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BuNGee Exploitation Action Plan

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Executive Summary

The BuNGee (Beyond Next Generation mobile broadband wireless networks) FP7 research project was established to address, in a cost efficient way, throughput densities substantially higher than available with today's systems – targeting an ambitious goal of 1 Gbps/km^2 cell throughput density.

The project addressed this goal by a combination of techniques: use of below-rooftop access base stations and a unique feeding architecture using a combination of licensed in-band spectrum and out-of-band license-exempt spectrum. Very high capacity feeding hubs with high-order spatial reuse were created using multi-beam antennas and advanced MIMO techniques, as well as use of millimetre wave radio links. Cognitive/ docitive techniques were developed for self-organization and optimized resource utilization in the radio and feeding networks.

BuNGee consortium members achieved most of the technological objectives set for the project, showed exceptional cooperation and demonstrated the accomplishment of their specific goals.

Live Demonstration of the BuNGee target technology was performed by consortium members, incorporating the main system components prototyped by the BuNGee partners:

- BuNGee Multi-beam antenna for Hub Base Station, designed by CASMA;
- Ultra high capacity mmWave 60 GHz point-to-point link, designed by SIKLU;
- Hub & Access BS prototypes developed by Alvarion and implementing 4G mobile broadband wireless access and broadband wireless backhauling networks with WiMAX/ IEEE 802.16 suite.

The high capacity radio cell prototype was implemented in the real urban cellular environment of Tel Aviv city, demonstrating close-to-the-target equivalent system throughput density of ~840 Mbps/km^2 in a real-field capacity-oriented deployment for outdoor users. This Live Demonstration proved viability and measured the effectiveness of the concepts developed in BuNGee. Additionally, CTTC performed design, implementation & validation of a real-time FPGA-based MIMO mobile WiMAX transceivers with limited feedback using the GEDOMIS® testbed, presenting significant progress in validation of MIMO limited feedback concepts developed in BuNGee.

The main objective of this deliverable is to describe the BuNGee project results direct or indirect exploitation action plan. The document defines a general strategy for the use of the BuNGee project results. Based on the obtained results, the information gathered from the technological and market developments, application scenarios and business cases is studied.

The report summarises the scope and objectives of the project and then provides an overview of the project outcomes. These project outcomes are classified in four categories: internal results, results relevant for dissemination, results relevant for standardisation, and results relevant for commercial exploitation. For each outcome, one or more leader(s) have been identified. Each outcome is defined, taking into account in particular: its status and distinctive features with respect to state-of-the-art solutions, the expected additional steps required for exploitation if relevant, the market segments that could potentially be addressed, and possible IPR issues to be taken into account.

The following BuNGee scientific and technological outcomes may be highlighted:

- BuNGee multi-tier architecture for capacity-oriented broadband wireless access networks, addressing the main elements of the BuNGee project and defining the BuNGee system.
- BuNGee multi-dimensional radio channel modelling and design of ray-tracing simulation toolset.
- BuNGee Multi-beam Antenna research based on a 8 x 8 antenna array and fixed phase-shifting Butler matrix.
- Research in advanced MIMO schemes, covering novel multi-beam assisted MIMO scheme (MBA-MIMO), design of MIMO with limited feedback, and the robust linear pre-coder design that minimizes the interference to the receivers explicitly taking into account quantization errors in the CSIT.
- Comparative analysis of PtP and PtMP backhauling technologies.
- BuNGee RRM & SON methods, algorithms and protocols design, including novel Cognitive & Docitive autonomous resource allocation and in-band backhauling RRM design.
- Modularized multi-layer system-level simulation toolkit and simulation of the selected BuNGee deployment scenarios.

The report then describes general context of BuNGee results exploitation, by providing more insights into the Mobile Broadband Wireless Access market and its dynamics. The current market situation is described as well as, drivers and market forecasts. Other sub-sections analyse specific target markets that are relevant for BuNGee:

- Mobile BWA Small Cells market segment,
- BWA PtmP mobile backhauling market segment.

The market for exploiting the technology developed in BuNGee is predicted to accelerate towards 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 also in future leading R&D projects.

In order to prepare a successful take up of BuNGee results in real applications, dissemination and, in particular, standardisation - are the keys. The report describes the effort of the consortium to promote BuNGee concepts and results in the relevant standardisation groups.

BuNGee had significant impact on industrial standardization by its contribution to ETSI standard - ETSI TR 101 534 was drafted based on the contributions submitted by the BuNGee partners and a substantial contribution was made to ETSI draft TR 101 589.

BuNGee project summary and scientific & technological outcomes were presented in a large number of scientific publications, presentations and technological and industrial events.

The report further provides an overview of the typical business cases for BuNGee results. Furthermore, for the most promising business cases, a detailed analysis is provided. This included:

- BuNGee Architecture - HetNet/ Small Cells deployment for Mobile BWA;
- Multi-Beam Antenna for Broadband Wireless Access networks;
- mmWave links for mobile backhauling;
- BeMImoMAX – FPGA HDL WiMAX MIMO Reference Design.

Finally, the exploitation strategy of each individual partner is described. Commercial exploitation of the BuNGee results is planned by the BuNGee industrial members (Alvarion, CASMA, SIKLU and Thales Communication & Security) and CTTC:

- Applying BuNGee HetNet deployment models and technical ideas in the real commercial Mobile and Fixed BWA deployments.
- Developing and starting commercial launch of the small form-factor Base Stations (Compact-/ Pico- BS) leveraging BuNGee-developed algorithms and mechanisms.
- Developing and promoting the BuNGee-proposed and validated in-band backhauling solution, based on the existing BWA eco-system.
- Promoting BuNGee-developed Multi-Beam Antenna for PtMP feeding hubs and Fixed Broadband Wireless Access applications.
- Developing and commercializing ultra-high capacity low-cost mmWave backhauling technology (in Licensed and LE spectrum).
- Commercializing FPGA-based MIMO transceivers technology with limited feedback - FPGA-ready HDL WiMAX MIMO reference design (BeMImoMAX).

BuNGee academic partners (UoY, CTTC and UCL) promote the project-developed ideas via academic work, scientific publications and participation in the relevant conferences and events.

PTC, the Polish telecom operator, is evaluating, analyzing and disseminating the BuNGee results, looking forward for industry-adaptation of the developed concepts. PTC believes that the BuNGee project results will find application in the processes of network planning, evaluation of network technologies to be deployed in the future and network evolution financial planning.

The 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.

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List of Acronyms

Abbreviation / acronym	Description
3GPP	3rd Generation Partnership Project
4G	4th Generation
ABS	Access BS
ART	Above Roof Top
ASN	Access Service Network
BHSS	Backhaul Subscriber Station
BRT	Below Roof Top
BS	Base Station
BTS	Base transceiver station. Equivalent to BS.
BW	Bandwidth
BWA	Broadband Wireless Access
BuNGee	Beyond Next Generation Mobile Broadband
CPE	Customer Premises Equipment
EPC	Evolved Packet Core (3GPP)
HBS	Hub Base Station
HW	Hardware
IC	Integrated Circuit
IDU	In-Door Unit
LE	License Exempt (frequency band)
LOS	Line of sight
LTE	Long Term Evolution
MBA-MIMO	Multi-beam assisted MIMO
MIMO	Multiple Input Multiple Output
MS	Mobile Station
ODU	Out-Door Unit
P2P, PtP	Point to Point (radio link)
PtMP	Point to Multi Point (radio links)
PHY	Physical Layer
RAN	Radio Access Network
RNP	Radio Network Planning
RRH	Remote Radio Head
RRM	Radio Resource Management
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RS	Relay Station
SDR	Software Defined Radio
SON	Self Organizing Network
SW	Software
TDD	Time Division Duplex
TDM	Time Division Multiplexing
Tx	Transmitter
UE	User Equipment
UL	Uplink
WiMAX	Worldwide Interoperability for Microwave Access

1 Introduction

The ultimate goal of the BuNGee project was investigation of Mobile Broadband Radio Access Network deployment principles, which enable the achievement of a *Throughput Density of 1 Gbps/ km^2 in a cost-efficient way*. BuNGee considers the deployment concepts that must become the enablers of IMT-Advanced and future mobile broadband wireless access networks.

The main technology investigation areas in the project were:

- Joint design of access and backhaul networks using heterogeneous radio elements, licensed and license-exempt (LE) spectrum to achieve maximum system capacity and QoS, such as:
  - In-band backhauling systems,
  - LE spectrum ultra-high capacity backhauling (mmWave links),
  - Integrated deployment of point-to-multipoint and point-to-point backhauling systems;
- Design of innovative antenna technologies, such as e.g. multiple fixed beam antennas, tailored to urban ultra-high capacity needs;
- Ultra-dense below-rooftop radio access network deployment, exploiting natural radio isolation of the urban environment (street buildings, etc.);
- Advanced MIMO and interference mitigation techniques tailored to the BuNGee deployment model, such as e.g. Multi-Beam assisted MIMO;
- BuNGee-specific Radio Channel modeling (in Backhaul and Access links) and system simulations;
- Innovative RRM and Self-Organization techniques design.

Most of the technological objectives set for the project were achieved by the BuNGee consortium members. Finally, project implemented the Live Demonstration of BuNGee target technology, presenting the high capacity radio cell prototype achieving close-to-target equivalent system throughput density of ~840 Mbps/ km^2 in a real-field capacity-oriented deployment in a dense urban area of Tel Aviv city [10].

The purpose of the document is to describe the dissemination and exploitation strategy of the project results by the project consortium members.

Section 2 of the document presents the BuNGee brief project summary following the description of the measurable project outcomes in the Section 3.

The project outcomes are classified according to their relevance (internal or external), applicability for dissemination and standardization activities and their exploitation impact.

Section 4 describes the state of the Mobile Broadband Wireless Access market and its dynamics and provides the market analysis for the selected BuNGee potential target market segments:

- Mobile BWA Small Cells market segment;
- BWA for fixed operators (utilizing BuNGee-developed multi-beam antenna);
- In-band backhauling (Point-to-Multipoint backhauling);
- Mobile BWA eco-system market segments, such as FPGA-based MIMO transceivers with limited feedback;
- Point-to-Point mmWave backhauling in licensed and license exempt spectrums.

This section also provides mapping of BuNGee outcomes into the potential target market segments.

Section 0 presents BuNGee standardization and dissemination activities performed during the project.

Section 6 analyzes the selected Business Cases applicable for BuNGee project outcomes, including:

- BuNGee Architecture - HetNet/ Small Cells deployment for Mobile BWA;
- Multi-Beam Antenna for Broadband Wireless Access networks;
- mmWave links for mobile backhauling;
- BeMImoMAX – FPGA HDL WiMAX MIMO Reference Design.

Section 7 presents exploitation activities of the project results by the individual industrial and academic partners.

Finally, Section 8 summarizes and draws the conclusions for BuNGee project exploitation results.

2 Project summary

BuNGee was established to address, in a cost efficient way, throughput densities substantially higher than available with today's systems. 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 demand for wireless broadband access is the highest, thereby seriously jeopardizing the wide scale uptake of IMT-Advanced technologies.

BuNGee targets dramatic improvement of the overall infrastructure capacity density of the mobile network by an order of magnitude (10x) 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. Such an ambitious requirement for capacity density is driven mainly by urban areas where the number of users per square kilometre and mobile data usage factor is expected to grow.

To achieve these goals, BuNGee invoked 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.

Realising 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 networks 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. Referring to the BuNGee architecture, it includes heterogeneous design of Hub BS (HBS) and Access BS (ABS) serving correspondingly backhauling and access links and Mobile Stations (MS), served by HBS and ABS.

The architecture makes use of the un-licensed spectrum for 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 performed 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 targeted development of 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-organising networks.

The cost consideration was an important element of the design. Thanks to the "below rooftops" deployment paradigm, BuNGee uses small (Pico-factor) outdoor Access Base Stations. The cost reduction is achieved by:

- Much lower transmission power for the ABSs itself;
- Avoidance of the costly roof leasing, as the deployment may use electricity poles, street lights, etc.;
- In-band backhauling approach relaxing backhauling requirements;
- Effective usage of license-exempt spectrum for the feeding link.

Cognitive radio principles were extensively used in maximizing the system capacity. This required 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 un-licensed spectrum based on traffic requirements (QoS, data rates). The un-licensed spectrum is used according to its propagation characteristics, bandwidth and interference levels. Based on European allocations for un-licensed spectrum, 5GHz and 60GHz are considered for backhauling. The fixed/nomadic usage of these frequencies and the multi-beam assisted MIMO made possible interference cancellation at the BS receiver.

The ultimate BuNGee goal was to prove feasibility of mobile broadband wireless access network deployment with target throughput density of 1 Gbps/ km^2 via simulations and system demonstration in the Live Test.

The project S&T Objectives were:

- Design of High-Capacity 4G Mobile Network that is Cost-, Spectrum- and Energy- efficient;
- Novel mobile Radio Access Network Architecture based on the joint 2-tier Backhaul and Access networks design;
- Innovative Usage of Licensed, Unlicensed and Unused Radio Spectrum;
- Exploring ultra-dense below-rooftop deployment of small cells in the Access Tier RAN;
- Dynamic Channel Modelling and Estimation considering BuNGee-specifics in Backhaul and Access Tiers;
- Design of unique feeding architecture using a combination of licensed in-band spectrum and out-of-band license-exempt spectrum:
    - Very high capacity feeding hubs with high-order spatial and spectral reuse;
    - innovative antenna technology - Multi-Beam Antenna concept, tailored to urban high capacity needs;
    - In-band backhauling;
    - Out-of-band LE ultra high capacity backhauling in mmWave spectrum;
    - Advanced MIMO techniques exploring spatial dimension of Hub Base Station – Multi-Beam Assisted MIMO, Network MIMO;
- Development of Advanced RRM techniques for interference management and reduced management complexity and SON mechanisms:
    - Autonomous radio resource assignment based on Cognitive/ Docitive techniques for self-organization and optimized resource utilization;
    - Cooperative technologies for MIMO operations and resource assignment at a Base Station;
    - Frame structures for in-band backhauling;
    - Network technologies;
- Deployment of the System Live Test as a proof of concept

To achieve the aforementioned objectives, BuNGee consortium work was organized as six Work Packages with interactions between them:

- WP1 - Requirements and BuNGee architecture,
- WP2 - Enabling Beyond Next-Generation Link Capacity,
- WP3 – RRM and Joint Design of Access & Backhaul,

- WP4 - Proof of concept,
- WP5 - Dissemination and Exploitation,
- WP6 - Project Management.

BuNGee consortium members achieved most of the technological objectives set for the project, showed exceptional cooperation and demonstrated the accomplishment of their specific goals. Among BuNGee technological achievements the following ones may be highlighted:

- Ultra-high capacity innovative wireless RAN Architecture has been designed based on the user and business requirements specified in the WP1.
- BuNGee developed ray-tracing and deployment capacity simulation tools for theoretical and experimental validation. A number of deployment scenarios were tested providing valuable reference for the real field implementations.
- Collaborative, Networked and Multi-Beam Assisted MIMO models were evaluated. BuNGee developed the methodology for more accurately matching parameters of Truncated Shannon Bound to expected link throughput and stochastic version of TSB for use in MIMO links.
- BuNGee developed robust linear precoder designs that minimize the interference to the receivers, explicitly taking into account quantization errors in the CSIT. BuNGee validated the expected performance of such schemes for the specific channel models and architecture.
- BuNGee-specific RRM algorithms and protocol suite were designed addressing the cognitive/ docitive resource allocation mechanisms for self-organization and optimized resource utilization in the radio and feeding networks.

The Live Demonstration was the culmination of the BuNGee activities, which were preceded by system-level simulations, component prototyping, system planning, engineering and integration testing in Lab conditions. The Live Demo was planned to measure the effectiveness of the concepts developed in BuNGee by deploying a high capacity radio cell prototype targeting 1 Gbps/km^2 throughput density demonstration in the real urban cellular deployment scenario of Tel Aviv city.

Serving as the project proof-of-concept, the Live Demo incorporated the main system components prototyped by the BuNGee partners:

- BuNGee Multi-beam antenna for Hub Base Station, designed by CASMA as a part of BuNGee research;
- Ultra high capacity mmWave 60 GHz point-to-point link, designed by SIKLU;
- Hub & Access BS prototypes based on Alvarion commercial 4Motion platforms implementing 4G mobile broadband wireless access and broadband wireless backhauling networks with WiMAX/ IEEE 802.16 suite.

The BuNGee Live Demo System has been successfully deployed in the Tel Aviv industrial park area around ALV building, proving the ability to achieve BuNGee targeted throughput density. The high-level diagram presenting the BuNGee Live Demonstrator is shown in the figure below:

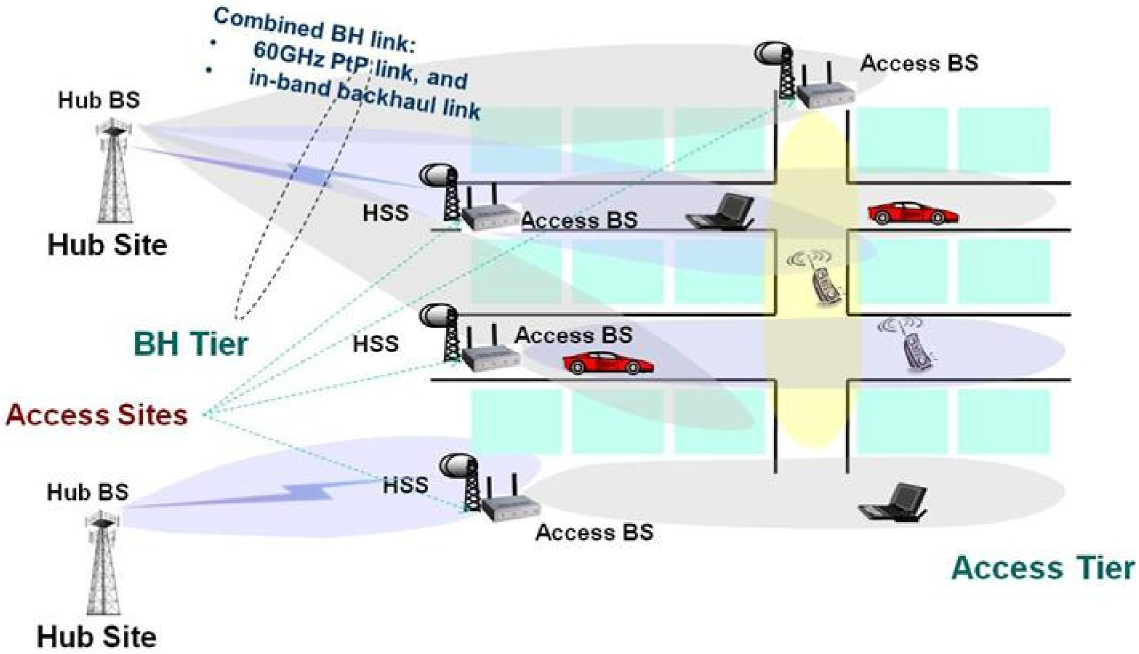


Figure 2-1: BuNGee Live Demonstrator diagram

Finally, the Live Test system clearly demonstrated close-to-target equivalent system throughput density of ~840 Mbps/ km^2 in a real-field capacity-oriented deployment in a dense urban area for outdoor users [10]. This experimental result also matches the results of system-level simulations. A number of scenarios were presented – including demonstration of in-band backhauling solution, multi-beam assisted MIMO evaluation, analysis of the natural building radio isolation in the below roof-top small cell deployment scenarios, etc.

Additionally, CTTC performed design, implementation & validation of a real-time FPGA-based MIMO mobile WiMAX transceivers with limited feedback using the GEDOMIS® testbed, presenting significant progress in validation of MIMO limited feedback concepts developed in BuNGee.

Summarizing the Live Demo results, BuNGee proves:

- HetNet deployment model, especially small cells installation below the roof-top leveraging the natural building isolation, ***proves to be the main drive for throughput/ capacity density***;
- Small cells backhauling represents the critical issue with both BuNGee feeding approaches – in-band backhauling and mmWave high capacity links, providing technically viable, economically cost-efficient and valuable solutions.
- Use of Multi-Beam Antenna proves to be an efficient way to increase capacity for the backhauling network or fixed/ portable deployments.
- Application of MIMO and resource allocation techniques across the beam domain promises significant performance gains.

Of prime importance in our mind is the planning of concrete actions to bring forward our wishes to contribute both in the public sharing of the consortium knowledge (*dissemination*) and the commercial exploitation and future use of the platforms that are built or brought in during the project life (*exploitation*).

BuNGee had an overwhelming contribution to ETSI standardisation, as the entire ETSI TR 101 534 [23] was drafted based solely on the contributions submitted by the BuNGee partners. In addition, a substantial contribution was made to ETSI draft TR 101 589.

BuNGee members performed extensive dissemination activities, having more than 90 publications, standardization activities, scientific publications, presentations at different technological events, two keynotes and workshop with ARTIST project as referred in section 5.2.

During the project, the BuNGee public website was managed, propelling the project ideas and activities.

Industrial Exploitation of BuNGee takes place by the BuNGee industrial members – Alvarion, CASMA, SIKLU and Thales Communications & Security.

We identified the following potential production areas:

1. Base Stations with “small cell” form-factor leveraging BuNGee developed algorithms and mechanisms – Compact BS or Pico-BS;
2. BuNGee-proposed and validated in-band backhauling solution leveraging the existing wireless BWA eco-system;
3. BuNGee multi-beam antenna for wireless small cells feeding and Fixed Broadband Wireless Access applications;
4. Ultra-high capacity mmWave backhauling technology (in Licensed and LE spectrum);
5. FPGA-based MIMO transceivers with limited feedback - FPGA-ready HDL WiMAX MIMO reference design (BeMImoMAX).

Alvarion and CASMA seek implementation of Multi-Beam Antenna in real operator’s environment targeting capacity-oriented deployments.

Alvarion promotes implementation of small cells in the real mobile BWA networks, leveraging BuNGee-evaluated HetNet concept of small cells deployment below roof-tops. Number of BuNGee-developed algorithms and protocol mechanisms is being implemented in the ALV commercial BWA platforms.

CTTC promotes licensing of the developed FPGA technology to Lyrtech Canada and further technology development (towards LTE) and commercialization.

SIKLU continues development and implementation of mmWave Backhauling technology for BWA operators.

BuNGee academic partners – UoY, CTTC and UCL, promote the project-developed ideas via the academic work, scientific publications and participation in the relevant conferences and events.

PTC, the Polish telecom operator, is evaluating, analyzing and disseminating the BuNGee results, looking forward for industry-adaptation of the developed concepts.

BuNGee members will continue to promote adaptation of BuNGee-developed advanced deployment concepts, interference management, MIMO, RRM and SON techniques.

3 Project outcomes

The following table provides an overview of the main outcomes of the BuNGee project and their intended use:

Table 3-1: BuNGee Outcomes

Outcome		From WP	Relevant for:			
			Internal use	Dissemination	Standardization	Exploitation
1	Overview of business and technical requirements for future next generation mobile broadband wireless access networks	WP1.1	V	V	V	
2	BuNGee Architecture	WP1.3	V	V	V	V
3	BuNGee multi-dimensional Channel Models	WP2.1	V	V		
4	Multi-Beam Antenna research for BuNGee architecture	WP2.2	V	V		V
5	Research of advanced MIMO schemes and interference cancellation/ mitigation techniques in BuNGee architecture, Multi-beam assisted MIMO design	WP2.3 WP3.2	V	V	V	V
6	Comparative analysis of backhauling technologies	WP2.4	V	V		
7	Cognitive/ Docitive RRM methods and protocols	WP3.1, WP3.2	V	V	V	
8	BuNGee SON mechanisms	WP3.1, WP3.2	V	V	V	V
9	Design of MIMO with limited feedback and FPGA-based MIMO transceivers prototyping activities	WP3.1 WP4	V	V	V	V
10	BuNGee In-band backhauling RRM and protocols design	WP3.1, WP3.2	V	V	V	V
11	BuNGee system level simulations	WP4.1	V	V		V
12	BuNGee Hub and Access BS prototyping	WP4.2	V	V		V
13	BuNGee Multi-Beam Antenna prototyping	WP4.2	V	V		V
14	BuNGee 60 GHz high-capacity backhauling link prototype	WP4.2	V	V		V
15	BuNGee Live Demonstrator of high capacity cell prototype	WP4.4	V	V		V

16	BuNGee public Web Site	WP5	V	V	V	
17	BuNGee ETSI technical report	WP5	V	V	V	

In the following part of this chapter the above listed main outcomes of the project are described in more detail according to a common format:

- *Description*: Explanation of expected outcome.
- *Status*: Status / readiness level of the outcome (e.g. model, prototype) at the end of the project. Distinctive features with respect to the state of the art / existing products / solutions and its potential impact.
- *Leader(s):* Beneficiaries responsible for achieving the described outcome.
- *Forecast*: Additional steps required (after the end of the project) to make the outcome exploitable in markets (and/or for further research, if envisaged). Description in which form (products, solutions, licences, …) the outcome could be exploited and for which application sectors. Estimated average time required to evolve from outcome to commercial exploitation. Potential or expected impact (qualified and, if possible, quantified).
- *IPRs*: IPRs measures taken or intended to be taken.

Table 3-2: Outcome 1 - Overview of business and technical requirements for future next generation mobile broadband wireless access networks

Description	The Report has been prepared based on publicly available market studies as well as on a series of interviews with telco experts and on PTC's owned statistics and its staff experience. The report describes the users' needs and expectations (QoS, service prices), usage characteristics (transmission requirement, time and special usage parameters) and then derives and forecasts the business opportunities. Business requirements formulated in the report strongly pertains to OPEX and CAPEX. A special economic tool has been also developed to analyse and compare cost of different network architecture deployment. It includes methodology of Total Cost of Ownership calculation based on operator experience and its operational practices. The tool was used in D1.1 to compare HSPA+ with BuNGee architecture costs, but it might be also used to analyse other architecture (e.g. WiMax).
Status	The user & business requirements were published in D.1.1 in M5 and then partially reviewed and referred in D1.2 and D1.3.
Leader(s)	PTC
Forecast	Based on the document structure, referenced include and the methodology proposed the requirements might be updated and refined according to the latest market report, forecasts and technology advancements.
IPRs	No IPR issues have been identified.

Table 3-3: Outcome 2 - BuNGee Architecture

Description	This outcome represents BuNGee deliverable D1.3 – Final BuNGee Architecture, addressing the main elements of the BuNGee project and defining the initial BuNGee system. Starting from the user and business requirements, the report describes the developed architecture, the lower level and higher level functional modules and prepares the protocol formats. Joint Access and Backhaul design principles, including in-band backhauling solution are defined. It describes BuNGee-developed antennas, including BuNGee Multi-Beam antenna for Hub BS and considers different radio propagation models for backhaul and access tiers. The main principles of the considered novel MIMO techniques, including multi-beam assisted MIMO and the important RRM and SON features are described. Special focus is given to Cognitive and Docitive frequency and power assignment features. On the deployment side, the

	selected deployment models are proposed. The performance of the proposed architecture, when using the below rooftop deployment model, is verified.
Status	The initial and final BuNGee architectures were described correspondingly in the deliverables D1.2 and D1.3. Final BuNGee architecture deliverable was published on M25 of the project.
Leader(s)	ALV, CTTC, CASMA, UoY, TCS, UCL, UTC, SIK, ART
Forecast	This document is an important step forward in defining the BuNGee system. It is further used as the baseline architecture for further BuNGee developments, especially BuNGee channel modelling, advanced MIMO schemes development, BuNGee RRM and protocols design, etc. The main highlights of BuNGee architecture were standardized in ETSI TR 101 534 report and implemented during the BuNGee high capacity cell prototype testing in the real field conditions in Tel Aviv urban area.
IPRs	No IPR issues have been identified.

Table 3-4: Outcome 3 - BuNGee multi-dimensional Channel Models

Description	In the context of BuNGee, which exploits many multi-dimensional properties of the wireless channel (MIMO, polarization, etc.) and relies on an aggressive frequency reuse, it is required that prediction models be capable to analyze propagation in depth, i.e. including polarization, delay and angular behavior of a channel, as well accurate modeling of interference. To this end, a 3-D ray-tracing tool was extended significantly beyond the state-of-the-art. Indeed, classic ray-tracing tools usually take into account line of sight propagation, specular reflection and diffraction, with penetration included when indoor propagation is considered. To BuNGee requirements in teems of deployment density and antenna beamwidth, it was necessary to implement propagation mechanisms such as penetration, polarized diffuse scattering and contributions by vegetation. These mechanisms enable to improve the prediction accuracy sometimes by 10 dB, which is significant in dense networks such as BuNGee.
Status	The above mechanisms have been implemented (C-language software) and experimentally validated, so the tool can be used to predict network coverage and SINR in all domains. This is the first tool capable of combining all these effects in a computationally efficient way.
Leader(s)	UCL
Forecast	The tool will be further improved to include complex obstacles. It is foreseen that ray-tracing tools will gain in importance in the future, given their excellent performance and the constant improvement of computer speeds.
IPRs	No IPR issues have been identified.

