Publishable summary

An IMT-Advanced key requirement for next generation systems is the support for unprecedentedly high throughputs per user. This implies an infrastructure composed of access and backhaul network, capable of supporting the resulting high capacity densities. The current next-generation technologies LTE and WiMAX support a mere 100Mbps/Km^2 in ordinary cellular deployment. This is insufficient, in particular in dense urban areas where the market demands for wireless broadband access is the highest, thereby seriously jeopardizing the wide scale uptake of IMT-Advanced technologies.

Beyond Next Generation networks (BuNGee) research project has been established with objectives to dramatically improve the overall infrastructure capacity density of the mobile network by an order of magnitude to an ambitious goal of 1 Gbps/Km^2 in the cell at a commercially viable cost – thereby removing the barrier to beyond next-generation networks deployment.

To achieve these goals, BuNGee aims at invoking several fundamental paradigm shifts in ultra-high capacity designs which pertain to:

- joint design of access and backhaul networks using heterogeneous radio elements, Licensed and License-Exempt (LE) spectrum, a cognitive radio approach, among others, aimed at achieving a maximum system capacity and QoS;
- ultra-dense below-rooftop radio network deployment, exploiting natural radio isolations;
- innovative antenna technologies tailored to urban ultra-high capacity needs;
- network and distributed MIMO & interference elimination techniques;
- autonomous architectures capitalising on very aggressive spatial and spectral reuse combined with high spectrum efficiency, by using novel antenna, RF, base-band and network techniques.

The project's research framework considers LTE and WiMAX to be the next generation mobile networks offering services required by IMT-2000. LTE Advanced and WiMAX II, on the other hand, are considered to be beyond next generation or 4G systems which are able to offer services as required by IMT Advanced. BuNGee sees itself as a facilitator and enabler for the future mobile broadband wireless networks.

Realizing the imminent need for increasing the capacity density of mobile broadband networks drives the deployment paradigm taken in BuNGee – increasing the density of base stations grid below the rooftops (e.g., on utility poles) and thereby bringing the backhaul network below rooftops. Having a denser base station grid (below rooftops), coupled with aggressive reuse of resources, allows to decrease significantly the transmission power and thereby the electromagnetic exposure in urban environments, thus contributing to the cost-, spectrum- and energy-efficient design.

The corner-stone of the novel BuNGee heterogeneous architecture, is the tightly coupled joint design of access and backhaul network, which is facilitated and driven by the fact that they both use the same bands and are becoming spatially very close. This architecture combined with the deployment approach and integrated usage of licensed and license-exempt spectrum, allows a significant increase of available capacity.

The architecture makes use of the un-licensed spectrum in both in-band backhauling and the access part of the network to serve user traffic with less stringent QoS requirements. The more demanding traffic is provided over the licensed spectrum. BuNGee targets research and development of the radio link prototype at a 60GHz, including the base-band and radio technologies.

For the Backhaul Tier, BuNGee developed a dual-polarization multi-beam antenna, which includes a number of narrow beams used for increasing the system capacity.

The proposed aggressive frequency reuse is enabled by the following factors:

- Extensive use of multi-beam antenna technology in the Backhaul Tier;
- Below-rooftop deployment of Access Tier, thereby reducing interference, due to the isolation caused by dense high buildings;
- Extensive usage of multi-beam assisted MIMO and advanced network MIMO technologies.
- To control the interference in high-density heterogeneous RANs with limited frequency channels, BuNGee developed Radio Resource Management (RRM) protocols, including:
    - Interference control protocols, at medium access and network levels – to prevent, eliminate or at least reduce intra-system interference exploiting the BuNGee architecture and antenna;
    - Autonomous radio resource assignment, including frequency channels allocation;
    - Other elements of Self-Organizing Networks (SON).

The cost is an important element of the design. Thanks to the “below rooftops” deployment paradigm, BuNGee uses small pico-factor outdoor ABSs where the cost reduction is achieved by much lower transmission power, avoidance of the costly roof leasing, as the deployment will use electricity poles, street lights, etc., in-band backhauling approach relaxing backhauling requirements and effective usage of LE spectrum for the feeding links.

