# A Resource Allocation Scheme for Multi-User MmWave Vehicle-to-Infrastructure Communication

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**Abstract.** Millimeter wave (mmWave) communications is increasingly seen as a means to meet the communication constraints demanded by the emerging Intelligent Transportation Systems (ITSs) applications. In this paper, a novel directional MAC protocol is designed that encompasses a resource allocation strategy unique to the mmWave Vehicle-to-Infrastructure (V2I) network in an urban setting. We specifically consider a network where each Base Station (BS), equipped with hybrid beamforming antenna arrays, concurrently serves multiple vehicles. Using models for the coherence bandwidth and coherence time specific to the mmWave vehicular channel, a robust resource allocation scheme is provided that the BS utilizes towards efficient multiuser scheduling. The novelty is in the multi-users scenario, time-frequency resource allocation designed specifically for the mmWave channel. To evaluate the network, a channel simulator is entirely built in MATLAB to carry out the link layer simulations.

**Keywords:** 5G, Vehicle-to-Infrastructure (V2I) communications, Directional MAC protocols, Millimeter wave (mmWave) antenna arrays, Hybrid beamforming, User mobility

## 1 Introduction

Vehicles equipped with increasing number of on-board sensors are progressively rolled out and are envisaged to make driving safer and automated. The number of on-board sensors currently on vehicles is at 100 units and is likely to double by 2020 [1]. Companies such as Ford and Waymo, are accumulating autonomous kilometers on public roads in test vehicles. Locally sensed data, hazard information can be shared with nearby vehicles via a road-side unit to realize smart cruise control systems [2]. Accurate, detailed maps, downloaded from road-side infrastructure can complement sensor data to realize fully autonomous driving [3]. Streaming and downloading UHD videos is possible. V2I communications can enable such applications provided vehicles can exchange data with a nearby infrastructure using high-speed mmWave links over short durations.

ITS depend on the Dedicated Short-Range Communication (DSRC) standards traditionally for vehicular communications. DSRC standard such as IEEE 802.11p has a maximum of 75 MHz reserved in the 5.9 GHz for ITS use. Despite its PHY layer being robust to Doppler spread and low-latency, it suffers from high collision probabilities under medium to high loads due to its contention based random access. Moreover,

the realistic maximum data rate does not exceed 6 Mbps [4]. This makes it unsuitable for reliable communication. The 3GPP's Long Term Evolution-Advanced (LTE-A) that specifies channel bandwidth up to 100 MHz has been suggested for use in vehicular communications [5]. But, the maximum data rate it supports is limited to 100 Mbps and end-to-end latencies exceed 100 ms [2]. Therefore, both DSRC and LTE-A fall short of meeting the communication constraints posed by the emerging ITS applications. Additionally, there is a lack of an universal agreement on V2I communication protocols for automotive safety among carmakers and mobile carriers.

Recently commercialized millimeter Wave (mmWave) systems show promise in ensuring Gigabit-per-second throughput and latencies smaller than 10 ms [6]. This can largely be attributed to the availability of contiguous GHz-wide spectrum in the mmWave regime. But, an order of magnitude increase in carrier frequency and very high symbol rate more than 1 GS/s makes mmWave systems, more so in the vehicular context, particularly prone to poor propagation characteristics, hardware impairments, and Doppler induced channel's frequency selectivity.

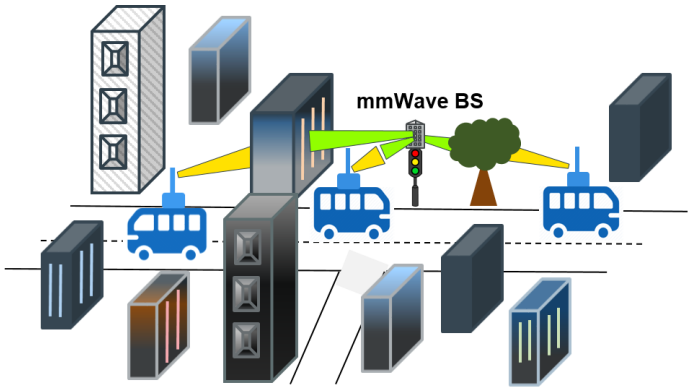



**Fig. 1.** A V2I network supporting directional links among mmWave BS and its associated multiple MSs

In mmWave systems, to combat the high path loss, both the base station (BS) and mobile stations (MSs) will employ highly directional beams realized using the large antenna arrays (see Fig. 1) to provide sufficient received signal power. Due to its high sensitivity to shadowing by obstacles, it is considered to be suitable for mostly short range (a few hundred meters) and point-to-point LOS communication [7]. The usage of highly directional antennas helps in achieving high-quality links since thermal noise dominates interference in mmWave links [8]. However, given the mobility of the vehicles and mobility-induced occlusions, frequent repointing of the beams is required and will cause misalignment of the beams resulting in loss of communication. This problem is addressed in [9] which proposes low-cost phased array module based highly directional mmWave steerable antenna design (employing MU-MIMO transmission mode) and prototypes with practical configurations shown to satisfy the require-

ments for gain, power, and beam-steering properties. Still, the beam training procedure is time-consuming and represents a significant time overhead limiting the useful data rate. Recent work suggests combining out-of-band information from on-board automotive sensors, communication signals at sub-6 GHz and GPS signals for fast, accurate mmWave V2I beam alignment [10] in high mobility scenarios.

