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TCCN Newsletter

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Chair's Message

Dear Fellow TCCN Colleagues,

Time flies and it has been four years since I served as the Vice-Chair and then Chair of TCCN. This will be my last message to you as the TC Chair.

I would also like to take this opportunity to thank all of you for your strong support of my work during the past four years. Together with you we have done some wonderful things together, including the establishment of the TCCN Newsletter, the active expansion of TCCN SIGs in several emerging and hot research areas, the close collaboration between the TC and the *IEEE Transactions on Cognitive Communications and Networking*, and the reactivation of TCCN Awards. Many of these efforts have been strongly supported by our previous TC Chair Ying-Chiang Liang as well. I look forward to the opportunity of continuing my contribution to the community in different roles in the many years ahead.

Moving forward, I am very happy to announce the TCCN Officers for the term of 2019-2020 as follows:

- Chair: Yue Gao (Queen Mary University of London, United Kingdom)
- Vice-Chair (Europe/Africa): Oliver Holland (King's College London, United Kingdom)
- Vice-Chair (Asia Pacific): Lingyang Song (Peking University, China)
- Vice-Chair (Americas): Daniel Benevides da Costa (Federal University of Ceará, Brazil)
- Secretary: Lin Gao (Harbin Institute of Technology, Shenzhen, China)

I would like to extend my heartfelt congratulations to the colleagues above. All of them have been dedicated contributors to the community, and several of them have served in various officer capacities. I am very confident of their capabilities and passions, and I am really glad that TCCN will be in very good hands in the next two years.

Look forward to seeing many of you in GLOBECOM soon.

Thanks and best regards,

Jianwei Huang
Chair, IEEE ComSoc TCCN

Professor and IEEE Fellow
IEEE ComSoc Distinguished Lecturer
Web of Science Highly Cited Researcher
Department of Information Engineering
The Chinese University of Hong Kong
http://jianwei.ie.cuhk.edu.hk/

Director's Message

Over the past couple of years, we have strived to reshape this newsletter to expose some of the more emerging topics related to the TCCN areas of interest. In this regard, we have covered a broad range of applications and techniques, ranging from ultra-reliable low latency communications (URLLC) to the Internet of Things. We have interviewed over a dozen experts in these fields, and included several interesting position papers and reviews of the state-of-the-art.

In this final TCCN Newsletter for which I will be the director, I am excited to cover two areas that will likely have impact in 5G and beyond: a) Communications with unmanned aerial vehicles (UAVs) and b) massive machine type communications (mMTC). In the UAVs area, we have reviewed two key papers from recent works. We have also had the pleasure to interview Dr. Christian Bettstetter from the University of Klagenfurt, Austria, is a leading expert in this area. Moreover, Dr. Halim Yanikomeroglu from Carelton University, who initiated much of the research on UAV communications, has also provided us with an exciting position paper in this domain. Within the context of mMTC, we have interviewed Dr. Giuseppe Durisi from Chalmers University, Sweden, Dr. Zaher Dawy from the American University of Beirut, Lebanon, and Dr. Toktam Mahmoodi from King's College, UK, who provided us with their outlook on the opportunities and challenges of mMTC. Finally, Dr. Ekram Hossain from the University of Manitoba, Canada, provided a position paper that outlines the role of NOMA in machine type communications.

Finally, I would like to thank our two feature topic editors: Dr. Daniel Benevides da Costa from UFC - Brazil and Dr. Omid Semiari from Georgia Southern University, USA, for their efforts in arranging the content of this Newsletter. Moreover, we want to thank all interviewees for sharing with us their experience and time. I would finally like to acknowledge the gracious support from the TCCN chair, Dr. Jianwei Huang and all TCCN officers over the past two years. I look forward to seeing future TCCN newsletters with more exciting research insights and discussions.

Walid Saad (S'07, M'10, SM'15, F'19) (walids@vt.edu) received his Ph.D degree from the University of Oslo in 2010. Currently, he is an Associate Professor at the Department of Electrical and Computer Engineering at Virginia Tech, where he leads the Network Science, Wireless, and Security (NetSciWiS) laboratory, within the Wireless@VT research group. His research interests include wireless networks, machine learning, game theory, cybersecurity, unmanned aerial vehicles, and cyber-physical systems. Dr. Saad is a Fellow of the IEEE. He is also the recipient of the NSF CAREER award in 2013, the AFOSR summer faculty fellowship in 2014, and the Young Investigator Award from the Office of Naval Research (ONR) in 2015. He was the author/co-author of six conference best paper awards at WiOpt in 2009, ICIMP in 2010, IEEE WCNC in 2012, IEEE PIMRC in 2015, IEEE SmartGridComm in 2015, and EuCNC in 2017. He is the recipient of the 2015 Fred W. Ellersick Prize from the IEEE Communications Society, of the 2017 IEEE ComSoc Best Young Professional in Academia award, and of the 2018 IEEE ComSoc Radio Communications Committee Early Achievement Award. From 2015-2017, Dr. Saad was named the Stephen O. Lane Junior Faculty Fellow at Virginia Tech and, in 2017, he was named College of Engineering Faculty Fellow. He currently serves as an editor for the IEEE Transactions on Wireless Communications, IEEE Transactions on Communications, IEEE Transactions on Mobile Computing, and IEEE Transactions on Information Forensics and Security.

Feature Topic: Unmanned Aerial Vehicle (UAV) Communications

Editor: Omid Semiari

Department of Electrical and Computer Engineering, Georgia Southern University
Email: osemiari@georgiasouthern.edu

Unmanned aerial vehicles (UAVs) have recently attracted significant attention in wireless commercial applications, both for acting as a user equipment or as an aerial base station. A typical use case for UAVs as wireless users is for package delivery in which the cellular network can help in controlling and managing the UAV trajectory for successful delivery of items. While interesting, there has been more focus on developing UAV systems to serve as aerial base stations, particularly in scenarios where the cellular network is partially damaged or not available at all (due to natural disasters or physical/cyber-attacks), or when additional capacity is needed temporarily (e.g., in hotspots). In fact, UAVs can play three fundamental roles in such scenarios: 1) Fast deployment in areas where additional coverage is needed to serve ground users; 2) Relay information for information delivery between two ground stations; 3) Collecting information from ground sources (e.g., to gather sensors data in precision agriculture applications).

However, successful deployment of UAVs in wireless networks is contingent upon addressing several challenges that can span diverse, interrelated domains including power optimization, trajectory optimization, control design, deployment, and interference and wireless (backhaul and access) resource management. To better understand the opportunities and challenges of the UAV-enabled wireless networks, for this feature topic, we have reached out to two experts in the field, Dr. Christian Bettstetter, professor and head of the Institute of Networked and Embedded Systems at the University of Klagenfurt, Austria, and Dr. Halim Yanikomeroglu, Professor at the department of Systems and Computer Engineering at Carleton University, Canada. In particular, we have discussed why UAV communication is an important research field, what are the main networking challenges for using UAVs as either wireless users or aerial base stations, what is the role of the fifth-generation (5G) system in supporting wireless UAV applications, and what are the open problems and future research directions for seamless integration and deployment of UAV communications in emerging wireless networks.

Furthermore, we are pleased to present a forward-thinking position paper entitled "Integrated Terrestrial/Aerial Network Architecture for 6G Wireless in 2030s", authored by Dr. Yanikomeroglu which discusses future role of aerial base stations in next-generation wireless networks. Finally, we have reviewed two of the key papers in this field and briefly overviewed their main outcomes.

Omid Semiari is an Assistant Professor at the Department of Electrical and Computer Engineering at Georgia Southern University. He received the BS and MS degrees in electrical engineering from the University of Tehran, in 2010 and 2012, respectively, and the PhD degree from Virginia Tech, in 2017. His research interests include wireless networks, millimeter wave communications, ultra-reliable and low-latency communications, context-aware networks, matching theory, and applied machine learning. In 2014, Dr. Semiari has worked as a research intern at Bell Labs, in Stuttgart, on anticipatory, context-aware resource management in cellular networks. In 2016, he has joined Qualcomm CDMA Technologies for a summer internship, working on LTE-Advanced modem design. Dr. Semiari is the recipient of several research fellowship awards, including DAAD (German Academic Exchange

Service) scholarship and NSF student travel grant. He has actively served as a reviewer for flagship IEEE Transactions and conferences and participated as the technical program committee (TPC) member for a variety of workshops at IEEE conferences, such as ICC and GLOBECOM.

Review of "Unmanned Aerial Vehicle With Underlaid Device-to-Device Communications: Performance and Tradeoffs"

IEEE Transactions on Wireless Communications, June 2016

by Mohammad Mozaffari, Walid Saad, Mehdi Bennis, and Mérouane Debbah

1. Objectives

This work provides a comprehensive performance analysis for a wireless network in which unmanned aerial vehicles can serve as aerial base stations and provide coverage for ground users. In addition, users can communicate with one another via underlaid device-to-device (D2D) links. The performance metrics that are studied in this work include: 1) average coverage probability and the system sum-rate as functions of the UAV altitude and the number of D2D users in a static scenario in which UAVs are not mobile, and 2) minimum number of visiting points for the UAV to cover the entire area and the overall outage probability for D2D users in mobile scenarios in which the UAV can move to optimize the coverage.

The results shed light on design aspects of UAV deployment as aerial base station. In particular, it is shown that an optimal value can be found for the UAV altitude at which the system sum-rate and coverage probability are maximized. Furthermore, tradeoffs for maximizing coverage and minimizing delay (equivalently, minimizing the number of visiting points for the UAV) are analyzed for mobile scenarios.

2. Relevance

UAVs have recently attracted substantial attention in wireless networks both as users and aerial base stations. For the latter case, UAVs can potentially increase the capacity and coverage of the existing cellular networks, particularly in post-disaster situations where cellular base stations could be damaged or completely nonoperational. In this regard, there is a need for comprehensive performance analysis of wireless networks in which UAVs serve as aerial base stations.