Cognitive radio principles are extensively used in maximizing the system capacity. This requires the evaluation of the achievable capacity in different spectrum blocks, as a function of the required data rates, QoS and SINR. The available spectrum is seen as an integrated resource and traffic is split between licensed and LE spectrum based on traffic requirements (QoS, data rates). The LE spectrum is used according to its propagation characteristics, bandwidth and interference levels. Based on the European allocations for LE spectrum, 5GHz and 60GHz are considered for backhauling. The fixed/nomadic usage of these frequencies and the multi-beam assisted MIMO makes possible interference cancellation at the BS receiver.

During the reported period, the final BuNGee ultra high-capacity architecture was defined, incorporating number of novel elements based on the functional specs and requirements specified during the 1st Year period. Evaluation of BuNGee-specific channel models had great importance in characterizing the overall BuNGee wireless systems performance, supporting the activities related to proper system-level simulations of the developed concepts and system capacity evaluation. The enhanced ray-tracing tool developed in BuNGee and incorporating BuNGee-specific HBS multi-beam antenna radiation patterns, was used to simulate the aforementioned channels, while the potential of the existing channel models such as WINNER II and IEEE 802.16 was simultaneously investigated. The advanced features of the ray-tracing tool developed within the project were validated by experimental campaigns in urban areas, using a state-of-the-art MIMO channel sounder. Complete description of BuNGee channel models was performed. Polarized MIMO aspects of HBS-to-HSS link are characterized and analysed in different BuNGee deployment topologies. The analysis included investigation of a number of parameters such as spatial fading, spatial correlation, Cross Polarization Discrimination (XPD) and Co-Polar Ratio (CPR). Additionally, wideband aspects of the above channel are detailed in terms of RMS delay spread and tapped delay model. Results elaborate the dependence of wideband parameters upon BuNGee-specific deployment and narrow-beam width antennas. Interference being one of the major challenges for the beyond next generation wireless networks was characterized. First potential interfering links in BuNGee architecture were identified and subsequently interference models of such links were evaluated in details. As a conclusion, dense deployment results into strong interference between polarized links. Therefore, efficient and robust frequency planning schemes are vital for the BuNGee architecture.

Complete HBS multi-beam high gain dual polarized antenna was designed and successfully evaluated in simulations. The complete 8 x 8 array with commercial Butler matrix was assembled and tested in the chamber. Effect of adding ‘tapering’ to the antenna array coefficients was studied proving that it can significantly improve side lobe performance with small gain reduction.

BuNGee developed novel extremely high capacity MIMO techniques specifically adapted to the BuNGee architecture and leveraging BuNGee-developed multi-beam high gain antenna:

- Multi-beam assisted MIMO (MBA-MIMO), where MIMO principles are applied in beam space following the antenna feed matrix, and
- Network-enabled MIMO, where two (or more) ABSs collaborate to transmit to or receive from a given MS, improving diversity and/or throughput.

BuNGee showed that the MBA-MIMO approach, employing joint beam processing at the HBS, can increase capacity by a factor of around 6 to 8 compared with conventional single beam processing, in which signals received by other beams are treated as interference. This is further increased by a factor of nearly two by the use of dual polarisation on the backhaul links. Altogether, this contributes to nearly doubling the overall capacity available from the BuNGee network, as demonstrated by the BuNGee network-level simulator.

In the access segment, the value of network-enabled MIMO is investigated and shown to increase capacity by at least a factor of 4 compared to the baseline frequency-planning scheme used in BuNGee, because it enables the whole access segment bandwidth to be used by all ABSs. However this results potentially in a large increase in the backhaul load. In view of this, the application of physical layer network coding was investigated, and found to be a promising approach to reduce backhaul load while providing most of the benefit of network-enabled MIMO.

On both backhaul and access segments it is assumed that precoding techniques will be used, as prescribed by wireless access standards such as WiMAX and LTE. Aspects of precoder selection are discussed, and an iterative interference cancellation approach is proposed for the implementation of ML detection. It is shown that this gives rise to significant gain compared to the more usual linear detectors, as well as making the task of precoder selection less critical. A more robust and efficient method than conventional techniques is developed for the transmission of channel state information (CSI) between receiver and transmitter, as required for the implementation of pre-coding, enabling significant reduction in the number of feedback bits required.