Going forward, we identify and address two significant challenges i.e. resolving multiple concurrent access requests and efficient resource allocation, towards realizing robust mmWave V2I communications.

We consider a BS positioned at the side of the road installed atop, say, the traffic lights, the lamppost, or other road-side infrastructure handling the V2I communications between multiple vehicles. Multiple vehicles can be making simultaneous access requests (see Fig. 2), which means that multiple request-to-send (RTS) packets from the MSs can potentially collide at a BS. Since each MS transmits independently while being deaf to others' transmissions, collisions are likely to be frequent and has to be embraced. Thanks to hybrid beamforming techniques, multiple concurrent beams can be realized, and further exploiting the spatial diversity, the multiple RTS requests can be resolved as each request can be serviced with a distinct RF chain. The mmWave channel is identified to possess a sparse nature due to the use of large bandwidths and multiple closely spaced antennas.

Specifically, the sparsity property can be exploited by employing a compressed sensing technique to reduce the complexity of the channel estimation. The Direction of Arrival (DoA) estimation can be carried out using compressive sensing by selecting only a subset of antenna elements at BS. The selected subset of the antennas serves the few MSs requesting access from the BS at any given time.

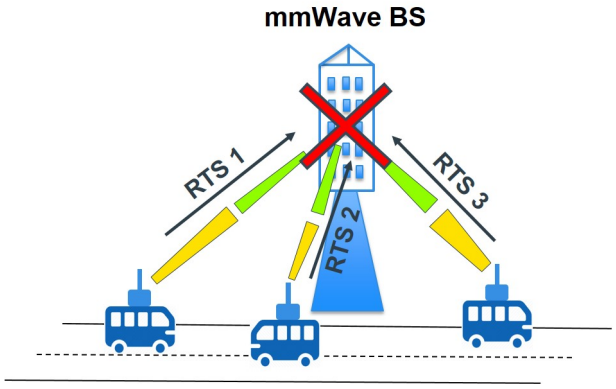



**Fig. 2.** Multiple colliding MSs' RTS

Post the successful association, the BS must then quickly schedule and serve the associated vehicles. The time-frequency resource at the BS must be efficiently allocated considering the asymmetric communication requirements of the vehicles. [11] show that time-frequency scheduling is more frequent compared to the spatial scheduling

based on a reasonable change in the covariance matrix of the channel. Moreover, hybrid beamforming results only in few beam directions (sparse in space), and so, we can restrict the packing to time and frequency dimension.

This work has the following contributions:

- **Novel directional multiuser MAC protocol** Since only a finite number of beams and a finite time-frequency resource are available at the BS, not all vehicles requesting access can be concurrently served. We design a MAC protocol that helps the BS service the vehicles in a manner that resource efficient and fair. This is the first multi-user solution considering a fully hybrid beamforming scheme where the BS can receive concurrently in multiple beam directions.
- **Resource allocation scheme:** We present a scheme where the BS allocates the time-frequency resource to every MSs based on solving a rectangular bin packing problem. Each time-frequency resource block associated with every vehicle is represented by a smaller rectangle, whose edges are determined by the vehicle's data needs and the duration it will continue to be in LOS with the BS from the time it sent its request. The objective involves a classic combinatorial optimization problem required to minimize the unused time-frequency resource at the BS.

The rest of this paper is organized as follows. In Sec. 2, the background on issues specific to mmWave V2I communication, hybrid beamforming is presented. We discuss related work in Sec. 3. In Sec. 4, we will formalize the design approach, followed by the presentation of the multiuser directional medium access protocol in Sec. 5. In Sec. 6, we then discuss the resource allocation scheme for multi-user mmWave vehicular communications. Here, we first design the radio frame specific to the scenario addressed and then, to enable scheduled multi-user efficient access of the finite time-frequency resource, we will qualify the packing objective, packing criteria. We then show how the resulting packing problem is identical to that of the online rectangular bin packing. The need for sophisticated, inexpensive tools to support vehicular simulations for link layer operations is stressed in Section 7. We then evaluate the performance of the resource allocation scheme using the built simulator and discuss the results. Sec. 8 concludes the paper.

## 2 Background

### 2.1 Issues Specific to mmWave V2I Communication

Millimeter wave communications differs from microwave in a number of ways: (i) different channel models, (ii) new hardware constraints due to the high operating frequency and bandwidths, and (iii) large arrays employed at both the transmitter and receiver.

• There is a lack of accurate channel models, as well as extensive measurement studies that characterize the vehicular scenarios [1].

• Outdoor millimeter wave communications suffer from high propagation and penetration losses. For this reason, frequency bands centered at 28 GHz, 38 GHz, 73 GHz, and in the 81–86 GHz range [12] have gained considerable interest as the losses are relatively less.

