Vehicular SUDAS for 5G High Mobility V2X Scenarios

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***Abstract*—In this paper, we present the Vehicular Shared User-Equipment (UE)-side Distributed Antenna System (Vehicular SUDAS) which enables high throughput wireless communication in high mobility scenarios. Vehicular SUDAS uses shared virtual antennas, termed UE-side Radio Units (URUs), which utilize both licensed band and unlicensed millimetre wave band to achieve a virtual MIMO gain in the in-vehicle UEs. A simulation study is performed to evaluate and analyze an upper bound of the maximum achievable sum rate of the proposed system, assuming perfect Doppler spread compensation, in high mobility scenarios. The proposed Vehicular SUDAS shows excellent performance, positioning itself as a strong contender for next generation Vehicle-to-X (V2X) communication services.**

I. Introduction

High data rates, ubiquitous availability, ultra-low latency, and high reliability are the key requirements of the next generation Vehicle-to-X (V2X) communication services in 5th generation (5G) communication systems [1]. Specifically, the need for high data rates in vehicles, such as trains, buses, and cars, is driven by the growth of multimedia application such as vehicle infotainment systems and in-vehicle video streaming. However, supporting high data rates in high mobility vehicular scenarios is technically challenging [2] particularly due to rapid variations in the channel conditions and inter-carrier interference due to Doppler spread. Even if the detrimental effects of high mobility are compensated by careful signal processing, high data rate wireless communication in vehicular scenarios remains a challenge due to the limited transmit power and communication bandwidth available in sub-6 GHz band.

On the other hand, spatial multiplexing using multiple-input multiple-output (MIMO) is a promising technology to improve data throughput. However, relatively low gain can be realized in practical scenarios using MIMO due to the limitations of size and number of antennas on mobile devices, especially handheld user-equpments (UEs). A technique to overcome this limitation is the use of virtual antenna arrays (VAAs) in which UEs exchange received signals with adjacent receivers to establish a virtual MIMO system [3]. However, these systems are further limited by the UE-side fronthaul links, used to exchange the received signals, due to in-band relaying interference with the transmitted signal.

Shared UE-side Distributed Antenna Systems (SUDASs), proposed in [4] for outdoor-to-indoor communication, avoid this interference by using a second unlicensed millimetre wave (mmWave) band for forwarding the signal from the virtual antennas to the UEs. A large available bandwidth of about 7 GHz in the 60 GHz unlicensed band makes it an ideal candidate for use in these UE-side fronthaul links. Furthermore, in this wide band, even single-input single-output (SISO) links with low spectral efficiency can achieve high peak data rates.

In SUDAS, a large number of virtual antennas, termed UE-side Radio Units (URUs), are used to forward a MIMO signal from a basestation (BS), that can be e.g. LTE or New Radio (NR) BS, to UEs using mmWave fronthaul links. Therefore, each URU acts as a relay: it possesses a sub-6 GHz antenna to receive the MIMO signal, which is transformed into a SISO signal on the mmWave channel and transmitted to the UEs. MIMO decoding is performed at the UEs after combining the signals received from the URUs.

An alternative to virtual MIMO at the UEs is the use of an in-vehicle access point (AP)[1] with wireless backhauling. However, such APs necessitate the use of a new network architecture, and a second communication protocol for the link to the UEs (such as WiFi). It may also necessitate an additional in-vehicle subscription of data services whereby a user cannot "reuse" his wireless Mobile Network Operator (MNO) subscriptions.

Instead, it might be interesting to explore the use of MIMO processing capabilities of UEs along with SUDAS to enable high in-vehicle data rates in vehicular scenarios. Based on this insight, this paper (i) Extends the SUDAS concept and presents an analysis on how the SUDAS concept could be used in vehicular scenarios (Vehicular SUDAS) involving high mobility. (ii) Shows how Vehicular SUDAS can be integrated with 3GPP networks to support enhanced Mobile Broadband (eMBB) services that require high throughput for vehicles moving at high speed. (iii) Presents a performance study considering combination of high data-rate and high mobility scenarios to enable access of uninterrupted high data rate applications to the users in a vehicle moving at high speed.

The paper is organized as follows: Section II presents the SUDAS concept in the context of vehicular scenarios (Vehicular SUDAS) considering both physical (PHY) and medium-access (MAC) layer aspects, as well as from the network architecture and management perspective. Section III defines the model that is used for the analysis of the Vehicular SUDAS performance. The simulation results and performance analysis of the proposed Vehicular SUDAS concept is presented in Section V. Finally, the paper is concluded in Section VI.

