Akinsanya, A., Nair, M., Pan, Y., & Wang, K. (2020). A Dynamic Resource Allocation Scheme in Vehicular Communications. In *A Dynamic Resource Allocation Scheme in Vehicular Communications*
<https://doi.org/10.1109/INFOCOMWKSHPS50562.2020.9162889>

Peer reviewed version

Link to published version (if available):
[10.1109/INFOCOMWKSHPS50562.2020.9162889](https://doi.org/10.1109/INFOCOMWKSHPS50562.2020.9162889)

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A Dynamic Resource Allocation Scheme in Vehicular Communications

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Abstract—A switched-beam based multiple-input-multiple-output (MIMO) vehicle-to-infrastructure (V2I) system can grant better system reliability as the signal-to-interference-plus-noise ratio (SINR) can be significantly optimized. In order to maximize the number of served vehicles by the simple switched-beam based V2I system, it is crucial to additionally introduce vehicle-to-vehicle (V2V) communication because (i) more than one vehicle might occupy a beam coverage, and (ii) vehicles may be out of the coverage region of a beam. In this paper, we proposed a cooperative infrastructure-beam allocation (IBA) and location-estimation (LE) scheme to optimize system coverage and reliability. IBA is an SINR optimization algorithm, and LE is a location-based proximity service for V2I and V2V communications respectively. Our simulation results show that a reliable beam coverage region in switched-beam V2I can be achieved with flexible value of SINR threshold. Also, the outage probability and average rates are directly dependent on set SINR thresholds. Finally, cooperation between V2I and V2V communication significantly improves the utility ratio which is further used as a metric for reliability.

Index Terms—Millimeter-Wave, V2X, Infrastructure-beam Allocation, Location-estimation, RRH, MIMO, Reliability.

I. INTRODUCTION

Recently, millimeter-Wave (mm-Wave) multiple-input-multiple-output (MIMO) has formed an integral part of the techniques to provide ultra-reliable and low-latency communication (URLLC) in Intelligent Transport System (ITS) [1]. mm-Wave MIMO, in particular, now plays symbolic part in vehicle-to-everything (V2X) by means of vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V2I) communications to provide safety-related services to vehicular users. In V2X communications, most authors have recently prioritized their focus mainly on how to increase the system capacity, thus sum-rate maximization [2], [3], [4], [5]. Particular importance has also been attached to how to guarantee the quality-of-service (QoS) in V2X in order to ascertain a reliable communication in the event of providing critical services such as delivery of safety messages. In order to provide a better QoS, authors in [2] assumed that all vehicles have perfect knowledge of the channel in a mm-wave analog beamforming system, i.e. perfect channel state information (CSI) and this assumption seems too optimistic in the case of moving vehicles that emanate into quasi-static or dynamic channels with imperfect CSI. Authors further neglected the effect of inter-beam interference. In order to increase the throughput of a vehicular communication system, authors in [4] proposed a beam-frequency algorithm. The assumption of fixed vehicles' position is again a radical preposition. In most cases, it is neither clear nor known how

to obtain this SINR threshold value from the requirements of V2I communications, which usually refer to transmission with a certain reliability and within a certain time period. Though, [2] and [4] assume that the achieved SINR should be above a particular threshold. Moreover, the EU 5G project METIS considered that 1600 byte packets should be received within 5ms and with a reliability of 99.999% to deliver traffic safety applications [5]. While switched-beam based system has been considered as a beamforming approach which features fixed number of beam patterns that are simultaneously directed toward different predefined angular directions to cover a cell range and equitably necessitates the principle of line of sight (LoS) [6], MIMO technology allows formation of larger number of beams and this emanates to beam allocation problem because approximately all the users can select the best beam for communication as only some of the beams can be allocated while unallocated beams are considered switched-off. Since the number of users is generally more than the number of beams in switched-beam based system, which results to allocation of all beams to users for efficient beam switching, hence we adopt Butler Matrix [7] as the conventional method to form beams.

