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Effects of Heterogeneous Mobility on D2D- and Drone-Assisted Mission-Critical MTC in 5G

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Abstract

Mission-critical machine-type communications (mcMTC) are starting to play a central role in the industrial Internet of Things ecosystem and have the potential to create high-revenue businesses, including intelligent transportation systems, energy/smart grid control, public safety services, and high-end wearable applications. Consequently, in the fifth generation (5G) of wireless networks, mcMTC have imposed a wide range of requirements on the enabling technology, such as low power, high reliability, and low latency connectivity. Recognizing these challenges, the recent and ongoing releases of the Long-Term Evolution systems incorporate support for low-cost and enhanced coverage, reduced latency, and high reliability for devices at varying levels of mobility. In this article, we examine the effects of *heterogeneous* user and device mobility – produced by a mixture of various mobility patterns – on the performance of mcMTC across three representative scenarios within a multi-connectivity 5G network. We establish that the availability of alternative connectivity options, such as device-to-device (D2D) links and drone-assisted access, helps meeting the requirements of mcMTC applications in a wide range of scenarios, including industrial automation, vehicular connectivity, and urban communications. In particular, we confirm improvements of up to 40 percent in link availability and reliability with the use of proximate connections on top of the cellular-only baseline.

I. EMERGING INTERNET OF MOBILE, RELIABLE THINGS

THE number of connected machine-type devices is expected to exceed 28 billion by 2021, thereby surpassing the number of human-centric connections significantly [1]. This fascinating development is a driving force behind the convergence of the physical and digital worlds that promises to create an unprecedented Internet of Things (IoT) market of 19 trillion USD over the next decade[1]. Currently, a diverse range of IoT use cases includes intelligent transportation systems, smart grid automation, remote health care, smart metering, industrial automation and control, remote manufacturing, public safety surveillance, and numerous other applications[2].

When it comes to technical requirements, these diverse use cases are expanding the market to comprise "low-end" massive IoT applications as well as significantly more complex "high-end" solutions that may be labeled as critical IoT. At one end of the scale, in high-volume IoT deployments, there are smart sensors that report on a regular basis to the cloud infrastructure. At the other end of the scale are advanced critical IoT applications that have stringent requirements in terms of communications reliability, availability, and latency [2]. Accounting for the rapid growth pace of various IoT applications, the ultimate objective of enabling machine-type communications (MTC) technology is to construct comprehensive connections among diverse stationary and mobile devices, as well as other *things* across extensive coverage areas.

Today, this construction is being decisively attempted by the fifth generation (5G) of mobile networks and the relevant standardization has recently started. Seamless connectivity support for mobility is particularly important for mission-critical MTC (mcMTC) devices moving at various speeds over a certain geographical area. Ironically, while mobility models have been routinely used in the evaluation of human-centric communications technologies, such as mobile ad-hoc and legacy cellular networks, the effects of mobility in *mobile* 5G systems that are targeting the mcMTC market are much less understood [3].

In the context of ad-hoc wireless networks, the impact of mobility on per-user throughput has been comprehensively characterized by [4]. For applications with loose delay constraints, where network topology may change over the timescale of single-packet delivery, the per-user throughput can increase dramatically when nodes are mobile rather than static. However, this important result may not be applicable in 5G networks that have strict latency budgets and where an infrastructure node arbitrates access to licensed spectrum resources.

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[1] J. Bradley, J. Barbier, and D. Handler, "Embracing the Internet of Everything," Cisco White Paper, CISCO. Available: https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoE_Economy.pdf [Accessed on 08/2016]

[2] Ericsson, "Cellular Networks for Massive IoT," White Paper. Available: https://www.ericsson.com/res/docs/whitepapers/wp_iot.pdf [Accessed on 08/2016]

Another line of research has established that employing multiple radio access technologies and multi-access networks can drastically improve connection reliability, robustness to link failures, as well as utilization of spectrum resources in environments housing devices with diverse capabilities and quality-of-service (QoS) requirements [5]. Most recently, the integration of ad-hoc and cellular technologies [6] facilitated novel applications of user-deployed and provisional wireless access points in the form of flying robots, or *drones*. This development has sparked new interest in understanding the benefits of multi-connectivity in the context of truly mobile access for IoT applications.

