An Efficient Requirement-Aware Attachment Policy for Future Millimeter Wave Vehicular Networks

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Abstract—The automotive industry is rapidly evolving towards connected and autonomous vehicles, whose ever more stringent data traffic requirements might exceed the capacity of traditional technologies for vehicular networks. In this scenario, densely deploying millimeter wave (mmWave) base stations is a promising approach to provide very high transmission speeds to the vehicles. However, mmWave signals suffer from high path and penetration losses which might render the communication unreliable and discontinuous. Coexistence between mmWave and Long Term Evolution (LTE) communication systems has therefore been considered to guarantee increased capacity and robustness through heterogeneous networking. Following this rationale, we face the challenge of designing fair and efficient attachment policies in heterogeneous vehicular networks. Traditional methods based on received signal quality criteria lack consideration of the vehicle’s individual requirements and traffic demands, and lead to suboptimal resource allocation across the network. In this paper we propose a Quality-of-Service (QoS) aware attachment scheme which biases the cell selection as a function of the vehicular service requirements, preventing the overload of transmission links. Our simulations demonstrate that the proposed strategy significantly improves the percentage of vehicles satisfying application requirements and delivers efficient and fair association compared to state-of-the-art schemes.

I. INTRODUCTION

In recent years, there has been a significant interest in the context of Cooperative and Intelligent Transportation Systems (C-ITSSs), which have rapidly emerged as a means to guarantee a safer travel experience and to support multimedia services [1]. The potential of autonomous vehicles can be fully unleashed through direct wireless communications to and from roadside infrastructures, a concept that is usually referred to as Vehicle-to-Infrastructure (V2I) networking. Although the Long Term Evolution (LTE) standard presently represents the principal wireless technology offering V2I transmission services [2], future vehicular networks will have ever more stringent regulations in terms of road safety and traffic management [3]. In particular, next-generation vehicles will be equipped with sophisticated instrumentation (e.g., high-resolution LIDAR and camera sensors) which will be the source of unprecedentedly high data rates (in the order of hundreds of gigabits per second, according to some estimates [4]): LTE-based vehicular networks were primarily designed to provide coverage and are therefore unsuitable to accommodate such huge change in the traffic trends.

In this context, the automotive industry has devoted efforts to specifying new communication solutions, e.g., operating in the millimeter wave (mmWave) bands above 10 GHz, that allow vehicles to use very large bandwidths to communicate, thus guaranteeing very high transmission speeds [5]. Although this new band has gathered great attention for V2I applications, the mmWave paradigm comes with its own set of challenges [6]. In particular, mmWave transmissions suffer from severe path loss and susceptibility to blockage, and prevent long-lived communications, a critical prerequisite for safety operations.

One promising approach to handle mmWave limitations is to increase the density of the base stations (BSs), to reduce inter-site distance and establish stronger access channels. Massive Multiple Input Multiple Output (MIMO) techniques have also emerged as a means to provide an additional beamforming gain to the link budget, compensating for the increased propagation loss. Moreover, heterogeneous networking [7], [8] has recently been considered to improve network capacity, e.g., by combining a reliable sub-6 GHz link (e.g., using LTE) with a high-capacity mmWave connection. Despite some encouraging features, heterogeneous networking deployments lack at least one important design aspect, which is how to efficiently and fairly associate vehicles to the network. Maximum downlink received power based association, for example, typically leads to a limited number of nodes actually getting served by mmWave cells due to their much more unstable propagation characteristics compared to LTE cells. Maximum rate based association, on the other hand, tends to prioritize mmWave BSs over legacy ones due to the much larger bandwidth available to high-frequency systems. This load disparity inevitably leads to suboptimal resource allocation, with a large number of vehicles experiencing poor data rates in overloaded cells while the resources in other lightly loaded cells can be underutilized.

Following this rationale, in this paper we address the issue of balancing network association requests between LTE and mmWave BSs, avoiding the overload of transmission links. To do so, we design a novel Quality of Service (QoS) aware attachment strategy that identifies the most appropriate destination cell as a function of the vehicle’s individual requirements and traffic demands. Our results show that the proposed approach, which biases the received signal quality criteria with additional information about network loading and vehicle requirements, can significantly improve the connectivity performance compared to conventional association solutions, even considering scarcely deployed networks. It also offers good connectivity to cell-edge vehicles, i.e., the more channel-constrained network entities, and guarantees a fair distribution
of the available resources across the cell.