3. Main Challenges

This work considers a complex network scenario whereby a UAV can serve a number of ground users at the downlink, while such transmission must coexist with D2D communications among a subset of ground users. As such, it will be critical to manage the interference between downlink transmissions and D2D links by optimizing the operation of the UAV, i.e., finding an optimal altitude or the locations for the UAV to serve ground users. Additionally, it is prominent to understand the underlying tradeoffs between maximizing coverage and minimizing delay when using a UAV as a mobile aerial base station. That is, while more number of visiting points by the UAV can enhance the coverage, it will also introduce more delay to serve a particular user at the downlink. This paper provides a comprehensive performance analysis for such a network via stochastic geometry.

4. Key Results

The outcomes of this work are several insightful design aspects for deploying UAVs as aerial base stations for covering ground users that coexist with other D2D user transmissions. The performance of this network is studied for both static (UAV is not mobile) and mobile (UAV can change its location) scenarios.

For the static case, the optimal value for the UAV altitude is found that results in the maximum coverage probability for downlink users. Moreover, the optimal altitude is also found for another case that considers the sum-rate of the entire network (downlink users and D2D users) as the objective function. The results show that the UAV needs to reduce its altitude as the density of D2D users increases. To maximize the sum-rate across the network, the UAV needs to adjust its altitude in accordance with the density of D2D users.

For the mobile scenario, the tradeoff between coverage and the service outage (that results from large number of visiting points for the mobile UAV which increases the delay) is studied. Naturally, to increase the coverage, the number of visiting points must be increased. In addition, it is shown that the number of visiting points depend on the number of D2D users.

Review of "Energy-Efficient UAV Communication With Trajectory Optimization"

IEEE Transactions on Wireless Communications, June 2017

by Yong Zeng and Rui Zhang

1. Objectives

This work develops a novel energy-efficient solution for UAV communications where a UAV communicates with a ground terminal. The goal is to maximize the energy efficiency of such communication defined as the number of information bits communicated normalized by the UAV propulsion energy consumed. To this end, the authors have investigated the underlying tradeoffs between maximizing throughput and the energy consumption. That is, while placing the UAV to the nearest point to the ground terminal can maximize the throughput, such approach turns to be power inefficient (as the power consumption for hovering is significant) if not impossible (e.g., for fixed-wing UAVs). Therefore, the authors have proposed an energy-efficient trajectory design for the UAV to maintain the balance between the throughput and the power consumption.

2. Relevance

Unmanned aerial vehicles (UAVs) can play various roles in wireless communication networks by acting as aerial base stations to serve ground users or by collecting/relaying information when a permanent cellular network is not available. Such applications are particularly important in fast service recovery once the conventional cellular infrastructure is damaged by natural disasters or human attacks. For such scenarios, it is important to find efficient solutions to optimize the performance of UAV-assisted network in terms of power and spectral efficiency. This work accordingly addresses critical problems pertaining energy-efficient UAV communications.

3. Key Challenges

While UAVs are seen as an attractive solution to improve data rate and remove coverage holes in a wireless network, UAVs are inherently constrained with limited energy which can significantly impact the efficiency and their effective time-of-operation. This rather limiting factor poses new challenges in terms of design and operation of UAV wireless networks compared with the conventional terrestrial networks. For example, while both ground users and UAVs have power constraints, such limitation is more evident for UAVs as the available limited power must be used both for signal transmissions along with propulsion power consumption (to maintain UAV hovering and support its mobility). It is worthy to note that the propulsion power consumption can easily dominant the required power for signal transmissions. Moreover, the propulsion power depends on the speed and acceleration of the UAV. Hence, these factors must be taken into account while optimizing the performance of UAV communications.

4. Main Results

The analytical results show that if no constraint is considered for the UAV trajectory, optimizing the communications in terms of rate-maximization or energy-minimization will lead to poor energy efficiency. To address this challenge, the authors have considered a special scenario in which the UAV trajectory is circular with certain flight radius and speed. Then, these trajectory parameters are optimized to maximize the communications throughput subject to the UAV's limited energy. Additionally, the problem of maximizing the energy efficiency is studied while considering trajectory constrains for the UAV such as the maximum/minimum speeds and acceleration. To solve this problem, an efficient algorithm is proposed to find the approximately optimal trajectory based on linear state-space approximation and sequential convex optimization techniques.

The analytical and simulation results show that compared with rate-maximization or energy-minimization schemes, the developed approach can achieve substantial gains in terms of energy efficiency.

Interview with Dr. Christian Bettstetter

Institute of Networked and Embedded Systems, University of Klagenfurt, Austria

To start, could you please explain why "communications" matter for unmanned aerial vehicles (UAVs) and what are typical applications in which UAVs need to communicate? (OS)

CB: Small commercial UAVs are used in various fields, including aerial monitoring in industry and agriculture, support for first responders, and delivery of goods. Wireless communications is essential in many applications if information sensed by a UAV must be processed on the ground. For example, consider UAVs that perform live streaming of aerial videos to support rescue personnel. Communication is also essential in the other direction for steering a UAV during flight. Last but not least, multiple UAVs may coordinate themselves using ad hoc communications without involving any ground station.

What are the main networking challenges to provide connectivity for UAVs as wireless users? (OS)

CB: Off-the-shelf equipment is not made for communication with aerial devices. Using a standard WiFi access point on the ground and Wifi transceivers on a flying UAV yields data rates and radio ranges that are lower than expected, partly due to the antenna characteristics. Another issue is that operation in unlicensed bands might be too vulnerable for mission-critical UAV communications, which leads to a demand for frequency bands dedicated to UAVs. Also cellular networks are currently not designed for flying devices: various problems related to cell selection, handover, and interference occur and need to be solved.

Could you please comment on service requirements (e.g., data rate, latency, etc.) for UAV communications? (OS)

CB: The communication requirements strongly depend on the application. We are currently working on a very demanding scenario in which multiple, collaborating UAVs explore an unknown environment but their control and navigation is purely based on cameras and other local sensor data without any GPS. Offloading the computation from the UAVs to a ground computer would require 100 to 500 Mbit/s per UAV in the uplink. The latency requirements are also strict but not fully understood yet, partly because it is still unclear where to process which information.

Do you see UAVs to serve as aerial base stations in future wireless networks (please elaborate on challenges such as backhaul support, power, reliability, etc.)? When do you expect them to be commercially available and/or deployed? (OS)

CB: There are mobile mini base stations that can be transported and operated by UAVs in the air as well as on the ground, which is useful in case of disasters when ground infrastructure is no longer available. Other than such emergency scenarios, I am skeptical about UAVs serving as base stations. In my research, I utilize UAVs always as mobiles or relays.

Where do you position the fifth-generation (5G) system as an enabler for wireless UAV-based applications? What are the enabling techniques that can be borrowed in UAV communications? (OS)

CB: 5G promises high data rates and very low latencies, which are both important for many UAV applications. Beyond this, mobile edge computing will play an important role, as computations and data fusion from multiple UAVs can by offloaded to the edge with low latency.

Could you please introduce some of your most recent projects and research results related to UAV communications? (Please explain the key idea and interesting findings) (OS)

CB: Our work with UAV systems started more than ten years ago with the development of a prototype for aerial imaging to assist rescue teams. UAVs fly over specified areas, take images, and provide an accurate and up-to-date overview picture of the environment. This task required flight path planning, communication of images, and image stitching (Ad Hoc Networks, 01/2018). For example, we proposed an antenna extension to 802.11 transceivers to be used as aerial devices and characterized the path loss and fading along with some performance measurements (IEEE INFOCOM 2013). We have gained a lot of hands-on experience over the years, paving the way for further experimental research.

Most of my UAV projects are interdisciplinary, involving colleagues from control engineering, computer vision, multimedia and wireless communications, and artificial intelligence. An ongoing project develops a system of UAVs flying in a forest to automatically estimate ecological and economic factors of this forest.
Another project integrates and connects UAVs to 4G+ and later 5G networks in collaboration with T-Mobile. Besides such applied projects, I work on fundamental issues in robot swarms, for example, on joint synchronization and distributed coordination.

Beyond your own work, are there any resources that you would like to recommend, especially to those who are new in this field? (OS)

CB: I'm convinced that research on UAV networks should involve experimental work. In this context, I follow the work of David Gesbert (EURECOM, ERC grant PERFUME), who develops e.g. self-positioning aerial relays. Petar Popovski (Aalborg, ERC grant WILLOW), who is an expert in ultra-reliable and low latency wireless communications, also gained interest in UAV communications. Some other researchers that come to my mind are Timothy X Brown (CMU), Raj Jain (WUSTL), Tommaso Melodia (Northeastern), Yasamin Mostofi (UCSB), Enrico Natalizio (Compiègne), Sofie Pollin (Leuven), Walid Saad (VT), Luca Sanguinetti (Pisa), Halim Yanikomeroglu (Carleton), Christian Wietfeld (Dortmund), Rui Zhang (Singapore), and their team members.

Newcomers should read tutorial articles on UAV communications and networking: the ones by İlker Bekmezci et al. (2013), Lav Gupta et al. (2015), Yong Zeng et al. (2016 and 2018), Samira Hayat et al. from my group (2016), and Mohammad Mozaffari et al. (2018). There is also a book "UAV Networks and Communications" edited by Kamesh Namuduri and others.

If you want to do experimental research, you should become familiar with the Robot Operating System (ROS), a UAV hardware platform suited for your objectives, and the legal and safety issues related to your work

What are the most important open problems and future research directions towards seamless UAV communications? (OS)

CB: Some applications require UAVs to be integrated into cellular networks due to
their wide-area coverage. Such integration will only work if base stations have a different radio coverage than today, i.e., the design and tilting of antennas or sectorization needs to be adapted for ground-air communications. This should ideally be done in a way that ground devices do not suffer from the new „aerial devices," which will require a special radio resource, interference, and handover management.

An open issue is that many UAV applications require more data in the uplink than in the downlink — in particular, videos and images — while current cellular networks are designed in the opposite way, they support more data in the downlink.