In *this article*, we aim to thoroughly quantify the impact of heterogeneous mobility in 5G networks that support mcMTC to enable advanced IoT applications. To this end, we consider a multi-connectivity system where devices can utilize cellular, direct Device-to-Device (D2D), and drone-assisted connections to communicate and access information. In particular, we focus on system-level performance characterization in representative 5G-grade IoT scenarios featuring mixed mobility patterns. The legacy Long-Term Evolution (LTE) cellular systems are adopted as a benchmark where the devices are served over the infrastructure-based connections. These are compared with proximity services (ProSe)-based LTE solutions, where additional connectivity is made available by employing both D2D links between proximal devices and communications via "mobile" access points; that is, drones.

II. TOWARDS A CONVERGED 5G-IOT ECOSYSTEM

A. MTC Requirements and Challenges in 5G Standardization

The rapid proliferation in numbers and functionalities of IoT devices has meant that the standards community is decisively advancing to outline the novel 5G mobile technology. To this end, the vision for the future development of International Mobile Telecommunications (IMT) and beyond was published [7], which presents the overall objectives and requirements for such next-generation systems. That document introduces three broad classes of usage scenarios with very different performance requirements: (i) enhanced mobile broadband, (ii) massive machine-type communications, and (iii) ultra-reliable and low-latency communications.

The 3rd Generation Partnership Project (3GPP) is eagerly responding to this initiative by starting to ratify a new, non-backward-compatible radio technology in centimeter- and millimeter-wave spectra, and the early commercial deployments of this *new radio* technology are planned for 2018-2020. It is expected that 3GPP's *new radio* will be accompanied by further LTE evolution in parallel. Recognizing the benefits of cellular networks built around a global standards suite, the work in 3GPP includes technology components such as LTE Wi-Fi Link Aggregation (LWA), Licensed Assisted Access (LAA), D2D communications to support smart phone relaying for wearables, power saving for MTC devices, MTC service enabling layers (oneM2M), as well as support for low-throughput and low-complexity MTC devices, realized both as a new LTE User Equipment (UE) category (Cat-M1) and a new narrow-band IoT (NB-IoT) radio interface in LTE Release 13 [8]. For MTC, these developments primarily mean a clear distinction between "massive" and "critical" usage scenarios, even though certain IoT applications may simultaneously belong to both categories (for example, critical industrial alarms).

Given the decisive past progress in 3GPP to support MTC requirements (which started as early as in 2005), and the ongoing efforts to define the NB-IoT radio interface, many massive MTC usage scenarios can already be accommodated by existing LTE releases. However, the enhancements promised by the *new radio* are needed in order to enable large-scale deployments of mcMTC applications, as their main demands are aligned along the lines of mobility (with speeds of up to 500 km/h) and latency (with end-to-end delays of under 1 ms) [7]. This support is crucial in order to promptly leverage the rich business opportunities around mcMTC as part of 5G landscape, but it also poses many important system design questions.

In order to support more reliable consumer and industrial IoT applications [9], we envision that leveraging and integrating across the available heterogeneous access options, such as multi-radio uplink, downlink, and direct D2D link, will be crucial. The latter is particularly attractive, as the distinction between the network and the user equipment is becoming blurred, which offers excellent opportunities to utilize specialized UE as part of increasingly complex network tasks. This trend goes hand in hand with improved degrees of intelligence in the networked devices, from sensors, wearables, and UE to connected cars and mobile robots, which require very different levels of support for mobility, reliability, and spectrum management [10]. As cooperation between network and user equipment is becoming essential to improve performance of future IoT applications, the impact of more frequent handovers becomes a growing concern [11].

The promising market of connected – and, soon, self-driven – cars imposes unprecedented requirements in the form of extreme latency and reliability of data delivery at very high-speed mobility. This is particularly challenging given the fundamental fact that higher mobility naturally contradicts better reliability. As the respective operational models in the emerging Vehicle-to-Everything (V2X) business are taking shape, we will need a comprehensive set of tools to handle the unconstrained mobility. This demand is particularly pressing since the impact of mobility has not been revisited in network architectures for a decade or so and now – as we are entering a new era of converged 5G-IoT – is an appropriate time to understand and analyze the various implications of mobility on system performance, as well as to possibly rethink the ways of managing it in 5G networks.

