Improving Initial Access Reliability of 5G mmWave Cellular in Massive V2X Communications Scenarios

Antonino Orsino[1,2], Olga Galinina[2], Sergey Andreev[2], Osman N.C. Yilmaz[1],
Tuomas Tirronen[1], Johan Torsner[1], and Yevgeni Koucheryavy[2]
[1]Ericsson Research, Finland
e-mail: {antonino.orsino, osman.yilmaz, tuomas.tirronen, johan.torsner}@ericsson.com
[2]Tampere University of Technology, Finland
e-mail: {olga.galinina, sergey.andreev, evgeni.kucheryavy}@tut.fi

Abstract—**Future automotive systems are expected to significantly benefit from a range of diverse mechanisms and capabilities that will be offered by the emerging fifth-generation (5G) cellular technology. In particular, one of the most prominent 5G use cases is represented by the Vehicle-to-Everything (V2X) context, which aims to enhance people's driving experience with collective safety and infotainment applications (e.g., autonomous driving, driver assistance, and contextual information). To achieve the requirements of better reliability, lower latency, and higher data rate, the use of extremely high frequencies (known as millimeter-wave, mmWave) is envisioned as an efficient solution. In fact, very high numbers of sensors deployed on vehicles introduce a serious challenge for the initial access procedure due to likely collisions in case of massive connection attempts. For that reason, the goal of this work is to offer improvements to the reliability of the initial access procedure for 5G mmWave cellular in massive V2X communications scenarios. In doing so, we propose to exploit *redundant* preamble transmissions in order to faster acquire a data transmission opportunity. Our obtained results indicate that by sending multiple replicas of a random access preamble the success probability to transmit at the first attempt is at least twice higher than that with the legacy approaches where a single random access preamble is being sent.**

I. INTRODUCTION

Over the recent years, we have observed a series of technological breakthroughs, which pushed the automotive industry to define new categories of vehicles, such as connected and autonomous cars. These employ a rich set of functions for detecting obstacles, processing videos and images related to driving, and offering temporary control of a vehicle, among many others [1]. Along these lines, a multitude of on-board sensors, including automotive radars, infrared and visual cameras, light detection and ranging (LiDAR) devices, as well as ultrasonic and motion sensors have to be deployed. In particular, scenarios, where vehicles establish communication links with other entities (infrastructure, proximate vehicles, humans, etc.), have recently gained momentum under the notion of vehicle-to-everything (V2X).

While most of the V2X scenarios are typically labeled as "ultra-reliable and low latency communications" (URLLC) use cases – especially in remote control and safety applications – some of them can also be "massive" at the same time. As a matter of fact, the sheer numbers of cars in urban areas (each equipped with a large number of sensors) may pose a challenge for network operators due to extreme load that should be handled reliably and with low delays. Accordingly, we argue that certain V2X use cases are located at the intersection of critical and massive machine-type communications (mMTC) [2].

In these massive V2X communications scenarios, the traffic loads produced by a plethora of automotive mMTC devices may be difficult to handle with the conventional cellular and dedicated short-range communications (DSRC) solutions due to relatively scarce radio resources. Accounting for the fact that many automotive sensors have limited operating ranges, this situation is aggravated by the need to transfer raw sensor data with close to no preprocessing to reduce communications latency at higher speeds. Fortunately, with the emerging fifth generation (5G) cellular systems that employ millimeter-wave (mmWave) radios operating at extremely high frequencies and providing with gigabit-per-second throughputs, the impending network capacity challenge can be resolved even for higher data rate sensors [3].

It is known that mmWave carrier frequencies make the propagation conditions more unpredictable due to blockage of the signal by solid objects, including human bodies. This may lead to frequent transmission interruptions and reconnections between the serving mmWave small cells. With further increased dynamics due to vehicular mobility, a bottleneck of the 5G mmWave system in V2X applications is the initial access procedure applied before the actual data transfer can commence. Initial network entry in cellular typically relies on random-access mechanisms and may be subject to excessive collisions in case of massive connection attempts [4], especially for highly directional mmWave systems. This is because of more complex beam alignment, which leads to longer delays before a transmission can be initiated [5], hence reducing the overall operational reliability.

Prior work in the area focused on network access and overload control in conventional cellular systems by considering several key performance indicators: *(i)* access delay, *(ii)* access success probability, *(iii)* service-quality guarantees, *(iv)* energy efficiency, and *(v)* traffic load. However, research on initial access efficiency in mMTC scenarios for highly directional mmWave systems is still in its infancy, as most of the past work concentrated so far on adapting the existing methods that have been developed for 3GPP LTE technology [6], [7].