LE spectrum 60GHz ultra high-capacity wireless PtP link was designed and prototyped. Field performance testing proved feasibility and commercial value of the emerging mmWave technology for Backhaul Tier, especially relevant for small cells deployment. The prototype link demonstrated throughput of more than 130 Mbps at relatively low modulation and coding rates, with potential of getting more than 1 Gbps at higher MCSs. The prototype link displayed simplicity of installation, un-obtrusive view and high technology cost-efficiency becoming high promising candidate for small cells wireless backhauling.

In-band backhauling solutions were explored and innovative approach, enabling reuse of the existing industrial BWA eco-system, was proposed, prototyped and tested. This included novel network reference architecture and temporal design for joint access and backhaul networks including frame structures for spectrum sharing in time domain and frame structure elements for SON support. The relay technology has significant advantages in its capability for in-band operation due to the sharing of resources between the backhaul and access tiers. Under coverage-limited conditions the relay approach makes a lot of sense, and also promises to be economically efficient. Under the capacity-limited conditions the relay approach uses valuable in-band spectrum for backhauling, and hence might be less efficient comparing to other backhauling technologies (such as e.g. out-of band 60 GHz PtP links). However, even in capacity-limited conditions, in-band backhauling presents a valid and cost-wise attractive solution as a backhauling for small cells deployed below the rooftops, especially at the initial stages of radio access network deployment.

Backhauling Multi-Link Aggregation feature was designed, prototyped and successfully demonstrated in Live Demo, representing joint use of LE and Licensed spectrum for the Backhauling Tier by integrating in-band backhauling solution in the licensed spectrum and PtP 60 GHz link in LE spectrum. The proposed Access Multi-Link Aggregation feature may be used for inter-technology link aggregation in the Access Tier, including LE spectrum technologies.

The novel RRM and SON features of the joint access and backhaul radio network were defined addressing the algorithms and mechanisms for spectrum sharing between the access and backhaul tiers, interference mitigation across the wireless network, scheduling support and the dynamic frequency planning solutions based on centralized and distributed architectures. Evaluation and design of Autonomous Distributed Cognitive Radio Dynamic Resource Assignment was performed implementing cognitive and docitive RRM mechanisms. BuNGee applied Cognitive/ Docitive approaches in the frequency/ channel assignment and power control. For the network-wide cognitive/ docitive power control, power is allocated following some advanced and distributed Q-Learning algorithms which rely on reinforcement learning in machine learning.

A basic cognitive radio approach was modelled assuming a spectrum sensing function is located at the receiver. Large set of system-level simulations was performed, presenting significant improvement that may be achieved using spectrum sensing in conjunction with the frequency planning approach (cognitive radio RRM). Simulations proved improvement of the system QoS (significantly reducing the system delay) in the uniformly distributed MS scenario while achieving throughput density of around 0.85Gbps/km2.

Other SON features accelerating BS setup time and simplifying the setup procedure were developed in BuNGee and finally prototyped and implemented in the Live Test.

The BuNGee two-layer simulation tool developed during the project Y1 period was enhanced to address the new deployment scenarios/ topologies and BuNGee-developed multi-beam assisted MIMO. Number of additional simulation scenarios were developed providing valuable impact for total system capacity estimations. In the frequency planning approach with outdoor only MSs and point-to-point MIMO, simulations proved capability to achieve the overall throughput density of 1.05 Gbps/km^2, which is above the 1Gbps/km^2 target. Modeling of the MBA-MIMO in system-level simulations for outdoor street-level MSs presented the overall throughput density boost to around 2 Gbps/km^2 in the pessimistic scenario and to more than 2.2 Gbps/km^2 in the optimistic scenario, drawing the upper boundaries of the potential improvement that can be achieved by applying MBA-MIMO at the Backhaul Tier.

BuNGee subsystem prototypes were developed and successfully tested by the Partners including high-capacity 60 GHz PtP backhauling link, multi-beam antenna and Hub/ Access BS prototypes. Real-time FPGA-based MIMO mobile WiMAX transceivers with limited feedback were developed and successfully tested. The Live Demo system incorporating the developed prototypes was successfully integrated and tested in Lab environment. Finally, the high capacity radio cell prototype was implemented, operated and analyzed in the real urban cellular deployment scenario of Tel Aviv city. The Live Demo system demonstrated *the close-to-the-target equivalent throughput density of ~840 Mbps/km^2 for outdoor users* *in real mobile environment of the dense urban area of Tel-Aviv city with reasonable GoS*. The system deployed in the Live Demo also demonstrated functionality and efficiency measurements of the components, concepts and features developed in BuNGee.

