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5G Vision, Enablers and Challenges for the Wireless Future

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White Paper

5G Vision, Enablers and Challenges for the Wireless Future

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Angeliki Alexiou, University of Piraeus

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Authors

Full Name	Affiliation	Contact
Angeliki Alexiou	University of Piraeus	aalexiou@ieee.org
Panagiotis Demestichas	University of Piraeus	pdemest@unipi.gr
Andreas Georgakopoulos	University of Piraeus	andgeorg@unipi.gr

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1. Introduction: What is 5G?

“From the smallest personal items to the largest continents, everything, everywhere will be digitally connected, and responsive to our wants and likes” [1], comprises today’s vision for the communication network of the future. This vision is strongly supported by recent market studies conducted by global organisations, telecom companies, and operators, which indicate that mobile data traffic is (at least) doubled every year and will exceed traffic from wired devices by 2018.

Wireless communications are expected to dominate everything, everywhere, mainly empowered by revolutionary 5G radio network technologies. Accelerated by the dramatic impact of applications of the kinds of social networking (currently accounting for 10% of total data traffic [2]), and machine-to-machine (M2M) communications (600-800 million active cellular M2M devices by 2019 [2]), the centre of gravity for 5G will be shifted further to application-driven connectivity, transparently deployed over various technologies, infrastructures, users and devices, towards realizing the concept of Internet of Everything.

In the following sections of the White Paper, an overview is provided of the expectations and requirements, as envisioned by current understanding of what 5G should deliver, promising technology enablers are presented, novel system concepts are described along with the associated paradigm shifts and the new ecosystem of 5G services is explained as an accelerator for technology innovation, economic growth and social proliferation.

2. 5G expectations, requirements and challenges

2.1 Capacity scaling

The major enabler of the “anything-anywhere-anytime” communication paradigm is wireless connectivity, since it provides a ubiquitous and cost-efficient inter-connection platform. Naturally, wireless connectivity is associated with the availability of infrastructure (e.g., base station) that will act as a gateway for a device to connect to the Internet. However, mere infrastructure availability is not enough to support the massive traffic loads and exceptional user data rates of the future network, i.e., the conventional, “coverage-oriented”, macro base-station deployment of previous cellular generations cannot provide the necessary frequency reuse levels. Towards this end, the concept of small-cell has been introduced in order to provide “capacity injections” to the network. Nevertheless, this approach has practical limitations since providing ubiquitous connectivity to a large-scale area requires massive deployment of low-power base stations, an operation whose cost in terms of deployment and maintenance is prohibitive to a network operator.

It is envisioned that in a future 5G network users should enjoy the experience provided by a massive infrastructure deployment density over large geographical areas that is technologically and financially feasible. This vision is expected to open up new niche and business opportunities and promotes the introduction of new value chain actors.

2.2 Crowded Local Access

The proliferation of mobile broadband access (first delivered by 3G-HSPA and now taken to a next level by 4G LTE-A networks), supported by the advent of high-end smart-phone devices, along with the rapidly evolving social networking and cloud services in the Internet world, have blurred the borders between the content and the communication medium devoted to carry the content. We are now moving from the scenario where a user used to consume static information posted in the Internet (e.g., web browsing, file downloading), to a new era where the Internet information is created dynamically and at any time of the day by the users who are both creating and consuming the Internet content (e.g. through video and image uploading, posting/interacting with other people in social networks, etc.). This leads to ever-increasing levels of mobile data volume that today’s networks design/plan seems inadequate to support, even for the not-so-distant future. What is even more challenging, is supporting the large temporal and spatial dynamic range of mobile data. In particular, extreme peaks of mobile traffic could occur in a specific place (e.g., a bus-stop, a stadium hosting a football match) and at a specific time (while waiting for the bus, when a goal is scored).

Massive data volume local access for dynamic crowds is a key scenario for the network of the future, which should be addressed through the interplay of various technological and architectural innovations.