• In mmWave urban environments, penetration through just one wall incur losses $\sim$30 dB, particularly for buildings structures with steel concrete and energy saving windows. This implies propagation that involves penetrating through the buildings is not a relevant effect [13]
• Gaseous absorption, in particular, is insignificant for the cellular deployments, where base station spacing's might be on the order of 200 m [14].
• The use of directional antennas makes the mmWave links quite sensitive to occlusions/blockages resulting from concrete buildings, foliage, pedestrians.
• The availability of strong LOS/NLOS links is shown to be highly location and orientation specific implying the strongly site specific nature of mmWave link [15]. This suggests paying close attention to the geometry and building materials of the specific urban environment at a potential mmWave BS location.
• To overcome the severe shadowing and path loss at millimeter-wave, amplifiers need to generate enough power by operating in the saturation region. As a result, the received signal is likely to be severely affected by nonlinearities [12].
• mmWave communications can be impacted significantly by CFO (due to clock frequency mismatch) and phase noise (due to imperfections in the local oscillators) as oscillators at millimeter-wave frequencies are not as accurate compared to those at microwave frequencies [16]. This can become important when dealing with the Doppler spread arising due to the user mobility. Doppler spread may introduce different frequency shifts [17]. Carrier synchronization algorithms that are usually designed to track only one frequency offset will find it difficult to eliminate the frequency spread caused by Doppler.
• In mmWave, given the need for quick reconfiguration and the reduced coherence due to high mobility, the beamswitching technique may be preferred over beamsteering [18, 19]. In this approach the beam patterns that can cover the entire region are pre-configured and the final tuning concerns only the selection of one of these patterns.

### 2.2 Hybrid beamforming

Analog beamforming is not suitable for multi-user mmWave systems for it does not scale with the number of users. On the other hand, digital beamforming requires as many radio-frequency (RF) chains as the antennas used. This is prohibitive due to the high cost and power consumption at mmWave. Hybrid beamforming reduces the complexity of digital beamforming while improving the performance of analog beamforming [20]. Hybrid analog-digital beamforming is increasingly preferred in multi-user systems as it considers both digital and analog precoder/combiners and allows for more designing freedom than analog beamforming. As a result, few RF chains can drive a large number of antennas making for a feasible architecture in mmWave as it best trades off complexity (energy losses) and flexibility. The multi-user association phase will benefit from a fully hybrid precoding/combining scheme wherein both BS and MSs may form multiple beams.

Unlike analog only precoding/combining that allows only one beam per time, hybrid precoding allows for multiple beams thanks to spatial multiplexing which is useful in multi-user scenario [21]. Considering the case that the BS allows multiple streams and communicates with each MS via only one stream, we have the number of streams $N_S =$

$U$. It is reasonable to assume that the number of beams is equal to the number of users since spatial multiplexing gain of a multi-user hybrid precoding system, with $U \leq N_{RF}$, is limited by $min(N_{RF}, U)$, where $N_{RF}$ is the number of RF chains and $U$ is the number of users [22].

## 3 Related Work

In the V2I context, progress has been made in tackling technical challenges relating to accurate channel models, reduction in beam alignment overhead, Doppler compensation mechanisms.

### 3.1 Fast beam configuration using out-of-band information

The IEEE 802.11ad standard specifies a MAC layer which involves an exhaustive beam searching step. This is well suited for an indoor environment given the high likelihood for human blockages and incidental motion such as turning.

### 3.2 User Association Phase

The aim of the user association phase is to robustly align beams and quickly attain connectivity, a procedure to be successfully completed prior to communication. Unlike microwave, initial access in mmWave is very challenging due to the need for beam alignment [23]. Significant delay can be incurred by wastefully testing useless beam combinations at both ends. This phase necessitates the BS periodically transmit synchronization signals while the users scan for the presence of these signals to detect the base station, and learn the timing and direction of arrivals.

[24] proposes a directional cell discovery procedure where the mmWave BS uses omnidirectional and random directional transmissions, and the MS performs either analog, digital or hybrid beamforming. The use of omnidirectional transmission of synchronization signals at the BS during user association will reduce coverage, while random directional transmission will result in large delays. Moreover, the procedure employs either random beamformers or no beamforming for the transmission of synchronization signals. Clearly, more sophisticated beamforming or even deterministic search patterns are likely to prove superior. We account for the above shortcomings in the design of our user association phase in our MAC protocol.

### 3.3 Directional MAC Protocols

Carrier sense based protocols like the CSMA/CA is ill-suited for contention resolution in mmWave networks as Clear Channel Assessment (CCA) will be impaired due to the high directionality of the beams. [25] provides a modified CSMA/CA protocol, aimed at current mmWave standards, that addresses the inefficiency of prolonged back-off time (CSMA/CA) by the inclusion of a collision notification signal. However, they make simplistic impractical assumptions towards resolving multiple RTS that collided at the BS. We identify this as one of the critical MAC layer design aspects.