In this paper, we propose a dynamic resource allocation technique into a scenario, where the number of beams is more than the number of vehicle, and this involves a cooperative application of infrastructure-beam allocation (IBA) for V2I and location-estimation (LE) service for V2V, which supports autonomous vehicle selection [8], (wherein more than a vehicle occupies a beam coverage), to improve outage and maximize network coverage. Our proposed solution exploits the use of dedicated remote radio head (RRH) [9], [10], [11], [12], [13], co-located within an existing traffic infrastructure. We acknowledge speculative properties of V2I, such as LoS channel condition with imperfect CSI [14], [15].

- We study a cooperative SINR-aware beam allocation scheme that accounts for QoS requirements of vehicles by taking into consideration the location uncertainties.
- We formulated an SINR optimization problem for V2I to ensure reliability amongst all the vehicles within the coverage area.
- We proposed an infrastructure-beam allocation (IBA) and location-estimation (LE) algorithm as a solution to the problem. We present our simulation results that the outage probability corresponds directly with the coverage regions.

Fig. 1. System model for a dynamic vehicular communication configuration

II. SYSTEM MODEL

We consider a downlink communication system consisting of a dedicated RRH which features a multi-user mm-Wave switched-beam directional antenna of equally spaced linear array antenna elements to provide different traffic information, and a number of dual-antenna aided vehicles, along a road segment of length d_R as shown in Fig. 1. The RRH simultaneously form B beams toward K dual-antenna (for simultaneous V2I and V2V communications at frequencies f_1 and f_2 respectively) aided vehicles. We adopt the position uncertainty model based on estimated and actual user locations considering Manhattan mobility model in [16]. Since $B > K$, we assume that only one beam can serve one vehicle at a time and unserved vehicles form the candidates for inter-vehicle (V2V) association. We assume that (i) the RRH is located at the centre of d_R (ii) the spatial locations of the vehicles are quasi-static during one time frame i.e. the locations do not record a significant change within a frame, but dynamic over multiple frames and (iii) all unallocated beams are considered switched-off.

Let $\mathcal{B} = \{1, \dots, B\}$ denotes set of beams, and $\mathcal{K} = \{1, \dots, K\}$ denotes set of vehicles. The received power, $P_{k,b}$, at k -th vehicle due to the b -th beam, for the V2I LoS channel at f_1 is given as

$$P_{k,b} = \sum_{b=1}^B c_{k,b} \cdot p_b \cdot D_b(\theta_k) \cdot h_{k,b} \quad (1)$$

where $D_b(\theta_k)$ is the directivity of the b -th beam with respect to an angle of departure (AoD) of θ_k to the k -th vehicle. $h_{k,b}$ denotes the Rician channel gain between the b -th beam of the RRH to vehicle k . $c_{k,b} \in \{0, 1\}$ represents beam allocation indicator. $c_{k,b}=1$ if beam b is allocated to vehicle k ; otherwise, $c_{k,b} = 0$. Therefore, $\sum_{b=1}^B c_{k,b} \leq 1$. The transmit power, p_b , allocated on beam b when $c_{k,b} = 1$ is given by

$$p_b = \frac{P_t}{\sum_{k=1}^K \sum_{b=1}^B c_{k,b}} \quad (2)$$

where P_t is the total RRH power. The time varying channel impulse response $h_{k,b}$ is given as

$$h_{k,b} = \sqrt{\frac{1}{\rho_{k,b}}} \sum_{l=1}^L \alpha_l \delta[t - \tau_l(t)], \quad (3)$$

where at time t , α_l is the path amplitude of the l -th resolved path, $\tau_l(t)$ is the time varying delay for the l -th path, δ is the Dirac delta function and L is the number of paths. $\rho_{k,b}$ is the average free-space pathloss between the paired vehicles. Therefore, the maximum achievable (V2I) rate for vehicle k associated with the b -th beam can be given by

$$R_k^{V2I} = W^{V2I} \log_2(1 + \gamma_k) c_{k,b}, \quad (4)$$

where W^{V2I} is the V2I signal transmission bandwidth.

$$\gamma_k = \frac{P_{k,b}}{I_b + \sigma_k^2}.$$

γ_k is the the received SINR and I_b denotes the inter-beam interference. σ_k^2 is the additive white Gaussian noise (AWGN) power of the receiver.