2.3 Massively available connectivity

A transformative vision for our society consists of connecting practically everyone and everything to the Internet ("Internet-of-Everything" or IoE). On the one hand, human-initiated communications become more and more challenging due to the increased demand for wireless data access at any time of day and at any place (e.g., work, home, entertainment). On the other hand, new applications involving machine-initiated communications are emerging, including smart metering (sensors/actuators), e-health (monitoring of health status), intelligent transportation (fleet tracking and traffic avoidance). Differently from the conventional design rules of mobile broadband networks that focus on increasing the achieved (peak) data rate per device, the machine communications paradigm primarily targets the support of massively increased densities of devices generating low-rate sporadic data. This traffic activity can cause geographically and temporarily concentrated data bursts, which drive current networks to overloading.

5G will accommodate for bursty IoT communications by providing the necessary infrastructure and operations to handle the vastly diversified quality-of-service requirements.

2.4 Reliability and Latency or 5G as the 'network of control'

Wireless evolution has always been viewed as a race to achieve ever increasing (or 'infinite') capacity, either in terms of data rates, connectivity reliability and/or massiveness. In the future Internet of Everything it may well be the case that capacity alone is not panacea. Round-trip latency *together* with availability and capacity, thus satisfying *heterogeneous* performance criteria might be the real and new challenge and paradigm shift. The Tactile Internet was described in [3] as "the typical interaction latency required for a tactile steering and control of real and virtual objects, without creating cyber-sickness". The capability to reliably communicate and control at the speed of human senses and / or substitute human monitoring, decisions, action, and communications by those that involve (partially or totally) devices is expected to change the way people work, socialize, live proliferate and communicate.

The race for infinite capacity in 5G may offer an opportunity to create impressive results on networks performance but can easily be trapped in situation where excellent solutions are looking for problems. The realization of the Tactile Internet or the Network of Control will open up an "unforeseeable plurality of new applications, products, and services", as stated in [3].

2.5 Services and User Experience

From the viewpoint of Service Creation and User Experience:

- 5G will be a holistic solution starting from the needs of various applications and proceeding to technical solutions but finally integrating solutions tighter than previous generations have done.
- 5G will become experience based approach where technologies are used for providing user experiences.
- 5G extends the notion of user to include both humans and machines. This is a clear difference to previous approaches in which mainly human users have been considered.
- 5G will be affected by many other fields and as such the business will be changed.

3. 5G Design and Architecture Principles

3.1 Network Densification

Cellular infrastructure densification is a concept that has been applied as early as in 2G voice-oriented systems, mainly as a tool for locally enhancing performance of an already deployed system. In particular, cell splitting and sectorization, supported by careful frequency planning were employed in order to increase sustained voice capacity in areas of the network experiencing heavy traffic [4]-[7].

Specifically, an operator can deploy around 1.000 macro cells for covering a city of a few million inhabitants. Within the next few years it is anticipated that there can be around 100 small cells underlying each macro cell. This can be justified through two main observations. First, within each macro cell there can be 500 – 1000 apartments, offices and/or shops; a percentage of these apartments will have an indoor small cell of the particular operator; it is reasonable to assume that there can be tens or few hundreds of indoor small cells underlying the macrocell. Second, in parallel, there will be a set of outdoor small cells underlying each macrocell; this number can be 2-10, in areas of low to considerably high traffic; nevertheless, the number can even reach the order of 100, in ultra-high traffic areas. On aggregate it is reasonable to expect: (i) 100 small cells per macro cell, or 100.000 small cells in a city of few million inhabitants; (ii) a rising trend regarding this number; this will eventually lead us to realms that can be characterized as ultra-dense networks.

The *challenge* with ultra-dense networks is to deploy and operate the appropriate set of cells, so as to carry the user-plane traffic, without severely increasing the signaling traffic (increases with the number of cells), by minimizing the impact of mobility and radio conditions, and by achieving cost and energy efficiency.