B. Representative 5G-grade mcMTC scenarios

Today, the landscape of the global consumer and industrial IoT business is already extremely broad, stretching from wearable fitness trackers and health care devices to consumer electronics and connected cars. The most challenging study cases emerge in the form of crowded urban scenarios with very high connectivity demands, possibly under unreliable network coverage [12]. In addition to this, in environments with high-speed unrestricted mobility, the availability and reliability of wireless link are of primary importance to ensure strict service-level agreements in new markets around 5G-grade applications and services.

To address the performance of these connected machine-centric networks, we evaluate the relevant mixtures of realistic mobility models and study their effects on the availability and reliability metrics under partial cellular network coverage. In particular, we focus on three reference study cases that constitute representative 5G-grade mcMTC scenarios with very diverse application requirements, see Fig. 5.

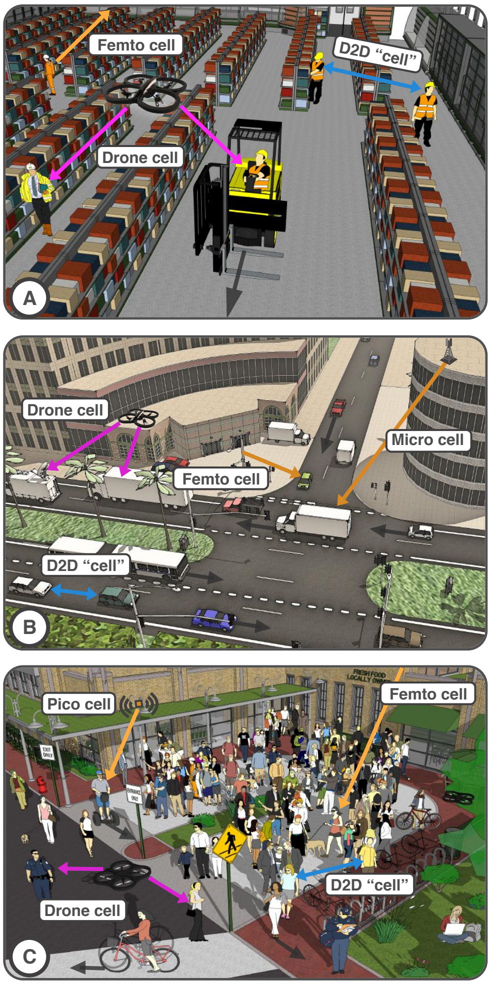

Fig. 1. Characteristic 5G-grade IoT study cases

Industrial automation (CASE A). Factories of the future will be something more than the standalone "connectivity islands". There is, in fact, an ongoing trend to connect them as part of a broader industrial ecosystem. Accordingly, we consider the typical mobility aspects related to the supply chain processes within the factory itself or in proximity to its buildings. We focus on time constrained communications for the management of assets and goods as part of the on-site production and logistics sectors. This scenario becomes of interest since reliable management of the entire supply chain is crucial to avoid faults and improve the overall factory automation efficiency[3].

Vehicular connectivity (CASE B). Communications in the V2X study case comprise data exchange between a connected vehicle and: (i) another vehicle (i.e., Vehicle-to-Vehicle (V2V)); (ii) a road infrastructure (i.e., Vehicle-to-Infrastructure (V2I)); (iii) a personal device moving with pedestrian speeds (i.e., Vehicle-to-Pedestrian (V2P)). Here, the transmitted information can be periodic messages such as speed, positioning, and time related data needed to support critical safety and best effort

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[3] Note that connectivity between the factory entities (e.g., robots, sensors, vehicles, workers) does not necessarily require ultra-low latencies, as response times are typically less constrained for humans than for machines.

TABLE I
UTILIZED MOBILITY MODELS

Mobility model	Corresponding application	Brief description
Random Walk	Short time scale movement of humans and vehicles	The random travel direction is uniformly distributed in $[0, 2\pi]$. The speed follows the distribution between the boundary values. After a constant time interval, a node computes new direction and speed for future movement.
Levy Flight	Long time scale movement of humans and vehicles	Multiple short "runs" within a restricted area are interchanged with long-distance travels in a random direction.
Manhattan	Movement of vehicles and pedestrians in urban environment	At each cross-road intersection, a node chooses to continue in the same direction with probability of 0.5, while turns left or right with equal probabilities of 0.25.
Reference Point Group	Mobility of drones	Models group behavior of a set of nodes where each one follows the logical center (identified by the *group leader*). The nodes additionally have their own short time-scale Random Walk mobility within the group.

entertainment applications, as well as offer efficient and comfortable driving experience. In this context, D2D interaction and "mobile" access points, including drones, may be of particular interest to achieve higher communications reliability and improved connection availability.