Let $\mathcal{K}_z = \{1, \dots, k_z, \dots, K_z\}$ be the set of vehicles associated with RRH beams. Hence, K_v denotes the vehicle candidates available for V2V pairing ($K - K_z$) which establish direct communication links with K_z vehicles. It is assumed that all the vehicles are moving in the same direction of travel (Fig. 1). The candidates for V2V pairing are selected from the K_v pool. The maximum V2V rate at time t for any k_v -th vehicle is given by

$$R_{k_v}^{V2V} = \sum_{k_z \in \mathcal{K}_v} \log_2(1 + \gamma_{k_v}) \quad (5)$$

where

$$\gamma_{k_v} = \frac{P_{k_z}^T h_{k_v}(t)}{I_{k_v} + \sigma_k^2}$$

where $P_{k_z}^T$ is the transmit power of the k_z -th vehicle ($k_z \in \mathcal{K}_z$) which pairs with the vehicle k_v and I_{k_v} is the interfering signal to vehicle k_v paired to k_z from all the other vehicles in the set $\mathcal{K}_v$. h_{k_v} is the V2V time varying channel impulse response.

The coverage area of every beam can be identified by defining its outage probability (OP) [17], [18], [19], which is the probability that the output SINR falls below a specified SINR threshold value, γ_{th} . Some vehicles might be out of a specific coverage region of an RRH beam and if a vehicle is not served for a long period, system reliability can be compromised, which is undesirable for reliability sensitive scenario. Therefore, reliability remains a crucial performance measure for vehicular communication systems. In this paper, the utility ratio is further used to evaluate the system reliability, and it is defined as the ratio of the number of served vehicles to the total number of vehicles within the network coverage area.

$$\text{Utility Ratio} = \frac{\sum_{k=1}^K \sum_{b=1}^B c_{k,b}}{K}. \quad (6)$$

III. SINR OPTIMIZATION ALGORITHMS

A. Problem Formulation

In V2I communication, reliability is reflected by packet error rate (PER) which is related to the received SINR values. Our goal is to maximize the SINR to improve reliability based on quality state information (QSI) to optimize reliability amongst all available vehicles within the coverage area. The IBA optimization problem for V2I is formulated as

$$\max_{c_{k,b}} \sum_{k=1}^K \sum_{b=1}^B \gamma_k \quad (7)$$

$$C1: \sum_{b=1}^B c_{k,b} \leq 1, \quad \forall k \in K \quad (7a)$$

$$C2: \sum_{k=1}^K c_{k,b} \leq 1, \quad \forall m \in B \quad (7b)$$

$$C3: c_{k,b} \in \{0, 1\}, \quad \forall k \in K, \quad (7c)$$

Constraints (7a)-(7b) indicate that each beam can be used by at most one vehicle and only one vehicle can associate with at most one beam. Constraint (7c) specifies the decision variables of the formulated problem, which takes a value of 1 if beam b is switched-on and allocated to at most one k vehicle and 0 otherwise.

B. Infrastructure-Beam allocation (IBA) algorithm

All vehicles at all corresponding angular location compute the received SINR of M -switched beams using the corresponding directivity of each beam and returns the information on maximum SINR with the corresponding index to the RRH. The RRH thereafter assigns each beam to the best vehicle with largest SINR value. Hence, IBA algorithm (Algorithm 1) consists of three steps.