### 3.4 Coherence Time and Coherence Bandwidth

**Coherence Time ($T_C$)** High Doppler, arising from mobility of the *MS*, results in a reduced channel coherence time, introducing time-selective fading. The Doppler spread is directly proportional to the carrier frequency. This means that for the mmWave radios, that operate at an order of magnitude higher frequency compared to microwave bands, it will be 10 to 30 times higher. The classical result is that the coherence time is inversely proportional to the maximum Doppler frequency, $T_C \sim 1/f_D$ (where $f_D = \frac{vf}{c}$). This however is not accurate for mmWave systems employing directional antennas. The authors in [26] show that the directional reception leads to smaller Doppler spread resulting in a larger coherence time and provide a mathematical relation between coherence time, in LOS conditions, and small beam-width $\theta$ of the MS:

$$T_C(\theta) = \frac{D_\lambda}{f_D \sin(\alpha_{LOS})} \cos^{-1}(2\theta^2 \log R + 1) \text{ where } D_\lambda = D/\lambda \tag{1}$$

The description and typical value of the parameters involved in $T_C(\theta)$ is given in Table 1. They further show that the chosen range of $\theta$ must feasible in practice and makes

**Table 1.** Typical value of parameters in $T_C(\theta)$

| Parameters | Description | Typical Value |
|---|---|---|
| $\theta$ | Vehicle antennas' beamwidth | $5^\circ$ |
| $v$ | Max. receiver speed | 30 m/s |
| $f_c$ | Carrier frequency | 60 GHz |
| $\lambda$ | Carrier wavelength | 5 mm |
| $f_D$ | Max. Doppler | $v/\lambda$ |
| $D$ | Tx-Rx distance | 50 m |
| $\alpha_{LOS}$ | Angle of arrival of the LOS path | $0^\circ - 90^\circ$ |
| $\mu_r$ | Pointing angle | $0^\circ - 90^\circ$ |
| $R$ | Target correlation | 0.5 |

for beams that aren't too narrow or too wide, so that both the pointing error and the Doppler do not limit performance.

Moreover, [26] describes a beam coherence time, $T_B$, with regards to the constant need for beam realignment owing to the mobility of the vehicle. The authors define $T_B$ as the duration after which the signal power drops by half due to beam misalignment. It is shown that for realistic parameter settings, $T_B \gg T_C$ (by an order of magnitude), implying that beam realignment needn't be performed in the interval, $T_C$, during which the vehicle is communicating.

**Coherence Bandwidth ($B_C$)** The authors in [27] provide a best description model,

$$B_C = \alpha \cdot e^{-\beta \cdot RMS-Delay-Spread} \tag{2}$$

for the relationship between coherence bandwidth and root-mean-square (rms) delay spread in an indoor setting as there is no clear relationship between those two parameters. Moreover, they inform us of the random behavior of delay spread with receiver position for channels dominated by a strong direct path. The measurement campaign [28] carried out at 62.4 GHz in suburban street setting with wide-beam-width antennas show that the coherence bandwidth is highly variable with the location of the *MS* relative to the *BS*. Therefore, measuring the correlation coefficient between the signal envelopes over several frequency spacings are insufficient to characterize the frequency correlation function of the channel. Coherence bandwidth ($B_C$) is shown in [29] to depend on the street layout, frequency, antenna heights, and street width. In LOS propagation, however, the multipath components are sparse and, in contrast to 28 GHz, measurements at 73 GHz found fewer, but stronger multipath components (Refer to Table V in [30]). Delay spread [31] is generally much lower due to the usage of directional antennas. Measurement campaign [32] carried out in urban low-rise environments in LOS environments, determined that using beamwidth of $10^{\circ}$ at 28 GHz, RMS delay spreads (over all TX-RX location combinations) are less than 25 *ns* (with $\mu \sim 8$ *ns*). The experimental study [33] carried out at 55 GHz with narrow beamwidth antennas in an urban mobile setting estimates the coherence bandwidth to be greater than 66 MHz in a large number of cases and the smallest value of coherence bandwidth to be about 20 MHz. Also, the authors point out the usefulness of estimating the delay spread from the measured coherence bandwidth,

$$B_C = \frac{1}{2\pi \cdot Delay - Spread} \tag{3}$$

The above estimate despite being insensitive to the shape of the delay distribution (considering a simple geometrical model of the channel) is very in much in agreement with the value of $B_C$ produced from a smooth exponential distribution. From the observations in [31], [32], and [33] discussed here, we can specify the range of coherence bandwidths:

$$20MHz \leq B_C \leq 132MHz$$

We can model the $B_C$ as random samples drawn from a probability distribution $P_{B_C}$ with the following property:

$$P_{B_C}(20MHz \leq B_C \leq 132MHz) = 1 \tag{4}$$

$$P_{B_C}(B_C \geq 66MHz) = 0.95 \tag{5}$$

## 4 Proposed Design Approach

We consider a fully hybrid precoding/combining scheme for the discovery phase. In our approach, the BS initiates the association with MSs by sending a synchronization message on multiple beams. This helps speed up the the association with the vehicles, while the process gain of the beam coding compensates for the reduced received mmWave signal power. With its concurrent beams, the BS then receives the multiple collision-free RTS requests. The association step is complete once the BS discovers all the contending MSs by exhaustively scanning the possible beam sectors.