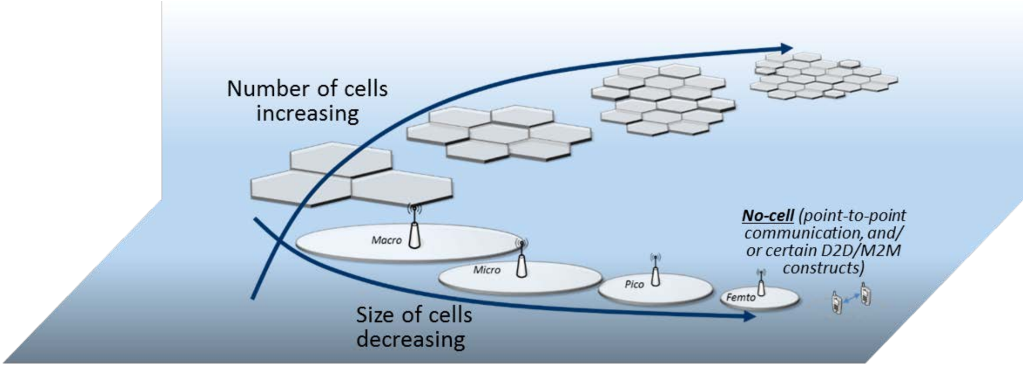

Figure 1.Network densification in 5G

In future (5G) networks, (ultra) network densification has a fundamentally different and more important role. In particular, network densification offers the advantage of proximal communications, which, in turn, provides the means towards fulfilling the following critical communication principles:

1. *Extreme, user-centric, spatial reuse of system bandwidth*, by partitioning the space to (arbitrarily) small cells, up to the point where the traditional notion of cell is no longer relevant and each UE is served in principle by one (or more) AN(s) (access nodes) exclusively dedicated to that UE;
2. *Reduction of path loss effects*, by bringing the access infrastructure "closer" to the user.

Even though it is commonly understood that fulfillment of the above principles is necessary, in order to accommodate the exponential increase in traffic load expected for the future network, it is not clear whether the promised capacity gains can actually be achieved. Practical limitations on infrastructure deployment along with opportunistic exploitation of devices as content providers, renders the carefully designed AN deployment of previous wireless networks impossible (if not irrelevant). A snapshot of the system's AN positions will depict heavy irregularities, with regions having many (available) ANs very close together, and regions of locally smaller AN density. This essentially random AN deployment raises questions whether such a network is able to provide the promised performance gains, as the degree of fulfillment of the above mentioned principles is not clear, and, more importantly, the interference environment is fundamentally different from the one experienced by traditional cellular networks, which may suggest that a uncoordinated system operation has no hope in exploiting the proximity gains.

Towards understanding the impact of densification under irregular (random) AN placement, the seminal work of

[8] leveraged stochastic geometry (SG) for analyzing the downlink SIR distribution experienced in an ‘infinite area’ network with AN positions uniquely characterized by its density. It was shown that in an ever-densified interference-limited network, where UEs associate with their closest AN and no coordination among transmissions is applied, interference and useful signal power increase at the same rate, hence the achieved signal-to-interference (SIR) levels are preserved. It can therefore be concluded that, from a system perspective, network densification indeed enables extreme spatial reuse of system bandwidth, with an increase of AN density directly translated into an increase of total system capacity. However, the system perspective of [8] as well as of relevant works that followed, ignores the impact of multiple-access/resources allocation on user rate, and, therefore, fails to characterize the perceived rate performance levels per UE, which are of greater importance towards a user-centric future network deployment. To address these limitations, new tractable analytical modeling approaches focusing on user-centric performance metrics and covering various density regions are necessary for thoroughly characterizing the impact of densification.

Although analytical assessment approaches are able to provide insights on the fundamentals of UDNs operation, their tractability heavily depends on the adoption of (over)simplifying assumptions. Detailed system-level simulation models are therefore necessary in order to capture the effect of, e.g., realistic traffic models and propagation conditions, and investigate the potential of sophisticated radio resource management algorithmic approaches. In this context, a second line of works has recently emerged in the literature, towards estimating the densification requirements for a set of potential 5G traffic load and QoS targets [10], [11], [12]. The common conclusion for all the presented works is that their ambitiously set 5G capacity objectives require one to two orders of magnitude greater infrastructure density than today, i.e., validate the necessity of UDNs. A major limitation of these studies is that they do not explicitly consider performance optimization aspects, achieved through intelligent, network-wise coordination mechanisms. Investigation of coordination is of great importance as it has the potential to reduce the effect of interference and exploit the proximity of a UE to many ANs, a system attribute inherent in UDNs and not present in previous wireless generations. However, it is not clear whether incorporation of sophisticated coordination on top of a UDN is indeed necessary since it may be argued that the proximity gains offered by the dense deployment alone are sufficient.