Another important issue is the tradeoff between communications and computation in the context of multi-UAV systems with delay constraints. It addresses the question: Which data should be processed locally and which data should be communicated to whom and when?

Christian Bettstetter is professor and head of the Institute of Networked and Embedded Systems at the University of Klagenfurt, Austria, and founding scientific director of Lakeside Labs

GmbH, a research and innovation company. He holds a Dr.-Ing. degree (summa cum laude) in electrical and information engineering from Technische Universität München, Munich, Germany. His research contributions are in wireless and self-organizing systems with applications in telecommunications and robotics. In 2008, he became interested in multi-drone systems and since then has been working on aspects of communication, coordination, and path planning. He is a core faculty member in the Karl Popper school on networked autonomous aerial vehicles.

Position Paper: Integrated Terrestrial/Aerial Network Architecture for 6G Wireless in 2030s

Halim Yanikomeroglu
Carleton University, Ottawa, Canada

I. Brainstorming for 6G Wireless

The 5G standards are currently being developed with a scheduled completion date of late-2019; the 5G wireless networks are expected to be deployed globally throughout 2020s. As such, it is time to reinitiate a brainstorming endeavor followed by the technical groundwork towards the subsequent generation (6G) wireless networks of 2030s.

II. 6G Network Architecture

One reasonable starting point in this new 6G discussion is to reflect on the possible shortcomings of the 5G networks to-be-deployed. 5G promises to provide connectivity for a broad range of use-cases in a variety of vertical industries; after all, this rich set of scenarios is indeed what distinguishes 5G from the previous four generations. Many of the envisioned 5G use-cases require challenging target values for one or more of the key QoS elements, such as high rate, high reliability, low latency, and high energy efficiency; we refer to the presence of such demanding links as the super-connectivity.

However, the very fundamental principles of digital and wireless communications reveal that the provision of ubiquitous super-connectivity in the global scale – i.e., beyond indoors, dense downtown or campus-type areas – is infeasible with the legacy terrestrial network architecture as this would require prohibitively expensive gross over-provisioning (over-engineering). The problem will only exacerbate with even more demanding 6G use-cases such as UAVs requiring connectivity (ex: delivery drones), thus the 3D super-connectivity.

We envision a 5-layer vertical architecture (vertical HetNet, VHetNet) composed of fully integrated terrestrial and aerial layers for 6G networks of 2030s:

- Layer 1: Terrestrial (macro-, pico-, and femto-) BSs
- Layer 2: Aerial-BSs (flying-/UAV-/drone-BSs); altitude: up to several 100 m
- Layer 3: High Altitude Platforms (HAPs) (floating-BSs); altitude: around 20 km
- Layer 4: Very Low Earth Orbit (VLEO) satellites; altitude: up to 1,000 km
- Layer 5: Geostationary Orbit (GEO) satellites; altitude: 35,786 km

The above highlighted five layers provide connectivity. An additional element of the aerial networks is the aerial users, or aerial user equipments (AUEs), which require connectivity.

III. Aerial Networks Related Documents in 3GPP

There is an increasing level of awareness in 3GPP on AUEs as well as HAPs and satellites (in particular, VLEO satellites) which correspond to layers 3-5 of the envisioned 5-layer architecture (it goes without saying that the densification in the legacy layer 1 has always been at the centre of the 3GPP discussions). Here are some of the relevant 3GPP documents:

- TR38.913 – Study on Scenarios and Requirements for Next Generation Access Technologies
- TS22.261 – Service Requirements for Next-Generation New Services and Markets; Stage 1
- TR38.811 – Study on NR to Support Non-Terrestrial Networks (NTN)
- TR36.777 – Enhanced LTE Support for Aerial Vehicles
- TR22.822 – Study on Using Satellite Access in 5G; Stage 1
- TR22.829 – Enhancements for UAVs

The ABS concept (layer 2) is arguably one of the most forward-looking and innovative components of the envisioned architecture. To the best of our knowledge, no 3GPP document thoroughly discusses the ABS concept at the time of writing of this article. In the rest of this short article, we will exclusively focus on layer 2 of the envisioned architecture, the layer of aerial-BSs (ABSs).

IV. Layer 2: Aerial BSs

It should be noted that ABS is a fairly broad term, as such, a variety of non-terrestrial BSs can be referred to as ABSs, including HAPs and even satellites. However, in this article, we use the term ABS to refer to a BS mounted on a rather small and light-weight electric-powered UAV with both flying and floating (hovering) capabilities in altitudes up to a few hundred metres above the ground (it should be noted that in many countries legislations exist limiting the operations of UAVs including their maximum height, which is 400 feet in the US). The envisioned ABSs operate preferably in a fully autonomous manner.

As we move forward towards 2030s, there will be use-cases which will require extremely high link rates and/or area rates (ex: AR/VR goggles and 3D holography). In such scenarios, even a few UEs may result in substantial traffic in the network. To make the situation more complex, those few UEs may appear practically anywhere in the network, not necessarily in the hotspot areas. In order to make sure that any UE in the network is always sufficiently close to a BS (i.e., not-too-high path-loss, and thus, not-too-low spectral efficiency), an extremely densified wide area network will be required. As a consequence of this brute-force design strategy targeting the worst-case situations, most regions in this ultra-dense wide area network will end up being lightly loaded (or even idle) most of the time – a highly inefficient design which results in gross over-engineering, which is therefore infeasible economically. In other words, the legacy static network architecture cannot provide cost-effective super-connectivity beyond limited areas in which a high level of traffic expectation exists statistically, such as hotspots.

We propose the ABS concept as a disruptive solution for on-demand temporary capacity injection especially when an unpredictable traffic surge occurs in space & time. The key idea is to increase the agility of the network by adding BSs whose locations can be changed dynamically and opportunistically in 3D based on the UE traffic demand in space and time. This results in a leaner terrestrial network with fewer terrestrial BSs (TBSs) deployed for median traffic rather than for the worst-case traffic in space & time. In our view agility in all aspects will be the most important feature of the 6G networks.

Due to a number of reasons, including policy as well as the current limited capabilities of small UAVs such as the rather short flight time, the employment of the envisioned autonomous ABSs does not seem to be realistic in the near future; as such, we present this solution as an anchor element in 6G networks of 2030s.

It worth noting that the use of some sort of non-terrestrial BSs (such as balloon-mounted ones) in natural disaster situations in which the terrestrial network is (at least partially) not operational is a more near-term concept with a different motivation, which may be realized even today as part of the 4G LTE networks. It should be clear that the envisioned ABS concept is much more dynamic and sophisticated; it is an element of an integrated terrestrial/aerial network.

V. ABS versus TBS

There are at least 5 major differences between an ABS and a TBS:

a) An ABS is movable in 3D and in real time, while a TBS remains fixed.

b) The backhaul of an ABS is wireless, while that of a TBS is wired in general (in essence, an ABS is a relay).

c) An ABS relies on a battery for energy (or on some alternative energy sources), while a TBS is connected to the energy grid.

d) The propagation channel characteristics of an ABS will be quite different than those of a TBS; for instance, an ABS will likely experience line-of-sight (LOS) conditions much more often than a TBS.

e) The network topology of an integrated terrestrial/aerial network is different than that of a legacy terrestrial network, which will likely result in unprecedented interference situations.

All of these differences result in rich research problems.

VI. Concluding Remarks

In the absence of a clear technology roadmap for the 2030s, this article presents, to a certain extent, an exploratory view point to stimulate further thinking and creativity.

The integrated terrestrial/aerial network architecture paradigm is not a hype nor it is about one single transient technology. Rather, this an extremely rich and diverse, multi-disciplinary framework which is at the intersection of ICT (information and communication technologies), artificial intelligence, data analytics, aerospace, robotics, autonomous systems – just to state a few.

This paradigm will become more and more important in the next decade and will stay relevant not in 2030s but in the foreseeable future.

We are certainly at the dawn of a new era in wireless research and innovation; the next twenty years will be very interesting.

VII. Further Readings from my Publications

[1] I. Bor-Yaliniz, M. Salem, G. Senerath, H. Yanikomeroglu, "Is 5G ready for drones?: A look into contemporary and prospective wireless networks from a standardization perspective", to appear in *IEEE Wireless Communications Magazine*.

[2] I. Bor-Yaliniz, A. El-Keyi, H. Yanikomeroglu, "Spatial configuration of agile wireless networks with drone-BSs and user-in-the-loop", to appear in *IEEE Transactions on Wireless Communications*.

[3] X. Zhou, J. Guo, S. Durrani, H. Yanikomeroglu, "Underlay drone cell for temporary events: Impact of drone height and aerial channel environments", to appear in *IEEE Internet of Things Journal*.

[4] X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, H. Yanikomeroglu, "Airborne communication networks: A survey", *IEEE Journal on Selected Areas in Communications*, Sep. 2018.

[5] F. Lagum, I. Bor-Yaliniz, H. Yanikomeroglu, "Strategic densification with UAV-BSs for cellular networks", *IEEE Wireless Commun. Letters*, Jun. 2018.

[6] I. Bor-Yaliniz, S.S. Szyszkowicz, H. Yanikomeroglu, "Environment aware drone-base-station placements in modern metropolitans", *IEEE Wireless Commun. Letters,* Jun. 2018.

[7] M. Alzenad, A. El-Keyi, H. Yanikomeroglu, "3D placement of an unmanned aerial vehicle BS for maximum coverage of users with different QoS requirements", *IEEE Wireless Commun. Letters,* Feb. 2018.

[8] M. Alzenad, M.Z. Shakir, H. Yanikomeroglu, M.-S. Alouini, "FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks", *IEEE Communications Magazine,* Jan. 2018.

[9] M. Alzenad, A. El-Keyi, F. Lagum, H. Yanikomeroglu, "3D placement of unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage", *IEEE Wireless Commun. Letters,* Aug. 2017.

[10] I. Bor-Yaliniz, H. Yanikomeroglu, "The new frontier in RAN heterogeneity: Multi-tier drone-cells", *IEEE Communications Magazine*, Nov. 2016.

Halim Yanikomeroglu (F'17) is a Full Professor at Carleton University, Canada.

