



GreenTouch Technical Solutions for Energy Efficient Mobile Networks

**Improving the nationwide energy efficiency in
2020 by more than a factor of 10000 in relation to
the 2010 reference scenario.**

A GreenTouch White Paper

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Executive Summary

GreenTouch [2] has published the final results of its Green Meter study in June 2015 in a WhitePaper [1], covering fixed and wireless access networks, metro networks and core networks. This white paper details the finding of the Mobile Working Group, regarding the Mobile Access networks.

The Mobile Working Group concentrated its activities on architectures and technologies that enable the radio access network to provide - in the most energy efficient way - full coverage and the capacity and performance that will be needed in the year 2020 [14] [15].

These technologies were investigated in the Mobile Working Group by three umbrella projects namely the Beyond Cellular Green Generation (BCG²) project, the Green Transmission Technologies project (GTT) and the Large Scale Antenna Systems (LSAS) project. The architecture subgroup developed a methodology to evaluate the energy efficiency for a hypothetical nationwide wireless network and applied this toolset to benchmark all proposed approaches and technologies between each other and versus the 2010 reference. The GreenTouch proposal for a sustainable future mobile architecture is then created by selecting the most energy efficient technologies separately for each deployment area, such as city centers or country sides.

The energy efficiency of mobile networks depends on the usage pattern and is measured as the electrical energy spent per transmitted data volume averaged over a period of time, i.e. in Joule per bit. The efficiency of a nationwide operator network is obtained by averaging the energy spent over a wide range of deployment and operational conditions, from busy hours in metropolitan areas down to rural areas at night times with very low traffic demand. We analyzed network traffic patterns and defined a representative traffic model for all the use cases, including user densities as well as the anticipated, near-exponential rise in mobile data traffic between 2010 and 2020. An advanced power model has been developed that provides realistic hardware power consumption values for a diversity of cellular base station types and operation conditions, while incorporating hardware technology trends.

This complementary set of several models is used to predict the overall network behavior, the energy consumption and energy efficiency for a variety of deployments across technologies and environments, for example the massive roll out of small cells or for futuristic base stations with hundreds of antennas or new management schemes with intelligent sleep modes. To calculate the potential energy efficiency gains for the GreenTouch technologies and solutions, a reference scenario using the best available technologies and traffic data from the year 2010 has been defined. This reference energy efficiency is then compared with the efficiency of the GreenTouch mobile architecture assuming the traffic volume for the year 2020 and the selected most energy efficient technologies.

This white paper summarizes the methodology and the final results of GreenTouch for wireless access networks. Using this approach we provide an architecture showing that it is possible to achieve an energy efficiency improvement of more than a factor 10000 in relation to the 2010 reference scenario. Even with the much higher traffic anticipated in 2020, the network energy consumption can be lowered by a factor of 110.

GreenTouch has also publicly launched an interactive application, called “GWATT for GreenTouch” [3] to visualize the portfolio of technologies and their energy impact. This tool can be used to visualize the impact on energy efficiency if one deploys the technologies described in this white paper in the different geographical areas.

1. Background

The Mobile Communications Working Group in GreenTouch [2] was focused to contribute research to improve energy savings in wireless access networks. These savings will accrue with innovations in architecture, access nodes, and deployment of the mobile communication network for future generations. Examples of areas for research include air interface technologies, radio resource management, Multiple-Input-Multiple- Output antenna systems and other antenna technologies, relays and cooperative transmission, power amplifier technologies, base station architectures, baseband processing, backhaul technologies, network topologies, deployment strategies, and operation and management concepts.

An additional challenge for the Mobile Working Group was to define a methodology how to measure the energy efficiency for a nationwide mobile network taking into account the inhomogeneous user distribution in city centers compared to rural areas.

Participants from mobile vendors, mobile operators, device manufacturers, and academia collaborated in three large umbrella projects -- the Green Transmission Technologies (GTT), Large Scale Antenna Systems (LSAS), and Beyond Cellular Green Generation (BCG²) -- and an architecture sub-group that defined the common methodology and integrated the results from the umbrella projects to define the GreenTouch mobile architecture.