A time-frequency resource allocation scheme carried out post completion of the user association phase, is developed. The protocol is utilized by the BS for efficient multiuser uplink/downlink scheduling. The protocol is specifically designed considering the bandwidth needs and time the vehicle will continue to be in LOS. Every MS is assigned a portion of the time and an independent set of consecutive frequency subcarriers, thereby allowing for heavy multiplexing of MSs. The fundamental problems we tackle here are: (i) how to decide the bounds for each such rectangular resource block, $T_k$ and $B_k$, and (ii) how to pack these resource blocks tightly within the broader systems-defined constraints of $T_{tot}$ (time) and $B_{tot}$ (frequency). The problem is formulated as a rectangle bin packing problem, where the optimized packing is determined by considering the objective that minimizes the unused areas, i.e. the resources not allocated to the users and therefore wasted.

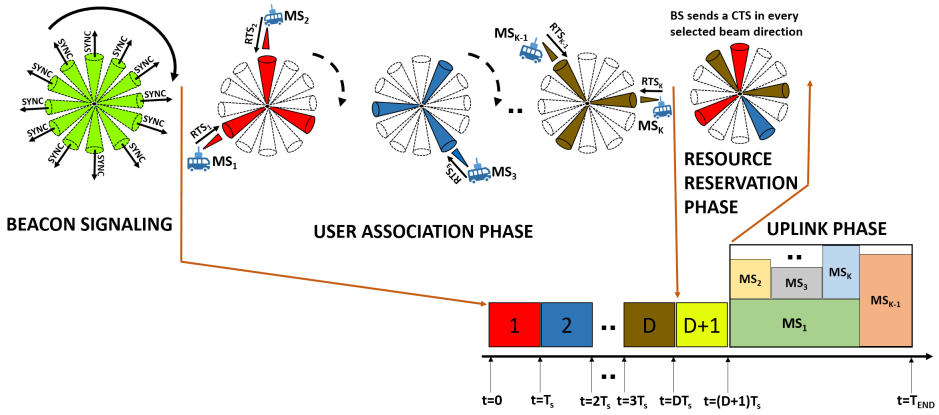



**Fig. 3.** Directional MAC Protocol operating in three phases. Lock step switching of random start, fixed orientation beam patterns at BS.

## 5 Multiuser Directional Medium Access Protocol

The BS must be able to serve, within its operating range, multiple MSs which are likely to be in random road locations. Let the hybrid beamforming BS can serve a few beam directions, say N, concurrently. So, in order to keep the intial beam steering complexity to a minimum, its best the BS adopts beam switching towards user association. Let M beam directions (we will refer to the same as simply beams henceforth) be required at the BS to cover all the possible M beam sectors where the MSs will be present. We assume that no more than N beams can simultaneously be active among the entire set of M beams.

Beam switching with the N beams can happen in one of the following ways:

1. random orientation of beam directions and switching of beams occurring in lock steps.

2. fixed orientation of the beams with random start and switching of beams occurring in lock steps.
3. fixed orientation of the beams with a random switch of beams.

Using concurrent beams to establish connection between BS and MSs may require mitigating inter-beam interference. So, we select beams that are maximally spaced apart. Given the likelihood of selecting very close beams in option 1) and an increased beam switching complexity in 3), we prefer the option 2).
The BS in the association phase picks $m_{UA}$ (very few) beam directions that are maximally spaced out with beamwidth, $\theta_{UA}$, that may relatively be wider than the beamwidth, $\theta_{RA}$, used in the resource allocation. This allows the BS to scan angular sectors quickly and thereby keep the user association overhead to a minimum.
Let us say that the BS serves no more than $N$ users in the uplink phase and $D$ be the maximum number of switches required for the BS to scan the beam sectors. We have,

$$m_{UA} \leq N \ll M \tag{6}$$

$$\theta_{UA} \geq \theta_{RA} \tag{7}$$

$$D = \lceil M/m_{UA} \rceil \tag{8}$$

The lock step switching time is represented as $T_S$ seconds.

As shown in Fig. 3, the proposed protocol operates in four distinct phases. Next, we will describe the protocol operation.

**I. Beacon Signaling Phase:**

1. BS transmits a synchronization signal S in all the beam directions one after the other, say, in a clockwise manner.
2. MS(s) receive and decode S to synchronize with the BS. Specifically, they perform channel estimation and estimate the necessary beamforming direction.

**II. User Association Phase:**

1. At t = 0, the MS(s) which successfully completed the previous step, transmit a RTS to the BS in the same beam sector.
2. The BS receives and decodes the RTS. When successful, the BS and the corresponding MS are now associated.
3. The BS stops switching the fixed orientation beam pattern only when the associated vehicles reach $N$; even if all the $D$ beam directions are exhausted.

**III. Resource Reservation Phase:**

1. When the number of associated MSs reaches $N$, the BS sends out the CTS along the selected beam directions.
2. The corresponding MS decode the CTS to become known of the exact time-frequency resource it is scheduled for access.