This paper aims at offering improvements to the initial access efficiency (primarily in terms of its reliability and, consequently, access latency) for 5G mmWave cellular in massive V2X communications scenarios. We propose to introduce transmission *redundancy* by sending multiple replicas of the random-access preamble whenever an idle-mode mMTC device attempts to connect to the network. We note that the concept of redundancy has already been considered in 3GPP Release 13 with the enhancements for MTC (eMTC) and the narrowband Internet of Things (NB-IoT). However, the proposed access scheme has not been exploited in mmWave-based *mobile* scenarios, such as those pertaining to the V2X use case. In fact, by sending multiple replicas of the same random-access preamble it is possible to increase the chances of acquiring a data transmission opportunity at the first attempt. Along these lines, we on the one hand guarantee that a higher number of mMTC devices can initiate their data transfer to e.g., their serving mmWave base station, and on the other hand ensure that the entire initial access procedure is executed without incurring extra delays, despite higher dynamics and directionality in mmWave-based V2X setups.

The rest of this text is structured as follows. Section II elaborates on the feasibility of utilizing mmWave cellular technology to support massive V2X use cases. Section III introduces our developed concept of transmission redundancy and connects it to the recent initial access proposals for 5G mmWave cellular. Further, Section IV outlines a characteristic massive V2X scenario that employs our concept and conducts its thorough performance evaluation with ray-based and protocol-level modeling techniques. Finally, Section V concludes the paper by summarizing our main findings.

II. USE OF MMWAVE FOR MASSIVE V2X SCENARIOS

The higher transmission rates and lower transfer delays of today's wireless systems coupled with decisive capacity enhancements promised by the emerging 5G mmWave cellular are expected to support growing densities of automotive mMTC devices, up to 200 items per vehicle by 2020 [8]. Clearly, serving massive volumes of sensory data (especially from bandwidth-hungry radars and cameras) translates into heavier traffic loads that are impossible to accommodate with the current microwave-based network infrastructures. To this end, the use of mmWave bands offers larger amounts of radio spectrum, enables higher order modulation, and facilitates advanced multiple-input multiple-output (MIMO) operation. As a result, this enhances spectral efficiency as well as enables higher data rates (i.e., on the order of Gbit/s) as compared to the performance achieved in conventional systems operating at below-6-GHz carrier frequencies [9].

Furthermore, deploying higher numbers of directional transceivers based on mmWave radio access technology (RAT) may also aid in overcoming the blockage effects that negatively impact the propagation of mmWave radio signals. For instance, directional transmitters on the front and rear bumpers of a car can be employed for vehicle-to-vehicle (V2V) communications, whereas those positioned on top of a vehicle may be dedicated to offering vehicle-to-infrastructure (V2I) connectivity (see Fig. 1). The latter is because the network infrastructure is typically installed at higher elevations in order to provide with line-of-sight link conditions and thus lower the probability of blockage.

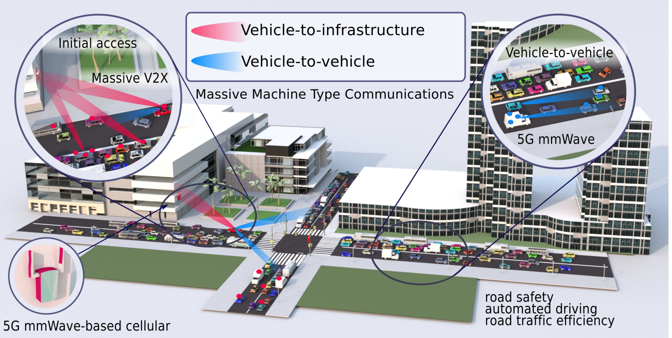

Fig. 1. Representative urban V2X scenario over 5G mmWave cellular.

In utilizing 5G mmWave systems for highly mobile V2X applications, the development of more efficient control layer procedures becomes crucial. In particular, one of the key challenges here is the design of a suitable initial network access mechanism that is capable of handling large volumes of potentially moving mMTC devices. In fact, following 3GPP's standardization efforts to improve reliability and reduce latency in 5G systems, new initial access solutions need to be proposed, which would be mindful of frequent cell reassociations (and the corresponding cell search overheads) in the presence of vehicular mobility.

Due to the limited set of available preambles (and thus the associated access codewords), the current 3GPP LTE Random Access (RA) procedure suffers in terms of capacity whenever the number of devices accessing the network increases. This implies higher delays and battery consumption, which in turn translates into lower reliability. Therefore, our work introduces a novel concept that improves the initial access operation in 5G mmWave cellular for massive V2X applications. It is based on adding *transmission redundancy* that aims to increase access reliability and decrease beam alignment latency in the course of initial network entry.