His research interests cover many aspects of wireless technologies with a special emphasis on cellular networks. He has coauthored 350+ peer-reviewed papers including 125 in the IEEE journals; these publications have received more than 11,000 citations. He has been one of the most frequent tutorial presenters in the leading international IEEE conferences (29 times). He has had extensive collaboration with industry which resulted in 24 granted patents (plus about a dozen applied). During 2012-2016, he led one of the largest academic-industrial collaborative research projects on pre-standards 5G wireless, sponsored by the Ontario Government and the Canadian industry. He served as the General Chair and Technical Program Chair of several international IEEE conferences.

Feature Topic: Massive Machine-Type Communications (mMTC)

Editor: Daniel B. da Costa

Department of Computer Engineering
Federal University of Ceará (UFC)
Sobral-CE-Brazil
danielbcosta@ieee.org

According to ITU-R, the three generic services that will be supported by 5G are enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). In order to allow the coexistence of these heterogeneous services over 5G, there are a plenty of innovative solutions, techniques, and architectures. For instance, network slicing arises as an efficient tool to ensure such coexistence by allocating network computing, storage, and communication resources among the active services with the aim of guaranteeing their isolation and given performance levels.

Particularly, in mMTC billions of machine-type devices (MTD) will be connected wirelessly within a given area and will generate diverse forms of data traffic with varying requirements in terms of delay, per-link and total bit error rate, reliability, energy consumption and security. A key issue brought by mMTC is how to connect this massive number of MTDs to the Internet. It is predicted that in total about 11.6 billion devices need to be connected by 2020, in which 67 percent of mobile devices will be smart devices, and up to 98 percent of mobile data traffic will be generated from these smart devices by 2020. Both human-centric communications and mMTC require the support of mobile cellular systems, which creates new problems in the design of the future cellular networks. One of the main challenges is the capability to support short packet transmissions, since short packets are the typical form of traffic generated by machine-type devices and exchanged in mMTCs, which is not done adequately in the current wireless cellular networks designed for human-centric communications. Another challenge is to develop market models for understanding the interactions between mobile operators, service providers, vertical sector customers, and regulatory services. MTC is definitely a new paradigm for revenue generation for cellular operators, yet these services cannot be easily integrated into existing cellular subscription and activation models.

In the next sections, we present one position paper on mMTC and three interviews with leading experts in the field. The position paper has been written by Profs. Ekram Hossain and Mr. Yasser Al-Eryani, and the three interviews have been carried out with Profs. Guiseppe Durisi, Zaher Dawy, and Toktam Mahmoodi. I take this opportunity to thank them for their precious contributions to this feature topic.

Daniel Benevides da Costa (S'04-M'08-SM'14) was born in Fortaleza, Ceará, Brazil, in 1981. He received the B.Sc. degree in Telecommunications from the Military Institute of Engineering (IME), Rio de Janeiro, Brazil, in 2003, and the M.Sc. and Ph.D. degrees in Electrical Engineering, Area: Telecommunications, from the University of Campinas, SP, Brazil, in 2006 and 2008, respectively. His Ph.D thesis was awarded the Best Ph.D. Thesis in Electrical Engineering by the Brazilian Ministry of Education (CAPES) at the 2009 CAPES Thesis Contest. From 2008 to 2009, he was a Postdoctoral Research Fellow with INRS-EMT, University of Quebec, Montreal, QC, Canada. Since 2010, he has been with the Federal University of Ceará, where he is currently an Associate Professor.

Prof. da Costa is currently Editor of the IEEE Communications Surveys and Tutorials, IEEE Access, IEEE Transactions on Communications, IEEE Transactions on Vehicular Technology, and EURASIP Journal on Wireless Communications and Networking. He has also served as Associate Technical Editor of the IEEE Communications Magazine. From 2012 to 2017, he was Editor of the IEEE Communications Letters. He has served as Guest Editor of several Journal Special Issues. He has been involved on the Organizing Committee of several conferences. He is currently the Latin American Chapters Coordinator of the IEEE Vehicular Technology Society. Also, he acts as a Scientific Consultant of the National Council of Scientific and Technological Development (CNPq), Brazil and he is a Productivity Research Fellow of CNPq. Currently, he is the Chair of the Special Interest Group on "Energy-Harvesting Cognitive Radio Networks" in IEEE Cognitive Networks Technical Committee.

Prof. da Costa is the recipient of four conference paper awards. He received the Exemplary Reviewer Certificate of the IEEE Wireless Communications Letters in 2013, the Exemplary Reviewer Certificate of the IEEE Communications Letters in 2016 and 2017, the Certificate of Appreciation of Top Associate Editor for outstanding contributions to IEEE Transactions on Vehicular Technology in 2013, 2015 and 2016, the Exemplary Editor Award of IEEE Communications Letters in 2016, and the Outstanding Editor Award of IEEE Access in 2017. He is a Distinguished Lecturer of the IEEE Vehicular Technology Society. He is a Senior Member of IEEE, Member of IEEE Communications Society and IEEE Vehicular Technology Society.

Interview with Dr. Zaher Dawy

Department of Electrical & Computer Engineering, American University of Beirut
Email: zd03@aub.edu.lb

How do you define future massive machine-type communication (mMTC) networks, and what will be the business cases for such 5G networks?

ZD: mMTC refers to wireless network scenarios with an ultrahigh density of devices in a given geographical area running services that do not require human interaction. Typical ultrahigh density would be in the range of one device or more per m2, that is, around 10,000 devices in an area of 100m by 100m. The notion of device in mMTC is broad as it can range from miniature implantable biosensors to vehicles, including smartphones and tablets when used for sensing purposes. The business cases for mMTC are enormous as they span all major vertical industries, from health to transportation and industrial enterprises; mMTC serves as 5G enabler for real-time intelligent monitoring, automation, and data-driven decision making.

Could you please explain the most pertinent mMTC techniques/scenarios and research directions for 5G?

ZD: The realization of mMTC in 5G networks requires innovative solutions for the design, deployment and operation of both devices and network nodes. The prime challenge is the diversity of mMTC use cases in terms of characteristics, requirements and stakeholders. mMTC scenarios can, for example, vary from an ultrahigh density of sensors deployed in hard-to-reach underground fixed locations for environmental monitoring applications to an ultrahigh density of sensors deployed in fleets of cars moving with varying speeds for intelligent transportation system applications. For the former, energy consumption, complexity and cost are essential requirements whereas for the latter, delay, throughput and reliable handovers are essential requirements.

Therefore, there is not a “one size fits all” solution, technique, or architecture when it comes to supporting mMTC over 5G. Instead, there should be a bouquet of flexible and inter-operable solutions, techniques and architectures to choose from and customize per use case in order to meet the target performance requirements of the different vertical sectors with optimized efficiency.

Some of the pertinent mMTC techniques for 5G with open research problems include the following: novel signaling protocols and procedures with significantly reduced uplink and downlink overhead; new sleep mode states and paging mechanisms with ultra-low energy consumption; flexible physical layer and multiple access designs that efficiently support diverse traffic patterns with transmission speeds that can vary from bps to Gbps and from payloads of few bytes to payloads of mega-bytes; data aggregation and reduction algorithms combined with multihop communications; in-device processing combined with edge computing and caching to support predictive analytics; software defined radio (SDR) designs that can meet the longevity requirement as the 5G standard evolves since the lifetime of some mMTC devices can possibly reach 10-20 years before replacement.

Could you please elaborate on the main role of mMTC in key vertical industries? How does the telecoms sector engage with them during the standardization phase? How does it actually build these state-of-the-art networks? Is 2020 a realistic deadline?

ZD: mMTC will play a principal role in advancing large-scale vertical industries that span sectors such as personalized health, smart cities, industrial automation, environmental monitoring, safety and security, among others. From a business perspective, these vertical sectors provide new needed revenue streams and expansion opportunities for mobile cellular operators; from a research perspective, there are additional interesting open problems related to the economic aspects such as market sharing, resource leasing, smart pricing, multi-device data bundling, etc.

Engagement with the key vertical sectors during the 5G standardization process is essential to capture accurately the traffic characteristics and performance requirements of the diverse relevant use cases, which should contribute to shaping the design and capabilities of the standard. On another front, this is also important to push towards the integration of 5G connectivity modules within third-party devices that are widely utilized in various vertical industries. From a timing perspective, there is no golden target year or deadline; in my opinion, it is an ongoing process that has already been initiated few years ago and has made notable steps, e.g., via the standardization of LTE-M and NB-IoT and as demonstrated by success stories from different sectors and countries. Yet, we are still at a relatively start-up phase with lots of potential and growth opportunities ahead, that will be realized with the deployment of 5G networks and in the future with the design of beyond 5G technologies.

Could you please briefly introduce the most recent research project that you have done in mMTC?

ZD: Most recently, we have been working on a research project that is focused on enhancing the energy efficiency of devices in mMTC scenarios with dense sensors deployed in fixed hard-to-reach areas [1]. In particular, we are designing, analyzing, and experimentally validating RF-based wake-up solutions that can switch on devices using ambient signals from base stations or access points. We define a new deep sleep state similar to the power saving mode in the 3GPP standards, however, with the difference that the device becomes completely off and does not leave the deep sleep state when a timer expires but instead upon receiving an explicit RF wakeup signal from its serving base station.

To enable this, a customized wake-up hardware module should be designed and integrated in order to capture the RF wake-up signal and initiate an interrupt trigger to activate the main circuitry of the device. In order to improve the power efficiency, the energy consumption of this extra wake-up receiver should be extremely low, and as close to zero as possible. The wake-up module normally contains three main components: the matching network, a rectifier and an ID detector. The crucial task of the matching network is to reduce the transmission loss from the antenna to the rectifier circuit and to increase the input voltage of the rectifier. The rectifier converts the RF-signals captured by the antenna into DC-voltage. The ID detector is responsible for extracting a signature from the received RF signals and comparing it with the device's ID; in case of matched IDs, it will trigger an interrupt to activate the main circuitry of the device and transit from the deep sleep mode to the idle mode. A major research challenge here is embedding the ID within the RF signals to be decoded by the wake-up front-end circuit while the device is completely off. This RF-based wake-up design can be considered as an RF paging procedure. Normally, paging requests are exchanged through standard protocol messages and require processing and storage capabilities while the device is switched on; in our work, we aim at achieving similar paging functionality but at the wake-up circuit front-end level while the device is completely off.