2. Methodology

Many approaches to the energy efficiency of Mobile Networks have been studied, within and outside GreenTouch. It is commonplace nowadays that such analysis cannot just minimize the emitted RF power but needs to cover all of the base station (BS) hardware and even the backhaul link towards the core network. Further, for the overall aspiration of GreenTouch it is not sufficient to study the gains in a special scenario but to quantify how this scenario contributes to the global scale of power consumption. To this end, the Mobile Working Group has developed [4][5][23] and applied a comprehensive framework of models and simulation assumptions that provides quantitative and comparable results of BCG², LSAS and GTT, brings them together in an optimized network architecture and allows a comparison with selected reference scenarios. These models will be summarized in the following sections.

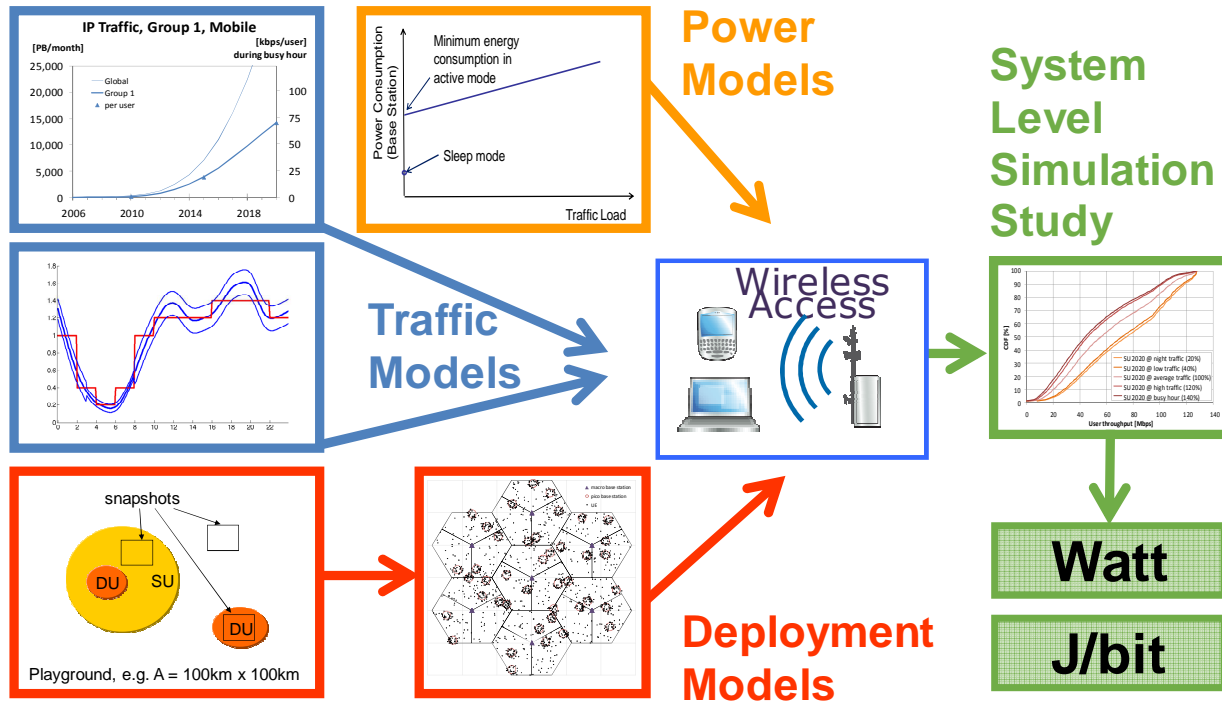


Figure 1 Models and Metrics of the Green Meter Framework for Mobile Networks

Metrics

In the literature [21] several metrics have been proposed, but energy efficiency is best measured in bit/J. The GreenTouch mission is to improve the energy efficiency by a factor of 1000. The overall network comprises coverage limited areas with low utilization as well as other areas that are very busy and can be capacity limited. These parts of the network perform with very different energy efficiencies. However, for adding and weighting a range of scenarios each with well defined traffic levels (see below) it is easier to use the energy intensity¹, i.e. the energy spent per unit of traffic in J/bit. The conversion to the overall energy efficiency is straight forward.

According to the finding that the energy efficiency strongly depends on the traffic level and with the observed near-exponential traffic growth, we also evaluate the energy consumption. This reflects the actual effect of mobile networks on the operational expenses (energy cost) and on the climate (carbon dioxide footprint) and is described as the total annual energy consumption, in J or rather kWh/year.

Besides the energy metrics, also performance metrics are considered. System level simulations provide the system throughput in Mbps/km², the average throughput per user in Mbps and the 5%ile of the user throughput, used as measure for the cell edge performance. These metrics are used to ensure that the simulated network performance complies with the specified performance requirements, i.e. the energy saving does not compromise the network QoS.