The main target of our proposal is to facilitate situations, where an mMTC device is changing its state from *idle* to *connected*. This control plane transition is triggered more often in mmWave systems than in conventional LTE deployments due to *(i)* intermittency of the links and *(ii)* frequent idle mode cycles. Indeed, mmWave propagation may lead to more frequent connection re-establishments that require proper alignment for directional transmission and reception [5]. As communicating devices in V2X mMTC are inherently mobile, occasional inter-RAT handovers (e.g, between mmWave and WiFi or LTE) are also expected due to irregular mmWave coverage, especially at the early stages of 5G deployment.

III. Improved Access Reliability in 5G mmWave

A. Principles of Initial Access in Cellular

While 5G mmWave cellular expects to deliver the capacity needed to support the high data rates of advanced car-mounted sensors, the emerging latency-sensitive and real-time automotive applications (such as "See Through" and "Bird's Eye View" [3]) may be significantly disadvantaged in case of lengthy initial access. It is typically invoked at transitions from idle to active mode as well as during handovers (i.e., under certain conditions), and can in principle be implemented as *(i)* a contention-free procedure or rely on *(ii)* a contention-based RA mechanism. The latter is more feasible in urban V2X scenarios due to dynamic and unpredictable load produced by high and varying densities of vehicles [10].

It is generally expected that RA in mmWave cellular will adopt as a baseline the core principles of that in 3GPP LTE technology [11]. However, enhancements have already been proposed in the 3GPP standardization process for the case where higher frequencies are used. In particular, emerging initial access protocols for mmWave will leverage the *four-stage procedure*. On top of this, it is assumed that mmWave cellular base station (BS) periodically broadcasts dedicated synchronization signals (SS), which allow the devices to estimate the beam direction towards the BS, e.g., based on the channel reciprocity. An example is summarized as follows (see also Fig. 2):

1) A newly activated mMTC device attempts to establish a connection to the intended BS based on its SS measurements. It thus selects a subset of random access channel (RACH) resources (across time and frequency) together with a subset of RACH preambles to be transmitted within a single beam at the next available RACH occasion. Importantly for mmWave, one RA preamble may potentially be identified by frequency, time interval, and sequence [11].
2) The BS then detects the RACH preambles and estimates the direction towards the sending device. It replies by transmitting a random access response (RAR) that contains service information on the timing alignment, the initial uplink grant, and the Cell Radio Network Temporary Identifier (C-RNTI) to all of the mMTC devices associated with the received preamble identifier and located within the given beam.
3) The device awaits the response during the RA response window and then, if the RAR is received, it transmits the connection request according to its uplink grant over PUSCH.
4) If at stage "1" only one mMTC device has selected a particular preamble sequence and resource, then the BS successfully receives its connection request and grants resources for the requested data transmission. If, however, two or more devices within the same BS antenna beam receive the RAR with the same preamble identifier, then a collision occurs and at best only one of the contending devices can receive the data transmission grant (that is, if a "power capture" effect [12] takes place). Those not receiving the data grants or RAR messages at stage "2" are forced to initiate a backoff procedure and retransmit at the next RACH occasion.

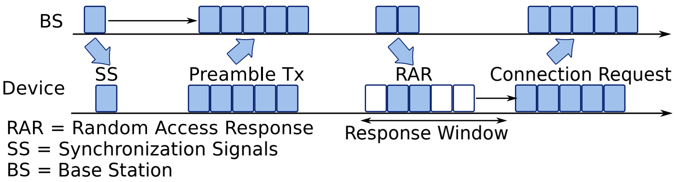

Fig. 2. Illustration of random-access procedure in cellular.

We note that despite the fact that the structure of the RA procedure is fairly straightforward, the actual timings as well as the numbers of available preambles and RACH periodicity remain undefined in the current 3GPP Release 15 specifications (and the associated technical reports) and may depend on the scenario in question. An example of the currently proposed RACH numerology for above 6 GHz, which can be utilized entirely or partially by the BS, is summarized by Table 1 in [11]. Further, the very high directivity of mmWave antennas and hence the presence of multiple beams may result in the need of applying *more time-consuming* sector sweep procedures, which incur considerable overheads.

B. Proposed Redundancy-based Control Procedure

An adequate reliability improvement scheme for RACH in 5G mmWave systems requires, for instance, maximizing the probability of successful connection request at the first attempt. One possible solution to do so has been proposed for LTE systems in [6] and is based on the consecutive transmission of different preamble sequences that may be exploited as orthogonal cover codes. However, for mmWave links, the orthogonality of such preamble-constructed codes may be severely degraded due to time-varying channels and frequency offsets. On the other hand, we propose to explicitly take advantage of the time-varying channel properties and introduce an *adaptive dynamic control procedure* that optimizes the probability of successful transmission at the first attempt.