Table 3-5: Outcomes 4 and 13 - BuNGee Multi-beam Antenna research and prototyping

Description	CASMA has designed and developed a Hub Base Station slant dual-polar c17 dBi antenna intended to communicate with a cell of Hub Subscriber antennas within the BuNGee architecture. The antenna covers a 90˚ radius using multi-beam Butler matrix technology producing 6 beams each of 15˚, in both +45˚ and -45˚ polarisations working at a centre frequency of 3.5 GHz.
Status	The prototype has been developed in CASMA's labs and anechoic test chamber; completed and used in the live test in Tel Aviv. The measured results have been shared with other partners in the consortium and used for ray tracing analysis as part of the BuNGee project. The use of this multi-beam technology will have tremendous impact on the WiMAX and LTE etc. systems in the future.

Leader(s)	CASMA
Forecast	The antenna will be further refined with a view to mass production hopefully in late 2012 and sales into communications markets such as WiMAX and LTE looking to increase their data capacity with the minimum of antenna installations. The concept has been proven by the BuNGee live test so the potential is considerable – we believe the market could be for 1000+ antennas in 2013 - 15.
IPRs	No IPR issues have been identified.

Table 3-6: Outcome 5 - Research in advanced MIMO schemes

Description	• Novel multi-beam assisted MIMO (MBA-MIMO) schemes based on joint beam processing for use in wireless backhaul system with BuNGee multi-beam antenna • Channel state information transmission scheme and transceiver design framework based on channel Gram matrix quantization • Approach based on a generalized Truncated Shannon Bound for MIMO link throughput simulation within system level simulator • Evaluation of benefits of network-enabled MIMO in BuNGee network • Application of wireless network coding to enable resource sharing and capacity enhancement in wireless backhaul network
Status	A simplified MBA-MIMO scheme has been implemented in BuNGee live test; the transceiver design framework has been demonstrated in a hardware test-bed; the MIMO-TSB approach has been demonstrated with the BuNGee system-level simulator; wireless network coding applications are currently in simulation form only, but further development leading to a demonstrator is under way.
Leader(s)	UoY, CTTC
Forecast	A number of these aspects are likely to lead to commercialisation in collaboration with BuNGee industrial partners, and others
IPRs	Commercialisation is under way in some areas; IPR issues will be addressed as appropriate.

Table 3-7: Outcome 6 - Comparative analysis of backhauling technologies

Description	This outcome focused on technological and economical comparison between various technologies that may be used for dense cellular network backhauling. It includes a case study showing how mm-wave backhauling at 60GHz can be deployed in a real-live network.
Status	Report
Leader(s)	Siklu, Alvarion, PTC, CTTC, UCL
Forecast	BuNGee deliverable D2.4 was published on M23 and further used in the BuNGee Exploitation Report as a reference.
IPRs	No IPR issues have been identified.

Table 3-8: Outcome 7 - Cognitive & Docitive RRM Methods and Protocols

Description	The amount of elements to manage in the cost efficient high capacity BuNGee architecture is enormously high. Therefore, an autonomous SON RRM has been designed in the form of cognitive and docitive algorithms. Cognitive algorithms are

	known to learn the best resource allocation actions over time; docitive, in addition, facilitate the exchange of acquired knowledge among resource schedulers in different HBSs and ABs.
Status	The algorithms have been researched and their performance evaluated by means of extensive simulations. Furthermore, they have been standardized through latest ETSI BRAN standardization activities. The impact is thus potential enormous since it significantly simplifies the management of the increasingly complex and heterogeneous wireless networks of the future.
Leader(s)	CTTC, UoY, TCS
Forecast	The developed cognitive and docitive SON algorithms are ideal for companies with a native SON portfolio, such as www.edenrockcomm.com, www.beesonetworks.com, or http://airhopcomm-web.com/. It is also of enormous benefit to large players like Nokia, Orange, Vodafone, etc.
IPRs	CTTC has IPR in form of trade secrets and general knowledge in general about this topic. There are no patents so far.

Table 3-9: Outcome 8 and 10 - BuNGee SON mechanisms, In-band backhauling RRM and protocols design

Description	This outcome represents BuNGee deliverables D3.1 and D3.2 addressing correspondingly BuNGee RRM design, SON mechanisms and the BuNGee protocol suite. BuNGee RRM design explores methods that may enable joint design for access and backhaul networks. These design methods cover both use of licensed and unlicensed spectrum for the access/ backhaul links, where an important consideration that underlines the design - is the issue of overall backhaul network capacity and QoS that may be achieved. One of the major methods explored is dynamic channel assignment based on cognitive radio protocols explored as means to use and manage the same spectrum for access and backhaul, while another method utilizes point-to-point links in 60GHz license free mm-wave spectrum. The second part of the D3.1 deliverable consists of the definition of the Radio-Resource-Management (RRM) and self-organization of the joint access/backhaul network. Under this definition it investigates spectrum sharing between the access and backhaul wireless networks, defines the spectrum sharing algorithms and the frequency planning solutions, characterizes the scheduling support of resource assignment and defines the resource management protocol. Finally, in terms of network architecture, the document defines heterogeneous backhauling architecture and suitable models for it, and reviews the issue of network recovery in under the heterogeneous architecture assumption. In the network architecture, the physical collocation implications of the backhaul and access network end-terminals are analyzed. BuNGee Protocol Suite (presented in D3.2) describes BuNGee System Control Plane design translating BuNGee-developed RRM architecture and RRM/ SON related features into the general procedures and message flows. The document presents BuNGee RRM architectures through Centralized and Distributed RRM design, support of Centralized Dynamic Resource assignment, Autonomous Distributed Cognitive Radio Dynamic Resource assignment, Cognitive and Docitive RRM techniques, advanced BuNGee-specific MIMO schemes, and finally - RAN SON related procedures such as Automatic Neighbours Discovery, Neighbours Data Synchronization, Automatic FFR regulation, etc. The outcome provides the generic protocol design including: the feature or operation logic description, algorithm definition, the message flow and the protocol description through general purpose primitives and information elements that may be further detailed into standard-based protocols.

Status	BuNGee Deliverable D3.1 was submitted on M17 and D3.2 on M26 of the project. The outcomes were used to provide contributions for ETSI draft TR 101 589 standardization activities.
Leader(s)	SIKLU, ALV, CTTC, TCS, UoY, ARTTIC/ M. Goldhammer
Forecast	Some of the proposed and developed mechanisms were used in BuNGee Hub and Access BS prototyping and demonstrated in the BuNGee Live Test. Further commercialization of BuNGee developed RRM and SON mechanisms are expected. The developed algorithms and mechanisms have great potential to improve operation of commercial deployments and to increase efficiency in spectrum occupancy. The outcome results may be further exploited and enhanced by the industry players – such as wireless telecom vendors and research academic groups. BuNGee protocol suite primitives and message flows design may be further applied to the design of the specific broadband wireless access technology and may serve the basis for future contributions in standardization bodies of the SOTA wireless access technologies.
IPRs	No IPR issues have been identified.

Table 3-10: Outcome 9 - Design of MIMO with limited feedback and FPGA-based MIMO transceivers prototyping activities

Description	CTTC has designed, implemented and validated a real-time FPGA-based PHY-layer prototype based on mobile WiMAX. To this end, hardware and firmware developments for the GEDOMIS® testbed have been performed, which are mature enough for exploitation and commercialization activities (which are described in more detail below).
Status	CTTC has engaged in a professional marketing campaign through publications, leaflets, logo design, brochure and blog. This is to alert the academic and industrial communities about the availability of the developed hard and firmware. Response has been very good so far; e.g. a sales channel contract has been undersigned with Lyrtech R&D in Canada (see below for more details).
Leader(s)	CTTC
Forecast	The developed hard and firmware is an integral constituent to any company doing developing, testing and quick-prototyping of algorithms, protocols, hard/firmware for 4G and beyond networks. The successful relationship with Lyrtech R&D indicates that there is mature and addressable market.
IPRs	CTTC has IPR in form of trade secrets and general knowledge in general about this topic. One patent has been also filed which relates to some MIMO feedback operations.

Table 3-11: Outcome 11 - System-level simulator

Description	• Novel modularized two-layer system-level simulator to model both the BuNGee system and its surrounding environment.
	• Demonstrate the system capacity of BuNGee systems
	• Modularized structure to maximize the flexibility and the adaptivity of the simulator
	• Take into account key innovations of BuNGee:
	  • Dual-hop architecture
	  • Multi-beam directional antenna
	  • BuNGee Channel Model
	  • Advanced BuNGee MIMO techniques

	• Advanced RRM techniques
Status	The first system-level simulator tailored for the dual-hop BuNGee system. A number of beyond the state of the art techniques have been incorporated in to the system-level simulator, making the simulator different from other simulation models.
Leader(s)	UoY
Forecast	The system-level simulator is available internally to quantify the performance of key research areas addressed in BuNGee and their impact on the wider system environment, e.g. cognitive resource management, BuNGee MIMO techniques, Antenna amplitude tapering. It potentially can further contribute to other cognitive radio based FP7 projects.
IPRs	No IPR issues have been identified.

Table 3-12: Outcome 12 - BuNGee Hub and Access BS prototyping

Description	To measure the effectiveness and superiority of the BuNGee developed concepts, a high capacity radio cell prototype was built. The prototype was targeting 1 Gbps/Km^2 throughput density demonstration in the BuNGee Live Demo and served as the ultimate BuNGee proof-of-concept in real urban cellular deployment scenarios. The Hub and Access BS prototypes were developed based on Alvarion commercial 4Motion platforms implementing 4G mobile broadband wireless access and broadband wireless backhauling networks with WiMAX/ IEEE 802.16 suite. It implemented BuNGee developed architecture and some of the BuNGee developed mechanisms.
Status	The prototype of Hub and Access BS was developed in Alvarion's labs and further integrated with other prototypes provided by BuNGee partners – multi-beam antenna by CASMA and 60 GHz point-to-point backhauling link by Siklu. It was finally used in the BuNGee Live Demonstration in Tel Aviv. Number of demonstration scenarios presenting BuNGee achievements in the area of architecture, deployment model, protocols and mechanisms were prepared. The Hub and Access BS prototyping and System Level Integration activities are described correspondingly in the BuNGee deliverables D4.2.3 and D4.3.
Leader(s)	ALV
Forecast	Alvarion uses BreezeMax 4Motion and Compact product families for real field commercial deployments. BuNGee project provided significant boost and established confidence in the BuNGee-developed innovative architecture, deployment models and mechanisms.
IPRs	No IPR issues have been identified.

Table 3-13: Outcome 14 - BuNGee 60 GHz high-capacity backhauling link prototype

Description	BuNGee 60 GHz high-capacity backhauling link prototype
Status	Prototype
Leader(s)	SIKLU
Forecast	Siklu currently designs a commercial 60GHz backhaul product which is an ultra-small, all-outdoor point-to-point backhaul solution. The product is targeted at the emerging small cell market. The 60GHz backhaul technology enables rapid deployment anywhere, from street lamps to rooftops. Operating in the 57-66 GHz license-exempt band, the product is expected to be a low-cost backhaul solution, yet will be able to support gigabit per second throughput.

IPRs	BuNGee 60 GHz high-capacity backhauling link prototype

Table 3-14: Outcome 15 - BuNGee Live Demonstrator of high capacity cell prototype

Description	The BuNGee Live Demo was planned to measure the effectiveness of the concepts developed in BuNGee by deploying a high capacity radio cell prototype targeting 1 Gbps/Km^2 throughput density demonstration in the real urban cellular deployment scenario of Tel Aviv city. Serving as the project proof-of-concept, the Live Demo incorporated the main system components prototyped by the BuNGee partners: • BuNGee Multi-beam antenna for Hub Base Station, designed by CASMA as a part of BuNGee research; • Ultra high capacity mmWave 60 GHz point-to-point link, designed by SIKLU; • Hub & Access BS prototypes based on Alvarion commercial 4Motion platforms implementing 4G mobile broadband wireless access and broadband wireless backhauling networks with WiMAX/ IEEE 802.16 suite. Additionally, CTTC performed design, implementation & validation of a real-time FPGA-based MIMO mobile WiMAX transceivers with limited feedback using the GEDOMIS® testbed, presenting significant progress in validation of MIMO limited feedback concepts developed in BuNGee.
Status	The Live Demo was the culmination of the BuNGee WP-4 activities, which were preceded by system-level simulations, component prototyping, system planning, engineering and integration testing in Lab conditions, and showed exceptional cooperation of the Partners involved and demonstrated the accomplishment of their specific goals. Finally, the Live Test system clearly demonstrated close-to-target equivalent system throughput density of ~840 Mbps/ km^2 in a real field capacity-oriented deployment in a dense urban area for outdoor users. This result also matches the results of system-level simulations. Other demonstrated scenarios included: ▪ The elements of the BuNGee Architecture, protocols and algorithms; ▪ Below-rooftop outdoor deployments of a high density grid of access Base Stations, exploiting buildings isolation and near-LOS radio propagation along the streets to increase both the frequency reuse and the system capacity in a given area; ▪ BuNGee-developed high capacity wireless backhauling concepts including use of multi-beam antenna, innovative in-band backhauling schemes, ultra high-capacity mmWave links, joint use of licensed and license-exempt spectrums; ▪ Advanced MIMO schemes and interference mitigation techniques.
Leader(s)	ALV, CASMA, SIKLU, CTTC
Forecast	The concepts, features and algorithms developed by BuNGee and demonstrated during the Live Test are highly relevant to the broadband wireless communication industry and society. Analysis of the Live Demo testing and measurements results led to some industry-useful conclusions presented in the BuNGee deliverable D4.4. Specifically, the following developments may be highlighted: • Multi-beam antenna and the associated deployment concept targeting high-capacity fixed broadband wireless access networks. • The algorithms developed proving superiority of MIMO and interference mitigation/ cancellation techniques application across beam/ space domain in the newly presented deployment concept. • The below rooftop small cell deployment concept in the Access Tier, exploiting near-LOS radio propagation conditions along the streets and natural building isolation.

	• A novel in-band backhauling solution leveraging the existing wireless eco-system and providing a viable solution for small cell backhauling, especially at the initial stages of system deployment. • Ultra-high capacity mmWave backhauling links, providing the ultimate high performance and cost-efficient backhauling solution, suitable for small cell deployment topologies. • High level of integration between the backhauling and access tiers of the developed BuNGee architecture and SON features reducing the operational costs and improving overall system manageability. Alvarion will use the achieved results for deployment of next generation Mobile BWA solutions. Based on the identified technology gaps, Alvarion will promote further technology researches, developments and standardization activities.
IPRs	No IPR issues have been identified.

Table 3-15: Outcome 16 - BuNGee public Web Site

Description	The BuNGee website is located at http://www.ict-bungee.eu/ BuNGee's website constitutes one of the main communication channels within the project's Dissemination Plan. It provides complete external visibility as it contains general information on project goals, scope, focus and work progress, as well as on consortium partners. Moreover, it is used to share information (news, events, brochures, etc.) produced throughout the project. It consists of static data, which shall remain relatively unchanged throughout the dissemination phase of the project, and dynamic data, which requires constant updating. This updating shall be coordinated by the project's dissemination leader - ARTTIC. BuNGee's website is compliant with the FP7 Guidelines for Communication on Projects.
Status	The website is active and continuously updated
Leader(s)	ARTTIC
Forecast	The website will be offline within the few months after the end of the project, since no resources are available to its maintenance.
IPRs	No IPR issues have been identified.

Table 3-16: Outcome 17 - ETSI technical report

Description	The Report summarises the contribution of the BuNGee project to standardisation in ETSI BRAN and IEEE 802.16n and justifies the lack of contributions to ETSI TM4 and 3GPP. BuNGee had an overwhelming contribution to ETSI standardisation, as the entire ETSI TR 101 534 was drafted based solely on the contributions submitted by the BuNGee partners and reflecting the BuNGee research results. In addition, a substantial contribution has been made to the ETSI draft TR 101 589. BuNGee standardisation in ETSI confirms the conclusions of the Future Networks: Report of the Future Networks 7th FP7 Concertation Plenary Meeting, Brussels, 10 February 2011, showing that even the STREP projects can bring a substantial contribution to the ETSI standardisation.
Status	The contribution BRAN(12)000013 was approved for publication, as final draft of TR 101 534, by the HiperMAN Working Group and afterwards by the BRAN Plenary. It followed the interactions with the BRAN ETSI Officer and the editHelp staff, asking a small number of clarifications. The answers were prepared by the ETSI Rapporteur (Mariana Goldhamer) in collaboration with CTTC. Finally, the Rapporteur was announced that the standard was published on March 26, 2012. **The standard can be downloaded here**:

	http://www.etsi.org/deliver/etsi_tr/101500_101599/101534/01.01.01_60/tr_101534v010101p.pdf Based on a serious technical assessment, it had been found that there was no need for the TM4 standardisation, as the multi-beam antenna developed in BuNGee is already covered by ETSI type-compliance standards.
Leader(s)	ARTTIC
Forecast	N/A
IPRs	No IPR issues have been identified.

4 Mobile Broadband Wireless Access Market description

With more than 5.75 billion mobile devices in service across the globe - including 5.2 billion Global System for Mobile Communications/ Long Term Evolution (GSM-LTE) devices - mobile telephony is the most dominant form of communications on the planet. Mobile devices are stoking a dramatic and unprecedented transformation in personal communications and Internet access. And wireless technology is expanding the concept of mobility and connectivity beyond the traditional phone. The opportunity for operators and their vendor partners is not just in increasing voice and data subscribers, but also in connecting every facet of a person's technology world.

The main technologies enabling Mobile wireless communications were developed by 3GPP, 3GPP2 and IEEE/ WiMAX Forum standardization bodies with clear dominance by 3GPP. According to 4G Americas, more than 800 operators around the globe have chosen to use 3GPP networks, creating 5.2 billion connections (90 percent of the global cellular market).

Source: Rysavy Research, Mobile Broadband Explosion, September 2011 and 4G Americas, July 2011

Technology Name	Type	Characteristics	Typical Downlink Speed	Typical Uplink Speed	Network Deployments (as of July 2011)
GSM	TDMA	Most widely deployed cellular technology in the world. Provides voice and data service via GPRS/EDGE.	16 to 85 Kbps	8 to 85 Kbps	More than 800 in 219 countries
EDGE	TDMA	Data service for GSM networks. An enhancement to original GSM data service called GPRS.	70 to 135 Kbps	70 to 135 Kbps	More than 545 in 198 countries
HSPA*	CDMA	Data service for UMTS networks. An enhancement to original UMTS data service.	1 to 4 Mbps	500 Kbps to 2 Mbps	More than 400 in 157 countries
HSPA+	CDMA	Evolution of HSPA in various stages to increase throughput and capacity and to lower latency.	1.9 to 8.8 Mbps (in 5/5 MHz)	1 to 4 Mbps (in 5/5 MHz)	143 in 74 countries
LTE	OFDMA	New radio interface that can use wide radio channels and deliver extremely high throughput rates. All communications handled in IP domain.	6.5 to 26.3 Mbps in 10/10 MHz	6 to 13 Mbps in 10/10 MHz	25 in 17 countries

*HSPA and HSPA+ throughput rates are for a 5 + 5 MHz deployment

Figure 4-1: 3GPP family of Technologies

The set of 3GPP technologies provides various options for connected device solutions, depending on cost, bandwidth and latency or coverage requirements:

Source: Rysavy Research, Mobile Broadband Explosion, September 2011, and Yankee Group, 2011

Technology Name	Typical Downlink Speed	Typical Uplink Speed	Latency (Milliseconds)	Yankee Group Estimate Relative Average Module Pricing (X=100%-LTE Module)	Sample Use Cases
GSM/GPRS	16 to 85 Kbps	8 to 85 Kbps	700 ms	.18X	Parking meters, container tracking
EDGE	70 to 135 Kbps	70 to 135 Kbps	300 to 600 ms	.25X	Consumer and fleet telematics
HSPA*	1 to 4 Mbps	500 Kbps to 2 Mbps	100 to 125 ms	.35X	E-readers, smart meters
HSPA+	1.9 to 8.8 Mbps	1 to 4 Mbps	<50 ms	.75X	Video surveillance, interactive kiosk
LTE	6.5 to 26.3 Mbps in 10/10 MHz	6 to 13 Mbps in 10/10 MHz	10 ms	X	Video surveillance, doctor/patient consultations, digital signage, tablets

Figure 4-2: 3GPP Technologies relative cost estimations

Recent emerging technologies for 4th generation of Mobile Broadband Wireless Access were:

- taking the evolutionary path 3GPP LTE technology, and
- emerging WiMAX technology defined by IEEE and WiMAX Forum.

Both technologies pretended to satisfy IMT-Advanced requirements (LTE-Advanced and WiMAX-2). Observing the recent market dynamics, LTE becomes the dominant mobile broadband wireless access technology with 100s cellular operators worldwide having announced their plans to deploy it, while WiMAX is experiencing gradual decline and expanding mainly in fixed broadband wireless access, backhauling and vertical market segments.

While some carriers (e.g. Verizon) have already started LTE deployment, industry analysts expect to see the bulk of operators launching with LTE in 2013 and 2014. The benefits of 4G and LTE are significant and when 4G access equipment becomes more available and penetrates various consumer devices, 4G mobile broadband will prove to be disruptive technology that changes how we communicate, work, entertain, and perform day-to-day tasks

The BuNGee research project is looking at achieving, in a cost efficient way, throughput densities substantially higher than available with today's systems. State-of-the-art LTE and WiMAX mobile wireless access technologies support a mere 100Mbps/Km^2 in ordinary cellular deployments. BuNGee targets throughput levels of at least 1 Gbps/km^2. The project addresses this goal by a combination of techniques in ultra-high capacity design: use of below-rooftop access base stations (small cell form factor) and a unique feeding architecture using a combination of licensed in-band spectrum and out-of-band license exempt spectrum. Very high capacity feeding hubs with high-order spatial reuse are created using novel BuNGee multi-beam antenna technology and advanced MIMO techniques, as well as use of millimeter wave radio links. Cognitive/ docitive techniques were developed for self-organization and optimized resource utilization in the radio and feeding networks.

BuNGee considers Mobile Broadband Wireless Access as the main target market for its developments, assuming market further segmentation into the following areas:

- Mobile BWA Small Cells market segment;
- BWA for fixed operators (utilizing multi-beam antenna);
- In-band backhauling (Point-to-Multipoint backhauling);
- Mobile BWA eco-system market segments – such as FPGA-based MIMO transceivers with limited feedback;
- Point-to-Point mmWave backhauling (in Licensed and LE spectrums).

Mapping between the BuNGee outcomes and the potential Mobile BWA market segments is presented in the table below:

Table 4-1: BuNGee Outcomes mapping into the potential market segments

Outcome	Description	Potential market segment
Outcome 1	*Overview of business and technical requirements for future next generation mobile broadband wireless access networks*	Mobile Broadband Wireless Access market
Outcome 2	*BuNGee Architecture*	Mobile Broadband Wireless Access market, Small Cells segment for Mobile BWA, PtmP Backhauling for mobile small cells, PtP Backhauling for mobile small cells
Outcome 3	*BuNGee multi-dimensional Channel Models*	Mobile Broadband Wireless Access market
Outcome 4	*Multi-Beam Antenna research for BuNGee architecture*	Mobile Broadband Wireless Access market, Fixed Broadband Wireless Access
Outcome 5	*Research of advanced MIMO schemes and interference cancellation/ mitigation techniques in BuNGee architecture, Multi-beam assisted MIMO design*	Mobile Broadband Wireless Access market, PtmP Backhauling for mobile small cells
Outcome 6	*Comparative analysis of backhauling technologies*	PtmP Backhauling for mobile small cells PtP Backhauling for mobile small cells
Outcome 7	*Cognitive/ Docitive RRM methods and protocols*	Mobile Broadband Wireless Access market, Small Cells segment for Mobile BWA
Outcome 8	*BuNGee SON mechanisms*	Mobile Broadband Wireless Access market, Small Cells segment for Mobile BWA
Outcome 9	*Design of MIMO with limited feedback and FPGA-based MIMO transceivers prototyping activities*	Mobile Broadband Wireless Access market, Small Cells segment for Mobile BWA
Outcome 10	*BuNGee In-band backhauling RRM and protocols design*	Small Cells segment for Mobile BWA, PtmP Backhauling for mobile small cells
Outcome 11	*BuNGee system level simulations*	Mobile Broadband Wireless Access market, Small Cells segment for Mobile BWA

Outcome 12	*BuNGee Hub and Access BS prototyping*	Mobile Broadband Wireless Access market, Small Cells segment for Mobile BWA
Outcome 13	*BuNGee Multi-Beam Antenna prototyping*	Mobile Broadband Wireless Access market, Fixed Broadband Wireless Access
Outcome 14	*BuNGee 60 GHz high-capacity backhauling link prototype*	PtP Backhauling for mobile small cells
Outcome 15	*BuNGee Live Demonstrator of high capacity cell prototype*	Mobile Broadband Wireless Access market
Outcome 16	*BuNGee public Web Site*	Mobile Broadband Wireless Access market, BWA for fixed operators, Small Cells segment for Mobile BWA, PtmP Backhauling for mobile small cells, PtP Backhauling for mobile small cells
Outcome 17	*BuNGee ETSI technical report*	Mobile Broadband Wireless Access market

Further subsections outline the current and forecasted mobile BWA market segments situation and dynamics.

4.1 Mobile Broadband Wireless Access market trends

Emerging wireless networking technologies and the ability to embed connectivity to these networks in virtually all types of devices are creating a new connected future. While the growth of Internet connectivity globally has been well documented, it was actually constrained by fixed broadband connectivity and a PC-centric worldview. That changed with the introduction of smartphones and 3G connectivity. But unleashing the true power of the Internet actually involved moving beyond even smartphones. The tremendous expansion and evolution of wireless networks combined with growing end-user demand for ubiquitous voice and data access has helped set the foundation for a new generation of smart mobile devices. Yankee Group predicts that a new segment of connected devices, including enterprise machine-to-machine (M2M) connections, tablets and e-readers, will grow to more than 800 million units by 2015 (refer to Figure 4-3).

But there is even greater potential beyond just these existing connected device segments. Some industry players, such as Ericsson and Intel, predict the connected device segment will reach 20-50 billion connections by 2020. It has already begun by combining user demand, network evolution and an ecosystem that is breaking down barriers.

Source: Yankee Group, 2011

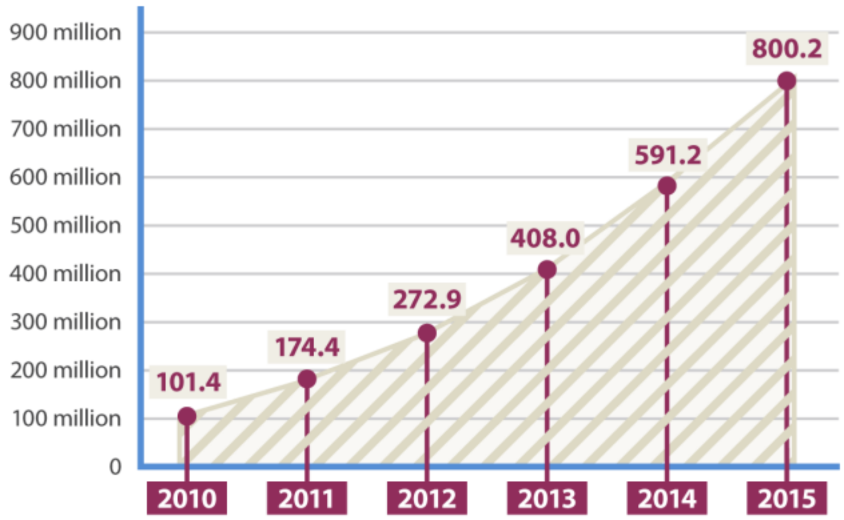


Figure 4-3: Total Global Cellular Connected Devices, 2010-2015

As a result of a timely combination of high-quality 3G networks, compelling services, intuitive handsets such as the Apple iPhone and attractive price points, the mobile market will expanding rapidly. According to Infonetics [18], mobile data traffic is expected to rise rapidly, with around one billion mobile broadband users coming online by 2013.