The rest of this work is organized as follows. In Section II, we discuss related work on heterogeneous networking and user association techniques, while in Section III we present the different attachment strategies we consider in our analysis. In Section IV we describe our simulation scenario and parameters, and present our main results and discoveries. Finally, Section V concludes the paper and gives suggestions on possible extensions for future research.

II. RELATED WORK

One of the main challenges of multi-radio heterogeneous networking is the design of the optimal user association technique that avoids system overload and best distributes the available resources among the users.

Different studies have been conducted in this field, the most relevant ones taking network metrics into account, e.g., the distance from the BSs, path loss, Signal-to-Noise Ratio (SNR) or data rate. For example, Chen et al., in [9], proposed joint optimization of channel selection, user association and power control to maximize spectrum and energy utilization efficiencies. In [10], Corroy et al. presented a new theoretical framework to study cell association for the downlink of multi-cell networks and developed a dynamic method that associates users to macro or pico nodes while maximizing the sum rate of all network users. Cell range expansion theory has also been used in [11] to perform user association based on the biased measured signal, i.e., balancing the load among high- and low-power BSs.

Lately, researchers have tried to solve the user association problem using advanced mathematical tools, in particular game theory [12] and combinatorial optimization [13]. For instance, in [14], the authors have proposed load balancing methods for multi-tier networks with massive MIMO BSs and demonstrated that the load-based association scheme terminates in a Nash equilibrium. Similarly, Xu et al., in [15], presented a centralized user association algorithm that targets rate maximization, proportional fairness, and joint user association and resource allocation in a MIMO scenario. In [16], game theory was used to model user association in heterogeneous networks to guarantee QoS to human-initiated traffic while providing fair resource allocation for machine-to-machine services. In [17], Liu et al. formulated the user association issue as a nonlinear combinatorial problem and proposed a centralized scheme which guarantees fair and energy efficient attachment through Lagrange multipliers. In [18], the authors formulated a logarithmic utility maximization problem for single-BS association, and showed that equal resource allocation is actually optimal, over a sufficiently large time window. However, most popular mathematical optimizations only apply to scenarios where the traffic flow generated by endnodes is approximately static. However, in the real world, traffic is not stable nor accurately predictable, thereby making traditional model assumptions invalid.

Stochastic geometry [19] has also emerged as a computationally tractable approach to model and analyze the performance of multi-tier heterogeneous networks [20]. In this regard, Dhillon et al., in [8], exploited stochastic geometry to evaluate the performance of user association, based on received signal quality criteria, in a multi-tier cellular system. In a similar way, the authors in [21] formulated a throughput maximization problem subject to QoS constraints, and provided insights into the optimal spectrum allocation technique.

Most prior work on network association applies to LTE-only scenarios. LTE and mmWave heterogeneous networking, on the other hand, is much more sensitive to the cell association policy because of the significant propagation disparities of the two radios, and calls for innovative solutions that depend on the radio technology characteristics. In [22], Singh et al. made the case that, although mmWaves generally represent the preferred access technology, offloading users to more reliable radio interfaces may dramatically improve the rate of cell-edge users in case of sudden channel degradation. Similarly, the authors in [23] proposed a novel uplink measurement system that, with the joint help of a local administrator operating in the LTE band, coordinates user association requests as a function of the instantaneous load conditions of the surrounding cells, thereby promoting fairness in the network.

The aforementioned association policies were proposed for cellular networks, which might not be fully representative of a vehicular system due to the more challenging propagation and traffic characteristics of highly mobile vehicular nodes. Although some recent works in the literature have tried to provide preliminary insights into user association also in the context of vehicular networks [24], e.g., leveraging reinforcement learning [25], there remain many open problems which call for innovative modeling and design solutions. Our work tries to fill this gap by extending traditional cellular-based attachment algorithms and integrating physical-layer metrics with application requirements at the higher layers.