One of the expected distinguishing features of 5G mmWave cellular is its support of multiple/repeated RACH preambles [11]. Namely, one may assume that a device can select not just a single but several RA preambles and transmit them within the same beam. Naturally, sending multiple RACH preambles implies that the RAR messages will be received independently for each preamble together with the grants to initiate the data transfer in case of successful connection request transmission.

By adding such redundancy, the RA scheme performance may be significantly improved in terms of the probability of successful transmission at the first attempt, as compared to the conventional LTE system design. Assuming that the BS regularly broadcasts the preferred backoff window size W and informs all of the mMTC devices as to whether they are expected to transmit one or K multiple preambles within a subset of RACH resources, we may employ our random access procedure designed in [13].

The main idea of the algorithm in [13] is to dynamically control K and the transmission probability p (that is directly translated into the backoff window W) subject to the immediate load conditions. In case if the actual number N_j of currently active mMTC devices is known in advance, the said algorithm provably minimizes the probability of successful transmission; however, when such information is not available and the immediate number of active sensors is estimated by the past channel history, it provides an efficient heuristic control scheme.

In particular, for the RACH occasion j the number of simultaneously active sensors N_j may be predicted by using the maximum likelihood estimation, where the most probable event is defined based on the channel outcome $\mathbf{v}_{j-1} =< n_i, n_s, n_c >$ observed after the preceding RACH occasion $j-1$. Here, n_i, n_s, n_c denote the number of idle, successful, and collided preambles, respectively. The point $\tilde{N}_j$ that delivers the maximum of likelihood may be tightly approximated by the point of maximum of the following function of the same shape as $\Pr\{\mathbf{v}_{j-1}|N_{j-1}\}$:

$$g(\mathbf{v}_{j-1}, N_{j-1}) = \mu(N)^{n_s} e^{-\mu(N)M} \left(e^{\mu(N)} - 1 - \mu(N)\right)^{n_c}, \quad (1)$$

where $\mu(N) = N_{j-1}K/M_{j-1}$ and $n_i+n_s+n_c = M_{j-1}$ is the total number of preambles available at the attempt j. Deriving the gradient of the function (1) that provides the optimal value of μ^*, we may estimate the number of currently active MTC devices as:

$$\tilde{N}_j = \begin{cases} \max\left\{1, \left[\frac{1}{p_{j-1}}\mu^* \frac{M}{K_{j-1}} + \lambda M\right] - S_{j-1}\right\}, n_c > 0, \\ \max\left\{1, \left[\frac{1}{p_{j-1}} n_s \frac{1}{K_{j-1}} + \lambda M\right] - S_{j-1}\right\}, n_c = 0, \end{cases} \quad (2)$$

where S_{j-1} is the number of devices successful at the previous attempt $j-1$, λ is the estimated number of activating devices per interval between the consecutive attempts, and (K_{j-1}, p_{j-1}) is the broadcasted set of control parameters.

Further, there are essentially two options as follows:

- An estimate $\tilde{N}_j$ is less than a half of the available RACH resources $M/2$; hence, $p_j = 1$ (which means that the backoff window size is set to zero) and $K_j \geq 1$. The exact values of the optimal $K_j(\tilde{N}_j)$ are precalculated based on combinatorial expressions as shown in [13] and stored at the BS. This option corresponds to a lightly loaded system.
- An estimate $\tilde{N}_j$ is greater than a half of the available RACH resources $M/2$; hence, $p_j = \min\left(1, \frac{M}{\tilde{N}_j}\right) < 1$ (i.e., the recalculated backoff window size is larger than zero and is advertised by the BS) and $K_j = 1$. This option corresponds to a heavily loaded system.

The improvements considered in this work relate to the case where $K \geq 1$, which is a realistic situation for cellular systems. However, for the sake of completeness, we also include the reference case of $K = 1$ with the goal of performance benchmarking. As formally verified in [13], the proposed approach increases the probability of transmission at the first attempt and thus may improve other RA performance indicators, such as access latency. Here, if the channel conditions are favorable and all of the RA preambles are delivered successfully at all times, the redundancy gain may be rather marginal. However, for the error-prone channel (which is a more typical case for the less stable mmWave links), one may observe significant benefits as we demonstrate in the following section.

IV. MODELING INITIAL ACCESS IN V2X OVER MMWAVE

The performance evaluation methodology employed here is built on a set of radio propagation properties obtained with the use of our in-house 3D ray-based modeler [14]. We also utilize our recent framework in [13] for analyzing random-access systems with replications as part of the initial network entry process. In particular, the latter accepts at its input the 3D channel modeling results produced by the ray-based simulator and quantifies the improvements in the probability of transmitting a random-access preamble at the first attempt. This is meant to demonstrate the gains in channel access probability (i.e., reliability) and the respective latency on top of the legacy LTE-based solutions that are in use today.