Different types of the devices and various usage scenarios may be considered as presented in the following subsections.

4.1.1 Connected Devices

The world of connected devices is broad and spans handsets, e-readers, connected digital signs, smart meters and fleet tracking devices.

Yankee Group suggests classifying them into three groups: enterprise M2M devices, consumer M2M devices and connected computing devices:

- Enterprise M2M devices – service specific business needs Including fleet telematics devices, digital signs and smart grid terminals;
- Consumer M2M devices - includes consumer tracking and navigation devices, e-readers and mHealth devices that run applications for consumers;
- Connected computing devices, which are built around multimedia. including computing devices such as tablets, laptops and smartphones that help consumers browse the Web, listen to music and watch video.

Connected devices across all three categories will continue to proliferate, driven by accelerating evolution of next-generation wireless networks, advances in wireless modules and a rapidly expanding eco-system of solution providers.

Connectivity has transformed the way consumers and enterprises interact with their devices and assets. The following trends have led industry players and end-users across the value chain toward embedded connectivity:

- Consumers demand a compelling customer experience;
- Consumers demand connectivity at all times;
- Device manufacturers can target new segments of the consumer population;
- Network providers can monetize new services;
- Businesses can gain a competitive advantage over their peers.

Source: Yankee Group, 2011

	Enterprise M2M	Consumer M2M	Computing Devices
Applications and Content	Enterprise applications Process-specific Machine interaction	Consumer applications Single-application Human interaction	Computing-oriented Rich multimedia Human interaction
Device Hardware	Thin clients Significant processing in the cloud	Thin clients Processor light or processing in the cloud	Thick clients Processor-heavy
Network Connectivity	Narrowband - broadband Batch to real-time	Narrowband - broadband Batch to real-time	Broadband Real-time
Examples	Fleet telematics Digital signage Smart grid	E-readers Tracking devices mHealth	Tablets Smartphones Laptops/netbooks

Figure 4-4: The World of Connected Devices

Consumers use connected computing devices to play online games and stream music or video content. In fact, every device in Yankee Group's connected computing bucket comes with high-bandwidth requirements. Consumer data usage on smartphones provides an illustration. According to data collected from Yankee Group's Mobile Adoption Panel, the average smartphone consumes more than 12.1 MB of cellular data each day. Moreover, consumers running streaming video applications on their smartphones transmit roughly 5 MB of data each minute. Consumers also display sensitivity to latency issues, and multimedia applications must deliver packets in real time to keep consumers happy.

Most consumer M2M devices place far less strain on cellular networks. For instance, e-readers will only transmit 300 KB of data for every e-book download. And both tracking devices and mHealth monitors only transmit kilobytes of location or vital sign information.

According to Yankee Group consumers survey (2011), consumers rate very high the connectivity wherever they go (connectivity at all times) - more than 88 percent place a high value on fast Internet speeds, 69 percent say they need to be connected at all times and 63 percent say their mobile devices are highly important to their social lives.

In 2010, U.S. carriers saw their data revenue grow by roughly 23 percent. However, during the same period, mobile data traffic grew by more than 132 percent. As data traffic makes operators' traditional device sales less profitable, operators are looking to new segments of the market. I.e. operators are seeking to monetize new services, one of which is M2M communication, dramatically increasing the number of connected devices, with small ARPU, but relatively high margins.

While connected consumer devices attract more media attention than connected enterprise devices, the role of connectivity in enterprise applications should not be discounted. Although many connected enterprise applications have been around for the better part of the decade, real growth in the area is accelerating in 2011 and will continue to swell through 2015. Yankee Group anticipates U.S. cellular M2M connections for enterprise purposes to nearly triple from their 2011 levels of 81.3 million to 219.2 million in 2015, a CAGR of almost 23 percent.

Source: Yankee Group, 2011

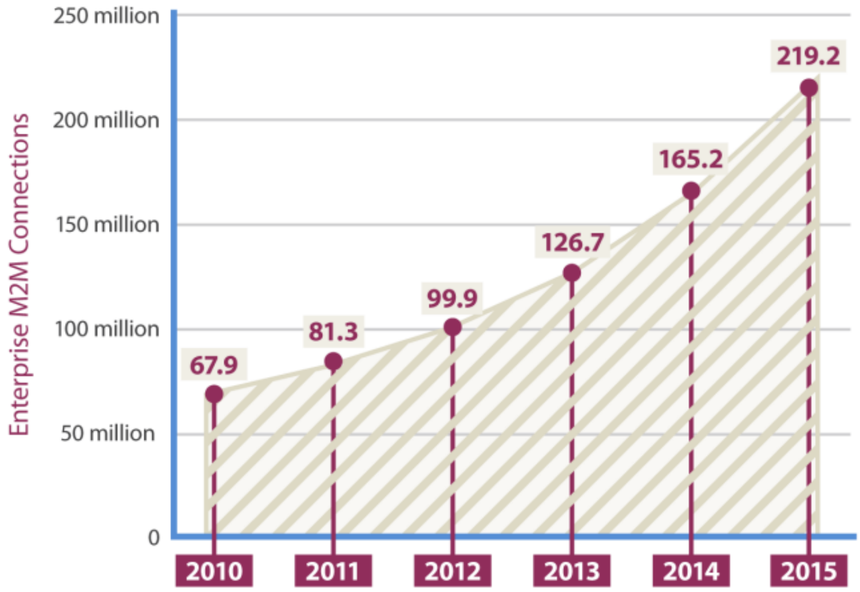


Figure 4-5: Global Cellular M2M enterprise Connections, 2010-2015

4.1.2 Real market application examples and customer benefits

Building a business case and optimizing Total Cost of Ownership (TCO) is the priority task for the enterprise companies representing users of the mobile wireless networks. Companies are looking toward connectivity as a way to drive additional business benefits both internally and externally. On the other side of the equation, companies are challenged with reducing TCO for their connected device investments. From a business case perspective, most successful implementations begin with an objective of focusing on either the customer service-oriented benefits or internal cost-efficiencies. By focusing on a key internal or external pain point, companies can identify KPIs that will drive ROI.

Several connected device applications have already deployed widespread, as presented below.

4.1.2.1 Enterprise Applications

1. **Fleet Telematics**

Solution providers have been connecting fleet vehicles for more than a decade, while recently migrating from legacy technologies (satellite, etc.) to cellular networks (driven by improved coverage and decreased hardware prices). Yankee Group expects cellular connections used for fleet management purposes in the U.S. to grow from about 3.6 million today to 7.5 million by 2015, a CAGR of 16 percent.

Companies that deploy fleet management applications often realize a rapid ROI in the form of reduced fuel costs, greater productivity, safer drivers and more efficient distribution channels. Enterprises with fleet telematics solutions can further maximize their benefits by pairing their technology with an inventory management system.

2. **Health Care**

A tremendous amount of money may be saved by utilizing remote monitoring systems for patients suffering from chronic conditions such as heart disease, diabetes and chronic obstructive pulmonary disease, etc. These remote systems would allow patients to be monitored in their homes, reducing health care cost and freeing up valuable medical resources. Embedding medical devices, rather than requiring patients or medical personnel to manually upload data stored on the device, drastically reduces human error in the data transfer process and creates accurate information that doctors can act on with confidence.

Patients enjoy a more comfortable medical experience, avoiding hospital visits by using remote monitoring technology or travelling with a wirelessly enabled pill reminder system such as Vitality GlowCaps. Medical equipment manufacturers gain greater insight into the performance of their machines, providing the opportunity to guarantee uptime and sell advanced SLAs. Doctors benefit from tools that allow them to better serve patients and observe more accurate patient data in settings outside the hospital, which is crucial in properly diagnosing conditions. Insurance companies can more accurately assess patient risks and reward subscribers with healthier lifestyles.

3. Transaction-based applications (aTM/ PoS/ Kiosk/ Vending Machine)

Embedding connectivity into Points of Sale (PoSs) and kiosks can create more efficient workforces in traditional retail environments or generate sales opportunities in previously untapped markets.

Transaction-based applications gain tremendously from wireless technology because mobility enables deployers to shift their assets to high-traffic areas or areas where building fixed-line connectivity would be costly. In addition, transaction-based devices benefit from a service-repair standpoint and enjoy increases in uptime by immediately alerting technicians when a problem occurs. Mobile PoS terminals can increase workforce productivity. Finally, embedding wireless connectivity into ATM machines provides much greater security through applications such as video surveillance and location tracking in the event of theft.

4. Energy (Smart Grid solutions)

Connected energy represents one of the largest potential markets for connected devices, with millions of households and enterprises with electricity and water needs several utilities already are deploying smart grid solutions and working closely with 3GPP operators and network builders in either building out their own private networks or building agreements to connect meters on public networks.

Several examples of applications and use cases may be mentioned – AMI, Distribution automation and control, Load profiling/ smart tariffs, Substation automation, etc.

5. Digital signage

As one of the more nascent vertical markets, digital signage will grow dramatically in concert with lower wireless access hardware costs and greater pervasiveness. Digital signage can vary from commercial-grade television screens in a retail environment to multi-million-dollar scoreboards in sports stadiums across the country.

Overall, Yankee Group expects enterprise M2M connections worldwide to nearly triple from 81.3 million in 2011 to 219.2 million in 2015, a CAGR of 22 percent (as presented in the Figure 4-6).

Source: Yankee Group, 2011

Category	2011 Cellular Connections	2015 Cellular Connections	CAGR	Monthly ARPU 2011/2015	Factors Affecting Growth Rate
Consumer Telematics	19.8 million	34.1 million	11%	$3.84/$4.27	Adoption by major automotive manufacturers
Fleet Telematics	6.4 million	14.5 million	18%	$4.39/$4.26	Increased use of cellular over satellite-based technology
Industrial Applications	17.5 million	30.7 million	12%	$5.32/$4.56	Lower hardware costs and clear service benefits
Security Applications	12 million	18.3 million	9%	$1.72/$2.62	High-bandwidth streaming for surveillance applications; application layering
Vending/ATM/ PoS/Kiosk	12.6 million	28.5 million	18%	$1.73/$1.72	Clear ROI from reduced truck rolls and repair expenses; mobilization of sales forces in retail environments
Connected Energy	9.2 million	77.3 million	53%	$1.56/$1.32	Continued government smart grid funding/initiatives; increased bandwidth overhead with cellular technology for advanced applications
Rent-to-Own/ Subprime Lending	1.3 million	2.6 million	15%	$1.03/$0.87	Very nascent market segment; increased confidence among lenders if asset recovery technology proves successful
Pay-as-You Drive Insurance	960,000	9.4 million	58%	$4.68/$3.97	Major insurance companies should follow Progressive's lead
mHealth	815,000	1.7 million	15%	$4.04/$3.98	Possible government initiatives for electronic health records; establishment of open standards
Digital Signage	699,000	2.1 million	25%	$12.16/$11.86	Cellular digital signage opens opportunity for new sign locations and maneuverability; cheaper connectivity
TOTAL M2M	81.3 million	219.2 million	22%	$3.36/$2.89	

Figure 4-6: M2M Connections for enterprise applications Worldwide, 2011-2015

4.1.2.2 Consumer Applications:

1. **Consumer Telematics**

Modern in-vehicle telematics systems introduce network connectivity, in-vehicle embedded systems, and next-generation applications. Consumers have already expressed substantial interest in these offerings.

2. **Education**

Many of manufacturers have already positioned their tablets and e-readers as learning tools for students. School administrators are trialing tablets. Major universities are evaluating e-readers. Most of them will require network connectivity. But e-textbooks are just the beginning. Several developers are creating educational software specifically designed for students.

3. **Consumer electronics**

The steep adoption curves of today's consumer electronics devices continue to make headlines. Embedded connectivity plays significant role in selling these devices. In Yankee Group's consumer survey, respondents assess the importance of Internet connectivity across a range of form factors:

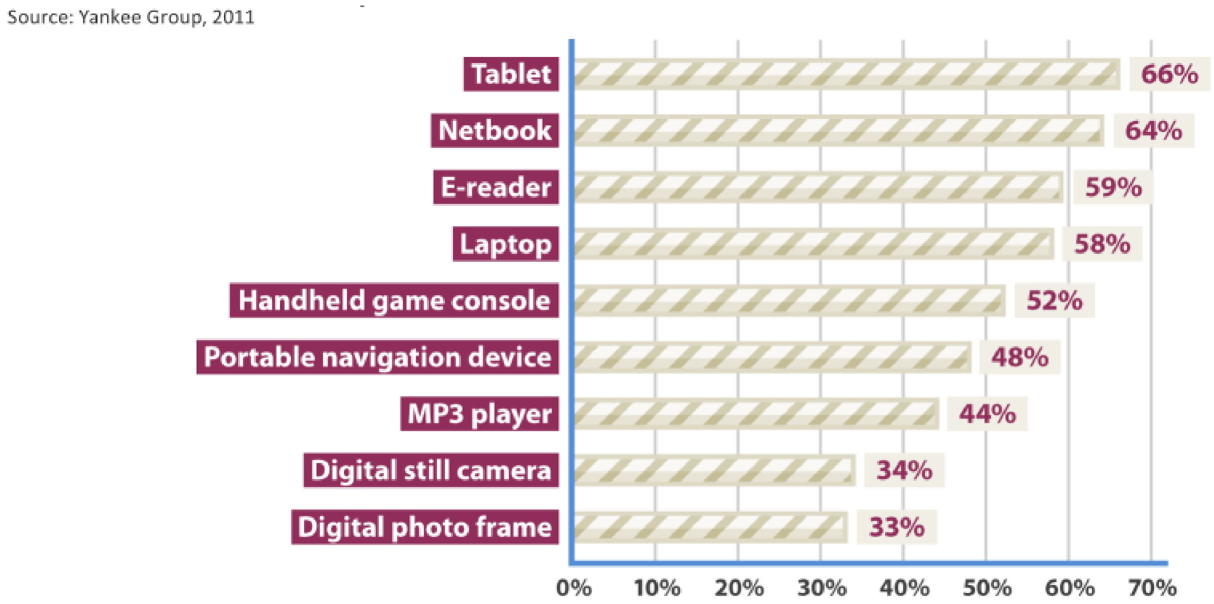


Figure 4-7: Consumers Crave Connectivity

As may be seen from the diagram above, nearly 70 percent of consumers say connectivity is indispensable on their tablet and netbook devices. In fact, Yankee Group's consumer survey finds that more than 33 percent of all tablets ship with embedded connectivity.

Connectivity has created new product categories – such as e-readers and always-on connected digital photo frames.

The figure below presents just one of the opportunities in connected consumer electronics. Yankee Group expects global e-reader sales to grow at a 51.7 percent CAGR, from just 10.7 million units in 2010 to more than 86.9 million units by 2015. More than a third of these devices will sell with embedded connectivity.

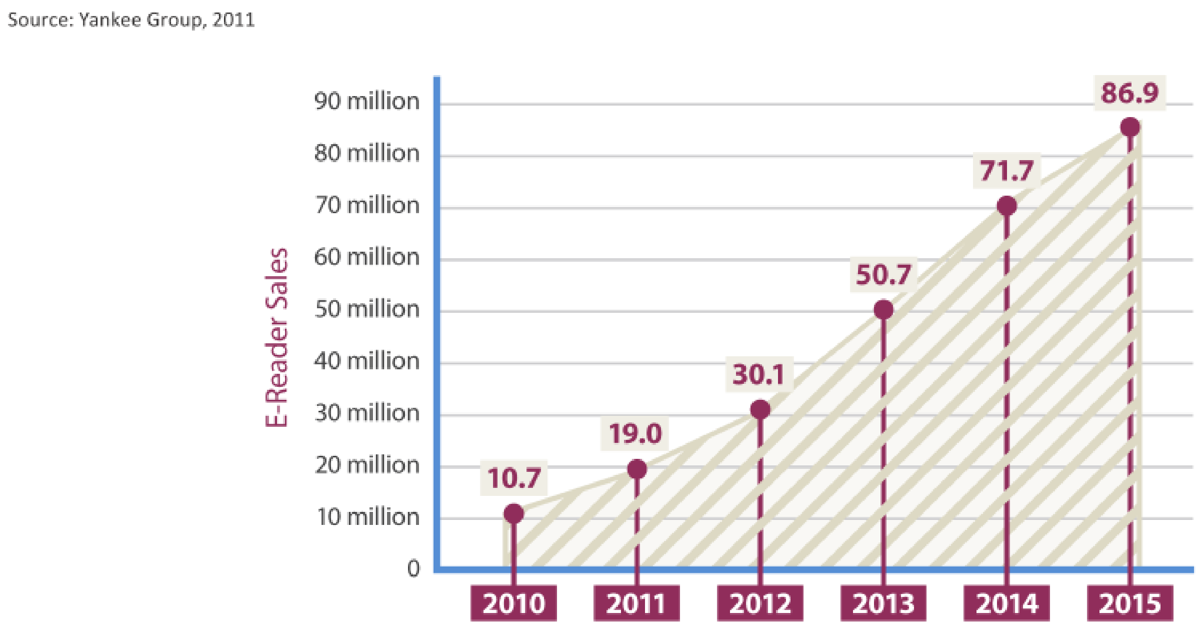


Figure 4-8: Global e-Reader forecast, 2010-2015

4.1.3 Conclusion

In the year 2000, fixed Internet access made PCs all the more valuable, and nearly a billion units were sold. In the next 10 years, the mobile computing revolution promises even larger shipment figures. By 2020, Ericsson forecasts a global installed base of more than 50 billion connected devices. Established M2M verticals such as fleet telematics will comprise some of this growth. But hot new categories will also emerge. Yankee Group expects connected energy deployments to grow at a 65 percent CAGR to 15 million connections by 2015. Pay-as-you-drive insurance providers will add 3.4 million connections in the next four years. And consumer devices such as tablets will fly off store shelves. By 2015, nearly half a million consumers around the world will use a tablet to connect to their favourite multimedia.

By embedding cellular connectivity into their devices, OEMs differentiate their brands and keep consumers happy. According to Yankee Group surveys, more than 69 percent of consumers demand ubiquitous connectivity, and 88 percent want connectivity at broadband speeds. Businesses are also turning to connectivity to cut costs and broaden margins.

Mobile Broadband Wireless Access networks must be ready to accommodate and provide service to all these devices resulting in tremendous access network capacity growth and cost reduction.

4.2 Mobile BWA Small Cells market segment – current situation and forecast

Less than a decade after the first deployments of WCDMA-based 3G systems, the cellular communications industry has moved on to the next set of new developments, implementing HSDPA (high-speed downlink packet access), HSUPA (high speed uplink packet access) and more recently HSPA+. WiMAX/ LTE are the next technology generation, and is closely linked with the emerging concept of the next-generation mobile network (NGMN). Realizing the potential of LTE requires the use of innovative, fine-grained network architectures based on small cells.

Mobile BWA technologies, such as LTE and WiMAX represent an attractive revenue generating opportunity for operators. It can be used to target premium services at users who need and can afford them, and to relieve capacity problems in areas where existing networks are congested. It is also intended to achieve a dramatic reduction in cost-per-bit of transmission to the operator – translating revenue into profit. Whatever the advantages, realizing such networks presents significant challenges. In seeking to move ever closer to the theoretical information-bearing limits of the wireless spectrum, LTE uses wider channel bandwidths, advanced coding and OFDMA (orthogonal frequency division multiple access) modulation methods that require unprecedented signal processing power. Also built-in from the outset is the use of techniques such as multiple input-multiple output (MIMO),that combine signals from several antennas to enable more effective communication.

The nature of LTE points to a fundamental shift in the architecture of the network itself, with smaller cells, closer to the user, being a key element in the mix. Several factors mean that this trend is likely to go further, faster than has previously been expected. First, the physics of radio communication makes it difficult to attain higher and higher performance from a system that places large base stations at a significant distance from the handset or user equipment (UE). The most fundamental “laws” of communications, established sixty years ago by Claude Shannon and Ralph Hartley, mean that the full benefits of LTE can only be gained by using cells of a much smaller size than are currently employed. Moreover, usage patterns and user expectations are also evolving. More and more cellular communications take place indoors. In this situation, using a macrocell network for high-speed data transmission has been compared to “trying to fill a cup from a fire hose spraying through an open window”. These drivers mean that architectures based on small cells serving few users (small cells) will be much more than a convenient revenue-generating add-on for LTE operators: they will be the foundation of the network. But such a deployment model also emphasizes the fact that a small cell is much more than just a scaled-down macrocell. It requires a high degree of intelligence, so that it can deliver low installation and operating costs. Additionally, the lower unit cost will benefit CapEx – especially for high-volume consumer deployments. The scales of selling price per system for Pico BSs (ASP per unit) are around $1-$3K.

The physical problem becomes worse as frequency increases, and is intensified by the use of more advanced modulation and coding schemes to enhance data rates. The additional attenuation reduces throughput for those users indoors, but there is another effect too: if the traditional macrocell allocates more power to reach the user, this increases the interference for other users and/or cells. Such realities inevitably have a quantifiable, negative impact on cell capacity, making it impossible to deliver performance improvement compared to 3G.

Macrocell approaches are also limited by two of the most fundamental “laws” of communications theory: Shannon’s Law, and a newer observation, made by Dr Martin Cooper, and sometimes called “Cooper’s Law”.

Shannon’s Law establishes an upper limit on the coverage and/or capacity of a communications link as a function of a minimum ratio between the energy per bit of a signal and the noise spectral density in the channel being used. Modern systems come close to the Shannon’s described fundamental limit. The energy per bit at the receiver depends on the transmitter power, the path loss (dependent upon frequency, physical separation, obstructions and terrain), and the size of the antennas at each end. The noise spectral density depends on physical fundamentals, the receiver performance, and the amount of interference in the channel .As a result, an increase in transmission frequency or bit rate in a system at, or near, the theoretical limit can only be attained by boosting transmitter power, reducing cell size, or using MIMO (effectively creating additional, parallel, channels to give potentially up to N times the Shannon capacity between the two points). The same kind of argument establishes the maximum data rate attainable from a given channel: that is, it establishes the capacity limit. Using a more powerful signal increases the information-carrying capacity of the channel. But when more users attempt to access the same channel or those closely adjacent by increasing the transmission power, the noise environment can become significantly worse, neglecting the positive effects of boosting signal strength. Eliminating such conflict is a big component in the efficiency gains offered by small cells.

Coopers Law observes that the number of radio frequency conversations which can be concurrently conducted in a given physical area has doubled every 30 months since Marconi’s earliest radio transmissions. This 30-month doubling has yielded a one-million-fold overall increase in capacity in the last 45 years alone. Of this, it is estimated that 25x is due to using more spectrum; 5x is due to better modulation techniques; and 5x is down to frequency division. But by far the biggest factor, some 1600x, is due to spectrum re-use: the effects of confining the area needed for individual interchanges within smaller and smaller cells. Cooper’s Law demonstrates that spectrum re-use is the most potent method for increasing network capacity.

By installing a large number of smaller cells, operators can overcome the problems of signal attenuation and make use of the powerful ability of spectrum re-use to increase network capacity.

But some concomitant negative effects must be eliminated – efficient interference management solutions, small cells operational simplification (self-organization, autonomous operation, etc.)

According to Frost & Sullivan research [19], Picocell market, although delayed in mass deployment, is believed to be driven by some important and real drivers. Among the key drivers are the needs to extend coverage and capacity for existing and emerging wireless services, reduce backhaul costs and provide cost-effective macro network offload. Picocells are expected to be strategic to 4G (WiMAX/ LTE) deployments. That is, these products are expected to be an integral part of an operator’s 4G deployment plans, and are not expected to be deployed only to fill gaps in coverage, as has been the case so far. Hence, Picocells are expected to experience high growth rates as more and more operators begin their 4G (such as LTE) deployments.

The revenue in the Picocell product segment was estimated to be USD 0.23 billion in the calendar year 2009 and expected to grow to 1.82 billion by the end of 2015 at a CAGR of 34.4 percent.

The number of units shipped in the calendar year 2009 in the Picocell segment was estimated to be 0.1 million. It is expected to grow to 1.1 million in the calendar 2015 at a CAGR of 36.2 percent. Since, the Picocell product segment is relatively matured, the revenues are even split across the two main regions of North America and EMEA. The APAC (Asia Pacific) region is expected to be a key driver for the Picocell segment, and is expected to grow from 10.0 percent of the revenue in 2009 to 25.0 percent of the revenue in 2015. The developed regions for the Picocell segment are expected to evolve to 3G and 4G Picocells, while the developing regions, such as APAC, are expected to drive the 2G Picocell market, especially in the near-to-mid term of the forecast period. While 2G Picocells were estimated to account for almost 99.0 percent of the units shipped in 2009, that number is expected to reduce to 40.0 percent by 2015.

Interference, handover and interconnectivity issues were some of the earliest technology challenges that worked as strong restraints in that segment and yet to be tested in real, large scale deployments.

Features related to Self Organizing Network (SON) have emerged to be key areas of differentiation in addition to features such as standards based solution, breadth of product offerings, and key metrics such as the number of channels. The implementation of Self Optimized Network (SON) is not just about zero-touch implementation but also about end-to-end integration and interfacing with the back office systems within the operator itself.

Picocell products are expected to experience strong growth based on some real and well-understood drivers in the industry. Frost & Sullivan considers the Picocell product segment to be currently in the growth stage.

4.3 Wireless PtMP mobile backhauling market segment – current situation and forecast

According to the Maravedis report [20], during 2010, the Point-to-Multi-Point (PtMP) microwave backhaul market reached US$146M.

It is a growing, complex, still forming market, with different coexisting technologies, Microwave, Non-Line of Sight (NLOS), WiMAX and WiFi. The traditional microwave market and WiFi vendors are in stiff competition with each other.

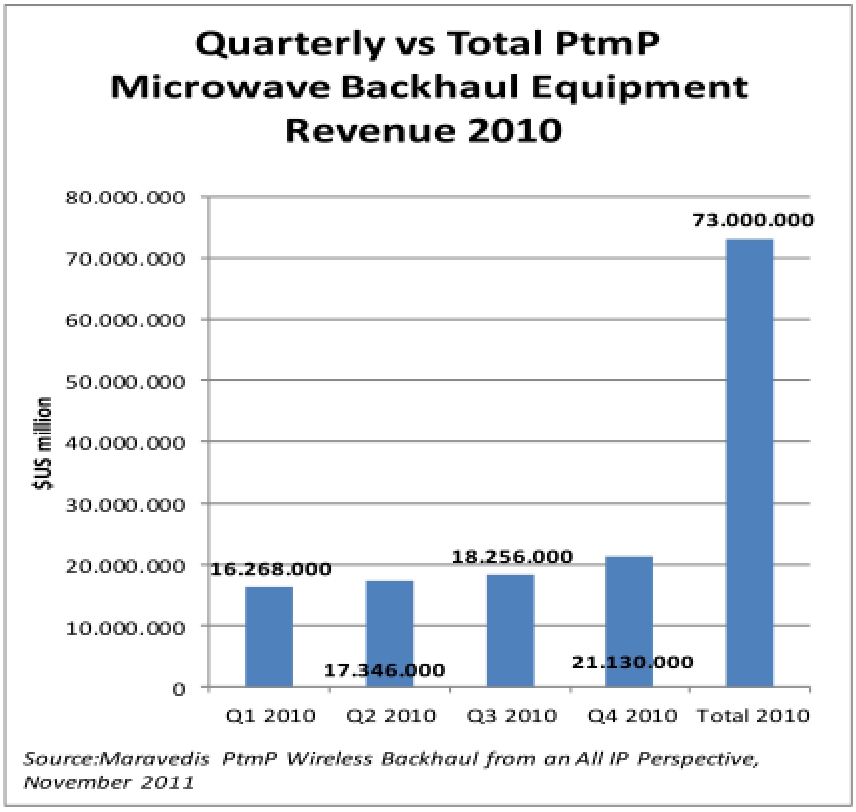


Figure 4-9: Quarterly PtmP Microwave Backhaul Equipment Revenue 2010

At the end of 2011, 15% of the installed backhaul market worldwide will be Point-to-Multipoint with the remaining 85% Point-to-Point. Between Q1 and Q2 2011, PtmP equipment shipments increased by 11%.

Although operators preferred PtP wireless technology, the PtMP was very attractive as the best alternative in high density areas. The increase in PtMP shipments was anticipated as an emerging market, although both PtP and PtMP are expected to complement each other, particularly in the cities where 4G mobile BWA networks require full coverage for high capacity.