**IV. Scheduled Resource Access Phase:**

1. Every associated $MS_k$ establishes uplink with the BS in its allocated $RSB_k$.
2. At t = $t_{END}$, uplink is complete.
3. BS restarts from the Beacon Signaling Phase

# 6 Resource Allocation for Multi-User mmWave Vehicular Communications

Given the stringent beam-steering requirements and site-specific nature of connectivity in mmWave, the requests of time-frequency resource from the MSs will be asymmetric. In this section, the time-frequency resource allocation at the BS for the mobile outdoor mmWave small-cell communication is discussed. The resource allocation is then mathematically formulated as a two dimensional rectangular bin packing problem. Determining the optimized packing to the stated problem involves three key steps:

1. Picking for every instance of the problem, the boundaries of the rectangular bin and the smaller rectangular pieces using the relevant models. The width and height of the rectangles together are referred to as the boundaries.
2. Identifying the set of packing constraints with respect to orientation, unused areas etc.
3. Using a computationally-feasible algorithm to determine the optimized packing satisfying the above constraints.

We will discuss these steps in detail in the subsequent sections.

## 6.1 Radio Frame Design

Let $T_{C,k} := T_{C,k}(v, \theta)$ represent the coherence time experienced by the mobile $MS_k$ moving at speed v and steering a beam of width $\theta$ and $B_{C,k}$ represent the coherence bandwidth experienced by the $MS_k$.

We will refer to the smallest discrete unit of time-frequency resource that the BS can

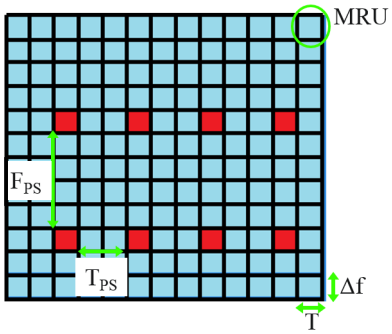



**Fig. 4.** Radio frame showing the important PHY parameters

handle as the Minimum Resource Unit (MRU). The MRU can be represented as a tuple (T, $\Delta$ f) and visualized as one small blue box with black boundaries in Fig. 4 & Fig. 5.

Let $T_C^{min}$ and $B_C^{min}$ be the minimum possible coherence time and coherence bandwidth.

$$f_D^{max} \ll \Delta f \ll \frac{1}{T_{CP}};\ T_{CP} \geq T_{Delay-Spread} \tag{9}$$

$$T = T_{CP} + T_{DATA};\ T_{DATA} = N_{CP} \cdot T_{CP} \tag{10}$$

$$T_{PS} \leq \frac{1}{K_T} \cdot T_C^{min};\ T_C^{min} = \min_k T_{C,k}(v,\theta) \tag{11}$$

$$F_{PS} \leq \frac{1}{K_F} \cdot B_C^{min};\ B_C^{min} = \min_k B_{C,k} \tag{12}$$

The PHY parameters that determine the radio frame, tabulated in Table 2, are obtained by setting $f_D^{max}$, $T_{CP}$, $N_{CP}$, $T_C^{min}$, $B_C^{min}$, $K_T$, $K_F$ at 5 $KHz$, 10 $ns$, 15, 25 $ms$, 20 $MHz$, 2, 5 respectively, and using the above inequalities.

**Table 2.** PHY parameters relevant to the Radio Frame

| Parameters | Description | Typical Value |
|---|---|---|
| $T$ | OFDM Symbol Time | 0.16 $\mu s$ |
| $\Delta f$ | Sub-carrier Spacing | 25 $KHz$ |
| $T_{PS}$ | Pilot Spacing (in time) | 10 $ms$ |
| $F_{PS}$ | Pilot Spacing (in frequency) | 3 $MHz$ |

### 6.2 Resource Block (RB) Allocation

• **Notation:** Let there be $N$ MSs in the coverage area of the BS and only $K$ MSs ($K \ll N$) among them request uplink access from the $BS$ at time $t$. Let the MSs be represented by the set $\mathscr{N} := (1,2,..,i..,N)$ and the $K$ MSs by the set $\mathscr{K} \subset \mathscr{N}$.
Let $T_k$ and $B_k$ represent the requested time and bandwidth for access by the vehicle $MS_k$.
At the BS, let the total time and total bandwidth available at the start of resource allocation phase be $T_{tot}$ and $B_{tot}$ respectively. We set $T_{tot}$ and $B_{tot}$ similar to that of IEEE 802.11ad standard.

$$T_{tot} = [100 - 1000]\ ms \tag{13}$$

$$B_{tot} = 2\ GHz \tag{14}$$

We denote the Resource Block (RB), available at the $BS$ at time $t$, as an ordered pair $RB^t := (T_{tot}, B_{tot})$. At time $t$, MS$_k$; $k \in \mathscr{K}$, request for a Resource Sub-Block (RSB) and the BS schedules all/some of the K MSs for uplink access. The BS having to accommodate asymmetric RSB requirements, might not be able to schedule all MSs requesting access. Simply put, if $MS_k$'s request gets accepted, the BS assigns $MS_k$ an RSB spanning a bandwidth $B_k$ and time-slot $T_k$ i.e. $RSB_k^t := (T_k, B_k)$, else if the request is rejected by BS, $MS_k$ contends to gain uplink access at a later time i.e. say at the start