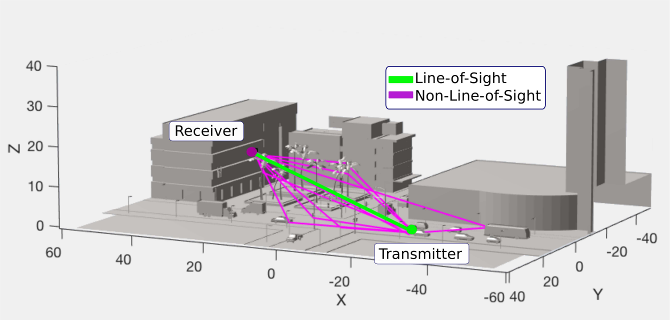

Fig. 3. A representative snapshot of ray-based simulations.

A. Ray-based Simulator Design

In order to comprehensively analyze the proposed redundancy-based random access system, the mmWave radio propagation in the considered V2X scenario of interest has to be thoroughly investigated. In fact, different channel environments may produce very dissimilar channel properties that can severely impact the system-level metrics. For that reason, in this work we aim to characterize the propagation behavior within the reference scenario illustrated in Fig. 1 with the use of a custom ray-based modeler [14]. The latter is capable of capturing the needed mmWave channel properties, such as the line-of-sight (LOS) and non-LOS (NLOS) path loss, the received power, the angle of arrival (AoA), the angle of departure (AoD), etc.

In particular, our utilized tool is completed in Matlab and – as shown in Fig. 3 – exploits the *shooting and bouncing ray* (SBR) methodology to provide accurate and relatively fast estimation of the signal field strength in the presence of complex objects (e.g., highly detailed cars and buildings, lampposts, trees, etc.) and materials (metals, dielectrics, and multi-layered) according to the principles of geometrical optics (GO) and uniform theory of diffraction (UTD).

For the purposes of our study, the reference massive V2X scenario incorporates a number of vehicles deployed around an urban intersection with the traffic lights. To collect sufficient statistics for the use in our subsequent analysis, we considered a large number of potential mmWave BS locations that may result from alternative network planning choices. We focused on uplink communication where small cells only receive information from the mMTC devices deployed on cars across the area. Moreover, each of the modeled vehicles featured a variable number of transmitters that are coupled with bandwidth-hungry sensors deployed on them.

For each feasible mmWave channel between a transmitter (Tx) and each receiver (Rx), we calculated the following important properties: *(i)* LOS and *(ii)* NLOS path loss, *(iii)* received power, *(iv)* AoA, *(v)* AoD, and *(vi)* distance (or time) that a certain ray covers to reach a given Rx. The core simulation parameters are summarized in Table I.

TABLE I
MAIN SIMULATION PARAMETERS

Parameter	Value
Ray-based modeling	
Frequency	28 GHz
Bandwidth	1 GHz
Tx power	23 dBm
Rx/Tx antenna gain	calculated based on beamwidth
Beamwidth	30^o
# of devices per vehicle, N_c	5
Protocol-level simulation	
$\sigma_{\text{LOS}}/\sigma_{\text{NLOS}}$	4/9 dB
Rx power threshold	-80 dBm
# of available RACH preambles	20
Inter-activation time	0.5/0.05s
Interval between two RACH Tx	1.250ms
Frame length	1.250ms
Slot length	0.125ms

B. Protocol-Level Assessment of V2X System

Further, out of all the potential mMTC device (Tx) locations we randomly select N_c sensors per car, which are assumed to activate during a particular simulation run. For all the mMTC devices, we consider the values of the average power and the LOS/NLOS flag in correspondence to the best selected path, which is based on the results of our ray-based modeling summarized in the previous subsection. For the tagged beam of certain beamwidth θ, we then randomly choose the activated sensors according to their inter-activation interval i.e., the probability p that can also be translated into the expectation of the interval between the activations for a particular device.

For certainty, we assume that a RACH occasion (termed transmission opportunity in LTE) is available at the beginning of each frame. At every RACH occasion, we consider a variable set of active mMTC devices, for which we update their instantaneous power as the average power plus an additional power offset (e.g., a random variable distributed according to the normal distribution with the standard deviation of $\sigma_{\text{LOS}}/\sigma_{\text{NLOS}}$=4dB/9dB for LOS/NLOS [15], respectively). The average power is based on a fixed value, where the directivity gain is a function of the beamwidth. As a result, the instantaneous power values are different for each RACH preamble transmission as well as for every RACH resource associated with multiple preamble transmissions of the same device.