III. ATTACHMENT POLICIES

When a vehicular node (VN) enters a vehicular network for the first time, it needs to establish an initial physical link connection with a cell, a procedure that is usually referred to as network attachment [26]. Traditional attachment procedures monitor the quality of the received signals, which is typically expressed in terms of SNR, and select, as a target cell, the BS from which the maximum SNR was experienced. This procedure is described in Sec. III-B and represents the benchmark solution of our analysis. In this work we target tight integration of classic physical-layer performance metrics with additional network information in the upper layers. In particular, a maximum rate attachment policy, which takes data rate estimates into account, and a requirement-aware attachment policy, which biases cell selection as a function of the VN’s traffic requirements, are proposed in Secs. III-C and III-D respectively.

A. System and Channel Models

Let $\mathcal{M}$ be the set of VNs and $\mathcal{N}$ be the set of BSs. In particular, $\mathcal{M}_{m} \subseteq \mathcal{N}$ is the set of BSs operating in the mmWave band, and $\mathcal{N}_{L} \subseteq \mathcal{N}$ is the set of BSs operating in the legacy band. In V2I networks, we expect other vehicles, pedestrians and environmental objects to block the link connecting the
target VN and its serving BS. It is therefore necessary to distinguish between Line of Sight (LOS) and Non Line of Sight (NLOS) nodes. For LTE, we consider the 3GPP model in [27] for an outdoor scenario. The LOS path loss probability is given by

$$P_{\text{LOS}}(d) = \min\left(\frac{0.018}{d}, 1\right) \left[1 - \exp\left(-\frac{d}{0.063}\right)\right] + \exp\left(-\frac{d}{0.063}\right),$$

\hspace{1cm} (1)

where $d$ is the distance in km between the VN and the candidate BS, while the complementary NLOS probability is given by $P_{\text{NLOS}}(d) = 1 - P_{\text{LOS}}(d)$. For mmWave cells, we consider the 3GPP model in [28] for a UMi-Street-Canyon scenario. Accordingly, the LOS path loss probability is given by

$$P_{\text{LOS}}(d) = \begin{cases} 1 & \text{for } d \leq 18 \text{ m} \\ \frac{18}{d} + \exp\left(-\frac{d}{30}\right) \left(1 - \frac{18}{d}\right) & \text{for } d > 18 \text{ m} \end{cases}$$

\hspace{1cm} (2)

while its complementary NLOS probability is computed as $P_{\text{NLOS}}(d) = 1 - P_{\text{LOS}}(d)$. The path loss, for the LOS and NLOS conditions, in dB, is given in [27] and [28], for LTE and mmWave respectively.

The channel quality between BS$_j$, $j \in \{1, \ldots, |\mathcal{N}|\}$ and VN$_i$, $i \in \{1, \ldots, |\mathcal{M}|\}$, is measured in terms of SNR

$$\text{SNR}_{ij} = 10 \log_{10} \left( \frac{G_{ij} \cdot P_{tx}}{PL_{ij} \cdot N_0 B} \right),$$

\hspace{1cm} (3)

where $N_0$ is the thermal noise power spectral density, $B$ is the available bandwidth, $P_{tx}$ is the transmit power and $PL_{ij}$ is the path loss between BS$_j$ and VN$_i$. The term $G_{ij}$ represents the cumulative antenna gain between BS$_j$ and VN$_i$, which is a function of the number of antenna elements that each network node is equipped with. In case of LTE communications, a single omnidirectional antenna is used, therefore $G_{ij} = 1$, $\forall i$, $\forall j$. On the contrary, mmWave nodes form directional beams through Uniform Planar Arrays (UPAs) composed of multiple antenna elements, so that $G_{ij} \gg 1$ when beam alignment is achieved [31].

### B. Maximum SNR (MS) Policy

The maximum SNR (MS) policy represents one of the most common techniques for performing user association: VN$_i \in \mathcal{M}$ always connects to BS$_{j_{\text{MS}}}(i) \in \mathcal{N}$ (either LTE or mmWave) that provides the maximum downlink average SNR, i.e.,

$$j_{\text{MS}}(i) = \arg \max_{j \in \{1, \ldots, |\mathcal{N}|\}} \{\text{SNR}_{ij}\}, \; \forall i \in \{1, \ldots, |\mathcal{M}|\}$$

\hspace{1cm} (4)

where SNR$_{ij}$ is as in Eq. (3). Notice that, in an urban heterogeneous scenario, the MS policy does not guarantee that the BS with the maximum SNR coincides with the closest one. First, LTE BSs are generally preferred over mmWave ones due to the very low path loss experienced at below-6 GHz frequencies even at long distances. Second, the mmWave signal is much more sensitive to penetration loss than LTE links and, therefore, if the geographically closest mmWave BS is obstructed, a further BS in line of sight can potentially offer a better service (experiments performed for NLOS situations resulted in SNR degradation of more than 20 dB compared to LOS propagation [32]).