Maravedis expects the wireless PtMP backhaul equipment market to reach US$1 billion by 2016 from $200 million in 2011. Beyond 2013, the rise of LTE deployments, in combination with small cells growth, will drive the growth of PtMP's market adoption.

By 2016, the Non-Line of Sight (NLOS) equipment revenues will reach 35% of the total PtMP. In first half of 2011, many NLOS vendors were testing their PtMP products in the TDD spectrum bands as they move toward the 2nd generation product releases in 2012. The operators' requirement for a full pico cell backhaul solution should increase the NLOS equipment revenues from 2011-2016 at close to growth rate of 50% per year.

The forecast shows a continued market growth for the next few years (average growth rate per year is 31%), driven mainly by the small cells market and new LTE deployments that will almost triple in 2012 compared to 2010 and see continued growth after 2013. That makes 2013 the reflection point beyond which the market is estimated to grow faster. Maravedis also expects a significant increase in small cells deployment by 2013, as operators will need to add more capacity and deploy new base stations to provide good quality of experience over LTE networks.

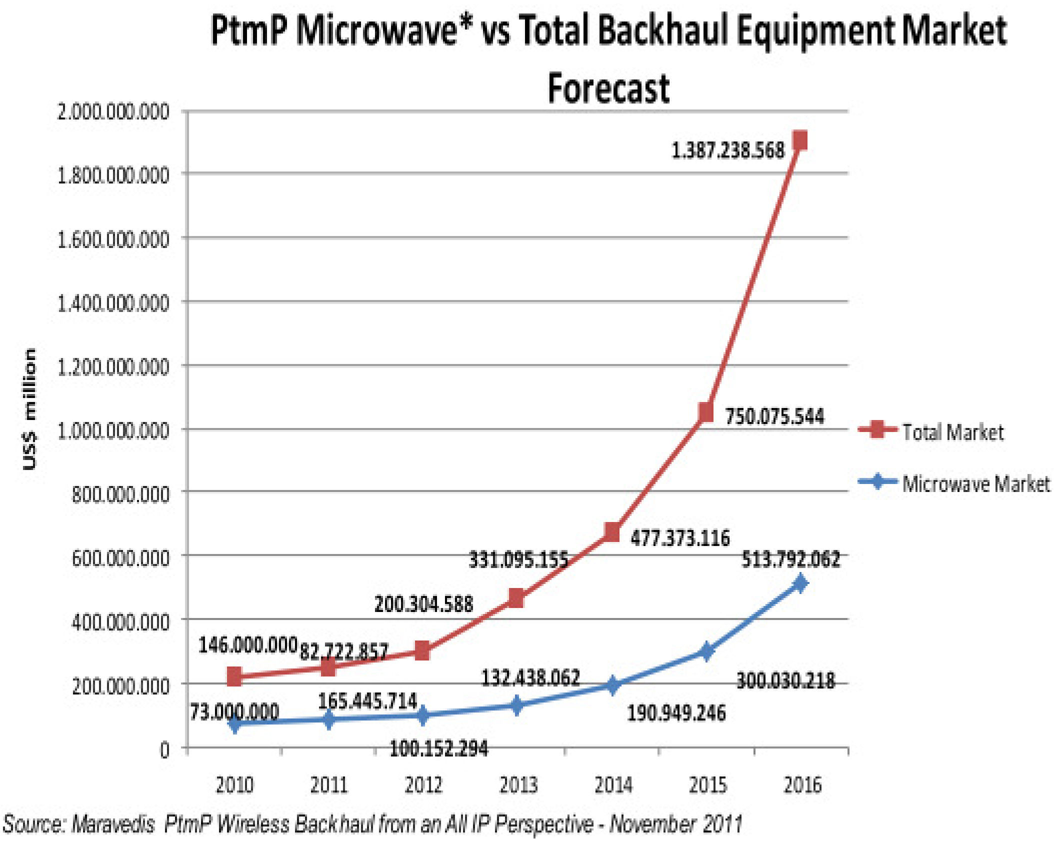


Figure 4-10: PtMP Microwave vs. Total Backhaul Equipment Revenue Forecast[1] 2011-2016

Africa has been the only region in the world where microwave shipments continued to grow throughout 2010 into the first half of 2011. Sales increased over 60% in the second half of 2011, with all microwave vendors indicating the African continent, predominantly the South African market, as the region with the strongest activity and the highest competition. Although Middle Eastern revenues doubled from Q1 to Q2, this increase was not enough to match or surpass Africa. The Middle East continues to hold a market share 40% less than Africa's, continuing the trend seen in 2010.

PtmP microwave shipments to Europe decreased in 2010. In Europe, reliance is on PtP, with PtMP still only in testing for high-density urban areas such as London or Paris.

This forecast reflects trends indicating that both the Middle East and Africa will experience continued growth until 2016, reaching US$168M and US$217M respectively. Each region will be positively affected by the new LTE deployments that will require higher capacity and quality customer experience.

Europe will continue to grow, but there will be strong competition from other technologies such as NLOS that will erode revenue share through deployments in the high-density areas where fiber cannot reach or is too expensive or time-intensive to deploy.

[1] Some inconsistency is observed in the Total Market figures matching the Y-axis. In spite of this, the Figure is considered providing valuable indication for the market state and forecast.

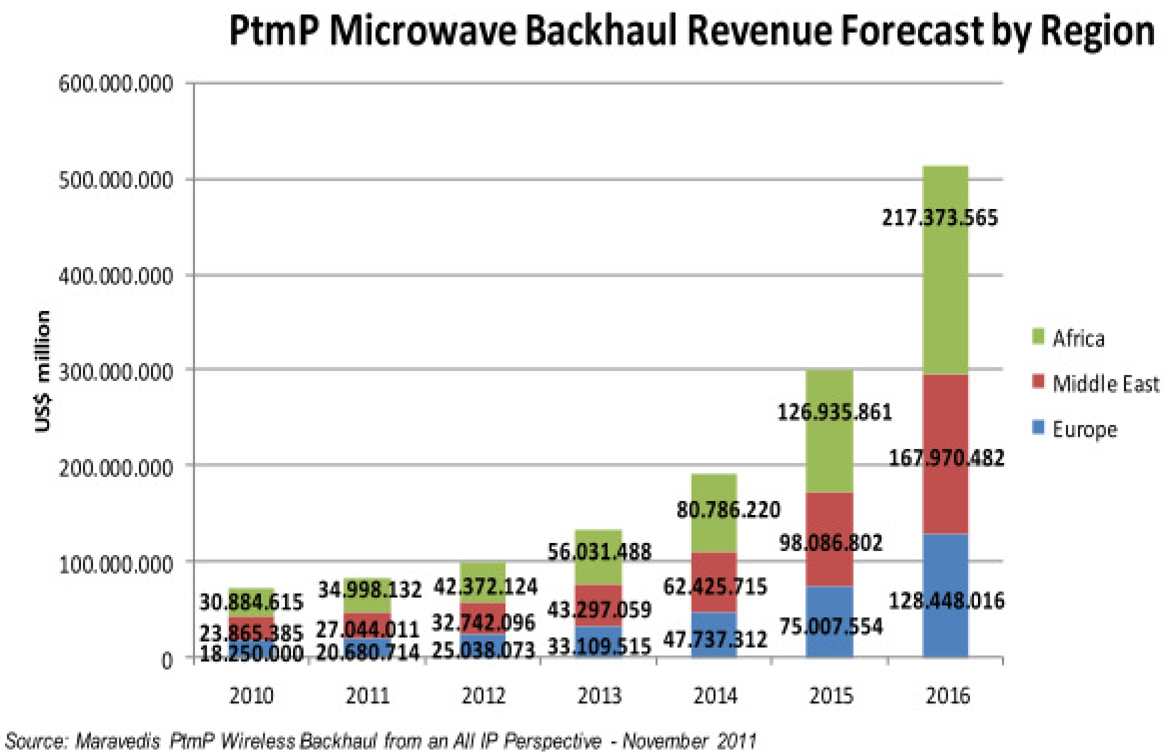


Figure 4-11: PtMP Microwave Backhaul Equipment Revenue by Region Forecast 2011-2016

PtMP typically requires less than half the hardware for coverage over PtP, showing reductions in CAPEX of up to 50% and in OPEX of up to 70%, according to vendors' claims. In addition, operators can maximize their return on investment by enabling faster time to revenue. Additional capacity can be inserted on a channel-by-channel, sector-by-sector basis, allowing the operator to minimize initial capital expenditure and tailor subsequent investments to match growing subscriber numbers.

The FDD systems refer strictly to bi-directional voice service since these occupy a symmetric downlink and uplink channel pair. However, as a trend and on a per case basis, TDD is the choice and provides the ability to define the percentage of Upload versus Download traffic (asymmetric). Whether we refer to NLOS or microwave technology, the time-to-deploy for a new connection or even a cell site is significantly reduced to a few hours.

Key small cells features are small size, lightweight products deployed outdoors that are able to withstand harsh weather conditions. The small cells, Outdoor Metro Pico/Femto, could easily be supported from PtmP products, adding extra capacity to the cell site and the aggregation node. Ideally, all this hardware should be flexibly mounted on any street level deployment (light pole or rooftop), with intelligent and independent power features (Power of Ethernet), support for all weather conditions standards, for availability in 30-50 mm/hr rain and temperatures ranging from –45℃ to + 55℃. Split mount equipment will still be a player, but the footprint will move very close to zero.

Lower-microwave equipment in the sub-6GHz bands is much better suited to low-density urban and suburban settings, but where equipment is restricted to line-of-sight connections, a substantial percentage of potential subscribers will remain inaccessible in a macro cellular (large-cell) network architecture. Advanced NLOS equipment will allow almost any given customer access, but depending on the spectrum utilized by the network operator and the area served by a base station, coverage may still be inadequate because of range and capacity limitations rather than obstructions. Unquestionably, the new NLOS equipment will permit the network operator to exploit the available spectrum far more effectively than has been possible with first-generation, and especially second-generation equipment, with its more or less stringent line-of-sight limitation.

Currently, there is no substantial volume of PtMP market. The estimated average annual growth rate is close to 50%. This growth will be due primarily to the growing three-figure LTE deployments, and the immediate need for full coverage in low-density areas. In addition, backhaul is the key enabler of the future development of the small cells market.

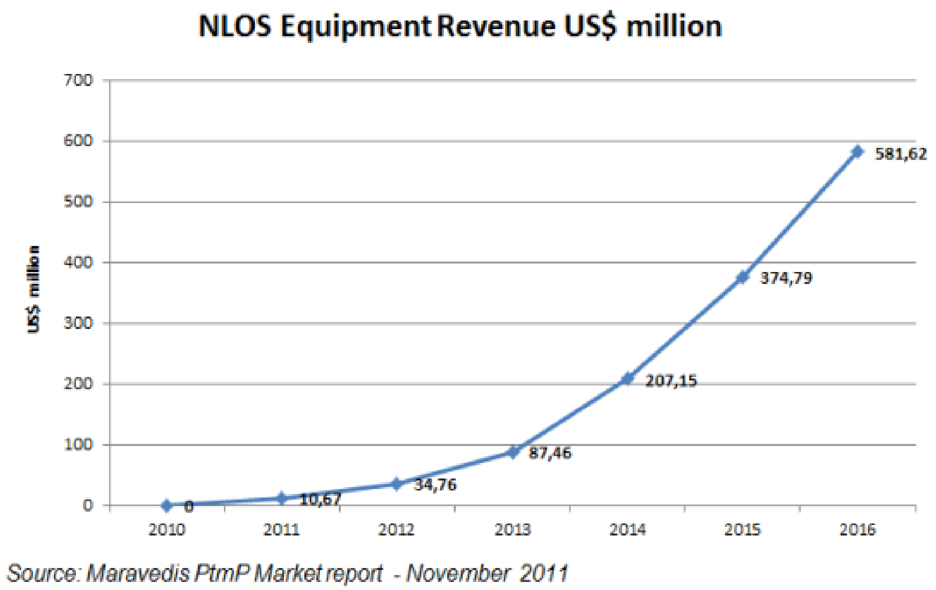


Figure 4-12: NLOS PtMP backhaul market forecast 2011-2016 in sub-6GHz frequency bands

4.4 PtP backhauling for small cells

In its latest issue of outdoor small cells market data, ABI Research forecasts that the equipment market will grow to be worth $14.3 billion by 2017. Including outdoor femtocells, picocells, microcells, and carrier Wi-Fi access points, at just over 1 million units forecast in 2012, the number of outdoor small cells sold will surpass the 954,000 macrocells forecast for this year.

“We believe that outdoor small cells have distinctly different characteristics, including the need for carrier grade software, wider temperature ranges, and more sophisticated RF from indoor consumer and enterprise femtocells and we are now forecasting these separately from indoor residential and enterprise units,” says Nick Marshall, principal analyst at ABI Research.

These findings are part of ABI Research’s Small Cells and Carrier Wi-Fi Research Service which includes additional Competitive Analyses, Vendor Matrices, Market Data, and Insights.

The staggering numbers of smart devices used today and the shift of their usage toward entertainment consumption such as video create a new challenge and opportunity for Mobile Service Providers (MSPs). Mobile devices such as smart phones, tablets and laptops enable users to consume bandwidth hungry content wherever they go with high-definition quality. It is estimated that the bandwidth capacity needed to ensure the service delivery at the quality needed will exponentially grow in coming years as shown in the below diagram:

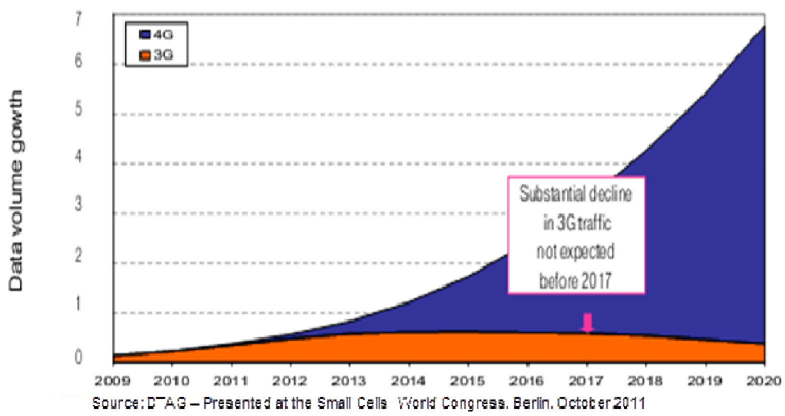


Figure 4-13: 3G vs. 4G data traffic dynamics

The Mobile Service Providers (MSPs), in their efforts to improve their services, are looking into new technologies that will allow their users to benefit their new smart devices. Up until now, the common practice of placing a central macro base station to cover entire neighbourhood was good for voice and low bandwidth data services. The current agreement between operators and vendors is that there is a need for a second layer of smaller cells to answer the new user bandwidth and quality demands. Survey among MSPs shows that more than 60% of them intend to use smaller cells technologies in the near future infrastructure buildup. The small cell market size as a result is expecting to 3 million units in 2016 (Infonetics Research, March 2012).

Point-to-point links at 60GHz offer an attractive solution to backhauling the underlay layer of small cells, due to their low-cost, capability to support high throughput and high immunity to the interference by virtue of the Oxygen absorption present in the 60GHz frequency band.

The explosive growth of small cells coupled with the performance advantages and cost-effectiveness of wireless backhaul will ignite the mobile backhaul market. Mobile Experts forecast that shipments of both NLOS and mm-wave backhaul equipment will exceed 1.8 million units in 2016, representing more than $1.5 billion annual revenue.

Despite this, wireless backhaul faces many challenges. One not often discussed is the sophisticated coordination required by future picocells. For example, a network can triple its capacity (and achieve as much as 12x data rate for users at the cell edge) through the use of Coordinated MultiPoint (CoMP) and Interference Rejection Combining (IRC) approaches. These techniques require low-latency backhaul, as well as very high throughput levels so that a central bank of baseband processors may combine signals and reject interference. These small cells will likely rely on fiber. As fiber increasingly reaches the macro cells and becomes available at the street installations, the number of small cell sites services by wireless backhaul will drop.

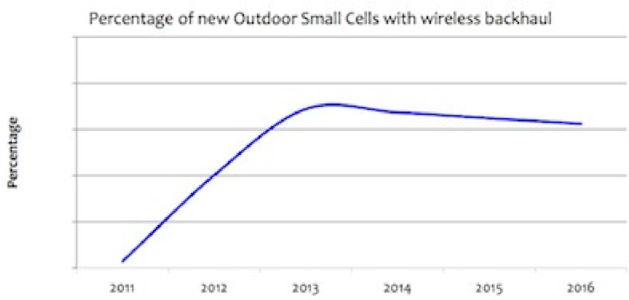


Figure 4-14: Percentage of Outdoor small cells with wireless backhaul [24]

Overall, small cells bring value because they enable very high data rates to locations which are far from any cell tower. Mobile operators will need several years to bring fiber to all possible small cell locations. Until that, the industry needs to embrace wireless backhaul techniques.

5 Standardization and Dissemination activities

BuNGee identified ETSI, 3GPP, IEEE and WMF as the relevant bodies for standardization activities. ETSI serves the basis for further potential developments in 3GPP and WMF and ***thus was prioritized for BuNGee activities.***

Additionally, TCS participated in 3GPP SA1 meetings. SA1 group defines the new services and expresses the requirements of these new services. Services that are defined in the group are mainly for commercial applications but some of them are for public safety applications. TCS was very interested in the public safety applications new requirements. One of these new services concerns direct communications between UEs for next generation 4G networks (release12). It has to be highlighted that this new service that is mandatory for public safety applications is detailed for public safety use cases but also for commercial use cases. It has been agreed in 3GPP SA1 group that both applications (public safety and commercial) will be treated at the same time and with the same deadline. Direct mode will so be used in both cases and will have impact to the networking schemes.

The other application that TCS followed was "group communications". This service that is mandatory for public safety applications will also be studied for commercial applications. This service will have less impact on the network architecture.

5.1 BunGee contribution to ETSI[2] and IEEE

In the December 2010 BRAN meeting, the first contribution BRAN(10)0086r2 was submitted by Mariana Goldhamer, in the name of the ETSI members active in BuNGee: Alvarion, Thales, Polska Telefonia Cyfrowa, Siklu and CTTC.

This first contribution included the following technical elements:

- Architecture for 1 Gbps/km^2 network, including the following features:
  1. Multiple access links aggregation;
  2. Backhauling link aggregation;
  3. Network MIMO (for Downlink and Uplink);
  4. Direct BS-BS or MS-MS communication.

The second contribution was prepared by Mariana Goldhamer and was discussed, modified and approved by BuNGee. The contribution was submitted to the BRAN#68 meeting, taking place in Sept. 2011, as BRAN(11)0046, authored by THALES, Polska Telefonia Cyfrowa, ALVARION S.R.L., Siklu Communication Ltd. and CTTC.

This contribution included the following elements:

- An improved system architecture figure, relevant for D3.1;
- Characteristics of the multi-beam antenna;
- Extensive text on multi-beam assisted MIMO, relevant for D1.2, and including:
  - An overview;
  - Up-link and down-link multi-beam assisted MIMO operation in licensed bands;
  - Network MIMO operation in uplink and downlink;
  - Hybrid MIMO operation in uplink and downlink.
- Extensive text on Radio Resource management, relevant to D3.1 and including:
  - Dynamic frequency allocation;
  - Self-organizing frequency allocation;
  - Cognitive band frequency allocation;
  - RRM for joint access and self-backhaul networks;
  - Joint access and self-backhaul.

[2] All standardization activities described in detail in project Deliverable 5.4

The contribution was presented and discussed in ETSI BRAN HiperMAN and was accepted as second draft of TR 101 534.

The third contribution was prepared by Mariana Goldhamer and was discussed, modified and approved by BuNGee. The contribution was submitted to the BRAN#69 meeting, taking place in Dec. 2011, as BRAN(11)0061, authored by Polska Telefonia Cyfrowa, ALVARION S.R.L., Siklu Communication Ltd. and CTTC.

It included the following new elements:

- The system network figure and the corresponding description were replaced, such to give a neutral view of the actual networking interfaces;
- Detailed deployment approaches were introduced, using the materials in D3.1 and D1.2 for the square and cross topologies;
- The figure with antenna characteristics was replaced by Cobham, to respond to specific ETSI requests;
- Was added the CTTC capacity simulation results for the entire system, while taking into account the joint access and backhaul design, taken from D3.1;
- Was added a section of direct inter-BS communication, taken from D1.2;
- Was added the capacity and spectrum calculation taken from D1.2.

The contribution was presented and discussed in ETSI BRAN HiperMAN and was accepted as third draft of TR 101 534.

The forth contribution was prepared by Mariana Goldhamer and was discussed and approved by BuNGee. The contribution was submitted to the BRAN#70 meeting, taking place in Feb. 2012, as BRAN(12)000013. Consolidated text for TR 101 534 was authored by Thales, Polska Telefonia Cyfrowa, ALVARION S.R.L., Siklu Communication Ltd. and CTTC.

The contribution provided the text, relevant for D1.2, the section named “Time resource allocation”, and addressed the spectrum sharing between the hub and access tiers, based on D1.2. In addition, the conclusion section was finalized. Because the meeting targeted the approval of the standard, the contribution made the requried editorial changes.

The contribution BRAN(12)000013 was approved for publication as the final draft of TR 101 534 by the HiperMAN Working Group and afterwards by the BRAN Plenary.

It followed the interactions with the BRAN ETSI Officer and the editHelp staff, asking a small number of clarifications. The answers were prepared by the ETSI Rapporteur, Mariana Goldhamer, in collaboration with CTTC.

Finally, the Rapporteur announced that the standard had been published on March 26, 2012.

The standard can be downloaded here:

http://www.etsi.org/deliver/etsi_tr/101500_101599/101534/01.01.01_60/tr_101534v010101p.pdf

Later, a new Work Item, TR 101 589, was adapted - at the BRAN meeting #70 from Feb. 2012, the ETSI members active in BuNGee submitted the following documents:

- BRAN (12)000011r1, the new Work Item proposal for “Very high capacity density BWA networks: Protocols”. The supporting companies were: Alvarion, Thales, Polska Telefonia Cyfrowa, Siklu and CTTC. The Rapporteur of the Work Item, based on Alvarion proposal, was Mariana Goldhamer.
- Supporting presentation BRAN (12)000014r1.

The main elements of the BuNGee architecture may be recognized in both the Work Item description and the supporting presentation, as reflected in D3.2. These are:

- RRM Functional Decomposition;
- Autonomous Distributed Cognitive Radio Frequency Assignment;
- Autonomous Distributed Dynamic Frequency Assignment;
- Learning and docition;
- Joint power and frequency control.

In the plenary meeting from 8 Oct. 2010, BRAN Technical Committee (TC) adopted the New Work Item unanimously.

In the December 2010 BRAN meeting, the first contribution BRAN(10)0086r2 was submitted by Mariana Goldhamer, in the name of the ETSI members active in BuNGee: Alvarion, Thales, Polska Telefonia Cyfrowa, Siklu and CTTC.

This first contribution included the following technical elements:

- Architecture for a 1 Gbit/s/km^2 network, including the following features:
  1. Multiple access links aggregation;
  2. Backhauling link aggregation;
  3. Network MIMO (for Downlink and Uplink);
  4. Direct BS-BS or MS-MS communication.

At the IEEE 802.16 meeting from January 2011, the contribution IEEE C802.16n-10/0068r1, "Proposal for 802.16n architecture with path and frequency resilience" was submitted by Alvarion and Thales.

This contribution proposed a new resilient architecture based on the subscriber-to-subscriber direct communication developed in D2.1 section 5.4. In addition, the solutions were proposed using the frequency allocation agility, as developed for multi-beam frequency allocation in D1.2 section 8 and D1.3 section 3.

The meeting discussed the solutions presented by us and Samsung + ETRI. Finally, the Samsung solution, based on the multi-hop relay connectivity, was preferred.

5.1.1 Impact of Current and Emerging Standards on Project Work

BuNGee had an overwhelming contribution to ETSI standardisation, as the entire ETSI TR 101 534 was drafted based solely on the contributions submitted by the BuNGee partners. In addition, a substantial contribution was made to ETSI draft TR 101 589.

The BuNGee standardisation in ETSI confirms the conclusions of the Future Networks: Report of the Future Networks 7th FP7 Concertation Plenary Meeting, Brussels, 10 February 2011, showing that even STREP projects can bring a substantial contribution to standardisation.

It has been found, based on a serious technical assessment, that there was no need for the TM4 standardisation, as the multi-beam antenna developed in BuNGee is already covered by ETSI type-compliance standards.

BuNGee also contributed to IEEE 802.16n, however the proposals were not accepted for inclusion in the IEEE 802.16n standard.

BuNGee members contributed in the WiMAX Forum to the WiMAX technology Road Map, introducing a number of BuNGee-essential technical topics, one of which, Heterogeneous Networks (HetNet) concept, was adapted as the Work Item for future WiMAX standardization releases.

Project contributions to the work of Standard Bodies are presented in the table below:

Table 5-1: Project contributions to the work of Standard Bodies

Partner Responsible	Standardization body	BuNGee contribution	Details	Schedule	Status	Partners responsible for the foreground
ALV	IEEE 802.16n	Contribution submitted (10/0068r1)	Path and frequency resilience	2010	Achieved	ALV, TCF
ART (MG)	ETSI BRAN	"Very high capacity density BWA networks: System architecture, economic model, technical requirements".		Approve d by ETSI	Achieved	ALV, CTTC, PTC, TCF, SIK

Partner Responsible	Standardization body	BuNGee contribution	Details	Schedule	Status	Partners responsible for the foreground
ART (MG)	ETSI BRAN	BuNGee RRM mechanisms and protocols (based on D.3.2 - control Channel)	NWI approved	Feb-12	Achieved	ALV, CTTC, PTC, TCF, SIK
ART (MG)		BuNGee Dissemination Report (D.5.4)		Jun-12	Achieved	All
ALV	WiMAX forum	BuNGee deployment model: Heterogeneous Network deployments(HetNet) – introduce it as a part of WMF road map, create Study Group, contribute relevant scenarios, map standardization activities.	Interference Management (ICIC) in WiMAX Hierarchical Networks (HetNets) - Contibution Submitted based on the materials prepared for BNG D.3.1, and D.3.2	2012	Achieved	ALV, TCF. SIK
ALV	IEEE HetNEt	BuNGee Architecture Design	Path and frequency resilience	2011-2012	opened	ALV
ALV	3GPP - COMP	Inter-BS communications to support Bungee defined mechanisms.		2011-2012	opened	ALV
ALV	3GPP - Relays activity	Time/ Frame structures as defined in BuNGee.		2011-2012	opened	ALV
ALV	3GPP	Multi-Beam antenna		2011-2012	opened	CASMA
TCF	TM4	Dual Polarised Multi-Beam Antenna	Amendment for EN 302 326-3	2012	opened	CASMA

5.2 Project dissemination objectives

The objectives were - to disseminate the achievements and results of the BuNGee project, and to raise awareness with the following means:

- Public web site,
- Dissemination material,
- BuNGee organisation and participation in public workshops.