Prior to every RACH opportunity, each mMTC device receives broadcast information from the BS related to the back-off window size and the number of RA preambles to transmit, K. For both the proposed technique ($K \geq 1$) and the baseline method ($K = 1$), we differentiate between two dedicated control algorithms that run at the BS. The first (*theoretical scheme*) assumes perfect knowledge on the actual number of active mMTC devices, N, within a beam; the second (*feasible practical scheme*) estimates the number of currently active devices by using ergodic processes based on the channel history of collisions and successful transmissions, as well as on the maximum likelihood estimation (for $K \geq 1$) [13] based on the channel history.

According to the broadcast control information, the active devices transmit K preambles at the beginning of a random access procedure. For a certain RACH occasion and RACH resource, we then “filter out” sensors with the instantaneous power below a given Rx threshold P_{thr}. After that, we analyze the outcome of a transmission over the respective PUSCH resource. We remind that in the case when two or more mMTC devices transmit over the same PUSCH resource, all their transmissions fail unless a “power capture” takes place. Here, 3 dB of difference in the signal is assumed to be required for it to happen. The remaining transmissions are considered to be lost.

As a result, the successful message delivery corresponds to at least one collision-free preamble transmission. The outlined procedure is repeated for all of the beams across multiple Rx positions (generated by the ray-based modeler) to ensure a statistically representative set. Finally, we assess the probability of successful message delivery by disregarding the preambles that have eventually been ‘lost’ due to collided connection requests.

C. Important Numerical Results

To abstract away the concrete RACH procedure timings and yet be able to evaluate the proposed system in detail, we hereinafter focus on characterizing the probability of a successful attempt to establish a connection at the initial access stage. In particular, we begin with Fig. 4 that illustrates how sensitive the system performance is with respect to the variable number of potential RACH resources (not only the number of RACH preambles, but also the capacity of PDCCH and PUSCH, so that the device receives its data transmission grant at the end of the four-stage RACH procedure). We thus provide two sets of plots: for the higher intensity of requests (on

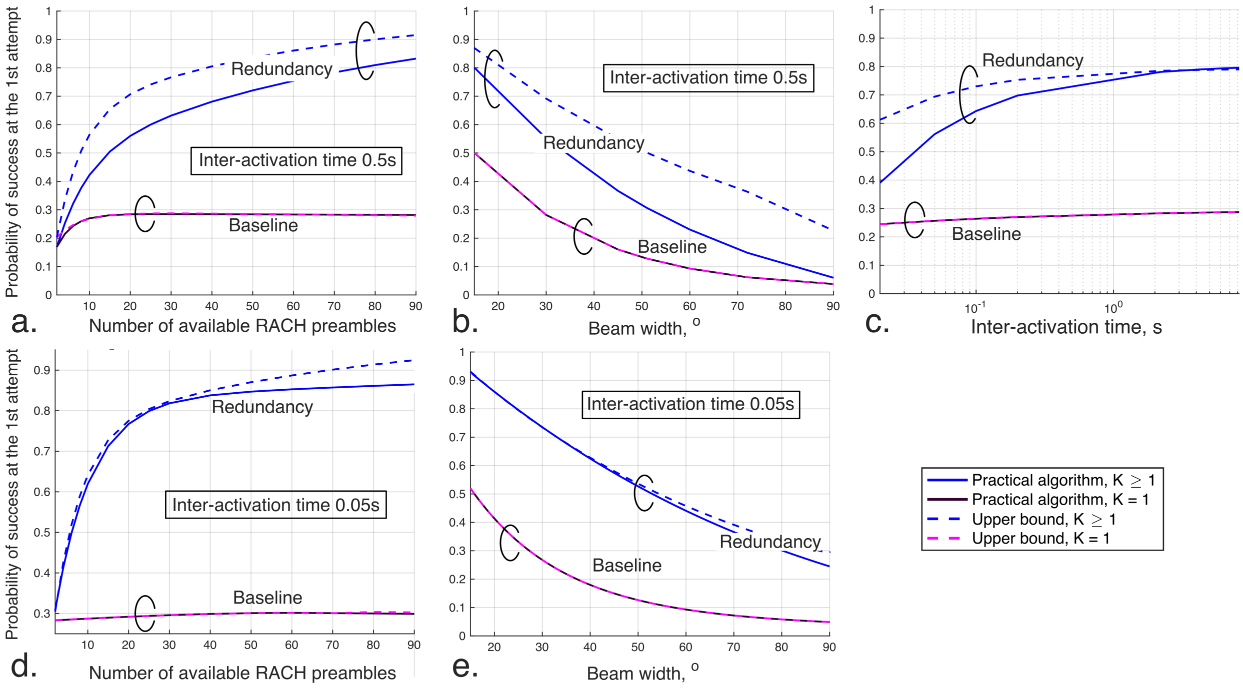

Fig. 4. Probability of failure at the first attempt of initial access vs. number of available RACH preambles.

average, once per 0.05s) and for the lower load (once per 0.5s).