In terms of research methodology, we are developing an analytical evaluation framework using tools from stochastic geometry for performance analysis and optimization [2], building RF wake-up hardware to demonstrate functionality under realistic operation conditions [3], and performing experimental measurements and studies using emerging techniques such as utilizing interference to boost efficiency [4] and drones to deal with the coverage problem in remote areas [5].

[1] Z. Dawy, W. Saad, A. Ghosh, J. Andrews, and E. Yaacoub, "Toward Massive Machine Type Cellular Communication", IEEE Wireless Communications, February 2017.

[2] N. Kouzayha, Z. Dawy, J. Andrews, and H. ElSawy, "Joint Downlink/Uplink RF Wake-Up Solution for IoT over Cellular Networks," IEEE Transactions on Wireless Communications, March 2018.

[3] H. Hodr, N. Kouzayha, M. Abdallah, J. Costantine, and Z. Dawy, "Energy Efficieny IoT Sensor with RF Wake-up and Addressing Capability," IEEE Sensors Letters, December 2017.

[4] S. Saab, N. Kouzayha, J. Costantine, and Z. Dawy, "Positive Impact of Interference in RF Energy Harvesting IoT Networks," IEEE PIMRC, September 2018.

[5] S. Saab, A. Eid, N. Kouzayha, J. Costantine, Z. Dawy, G. Virone, and F. Paonessa, "UAV-Enabled RF Sensor Wake-up," IEEE Confernce on Antenna Measurements & Applicaitons (CAMA), September 2018.

Beyond your own work, are there any resources that you would like to recommend, specially to those who are new in the field and want to learn more about mMTC? What are three key papers in the area?

ZD: There is a rich literature that relates to mMTC at all levels, including both research publications in addition to white papers by telecom vendors and operators. I chose a few set of papers that I think provide comprehensive information on important aspects with suggestions for open research directions and including a rich list of references within.

"Machine-to-Machine Communications in Ultra-Dense Networks—A Survey" by S. Chen et al., published in IEEE Communications Surveys and Tutorials in the third quarter of 2017, as it presents a comprehensive survery on recent works that span the various protocol stack layers including additional aspects related to standardization, applications, security and network virtualization.
"Wide-Area Wireless Communication Challenges for the Internet of Things" by H.S. Dhillon at al., publiushed in IEEE Communications Magazine in Februay 2017, as it presents a summary comparison of existing relevant wireless standards and technologies in addition to a theoretical treatment on random access transmissions versus schedueled transmissions in the context of mMTC.
"Massive Machine-Type Communications in 5G: Physical and MAC-Layer Solutions" by C. Bockelmann et al. published in IEEE Communications Magazine in September 2016, as it captures very well the challenges related to the physical and MAC layers with focus on solutions targeting short packet transmissions from a massive number of devices.
"Large-Scale Measurement and Characterization of Cellular Machine-to-Machine Traffic" by M.Z. Shafiq et al., published in IEEE/ACM Transactions on Networking in July 2013, as it presents extensive experimental measurement results on MTC traffic over cellular networks with insightful analysis using several performance indicators. The paper also includes traffic characterization and modeling based on the measurement data for different use case scenarios, with comparisons to standard smartphone traffic by mobile users.

Zaher Dawy received the BE Degree in Computer and Communications Engineering from AUB in 1998 and the Doctoral Degree in Communications Engineering from Munich University of Technology (TUM), Germany, in 2004. He joined the Department of Electrical and Computer Engineering at AUB in 2004 and was promoted to the rank of Professor in 2014. He currently serves as Coordinator of the Biomedical Engineering Graduate Program and Associate Provost with focus on research and graduate studies. His research and teaching interests are in the general fields of wireless communications, mobile networks, Internet of Things, computational biology, and biomedical engineering. For his research contributions, he received in 2012 the Abdul Hameed Shoman Award for Young Arab Researchers and in 2011 the IEEE Communications Society Outstanding Young Researcher Award in Europe, Middle East, and Africa Region. He is also the recipient of AUB's Teaching Excellence Award in 2008 and several professional service recognitions. He served as an Executive Editor for the Transactions on Emerging Telecommunications Technologies (Wiley), Editor for Physical Communications (Elsevier), and the Chair of the IEEE Communications Society Lebanon Chapter. He currently serves on the Editorial Board of IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, IEEE Communications Surveys and Tutorials, and Computer Networks (Elsevier).

Interview with Dr. Giuseppe Durisi

Chalmers University of Technology, Gothenburg, Sweden

How do you define future massive machine-type communication (mMTC) networks, and what will be the business cases for such 5G networks?

GD: Machine-type communications (MTCs), i.e., machine-centric rather than human-centric communications will form the backbone of the upcoming automated society. In 5G, they will come in two flavors: i) ultra-reliable, low-latency communications (URLLC), which will target wireless connections with stringent requirements on both latency and reliability; and ii) massive MTC (mMTC), which will focus instead on providing connectivity to a large number of devices that transmit sporadically a low amount of traffic.

I see mMTC as the key technology needed to scale up the internet of thing (IoT), from its current limited use in the consumer sector, to its general use by enterprises and public entities, including municipalities.

The country I live in, i.e., Sweden, has the objective to become best in the world in using the opportunities brought by digitalization. I believe that deploying mMTC solutions systematically at an enterprise and municipality level will be key to achieve this goal.

Once available, such IoT connectivity solutions will bring many advantages, which span from increasing revenues by enabling new business models, to increasing effectivity and decreasing costs. Pilot projects are already ongoing in different parts of the world where IoT technology is used for smart lightening, waste disposal, asset tracking, process monitoring and optimization, etc...

Connectivity solutions for mMTC are currently under development both in the licensed part of the spectrum (LTE and 5G) and the unlicensed part (low-power wide-area network (LP-WAN) solutions such as SigFox and LoRaWAN). One critical challenge in developing general mMTC solutions is that MTC devices will be extremely heterogeneous in terms of computational capabilities, cost, energy consumption, and transmission power. It will probably be hard to develop a single cellular technology able to address such heterogeneity, and there will be business opportunities for alternative specialized technologies, especially in the LP-WAN area.

Could you please explain the most pertinent mMTC techniques/scenarios for 5G?

GD: When I think of mMTC, I have in mind the following scenario: a wireless technology able to provide connectivity to a massive number of low-cost, low-complexity devices, which transmit sporadically small payloads. Supporting such a traffic typology requires a profound redesign of the radio-access network of current cellular systems, which are typically designed to maximize the throughput of only few active users. For example, the presence of a massive number of sporadically active users calls for asynchronous random-access protocols. Small payloads cause finite-blocklength effects that need to be accounted for to obtain accurate performance estimates. Furthermore, latency and energy efficiency considerations call for a redesign of control plane, aimed at minimizing protocol overheads. Finally, novel security and privacy protocols need to be developed, especially in the practically relevant use case in which low-complexity mMTC devices are connected to a powerful, but not necessarily trustworthy cloud server.

Could you please elaborate on the main role of mMTC in key vertical industries? How does the telecoms sector engages with them during the standardization phase? How does it actually build these state-of-the-art networks? Is 2020 a realistic deadline?

GD: Possible scenarios for mMTCs include structure and environmental monitoring, asset tracking, and process monitoring and optimization. The volume necessary for the success of such technology will come only if mMTCs will be used extensively in many of the services offered by municipalities. Examples may include maintenance of road signs and lightening, as well as smart waste disposal.

One challenge is that mMTCs as currently defined in 5G appear too heterogeneous for a single technology to cover all use cases. And this is true even if we focus on a single vertical scenario, say factory automation, where different MTC-enabled applications come with completely different throughput, latency, and reliability requirements. Compare for example the requirements on a wireless link used to control an actuator with the requirements on a link allowing an operator to access sensor data on a mobile device for monitoring purposes.

Telecoms are heavily involved in pilot projects in different vertical industries. For example, Chalmers is part of a successful project in the area of 5G-enabled manufacturing together with Ericsson, SKF, Volvo, and Siemens in which demonstrators for manufacturing system design, deployment, operation and maintenance are under development.

The 2020 deadline for 5G standardization seems very ambitious as far as both mMTC and URLLC are concerned. I am sure that these use cases will be at the center of several subsequent releases after 2020.

Could you please briefly introduce the most recent research project that you have done in mMTC?

GD: Over the last 6 years I have been working extensively together with many collaborators on the problem of developing communication-theoretic tools for the design of the physical layer of short-packet transmission systems. This toolbox is now fairly mature and ready to be used as ingredient for complex system designs beyond the physical layer.

In this respect, I have recently started two projects whose focus is precisely mMTC design. The first project, which is conducted together with two Swedish companies, QAMCOM and Blink Services, and is sponsored by the Swedish Foundation for Strategic Research, aims at investigating novel LP-WAN designs to support mMTC. One specific objective of the project is to optimally design a virtual network connecting LP-WAN owned by different service providers, to enable the deployment of services on a national scale.

The second project, which is supported by the Swedish Wallenberg AI Autonomous Systems and Software Program, deals with security and privacy in mMTC. Specifically, the project has the goal of designing low-latency, massive multi-client, verifiable delegation-of-computation protocols that provide the highest possible level of security and privacy compatible with the computational resources available at the mMTC devices.

Beyond your own work, are there any resources that you would like to recommend, specially to those who are new in the field and want to learn more about mMTC? What are three key papers in the area?

GD: There are many excellent works on the design of mMTCs. I would like to highlight the following three works, which have heavily influenced my view on this subject:

C. Bockelmann, et al., "Towards Massive Connectivity Support for Scalable mMTC Communications in 5G Networks," IEEE Access, vol. 6, pp. 28 969–28 992, 2018.