BuNGee members participation in Conferences and Scientific Events is presented in the table below:

Table 5-2: Participation in Conferences and Scientific Events

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
UCL UoY			COST 2100 - Pervasive Mobile & Ambient Wireless Communications	Athens, Greece	03/02/2010	Intergovernmental Framework - Cooperation with Other Research Actions
ALV	"BuNGee – Topics for IEEE 802.16 Standardization"	Mariana Goldhammer	The IEEE 802.16 Working Group on Broadband Wireless Access Standards	Orlando, US	15/03/2010	Academics and Industry
UCL	Report of Activities submitted to the EC	Claude Oestges	EuCAP - European Conference on Antennas and Propagation	Barcelona, Spain	11/04/2010	
CTTC	"Design, Implementation and Testing of a Real-Time Mobile WiMAX Testbed Featuring MIMO Technology"		The 6th International Conference on Test Beds and Reseach Infrastructure for the Development of Networks and Communities	Berlin, Germany	18/05/2010	
CTTC Presenting	"Differential Feedback of Channel Gram Matrices for Block Diagonalized Multi-user MIMO Systems"		International Conference on Communications (ICC)	Cape Town, South Africa	23/05/2010	IEEE Conference - Academics and Industry

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
CTTC Presenting	'Aggressive Joint Access & Backhaul Design For Distributed-Cognition 1Gbps/km System Architecture'		Eight International Conference on Wired/Wireless Internet Communications (WWIC)	Sweden	01/06/2010	
ALV Presenting	“Vision and Architecture Supporting Wireless GBit/sec/km2 Capacity Density Deployments”		Future Network & Mobile Summit 2010	Florence, Italy	16/06/2010	Academics and Private Sector
UoY Presenting	"Adaptive Linear Precoding for Iterative Maximum Likelihood Detection in Multi-Antenna Systems"		ISTC 2010	France, Brest	06/09/2010	
			The 6th IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2010)	Chengdu, China	23/09/2010	
CTTC Presenting			The Personal, Indoor and Mobile Radio Communications Symposium (PIMRC)	Istanbul, Turkey	26/09/2010	IEEE Conference - Academics and Industry
CTTC Presenting	"Energy Benefits of Cooperative Docitive over Cognitive Networks"		EUMW	Paris, France	26/09/2010	

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
ALV participating	Presentation of BuNGee		ARTIST-4G Workshop, EC Concertation meeting and RAS meeting	Brussels, Belgium	18/10/2010	
UoY	A Fixed Beamforming Approach Exploiting MIMO	Agisilaos Papadogiannis and Alister G. Burr	URSI 2011	Leicester, UK	12/01/2011	Experts community and Academics
ALV	Working with ETSI: ISG or Technical Committees	Marianna Goldhammer, Markus Mueck	EC Concertation meeting	Brussels, Belgium	09/02/2011	Experts community and EC funded projects
ALV	Spectrum impact questionnaire for research projects funded under FP7	Consortium	EC request to Robert Horvitz		01/05/2011	Experts community and EC funded projects
CTTC	A Real-Time FPGA-based Implementation of a High-Performance MIMO-OFDM Mobile WiMAX Transmitter	. Font-Bacha, , N. Bartzoudisa, A. Pascual-Iserteа,b, D. Lopez Buenoa	MOBILIGHT '11 - The 3rd International ICST Conference on Mobile Lightweight Wireless Systems	Bilbao, Spain	09/05/2011	Experts community and Academics
UoY	Multi-beam Assisted MIMO - A Novel Approach to Fixed Beamforming	Agisilaos Papadogiannis and Alister Burr	Future Network and Mobile Summit 2011	Warsaw, PL	15/06/2011	Experts community and Academics
CTTC	Robust Linear Precoding for MSE Minimization in MIMO Broadcast Systems with Channel Gram Matrix Feedback	D. Sacristán-Murga, M. Payaró, A. Pascual-Iserte	SPAWC 2011	San Francisco	26/06/2011	Experts community and Academics

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
CTTC	"A Real-Time FPGA-based Mobile WiMAX Transceiver Supporting Multi-Antenna Configurations"	Font-Bacha , N. Bartzoudisa, A. Pascual-Isertea,b, D. Lopez Buenoa	Argentine Conference of Micro-Nanoelectronics, Technology and Applications (CAMTA) Argentine School of Micro-Nanoelectronics, Technology and Applications (EAMTA)	Buenos Aires, Argentina	06/08/2011	Experts community and Academics
CTTC	"PROTOTYPING PROCESSING-DEMANDING PHYSICAL LAYER SYSTEMS FEATURING SINGLE OR MULTI-ANTENNA SCHEMES"	Oriol Font-Bach, Nikolaos Bartzoudis, Antonio Pascual-Iserte, and David Lopez Bueno	EUSIPCO 2011	Barcelona, Spain	22/08/2011	Experts community and Academics
CTTC	Resource allocation between feedback and forward links: Impact on the system performance and the accuracy of the CSI	D. Sacristán-Murga, A. Pascual-Iserte, P. Tradacete	EUSIPCO 2011	Barcelona, Spain	29/08/2011	Experts community and Academics
UCL	Subspace Modelling of Multi-User MIMO Channels	N. Czink, B. Bandemer, C. Oestges, T. Zemen, A. Paulraj	IEEE VTC-Fall ’11	San Francisco, CA	01/09/2011	Experts community and Academics
ALV	Potential Study Items in TWG	Wladimir Yanover	TCC, TWG Wimax Forum	Bangkok, Thailand	01/09/2011	Experts community and Academics
UoY	High Density Capacity Communications Using Cognitive Radio	David Grace	Cognitive Communications Seminar - CORNET consortium	Tel Aviv, Israel	01/09/2011	Experts community and Academics

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
UCL	Cognitive radio resource management for Beyond Next Generation Mobile Broadband Networks	Claude Oestges and Nicolai Czink	PIMRC 2011	Toronto, Canada	11/09/2011	Experts community and Academics
SIK	mmWaves Backhaul for Hetergeneous Mobile Networks	Shahar Peleg	Carrier Ethernet World Congress	Amsterdam, NL	13/10/20 11	Experts community and Academics
UoY	Physical Layer Network Coding for Next Generation Wireless Broadband	Alister Burr University of York	UK COMNET	Southampton, UK	31/10/20 11	Experts community and Academics
UCL	Multi-Link Propagation Modeling for Beyond Next Generation Wireless, Loughborough Antennas and Propag	C. Oestges	Conf. – LAPC '11	Loughborough, UK	01/11/2011	Experts community and Academics
UoY	Efficient Interference Mitigating Strategies for Two-Way Relay Channels	Agisilaos Papadogiannis, Alister Burr, and Meixia Tao	IEEE ISWCS	Aachen, DE	06/11/20 11	Experts community and Academics
ALV	BuNGee project overview	Naftali Chayat	IEEE COMCAS 2011	Israel	07/11/20 11	Experts community and Academics
UoY	Cognitive radio resource management for Beyond Next Generation Mobile Broadband Networks	Tao Jiang, David Grace	WUN Cognitive Communications Consortium Meeting	Houston, US	05/12/2011	Academic/Industrial members of the WUN COGCOM Consortium
UoY	Physical layer network coding for 4G and beyond	[illegible] of York, U.K. and Agisilaos Papadogiannis, Chalmers University, Sweden Meixia Tao, Shanghai Jiaotong	UK-China Workshop on Beyond 4G wireless networks	London (University College)	13/12/2011	Experts community and Academics

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
CTTC	10 times Beyond LTE-A	Mischa Dohler	2021 TID Networking Summit	Spain	15/12/2011	Experts community and Academics
CTTC	NS2021: 10 Times Beyond LTE-A- Business Case, Technologies, Challenges	Mischa Dohler	2021 Networking Summit	Barcelona, Spain	28/12/2011	Telefonica stakeholders
UoY	Low - Complexity Iterative Detection for Overloaded Uplink Multiuser MIMO OFDM System	MinChen, Alister G. Burr	16th International ITG Workshop on Smart Antennas (WSA 2012)	Dresden, Germany	01/03/2012	Experts community and Academics
UoY	Parallel Multiple Candidate Interference Cancellation with Distributed Iterative Multi-cell Detection and Base Station Cooperation	Peng Li, Rodrigo C. de Lamare	16th International ITG Workshop on Smart Antennas (WSA 2012)	Dresden, Germany	02/03/2012	Experts community and Academics
UCL	SMALL SCALE STATISTICS OF FIXED RELAY POLARIMETRIC LINKS AT 3.5 GHz	Nizabat Khan, Claude Oestges	WCNC 2012	Paris, France	01/04/2012	Experts community and Academics
CTTC	Mutual Coupling Effects in Multi-User Massive MIMO Base Stations	Xavier Artiga, Bertrand Devillers	AP Symposium 2012	USA	08/07/2012	Experts community and Academics
UoY	Physical-layer Network Coding based Interference Exploitation Strategy for Multi-user Hierarchical Wireless Netwroks	Dong Fang, Peng Li, Alister Burr and rodrigo de Lamare	European Wireless Conference	Poznań, Poland	18/04/2012	Experts community and Academics
UCL-UoY	Impact of Multi-beam Antenna Amplitude Tapering on Co-Channel Interference and Backhaul Throughput Density	Nizabat Khan, Claude Oestges, Tao Jiang, David Grace, Alister G. Burr	WPMC 2012	Taipei, Taiwan		Experts community and Academics

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
UCL-UoY-ALV	Workshop on 4G Mobile Radio Access Networks Delivering Ubiquitous User Experience via Cutting Edge Technologies, workshop to be carried out with ARTIST 4G consortium		WCNC 2012	Paris, France	01/04/2012	Experts community and EC funded projects
CTTC	A real-time FPGA-based implementation of a high-performance MIMO-OFDM transceiver featuring a closed-loop communication scheme	Oriol Font-Bach, Nikolaos Bartzoudis, Antonio Pascual-Iserte and David Lopez Bueno	VTC2012-Fall	Québec City, Canada.	3-6 September 2012	Experts community and Academics
CTTC	The ETSI BRAN 1Gbps/km2 Cost-Efficient Cognitive Communications Architecture	P. Blasco, M. Dohler	Proceedings of 3rd International Workshop on Cognitive Information Processing (CIP)	Parador de Baiona (Spain)	28-30/05/2012	
CTTC	Distributed Strategies for Backhaul-Aware Self-Organizing Networks	P.Blasco, M. Bennis and M.Dohler	Globecom 2012			
UCL	Study of a Polarimetric Model for Diffuse Scattering in Urban Environment,	E.M. Vitucci, F. Mani, V. Degli Esposti, C. Oestges,	Proceedings of 6th European Conference on Antennas and Propagation - EuCAP,	Prague, Czech Republic	01/03/2012	
UoY	Beyond Next Generation Mobile Broadband Network System Capacity	Tao Jiang, David Grace	WUN Cognitive Communications Consortium	Ottawa, Canada	15/06/2012	

Partner Responsible	Title	Authors	Event	Location	Start date	Audience
CTTC	1Gbps/km2 Architecture http://www.youtube.com/watch?v=MNZ_6QEQE-o	Mischa Dohler	LTE World Summit	Barcelona, Spain	31/05/2012	

The Specialist Publications are presented in the table below:

Table 5-3: Specialist Publications

Partner Publishing	Title	Authors	Journal
CTTC Publication	"Differential Feedback of MIMO Channel Gram Matrices Based on Geodesic Curves	Daniel Sacrist´an-Murga and Antonio Pascual-Iserte	IEEE Transactions Wireless Communications
UoY Publication	"Efficient Selective Feedback Design for Multicell Cooperative Networks"	Agisilaos Papadogiannis, Member, IEEE, Hans Jørgen Bang, Member, IEEE, David Gesbert, Senior Member, IEEE, and Eric Hardouin, Member, IEEE	IEEE Transactions on Vehicular Technology
UCL	IMPACT OF TRANSMIT ANTENNA BEAMWIDTH FOR FIXED RELAY LINKS USING RAY-TRACING AND WINNER II CHANNEL MODEL".	Nizabat Khan and Claude Oestges	EuCap 2011
CTTC Publication	"A Real-Time MIMO-OFDM Mobile WiMAX Receiver: Architecture, Design and FPGA Implementation"	O. Font-Bacha, , N. Bartzoudisa, A. Pascual-Isertea,b, D. L´opez Buenoa	special issue of Elsevier journal of Computer Networks
UoY Publication	Bringing Mobile Relays for Wireless Access Networks into Practice – Learning When to Relay	Agisilaos Papadogiannis, George Alexandropoulos, Alister Burr, and David Grace	IET Communications
UCL publication	"Accuracy of Depolarization and Delay Spread Predictions Using Advanced Ray Based",	Francesco Mani, Franc¸ois Quitin and Claude Oestges	EURASIP
UoY Publication	"On the Maximum Achievable Sum-Rate of Interfering Two-Way Relay Channels"	Agisilaos Papadogiannis, Alister Burr and Meixia Tao	IEEE Communications Letters
UCL publication	"Analytical Multi-User MIMO Channel Modeling: Subspace Alignment Matters"	Nicolai Czink, Bernd Bandemer, Claude Oestges, Thomas Zemen, Arogyaswami Paulraj	IEEE TWC
UCL publication	"Ray-Tracing Simulations of Diffuse Scattering Angular Properties in Indoor Scenario"	Francesco Mani, Student Member, IEEE, Franc¸ois Quitin and Claude Oestges, Member, IEEE	TAP

Partner Publishing	Title	Authors	Journal
CTTC	"Transceiver Design Framework for Multiuser MIMO-OFDM Broadcast Systems with Channel Gram Matrix Feedback"	Daniel Sacristán, Miquel Payaró, Antonio Pascual-Iserte	IEEE Transactions on WC
CTTC	"Physical layer prototyping of high performance broadband wireless communication systems: from a high-level simulation model to a real-time implementation"	Nikolaos Bartzoudis, Oriol Font-Bach, Antonio Pascual-Iserte, and David Lopez Bueno	EURASIP Journal on Wireless Communications and Networking
UCL, UOY, CASMA	BuNGee backhaul network and joint beam processing		IEEE Trans VT
UCL	Small Scale Statistics of Fixed Relay Polarimetric Links at 3.5 GHz	Nizabat Khan, Claude Oestges	COST IC1004
UoY	Reinforcement learning based channel assignment for dual-hop BuNGee system		IEEE Transactions on VT
UoY	Efficient exploration based cognitive radio techniques exploiting multi-beam directional antenna		IEEE Transactions on VT
ALV	BuNGee research project	BuNGee consortium	COMCAS 2011 IEEE event
CASMA	"Beyond Next Generation Mobile Broadband: BuNGee" in The Masters of MIMO Series	Patrick Hemphill, Malcolm Ware	Microwave Journal, Vol. 55, No. 1 dated January 2012
UCL	Polarimetric Properties of Diffuse Scattering from Building Walls: Experimental Parameterization of a Ray-Tracing Model	Enrico M. Vitucci, Member, IEEE, Francesco Mani, Student Member, IEEE, Vittorio Degli Esposti, Member, IEEE and Claude Oestges, Member, IEEE	TAP
CTTC	MATLAB as a design and verification tool for the hardware prototyping of wireless communication systems	Oriol Font-Bach, Antonio Pascual-Iserte, Nikolaos Bartzoudis and David Lopez Bueno	MATLAB, InTech publishing
UCL	A Ray Based Method to Evaluate Scattering by Vegetation Elements	Francesco Mani and Claude Oestges	IEEE Transactions Antennas and Propagation (IEEE-TAP),

The BunGee website is located at http://www.ict-bungee.eu.

5.2.1 Publication acknowledgements

BuNGee partners are grateful to the EC commission for the help provided in the development of this platform and should include the following acknowledgment on any publication derived via BuNGee:

“This work has been undertaken in the framework of the BuNGee project: ICT-248267, which is partly funded by the European Community. The Authors would like to acknowledge the EC for their support and all the consortium members for their precious suggestions and review.”

6 Business Cases

This section analyses various business cases for BuNGee, i.e. potential market segments for deployment of BuNGee technology based solutions.

The following market segments/applications have been selected:

1. BuNGee Architecture - HetNet/ Small Cells deployment for mobile BWA markets and use of in-band backhauling for small cells;
2. Increasing BWA systems throughput density with BNG Multi-Beam antenna
3. mmWave links for Backhauling
4. FPGA-ready HDL WiMAX MIMO reference design (BeMImoMAX)

Each currently considered business case covers a certain market segment and is presented hereafter in a common format as follows:

- *Description*: Explanation of the use case/market segment.
- *Specific requirements*: Description of specific requirements (technical, legal, other) that need to be met to address this market segment.
- *Prerequisites for BNG*: Potential of and/or conditions for BNG based solutions to meet these requirements and prerequisites that need to be achieved to be able to address this specific market segment.
- *Market size*: Estimated total available market potential for the identified market segment; estimated potential revenue for BNG based business.
- *Competition*: Competing or alternative solutions, their strengths and weaknesses.
- *Added value of BNG*: What will be better in BNG based solutions than in any economically alternative viable alternative solution.
- *Business model*: Typical business model to address this market: e.g. products, service, IPR licensing.

The extended business case propositions comprise among others: a SWOT analysis, quantified expected economic impact, Return on Investment (ROI) from the investor's perspective and a review of costs factors and benefits of technology deployed in the market segment.

SWOT analysis is a strategic planning method used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project or in a business venture. It involves specifying the objective of the business venture, product or project and identifying the internal and external factors that are favourable and unfavourable to achieve that objective.

6.1 BuNGee Architecture - HetNet/ Small Cells deployment for Mobile BWA

To cope with the capacity crunch, operators are starting to deploy 3G/ 4G mobile networks in multi-layered macro- / small-cell architectures, referred to as heterogeneous networks (HetNet), where the "traditional" macro-cells provide the coverage and an underlay of small-cells is deployed to provide high-capacity hot spots.

BuNGee develops the HetNet approach into the new level of architecture design. The corner-stone of the novel BuNGee heterogeneous architecture, is the tightly coupled joint design of access and backhaul networks 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. Referring to the BuNGee architecture, it includes heterogeneous design of Hub BS (HBS) and Access BS (ABS) serving correspondingly backhauling and access links and Mobile Stations (MS), served by HBS and ABS.

BuNGee architecture enhances the HetNet concept with ultra-high capacity feeding network and below roof-top deployment of small cells. In backhaul tier, BuNGee articulates use of novel multi-beam antenna coupled with advanced MIMO techniques to increase spatial spectral reuse factor, use of in-band backhauling, joint use of licensed and license-exempt spectrums, etc.

Alvarion introduces the concepts developed in BuNGee project into its 4Motion product family of Macro- and Pico- Base Stations, network solutions and CPEs.

Table 6-1: BuNGee Architecture - HetNet/ Small Cells deployment for Mobile BWA

Description	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 demand for wireless broadband access is the highest, thereby seriously jeopardizing the wide scale uptake of IMT-Advanced technologies. Mobile operators are facing the tremendous demand for data with the explosion of smartphone use. Between 2011 and 2015, global mobile traffic is expected to grow 26-fold (source: Cisco VNI forecast), with connection speeds increasing significantly. Mobile BWA operators will be constantly seeking for their access network capacity increase by upgrading wireless access technology (moving e.g. to LTE and LTE-A) and introducing the novel deployment models (such as small cells deployment) while at the same time managing efficiently the associated costs. Beyond Next Generation networks research project (BuNGee) has been established with objectives to dramatically improve the overall infrastructure capacity density of the mobile network by an order of magnitude (10x) 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. Such an ambitious requirement for capacity density is driven mainly by urban areas where the number of users per square kilometre and mobile data usage factor is expected to grow. BuNGee sees itself as a facilitator and enabler for the future mobile broadband wireless networks. 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. Alvarion addresses the Mobile and Fixed BWA operators requirements with its state-of-the-art BreezeMax 4Motion portfolio and plans to introduce the innovative concepts developed in BuNGee project – small cells (Pico-cells) below roof-tops deployment, use of multi-beam antenna in Backhauling and Fixed BWA networks, use of in-band backhauling concepts, adaptation of novel RRM and SON features.
Specific requirements	The target deployment should enable data throughput density of 1 Gb/s/km^2 with 4G RAN technology implemented in the high-density urban environment providing reasonable Grade of Service (*GoS*) and the deployment cost structure. To address constantly growing capacity demand, there is a need for high spectral and spatial reuse – use of small cells, with low positioned antennas enabling high frequency reuse, and high signal-to-interference-and-noise ratio. The small cells are expected to be powered by a new class of BSs called Pico-BS. These BSs require small antennas, low cost, minimal maintenance and a broadband backhaul in order to be viable. BuNGee addresses these by developing innovative in-band backhauling concepts, ultra high-capacity point-to-point wireless links in mmWave spectrum and by novel methods contributing to interference reduction and RAN operation simplification.
Prerequisites for BNG	Realising 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 rooftop. 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 BuNGee 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 will be provided over the licensed spectrum. For the Backhaul Tier, BuNGee develops 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 targets development of Radio Resource Management 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-organising networks. The cost is an important element of the design. Thanks to the “below rooftops” deployment paradigm, BuNGee intends using small (Pico-factor) outdoor Access Base Stations. The cost reduction will be achieved by: • Much lower transmission power for the ABSs itself; • Avoidance of the costly roof leasing, as the deployment will use electricity poles, street lights, etc.; • In-band backhauling approach relaxing backhauling requirements; • Effective usage of license-exempt spectrum for the feeding link As presented in the D4.4 deliverable (Live Test Evaluation Report), the Live Test system clearly demonstrated close-to-target equivalent system throughput density of ~840 Mbps/ km^2 in a real field capacity-oriented deployment in a dense urban area for outdoor users. This result also matches the results of system-level simulations. Other demonstrated scenarios proved the feasibility and the efficiency of the developed concepts: • The elements of the BuNGee Architecture, protocols and algorithms; • Below-rooftop outdoor deployments of a high density grid of Access Base Stations (small cell factor), exploiting buildings isolation and near-LOS radio propagation along the streets to increase both the frequency reuse and the system capacity in a given area; • BuNGee-developed high capacity wireless backhauling concepts including use of multi-beam antenna, innovative in-band backhauling schemes, ultra high-capacity mmWave links, joint use of licensed and license-exempt spectrums; • Advanced MIMO schemes and interference mitigation techniques.
Market size	According to ABI research, the total revenues for pico-, micro-, and macrocell BS equipment 3G/4G are expected to reach $13 billion by 2015. As presented in the section 4.2, according to Frost & Sullivan research [17], the revenue in the Picocell product segment was estimated to be USD 0.23 billion in the calendar year 2009 and expected to grow to 1.82 billion by the end of 2015 at a CAGR of 34.4 percent. As presented in the section 4.3, according to Maravedis report [20], the wireless PtmP backhaul equipment market is expected to reach US$1 billion by 2016 from $200 million in 2011. Beyond 2013, the rise of LTE deployments, in combination with small cells growth, will drive the growth of PtMP’s market adoption.

Competition	The competing solution to increase RAN capacity may be: • Increase of operator's spectrum width. This would require either more spectrum in lower frequencies, which is problematic for operators - no licensed spectrum available, or move into higher spectrum bands, which may present number of technical and business issues. • Use of advanced PHY techniques – such as multi-user MIMO, beam forming, Coordinated Multi-point transmission (CoMP), etc. in the existing Macro-cells. These techniques may be particularly useful only when good SINR values are observed – thus also driving to the "small cell" deployment concept with LOS or near-LOS radio propagation conditions. On the other hand, these techniques cannot provide 26x to 50x fold capacity increase. In fact, as presented in the section 4.2 analyzing the "Cooper's Law effect", such a capacity increase may be achieved only by spatial spectrum reuse – i.e. making the "cells" smaller. Indoor solutions (such as Distributed Antenna Systems and Femto-cells), in our view, are not competing with BuNGee and are complementary to the proposed concepts.

Added value of BNG	Analysis of the BuNGee Architecture achievements done in Live Demo evaluation led us to the following conclusions:
	▪ HetNet deployment model, especially small cell installations below roof-tops, leveraging the natural building isolation and good near-LOS radio propagation along the streets, proves to be the main means of throughput/ capacity density increase in outdoor environment.
	▪ BuNGee architecture brings a huge diversity in transmission platforms, including high capacity backhaul which can bring an interesting support to future operator's deployment. Market shows an increasing need in throughput capacity, reducing the cell sizes to offer higher data rates per user. However the backhauling solution must also follow those improvements, which is harder and harder due to the increasing station number and location. BuNGee self backhauling strategy can here be used as a replacement to optical fibre and other wired strategies.
	▪ Small cells backhauling represents the critical issue for deployment of dense grid of Access BSs:
	    ▪ In-band backhauling proves to be economically cost-efficient, but limits the deployment capacity-wise (by exploiting part of "expensive" licensed spectrum for backhauling);
	    ▪ Use of mmWave backhauling technology provides both the required capacity and cost-efficiency, but may suffer from weather conditions and LOS requirements;
	    ▪ Joint use of In-band and dedicated out-of-band backhauling (e.g. mmWave links) provides the most viable solution for required reliability, but increases the cost of deployment.
	▪ Use of the Multi-Beam Antenna proves to be an efficient way to increase capacity of the broadband wireless network optimized for backhauling or fixed/ portable access. Full-scale mobile deployments may experience excessive interference levels when using MBA.
	▪ Application of MIMO and resource allocation techniques across the beam domain of Hub Base Station promises significant performance gains.
	
	BuNGee architecture becomes the key enabler for achieving wireless broadband:
	▪ network air traffic density growth;
	▪ CAPEX/OPEX benefits;
	▪ "Green Energy" efficiency.
	BuNGee also impacts positively the quality of life for European and worldwide consumers through its resulting low EMF radio exposure, "greener" less radiating handsets and smaller, less obtrusive antennas that blend into electricity poles, street lights, etc.

<table>
<tr><td></td><td>Macro- and small below-rooftop deployment schemes, as well as the use of dedicated solutions for indoor coverage, will reduce transmitted power in base stations and in user equipment, which in turn will reduce the impact on the human body, improve users' well-being as well as prolong battery life, another always-welcome outcome, particularly in view of the contemporary regulations for radiated power levels.

BuNGee networks SON capabilities are very well suited for small cells deployments, either to fill holes in the global coverage, temporary increase capacity in a given area (hot spot), or to add some pico-stations specific to restricted services (Public safety, PPDR, etc.). A reduced BuNGee-like deployment could respond to different increasing demands and operator's issues thanks to its adaptation capabilities. The service would then be inserted smoothly and would not require a dedicated frequency resource.</td></tr>
<tr><td>Business model</td><td>According to the “Cooper's Law” effect, the customers required capacity increase of Mobile BWA networks may be achieved only by spatial spectrum reuse – i.e. by adding new mobile cells. Embedding Small/ Compact Cells into the deployment presents high potential for the industry - allowing Mobile BWA operators to address the capacity demand and manage the deployment CAPEX/ OPEX costs.

According to the Senza Fili Consulting research [21], the Compact BS presents significant value for the operator compared to the traditional BS architecture approach.

The value proposition of Compact BS includes:
▪ Lower CAPEX, due to:
  ▪ Less expensive equipment;
  ▪ No ground equipment required;
  ▪ Lower installation costs.
▪ Lower OPEX, due to:
  ▪ Lower power consumption, no active cooling;
  ▪ Lower rent, because of equipment's smaller footprint and of use of non-traditional sites with lower site rental costs.
▪ Faster time to market:
  ▪ Single-box, preconfigured equipment requiring less expertise and time to install;
  ▪ Installation on existing infrastructure with reduced permitting requirements.
▪ Future-proof:
  ▪ SoC technology enabling software-defined radio functionality in a compact architecture;
▪ Green technology:
  ▪ Low power consumption, due to the absence of ground equipment and, especially, power-hungry cooling units;
  ▪ Off-grid operation using solar or battery power.</td></tr>
</table>

6.1.1 SWOT Analysis

Strengths:

- Ultimate capacity and spectral efficiency (as was demonstrated in the Live Test deployment in the real high-density urban environment), reaching the targeted 1 Gbps/km^2 throughput density.
- The cost savings in deploying small factor (Compact) BS equipment in terms of both OPEX and CAPEX.
- Presenting evolutionary path for the existing Macro- deployments and the existing WiMAX and 3GPP 3G/ 4G technologies.
- Low power transmissions in the Access Tier – resulting in the lower energy consumption and significantly lower human body exposure to radio transmissions.

Weaknesses:

- There is no sufficient experience in the industry for small cells deployment.

- Site acquisition for small cells is challenging – requires new business and operational arrangements.
- In-band backhauling concept even especially efficient at the beginning of the small cells deployment, but afterwards becomes restrictive when capacity demand further increases – it “wastes” operator’s licensed spectrum for small cells feeding (which otherwise may be used by the operator for user access). Mobile BWA Operators, in general, will prefer to use licensed spectrum for access, offloading feeding to another spectrums/ technologies (such as e.g. mmWave, 5 GHz, etc.)

Opportunities:

- Tremendous data requirement growth in Mobile BWA operator’ networks.
- The wireless industry eco-system becomes mature for small cells implementation presenting high level of chip integration (RFIC, SoC, etc,) and the relevant toolkits. Advances in multi-core chipset technology allow for the development of multi-mode Compact BS platforms that can combine low costs (femtocell-like) and deployment efficiency comparable to macro-, micro-, and pico-cell architectures (expected to kick start this transition around 2012).
- Alvarion’s sales and operational infrastructure is well developed to provide Mobile and Fixed BWA solutions for the operators.

Threats:

- Competition from large and especially Chinese 4G vendors - might be hard to penetrate the existing RAN with incumbent vendor. It is also hard to achieve radio PHY and networking compatibility between RANs of different vendors.
- High diversity of 3G - 4G market (different technologies: UMTS, HSPA/+, WiMAX, LTE, etc., different frequency bands).
- The peak of LTE market (forecasting high data capacity demand) may be delayed thus reducing the need of Pico-BSs.