[1]An out-of-vehicle access point would be infeasible due to high mobility of the vehicles.

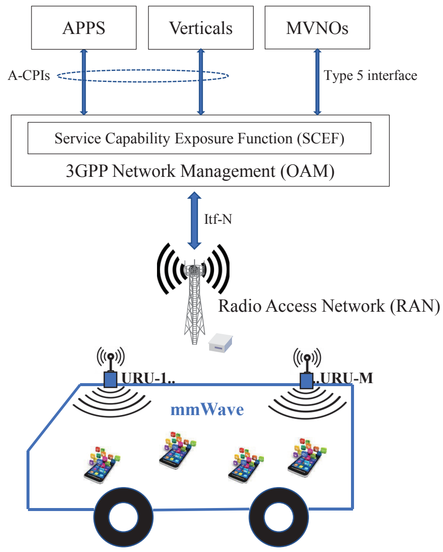

Fig. 1: Application of Vehicular SUDAS, e.g. in a bus, in a 3GPP 5G Network Environment

II. SUDAS CONCEPT FOR VEHICULAR RECEPTION

In this section, we present the system model, signal model, and the network architecture and management aspects of the proposed vehicular SUDAS.

A. Vehicular SUDAS System Model for Performance Evaluation

We consider a system comprising a BS equipped with N antennas, M independently operating URUs, and K users within a vehicle along the lines of the SUDAS outdoor-to-indoor system model given in [4]. The vehicle can be a coach (bus) or a car. The URUs are equipped with one antenna operating in the sub-6 GHz licensed band which is located on the exterior of the vehicle's body, and one antenna operating in the unlicensed mmWave band which is located on the interior of the body as shown in Fig. 1.

The BS employs a multi-carrier downlink transmission with N_F subcarriers (total bandwidth B Hz) in the sub-6 GHz licensed band. The URUs

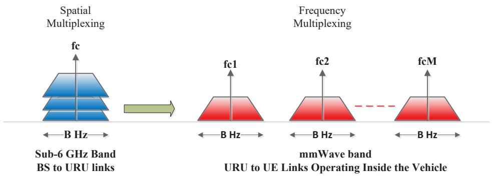

Fig. 2: Relaying of signal from sub-6 GHz licensed band to multiple sub-bands located in the mmWave band

receive the signal from the BS, translate the frequency to the unlicensed mmWave band, amplify the signal and transmit it to the UEs, i.e. the URUs represent AF relays. In order to avoid interference, each URU translates the received signal on a different frequency in the mmWave band, effectively occupying $M \cdot B$ Hz as shown in Fig. 2. The URUs are interconnected via high speed interconnects and can communicate with each other to perform joint reception of the signal.

A given in-vehicle UE receives the signals from M URUs which are used for MIMO decoding of the BS transmit signal.

As the vehicles are in motion, the received signal suffers from severe fading [5]. Additionally, the received signal suffers from Doppler spread due to high mobility which results in inter-carrier interference and channel estimation errors. In this paper, for simplicity and to obtain an upper-bound of the performance of vehicular SUDAS, we assume that the effects of Doppler spread including inter carrier interference are perfectly compensated at the UEs.

1) Vehicular SUDAS Channel Model: Let $\boldsymbol{d}_{\mathrm{DL}}^{[i,k]}$ denote the data-symbol on the downlink subcarrier i intended for user k, and $\boldsymbol{P}_{\mathrm{DL}}^{[i,k]}$ the corresponding transmit precoder matrix, then the received signal at the M URUs is given by

$$\boldsymbol{y}_{\mathrm{S}}^{[i,k]} = \boldsymbol{H}_{\mathrm{B}\to\mathrm{S}}^{[i]} \boldsymbol{P}_{\mathrm{DL}}^{[i,k]} \boldsymbol{d}_{\mathrm{DL}}^{[i,k]} + \boldsymbol{z}^{[i]}, \tag{1}$$

where $\boldsymbol{H}_{\mathrm{B}\to\mathrm{S}}^{[i]}$ denotes the $M \times N$ MIMO channel matrix, and $\boldsymbol{z}^{[i]}$ the additive Gaussian white noise (AWGN) with zero mean and covariance $\sigma^2 \boldsymbol{I}$.