This paper offers a comprehensive review of recent research activities on the design on mMTC for 5G, performed in the context of the Horizon2020 European Project FANTASTIC-5G.

Y. Polyanskiy, "A perspective on massive random access," in IEEE Int. Symp. Inf. Theory (ISIT), Jan. 2017.

This article offers a novel framework for the information-theoretic analysis of random-access protocols. One take-home message of this article is that the currently available random-access solutions are highly suboptimal in terms of energy efficiency.

M. Berioli, G. Cocco, G. Liva, and A. Munari, Modern random access protocols, ser. Foundations and Trends in Networking. now Publishers, 2016.

A large body of work on random access protocols has been developed over the last decade in the context of satellite communications. This book reviews the most promising strategies---a sure source of inspiration for the design of novel mMTC protocols.

What are the most important open problems and future research directions towards mMTC?

GD: The work by Polyanskiy (2017) has illustrated that classic random-access protocols, which were originally developed to maximize throughput, perform poorly when analyzed through the lens of energy efficiency. Many researchers have recently developed alternative coding schemes, which approach the fundamental limits unveiled by Polyanskiy (2017). However, most of these analyses are performed on simplified channel models. Assessing whether these alternative solutions are robust against the impairments typically encountered in mMTCs (asynchronism, lack of channel knowledge, phase noise) is an important research direction.

Next-generation 5G networks will need to support other traffic types than just mMTC. How to guarantee optimal coexistence between drastically different service types is a crucial research question. As for the case of fading in a multiuser environment, one should be able to exploit this heterogeneity in the protocol-design phase to improve performance, a concept we referred to as "reliability diversity" in a recent contribution.

A final important research issue is privacy and security. Short payloads combined with latency constraints, and limited computational capabilities at the devices make it hard to adapt current cryptographic methods to mMTC. Recent nonasymptotic information-theory results have given us a precise way to characterize the tradeoff between reliability, energy efficiency, and throughput in the transmission of short payloads. However, very little is available on the characterization of the latency and energy overheads required to implement security and privacy protocols.

The massiveness and the sporadic nature of the MTC traffic poses unique novel challenges that the research community has started investigating only very recently. I believe that there are many opportunities to bring novel research ideas into practice, both in 5G and in LP-WAN.

To conclude, I would like to thank my collaborators Martin Edofsson, Johan Lassing, Gianluigi Liva, Yury Polyanskiy, Petar Popovski, Osvaldo Simeone, Kasper Fløe Trillingsgaard, and Andreas Wolfgang, who helped me refining my view on mMTC.

Giuseppe Durisi (S'02--M'06--SM'12) received the Laurea degree summa cum laude and the Doctor degree both from Politecnico di Torino, Italy, in 2001 and 2006, respectively. From 2006 to 2010 he was a postdoctoral researcher at ETH Zurich, Zurich, Switzerland. In 2010, he joined Chalmers University of Technology, Gothenburg, Sweden, where he is now professor and co-director of Chalmers information and communication technology Area of Advance. Dr. Durisi is a senior member of the IEEE. He is the recipient of the 2013 IEEE ComSoc Best Young Researcher Award for the Europe, Middle East, and Africa Region, and is co-author of a paper that won a ``student paper award'' at the 2012 International Symposium on Information Theory, and of a paper that won the 2013 IEEE Sweden VT-COM-IT joint chapter best student conference paper award. In 2015, he joined the editorial board of the IEEE Transactions on Communications as associate editor. From 2011 to 2014, he served as publications editor for the IEEE Transactions on Information Theory. His research interests are in the areas of communication and information theory and machine learning.

Interview with Dr. Toktam Mahmoodi

Centre for Telecommunications Research, King's College, London

How do you define future massive machine-type communication (mMTC) networks, and what will be the business cases for such 5G networks?

TM: Smart city is a perfect example of an arena where mMTC comes to the picture in a very diverse form. Various infrastructure in the city, all aspects of intelligent mobility including connected cars, public transports, and road traffic management, tourism services such as cultural events, museums, and in fact the relation these services have with the transportation system, and finally smart home and connected appliances, all come together in one massive connectivity space. The beauty of smart city arena comes from multitude of angles including diversity of connectivity solutions and connected devices, the extent of creativity it can spark within the creative community coming up with exciting applications, and the inevitably large number of users who will be part of one or many of the above services.
In terms of business cases, many of the above have already attracted industry and are on their way to the market. The intelligent mobility currently drives £1.4 trillion market, and authorities in metropolitan cities with diverse means of mobility and massive number of users, e.g. Transport for London (tfl) in London, are moving forward. In tourism service, an exciting project currently in the execution phase is the "Smart Tourism" led by university of Bristol, working on a tourism market of £1.75 billion annual economy. These are all indications of the significance of market opportunities in this sector.

Could you please explain the most pertinent mMTC techniques/scenarios for 5G?

TM: The major issue of mMTC has been the large number of devices accessing the network potentially simultaneously, and while massive access in the RAN has been widely studied in 4G, the need for extra reliability in 5G, and a different degree of "massive" in number of connected devices, open new challenges in this area. The impact of massive access on the core network is yet another issue, which has not been sufficiently addressed. One of the our recent studies in this area, for example, is to rethink the basis of connectivity model in 5G for serving mIoT, which could be a prominent solution in handling massive simultaneous access attempts to the core network.

Could you please elaborate on the main role of mMTC in key vertical industries? How does the telecoms sector engage with them during the standardization phase? How does it actually build these state-of-the-art networks? Is 2020 a realistic deadline?

TM: One prominent example of such vertical industry is automotive and intelligent mobility as a whole chain of service (all means of public transport, road authorities, etc.). The automotive sector, given their constant exposure to technology, have been tightly engaged with the telecom industry in developing new technologies, shaping standards and ensuring timely delivery of smart mobility services to the market, and hence 2020 is a realistic target for many of the ongoing research in this domain to become reality. There are currently number of different projects in Europe working on bringing the connected autonomous driving and its integration in the connected road/infrastructure/city to life, and 5GCAR is one example of those projects. It is interesting to see how these projects could bring telecom and vertical industries (in this case automotive) together, and how they bring proof-of-concept development out from the lab and to the test roads.

Could you please briefly introduce the most recent research project that you have done in mMTC?

TM: One of the exciting works we have done recently is developing the concept of SymbioCity, which defines the symbiotic relationship between smart city and the networking infrastructure, hosting smart city services. While network provides the basic means of communication for the smart city services, it can also benefit from the data acquired by these services and run with higher performance and better efficiency (self-optimize and self-organize). Given that networking infrastructure is becoming more and more fluid in design by being software-based and having virtualized functionalities, the extent of these self -optimization and -organization has become wide and diverse aspects of the network can potentially be designed by embracing the concept of SymbioCity.

Beyond your own work, are there any resources that you would like to recommend, specially to those who are new in the field and want to learn more about mMTC? What are three key papers in the area?

TM: The "Towards Massive Connectivity Support for Scalable mMTC Communications in 5G Networks", published in IEEE access in May 2018 is one of the thorough papers on 5G mMTC, I read recently, and I can recommend to all those who want to get a good overview picture. This paper studies different medium access techniques and how they perform in the event of large number of simultaneous access to the network.

What are the most important open problems and future research directions towards mMTC?

TM: The large number of network access has been the main challenge in the mMTC, while this challenge has become more significant with the extra requirement on latency and reliability in 5G. Despite many research works, there are still numerous open problems associated to this particular challenge. The impact "massive data" collected by the mMTC network can have on running better communication services, also offers immense number of interesting research problems.

Toktam Mahmoodi is an Associate Professor in Telecommunications and Director of the Centre for Telecommunications Research (CTR) in King's College London. Previously, she was visiting research scientist at F5 Networks, research associate in Imperial College London, Mobile VCE researcher, and telecom R&D engineer. Toktam is and has been involved in number of European FP7 and H2020 projects on 5G mobile networks, vehicular communications, and Software-defined Networking. She is executive editor of Transactions on Emerging Telecommunications Technologies, series guest editor of JSAC on network softwarization, and area editor of IEEE Communications Standard Magazine on management & orchestration. Her research focuses on the areas of mobile and cloud networking, and includes ultra-low latency networking, network virtualisation, mobility management, network modelling and optimisation. She also works on applications of mobile communications in the healthcare, smart cities, industrial networks and intelligent transportation.

Large-Scale NOMA: Promises for Massive Machine-Type Communication

Ekram Hossain and Yasser Al-Eryani

***Abstract*—We investigate on large-scale deployment of non-orthogonal multiple access (NOMA) for improved spectral and power efficiency in cellular networks to provide massive wireless connectivity (e.g. for machine-type communication [mMTC]). First, we describe the basics of single-antenna NOMA technology and its extension to co-located multiple-antenna NOMA as well as coordinated multipoint transmission (CoMP)-enabled NOMA technologies. Then we discuss some of the practical challenges of large-scale deployment of NOMA such as the inter-NOMA-interference (INI), inter-cell interference, and hardware implementation complexity. To this end, we present one key enabling technique to overcome the challenges of large-scale deployment of NOMA. Generally speaking, for a feasible large-scale NOMA implementation, sophisticated diversity enhancing techniques can be used to compensate for the degradation in coding gain and to decrease the complexity resulting from excessive INI and increased level of required successive interference cancellation (SIC). Furthermore, to massively extend NOMA over the network coverage area, NOMA transmitters have to cooperate in a generalized manner to serve all nearby users simultaneously.**

***Index Terms*—Massive machine-type communication (mMTC), non-orthogonal multiple access (NOMA), successive interference cancellation (SIC), diversity enhancing techniques.**

I. Introduction

Supporting a massive numbers of wireless-connected devices that communicate with each other simultaneously will be an inherent property of the fifth generation (5G) and beyond 5G (B5G) systems. Massive-scale connectivity between various communication devices (e.g. vehicles, sensors, mobiles, etc.) will enable us to form the internet of everything (IoE) that bridges the gap between the 'Cyber' and the 'physical' worlds. For this so called massive machine-type communication (mMTC), efficient, reliable, and fast communication methods will be required to enhance and control data flows among these devices. As an example, autonomous driving and intelligent transportation systems require that hundreds of machines to be coordinating and communicating simultaneously within a certain geographical area. Communications among these machines must be reliable and fast in order to provide a safe driving environment. This can be achieved by increasing the capacity of wireless systems to support significantly higher data rates and/or number of devices. It may also be used to reduce power consumption on mMTC distributed devices.