6.1.2 Distribution structure

Alvarion implements direct or 2-tier sales channel-based distribution practice. Big projects normally require Alvarion to become front-end and project integrator, while in smaller projects, especially with limited interoperability (such as e.g. small Fixed BWA and WISP projects) Alvarion acts indirectly, operating via the sales channels.

During the new technology or new deployment concept adaptation phase (when higher implementation risks are expected), Alvarion will act as a front-end, providing integrated solution to the customer.

Alvarion also may practice OEM based sales to one of Tier 1 TEM.

6.1.3 Economic impact

BuNGee Architecture scalable design proved feasibility of achieving, in a cost efficient way, throughput densities substantially higher than available with today’s systems. Throughput levels of at least 1 Gbps/km^2 are targeted. This goal is addressed by a combination of techniques: use of below-rooftop access base stations and a unique feeding architecture using a combination of licensed in-band spectrum and out-of-band license exempt spectrum. Very high capacity feeding hubs with high-order spatial reuse are created using multi-beam antennas and advanced MIMO techniques, as well as use of millimeter wave radio links. Cognitive/docitive techniques were developed for self-organization and optimized resource utilization in the radio and feeding networks.

This provides the evolutionary approach by the definition of the most appropriate mix of technologies in terms of feasibility (current and in the near future), energy-efficiency (both for energy-usage and for radiated power to address the recent health issues) and cost in order to enable a pervasive small cells deployment that reveals mandatory within the next 4-5 years.

The solution will allow Mobile BWA operators to grow in a scalable way addressing the user’s data demand and generating added value for the entire communication eco-system – creating new connecting devices types and new application use cases and scenarios. Emerging wireless networking technologies and the ability to embed connectivity to these networks in virtually all types of devices are creating a new “connected” future. According to some industry players, the connected device segment will exceed 50 billion connections by 2020.

6.1.4 Return of Investments (ROI)

The TCO model developed and presented in Senza Fili report [21], compared distributed and Compact BSs, looking at CAPEX and OPEX over a five-year period in a large mobile operator scenario.

Cost savings over a five-year period for a large mobile operator using a Compact BS can reach $48,390 for a single-sector BS (42% overall cost savings, derived from a 58% reduction in CAPEX and a 32% reduction in OPEX), and $68,220 for a three-sector BS (38% overall cost savings, derived from a 48% reduction in CAPEX and a 30% reduction in OPEX), as presented on the below figures:

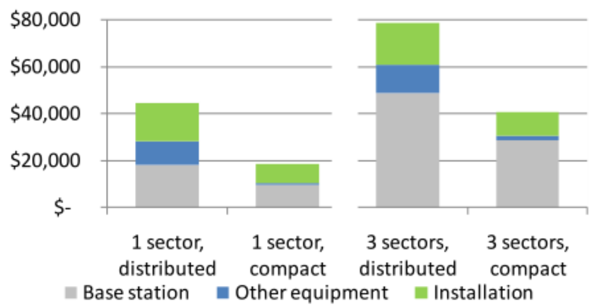


Figure 6-1: Distributed vs. Compact BS CAPEX (Year 1)

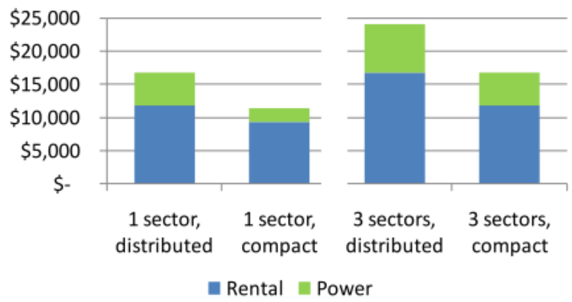


Figure 6-2: Distributed vs. Compact BS OPEX (Year 1)

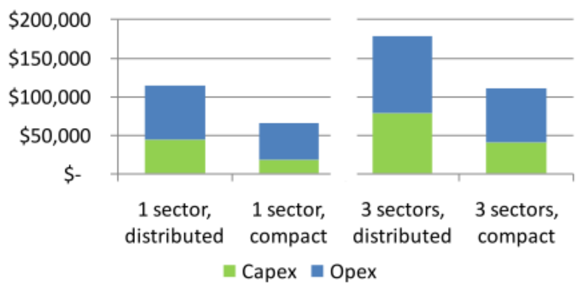


Figure 6-3: Discounted RAN costs (five-year period)

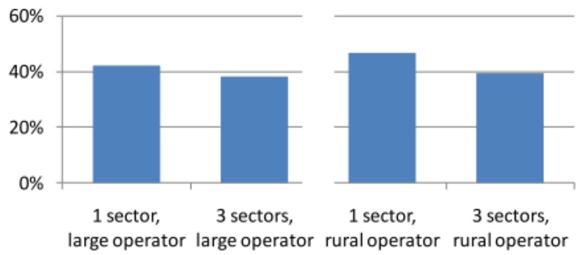


Figure 6-4: Per-site cost savings with a compact BS cell site over a distributed BS cell site

6.2 Multi-Beam Antenna for Broadband Wireless Access networks

The BuNGee project has formed the backbone of research into the construction and use of the multi-beam antenna. As such, given the time restraints the prototype has performed to expectations but still needs to be packaged in a way to be more ergonomic; easier to produce in volume and lower cost than a set of individual antennas.

Table 6-2: Multi-beam Antenna for BWA networks

Description	The BuNGee multi-beam Hub Base Station antenna has been specially developed for the BuNGee project by CASMA using an innovative beam forming approach. In conjunction with an integral Butler matrix assembly it produces 2 sets of 6 high-gain, narrow beams of +/-45˚ polarisation for MIMO which radiate within a 90˚ arc to a network of dual-polar Hub Subscriber Station antennas within a few hundred metres. Part of the critical design was to construct a low cost dual-slant polarised element which provided the fundamental wide beamwidth whilst maintaining good cross-polarisation and high isolation between elements. Second requirement was to create 8 dual-polar “Sector” elements which could be mounted a half wavelength apart, which is necessary to provide low sidelobe beam squint.
Specific requirements	When installed as part of the complete BuNGee system the multi-beam antenna contributes to the target data throughput of 1Gbps/km² within the cell in which it operates. This has been proven in live tests. Reduced interference between the sub-divided cells can be controlled by reducing sidelobe level. This can be achieved by providing amplitude tapering across the 8 dual polar “Sector” elements, which can be applied internally. The considerable flexibility of this antenna therefore makes it a potentially very marketable product for WiMAX/LTE etc. applications.
Prerequisites for BNG	As above; normally used in sets of four per cell to give 360˚ coverage, to be used in conjunction with a network of Hub Subscriber Station dual-polar antennas. Marketing prerequisites are that the BuNGee system as a whole has to be actively promoted in order to exploit the use of the antennas within the system.
Market size	Potentially very large as the need for ever-greater data throughput becomes a priority in urban areas. It is worth noting that while the multi-beam antenna technology is a pivotal part of BuNGee, it can also be used in WiMAX/LTE, etc. applications outside the BuNGee discipline. Building owners and landlords may be restrained by local by-laws relating to deployment of nests of antennas on roof-tops so the idea of a single multi-beam antenna has merits. This technology may have other applications where interference is an issue and narrow beams are required, which could be for security or even military applications. Other radio technologies such as COFDM could use this type of multi-beam antenna to provide longer range over a wide area with a non-moving antenna.
Competition	Other antenna manufacturers may produce competitive multi-beam antennas in time although CASMA has not been aware of a direct competitor that provides +/-45˚ polarisations with beams where the cross-over points are only 3dB down from the peak. During the life of the project our in-house development and near-field testing facilities have allowed us to have total control over the design specifically for the

	BuNGee project. Competing systems would need 6 individual antennas, which would take up larger area which may not be appropriate to the proposed installation.
Added value of BNG	The EU funding made available to us for development of the antenna has enabled us to explore avenues of innovative research, particularly with regard to multiple beam forming, and to physical construction that is particularly targeted at the BuNGee system. The resulting antenna package replaces 6 or even 12 individual antennas, with associated savings in material cost. Also the benefits of low mast rental of the multi-beam antenna as well as under-roof mounting of the Hub Subscriber Station antennas as required by BuNGee will reduce the outlay for installers / consumers.
Business model	The main target for the technology that has been developed are OEMs which have a need to increase levels of data through-put in dense urban environments. The antenna can be used with multiple radios, but the system behind the radio must be capable of handing such capacity, so the business case for the multi-beam antenna requires specific RF environment, which is limited to those customers who will have such a need. The application will go beyond WiFi/LTE and into merging of fixed and mobile 4G networks. The technology will be applicable to other bands and technologies. Bungee has allowed the development of the technology to demonstrate the multi-beam antenna's benefit in the system and for CASMA to develop B-Model antennas which will have sufficient level of integration (removal of 16 phase-matched cables) in a full PCB-based beam-former and antenna unit to be demonstrated in pre-production systems. It is the intention to build a small number of units which will enable customers (OEMs and System providers) to test products in the field during 2012. Following detailed trials and understanding the cost structure for the final unit will allow provision of quotes for cost-effective production units ready for when the market demand is created. The market could be for 1000+ antennas during 2013-2015 worth Euro 2-3 M, and significantly higher beyond that.

6.2.1 SWOT Analysis

Strengths:
- The finished product will be more compact than individual antennas;
- It will be more economical to mount so reducing mast rental;
- Excellent technical backup and support within CASMA;
- Antenna also suitable for systems other than BuNGee.

Weaknesses:
- Difficulty with being able to manufacture the Butler matrix component cheaply;
- Antenna narrow-band so dedicated designs necessary for different frequencies.
- 90˚ beam may be restrictive
- Sidelobe suppression achieved through attenuation

Opportunities:
- CASMA sales team in position to promote and market antenna;
- Company already supplies WiMAX, etc. so established in the marketplace
- Pent up demand for bandwidth in dense environments requires this solution
- Other solutions require high level of digital overhead
- Technology is scalable to other bands and other configurations

Threats:
- Competing antennas appearing on the market;
- Use of better performing multiple antennas – more efficient (although larger)
- Digital beam-forming
- Market demand does not grow at expected rate

6.2.2 Distribution structure

CASMA's distribution structure is through its own sales teams and representatives in major countries. As we already sell into the WiMAX, LTE etc. markets, promoting the BuNGee system and antennas is the next logical step.

6.2.3 Economic impact

The economic impact of BuNGee as a complete system is difficult to gauge. However as the antennas can be used in other communications systems it seems clear that a market already exists for them subject to competitive pricing. If BuNGee becomes a standard CASMA can hope to capitalize on supplying antennas to support it.

6.2.4 Return of Investments (ROI)

As previously stated the antenna has a potential demand in the WiMAX / LTE marketplace for applications besides BuNGee. As such the investment could be recouped over a short period of time; if BuNGee is rolled out in the medium term the extra sales of antenna sets would ensure this, notwithstanding extra expenditure in further productionising the antenna for ease of manufacture and reducing component cost.

6.3 mmWave links for mobile backhauling

Table 6-3: mmWave PtP links for mobile backhauling

Description	Mobile operators are facing exponentially increasing demand for data with the explosion of smartphone use. Between 2011 and 2015, global mobile traffic is expected to grow 26-fold (source: Cisco VNI forecast), with connection speeds increasing significantly and the majority of traffic devoted to data and video. To cope with this capacity crunch, operators are deploying 3G and 4G-LTE macrocells. However, an additional capacity boost is required, particularly in dense urban areas. To achieve this, carriers are increasingly deploying 4G-LTE mobile networks in multi-layered macro-cell / small-cell architectures, also referred to as heterogeneous networks, where the "traditional" macro-cells provide the coverage and an underlay of small-cells is deployed to provide high-capacity hot spots. Siklu designs the EtherHaul-600, an ultra-small, all-outdoor small cell backhaul product that enables rapid deployment anywhere, from street lamps to rooftops. Operating in the 57-66 GHz license-exempt band, the EtherHaul-600 provides scalable gigabit throughputs, allowing operators to meet the capacity needs of today and future-proof the backhaul network. The EtherHaul-600 offers extremely low power consumption and plug-and-play installation into an operator's Self Organizing Network (SON) with a full suite of integrated networking capabilities. As a result of Siklu's innovative all-silicon design, equipment costs are dramatically reduced to a fraction of other millimeter wave solutions. This represents a key stepping stone to the mass deployment of small cells.
Specific requirements	The small-cells will be installed at the street level - on street lights, lamp poles, and building walls - so they are as close as possible to the mobile broadband consumers. Consequently, the small-cells and associated backhaul equipment are required to be "invisible" with a very small form factor that blends naturally into the street level environment. Thousands of small cells will be deployed to provide the required capacity boost in a typical highly populated metropolitan area. Consequently, both the small-cells and the associated backhaul network must be at an unprecedentedly low cost. Total cost of operation (TCO) must be lowered significantly as well, through reduced power consumption and ease of installation.
Prerequisites for BNG	Backhauling using mm-waves at 60GHz becomes a viable technology in high capacity, dense urban networks, where the distances between cell sites are of the order of 300 meters

<table>
<tr><td>Market size</td><td>The explosive growth of small cells coupled with the performance advantages and cost-effectiveness of wireless backhaul will ignite the mobile backhaul market. Mobile Experts forecast that shipments of both NLOS and mm-wave backhaul equipment will exceed 1.8 million units in 2016, representing more than $1.5 billion annual revenue. Source: Backhaul for small cells: A 1.5 billion dollar market opportunity; Jonathan Wells, Mobile Experts, 11/21/2011</td></tr>
<tr><td>Competition</td><td>
<table>
<tr><th></th><th>Frequency used</th><th>License required</th><th>NLOS/LOS</th><th>Main Usage</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Wi-Fi</td><td>2.4GHz or 5GHz</td><td>License free</td><td>NLOS</td><td>Public wireless communication</td><td>Easy to install</td><td>Very busy spectrum where any consumer can become a transmitter</td></tr>
<tr><td>Inband Access Spectrum (LTE & WiMAX)</td><td>1.9 – 3.6 GHz</td><td>Licensed</td><td>NLOS</td><td>Public wireless communication</td><td>Use the same spectrum used to deliver the service</td><td>The spectrum is very expensive and mostly used for service provision</td></tr>
<tr><td>Microwave</td><td>6-38GHz</td><td>Licensed</td><td>LOS</td><td>Macro Cell backhaul</td><td>Wide spread technology</td><td>Spectrum congestion, Size (requires large antennas) and high spectrum licensing costs</td></tr>
<tr><td>60 GHz</td><td>57-66 GHz</td><td>License free</td><td>LOS</td><td>Mainly used for small cells backhaul</td><td>Easy radio planning, very low interference to other transmitters, Small devices</td><td>Require antenna alignment. Relatively short distances.</td></tr>
<tr><td>E-Band</td><td>70-80GHz</td><td>“Light License” or Licensed</td><td>LOS</td><td>Backhauling</td><td>Easy radio planning, very low interference to other transmitters, Small devices</td><td>Size (requires a minimum size antenna to meet regulation requirements</td></tr>
<tr><td>Fibre</td><td>NA</td><td>NA</td><td>NA</td><td></td><td>Unlimited capacity where available</td><td>High installation costs and long time to deploy where not available</td></tr>
</table>
</td></tr>
<tr><td>Added value of BNG</td><td>As a part of BuNGee research project, the low-cost highly integrated prototype 60GHz backhauling link was developed by Siklu and tested in the Live Test scenario proving the feasibility and efficiency of the presented concept. As a part of BuNGee Architecture design, this link was aggregated with in-band feeding link providing joint “multi-link trunk” and overcoming the associated technologies limitations (rain sensitivity of mmWave spectrum and much lower capacity of the in-band backhauling in the licensed spectrum).</td></tr>
<tr><td>Business model</td><td>Siklu plans to sell the EtherHaul-600 small-cell backhaul product to Tier 1 mobile operators mainly through OEM partners with established RAN vendors and wireless backhaul specialists. The product will be sold to Tier 2 and Tier 3 mobile operators through country / regional distribution channels</td></tr>
</table>

6.3.1 SWOT Analysis

Strengths:

- Unique and disruptive RFIC and antenna technology
- End-to-end, highly integrated product

Weaknesses:

- Limited range of up to 300 meters
- Requires line-of-sight installation which may not be available at all small cell sites

Opportunities:

- Huge market potential
- Virgin market waiting for an enabling backhaul solution
- No dominant solution available today

Threats:

- Competing non-line-of-sight solutions

6.3.2 Distribution structure

Siklu plans to sell the EtherHaul-600 small-cell backhaul product to Tier 1 mobile operators mainly through OEM partners with established RAN vendors and wireless backhaul specialists. The product will be sold to Tier 2 and Tier 3 mobile operators through country / regional distribution channels

6.3.3 Economic impact

Ultra high-capacity backhauling links technology in mmWave spectrum serve as the enabler of the next generation Wireless connected world, embedding Macro- and Pico-/ Small radio cells. It is critical to allow wireless connectivity of small cells, especially in high density urban areas – thus accelerating and simplifying the deployment, allowing flexibility in site acquisition and finally “uncapping” access network capacity providing wireless equivalent to fiber optics.

6.3.4 Return of Investments (ROI)

Thousands of small cells will be deployed to provide the required capacity boost in a typical highly populated metropolitan area. Consequently, both the small-cells and the associated backhaul network must be at an unprecedentedly low cost. Total cost of operation (TCO) must be lowered significantly as well, through reduced power consumption and ease of installation. As a result of Siklu’s innovative all-silicon design, the EtherHaul-600 TCO is dramatically reduced to a fraction of other millimeter wave solutions. This represents a key stepping stone to the mass deployment of small cells.

6.4 BeMImoMAX – FPGA HDL WiMAX MIMO Reference Design

Table 6-4: BeMImoMAX – FPGA HDL WiMAX MIMO Reference Design

Description	BeMImoMAX is a FPGA-ready HDL reference design developed at CTTC, which showcases a real-time PHY-layer implementation of the IEEE 802.16e-2005 standard (mobile WiMAX). BeMImoMAX combines a 2x2 MIMO scheme and a wide bandwidth of 20MHz to enable a high performance operation at baseband. Other antenna schemes are also offered as optional add-ons (i.e., SISO and 1x2 SIMO). The PHY-layer was first modelled in MATLAB using a subset of the flexible WiMAX-OFDM specifications. Each of the processing blocks comprising the MATLAB model of the receiver and transmitter were then mapped to custom VHDL code and co-simulations were carried out to verify functional correctness. The RTL code of BeMImoMAX -Release 1- was eventually prototyped using the VHS-DAC, VHS-ADC, DRC-V4 & SMQUADV4 boards of Lyrtech RD and validated using the full set-up of the

	GEDOMIS® testbed. BeMImoMAX is currently being modified -Release 1.1- to target the Lyrtech RD Perseus 601X and Radio 420X boards.
Specific requirements	To facilitate a meaningful entry into the market segment BeMImoMAX has been designed for, it needs to have sufficient bandwidth; sufficiently powerful in terms of processing power; real-time; among other properties. All this is currently met and thus the system is marketable today.
Prerequisites for BNG	The technical prerequisites are the same as outlined above; they have been met due to the diligent design conducted within BuNGee. The market prerequisites are more stringent in that a suitable sales force or strong online marketing campaign needs to be invoked.
Market size	We are currently not able to quantify the market size, notably the addressable size. However, given that TTM is becoming a design bottleneck for many companies, this cutting-edge WiMAX/LTE-compliant prototype allows companies to reach their market quicker and more efficient. We thus expect the market to grow over the next years.
Competition	We are not aware of institutions like CTTC offering a comparable service. Of course, large companies have their testing and development facilities inhouse, which typically prevents them resorting to a system like ours.
Added value of BNG	We clearly cut development, implementation, troubleshooting and prototyping costs by offering a stable, tested and cutting-edge broadband hardware, in addition to the offered customer service.
Business model	The platform is thought to be commercialized by means of channels, such as Lyrtech RD who offer it to their customers at an extra margin and with the peace of mind that their hardware is eventually used; also, direct sales are possible; also, licensing of specific operational parts of the system is possible; finally, specific projects can be carried out on the platform.

6.4.1 SWOT Analysis

Strengths:

- enormous technical expertise within CTTC to backup any developments, problems, etc of said platform;
- technically very advanced platform meeting critical prototyping requirements;
- proven market through commercial relationship with Lyrtech RD.

Weaknesses:

- CTTC does not have visibility of a company since we are a non-for-profit centre;
- LTE and LTE-A compliant features still require some work (and thus time and money).

Opportunities:

- given that market is proven, CTTC is considering setting up a spin-off which will mitigate above weaknesses;
- opportunity to target companies around the world which develop products for LTE and LTE-A.

Threats:

- technology may outpace current development projections, eventually requiring a larger cash cushion to make this viable;
- competing solutions appear in the market.

6.4.2 Distribution structure

The current distribution structure of the marketable product is through a sales channel agreement with Lyrtech RD. This means that they are allowed to sell on the platform as is (and of course using their hardware) to their customers. This co-sell model is considered to be win-win in that Lyrtech gives their hardware more value and CTTC retains some fees.

6.4.3 Economic impact

In the current sales development stage, it is difficult to gauge the economic impact. However, given that a spinoff will eventually materialize, CTTC hopes to capitalize on the exponential sales stemming from said platform which had been developed within BuNGee.

6.4.4 Return of Investments (ROI)

Without considering any further development, i.e. neither technical nor commercial, the ROI for CTTC is a net-income from the fees stemming from the use of the platform. Since developments have been paid from the local and European fonts, the ROI is net. Said local and European bodies' ROI is through taxes paid from the income generated to CTTC. However, to further leverage on the value potential of the system, a startup is being planned.

7 Exploitation of the results by each partner

The technology developed during the project lifetime will form the basis for demonstrating the feasibility of ultra-high capacity mobile broadband wireless networks. The potential industrial exploitation will be based mainly on eventual further cooperation between consortium members beyond the project lifetime.

7.1 Industrial Partners

7.1.1 ALVARION

Alvarion plans to adapt the developed technologies in the real commercial projects and deployment scenarios. One of the conclusions of BuNGee research – is that HetNet deployment model, especially small cell installations below roof-tops, leveraging the natural building isolation and good near-LOS radio propagation along the streets, proves to be the main means of throughput/ capacity density increase in outdoor environment.

Alvarion intends to develop, manufacture and sell access and backhauling systems and algorithms that support and enable multi-tier concept of radio access network deployment. This will be based on a generic, scalable solution with similar, if not equal, features and algorithms in all types of BSs (macro-/ micro-/ pico-). As the outcomes of BuNGee, Alvarion performs cross-layer system design and develops algorithms and protocols optimizing the multi-tier network functionality and performance through combination of advanced handover metrics, inter-BS load balancing, interference mitigation techniques etc.

As another significant BuNGee outcome, Alvarion develops small cell (Access BS) technology – multi-standard Compact BS platform. Compact BS is a part of ALV 4G portfolio and is used as the integral part of ALV 4Motion product solution. Compact BS is planned to be used in various BWA deployment scenarios – such as rural broadband, urban/ sub-urban capacity-oriented deployments and as hot-spot capacity extensions.

It is an all-outdoor base station for fixed, nomadic and mobile wireless access in an easy-to-deploy, single compact box (~6 liters volume and ~8 kg weight), implementing multi-sector, multi-carrier (up to 4 x 10 MHz), 4X4 radio (4x27dBm with evolution to 4x36 dBm).

The powerful high performance modem implements true Software Defined Radio (SDR) technology and is based on a multi-core general purpose processor (GPP).

Alvarion presented this product during BuNGee Live Demonstration in Tel Aviv:

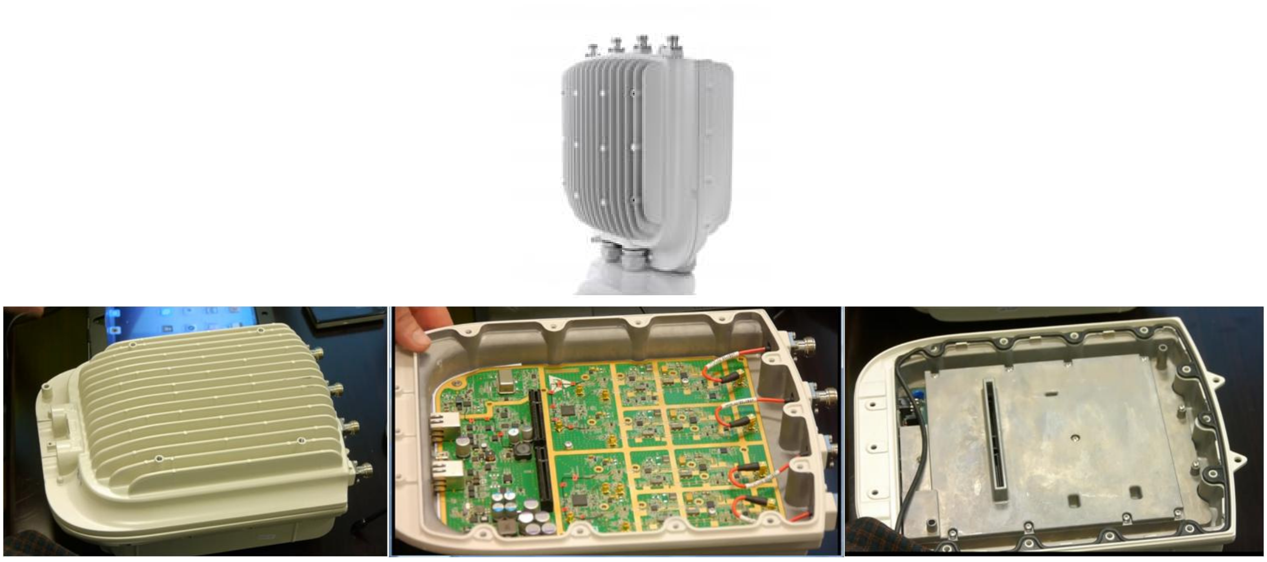


Figure 7-1: Small cell (Access BS) technology – housing, RF module, modem part (shielded)

Alvarion's foreground in features required for small cells and HetNet deployment strategy has been considerably increased during the project progress. Particularly, Alvarion gained knowledge, experience and confidence in the below roof-top small cell based radio network planning, deployment strategy and radio optimization, as it was demonstrated in the Live Demo.

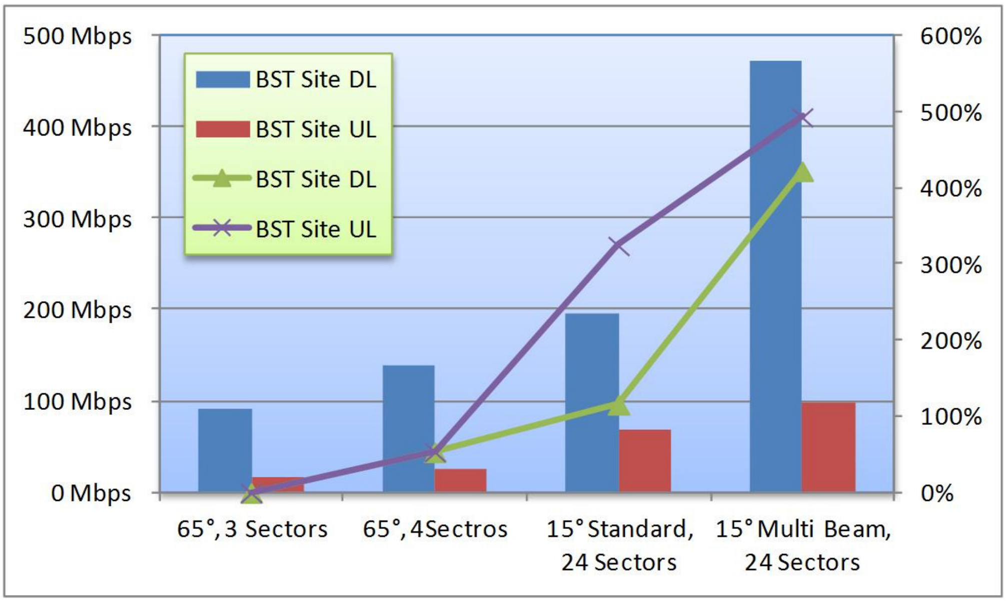
Future use of Compact BS includes HetNet/ Small Cells deployment scenarios with various backhauling capabilities and access technologies such as WiMAX and LTE.

Alvarion expects exponential growth in sales of small factor base station (Compact BS) as the best fit for the budget-aware/ cost-driven deployments with outstanding CAPEX and OPEX figures and continuous growth in capacity demand. Alvarion has started sales in 2012 with 10s of thousands BSs resulting in multi-million revenue from this product and penetrating the market in 2012 with ~2.4% market share. We expect it to grow up gradually and achieve ~8% of market share, exceeding 100 M USD in 2014.

