simulated using the Remcom's ray tracing software Wireless Insite. Antenna arrays in the communicating vehicle are shown as red points. Uniform planar arrays are simulated both at the BS and the vehicle side.

The set of polar plots in Fig. 4 shows the DoAs for three of the five antennas in the vehicle when estimated from the radar signal at 76.5 GHz and the communication signal at 65 GHz. These results validate one of the assumptions in our system model: the strongest directions of arrival (DoAs) obtained from the covariance of $\mathbf{x}_{\mathrm{R},i}[k]$ are approximately equal to those obtained from the covariance of $\mathbf{x}_i[k]$.

At the BS side similar results are obtained. Fig. 5 shows the DoAs at the BS when estimated from the radar echo at 76.5 GHz and the communication signal coming from there different phased arrays in the vehicle operating at 65 GHz. The strongest DoAs extracted at the BS from the radar echo and the communication signals in a different band also coincide, which validate our second assumption in Section II.

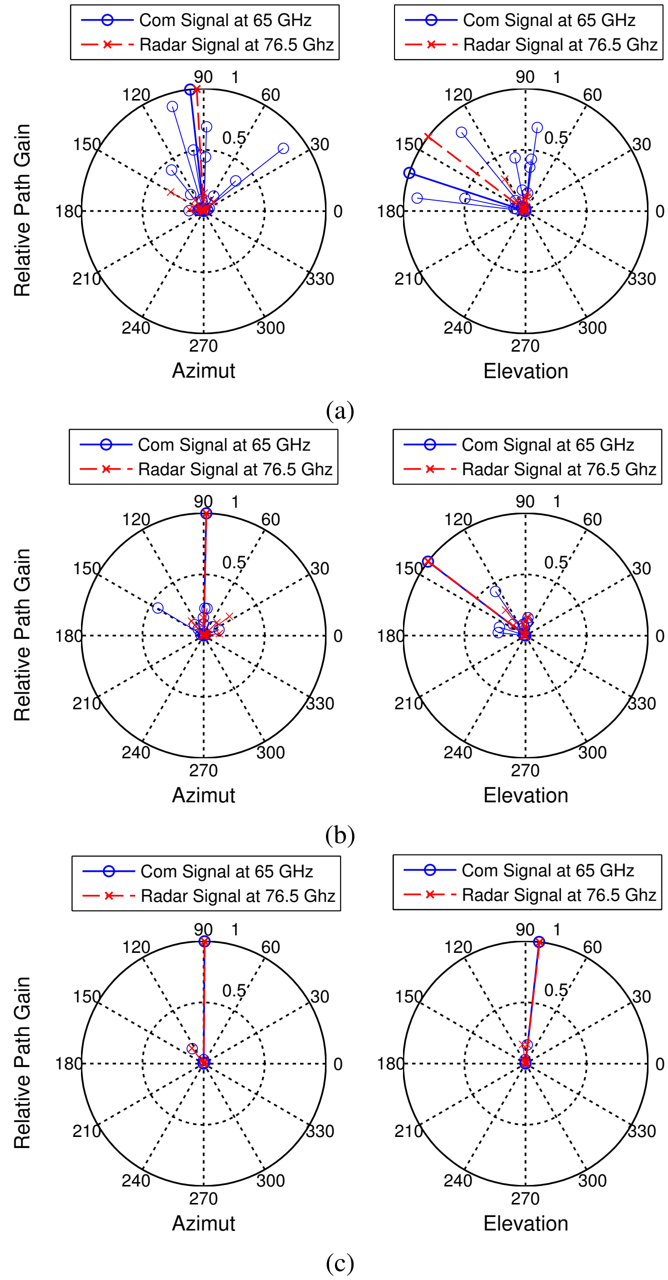
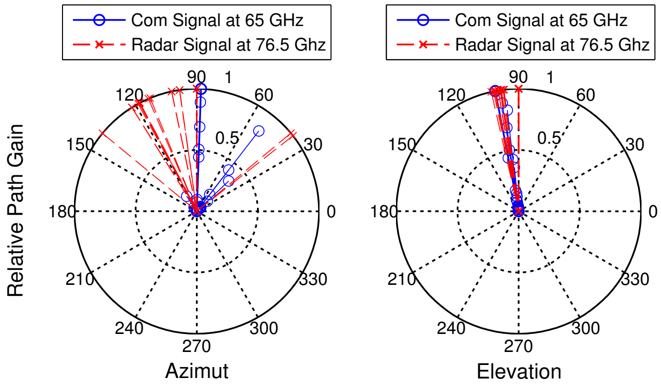
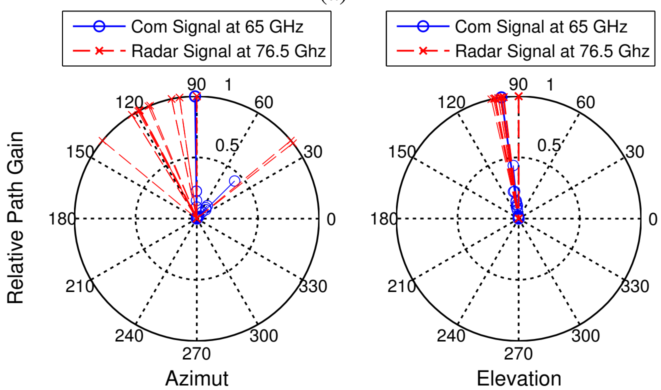


Fig. 4: DoAs estimated from the radar and the communications signal: (a) for the phased array located at c (b)for the phased array located at left side in the front part of the vehicle; (c) for the phased array on top of the vehicle.