Urban communications (CASE C). This study case covers a set of practical situations where a very large number of mobile end users, potentially carrying several wearable devices, are crowded together in locations such as stadiums, shopping malls, open air festivals, and other public events. The network infrastructure should in these cases be ready to accommodate high densities of active users and their connected devices with large amounts of aggregated traffic. Consequently, the key challenge in these environments is the provision of relatively reliable and available wireless connections to people moving according to certain pedestrian patterns and, likely, crossing areas with partial connectivity from the pre-deployed infrastructure network.

III. MOBILITY-CENTRIC PERSPECTIVE ON MCMTC

A. *Multi-Connectivity System Setup*

1) Available Connectivity Options: In the subsequent evaluation, we adopt the *legacy LTE* solution as our benchmark where cellular infrastructure serves the mcMTC devices of interest. In addition, proximity-based D2D communications between the involved devices and drone-assisted mobile access are considered to augment the connectivity experience. This set of technologies, referred to as ProSe-based LTE solution, leverages on D2D links whenever mcMTC devices have an opportunity to establish them in proximity (assuming a partner with the desired content), to improve the chances of reliably acquiring the relevant data.

In particular, drones that carry radio transceivers (i.e., drone small cells) are essentially *mobile* access points that provide better network coverage and bring higher data rates to the challenging locations where LTE layout may be under-provisioned. Further, we assume that the D2D connection setup is managed by the LTE infrastructure for device discovery, session continuity, and security arbitration, whereas Wi-Fi Direct links in unlicensed spectrum are selected as the actual D2D technology. Ultimately, mcMTC connectivity is considered to be *unreliable* in the situations when: 1) the device is outside of cellular LTE coverage; 2) it has no opportunity to establish a D2D link with a relevant partner; and 3) the device cannot be served by a neighboring drone small cell.

2) Characteristic Mobility Models: To comprehensively assess the effects of realistic mobility in our three mcMTC study cases, we consider four mobility models and their heterogeneous combinations. These models have been carefully selected to capture both short- and long-term time scales of mobility as appropriate for the chosen study cases. While some of the models originally come from the realm of human mobility, we flexibly adopt them to become representative of mcMTC moving patterns. We briefly summarize the selected models in Table I and highlight their main features.

First, with the Random Walk (RW) model, the devices move from their current to the new target position randomly by appropriately choosing their speed and travel direction; this behavior aims to capture the short-term mobility on the scale of tens of minutes. Further, the Levy Flight (LF) model is able to mimic movement patterns over a larger time span where mixed effects may be experienced. Another consideration is the Manhattan model that is widely used to follow the mobility of vehicles in urban settings. Finally, the Reference Point Group (RPG) model is particularly suitable to track the mobility of drones. To make it compliant with our scenarios, we assume that the drones follow a reference point, which is identified by the zone within the area of interest where the density of users is the highest. This setup allows the drone small cell to provide additional capacity and coverage in locations where large user densities may cause congestion and network overloads.

TABLE II
SIMULATION SETUP AND PARAMETERS

		CASE A	CASE B	CASE C
Application parameter	Amount of data	300KB	1500B	20MB
	Inter-arrival time	10s	100ms	1s
System parameter	Cell radius	100m	250m	500m
	Number of nodes*	100M/30H/20V	450V/50H	300H/650M/50V
	Density of nodes	0.75 node/m^2	1.0 node/m^2	1.0 node/m^2
	Mobility model	RW/Manhattan	Manhattan/LF	Manhattan/LF/RW
	Number of drones	5	10	10
	D2D range	50m		
	D2D link setup	1s		
	D2D target data rate	40Mbps		
	Drone altitude	[10-20]m		
	Drone speed	10km/h		
	Drone mobility	RPG		
	Simulation time	30 minutes		
	Number of simulation runs	1000		

* M = Machines, H = Humans, V = Vehicles.

3) Deployment Parameters: We consider three mcMTC scenarios that reflect the industrial automation (A), vehicular connectivity (B), and urban communications (C) applications. In all study cases, the concerned devices acquire information over the link that offers them the highest data rate. We compare the following access technologies: the legacy LTE cellular, Wi-Fi Direct for the D2D links, and millimeter-wave (mmWave) over licensed operator bands for drone small cells. For the mmWave technology, we select 28 GHz frequencies as a viable candidate for the 5G *new radio* where the channel propagation, building penetration, and reflection parameters are adopted from [13].