In particular, Fig. 4(a) and Fig. 4(d) demonstrate the evolution of both the proposed (blue) and the baseline (magenta) algorithms, which clearly confirms the advantages of utilizing transmission redundancy. The growing gap between the performance of two schemes in Fig. 4(a) is due to the fact that the proposed option compensates for the presence of errors in the channel better with the increasing amount of dedicated resources, while in Fig. 4(d) the system is close to empty almost all of the time, but our procedure intentionally yields K of not greater than a half of the total number of preambles. Moreover, as the dashed lines indicate the lower bound on the failure probability (based on theoretical algorithms with the known number of contenders, N), we observe that the practical scheme may be improved even further by appropriately adjusting the procedure of estimating N.

To address the mmWave specifics, we study the system response to the width of the antenna beam (varied from 15^o to 90^o, see Fig. 4(b) and Fig. 4(e)) for the two considered algorithms and their bounds. Naturally, the probability of establishing a connection drops in case of our baseline $K = 1$ as the directivity gain decreases, while the scheme with $K \geq 1$ shows better yet also degraded performance for wider beams. Interestingly, the proposed practical solution works almost as good as its theoretical upper estimate for narrower beams. Generally, the use of narrower beams results in more pronounced benefits of redundancy, since for wider beams an optimization of the proposed scheme will often result in $K = 1$ due to a higher number of contenders.

In our further analysis, the probability of failure to establish a connection at the initial access stage is demonstrated by varying the inter-activation time, see Fig. 4(c). Here, redundancy is employed to achieve the probability of success that is close to when the number of contenders N is known. However, a slight discrepancy that one may notice for the case when the inter-activation time is short (i.e., see the dashed and solid blue lines) is due to the tuning of the parameters. Importantly, the lower the sensor activation rate is (towards the right side), the larger the gap between the baseline and the proposed technique becomes. With extremely frequent requests, an increasing number of contenders lowers the performance of the considered solution to $K = 1$.

Finally, we construct a surface that illustrates the dependency of the successful connection probability on both the volume of the available resources and the total number of sensors per car (see Fig. 5). Note that the latter is of a commendatory nature as the actual number of sensors as well as the intensity of network access requests for future vehicular applications may not be known in advance. However, these results clearly manifest almost linear nature of change with respect to the car load as well as relatively marginal effect as compared to the performance sensitivity to the amount of RACH resources for the selected beamwidth of 30^o. Importantly, one may again observe that for the lower loads, the performance of our practical algorithm is extremely close to what the upper bound predicts, thus resulting in a decisive gain on top of the baseline.

Summarizing, the obtained results demonstrate that at massive loads and for a large number of sectors introducing redundancy might have a marginal impact on the initial access latency. However, for many other cases, this brings substantial improvements to the levels of reliability in *directional* contention-based initial access. We also expect that once the

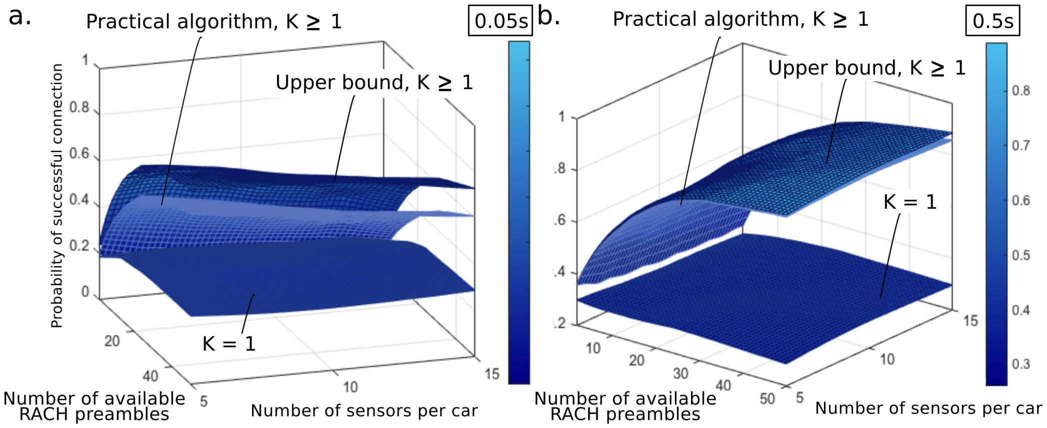

Fig. 5. Probability of successful connection at the first attempt vs. number of RACH opportunities and number of sensors per car.

numerology of the RACH procedure for mmWave is finalized in the upcoming 3GPP Release 15, it could be appropriate to reevaluate our representative scenario to assess the performance of the random access procedure in more detail.