¹ For energy intensity the weights of the scenarios are simply given by the fixed fractions of the overall traffic they serve. Thus they are independent of the network performance of the scenarios, i.e. the same for the reference and the improved scenarios.

Reference scenario and gain factor

The reference for the GreenTouch efficiency gain is the year 2010, the starting year of GreenTouch. However, we do not consider old installed equipment in the field, rather we base on the best available equipment on the market in 2010. For an apple to apple comparison we need to compute the efficiency of the 2010 network with the same modeling depth that we use for the proposed network innovations. To this end, a synthetic network is created, covering all inhabited areas with state-of-the-art LTE broadband equipment of 2010. Four competing operators are deploying networks with equal market shares. The Simulation results for this reference scenario yields an energy consumption roughly in line with the reported global consumption of all operators in 2010 [19]. This means, that the computed energy efficiency of the reference scenario is within a factor of 2 to the efficiency of the actual installed basis of operator networks (2G, 3G and first patchy LTE rollouts) in 2010. Note however, that the synthetic full coverage LTE network provides way more capacity than the installed networks in 2010.

For 2020, we apply the best technology that will be available, covering optimizations of existing LTE hardware and standard compliant management techniques as well as current research topics like interference coordination, massive MIMO and separation of data and control traffic. We apply the massively higher traffic volume (for 2020, a 89-fold increase of traffic has been estimated [5]) to compute the achievable energy efficiency in 2020 and the improvement factor over the reference scenario.

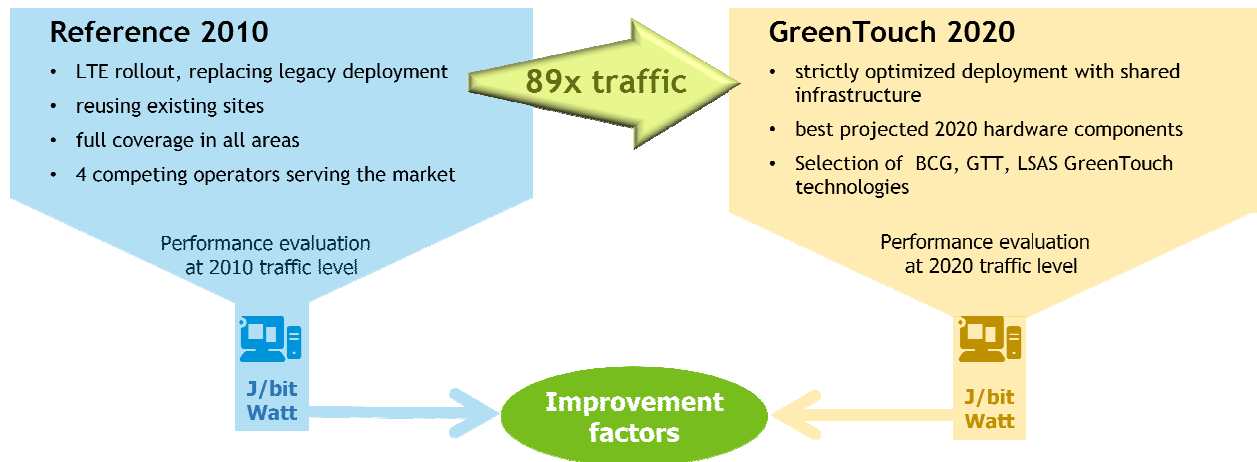


Figure 2 Reference scenario and computation of the efficiency gain factor

Due to the high traffic increase, significant energy efficiency improvements over the 2010 reference are already achieved from the economics of scale (caused by high network energy cost for area coverage), without any innovation introduced. Therefore, additional comparison scenarios with the 2020 traffic are studied: In worst case, just the minimum necessary reinforcement are added to the 2010 state-of-the-art network (i.e. carrier aggregation in dense urban areas) to serve the higher traffic. A second, more evolutionary scenario also reuses the same network, but replaces all of the 2010 hardware by a 2020 generation of equipment, extending the historic trend of 5% CAGR better efficiency over the 2010-2020 time frame. Additionally, this evolutionary scenario for 2020 deploys improvements that were on the road map before the GreenTouch Initiative started, i.e. RRHs, 20MHz bandwidth and HetNets with a limited deployment of Small Cells in a separate RF band.