The demonstrated HetNet deployment model with small cells implemented below the rooftops and exploiting near-LOS radio propagation along the streets and natural building isolation, proved to be the main tool of the throughput/ capacity density increase in the access network. Performance of the developed Multi-Beam Antenna was tested in a real field scenario, matching the predicted figures and the requirements and proving to be an efficient way to increase capacity density in the backhauling network. Limited demonstration of MBA-MIMO in the Live Test showed the performance gain of up to 30% when applying MIMO processing across the two adjacent beams. Even more significant gain is expected when applying MIMO techniques and spatial multiplexing across all the beams of a Hub BS.

60 GHz PtP backhauling technology was tested in the Live Demo proving its exceptional performance, cost-efficiency and unique advantages for small cells backhauling in capacity-driven broadband wireless networks deployments. The Live Test proved that the proposed in-band backhauling solution, using the existing BWA eco-system, is feasible and addresses both: in-band backhauling performance optimization and system cost reduction, thanks to the economy of scale of the widely developed eco-system. The experimental results of the proposed L3-based network architecture were acceptable for proper system operation showing no functional or significant system performance degradation. The proposed temporal separation between Access and Backhaul radio frames proved to be operational and efficient solution, significantly improving system performance. Joint use of Licensed and LE spectrum for the Backhauling Tier was successfully demonstrated by presenting Backhauling Multi-link Aggregation functionality where PtMP BWA system in licensed spectrum (in-band backhauling) was integrated with 60 GHz LE spectrum ultra high capacity PtP link.

Technology- and industry-valuable conclusions were derived during the BuNGee Live Test deployment, demonstration and evaluation as summarized in Live Test Evaluation Report, identifying also the main technology gaps and recommending the future potential investigation areas of high interest.

BuNGee extensive dissemination activities included more than 90 scientific publications, papers and presentations in the selected public conferences, workshops and significant events in front of the international wireless community specialist audiences.

BuNGee had significant impact on industrial standardization by its contributions to ETSI standard - ETSI TR 101 534 was drafted based solely on the BuNGee contributions. In addition, a substantial contribution was made to ETSI draft TR 101 589. BuNGee members were also active in WiMAX Forum promoting BuNGee ideas and technological achievements and followed up 3GPP activities.

BuNGee public website was established and managed, propelling the project ideas and activities:
http://www.ict-bungee.eu/

Commercial exploitation of the BuNGee results is planned by the BuNGee industrial members and includes: deployment of BuNGee HetNet models and technical ideas in the real commercial Mobile and Fixed BWA projects, development and commercial launch of the small form-factor (Pico-) BSs, promoting BuNGee-developed Multi-Beam Antenna for PtMP feeding hubs and Fixed BWA applications, promoting BuNGee-developed in-band backhauling solutions, development and commercialization of ultra-high capacity low-cost mmWave backhauling technology, commercializing FPGA-based MIMO transceivers technology with limited feedback. BuNGee academic partners promote the project-developed ideas via academic work, scientific publications and participation in the relevant conferences and events. BuNGee consortium members achieved most of the technological objectives set for the project, showed exceptional cooperation and demonstrated the accomplishment of their specific goals. BuNGee project leveraged the existing partnerships between the consortium members and other stakeholders - industrial companies, research laboratories and official institutions, promoting the project results and technology exploitation opportunities. Participation in the project stimulated valuable knowledge accumulation and transfer between the consortium members and IPR generation activities.

We expect the project to have significant impact on the European and world wide society. The multi-tier deployment approach and the technology measures, elaborated in the project, will allow the wireless operators worldwide to enhance capacity and coverage, thus providing seamless broadband experience for wireless mobile customers, opening new worlds of user experience, creating new types of connected devices (including human- and machine-operated devices) and finally improving operator’s business model. The market for exploiting the technology developed in this project is predicted in acceleration and the build-up to 2015, when BuNGee technology might become essential for addressing the mobile wireless data traffic growth demand. BuNGee has good chances to be a pre-commercial development reference platform and to be the reference technical model in future leading R&D projects.