The UDN concept introduces a paradigm shift from the well-known small-cell to a cell-less wireless future, by integrating:

- *Operator-driven hyper-dense small-cell deployments, bringing a multiple orders of magnitude increase in the number of available infrastructure elements per user device;*
- *Complementary radio access technology networks (such as WiFi) operated by alternative providers, typically in enterprise environments (such as stadiums, airports, shopping malls);*
- *User-deployed home infrastructure, such as wireless routers for internet access, femto-cells, machine-to-machine gateways;*
- *“Crowdsourced” high-end user devices (such as smart-phones) equipped with various wireless interfaces, and acting as adhoc providers of network access in highly dense device scenarios.*

3.2 Network Softwarization and Virtualization

In the direction of improving the resource utilization there are also the concepts of software-defined networking (SDN) and network function virtualization (NFV). The basic SDN architecture involves 3 layers namely infrastructure layer, control layer and application layer plus various APIs for the communication between layers. In more detail, the infrastructure layer comprises network devices and equipment. The control layer provides “SDN Control Software” and “Network services” for addressing requirements of the applications which are available in the application layer via specific APIs. The application layer provides open API links with other applications or systems. Also, it can be noted that the control-data plane interface which is depicted in Figure 2 is used for the interconnection of the infrastructure layer (network devices) with the control layer (network services). The fundamental idea behind SDN is to separate the forwarding functions from the networking (control/management-plane) intelligence.

The NFV concept is complementary. It advocates that certain network functions can be virtualized, i.e., be taken out of the proprietary network elements and be offered through a cloud infrastructure. Virtualization solutions can accelerate the application/service deployment times and also for enabling the introduction of intelligence. For instance, through the standardized interfaces of the SDN model there can be instructions on how to handle new applications/services. Likewise, through NFV there can be an easier implementation of applications/services and networking intelligence (activation in cloud, and instructions towards forwarding-elements).

The overall *challenge* in 5G, is to evaluate the potential of these concepts, in terms of impact in the application/service deployment times, QoS/QoE, and costs of implementing, and of operating the resulting networks.

Wireless Network Softwarization and Virtualization introduces another paradigm shift by exploiting cloud computing model principles, in order to provide on-demand, cost-efficient and service-oriented networks on-the-fly. It involves the decoupling of the hardware infrastructure and the supported functionalities, by:

- *Leveraging mainly general-purpose (commodity) hardware (e.g. general purpose processing units etc.) and relevant facilities (e.g. IT data-centres);*
- *Relying on software implementations for all the system functionalities, including baseband processing, radio resources scheduling, network routing, etc.;*
- *Dynamic on-demand network configuration and management during runtime, in terms of allocated physical infrastructure and network operations (e.g. air-interface, radio resources management algorithms), by optimising the cost, energy-efficiency or other metrics, creating the perception of "infinite" and "elastic" network scalability.*