Traffic models

The traffic load is based on the reported traffic per user per month in 2010 and extrapolates the growth trends until 2020 [5]. This study focuses on the developed markets of North America, Western Europe and Japan (aka Group 1 countries), where reliable data are available².

The total network traffic to be served depends on the population density. However, the traffic is not spread evenly over the area, rather traffic demand (and thus network layout) is very different between dense urban areas and rural areas. Table 1 gives the evolution of traffic per user for the time scale of 2010 - 2020, the diurnal load cycle and the breakdown into area types. In dense urban areas an even finer granularity (hot spots) will be introduced in the Figure 5. Note, that large areas (e.g. wilderness in Canada or Scandinavia) are basically unpopulated. We thus model all population in 30% of the area and 70% of the Group 1 area is not covered by broadband services [20].

The network deployment is required to serve not only the monthly average traffic but takes into account the daily load cycle between night and busy hour. Additionally, network capacity is designed for 25% higher traffic than during busy hour, to stay at least 6 month ahead of the 2010-2020 CAGR traffic growth.

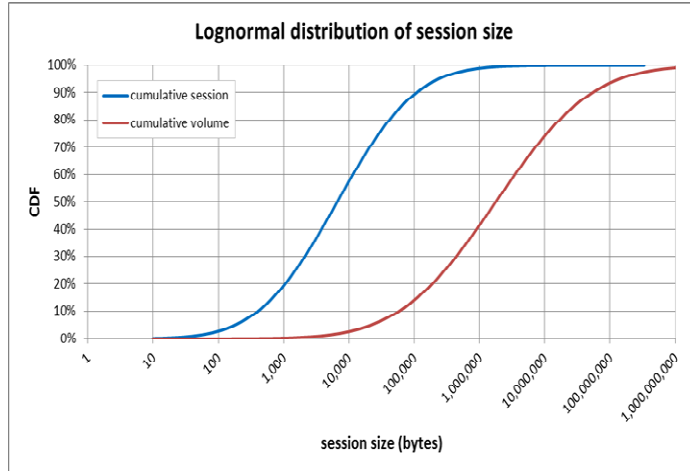
| Traffic evolution | Data volume per user | night 2h/day | morning 4h/day | average 4h/day | high time 8h/day | busy hour 6h/day |
|-------------------|----------------------|----------------------|----------------------|-----------------------|-----------------------|-----------------------|
| 2010 | 183MB/month | 20% of average level | 40% of average level | 100% of average level | 120% of average level | 140% of average level |
| 2020 | 16.3GB/month | | | | | |

| Area Type | Dense urban (DU) | Urban (U) | Suburban (SU) | Rural (Ru) |
|--|---------------------------|---------------------------|---------------------------|---------------------------|
| Population density | 10000/km ² | 1000/km ² | 300/km ² | 30/km ² |
| Fraction of network area (of populated area) | 0.33% | 3% | 10% | 86.7% |
| Percentage of the network data traffic | 27.9% | 25.1% | 25.1% | 21.8% |
| Busy Hour traffic demand in 2010 | 7.92 Mbps/km ² | 0.79 Mbps/km ² | 0.24 Mbps/km ² | 0.02 Mbps/km ² |
| Busy Hour traffic demand in 2020 | 702 Mbps/km ² | 70 Mbps/km ² | 21 Mbps/km ² | 2.1 Mbps/km ² |

Table 1 Temporal and spatial distribution of traffic demand in 2010 and 2020

Network energy efficiency is further affected by the service mix of the traffic. Large sessions imply longer sleep intervals between service requests, small session imply higher arrival rates of requests with higher signaling overhead. Using operator network traces, it turns out that actually many mobile connections transmit only a few tens of Bytes. We propose a representation of the session size distribution by two service types with 10kB requests (small packets) and 2 MB requests (large packets). This aspect of the traffic model was not covered in the earlier study [5].

² The focus on these markets also avoids methodological issues from population growth and migration patterns into cities. Further, the lack of an electricity grid in many developing markets requires the use of diesel power, which introduces additional inefficiencies for the mobile network power consumption.



| Session type | Session volume | Service arrivals | Traffic share |
|---------------|----------------|------------------|---------------|
| small packets | 10 kB | 96.9 % | 13.6 % |
| large packets | 2 MB | 3.1 % | 86.4 % |
| Average | 71.4 kB | | |

Figure 3 Distribution of session size in network traffic and representative model with two service types.