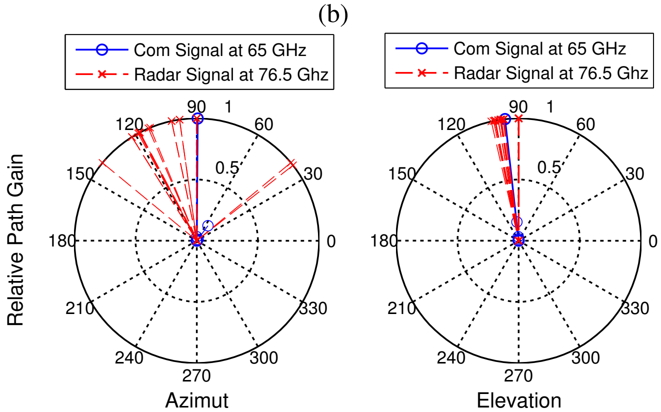
Now we analyze the spectral efficiency of the proposed protocols and precoder/combiner design algorithms. Fig. 6 shows the spectral efficiency obtained for the uplink between two of the transceivers in the vehicle and the BS. The perfect covariance and the sample and compressed estimates provide similar results for the front left antenna, but there is still a significant gap with the upper bound that could be further reduced with new designs of the combiners/precoders. We propose as future work, the design of the RF combiners



(a)

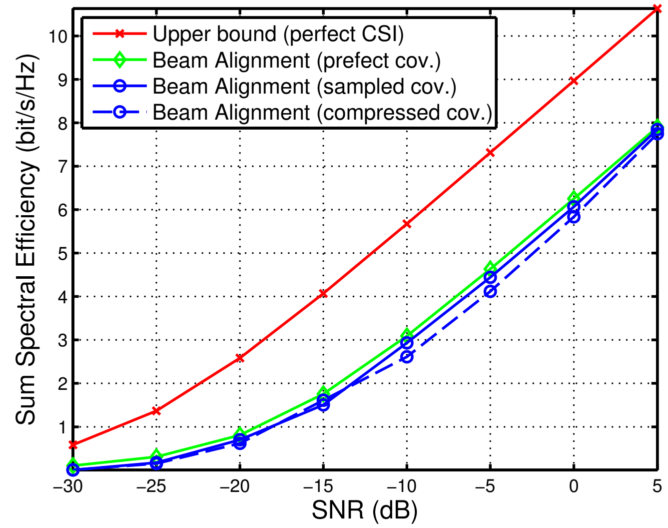


(b)

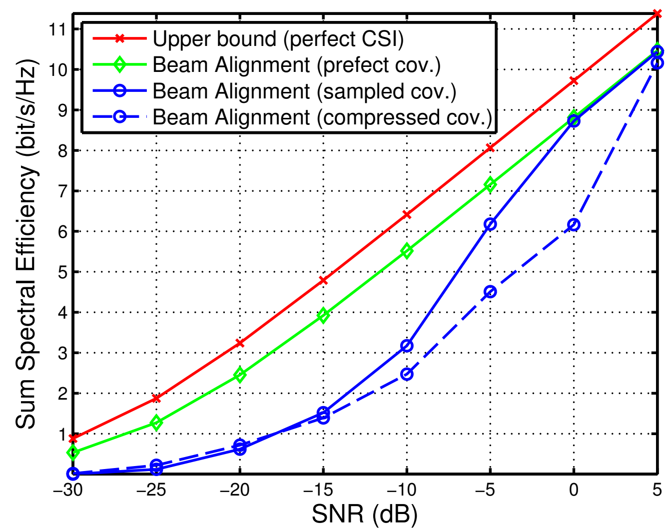


(c)

Fig. 5: DoAs estimated at the BS side from the radar echo and several communication signals coming from the phased array at: (a) the left side in the front part of the vehicle; (b) the right side in the front part of the vehicle; (c) the top of the vehicle.



(a)



(b)

Fig. 6: Spectral efficiency obtained for the backward links between the front left (a) and the top (b) phased arrays in the vehicle and the BS.

using the maximization of the combined signal power, while finding an alternative criterion for the design of the baseband component. The compressive estimation of the covariance based on LS does not provide good results in some cases, like in the top antenna array. We propose to exploit mmWave channel sparsity to define an alternative compressive estimator of the covariance.

V. Conclusions

The main goal of this paper is to introduce the concept of radar aided vehicular communication and confirm that radar can be a useful source of side information that helps configure the mmWave V2I link. The proposed practical algorithms have to be seen as a preliminary solution to confirm the viability of the approach, but they can be further refined. For example, the high mobility feature has to be considered, incorporating a prediction of the evoution of the channel information to further refine the configuration of the beams. Different criteria for the design of the RF and BB combiners/precoders can also be considered to reduce the gap in spectral efficiency obtained with the proposed algorithms.

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