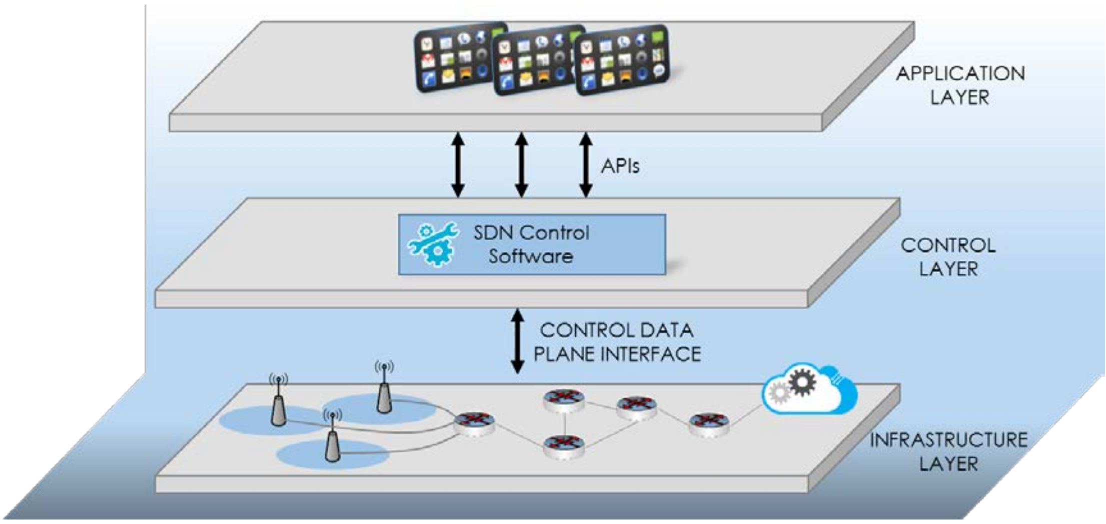

Figure 2.Basic SDN architecture and layers

3.3 Universal resources and network management

Densification, softwarization and virtualization of future networks introduce a whole new ecosystem where the notion of "resource" needs to be re-defined as it may now refer to every possible network component, such as the radio access physical infrastructure nodes (antennas, base-stations), backhaul, spectrum, computing power, etc. Optimizing, managing and owning resources in this new landscape entails opportunities and challenges both technical and business modeling/economical. The traditional Mobile Value Chain may need to be disrupted by new types of stakeholders and new approaches to resources sharing. Going beyond today's cell site sharing concept by breaking the network into various sub-components and transforming the resources to "commodities", novel ownership and control models need to be devised. Empowered by virtualization, resources sharing allows building a network from commodities, tailored to the application(s) it needs to provide. For example, on-demand video streaming (Netflix, amazon-prime) imposes totally different requirements (allocated spectrum, backhaul latency, video processing) and is associated with vastly diverse revenue model, compared to an IoT application (e.g. geographically and temporally sporadic smart-metering).

Furthermore, densification, softwarization and virtualization through SDN and NFV concepts create a new landscape in 5G networks which needs to be properly managed in order to meet the 5G requirements as set by the industry for optimal quality of communication, enhanced capacity, support of high mobility, ultra-low latencies and energy and cost efficiency. It is a fact that the achievement of optimality (acceleration of deployment, QoS/QoE, cost efficiency, energy efficiency), in demanding and variable contexts through the exploitation of the appropriate system capabilities can only be done through a constantly agile system behavior. Therefore, essential advances in network management are necessary.

Main output of network management mechanisms should be the optimal and feasible system configuration that can be applied for handling a specific context of operation. The output can be automatically applied or be suggested as prescription. This enables the classification of the importance of actions, and the gradual acquisition of trust (from the operators towards new management mechanisms), towards the full automation. The optimality of the output is associated with the: (i) handling of the target contexts, i.e., QoS/QoE, cost/energy aspects; (ii) the speed and reliability with which decisions can be taken regarding how to handle contexts.

It should be noted that in every generation there are significant upgrades in the associated management. For instance, in 4G we witnessed the introduction of self-organizing-network (SON) concepts [13]. In this respect, it can be envisaged that 5G will also have advances. A promising direction seems to be that of machine learning and knowledge-based optimizations [14]. The reason is to obtain wider insights on the situations encountered and on the solutions used, and to conduct context handlings with higher speeds and reliability.