The capacity of wireless systems however is limited by the availability of spectrum resources. To improve the capacity under limited spectrum resources, sophisticated designs for wireless access and resource allocation will be required. In this context, non-orthogonal multiple-access (NOMA) has emerged as a potential technology to tackle the problem of improving wireless network capacity under spectrum scarcity [1]. The main concept of NOMA (in uplink and downlink) is: in a certain frequency sub-band, signals for multiple users are superimposed in the power domain such that the resultant received signal has a distinct power levels for every user. At the receiver side, successive interference cancellation (SIC) is used to filter out the undesired signals. Generally, SIC can be conducted at the codeword level, symbol level or using reduced complexity-maximum likelihood detection (R-ML). However, codeword and symbol levels SIC are preferable methods due to their ability to suppress interference from adjacent devices and their relatively low complexity [2, Table 2].

Theoretically, NOMA has been observed to outperform orthogonal multiple access (OMA) schemes such as OFDMA, CDMA and TDMA, in terms of spectral efficiency. Additionally, under the low-rate requirements of mMTC terminal devices, large-scale NOMA can achieve a significantly high power efficiency when a similar bandwidth as that of OMA system is utilized[1]. However, two major drawbacks of NOMA on its simplest form (single antenna and single base station at transmitter(s) and receiver(s)) limit its usage in a large-scale regime. The first drawback is the increased level of inter-NOMA-interference (INI), which is the interference caused by other users using the same NOMA cluster. When the number of NOMA users in a certain NOMA cluster increases, those users with lower link quality will have to deal with larger number of unfiltered INI signals. The second drawback is the hardware complexity of SIC that increases significantly with the number of users per NOMA cluster [3].

We investigate on a number of enabling techniques that may be used to overcome the challenges of large-scale NOMA (e.g. high INI and high hardware complexity requirements). NOMA can be deployed either in the uplink or the downlink of a wireless system. In this article, we focus on downlink NOMA as discussions can be easily applied to uplink NOMA. The rest of this article is organized as follows. Section II describes the basics of single-antenna, multi-antenna, and CoMP-enabled NOMA technologies. The hardware requirements for large-scale NOMA are discussed in Section III. Section IV outlines a key enabling technique that can support implementation of

The authors are with the Department of Electrical and Computer Engineering at the University of Manitoba, Canada (Emails: {Ekram.Hossain, Yasser.Aleryani}@umanitoba.ca).

[1]In this article, large-scale NOMA refers to the use of relatively high number of users per single NOMA cluster throughout a single frequency sub-band.

large-scale NOMA. We conclude the article in Section V.

II. NOMA Techniques

This section describes several enabling technologies the NOMA scheme can be integrated with.

A. Single-Input Single-Output (SISO)-NOMA

In an m-user SISO-NOMA cluster, the transmitted signal is given by $x = \sum_{i=1}^{m} \sqrt{p_i} s_i$ such that $\sum_{i=1}^{m} p_i \leq p_t$, where p_i is the transmitted power assigned to the i-th NOMA user, s_i is the signal to be sent to the i-th NOMA user, and p_t is the power budget of NOMA transmitter per sub-band. Accordingly, the received signal at the i-th user end is given by

$$y_i = h_i x + w_i, \quad \forall\ i = 1, \ldots, m, \tag{1}$$

where h_i is the complex channel gain of the i-th user and w_i is the noise plus interference for the i-th user. For NOMA, the magnitudes of channel gains between the NOMA transmitter and receivers are first ordered such that $|h_1| \geq \ldots \geq |h_m|$. Thereafter, power fractions are assigned to every superimposed signal such that $p_1 \leq \ldots \leq p_m$. This is done under the condition that the received signals' power at the i-th NOMA user must be separated from other signals' powers by a minimum SIC hardware sensitivity value [4]. Following this power allocation mechanism, the i-th user will be able to remove all signals with higher power weights than its desired signal through multi-level SIC techniques [2]. Therefore, the achievable throughput at the i-th user is given by

$$R_i = B \log_2 \left(1 + \frac{p_i \gamma_i}{\sum_{j=1}^{i-1} p_j \gamma_i + 1}\right), \tag{2}$$

where B is the allocated bandwidth per NOMA cluster and $\gamma_i = \frac{|h_i|^2}{I_i + N_i}$, in which I_i and N_i are the inter-cluster interference (ICI) power and the noise power at the receiver input of the i-th user, respectively. To compare the performance of large-scale SISO-NOMA with that of OMA, Fig. 1 shows a graphical approximation of the ϵ-outage capacity for SISO-NOMA with different cluster sizes (m). Here, ϵ is the maximum allowable outage to achieve a capacity of C_ϵ. In order to investigate SISO-NOMA at the large scale regime, we have used constant transmission power scheme that complies with NOMA protocol and does not affect the insights extracted from the provided results[2]. It can be noticed that increasing the number of users per NOMA cluster causes a significant degradation on the system coding gain (i.e. the performance curve shifts to the right).

In mMTC networks, communicating devices may be significantly small in sizes and distributed within remote areas which makes it difficult to guarantee a permanent power sources for all devices at all times. Accordingly, power consumption plays a critical rule in the design of mMTC networks and devices.

[2]Optimal transmission power allocation scheme for an m-user SISO-NOMA system was presented in [5].

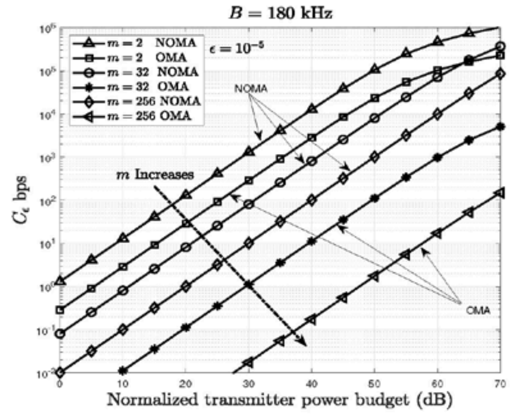

Fig. 1: C_ϵ versus normalized transmission power budget.

By using NOMA at the large-scale regime, higher spectral efficiency and/or lower power consumption can be achieved. As an example, under the same minimum rate requirements for OMA and NOMA, the required NOMA transmission power per cluster can be significantly reduced when the entire OMA bandwidth is utilized. In general, spectrum-efficiency and energy-efficiency trade-offs can be exploited when deploying large-scale NOMA in mMTC networks.

B. MIMO-Enabled NOMA

The extension of NOMA scheme to multiple-input multiple-output (MIMO) systems can be considered as the first intuitive solution to integrate NOMA with more sophisticated wireless technologies. There are quite a number of papers in the literature that discussed the merging between MIMO systems and NOMA scheme with different layouts. In this section we present, as an example, a clustering algorithms proposed by [5] to find the best utilization of MIMO-enabled NOMA system. Fig. 2 shows the proposed clustering model for MIMO-enabled downlink NOMA in which a transmitter with a group of antennas transmits to a set of users simultaneously using the same transmission sub-band. Generally, every transmitting an-

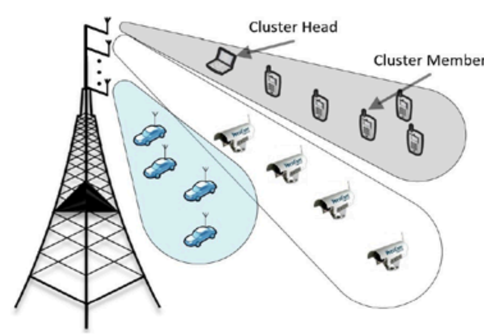

Fig. 2: MIMO-NOMA transmission in downlink.

tenna defines its own cluster set of receiving users and applies NOMA-based power allocation per cluster. Additionally, to reduce inter-cluster interference, transmitting antennas apply beam-forming (for example, zero-forcing beamforming) to allocate every cluster a share of the overall transmission power budget [4].

For large-scale MIMO-enabled NOMA systems, every cluster should have an order of tens of NOMA users (or even hundreds in the case of massive in-band NOMA scheme) that share the same in-band beam (same cluster). This increase in cluster size will result in an increase in the required transmission power per MIMO beam in order to guarantee a minimum rate per user (especially in presence of high inter-cluster interference). However, MIMO-enabled NOMA adds some degrees of freedom to achieve spectrum-power trade-off designs that comply with the notion of mMTC communication for which a significantly large spectrum efficiency and low power consumption are crucial. Accordingly, using the same OMA resources (i.e. available spectrum and power budget), with the appropriate design, MIMO-enabled NOMA may achieve similar performance with relatively lower power consumption.

C. CoMP-Enabled NOMA

In the last two subsection, we have discussed the NOMA scheme under one transmitter that has a single power budget to be allocated to different NOMA layouts (SISO and MIMO). In this section, we briefly discuss the integration of NOMA with the so called coordinated multi-point (CoMP) transmission. Specifically, we focus on joint transmission-CoMP (JT-CoMP) scheme in which multiple geographically distributed BSs serve different users using the same sub-band. All of the existing literature that focused on CoMP-enabled NOMA considered dividing users into cell-edge users and cell-centre users. Accordingly, every NOMA cluster is assumed to consist of one or multiple of the cell edge users and a one or multiple of cell-centre users.