We make the case that, although MS maximizes the SNR of vehicles, it does not properly reflect the achievable end-to-end throughput of users, thereby leading to suboptimal association decisions. This is because, even with a lower SNR, mmWave cells may potentially deliver higher data rates (due to the much larger bandwidth) compared to LTE cells. Moreover, downlink-based received signal quality criteria do not characterize well uplink scenarios where vehicles have strict battery limitations on their transmit power.

### C. Maximum Rate (MR) Policy

MS attachment schemes can be improved by biasing cell selection with side information, e.g., network load. A maximum rate (MR) approach is therefore proposed: VN$_i \in \mathcal{M}$ connects to BS$_{j_{\text{MR}}}(i) \in \mathcal{N}$ (either LTE or mmWave) that provides the maximum achievable data rate $R_{ij}$, i.e.,

$$j_{\text{MR}}(i) = \arg \max_{j \in \{1, \ldots, |\mathcal{N}|\}} \{R_{ij}\}, \; \forall i \in \{1, \ldots, |\mathcal{M}|\}$$

\hspace{1cm} (5)

In this paper, the achievable data rate $R_{ij}$ between BS$_j$, $j \in \{1, \ldots, |\mathcal{N}|\}$ and VN$_i$, $i \in \{1, \ldots, |\mathcal{M}|\}$ is an indication of the cell’s maximum capacity and is computed from Shannon’s formula as a function of the SNR, i.e.,

$$R_{ij} = \frac{B}{m_j} \log_2(1 + \text{SNR}_{ij})$$

\hspace{1cm} (6)

where $B$ is the available bandwidth and $m_j$ is the number of vehicles connected to BS$_j$. Our results therefore represent an upper bound for the throughput of the VNs, as we do not investigate the effect of medium access control mechanisms nor that of higher-layer retransmissions. We also assume that, if the measured SNR is below a predefined threshold SNR$_{th}$, the data rate is equal to 0.

The MR strategy generally guarantees higher average throughput compared to the MS approach [23]. However, it is recognized that maximizing the data rate of all vehicles may result in an unfair data rate allocation [10]. In particular, the huge bandwidth available to mmWave systems would make the load of mmWave cells much heavier than that of LTE ones, hence resulting in mmWave cells that are congested.

### D. Requirement-Aware (RA) Policy

To cope with MS and MR limitations, we propose a requirement-aware (RA) attachment policy which simultaneously maintains fairness and balances the traffic load among the cells. The association decision is therefore made as a function of the vehicle’s individual QoS requirements and the availability of radio resources.

In the context of C-ITSs, we expect heterogeneous application requirements (e.g., in terms of throughput, latency, reliability) which, although not yet fully specified, have already been outlined by the 3GPP in [3]. The RA policy tries

\footnote{Different PHY-layer metrics can be used to measure signal quality [29]. In our paper, we chose to use the SNR (as considered in previous works, e.g., in [30]).}

\footnote{In this work, four classes of vehicular traffic, with different throughput, latency and reliability constraints, are considered, as illustrated in Sec. V-A.}
A. Simulation Scenario and Parameters

The parameters used in our simulations are based on realistic system design assumptions and are reported in Table 1.

| Parameter | Value | Description |
|-----------|-------|-------------|
| $A$       | 1 km$^2$ | Simulation area |
| $h_{BS}$ | 30 m | Height of BS |
| $h_{VN}$ | 2 m | Height of VN |
| $UPA_{BS}$ | $8 \times 8$ | BS antenna array |
| $UPA_{VN}$ | $4 \times 4$ | VN antenna array |
| $N_{sim}$ | 2000 | Simulation runs |
| $SNR_{th}$ | $-5$ dB | SNR threshold |
| $f_L$ | 2.4 GHz | LTE central frequency |
| $f_m$ | 28 GHz | mmWave central frequency |
| $P_{TX,L}$ | 46 dBm | LTE BS TX power |
| $P_{TX,m}$ | 27 dBm | mmWave BS TX power |
| $B_L$ | 20 MHz | LTE bandwidth |
| $B_m$ | 1 GHz | mmWave bandwidth |
| $\lambda_L$ | 4 BS/km$^2$ | LTE BS density |
| $\lambda_m$ | $\{4, \ldots, 80\}$ BS/km$^2$ | mmWave BS density |

Table 1: Simulation parameters.