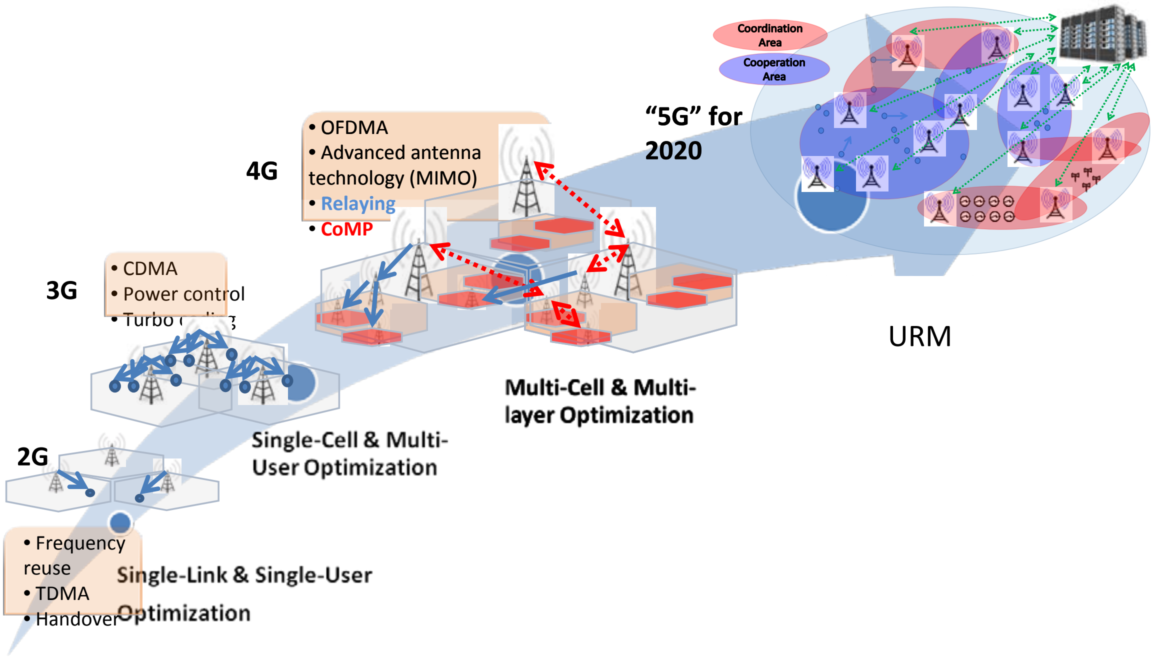

Figure 3. Wireless Evolution towards 5G - Universal Resources Management (URM) to solve the Resources Allocation problem by means of Coordination and Cooperation

4. 5G Technology Enablers

Towards achieving such an ambitious 5G vision, the wireless research community has already started building on the huge success of previous cellular network generations (from 2G up to 4G) and commonly considers the following three technical directions as enablers of the 5G network [15], [16]:

- **Incorporating more spectrum**: Harness the pool of cm-Wave licensed bands (such as the 3.4-3.8 GHz band, which is emerging as a new small-cell band), unlicensed bands (such as the 5 GHz WiFi band, which is also considered for operation of the unlicensed version of LTE, known as LTE-U/LAA in Release 13 and onwards), and even the unallocated, higher frequency bands in the mm-Wave regime (28, 38, 70 GHz).

- **Densifying infrastructure for improved local access**: Benefit from higher spatial reuse of resources, by deploying hyper-dense small-cell clusters (3GPP Release 12 and onwards) and/or exploiting WiFi technology for offloading significant amounts of traffic in hotspot and indoor areas.

- **Inventing new spectral efficiency and user multiplexing radio technologies** for macro and small-cell access nodes: Relax tight orthogonality in current LTE air-interfaces (e.g. GFDM waveforms), enrich current systems with asynchronous and non-orthogonal multiple-access (SCMA, NOMA schemes), advance inter-cell cooperation and coordination for interference management (CoMP), exploit massive antenna elements to create spatially isolated streams over the same spectral/temporal resource unit (Massive/FD-MIMO), and incorporate High-order Multi-User MIMO to emerging Wi-Fi standards (802.11ad, ax).

Although there is currently a large number of promising technologies under consideration, one could summarize the *most significant 5G technology differentiators* in the following [16], which share the common fundamental and innovative concept of **proximal communications**: exploit massive UE densification to access the network via a proximal link (M2M, D2D, ..), as depticted in Figure 4:

1. **Device-centric architectures and D2D**: The base-station-centric architecture of cellular systems may go through reconsideration. In contrast to infrastructure-centric architectures, the concepts of uplink and downlink, and control and data channels, may prove inadequate or too limiting in view of the adoption of proximal communication scenarios enabled by heterogeneous extreme densification. Furthermore, exploiting intelligence at the edge of the network with Device-to-Device (D2D) connectivity and/or smart caching at the mobile side may offer an excellent network load balancing opportunity, given the overhead signaling limitation that centralization (through virtualization) could entail.

2. **Millimeter Wave (mmWave)**: Although far from fully understood, mmWave technologies have already been standardized for short-range services (IEEE 802.11ad) and deployed for niche applications such as small-cell backhaul. The potential of mmWave for a broader use in 5G remains to be validated, especially in terms of resources and interference management.