In our three scenarios, we assume that the LTE coverage is *partial* within the modeled area, which corresponds to when the network is either under-provisioned (e.g., in rural regions) or serves challenging environments (e.g., with obstacles for signal propagation, such as walls, in the basements, etc.). We therefore consider that reliable cellular connectivity for the mcMTC devices in all study cases is only available over about 70% of the total area of interest based on deterministic modeling, since network coverage may be intermittent at the cell edges and beyond.

Further, the human users and networked mcMTC devices are allowed to move freely within the considered location according to their specific mobility patterns. For CASE A, the setup is represented as an indoor/outdoor area of [200,200]m where industrial robots and machines (i.e., in the indoor part) are first deployed uniformly and then move around within a range of two meters at low speeds (i.e., around 1 km/h). The logistics related procedures are carried out by humans and vehicles where the corresponding mobility is modeled according to the RW model.

For CASE B, our setting is the area of [500,500]m where connected vehicles drive according to the Manhattan model. For more realistic simulations, we also add some background data traffic from pedestrian users. The latter are characterized by the LF mobility with α factor of 1.5. Finally, CASE C represents a crowded urban scenario where vehicles and users that carry a number of wearable devices are initially deployed within the area of [1000,1000]m and then move around. The respective mobility models are the Manhattan model for vehicles and the LF or the RW models for humans (i.e., people prefer LF or RW pattern probabilistically) where the maximum speed of the nodes is limited by 20 km/h. For further information and details on the simulation settings refer to Table II.

B. Selected Numerical Results

The reported performance assessment has been conducted with our custom-made simulator, named WINTERsim[4]. The main objective of this system-level analysis is to reveal the effects of heterogeneous device mobility in the 5G-grade mcMTC scenarios outlined in Section II-B, as well as to quantify the contributions of various multi-connectivity options to the overall communications reliability.

Hence, the output metrics of our evaluation are: (i) the *availability rate*, that is, the proportion of users that experience certain connectivity, even though successful acquisition of all the desired data may not be guaranteed; (ii) the *reliability rate* defined as the actual data acquisition probability with which the mcMTC devices are able to successfully receive their data of interest; and (iii) the *impact of connectivity options* characterizing the relative shares of different multi-connectivity links,

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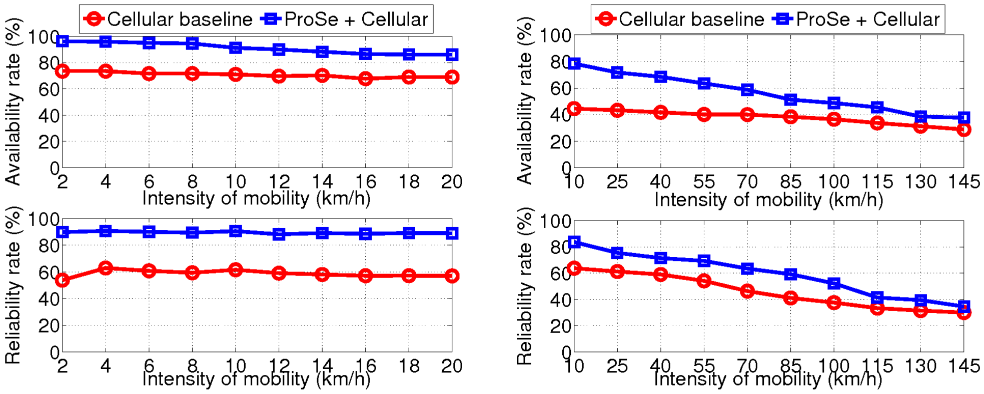
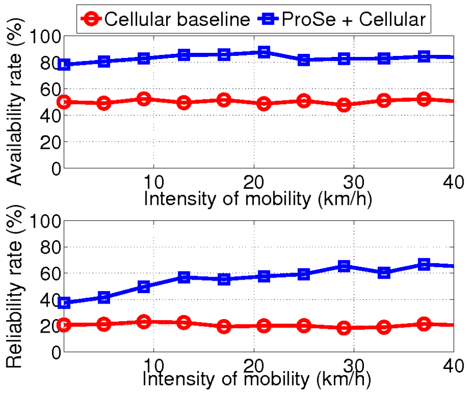
[4] WINTERsim system-level simulator: http://winter-group.net/downloads/ [Accessed on 08/2016]



(a) Industrial automation.