IV. PERFORMANCE EVALUATION

In Sec. IV-A we present the simulation scenario and parameters we consider in our analysis, in Sec. IV-B we overview our performance metrics and in Sec. IV-C we compare the performance of the proposed V2I attachment mechanisms.

d) Vehicular traffic classes: In the context of C-ITSs, following the description in [31], we consider four different categories of vehicular traffic, to reflect the heterogeneity of future V2I applications’ characteristics and requirements.

- Class 1 (e.g., basic safety) Very high levels of communication stability are required, due to the potential consequences of communication errors, although data rates are below 1 Mbps.

Fig. 1: Example of simulation scenario in which LTE and mmWave BSs are deployed according to a PPP of density $\lambda_L = 4$ BS/km$^2$ and $\lambda_m = 80$ BS/km$^2$, respectively.
Class 2 (e.g., advanced safety, collision avoidance) High degrees of reliability are required, and data rates of at least 10 Mbps should be supported.

Class 3 (e.g., infotainment, cooperative perception) Data rate requirements are in the order of hundreds of Mbps, while latency is reasonably tolerated.

Class 4 (e.g., semi- or fully-automated driving through extended sensors) The data rate demands are proportional to the resolution of the exchanged sensory data and likely exceed 1000 Mbps for high-quality uncompressed camera measurements (e.g., ProRes 4444 with 4K resolution requires around 1200 Mbps). Latency requirements depend on the desired degree of automation.

Let $\mathcal{M}_k \subseteq \mathcal{M}$ be the subset of VNs belonging to class $k$, $k \in \{1, \ldots, 4\}$. A VN is assigned to one of these classes with equal probability\(^3\) so that

$$P_k = P[VN \in \mathcal{M}_k] = 0.25 \quad \forall k \in \{1, \ldots, 4\} \quad (8)$$

### B. Performance Metrics

The performance evaluation is conducted as a function of the density of mmWave BSs and the attachment policy. Our results are obtained following a Montecarlo method in which $N_{sim}$ simulations are repeated to make the conclusions statistically robust. Let $\bar{R}_{ij,\ast}$ be the data rate that $VN_i \in \mathcal{M}$ experiences when attached to the best BS $r_{ij,\ast} \in \mathcal{N}$ according to either of the attachment policies described in Sec. III. In particular, we consider the following performance metrics.

- **Mean data rate per class** $\mathbb{E}[\bar{R}]_k$, which is computed as the sum of the data rates experienced by VNs belonging to traffic class $k$, divided by the total number of VNs of that class, i.e.,

  $$\mathbb{E}[\bar{R}]_k = \frac{\sum_{i \in \mathcal{M}_k} \bar{R}_{ij,\ast(i)}}{|\mathcal{M}_k|} \quad \forall k \in \{1, \ldots, 4\} \quad (9)$$

- **Mean data rate of the 10% worst VNs per class** $P_{30\%}$, the average data rate relative to the worst 10% of VNs of class $k$ (which represents the average performance of cell-edge nodes, i.e., the most resource-constrained network entities).

- **Percentage of VNs satisfied** $p_{sat}$, the percentage of VNs in the network that reach the minimum data rate requirements specified by the corresponding traffic class, as characterized in Sec. IV-A. I.e.,

  $$p_{sat} = \frac{\sum_{i \in \mathcal{M}_k} 1[\bar{R}_{ij,\ast(i)} > \bar{R}_i]}{|\mathcal{M}_k|} \quad \forall k \in \{1, \ldots, 4\} \quad (10)$$

where $\bar{R}_i$ is the data rate requirement for VN$_i \in \mathcal{M}$.

- **Percentage of VNs attached to LTE** $P_{LTE}$, the percentage of VNs in the network that are served by an LTE BS.