3. **Massive-MIMO** involves utilizing a very high number of antennas to multiplex messages for several devices, focusing the radiated energy towards the intended directions while minimizing intra- and inter-cell interference. Massive-MIMO may require major architectural changes, in particular in the design of antennas and air interface (waveforms and pilots).

4. **Machine-to-Machine (M2M) communication in the future Wireless Internet of Things:** Tactile Internet vision [3] is tightly associated with another 5G technology differentiator. The integration of M2M is a cellular dominated world. That would mean to address the challenge of supporting a massive number of low-rate devices, in a plethora of diverse scenarios, and very-low-latency data transfers.

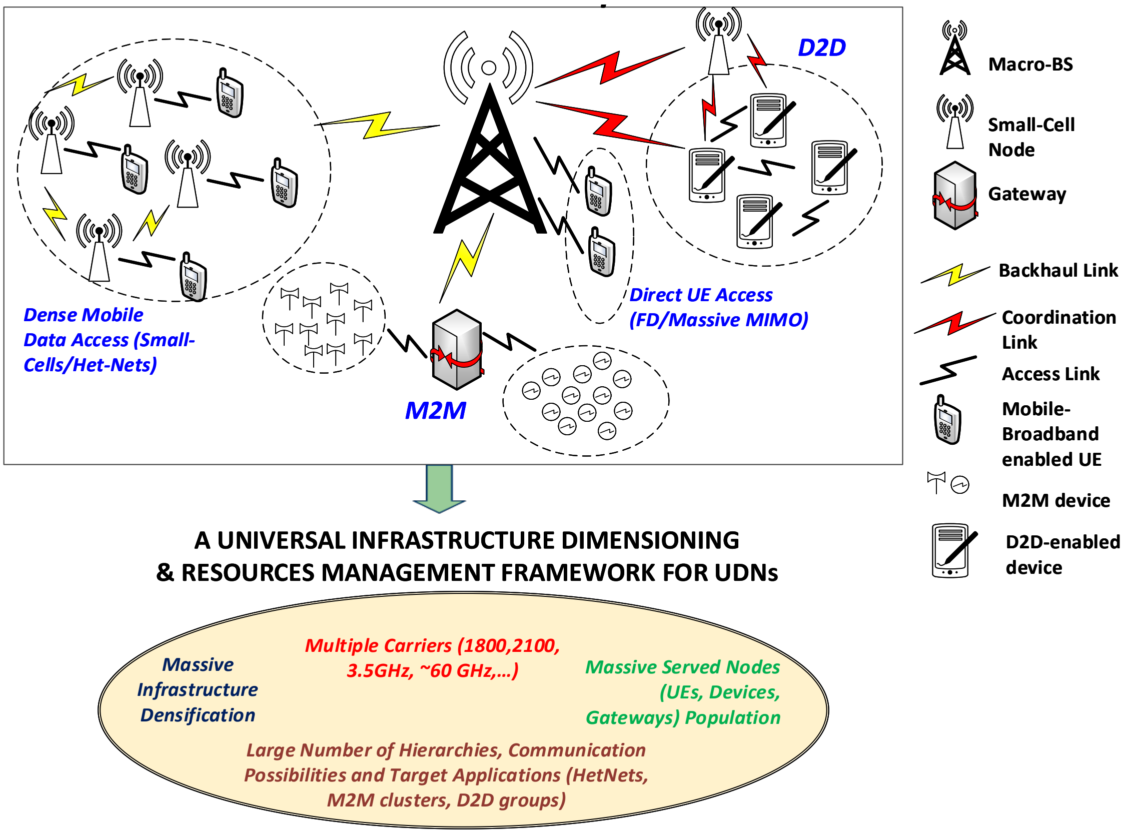

Figure 4. A Universal Infrastructure Dimensioning and Resources Management framework for UDN

5. Epilogue

Whether the ‘real’ 5G revolution is about new technology enablers, novel system architectures, alternative views on resources management and ownership or new business models and a new application ecosystem is an ongoing debate that involves a great deal of wishful thinking and visionary predictions.
Nevertheless, one could start by identifying today’s networks fundamental limitations, such as

- lack of flexibility and scalability in the cellular regime
- heavy constraints on network upgradeability (cost, downtimes) and limiting flexibility in supporting multiple radio technologies
- business models not flexible enough to offer new niche opportunities and allow for the large investments required by the 5G network.