(b) Vehicular connectivity.



(c) Urban communications.

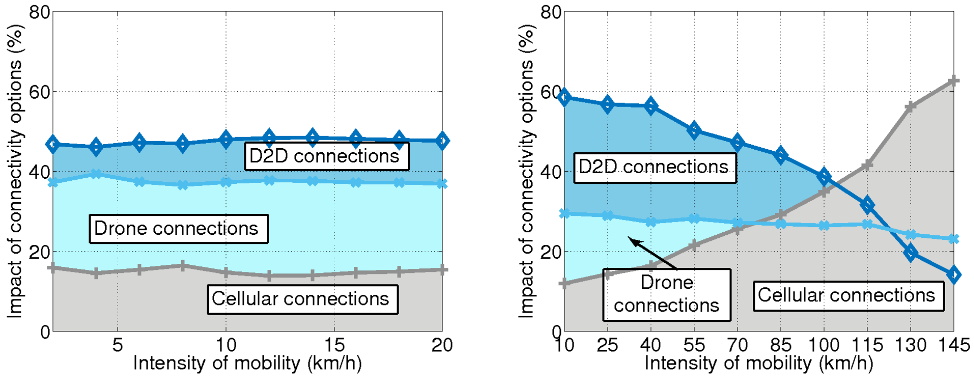
Fig. 2. Analysis of system performance in terms of availability and reliability rate as a function of the average device speed in the considered study cases.

including cellular-, D2D-, and drone-based alternatives. With our system-level analysis, we are also able to evaluate other metrics of interest, such as the number of handovers between the available connectivity options, the handover delay, and the signaling load caused by unnecessary handovers.

The availability and reliability rates in the three scenarios under investigation have been simulated over a period of 30 minutes, and are summarized in Fig. 6. As we learn from these curves, for CASE B higher mobility speeds affect the system-wide performance considerably. By contrast, in case of low mobility, the results do not vary dramatically, which holds for CASES A and C. For the vehicular scenario, D2D communications and drone small cells demonstrate diminishing benefits with the growing intensity of mobility (i.e., 100 km/h and beyond). However, the ProSe-based solution still offers consistent improvements on top of the legacy LTE baseline in all of the study cases. In particular, the gains in terms of the data acquisition rate vary from 25% to 35% for CASES A and C, as well as from 5% to 40% for CASE B. With respect to the reliability rate, we see an increase of 25% and 20% on average when considering CASES A and B, whereas the improvements for the CASE C reach 40%.

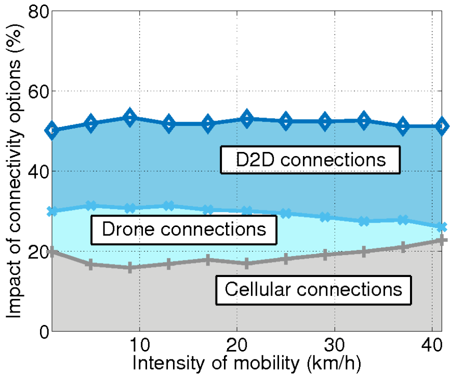
The impact of alternative connectivity options in the studied scenarios is reported in Fig. 7. Interestingly, we conclude that D2D connections are utilized the most for mcMTC data acquisition. The explanation behind this fact is in the large number of potential contact opportunities for proximate users. However, with the growing intensity of mobility, the number of feasible contacts drops and hence contact duration becomes the dominant factor that determines the chances of receiving the relevant content successfully. A similar trend is observed in Fig. 7(b) where at the speeds of above 85 km/h the devices prefer – by attempting to maximize their throughput – the more stable cellular LTE connections to any proximate links. In contrast, the impact of mobility is not as severe in Fig. 7(a) and Fig. 7(c) where D2D- and drone-based links are used more often than the infrastructure-based connections.

In summary, for the scenarios with low (CASE A) and limited (CASE C) mobility, link availability and reliability may not be affected dramatically by the device mobility. However, this situation could change for other types of similar mcMTC applications having different packet sizes [14]. In these study cases, exploiting D2D- and drone-assisted communications leads to a significant improvement in the data acquisition rates as well as brings along higher reliability. On the contrary, in the very different vehicular scenario where the intensity of mobility is typically higher (CASE B), we observe a considerable



(a) Industrial automation.