The signal $\boldsymbol{y}_{\mathrm{S}}^{[i,k]}$ is transmitted over the mmWave channel after frequency translation and precoding with a matrix $\boldsymbol{F}_{\mathrm{DL}}^{[i,k]}$ to the K UEs. The signal received at UE k from the M URUs is given by

$$\begin{aligned} \boldsymbol{y}^{[i,k]} = \boldsymbol{H}_{\mathrm{S}\to\mathrm{UE}}^{[i]} \boldsymbol{F}_{\mathrm{DL}}^{[i,k]} \boldsymbol{H}_{\mathrm{B}\to\mathrm{S}}^{[i]} \boldsymbol{P}_{\mathrm{DL}}^{[i,k]} \boldsymbol{d}_{\mathrm{DL}}^{[i,k]} + \\ \boldsymbol{H}_{\mathrm{S}\to\mathrm{UE}}^{[i]} \boldsymbol{F}_{\mathrm{DL}}^{[i,k]} \boldsymbol{z}^{[i]} + \boldsymbol{n}^{[i]}, \end{aligned} \tag{2}$$

where $\boldsymbol{H}_{\mathrm{S}\to\mathrm{UE}}^{[i]}$ denotes the $K \times M$ diagonal channel matrix for the mmWave channel and $\boldsymbol{n}^{[i]}$ the additive Gaussian white noise (AWGN) with zero mean and covariance $\sigma^2 \boldsymbol{I}$.

2) Sum rate: Based on the signal model given above, the sum rate for user k is given by

$$R^{[k]} = \sum_{i=1}^{N_F} s^{[i,k]} \log_2 \det \left(\boldsymbol{I} + \boldsymbol{\Gamma}_{\mathrm{DL}}^{[i,k]} (\boldsymbol{\Theta}^{[i,k]})^{-1} (\boldsymbol{\Gamma}_{\mathrm{DL}}^{[i,k]})^{\mathrm{H}} \right), \tag{3}$$

where

$$\boldsymbol{\Gamma}_{\mathrm{DL}}^{[i,k]} = \boldsymbol{H}_{\mathrm{S}\to\mathrm{UE}}^{[i]} \boldsymbol{F}_{\mathrm{DL}}^{[i,k]} \boldsymbol{H}_{\mathrm{B}\to\mathrm{S}}^{[i]} \boldsymbol{P}_{\mathrm{DL}}^{[i,k]}, \tag{4}$$

$$\boldsymbol{\Theta}^{[i,k]} = \sigma^2 \left(\boldsymbol{I} + \boldsymbol{M}^{[i,k]} \right), \tag{5}$$

$\boldsymbol{M}^{[i,k]} = \boldsymbol{H}_{\mathrm{S}\to\mathrm{UE}}^{[i]} \boldsymbol{F}_{\mathrm{DL}}^{[i,k]} (\boldsymbol{H}_{\mathrm{S}\to\mathrm{UE}}^{[i]} \boldsymbol{F}_{\mathrm{DL}}^{[i,k]})^{\mathrm{H}}$, and $s^{[i,k]}$ are boolean variables denoting whether subcarrier i is assigned to user k.

The precoder matrices $\boldsymbol{P}_{\mathrm{DL}}^{[i,k]}$, $\boldsymbol{F}_{\mathrm{DL}}^{[i,k]}$, and subcarrier allocation variables $s^{[i,k]}$ are chosen to maximize the sum rate. The resource allocation algorithm, based on alternating optimization, from [4] is used to find the optimal precoder matrices and subcarrier allocations.

B. Vehicular SUDAS in 3GPP 5G Networks

The proposed Vehicular SUDAS concept is compliant with the 3GPP 5G Networks scenario. In this scenario, a public transport vehicle such as a bus moving at a high speed is considered. Fig. 1 illustrates the functional blocks of the proposed concept and its applicability in a 3GPP LTE system. The adopted network architecture framework helps in network resource allocation and relaying the data to multiple users facilitating high data rates for a large number of users moving at high speeds [6].