The principles of densification, virtualization, softwarization and commoditization of resources could well be a way towards breaking these barriers.

6. References

[1] “The World in 2025: 10 Predictions of Innovation,” THOMSON REUTERS report, [Online]. Available: http://sciencewatch.com/sites/sw/files/m/pdf/World-2025.pdf

[2] “Cisco Visual Networking Index: Forecast and Methodology 2013-2018,” Cisco, Jun. 2014. [Online]. Available:http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.pdf

[3] Gerhard P. Fettweis, “The Tactile Internet – Applications & Challenges”, IEEE Veicular Technology Magazine, Vol. 9, No. 1, pp. 64 – 70, March 2014

[4] A. Alexiou, “5G on the count of three paradigm shifts”, ITU-R Working Party 5D Workshop on Research Views on IMT Beyond 2020, Ho Chi Minh City, Vietnam, 12 February 2014, http://www.itu.int/dms_pub/itu-r/oth/0a/06/R0A060000600001PDFE.pdf

[5] Third (3rd) Generation Partnership Project (3GPP), Web site, www.3gpp.org

[6] P. Demestichas, A. Georgakopoulos, D. Karvounas, K. Tsagkaris, V. Stavroulaki, J. Lu, C. Xiong, J. Yao, "5G on the Horizon: Key Challenges for the Radio Access Network", IEEE Vehicular Technology Magazine, vol.8, no.3, pp.47-53, 2013.

[7] Y. Wang, J. Li, L. Huang, J. Yao, A. Georgakopoulos, P. Demestichas, "5G Mobile: Spectrum Broadening to Higher-Frequency Bands to Support High Data Rates", IEEE Vehicular Technology Magazine, vol.9, no.3, pp.39-46, 2014.

[8] Andrews, J.G.; Baccelli, F.; Ganti, R.K., "A Tractable Approach to Coverage and Rate in Cellular Networks," Communications, IEEE Transactions on , vol.59, no.11, pp.3122,3134, November 2011, doi: 10.1109/TCOMM.2011.100411.100541.

[9] H. ElSawy, E. Hossain, and M. Haenggi,“Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: a survey,” IEEE Communications Surveys and Tutorials, vol. 15, pp. 996–1019, Jul. 2013.

[10] Liang Hu; Luque Sanchez, L.; Maternia, M.; Kovacs, I.; Vejlgaard, B.; Mogensen, P.; Taoka, H., "Heterogeneous LTE-Advanced Network Expansion for 1000x Capacity," Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, 2-5 June 2013 doi: 10.1109/VTCSpring.2013.6692578.

[11] Gelabert, X.; Legg, P.; Qvarfordt, C., "Small Cell densification requirements in high capacity future cellular networks," Communications Workshops (ICC), 2013 IEEE International Conference on , vol., no., pp.1112,1116, 9-13 June 2013, doi: 10.1109/ICCW.2013.6649403.

[12] I. Hwang, B. Song, and S. Soliman, “A Holistic View on Hyper-Dense Heterogeneous and Small Cell Networks,” Communications Magazine, IEEE, vol. 51, no. 6, 2013.

[13] M. Peng, D. Liang, Y. Wei, J. Li, H.-H. Chen, "Self-configuration and self-optimization in LTE-advanced heterogeneous networks", IEEE Communications Magazine, Vol. 51, No. 5, 2013

[14] S. Sra, S. Nowozin, S. Wright, “Optimization for machine learning”, The MIT Press, Neural Information Processing series, September 2011.

[15] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, AC. K. Soong, and J. C. Zhang, “What will 5G be?,” IEEE Journal on Selected Areas in Communications, vol.32, no.6, pp.1065-1082, Jun. 2014.

[16] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, “Five disruptive technology directions for 5G,” IEEE Communications Magazine, vol.52, no.2, pp.74-80, Feb. 2014.

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Wireless World Research Forum
c/o Format A AG
Pfingstweidstrasse 102b
CH-8005 Zürich

Secretariat:
Vinod Kumar
e-Mail: vinod.kumar@wwrf.ch
Phone and Fax : +33611181622

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