Generally, under the JT-CoMP system, the received signal at the i-th user can be expressed as

$$y_i = \sum_{\forall\ m \in \mathbb{S}_{c,i}} h_{i,m} x_m + \sum_{\forall\ j \in \mathbb{S}_{nc,i}} h_{i,j} x_j + w_i, \qquad (3)$$

where $h_{i,m}$ is the complex channel gain between the i-th user and m-th BS, $\mathbb{S}_{c,m} (\mathbb{S}_{nc,m})$ is the set containing the indices of BSs serving (not-serving) the i-th user through a single sub-band. If the i-th user is identified as a cell-edge user, then more than one BS should transmit the same signal to that user. Fig. 3, shows a possible scenario of CoMP-enabled NOMA scheme. Using this scheme, the achievable throughput at the cell-edge user (denoted UE_1) and at the j-th user served by the i-th BS (denoted $\mathrm{UE}_{i,j}$) are expressed, respectively, as [6]

$$R_1 = \log_2 \left(1 + \frac{\sum_{i=1}^{2} p_{i,1} \gamma_{i,1}}{\sum_{i=1}^{2} \sum_{j=2}^{3} p_{i,j} \gamma_{i,1} + 1} \right), \qquad (4)$$

$$R_{i,j} = \log_2 \left(1 + \frac{p_{i,j} \gamma_{i,j}}{\sum_{k=j+1}^{3} p_{i,k} \gamma_{i,j} + I_{\text{inter}} + 1} \right), \qquad (5)$$

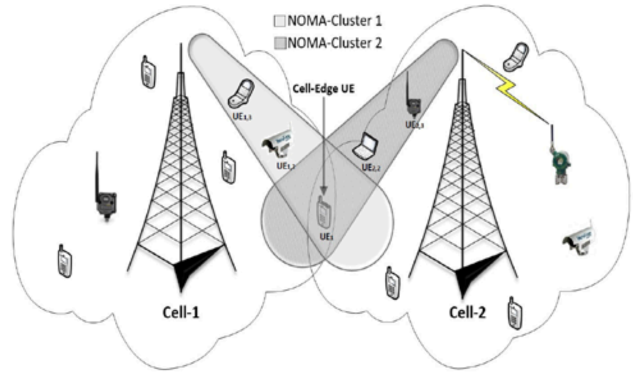

Fig. 3: CoMP-enabled NOMA with two cooperating BSs.

where $I_{\text{inter}} = \sum_{m=1, m \neq i}^{2} \sum_{l=2}^{3} p_{m,l} \gamma_{i,j}^{'}$ is the inter-cluster interference (ICI) caused by joint utilization of the same sub-band by two NOMA clusters. It can be noticed from Eq. (5) that being a cell-centre NOMA user will add an additional burden in the form of ICI (I_{inter}). In that regard, for large-scale NOMA, we have found that user performance is very sensitive to any further interfering components (in addition to INI component) even in the existence of sophisticated power allocation algorithms. This increases the difficulty of deploying a large-scale NOMA clusters under the conventional CoMP system. Nevertheless, CoMP-enabled NOMA with small cluster sizes was shown to significantly enhance average performance per user [6, Fig. 3].

III. Limitations and Requirements for Large-Scale NOMA

We discuss the limitations and requirements of NOMA deployment with large cluster sizes noting that studies on in-band large-scale NOMA is scanty in the existing literature.

A. High Interference Levels

Generally, there are two main interference components that affect the performance of NOMA receiver namely; the INI and the ICI. Based on NOMA protocol, users with lower channel quality will have to deal with interference due to those with higher channel quality. Accordingly, as the number of NOMA users per cluster (m) increases (see Eq. 2), users with low channel quality may suffer due to increased level of unfiltered INI components. Besides, ICI will occur due to the utilization of the same sub-band by more than one NOMA clusters. This can be done either within the same cell (such as MIMO-NOMA) or within different geographically separated cells (such as CoMP and multi-cell networks with a reuse factor greater than or equal to one [7]). It was found that under large-scale NOMA, user performance becomes very sensitive to small values of ICI. Therefore, sophisticated SIC mitigation technologies will be required to implement NOMA with a large cluster sizes.

B. Hardware Requirements for Large-Scale NOMA

The main idea of NOMA is based on the ability of the receiver to cancel a significant component of INI throughout SIC unit. Generally, due to the randomness of channel gains and the mobility of NOMA wireless receivers, a certain NOMA receiver should be able to cancel up to $m - 1$ signals at any arbitrary time slot (where m is the in-band NOMA cluster size). Accordingly, any design for large-scale NOMA receiver must take care of the following concerns:

(a) For large-scale NOMA, SIC must be achieved quickly and efficiently since NOMA is supposed to be operating at the time slot level.
(b) The increase of NOMA receiver sensitivity to different values of ICI at large cluster sizes.
(c) At large NOMA cluster sizes, differences among the received signals' power components at a certain NOMA receiver becomes smaller, especially for limited power budget. This will negatively affect the performance of SIC unit in decoding the highest weight signal. Accordingly, more complicated receiver designs will be required.
(d) Larger in-band NOMA cluster sizes means a larger number of required SIC operations which results in higher power consumption.

IV. An Enabling Technique for Massive-NOMA

When NOMA signal is enhanced such that the level of the desired power at every NOMA receiver is increased, the amount of interference is decreased and complexity of SIC is reduced, then the deployment of large-scale NOMA will become feasible. Traditional diversity enhancing techniques such as MIMO and CoMP could be a good candidate for large-scale NOMA scheme if the ICI component is mitigated efficiently. Here, we propose a novel cooperative NOMA scheme that enables the deployment of large-scale NOMA. Fig. 4 shows an example of the proposed scheme at which three BSs are cooperating to serve one large-sized NOMA cluster. Using this layout and with a proper network planing, the ICI

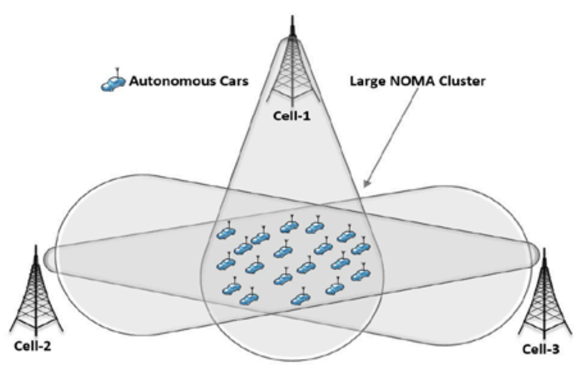

Fig. 4: Large-scale NOMA.

components may be significantly reduced. Additionally, using this system setup, the amount of desired signal at every NOMA receiver will be increased from more than one transmitter. Such an increase will result in larger power gaps (enhanced receiver sensitivity) and add more degrees of freedom on the required level of SIC for every NOMA receiver. Fig. 5 shows a simulation example of the proposed scheme. The variable

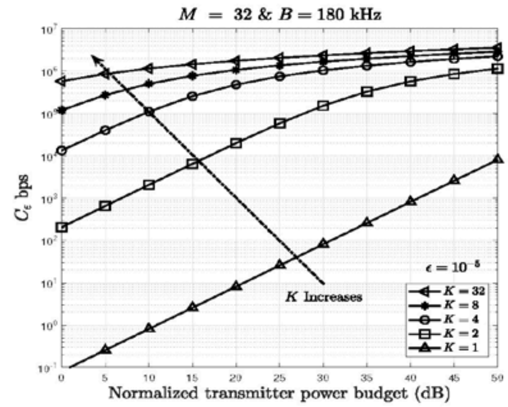

Fig. 5: C_ϵ versus normalized transmission power.

$K(M)$ denotes the number of cooperating NOMA transmitters(receivers). It can be noticed that even under significantly large M, increasing the number of cooperating transmitters enhances the system diversity gain significantly (increase in the slope of the performance curves).

V. Conclusion

NOMA can provide the required spectrum-energy efficiency trade-off required for mMTC networks. We have discussed several enabling technologies for NOMA (e.g. SISO-NOMA, MIMO-NOMA, CoMP-NOMA) and practical aspects of the deployment of large-scale NOMA (i.e. NOMA with large cluster sizes). To enable large-scale NOMA for massive mMTC, sophisticated diversity enhancing techniques need to be used to compensate for the severe degradation in coding gain and also to decrease the complexity of required successive interference cancellation (SIC).

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Ekram Hossain (F'15) is a Professor in the Department of Electrical and Computer Engineering at University of Manitoba, Canada http://home.cc.umanitoba.ca/ hossaina). He is a Member (Class of 2016) of the College of the Royal Society of Canada. Dr. Hossain's current research interests include design, analysis, and optimization of wireless, mobile, cognitive, and green commu- nication networks with emphasis on beyond 5G cellular networks. To date, his research works have received 23,000+ citations (in Google Scholar, with h index = 77). He was elevated to an IEEE Fellow "for contributions to spectrum management and resource allocation in cognitive and cellular radio networks". He received the 2017 IEEE ComSoc TCGCC (Technical Committee on Green Communications & Computing) Distinguished Technical Achievement Recognition Award "for outstanding technical leadership and achievement in green wireless communications and networking". He was listed as a Clarivate Analytics Highly Cited Researcher in Computer Science in 2017 and 2018. Currently he serves as the Editor-in-Chief of IEEE Press. Previously he served as the Editor-in-Chief for the IEEE Communications Surveys and Tutorials (2012-2016), Area Editor for the IEEE Transactions on Wireless Communications in the area of "Resource Management and Multiple Access" (2009-2011), an Editor for the IEEE Transactions on Mobile Computing (2007-2012), and an Editor for the IEEE Journal on Selected Areas in Communications - Cognitive Radio Series (2011-2014). He is a Distinguished Lecturer of the IEEE Vehicular Technology Society. Also, he is an elected member of the Board of Governors of the IEEE Communications Society for the term 2018-2020.

Yasser Al-Eryani was born in Sana'a, Yemen. He received a B.Sc. degree in Electrical Engineering from IBB University, Ibb, Yemen, in 2012 and received a M.Sc. degree in telecommunications engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, KSA, in 2015. He is now working towards his Ph.D. degree in electrical engineering at the University of Manitoba, Winnipeg, Canada. His research interests are design and analysis of wireless communication networks.

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