(b) Vehicular connectivity.



(c) Urban communications.

Fig. 3. Impact of available radio access technologies on overall connectivity. The vertical axes display the contribution of each connectivity option.

system-level performance degradation at the speeds of above 85 km/h. This is because proximity-based communications and drone small cells gradually lose their efficiency to provide additional capacity and coverage, while the only viable alternative remains to acquire data through the cellular infrastructure.

IV. TOWARDS FUTURE HIGHLY RELIABLE MCMTC

A. *Conventional Performance Assessment in Wireless Systems*

The considered three mcMTC applications, although remain fully suitable for the purposes of our performance evaluation, are only examples of the potential wide diversity of emerging critical IoT scenarios. Broadly, focusing on their reliability and sustainable operation requires a careful consideration and subsequent handling of many potential disruptions, such as interruptions in public services, data losses, remote control faults, and device malfunctions, among others. To analyze the occurrence probabilities of these unwanted events, the research community will need to develop a comprehensive set of tools suitable for monitoring and minimizing (or, at least, controlling) the probabilities of such rare events.

Today, a thorough performance assessment of modern wireless systems is *per se* a highly demanding task, which involves deep understanding of complex, cross-layer protocol structure as well as multi-layer composition of contemporary access networks. While analytical models tailored to a *specific* use case or functionality are somewhat successful in characterizing the system behavior in abstraction of many real-world factors, the resulting insights may appear to be rather limited in practice. As a consequence, analytical modeling of such complex networks often becomes overly complicated and feasible only in selected special cases.

In contrast, system-level simulations become the *de facto* method to assess the performance of complex multi-layer and heterogeneous wireless networks. Indeed, modern System-Level Simulator (SLS) tools require less abstraction work to capture the functionalities of the involved components compared to analytical assessment, while remain efficient enough to deliver the results of required precision within a reasonable time frame. Today, the latter is the main reason for the popularity of various SLS methodologies in both academia and industry to assess system Key Performance Indicators (KPIs). However, even advanced SLS tools may have difficulty in quantifying the probabilities of rare events, which are essentially (short-lived) situations that occur infrequently.

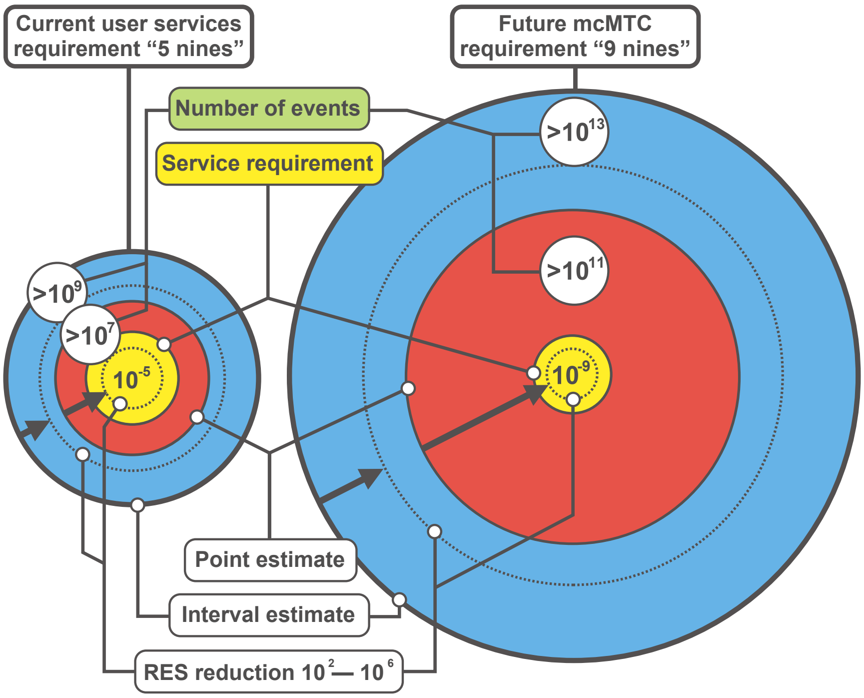


Fig. 4. Target requirements for current and future mcMTC applications

Therefore, aiming to assess the system-wide performance of future mcMTC applications, additional efforts are needed to optimize the respective system-level simulations for modeling the concerned rare events. In particular, for 5G-grade IoT services, the levels of availability of a network node are required on the order of 10^{-8}–10^{-12}, while the packet loss probability has to be on the scale of 10^{-9}–10^{-12}. An adequate analysis of these KPIs in conventional SLS tools still remains an extremely challenging task due to prohibitive runtime.