- **Jain’s fairness index** $J_k$, which gives an indication on whether network resources are shared fairly among the VNs. This index is computed separately for each traffic class, and is defined as in (23), i.e.,

  $$J_k = \frac{\left(\sum_{i \in \mathcal{M}_k} R_{ij,\ast(i)}\right)^2}{|\mathcal{M}_k| \sum_{i \in \mathcal{M}_k} R_{ij,\ast(i)}^2} \quad \forall k \in \{1, \ldots, 4\} \quad (11)$$

### C. Results and Discussion

**LTE Associations.** In Fig. 2 we plot the percentage of VNs served by LTE BSs, which gives an overview of how vehicles are distributed across the network. As expected, the different propagation characteristics of sub- and above-6GHz bands and the high imbalance in the available network resources could result in different conclusions as a function of $\lambda_m$ and the attachment policy. In general, the MS approach tends to associate most VNs to LTE BSs ($P_{LTE} \geq 60\%$ for all investigated density configurations) since they transmit with a higher power, have a larger communication range and are less affected by propagation and absorption loss compared to mmWave BSs. On the contrary, VNs are generally attached to mmWave BSs if the MR approach is preferred, since mmWave systems offer opportunities for order of magnitude higher data rates than operating at LTE, even at low SNR. Notice that, for the MR case, $P_{LTE}$ decreases for increasing values of $\lambda_m$ as a consequence of stronger mmWave channels (in case of sparsely deployed networks, i.e., $\lambda_m < 20$ BS/km$^2$, many mmWave BSs are in outage, thereby making LTE cells a desirable attachment solution despite the limited available bandwidth). Fig. 2 also demonstrates that the RA policy guarantees more fair resource utilization with respect to its counterparts. VNs are indeed almost equally distributed across LTE and mmWave BSs: class 1 and 2 VNs (i.e., around 50% of the overall traffic) are associated to LTE BSs, the only network entities satisfying strict reliability constraints, while

| Traffic Class | Description     | Data Rate   |
|---------------|-----------------|-------------|
| Class 1       | Basic safety    | 1 Mbps      |
| Class 2       | Advanced safety | 10 Mbps     |
| Class 3       | Cooperative Perception | > 100 Mbps     |
| Class 4       | Automated Driving | > 1000 Mbps |

**TABLE 2: Vehicular traffic classes requirements.**
class 3 and 4 VNs are associated to mmWave BSs to satisfy bold data rate requirements. For high values of $\lambda_m$, $p_{LTE}$ finally converges to 25%, that corresponds to the percentage of VNs belonging to class 1.

**Data Rate.** As another performance measure, in Figs. 3 and 4 we plot the average data rate that class 1 and class 4 VNs experience, respectively, when implementing either of the attachment policies presented in Sec. III. We consider a heavily loaded scenario in which an average of 10 vehicles per mmWave BS are deployed. At first glance we observe that, while all investigated attachment schemes satisfy class 1 data rate requirements, i.e., 1 Mbps (Fig. 3), MS and MR are generally not able to sustain class 4 requests, i.e., 1200 Mbps for 4K resolution cameras (Fig. 4), thereby making the proposed RA solution the only viable approach to maximize the communication performance for all categories of vehicular services. MR eventually meets class 4 requirements, though only for very high values of $\lambda_m$ (i.e., $\lambda_m > 70$ BS/km$^2$); such ultra-dense deployment, however, could be costly for network operators, in terms of capital and management expenditures, and should therefore be avoided. With the MS approach, VNs connect to BSs showing the instantaneous highest signal strengths and avoid instead nodes that provide lower SNR values (but possibly higher rates, due to their low traffic loads). With the MR approach, VNs connect to mmWave BSs and share the same amount of radio resources regardless of the individual traffic requirements, with class 1 VNs experiencing much higher date rate than requested, at the expense of class 4 VNs experiencing poor date rate in overloaded cells. On the other hand, the RA strategy, which biases association decisions with side information about vehicle requirements, tends to associate class 1 VNs to LTE cells (which, despite the limited capacity of the physical channel, can easily support class 1’s rate requests) and saves network bandwidth for those categories of VNs with the most stringent connectivity demands. Numerically, for class 4 VNs, RA delivers up to 1.5 times higher throughput compared to MR and a 2 fold throughput increase compared to MS.