- Step 1. A table is formed separately for different vehicle locations and number of beams. vehicle angular location is set based on θ_k .
- Step 2. Each beam is concurrently invited by each vehicle within the coverage of the beam for infrastructure-vehicle pairing and stores the beam directivity power for all invited vehicles.
- Step 3. Each beam searches the vehicle with largest directivity gain, thus SINR and performs infrastructure-vehicle pair in order to satisfy constraint (7b).

C. Location-Estimation (LE) algorithm

The spatio-temporal uniqueness of vehicular communications allow vehicles at close proximity to form V2V pair, and also enhances mitigation of nearby-interference. The instant geographical coordinates of each vehicle at the beginning of each time frame is sufficient for a successful V2V transmission. LE algorithm is a V2V autonomous vehicle selection algorithm based on adaptive heuristic search method to produce short communication path routing due to a global search capability.

Algorithm 1 IBA Algorithm

```

1: Input:  $\mathcal{B} = \{1, \dots, B\}$ ,  $\mathcal{K} = \{1, \dots, K\}$ ,  $\forall k \in K$ ,
    $\forall b \in B$ ,  $c_{k,b} \leq 1$ 
2: for  $k = 1$  to  $K$  do
3:   for  $b = 1$  to  $B$  do
4:      $b = \max_{c_{k,b}} \{D_b(\theta_{k,b})\}$ ;
5:     If  $\sum_{k \in \mathcal{K}} c_{k,b} = 0$  then
6:        $c_{k,b} = 1$ ;
7:     else
8:        $k^* = \operatorname{argmax}_{c_{k,b}} c_{k,b}$ ;
9:       Select vehicle  $k^*$  according to (7)
10:       $k = \operatorname{argmax}_{c_{k,b}} [\gamma_k]$ ;
11:      Allocate V2I beam  $b$  to vehicle  $k$ 
12:       $c_{k,b} = 1, c_{k^*,b} = 0 \quad \forall k \neq k^*$ ;
13:    end If
14:  end for
15: end for

```

LE algorithm maintains the number of vehicles in proximity within a distance threshold and consists of three steps.

- Step 1. Each k_z - vehicle searches and identifies its nearest neighbouring vehicle in K_v pool. K_z vehicles are potential Tx(s) of V2V communication while vehicles in K_v pool are the potential V2V Rx(s).
- Step 2. Each k_z vehicle computes the Euclidean distance to its nearest neighbouring Rx(s) to establish V2V communication link. Let u_{k_z} and u_{k_v} be the geographical coordinates of the V2V pairs k_z and k_v vehicles respectively. The Euclidean distance is computed as $d_{k_z, k_v} = \|\mathbf{u}_{k_z} \pm \mathbf{u}_{k_v}\|$.
- Step 3. K_z vehicles perform autonomous vehicle selection and establish inter-vehicle (V2V) association with any available k_v -th vehicle.

IV. PERFORMANCE ANALYSIS AND EVALUATION

We consider the scenario shown in Fig. 1. A system of a dedicated RRH with $B = 6$ directional beams and $K = 4$ dual-antenna aided vehicles are deployed for vehicular mobility in a single direction of travel. Simulation results are presented to evaluate the performance of outage probability, achievable rates, average rate and utility ratio of switched-beam based system for a vehicular communication system. The RRH is at the centre of the coverage range d_R at a height of 70m from the road. Also, the cooperative performance of IBA and LE algorithms is demonstrated via the MATLAB simulation platform. We adopt the close-in (CI) mm-Wave propagation model in [20], [21], written as $PL(f_1, d)[dB] = 20\log_{10}(4\pi f_1/c) + 10n\log_{10}(d) + X_{\sigma_{SF}}$, where c is the speed of light (m/s), d is the distance (m) which is the ratio of Tx-Rx distance d_T (d_{k_z, k_v}) to reference distance d_o , which is 1m. n is the pathloss exponent, and $X_{\sigma_{SF}}$ is the shadow fading (SF) which is a zero-mean Gaussian distribution, with a standard deviation of σ_{SF} . Table I describes the simulations parameters.