B. Applicable Techniques for Modeling Rare Events

To obtain the probabilistic reliability and availability parameters while utilizing SLS methods within a reasonable time span, we propose to rely on the Rare Event Simulation (RES) techniques. Depending on a particular RES implementation as part of the overall modeling framework, we differentiate between (i) Importance Sampling (IS), (ii) Variance Reduction Techniques (VRT), and (iii) Trajectory Splitting (TS). These methods have their roots in mathematical physics where they have been successfully applied to characterize the events that occur within the range of 10^{-10}–10^{-20} [15]. Indeed, for the envisioned mcMTC requirement of "5 nines" (i.e., 99.999%) reliability, the number of events to be modeled has to be at least 10^7 or 10^9 for point and interval estimates, respectively.

Going further towards the next-generation ultra-reliable mcMTC systems, we anticipate the need to offer availability on the order of "9 nines" to control the probabilities of the underlying rare events. Accordingly, the number of modeling samples to reach the desired accuracy levels would increase to 10^{11} and 10^{13}, which is not feasible for modern SLS tools. Based on our literature analysis across various applied fields, the use of RES methods may decrease the modeling times by 2 to 6 orders of magnitude [15], as it is illustrated in Fig. 8. However, the application efficiency of all the RES techniques depends significantly on the type of the metric of interest as well as the complexity of the simulation scenario in question. For these reasons, significant modifications to the simulation logic have to be introduced in order to make the entire process transparent for a system designer, which needs to receive prompt research attention.

For completeness, even though the use of RES techniques requires considerable integration efforts to make them supported within the existing simulation pipelines, here we provide useful recommendations for including these methods as part of large-scale SLS methodologies:

- large-scale SLS campaigns must be carefully designed first by applying simplified analytical or simulation models to understand the key qualitative trade-offs between the involved variables when identifying the most appropriate RES method to be used in final simulations;

- conducting practical test trials is critical for the efficient implementation of RES techniques within a large-scale SLS as this should allow for assessing the performance of the chosen method as well as the expected time to complete complex simulations;
- a specialized, single-purpose SLS tailored to a certain set of target applications may not only be much more efficient, but also necessary for the performance assessment of future IoT systems, since reduced complexity also simplifies implementation of RES methods.

V. CONCLUSIONS, KEY LEARNINGS, AND PERSPECTIVE

In this article, we studied the impact of heterogeneous mobility on connection availability and reliability in mcMTC scenarios when devices can use multiple connectivity options to establish wireless links. Since mcMTC are becoming an enabling technology in as diverse scenarios as industrial automation, vehicular connectivity, and urban communications, we utilized four appropriate mobility models to construct a realistic simulation environment around these scenarios. Our evaluation results demonstrate that with the increasing speed of movement, the availability of D2D links and drone small cells provide diminishing benefit over the LTE cellular-only baseline case. On the other hand, D2D connections and drone-assisted links are highly utilized and improve the availability and reliability of mcMTC data acquisition at low and moderate device speeds. In the vehicular scenario, the cellular infrastructure becomes the only viable communications alternative as speeds grow beyond around 60 km/h.

As a summary, the main contributions of this work are.

1. Analyzing the impact of mixed mobility on system-level performance in three characteristic mcMTC scenarios.
2. Quantifying the contributions of various connectivity options for a realistic mix of mobility models.
3. For rare events, a review of relevant modeling techniques that are suitable for large-scale mcMTC simulations.

Finally, the findings of this article have a strong impact on the landscape of IoT business where it offers opportunities but also poses formidable challenges to be overcome. Notably, it has become evident that the advocated heterogeneous multi-connectivity approach, including the use of D2D- and drone-assisted links, allows for meeting the stringent industrial control requirements at a relatively moderate capital expenditure (CAPEX) cost. On the other hand, the operational costs (OPEX) are likely going to be higher than in traditional business. Furthermore, the heterogeneity of the equipment used, i.e. fiber, masts, drones, licensed and license-exempt spectrum, etc., poses operational challenges which will need to be addressed by the rapidly growing industrial IoT ecosystem.

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