The 3GPP Operations Administration and Maintenance (OAM) system, responsible for 3GPP network management and administration, can fetch network information via the legacy northbound interface called Itf-N. The network information includes network information of the entire Radio

Access Network (RAN) such as traffic load, interference map including key performance indicators (KPIs) such as handover failures, throughput, user locations etc. [7]. The Itf-N interface is also responsible for controlling the network elements, monitoring the network performance and sending network status reports to the 3GPP network management system. To enable interaction of Over-The-Top applications/services (OTT), vertical industries and Mobile Virtual Network Operators (MVNOs) with the network management system, 3GPP has introduced the service capability exposure function (SCEF) [8], [9]. The primary function of the SCEF present at the operator trust domain is to securely enable selective service functionalities via the standard network application programming interfaces (APIs). The SCEF acts as an interface to facilitate interaction between third party applications and the 3GPP network. Such feature also allows third party applications to communicate their service requirements to the 3GPP infrastructure providers which help in adapting the network operations in a dynamic way to satisfy the performance needs of individual services with the aim to deliver desired Quality of Experience (QoE) to the end users. The implementation and amendments in the requests issued by the external third party applications to the 3GPP network provider can be done via establishing and monitoring the Service Level Agreements (SLAs). The interaction between the MVNOs and the 3GPP network may be established via the Type 5 interface, while OTTs or verticals can interact with the network via Application Controller Plane Interfaces (A-CPIs). 3GPP is considering employing APIs that are being developed in different standardization organizations such as Open Mobile Alliance (OMA) API for Machine Type Communication services and GSM Association (GSMA) Open API to enable interaction between other service providers and the 3GPP network. With the help of the framework presented in Fig. 1, the network gains the following capability and flexibility:

- To use Vehicular SUDAS for selected users or (traffic flows) only, depending on the SLAs between OTT and network provider, other users or (best effort traffic) may be served either directly via the BS in a conventional manner or via existing WiFi (non-3GPP) infrastructure.
- In case if the BS-SUDAS link is congested, the Vehicular SUDAS can dynamically transmit data to only selected group of users within the vehicle, thereby maintaining the performance demands of the high priority end users.
- To enable Vehicular SUDAS on-demand at desired locations to minimize Operational Expenses (OPEX).

III. Performance Evaluation And Analysis

In this section, we evaluate the performance of the proposed Vehicular SUDAS scheme via numerical simulations. For the simulation scenario, an outdoor BS with N transmit antennas, M URUs as a part of the Vehicular SUDAS, and K UEs located inside the vehicle is considered. The outdoor-to-vehicle channel is simulated using the QuaDRiGa framework [10]. The mmWave 60 GHz channel is modeled using [11] taking into account indoor metallic reflections [12]. As the focus of the outdoor-to-vehicle channel model is to capture the channel variations due to fading in high mobility, channel variations due to path loss are avoided by restricting the vehicle to a circular track around the BS. Further, the URUs are assumed to be uniformly distributed on the roof of the vehicle, and the UEs are located randomly inside the vehicle. The system parameters are chosen to conform to Long Term Evolution (LTE) Advanced Pro and Wireless Gigabit Alliance (WiGiG) standards for the BS-URU and URU-UE channels respectively. The detailed parameters are listed in Table I. The two scenarios considered for the simulation are as follows:

- In the first scenario, a bus having dimensions LxBxH 15mx2.5mx4m with M URUs travelling at 100 km/h on a circular track around the BS is used.
- In case of the second scenario, a car having dimensions LxBxH 5mx2mx1.5m with a setup similar to the first scenario is considered, where it moves at a speed of 130 km/h.

TABLE I: Table of simulation parameters

BS-URU Common parameters	
BS Antenna Gain	18 dBi
N_F	12000
Subcarrier bandwidth	15 kHz
Overall Bandwidth	180 MHz
K	2
BS-vehicle distance	100 m
Bus scenario	
N	32
M	32
Speed	100 kmph
Car scenario	
N	16
M	16
Speed	130 kmph
Relay-UE, 60 GHz	
Number of subcarriers	336
Subcarrier bandwidth	5.15625 MHz
Effective bandwidth	1.7325 GHz
Max. transmit power	23 dBm

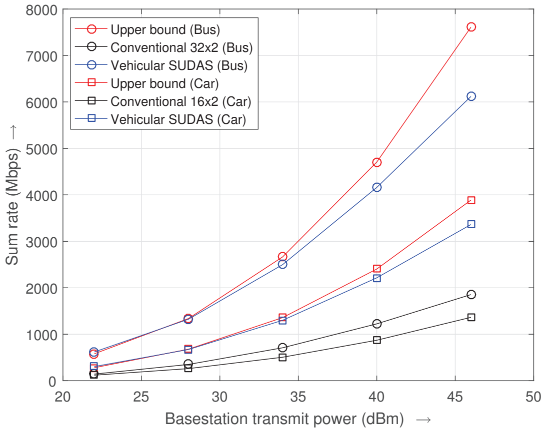

Fig. 3: Performance of the Vehicular SUDAS scheme as a function of the BS transmit power

Fig. 3 presents the sum rate across all users for the proposed Vehicular SUDAS framework as a function of the BS transmit power. The upper bound is the *max-flow-min-cut* [13]. The conventional scheme is obtained for UEs equipped with two built-in antennas, i.e. without Vehicular SUDAS.