Fig. 2 shows the outage probability with respect to the SINR values for the corresponding beam coverage region at

TABLE I
COMPUTATIONAL PARAMETERS

Notation	Parameter
Carrier Frequency Band	5.9 GHz (f_1); 5.860 GHz (f_2)
Noise Variance	-174 dBm/Hz
TX Power	33dBm for RRH; 30dBm for vehicle
Antenna height	2.5 m for RRH; 1.2 m for vehicle
Number of vehicles (K)	4
Number of Beam (B)	6
Path-loss Model	3D Urban Micro [20], [21]
Modulation scheme / Bits	QPSK / 2^8
Total RRH Tx Power	50 dBm
Beam Directivity	35 dB

the set SINR threshold of -6.5 dB. The outage probability can be significantly minimized by choosing smaller value of SINR threshold though it might be challenging to distinguish between individual beam coverage region. It is shown in Fig. 2 that the outage probability decreases with increasing values of received SINR over the angular location of respective beam coverage regions. The setting of SINR threshold can be flexible to ascertain a reliable and contiguous beam coverage region at any road segment (d_R) of interest.

Fig. 2. Outage Probability within the beam coverage of the angular locations with IBA algorithm. $B = 6, K = 4$.

Fig. 3 plots the rate in bits/s for cooperative IBA algorithm at bandwidth $W^{V2I} = 1$ GHz. 100000 Monte-Carlo iterations are performed for each angular location and their average is shown. Clearly, individual rate corresponding to the beam coverage region can be observed, and it can vary between 1Gbps to 600Mbps within the coverage region. When the probability of outage is high, it can further reduce. As explained previously, adjusting the SINR thresholds could improve the rates at the expense of higher overhead resulting from the need of distinguishing between the beam coverage regions.

Fig. 4 compares the average rate for IBA, LE and cooperative IBA+LE algorithms for resource allocation optimization over the average vehicle distance. An increasing V2V distance

Fig. 3. Rate for all angular locations. $M = 6, K = 4$

tends to reduce the effect of interference on associated V2I links which geometrically decreases the value of SINR, hence average rate. However, the achievable rate is also dependent on the total number of vehicle served (utility ratio) as well.

Fig. 4. Average rates for IBA, LE and IBA+LE algorithm. $B = 6, K = 4$

Fig. 5 compares the V2V+V2I utility ratio to the V2I utility ratio only. It is clearly seen that the utility ratio and hence reliability significantly improved with the joint application of IBA and LE algorithms which facilitates simultaneous V2I and V2V communications. Moreover, as the number of vehicles increases, the utility ratio gradually increases.

V. CONCLUSION

This paper has presented the performance of a cooperative and dynamic SINR-aware resource allocation scheme, which features infrastructure-beam allocation and location-estimation proximity-based service for V2V communications.

Fig. 5. Utility ratio comparison for V2V+V2I vs. V2I only. $B = 6$. $K = 4$

The IBA technique, presented a dynamic use of multi-directional beams at the infrastructure serving available vehicles and LE proximity-based service accounts for inter-vehicle association to simultaneously serve vehicles that are out of infrastructure-beam coverage. This paper has proposed and applied both IBA and LE algorithms with flexible SINR threshold. Results confirmed that corresponding outage and utility ratio solely depends on the set SINR threshold. Also, the outage probabilities correspond directly with the beam coverage regions. Finally, results prove that cooperative SINR-aware resource allocation and location-estimation proximity-based service for V2I and V2V respectively improves the coverage, average rate and utility ratio, thus the reliability of the vehicular communication systems.

ACKNOWLEDGEMENT

This work is currently supported by the European Union's Horizon 2020 Research and Innovation Programme, grant agreement No: 814956 (5G-DRIVE).

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