Alvarion extensively promotes capacity-driven applications such as PtmP Wireless Mobile Backhauling and Fixed BWA in the specific areas (such as e.g. rural) using BuNGee developed Multi-Beam Antenna. There are number of business scenarios where it may provide added value, enhancing capacity and reducing CAPEX/ OPEX (by significantly reducing number of BS sites).

One of the examples – Alvarion's real customer deploying Fixed BWA solution in sub-urban and rural areas, interested to increase capacity of its wireless access network in a cost-efficient way.

Studying the customer's deployment scenario, Alvarion presented business model for BWA network deployment with Multi-Beam Antenna. This business case was based on the Radio Network Planning (RNP) results and close-to-the-field system simulations. Compared to the traditional 3-sectors Base Station deployment with standard 65-degree antenna beam width, the proposed BuNGee-like deployment model of Hub Base Stations with 24-sector Multi-Beam antenna results in the BS capacity increase of around x5 times, while CAPEX (equipment HW – modem & radio unit resources) increases roughly x8 times.



Scenarios		Ant. Type	Modem resources	Sectors		BST Site Throughput	
				Ch. BW 10MHz	Ch. BW 5MHz	DL	UL
1	Current	65°, 3 Sectors	3	2	1	**91 Mbps**	**16 Mbps**
2	Evolution	15° Multi Beam, 24 Sectors	24	16	8	**472 Mbps**	**97 Mbps**

Figure 7-2: Fixed BWA network with Multi-Beam antenna simulations in real operator's network

This presents the considerable business case improvement as allows the Operator to reduce the number of BS sites that constitutes significant part of operator's costs (site acquisition and maintenance fee varies in different regions, but in general may reach 20 - 35% of operator's total access network costs).

The above study proves the efficiency and profitability of BWA network deployment with BuNGee-like Multi-Beam antennas. Alvarion plans to continue collaboration with CASMA in this area and will continue promoting this type of deployment models – both technically and commercially with the customers.

Another BuNGee achievement is the innovative in-band backhauling concept which presents the revolutionary approach towards flexible and efficient spectrum utilization enhancing the scalability of broadband wireless systems. It optimizes operator's footprint enabling flexibility of backhaul distribution to macro- and pico- cells. BuNGee Live Test proved the feasibility, usefulness and cost-efficiency of the taken technology approach as the feeder of the small cells deployed at the street-level below roof-tops.

The general view of the portable ABS site with in-band feeding as used in the BuNGee Live Demo is presented on the figure below:

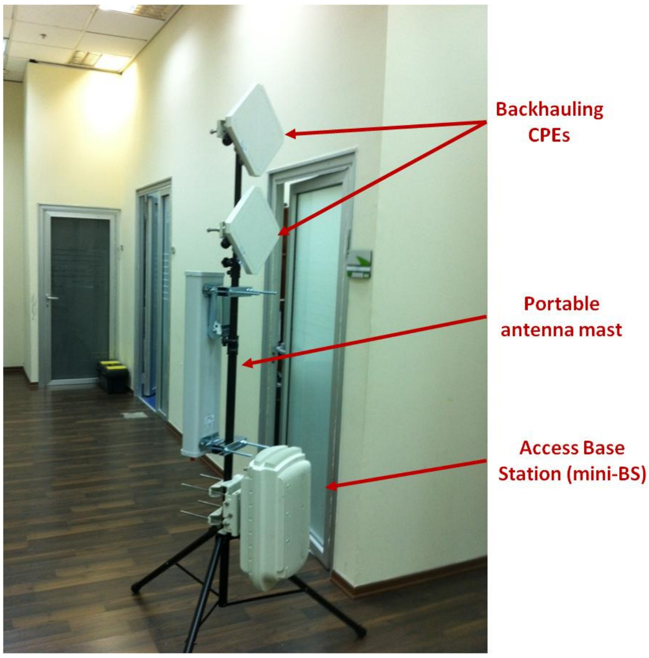


Figure 7-3: Portable Access Site construction view

During the project, Alvarion significantly increased understanding of the associated technology, gained experience and confidence in such solutions required for industrial and commercial progress. Alvarion will continue to improve and maintain the in-band backhauling solution developed in BuNGee at the demonstration level, trying to attract customers and industrial partners.

Alvarion believes that cooperation level achieved in BuNGee between industrial partners, especially with CASMA-developed Multi-Beam antenna and SIKLU-developed mmWave PtP backhauling, provides significant value for the company and promotes the involved solutions. Indeed, complex integration of PtmP in-band backhauling solution, PtP ultra high-capacity mmWave backhauling links, HetNet Mobile BWA macro- and small cells technology, as demonstrated in the BuNGee Live Test (and described in the Live Demo Evaluation Report D4.4), provides significant value and indicates the technology readiness and maturity for the real commercial deployments.

In the BuNGee framework Alvarion has gained lot of knowledge, theoretical basis and expertise from tight cooperation with academic partners – such as UoY and CTTC for improving wireless access network energy efficiency, design of cognitive resource and topology management, development of theoretical basis for advanced MIMO schemes, etc. and UCL for advanced radio channel modelling taking into account complicate BuNGee environment and multi-dimensional properties of the wireless channels. Alvarion plans to continue opportunity-based cooperation with BuNGee academic partners.

As a part of BuNGee activities, we have already contributed to standardization in the ETSI BRAN group, defining the capacity-oriented mobile broadband wireless access network architecture and wireless algorithms and protocols design.

Alvarion will continue to promote and further develop the BuNGee concepts both in industry, standardization bodies and with the real customers driving future mobile wireless access networks capacity growth.

7.1.2 THALES Communications and Security

THALES Communications & Security is a subsidiary of THALES group, a major leading professional and defence system manufacturer. TCS is specialised in communication networks and mobile radio communications for professional applications.

THALES Communication & Security especially contributed for BuNGee in the scenario definitions, the system architecture definition, and in Radio Resource Management developments, where cutting edge evolutions were done to improve existing architecture networks deployments.

One of the Bungee results that can be exploited by TCS is the SON architecture that has been defined and that allows to support high throughput. In TCS applications, the number of simultaneous users is limited compared to commercial applications but the networks have to be deployed in a very limited amount of time. Furthermore, one of the scenarios that has been defined for the SON network, concerns public safety applications. Specific requirements as well as solutions in the Bungee architecture have been designed for that and could be so useful for TCS future works.

Another important work in Bungee will be very interesting for TCS. This concerns the 60GHz demonstrator. Indeed, for some TCS applications there is a need for a very high throughput in millimetre frequencies. 60GHz frequencies allow use of directional antennas and this makes the link much more difficult to detect. Furthermore, all TCS applications are IP based applications. The 60GHz demonstrator is so of the specific interest as it has an Ethernet interface. This is very different compared to other existing solutions in the 60 GHz band which are using an HDMI interface. For all these reasons, 60GHz demonstrator developed in the scope of Bungee is a very interested result for TCS.

In the scope of Bungee, TCS had also the opportunity to participate in 3GPP SA1 meetings. This allowed TCS to have an overview of the new services that will be allowed in 4G networks and allowed also TCS to have an overview of new functionalities needed for public safety networks. TCS will continue to participate in 3GPP SA1 meetings and Bungee was important to allow the first participation.

7.1.3 SIKLU

Siklu designs the EtherHaul-600, an ultra-small, all-outdoor small cell backhaul product that enables rapid deployment anywhere, from street lamps to rooftops. Operating in the 57-66 GHz license-exempt band, the EtherHaul-600 provides scalable gigabit throughputs, allowing operators to meet the capacity needs of today and future-proof the backhaul network. The EtherHaul-600 offers extremely low power consumption and plug-and-play installation into an operator's Self Organizing Network (SON) with a full suite of integrated networking capabilities. As a result of Siklu's innovative all-silicon design, equipment costs are dramatically reduced to a fraction of other millimeter wave solutions. This represents a key stepping stone to the mass deployment of small cells.

Siklu has been committed to reducing the cost of high capacity wireless backhaul solutions since 2008. The company's success centers on an innovative silicon-based design of the millimetric wave radio system and components that has resulted in the lowest cost millimeter wave systems available. The EtherHaul radios deliver gigabit speeds over the millimetric wave spectrum and are ideal for urban wireless backhaul of macro, micro and small cells. Serving providers around the world, Siklu Communication is based near Tel Aviv, Israel.

7.1.4 CASMA

7.1.4.1 Developed Product

As part of the overall BuNGee structure, CASMA has designed, developed and produced a practical Hub Base Station dual polar, multi-beam antenna. The details have been published in deliverables D2.2 and D4.2.2, and the live test in Tel Aviv is well documented within the BuNGee project. The design is innovative in using sets of dual polar beams formed by Butler matrix technology which required research and experimentation with element spacing and phasing and development of a suitable bespoke Butler matrix tuned to the centre frequency of 3.5 GHz. The two outcomes are: firstly, a practical HBS antenna which can be incorporated in the BuNGee architecture, and secondly, an increased knowledge base and understanding of the theory and the practice of multiple beam forming principles.

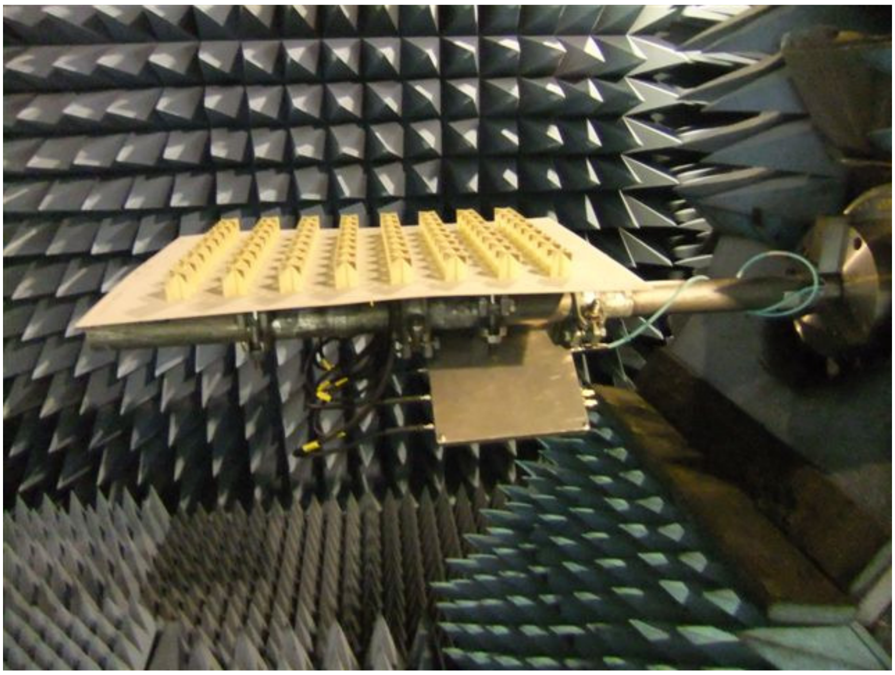


Figure 7-4: BuNGee multi-beam HBS antenna undergoing trials in CASMA's anechoic test chamber.

7.1.4.2 Exploitation

7.1.4.2.1 Background

CASMA's background is in research, development, production and sales of antenna systems for numerous applications from below 1GHz to above 25 GHz, using our in-house development and measuring facilities.

7.1.4.2.2 Foreground

Our foreground has been considerably increased during the progress of developing antennas for the BuNGee project, particularly understanding the interaction between antennas and MIMO technology, and of the behaviour of Butler matrix circuitry in combination with multi-beam antennas. We have also gained foreground in evaluating safe distance measurements in an urban environment as a result of the BuNGee project.

Figure 7-5: HBS antenna on top of mast during live test at Alvarion's premises, Tel Aviv.

7.1.4.2.3 Exploitation Activities

Exploitation of the BuNGee project and especially of the multi-beam antenna has consisted of CASMA's presence at communications and military trade shows, and publishing a descriptive article of the antenna in "Microwave Journal":

www.**microwavejournal**.com/**articles**/456-beyond-next-generation-m

We have had a trade presence at MTTS, AUVSI and DSEI shows where the BuNGee HBS antenna was either shown or its specification distributed to interested parties.

Interested commercial and military customers in both Europe and the USA with whom we are in contact include Airspan; Alvarion; ETI Industries; General Dynamics; Harris Corporation and Verizon. It is intended to maintain contact with these and other potential customers for communications systems to further promote the multi-beam antenna concept according to their applications.

The CASMA website has a page dedicated to the BuNGee project, in particular the HBS, HSS and ABS antennas:

http://www.european-antennas.co.uk/2011-12-bungee-progress.php

Within the website are hyperlinks to each partner in the BuNGee project as well as to the Seventh Framework Programme for Research and Technological Development (FP7).

7.1.5 PTC

Since 2011 PTC has been outsourcing a part of its network infrastructure. Currently the PTC's RAN and wireless backhaul is managed by a third party operator - Networks, which to some extent limits the earlier planned ways of BuNGee direct results exploitation.

The currently ongoing general exploitation activities and future plans include:

- Project results dissemination within PTC - sharing the project deliverables among PTC's selected engineers and manager (not involved / or only slightly familiar) in project details;
- Meeting with PTC colleagues and discussions of BuNGee key ideas and their impact (including economical) on the network building process;
- Transfer / discussion of BuNGee (public) results to/ with the Networks' colleagues who are responsible for RAN building process;
- Discussions with other colleagues from the T-Mobile group.

Specifically, as PTC coordinated the WP1 "Requirements and BuNGee architecture" and was the editor (and the main contributor) of the D1.1 deliverable "Functional BuNGee Specs., Economic model, Energy efficiency & Frequency bands", PTC, thanks to this project, deepen and systematized its knowledge on user needs, market trends, expectation and forecast regarding new services.

This knowledge, similarly as economic analyses carried out in WP1, may impact the PTC's product and network development strategy.

Finally, the Live Test demonstration (T4.4) outcome allowed PTC to compare the (implemented with WiMax technology) BuNGee testbed characteristics with the results of LTE trial recently being carried out at PTC.

7.2 Academic Partners

The following Academic Partners participated in the project: CTTC, UoY, UCL.

7.2.1 CTTC

Within the framework of BuNGee, CTTC has designed, implemented and validated a real-time FPGA-based PHY-layer prototype based on mobile WiMAX. To this end, hardware and firmware developments for the GEDOMIS® testbed have been performed, which are mature enough for exploitation and commercialization activities. Below, the developed prototype is described, whereupon we elaborate marketing, sales and further exploitation strategies.

7.2.1.1 Developed Product

The prototype product has the following features:

- closed-loop MIMO system (transmitter and receiver)
- with adaptive subcarrier allocation
- limited feedback generation and
- feedback processing.

Prototyping said system that serves the needs of current and next generation wireless communication systems implies (among other performance indicators)

- real-time operation
- wide bandwidth at baseband and
- flexible configurability of the PHY-layer.

Based on above requirements, a rigorous design methodology has been developed which is illustrated in below Figure 7-6.

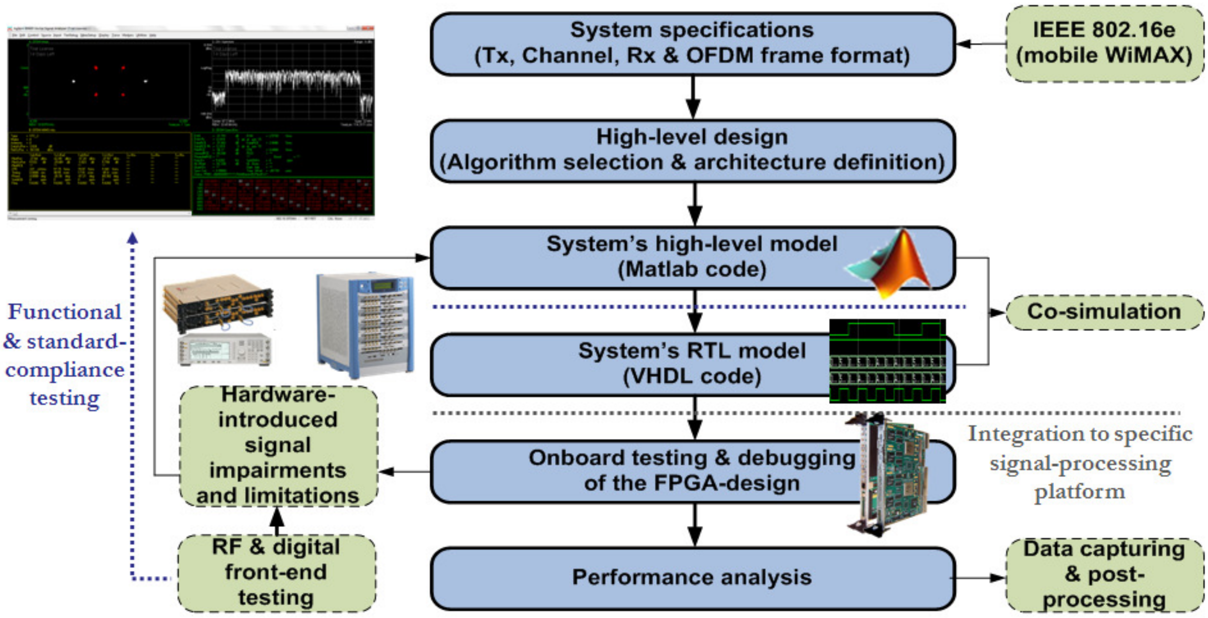


Figure 7-6: The design methodology steps.

After years of fruitful developments, more details of which are described in D4.4, the functional verification of the FPGA-based prototype in real-time operating conditions has been made by means of the GEDOMIS® testbed which is illustrated in Figure 7-7 and Figure 7-8.

The latter is an experimental platform that comprises a complete set of baseband prototyping boards (FPGA and DSP-based), signal generation equipment, high-end RF front-ends, signal analysis instruments, specialized software tools and APIs. A key instrument of the testbed is the EB Propsim C8 radio channel emulator, which can be configured to provide realistic mobility scenarios of both certified and user designed-customised channel models. The Propsim C8 accepts up to four input signals, a fact that enables the real-time channel emulation and system verification of different implementations and test scenarios, prior to field-trials.

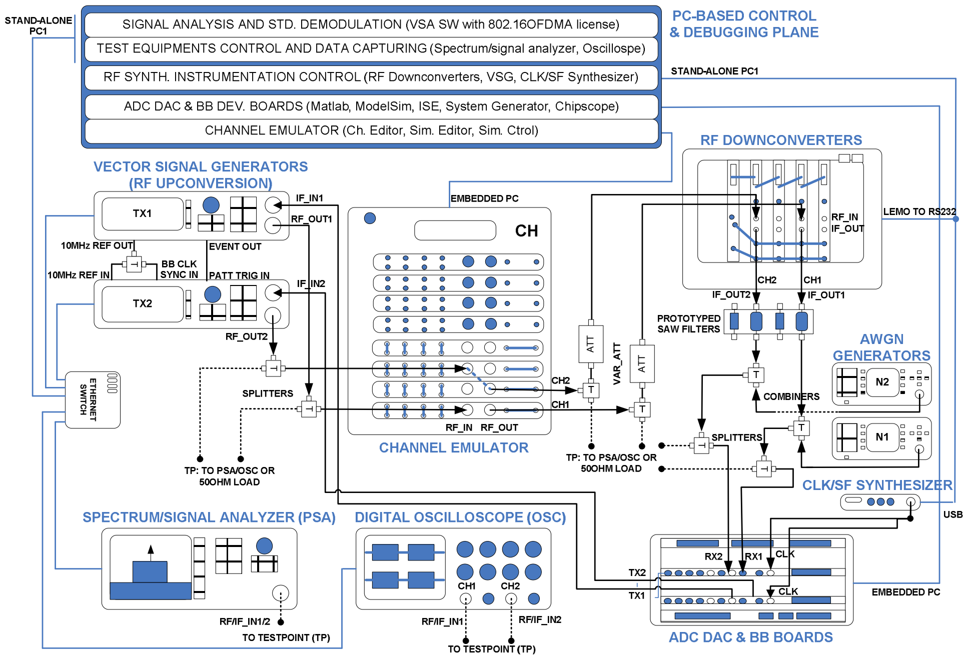


Figure 7-7: The complete hardware set-up of the GEDOMIS® testbed enables the prototyping and real-life validation of bit-intensive wireless-communication systems (PHY and MAC layer).

Figure 7-8: Laboratory photo of the GEDOMIS® testbed.

7.2.1.2 Product Marketing

As part of our participation to WP4 T2 and T3, we have conducted a wide variety of dissemination activities allowing us to market the developed prototype. This includes:

- publications,
- live demonstrations,
- a professionally-produced video showing the operation of the GEDOMIS® testbed,
- a professional brochure,
- a logo specifically designed for this product,
- and a blog web-page, which is the central reference of all the research and development activities related to GEDOMIS®.

7.2.1.2.1 Publications

Targeting a more academic and R&D-oriented audience, CTTC has published on the developed prototype:

- Book Chapter[3]
    - O. Font-Bach, A. Pascual-Iserte, N. Bartzoudis and D. López Bueno, "MATLAB as a Design and Verification Tool for the Hardware Prototyping of Wireless Communication Systems", Chapter in "MATLAB / Book 2", edited by V. N. Katsikis, Published by INTECH, 2012. ISBN 980-953-307-501-8 (in press).
- Ph.D. dissertation
    - Oriol Font-Bach, “Deployment, prototyping and validation of advanced real-time multi-antenna algorithms for adaptive communication systems”, to be examined in December 2012.
- Journal paper[4]
    - O. Font-Bach, N. Bartzoudis, A. Pascual-Iserte, D. López, A real-time MIMO-OFDM mobile WiMAX receiver: Architecture, design and FPGA implementation, Computer Networks Elsevier, Vol. 55, No. 16, pp. 3634-3647 (2011).
- Conference papers[5]

[3] Another chapter (under preparation) will be included in a book of Wiley publications (4th quarter 2012).
[4] Two more journal papers (currently under preparation) will be submitted to special issues of the EURASIP Journal on Advances in Signal Processing and the EURASIP Journal on Wireless Communications and Networking.
[5] A conference paper is under preparation and will be submitted to the WiMob 2012.

    - O. Font-Bach, N. Bartzoudis, A. Pascual-Iserte, D. López, Prototying Processing-Demanding Physical Layer Systems Featuring Single Or Multi-Antenna Schemes, in Proceedings of 19th European Signal Processing Conference (EUSIPCO 2011), 29-2 Sep. 2011, Barcelona (Spain).
    - N. Bartzoudis, O. Font-Bach, A. Pascual-Iserte, D. López, A Real-Time FPGA-based mobile WiMAX transceiver supporting multi-antenna configurations, in Proceeding of the 5th Argentine Conference on Micro-Nanoelectronics, Technology, and Applications (CAMTA 2011), 6-14 Aug. 2011, Buenos Aires (Argentina), pp- 1-6.
    - O. Font-Bach, N. Bartzoudis, A. Pascual-Iserte, D. López, A Real-Time FPGA-based Implementation of a High-Performance MIMO-OFDM Mobile WiMAX Transmitter, In *Mobile Lightweight Wireless System (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering)*, Volume 81, Spinger (2012) Part 1, p. 48-66.
    - Oriol Font-Bach, Nikolaos Bartzoudis, Antonio Pascual-Iserte, and David López Bueno, "Design, Implementation and Testing of a Real-Time Mobile WiMAX Testbed Featuring MIMO Technology", In: TRIDENTCOM, Vol. 46, Springer (2010) , p. 199-208.
- BuNGee deliverables
    - Participation in the D3.2.

7.2.1.2.2 Live Demonstrations

Three live demonstrations took place during the development of the CL MIMO mobile WiMAX system. The demos reflected intermediate development stages of the mentioned system.

1. European Nanoelectronics Forum, Madrid, November 2010	
2. DSPECIALISTS workshop, Berlin, May 2011	

3. Mobile World Congress 2012, Barcelona, February 2012	

7.2.1.2.3 Promotional Video

Two professional videos have been created which describe the PHY-layer design, implementation and validation of a MIMO mobile WiMAX receiver.

Figure 7-9: Promotional Video on prototype [Part I].

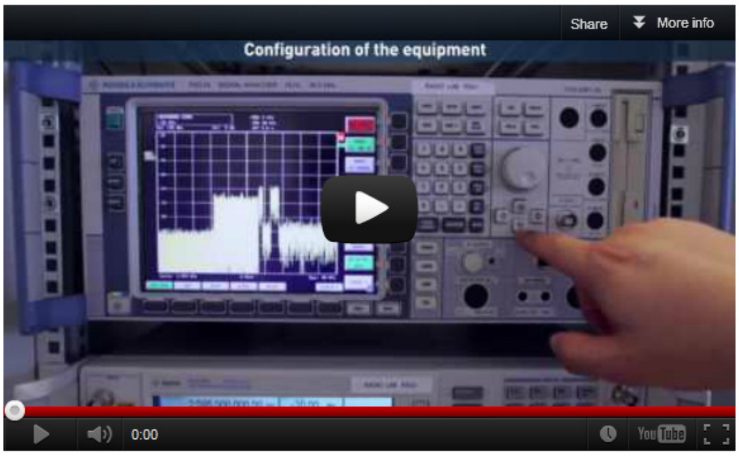


Figure 7-10: Promotional Video on prototype [Part II].

The explicit links these videos are available from are given here:

- http://www.youtube.com/watch?feature=player_embedded&v=NPeNeeM4kgA
- http://www.youtube.com/watch?v=vR-IAuJcf5c&feature=player_embedded
- or both at http://engineering.cttc.es/gedomis/

7.2.1.2.4 Product Brochure

The professional brochure is available upon request in printed and PDF form. An excerpt from the PDF and some pictures of the brochure are shown below for reference.

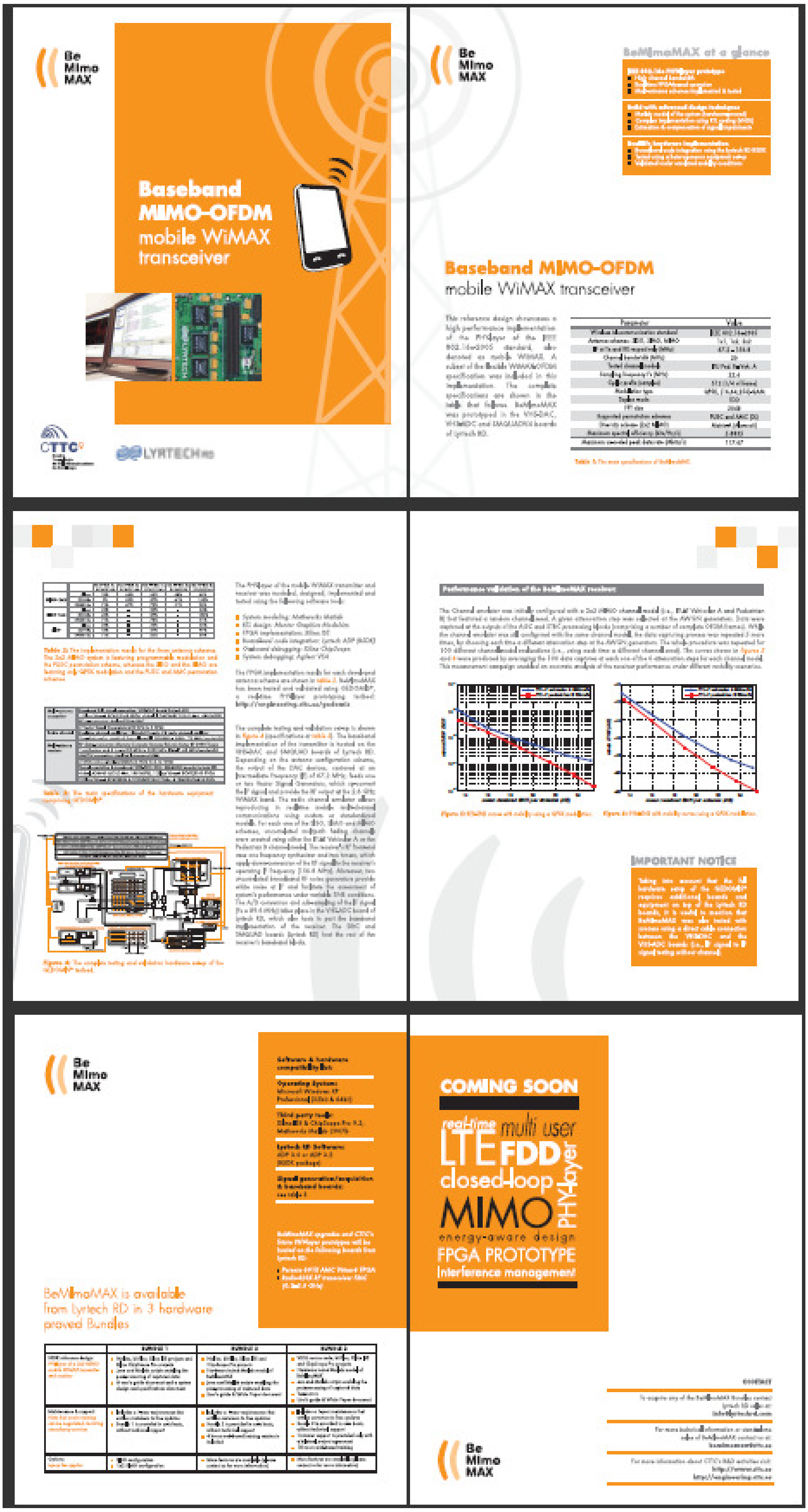


Figure 7-11: Excerpt from the PDF of the professional product brochure.