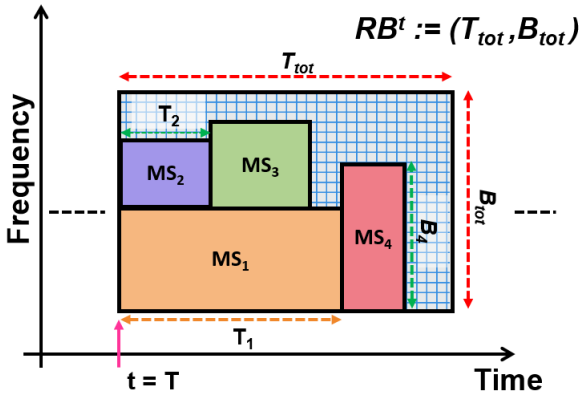



**Fig. 5.** Resource Block Allocation in the Time-Frequency Grid

of the next RB, at time $t + T_{tot}$.

The scheduling in the Time-Frequency Grid (TFG) can be thought of packing many smaller rectangles, $RSB_k^t$, in a bigger rectangle of fixed size, $RB^t$; visually represented in Fig. 5. Note that since both $RSB_k^t$ and $RB^t$ are made up of several MRUs, the edges of all the rectangles can be deemed to take on only positive integer values.

• **Packing Criteria:** To further qualify the objective in the scheduling step, we identify a pertinent set of requirements that the allocated RSBs need to satisfy:

1. Since the MS is expected to request for a RSB with $T_i$ that is highly location dependent, all pending requests must expire after $T_{tot}$ seconds. The MS has to contend for access again in the next RB. As a result, the scheduling cannot span multiple RBs thereby calling for an one-shot allocation of the RSBs. This means that the packing **does not span multiple bins**.
2. As each beam of the BS services only one MS in the allocated RSB, the RSBs are required to be **non-overlapping** in the RB.
3. Since the MS observes a channel that varies faster relative to the BS particularly due to required support for mobility, we emphasize that the RSB also has to be an ordered pair. This amounts to **fixed orientation and allowing no rotations** among the RSBs.
4. Since the mmWave channel access is expensive, the BS will allocate RSBs for the requests as and when they arrive. This means that the RSBs are **placed in the received order**. It is not removed from/repositioned within the RB post allocation.
5. For the system to be spectrally efficient, the BS will preferentially allocate adjoining RSBs that are similar to keep the spectrum switching overhead to a minimum. This calls for **guillotine packing** of the RSBs.

• **Packing Objective:** The BS has the following specific objective towards uplink access scheduling: Maximize the time-frequency resource utilization at the BS. The BS tries to minimize the amount of unallocated regions in the RB as shown in the Fig. 5. Put equivalently, the objective is to minimize the unused areas/whitespaces (trim loss) in the bigger rectangle. The above stated objective is identical to the two-dimensional

rectangular bin packing problem. The ordered tuple $(T_{tot}, B_{tot})$ represents the rectangular bin. [34] provides an algorithm, with time complexity $\mathscr{O}\left(n^2\right)$ and space complexity $\mathscr{O}(n)$, that helps maximize the utilization, $\mathscr{U}$, of the time-frequency resource:

$$\mathscr{U} = \frac{\sum_{k \in \mathscr{K}} I_k \cdot T_k \cdot B_k}{T_{tot} \cdot B_{tot}} \tag{15}$$

where $I_k \in \{0,1\},\ k \in \mathscr{K}$. Once an optimized packing is identified, the BS then schedules each $MS_k$ by sending out a $CTS_k$ on the corresponding beam. This opportunistic and dynamically adjusting design will significantly improve the performance.
It is to be noted that the problem of identifying the optimized packing discussed above is different from solving a 0/1 2D knapsack problem. This is because the latter disregards the geometric constraints; it aims to only identify which items i.e. rectangles to pack, and not the position of the rectangles.

## 7 Simulation Environment

Commercial 3D ray-tracing tools are now popular and are increasingly being used to accurately model channels for static indoor mmWave scenarios. Currently, such tools do not support vehicular simulations, particularly for link layer operations that involve directional, steerable beam patterns and therefore might prove unsuitable for our simulations. Moreover, such tools are quite expensive with yearly licenses costing in several thousands of dollars and also demand a steep learning curve before one can obtain useful results. For this reason, we specifically designed and built in MATLAB a simulator to address link layer operation characteristics of mmWave V2I network in an LOS urban setting with low-rise modern buildings.
The simulator window shown in Fig. 6 represents the 2D layout of a section of a city. The vehicular routes, the data needs for each vehicle is the input to the simulator. For all locations of the MS in its route, the azimuth and elevation angle pair which both the BS and the MS must point their beams at is determined and also displayed to help the user visualize the moving-vehicle scenario. We adopt the 3GPP microcellular model for the LOS probability [35] specified as,

$$P_{LOS}^{3GPP}(x) = min\left(1, \frac{18}{x}\right)\left(1 - e^{-\frac{x}{36}}\right) + e^{-\frac{x}{36}} \tag{16}$$

$$P_{Outage}(x) = 1 - P_{LOS}^{3GPP}(x) \tag{17}$$

The vehicular routes are assumed to be usually along the long streets and at times run between the narrow spacing among the buildings. The environment allows for modeling for the variable speed of the vehicles, the distinct link state (LOS & Outage), directivity gain of narrow beam antennas, tracking of beam directions, quite relevant to mmWave V2I networks.