The proposed Vehicular SUDAS framework significantly outperforms the sub-6 GHz conventional scheme. The Vehicular SUDAS system in both bus and the car scenarios performs close to the upper bound at low transmit powers. At high transmit powers, the Vehicular SUDAS scheme is limited by

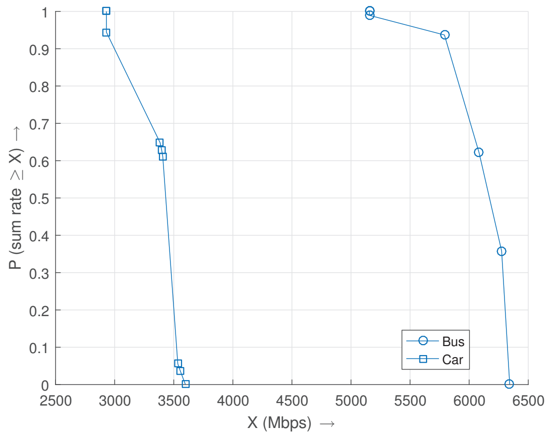

Fig. 4: Complementary cumulative distribution function (CCDF) of the sum rate at 46 dBm transmit power for the proposed Vehicular SUDAS scheme

the mmWave transmit power constraint. Compared to the sub-6 GHz conventional scheme, a significant gain of around 238% for the bus scenario and approx. 148% for the car scenario was observed due to the use of the Vehicular SUDAS.

Fig. 4 shows the complementary cumulative distribution function (CCDF) of the sum rate across all users at 46 dBm transmit power. From the figure, it can be seen that within the vehicle, a minimum sum rate of 3000 Mbps for car scenario, and 5800 Mbps for bus scenario can be obtained with 90% probability indicating that high wireless data-rates in high mobility conditions can be guaranteed at most times.

The standard deviation of the sum rate normalized by the average sum rate for the bus and car scenarios considering Vehicular SUDAS framework is illustrated in Fig. 5. It is observed that the Vehicular SUDAS framework has a relatively lower standard deviation from the average sum rate as a consequence of increased number of receive antennas (higher diversity order), thus resulting in an increased reliability.

IV. Conclusion

In this paper, we presented the Vehicular Shared UE-side Distributed Antenna System (Vehicular SUDAS) which enables high throughput wireless

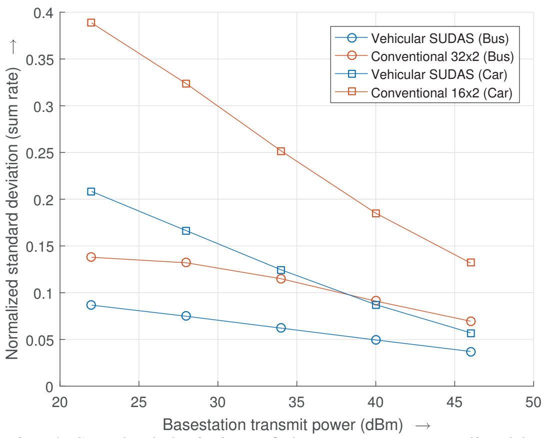

Fig. 5: Standard deviation of the sum rate normalized by the average sum rate

communication in high mobility scenarios. Vehicular SUDAS uses UE-side Radio Units (URUs) located on the body of a vehicle to transform high spatial multiplexing on the outdoor MIMO signal in a licensed band to high frequency multiplexing inside the vehicle in an unlicensed mmWave band. We described the physical layer and network aspects of Vehicular SUDAS and used computer simulations to evaluate the system's performance in practical high mobility scenarios. For the physical layer resource allocation, we used the algorithm from outdoor-to-indoor communication given in [4]. Simulations revealed that the proposed Vehicular SUDAS shows excellent performance, positioning itself as a strong contender for next generation Vehicle-to-X (V2X) communication services.

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