The same conclusions can be drawn from Fig. 5 which compares the attachment performance of different network loading regimes, considering a scenario in which 500 class 4 VNs are deployed overall. We see that, for densely loaded scenarios (i.e., $\lambda_m < 40$ BS/km$^2$), none of the investigated attachment policies satisfies the requirement of 1200 Mbps. Conversely, the throughput linearly increases with $\lambda_m$ since each BS serves fewer vehicles and can handle traffic requests more efficiently. Moreover, densification guarantees that the endpoints are progressively closer, thus guaranteeing improved signal quality and higher received power. The effect of densification is particularly evident for the RA cases (e.g., the data rate increases more than 5 times from 20 to 80 BS/km$^2$). The performance gap is even more significant when
the density $\lambda_m$ is increased, thereby moving from NLOS to LOS propagation.

The patterns we observed in the previous plots can be recognized considering also the data rate relative to the worst 10% of the users, i.e., cell-edge VNs, as illustrated in Fig. 6. Class 4 VNs are considered. We see that cell-edge VNs experience a significant data rate decrease with respect to the average values measured in Fig. 4, motivating efforts towards network densification to increase the coverage of cell-edge vehicles. Moreover, although none of the investigated attachment policies can meet class 4’s requirements, the RA approach still outperforms both MR and MS strategies in terms of data rate (+65% and an impressive +4600%, respectively, for $\lambda_m = 40$ BS/km$^2$).

**Fairness.** Although fairness is not necessarily a prerequisite for V2I systems (e.g., safety-critical operations shall deserve prioritization), it still represents a major concern that should be taken into account to guarantee a minimum level of performance to the cell-edge users (or, in general, to users experiencing bad channel conditions). In Fig. 7 we plot Jain’s fairness index $J_1$ for VNs of class 1 vs. $\lambda_m$. We demonstrate that the RA solution, which associates VNs with low data rate requirements to LTE cells, guarantees more fair cell association compared to traditional attachment schemes. On one side, MS strategies homogeneously attach VNs to LTE when a few BSs are deployed but, as $\lambda_m$ gets higher, start associating some of the VNs to mmWave BSs too (see Fig. 2), thereby offering completely different access channels. On the other side, MR strategies attach VNs to mmWave BSs which are generally not compatible with fairness as a result of the increased variability of the above-6 GHz channel. However, for high values of $\lambda_m$, i.e., when pushing the network into LOS regimes, MR’s fairness performance is deemed comparable to that of RA.

**Percentage of VNs Satisfied.** Finally, it is interesting to compare the three attachment algorithms in terms of percentage of VNs which satisfy application demands. We see that the MS approach, which tries to associate vehicles to LTE cells, is penalized by class 4 VNs whose very rigid data rate requirements cannot be sustained by low-bandwidth LTE connections. The performance particularly degrades when $\lambda_m \geq 5$ BS/km$^2$, i.e., when the number of VNs in the network starts increasing as a result of denser mmWave deployments, and then slightly increases when $\lambda_m \geq 20$ BS/km$^2$, i.e., when VNs that connect to mmWaves find LOS BSs. On the other hand, we observe that, although the MR approach guarantees a good level of satisfaction among the vehicles, i.e., $p_{\text{sat}} > 85\%$ for highly dense networks, with the RA scheme more than 95% of VNs are able to meet QoS demands even in low-density deployments. This is because RA discriminates association requests as a function of QoS requirements and balances VNs between LTE and mmWave BSs avoiding the overload of transmission links. Based on the above discussion, we therefore make the case that the proposed framework represents the most appropriate attachment strategy to maximize the communication performance.
V. CONCLUDING REMARKS

In this work we proposed a novel requirement-aware attachment strategy that delivers fair, robust and efficient vehicle association in heterogeneous networks in which both mmWave and LTE cellular infrastructures are deployed. In particular, we show that benchmark methods which bias cell selection decisions with received signal quality or network load information cannot support those categories of vehicular traffic with the boldest connectivity requirements, and can therefore lead to sub-optimal association. On the contrary, we demonstrated that the proposed approach, which makes attachment decisions as a function of the vehicular service requirements, prevents the overload of transmission links and represents the most appropriate strategy to meet QoS demands even considering low-density deployments.

As part of our future work, we will extend our implementation including advanced offloading techniques that distribute vehicles among the network cells even after the initial attachment decisions. Moreover, we will validate our simulation framework with an accurate mathematical analysis based on stochastic geometry or combinatorial optimization.

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