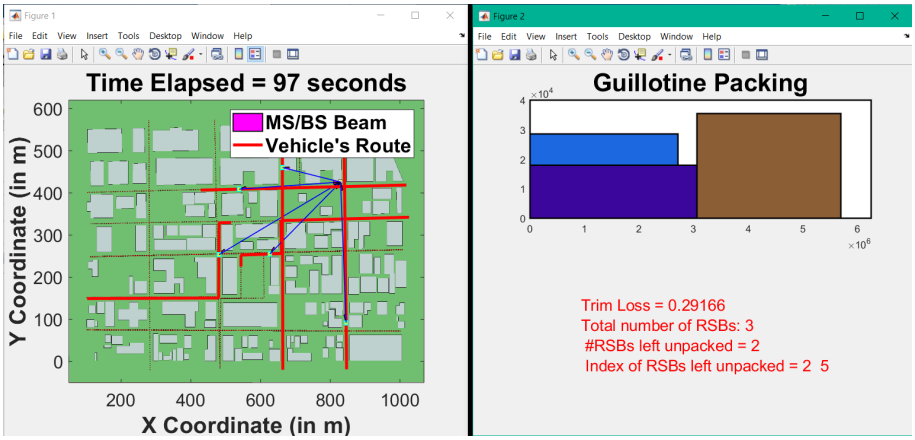



**Fig. 6.** mmWave V2I Simulator: BS serves multiple associated vehicles

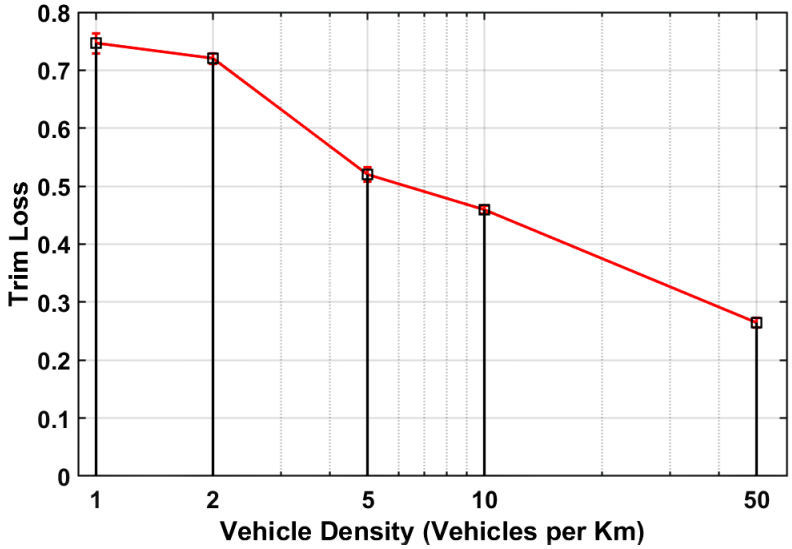



**Fig. 7.** Mean Time-Frequency resource utilization

### 7.1 Performance Simulations

We expect that with an increase in vehicle density, there will be a proportional increase in vehicles that come in LOS with the BS. The number of RTS requests at the BS will then increase which in turn will show an increase in the number of associated vehicles.

Random routes and corresponding start locations are picked for the vehicles to perform the simulations. The decreasing trend for trim loss seen in the Fig. 7 with the increase in vehicle density indicates the optimized packing of the RSBs and establishes the improved performance of the proposed resource allocation scheme.

## 8 Conclusion

The multi-user access in mmWave V2I communication is motivated by the usage of concurrent independent beams realized using hybrid beamforming antenna arrays. A new user association phase with deterministic switched beam patterns is developed. A resource allocation scheme that maximizes the time-frequency utilization at the Base Station is presented. The scheme performs combinatorial optimization on a packing objective that involves the rectangular bin packing problem. The design of the MATLAB-based simulator that is built for the link layer simulations is discussed. The simulation results demonstrate the improved time-frequency resource utilization with increasing density of the vehicles and decreasing street intensity.

The future work will focus on performing comprehensive simulations that account for distinct link states of directional links modulated by buildings and foliage obstructions, by using accurate models for the directional mmWave antenna, vehicle traffic flow, and relevant system parameters such as the transmit power level, signal threshold, inter-frame spacing etc. Such simulations should help characterize the system better - importantly, determine the aggregate throughput that results from the use of directional MAC protocol described in this work.

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