Figure 7-12: Pictures of the professional product brochure.

7.2.1.2.5 Product Logo

The logo of the product is given in below Figure 7-13.

Figure 7-13: Logo of the BeMimoMAX product.

7.2.1.2.6 Blog Website

A blog website has been put up by CTTC to ensure timely dissemination and exposure of latest developments related to the prototype. The address is:

- http://engineering.cttc.es/gedomis/

An excerpt from the blog is shown below for reference.

Figure 7-14: Up-to-date blog website for potential customers.

7.2.1.3 Product Sales

CTTC has managed to **commercialize** the VHDL and MATLAB IP developed during this project. **BeMImoMAX** (Baseband MIMO-OFDM mobile WiMAX transceiver) is a high-performance VHDL reference design that is **available to purchase by CTTC** [11] and **by the Canadian FPGA board manufacturer Lyrtech RD**[6] [12].

The negotiations with Lyrtech RD have lasted for more than 1 year and the product was finally launched during the Mobile World Congress 2012[7]. BeMImoMAX is also advertised in the Innoget technology broker webpage [13].

[6] Lyrtech RD features a global network of resellers, something that is expected to assist the marketing and commercialization objectives.
[7] CTTC has its first-time presence in this high impact event, in Catalonia's pavilion.

As per above, diverse marketing material has also been produced for the promotion of the IP (e.g., professionally produced brochures [14]).

The Lyrtech website, for instance, offers the product for sales and thus officially acts as technology partner and sales channel to CTTC's development team.

http://lyrtechrd.com/en/products/view/+bemimomax

BeMImoMAX

Quote Documentation/Downloads

- BeMImoMAX
- Applications/Fields
- Characteristics
- Multimedia
- Documentation
- Photos and Images

➢ Baseband MIMO-OFDM Mobile WiMAX Transceiver

BeMImoMAX is a FPGA-ready **HDL reference design** developed at CTTC, which showcases a real-time PHY-layer implementation of the IEEE 802.16e-2005 standard (mobile WiMAX). BeMImoMAX combines a 2x2 MIMO scheme and a wide bandwidth of 20MHz, which enable a high performance operation at baseband. Other antenna schemes are also offered as optional add-ons (i.e., SISO and 1x2 SIMO).

The PHY-layer was first modeled in **MATLAB** using a subset of the flexible WiMAX-OFDM specifications. Each of the processing blocks comprising the MATLAB model of the receiver and transmitter were then mapped to **custom VHDL code** and co-simulations were carried out to verify functional correctness. The RTL code of BeMImoMAX -**Release 1**- was eventually prototyped using the VHS-DAC, VHS-ADC, DRC & SignalMaster Quad boards of Lyrtech RD and validated using the full set-up of the GEDOMIS testbed. BeMImoMAX is currently being modified –**Release 1.1**- to target the Lyrtech RD Perseus 601X and Radio 420X boards.

The **Release 2.0** is planned for the second semester of this year. This new version of BeMImoMAX will provide a sophisticated reference design based on the IEEE 802.16e-2005 standard that will feature a real-time a closed-loop multi-antenna system with adaptive subcarrier allocation, adaptive modulation, feedback generation and feedback processing.

>> Highlights

- 20 MHz channel bandwidth
- Programmable modulation: QPSK, [16,64,256]QAM
- Maximum un-coded peak data rate: 117.67 Mbits/s
- Maximum spectral efficiency: 5.8835 bits/s/Hz
- BeMImoMAX surpasses current WiMAX performance requirements
- Matlab bit-true & cycle-true accuracy models
- VHDL implementation with high fixed point precision & negligible implementation losses
- Real-time FPGA-based operation
- Accounts interoperability dependencies of the entire processing chain (baseband, RF & channel)
- Estimates and compensates signal impairments
- Receiver's mobility validated using a channel emulator
- WiMAX standard compliance testing with Agilent's VSA
- Complete source code documentation
- Web-based training session

➢ Applications/Fields

>> Telecommunications

- 802.16
- Base transceiver stations
- Broadcasting
- MIMO
- WiMAX
- FemtoBTS
- Software-defined radio
- OFDM

>> Military and aerospace

- Digital communications
- Software-defined radio

>> Industrial

- Testing
- Instrumentation
- Channel simulation
- Channel analysis

>> Educational

- Modeling 4G systems
- RTL coding techniques for real-life 4G prototypes

- Estimation and compensation of signal impairments
- Testing and measurements of 4G systems

➢ Characteristics

>> Functions

- IP Cores

➢ Multimedia

>> Presentation

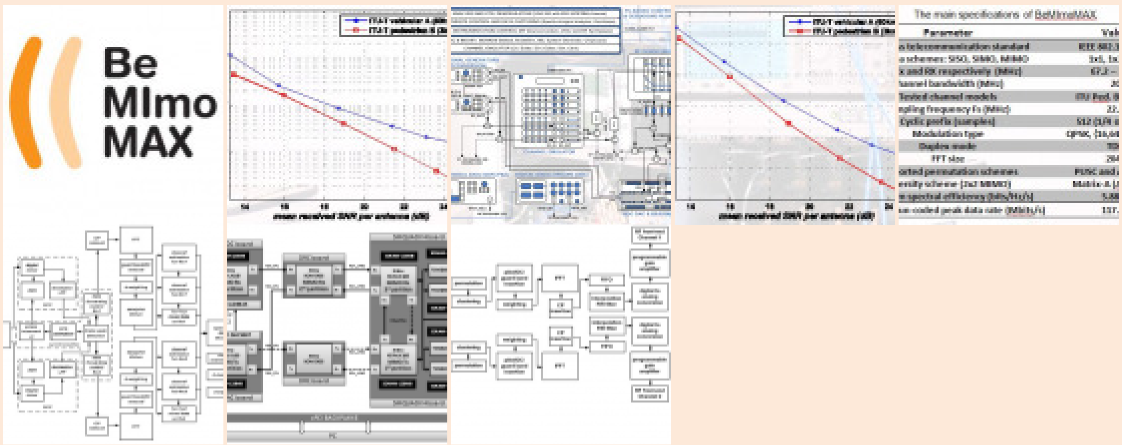
The following videos describe the PHY-layer design, implementation and validation of a MIMO mobile WiMAX receiver (development progress: July 2010) using the full hardware and software set-up of the GEDOMIS® testbed. To watch the two videos in High Definition please adjust the video quality from the player's panel.

- Part 1: http://www.youtube.com/watch?v=NPeNeeM4kgA
- Part 2: http://www.youtube.com/watch?v=vR-IAuJcf5c

➢ Documentation

bemimomax.pdf

➢ Photos and Images



7.2.1.4 Future Exploitation Plans

7.2.1.4.1 Background Information

CTTC is a non-profit private research centre established in Barcelona with the funding and support of the Regional Government of Catalonia. CTTC also receives financial support from industrial and publicly funded R&D projects. Research activities at the CTTC, both fundamental and applied, mainly focus on the physical, data-link and network layers of communication systems. In addition, the Engineering Unit develops hardware and software testbeds and demonstrators and also conducts technology-oriented research.

In terms of scientific outcome, CTTC publishes numerous peer-reviewed journal and conference papers per year, and currently counts on a healthy IPR portfolio. CTTC is very active in international fora, such as e-Mobility (expert group), ISI, es.internet, IETF, etc. The CTTC also participates very actively in industrial contracts and projects funded at the European and national levels (+65 projects since 2001). A non-exhaustive list of on-going/past projects encompasses IST-WIP (wireless mesh networks), IST-WINNER/WINNER2 (4G radio Interfaces), IST-PHYDIAS (multicarrier based cognitive systems); EUREKA-MARQUIS (multi-antenna systems); IST-COOPCOM (Cooperative Communications), FREEDOM (spectrum sharing and peer-to-peer systems), etc.

Besides, the CTTC has developed a number of testbeds, such as the EXTREME testbed (for hybrid cellular/mesh communications); and of course the GEDOMIS testbed developed and enhanced within BuNGee.

7.2.1.4.2 Foreground Information

CTTC has acquired an enormous set of foreground whilst executing the BuNGee project. The listed foreground distinguishes directly and indirectly acquired foreground, and pertains to the already executed period of the BuNGee project.

Direct foreground refers to the knowledge, expertise, etc, acquired within CTTC whilst working on the tasks assigned to CTTC, and pertains to the following: First, CTTC has acquired a solid background in prior art on ultra high-capacity architecture design, 4G and beyond 4G requirements, driven both by the technical community (IMT-A) as well as the user needs (through smart phone explosion). This has been well documented in the respective deliverables on architecture designs. CTTC has also been able to acquire a solid knowledge on the use of advanced PHY layer methods, related to limited and/or erroneous feedback schemes and advanced MIMO designed related thereto. This has been well documented in related deliverables of WP2. Furthermore, CTTC has had an enormous impact onto the design of SON-enabled RRM algorithms by introducing cutting-edge docitive algorithms which were shown to outperform even the cognitive algorithms developed by CTTC and the community at large. This has been documented in the related deliverables of WP3 as well as joint publications with BuNGee partners. Finally, the hardware team has acquired an enormous knowhow on firmware implementations for GEDOMIS which reflect the (academic) design work of the PHY layer team of WP2. All in all, the direct foreground acquired by CTTC thanks to the BuNGee project is utmost important to its further development in the context of follow-up European projects, industrial contracts, and eventually spin-offs.

Indirect foreground refers to the knowledge, expertise, etc, acquired by interacting with the project partners and/or external fora, and pertains to the following: First, CTTC has gained an enormous foreground on the needs and necessities of the industrial partners, notably Alvarion, Siklu, Cobham and in a more limited sense PMT and Thales. The inputs on the feasibility of various design approaches at PHY, RRM and hardware from Alvarion, Siklu and Cobham have been of great use, for instance. Furthermore, CTTC has been listening into and contributing to the ETSI BRAN standard where it is currently finalizing the standardization of its docitive algorithms.

Finally, it shall be mentioned that the business needs identified within the BuNGee project has had an enormous impact onto the current decision process of potentially establishing spinoff companies, notably along the exploitation of GEDOMIS and BeMImoMAX.

7.2.1.4.3 Exploitation Strategy and Activities

CTTC being a non-profit research institution, exploitation is mainly understood in disseminating results to ensure greater visibility and thus ability to attract industries/projects for further research and investigations. However, CTTC is going well beyond this by actively contributing to standards, actively shaping special issues and workshops on issues touched upon in the BuNGee project, and even aiding in recent spin-offs.

In more details, CTTC has had very prolific dissemination activities over the reporting period. Several conference and journal papers have been submitted and accepted, some of which are joint work between partners. More details on the exact contributions are provided in the respective reporting deliverable.

CTTC has further been active in ETSI BRAN to which, through the help of Alvarion and later Mariana Goldhammer, Pol Blasco and Mischa Dohler have had important inputs. CTTC has here helped with the general business requirements, resulting architectural design choices and, of course, the cognitive & docitive RRM approach, along with control protocol primitives to support the functionalities. We expect this to continue well beyond the project life time.

CTTC has also been pro-active in educational events and features. Notably, CTTC has been the co-organizer of one of IEEE's 4G high capacity workshops at WCNC 2012 in Paris in April 2012. Furthermore, CTTC is able to teach four of its PhD students (notably Pol Blasco, Daniel Sacristian, Ana Maria Galindo, and now Jessica Moysen) on the latest cutting-edge developments related to high-capacity cognitive RRM designs; these students are an enormous support in terms of publications, projects and possible future postdocs/staff members. It is also worth mentioning that the research activities enabled CTTC's staff to be much more trained on the issues of PHY-layer design, RRM and hardware/firmware work; notably, the trained people are: Nikolaos Bartzoudis, Miquel Payaró, Toni Pascual, Oriol Fonts, Carlos Bader and Mischa Dohler (six in total).

Exploitation from a more industrial perspective includes the fact that CTTC was able to negotiate a channels sales contract with Lyrtech R&D in Canada. Also, CTTC – through Nikolaos Bartzoudis – are considering to possibly spin-off the commercial activities.

In summary, the BuNGee project has enabled CTTC, as a non-profit research centre, to gain significantly larger visibility in the research, development and industrial community. This has allowed CTTC to train 4 PhD students and 6 staff members; and thus significantly beef up the potential in engaging in further forward-looking projects with the profile of BuNGee. This has already paid off in that a project on B4G technologies has been submitted and accepted (NEWCOM++), and is subject to kick-off.

7.2.2 UoY

University of York plans to exploit the results of BuNGee by collaborating with users and beneficiaries of the work and with wider industry, standards bodies and regulators. This is also likely to involve our joint lab-partner Zhejiang University who has good connections with Chinese industry. Results are also likely to influence teaching courses and wider education in general. UoY has extensive experience in organising specialist short courses, workshops and summer schools in this area.

Further development towards industrial exploitation is expected through collaboration with BuNGee industrial partners, such as Cobham Antennas and Alvarion, and with others, including BT and Toshiba Research Europe.

We have already contributed substantial algorithms and techniques from WP2 and 3 to the ETSI BRAN standardisation process. We will continue to assist with this as appropriate, such that these results can be better exploited by industry.

The key cognitive algorithms coupled with the BuNGee system architecture are already being developed further in York via the internal 'I-COMMS' project. This is implementing joint resource and topology management schemes for a BuNGee like system architecture as a way of improving the energy efficiency, delivering 'cognitive green radio'. It is likely that such algorithms will also be tested in software defined URSP board systems, with the aim of further refining the algorithms to assist in the exploitation process with industry. Key IPR from these extensions will be protected accordingly (see below). I-COMMS is being worked on by PhD students, so BuNGee will be indirectly helping to educate 4 PhD students.

It is also intended to take key elements of the cognitive resource and topology management algorithms and exploiting them in the new FP7 ABSOLUTE project, in which York is a partner. This will start in October 2012, and is aimed at extending LTE-A for emergency service and temporary event use. To achieve a working system, cognitive resource and topology management will be used to intelligently match temporarily unused radio spectrum and system resources to user demand. It is highly likely that techniques originally developed by BuNGee will in this way find their way in to LTE-A standardisation process for this application.

The work on wireless network coding will also be taken forward in the new FP7 DIWINE project, of which also York is a partner. This will begin in January 2013, and will develop a new "cloud" paradigm for dense wireless networks based on wireless network coding, for "internet of things" applications, including "smart grids" and industrial process control. It will also contribute to an ongoing project on distributed space time coding supported by the UK Engineering and Physical Sciences Research Council and BT.

Appropriate IPR protection techniques will be used to protect the IPR. Exploitation routes will be pursued vigorously, and York's Research Innovation Office will be consulted about appropriate paths. This could include the specialist venture capital organisation, IPGroup, which has a partnership agreement with University of York. It may also lead to direct exploitation of technology by the collaborators in the form of spin-outs or licensing. IP from the project will be vested in the University of York (and/or collaborators if appropriate). The University of York has a dedicated business development team to support:

- Review of IP generated by, or relating to the project (including patentability, background IP searching and freedom to operate);
- Protection of IP by patent (including funding patent costs);

- Negotiation with potential licensees and/or collaborators and arrangement of collaboration agreements, cross licensing contracts and development contracts;
- Development of business plans and investor engagement.

We have already been involved in one spin-out (SkyLARC Technologies Ltd).

7.2.3 UCL

7.2.3.1 Developed Expertise

In BuNGee, UCL has developed channel models for B4G architecture. To this end, significant improvements were brought to an existing ray-tracing tool. This technique is widely used to predict the behavior of propagation both in outdoor and indoor scenarios. Classic ray-tracing tools usually take into account line of sight propagation, specular reflection and diffraction, with penetration included when indoor propagation is considered. For BuNGee, which exploits many multi-dimensional properties of the wireless channel (MIMO, polarization, etc.) and relies on an aggressive frequency reuse, it is required that prediction models be capable to analyze propagation in depth, i.e. including polarization, delay and angular behavior of a channel, as well accurate modeling of interference. A 3-D ray-tracing tool has the great advantage to be able to provide inherently that kind of information, but to achieve a sufficient accuracy, it is necessary to implement propagation mechanisms such as penetration, polarized diffuse scattering and contributions by vegetation. This was one achievement of UCL in BuNGee, which has resulted in numerous publications and one PhD thesis (finalized in May 2012). A second thesis was initiated by BuNGee in the area of multi-link channel measurements. Thanks to the developed models, the requirements on channel measurements are now set up more firmly.

In addition to this increased expertise in ray-tracing modeling and channel measurement, UCL gained expertise in system-oriented channel modeling, in particular by collaborating with UoY and CTTC in WP2 and WP4, and by listening to the needs of industrial partners, namely Cobham and Alvarion.

7.2.3.2 Future Exploitation Plans

7.2.3.2.1 Background Information

In terms of scientific outcome, UCL publishes numerous peer-reviewed journal and conference papers per year. UCL also participates very actively in projects funded at the European and national levels. A non-exhaustive list of on-going/past projects encompasses IST-STARRS, IST-PHYDIAS (multicarrier based cognitive systems); EUREKA-MARQUIS (multi-antenna systems), etc.

7.2.3.2.2 Foreground Information

UCL has acquired a significant set of foreground whilst executing the BuNGee project.

Direct foreground refers to the knowledge, expertise, etc, acquired by UCL whilst working on the tasks assigned to UCL. For instance, UCL has acquired a solid background in prior art on ultra high-capacity architecture design, 4G and beyond 4G requirements and 4G channel models (WINNER II, etc.). This has been well documented in the respective deliverables on architecture designs. The direct foreground acquired by UCL researchers thanks to BuNGee is extremely valuable in the context of follow-up European projects, and industrial contracts.

Indirect foreground refers to the knowledge, expertise, etc, acquired by interacting with the project partners and/or external fora. In particular, UCL has gained an enormous foreground on the needs and necessities of the industrial partners, notably especially Alvarion and Cobham. The constraints from these partners on channel modelling design have been significant.

7.2.3.2.3 Exploitation Strategy and Activities

UCL being a university, exploitation is mainly understood in disseminating results to ensure greater visibility and thus ability to attract industries/projects for further research and investigations. In BuNGee, UCL has had numerous dissemination activities over the reporting period. Several conference and journal papers have been submitted and accepted, some of which are joint work between partners.

Journal Papers

- F. Mani, C. Oestges, A Ray Based Method to Evaluate Scattering by Vegetation Elements, *IEEE Trans. Antennas Propagat.* (in press).
- F. Mani, F. Quitin, C. Oestges, Ray-Tracing Simulations of Diffuse Scattering Angular Properties in Indoor Scenario, *IEEE Trans. Antennas Propagat. (in press).*
- E.M. Vitucci, F. Mani, V. Degli-Esposti, C. Oestges, Polarimetric properties of diffuse scattering from building walls: experimental parameterization of a ray-tracing model, *IEEE Trans. Ant. Propagat.*, vol. 60, No. 6, p. 2961-2969, June 2012.
- N. Czink, B. Bandemer, C. Oestges, T. Zemen, A.J. Paulraj, Analytical multi-user MIMO channel modeling: subspace alignment matters, *IEEE Trans. Wireless Comm.*, vol. 11, No. 1, pp. 367-377, January 2012.
- F. Mani, F. Quitin, C. Oestges, Accuracy of depolarization and delay spread predictions using advanced ray-based modeling in indoor scenarios, *EURASIP Journal on Wireless Communications and Networking*, 9 p., July 2011.
- C. Oestges, N. Czink, B. Bandemer, P. Castiglione, F. Kaltenberger, A. Paulraj, Experimental characterization and modeling of outdoor-to-indoor and indoor-to-indoor distributed channels, *IEEE Trans. Veh. Tech.*, vol. 57, No. 5, pp. 2253–2265, June 2010.
- Nizabat Khan, Claude Oestges, Yi Wang, Alister Burr and Agisilaos Papadogiannis, “The Potential of Hierarchical Wireless Networks Employing Joint Beam Processing”, *IEEE Transactions on Vehicular Technology* (to be submitted).

Conference Papers

- N.Khan, T.Jiang, D.Grace, A.G. Burr, and C.Oestges, “Impact of Multi-beam Antenna Amplitude Tapering on Co-Channel Interference and Backhaul Throughput Density” 15th Symposium on Wireless Personal Multimedia Communications, WPMC’12, Taipei, Taiwan (accepted).
- N.Khan, C.Oestges, “Small Scale Statistics of Fixed Relay Polarimetric Links Using Narrow Beamwidth Antennas at 3.5 GHz” 15th Symposium on Wireless Personal Multimedia Communications, WPMC’12, Taipei, Taiwan (accepted).
- E.M. Vitucci, F. Mani, V. Degli Esposti, C. Oestges, Study of a Polarimetric Model for Diffuse Scattering in Urban Environment, *6th European Conference on Antennas and Propagation - EuCAP*, Prague, Czech Republic, March 2012.
- C. Oestges, P. Castiglione, N. Czink, Empirical modeling of nomadic peer-to-peer networks in office environment, Proceedings 73th IEEE Vehicular Technology Conference Spring, VTC-Spring ‘11 (Budapest, Hungary), May 2011.
- C. Oestges, Multi-Link Propagation Modeling for Beyond Next Generation Wireless, Proceedings Loughborough Antennas and Propag. Conf. – LAPC ’11 (Loughborough, UK), Nov 2011 (<u>Invited Paper and Communication</u>).
- N.Khan, C.Oestges, “Impact of Transmit Antenna Beamwidth for Fixed Relay Links Using Ray-Tracing and Winner II Channel Models” *5th European Conference on Antennas and Propagation,* EuCAP’11, Rome Italy, April 2011.
- O. Marinchenco, N. Chayat, M. Goldhamer, A. Burr, A. Papadogiannis, M. Dohler, M. Payaro, C. Oestges, N. Khan, M. Ware, "BuNGee project overview," *Microwaves, Communications, Antennas and Electronics Systems (COMCAS), 2011 IEEE International Conference on* , vol., no., pp.1-9, 7-9 Nov. 2011.

UCL has further been active in disseminating BuNGee channel models in international platforms such as COST action 2100 and IC1004:

- N.Khan, C.Oestges, “Small Scale Statistics of Fixed Relay Polarimetric Links at 3.5 GHz” *COST IC1004 TD (11) 02025,* Lisbon Portugal, October 2011.
- F. Mani, F. Quitin, C. Oestges, Directional Spreads of Dense Multipath Components: a Ray-Tracing Approach, *COST IC1004 TD(11)02003*, Lisbon, Portugal, October 2011.
- E. M. Vitucci, F. Mani, V. Degli Esposti and C. Oestges, Polarimetric properties of diffuse scattering from building walls, *COST IC1004 TD(11)02006*, Lisbon Portugal, October 2011
- N.Khan, T.Jiang, D.Grace, A.G. Burr, and C.Oestges, “Impact of Multi-beam Antenna Amplitude Tapering on Co-Channel Interference and Backhaul Throughput Density” *COST IC1004 TD (12) 04019,* Lyon France, May 2012.
- F. Mani and C. Oestges, A ray-based method to evaluate scattering by vegetation elements, *COST IC1004 TD(12)04018*, Lyon France, May 2012.

- E. M. Vitucci, F. Mani, V. Degli Esposti and C. Oestges, "A study on polarimetric properties of scattering from building walls", *COST 2100 TD(10)11020*, June 2010.
- F. Mani and C. Oestges, Ray-Tracing evaluation of diffuse scattering in an outdoor scenario, *COST 2100 TD(10)12018*, Nov. 2010.

In summary, the BuNGee project has enabled UCL to publish a large numbers of scientific papers, and to educate 2 PhD students (one PhD degree awarded in 2012, one to be finalized in 2014). This effort has already paid off in that a project on B4G technologies has been submitted and accepted (NEWCOM++), and is subject to kick-off.

8 Conclusions

This document has outlined a clear and precise strategy for disseminating and exploiting the results of the ICT-248267 project BuNGee - Beyond Next Generation broadband wireless networks.

The plan for dissemination includes papers and presentations in the selected public conferences, workshops and significant events in front of the international wireless community specialist audiences.

The strategy of dissemination of BuNGee knowledge includes also important actions in the Standardisation (ETSI, WMF) bodies, to ensure a future harmonised standards adopted across the developed world. BuNGee had significant impact on industrial standardization by its contribution to ETSI standard - the entire ETSI TR 101 534 was drafted based solely on the contributions submitted by the BuNGee partners. 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.

During the project, the BuNGee public website was managed, propelling the project ideas and activities.

BuNGee consortium members achieved most of the technological objectives set for the project, showed exceptional cooperation and demonstrated the accomplishment of their specific goals.

As the culmination of the BuNGee activities, Live Demonstration of BuNGee target technology was performed, presenting the high capacity radio cell prototype addressing 1 Gbps/Km^2 throughput density in the real urban cellular environment of Tel Aviv city. It incorporated the main system components prototyped by the BuNGee partners:

- BuNGee Multi-beam antenna for Hub Base Station, designed by CASMA;
- Ultra high capacity mmWave 60 GHz point-to-point link, designed by SIKLU;
- Hub & Access BS prototypes developed by Alvarion and implementing 4G mobile broadband wireless access and broadband wireless backhauling networks with WiMAX/ IEEE 802.16 suite.

The Live Test system clearly demonstrated close-to-target equivalent system throughput density of ~840 Mbps/ km^2 in a real-field capacity-oriented deployment in a dense urban area for outdoor users. This experimental result was well in line with the results of system-level simulations performed by the BuNGee partners. The Live Demonstration proved viability and measured the effectiveness of the concepts developed in BuNGee.

Additionally, CTTC performed design, implementation & validation of a real-time FPGA-based MIMO mobile WiMAX transceivers with limited feedback using the GEDOMIS® testbed, presenting significant progress in validation of MIMO limited feedback concepts developed in BuNGee.

BuNGee industrial members (Alvarion, CASMA, SIKLU and Thales Communication & Security) and CTTC perform commercial exploitation of BuNGee results in the following areas:

- Applying BuNGee HetNet deployment models and technical ideas in the real commercial Mobile and Fixed BWA deployments.
- Developing and starting commercial launch of the small form-factor Base Stations (Compact-/ Pico- BS) leveraging BuNGee-developed algorithms and mechanisms.
- Developing and promoting the BuNGee-proposed and validated in-band backhauling solution leveraging the existing wireless BWA eco-system.
- Promoting BuNGee-developed Multi-Beam Antenna for PtmP feeding hubs and Fixed Broadband Wireless Access applications.
- Developing and commercializing ultra-high capacity mmWave backhauling technology (in Licensed and LE spectrum).
- Commercializing FPGA-based MIMO transceivers technology with limited feedback - FPGA-ready HDL WiMAX MIMO reference design (BeMImoMAX).

BuNGee academic partners (UoY, CTTC and UCL) promote the project-developed ideas via the academic work, scientific publications and participation in the relevant conferences and events.

PTC, the Polish telecom operator, is evaluating, analyzing and disseminating the BuNGee results, looking forward for industry-adaptation of the developed concepts.

BuNGee members will continue to promote adaptation of BuNGee-developed advanced deployment concepts and technological ideas.

The market for exploiting the technology developed in this project is predicted in acceleration in 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 also in future leading R&D projects.

As the current Mobile Broadband Wireless operators are facing the critical issues of capacity extension and in-building penetration, BuNGee provides technology and deployment models to address these challenges. 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 world wide 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.

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10 Release History

Release number	Date	Comments	Dissemination of this release (task level, WP/SP level, Project Office Manager, Steering Committee, etc)
1.0.0	09.08.12	Final version	Document submitted to EC