V. CONCLUSIONS

In this paper, we proposed to introduce transmission *redundancy* in order to send multiple replicas of the RACH preamble whenever an mMTC device in the idle mode attempts to connect to the network. Along these lines, we focused our attention on a typical V2X scenario represented by an urban intersection, where vehicles that are equipped with a high number of advanced sensors attempt to connect to the cellular infrastructure. Since the overall amounts of data generated by a multitude of automotive mMTC devices may incur high data loads, they are assumed to be handled by a 5G mmWave system operating at, e.g., 28 GHz frequencies.

Our performance evaluation methodology exploits a novel framework that accepts at the input a set of relevant channel properties generated with a detailed 3D ray-based modeler. The obtained numerical results confirm that introducing *redundancy* in the initial random access procedure brings substantial improvements in reliability of *directional* contention-based initial access as compared to state-of-the-art RACH schemes.

ACKNOWLEDGMENT

This work was supported by the Academy of Finland (projects WiFiUS and PRISMA), by the project TAKE-5: The 5th Evolution Take of Wireless Communication Networks, funded by Tekes, as well as by the Finnish Cultural Foundation and Jorma Ollila Grant (O. Galinina).

REFERENCES

[1] 5G-PPP, “5G Automotive Vision,” White Paper, April 2015. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White-Paper-on-Automotive-Vertical-Sectors.pdf

[2] S. Chen, R. Ma, H. H. Chen, H. Zhang, W. Meng, and J. Liu, “Machine-to-Machine Communications in Ultra-Dense Networks – A Survey,” *IEEE Communications Surveys & Tutorials*, vol. PP, no. 99, pp. 1–1, 2017.

[3] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, “Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing,” *IEEE Communications Magazine*, vol. 54, no. 12, pp. 160–167, December 2016.

[4] S. Andreev, O. Galinina, A. Pyattaev, M. Gerasimenko, T. Tirronen, J. Torsner, J. Sachs, M. Dohler, and Y. Koucheryavy, “Understanding the IoT connectivity landscape: a contemporary M2M radio technology roadmap,” *IEEE Communications Magazine*, vol. 53, no. 9, pp. 32–40, September 2015.

[5] M. Giordani, M. Mezzavilla, and M. Zorzi, “Initial Access in 5G mmWave Cellular Networks,” *IEEE Communications Magazine*, vol. 54, no. 11, pp. 40–47, November 2016.

[6] M. Condoluci, M. Dohler, G. Araniti, A. Molinaro, and J. Sachs, “Enhanced Radio Access and Data Transmission Procedures Facilitating Industry-Compliant Machine-Type Communications over LTE-Based 5G Networks,” *IEEE Wireless Communications*, vol. 23, no. 1, pp. 56–63, February 2016.

[7] S. Y. Lien, T. H. Liau, C. Y. Kao, and K. C. Chen, “Cooperative Access Class Barring for Machine-to-Machine Communications,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 1, pp. 27–32, January 2012.

[8] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, “Connected vehicles: Solutions and challenges,” *IEEE Internet of Things Journal*, vol. 1, no. 4, pp. 289–299, August 2014.

[9] W. Roh, J. Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, “Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 106–113, February 2014.

[10] N. Alliance, “NGMN 5G White Paper,” White paper, February 2015. [Online]. Available: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

[11] Ericsson, “R1-1706014: NR PRACH design and evaluations,” 3GPP Contribution, April 2017. [Online]. Available: http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_88b/Docs/R1-1706014.zip

[12] T. S. Rappaport, G. R. MacCartney, M. K. Samimi, and S. Sun, “Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design,” *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029–3056, September 2015.

[13] O. Galinina, A. Turlikov, S. Andreev, and Y. Koucheryavy, “Multi-Channel Random Access with Replications,” in *Information Theory (ISIT), 2017 IEEE International Symposium on*. IEEE, 2017, pp. 2538–2542.

[14] D. Solomitckii, Q. C. Li, T. Balercia, C. R. C. M. da Silva, S. Talwar, S. Andreev, and Y. Koucheryavy, “Characterizing the Impact of Diffuse Scattering in Urban Millimeter-Wave Deployments,” *IEEE Wireless Communications Letters*, vol. 5, no. 4, pp. 432–435, August 2016.

[15] 3GPP, “Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects,” 3GPP TR 36.814, March 2017. [Online]. Available: http://www.3gpp.org/ftp//Specs/archive/36_series/36.814/