Base station power model

The base stations are a key element in the development of sustainable communication networks, as they dominate the overall energy consumption of the mobile network. Moreover, the amount of base stations will further increase to support the growing traffic. Assessment of the energy consumption trend and development of highest energy efficient networks require realistic knowledge about the power consumption of today's and future base stations. GreenTouch addressed this by developing an advanced power model which quantitatively forecasts the power consumption over different base station architectures/types and configurations to cover a wide range of scenarios [7][8]. The implemented base station types include conventional large- and small-cell architectures (e.g. macro-, pico-cells), and also disruptive architectures such as the large scale antenna systems (LSAS). A multitude of parameters allow the user to specify the configuration in terms of e.g. transmit power, bandwidth, number of antennas, traffic load, etc.

To support future oriented network research, the GreenTouch power model also models the hardware technology evolution over the time range 2010–2020. This evolution is predicted based on the hardware technology trends at component level. These trends are gained and verified based on different sources, including literature, product designs and prototyping knowhow. Different base station types will scale differently over technology generations, depending on their power breakdown over their components.

A promising energy saving technique in the mobile network is putting base stations to sleep during idle times within periods of low data traffic. To support this concept, the GreenTouch power model quantifies the transition times of the base station components and sub-components, and uses this information to group the components and to create multiple deactivation levels. These levels can be exploited to select the appropriate deactivation depths according the idle time duration. However, the duration of idle times are generally limited due to signaling and control signals, even in the absence of data users.

As an output, the model gives the load dependent power consumption of the complete base station as well as the detailed consumption values over the up- and downlink transceiver and over the individual base station components (power amplifier, analog front-end, digital baseband, control and power supply). This scientifically founded power model [7][8] is applied to all studied mobile scenarios within GreenTouch.

In order to make this power model generally available to the industry and the research community, GreenTouch created an online version of the model [6]. This web-tool is available for free and supports quantitative research on mobile network energy efficiency

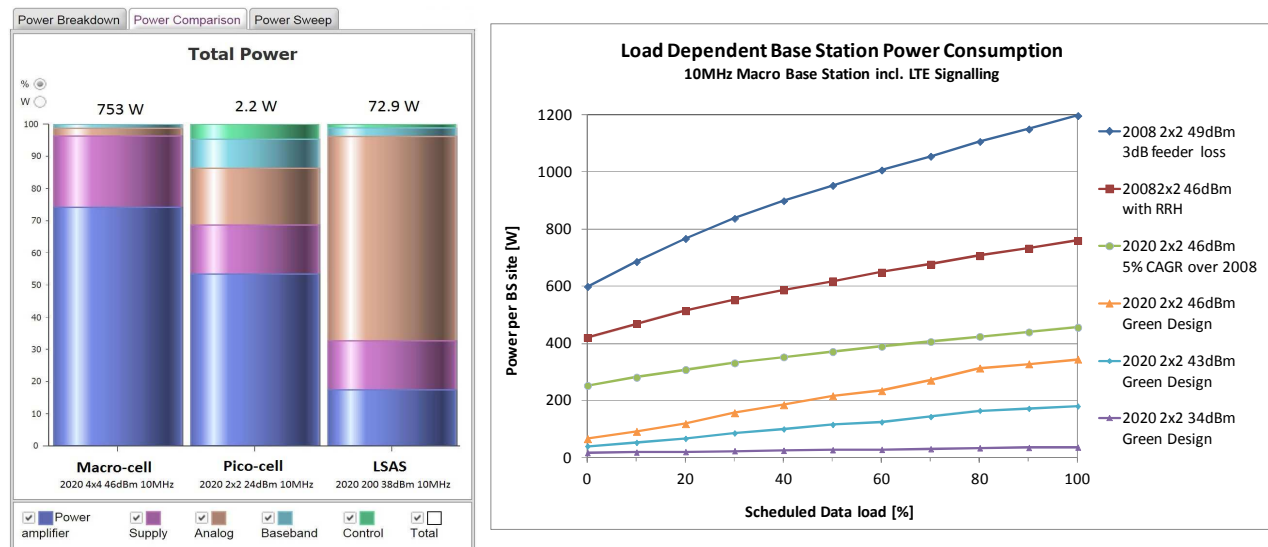


Figure 4 Example output of the GreenTouch BS power model.

Left: The breakdown into components strongly varies with the BS type (web tool screenshot).

Right: Load dependency and effect of configuration and technology scaling from 2010 to 2020.

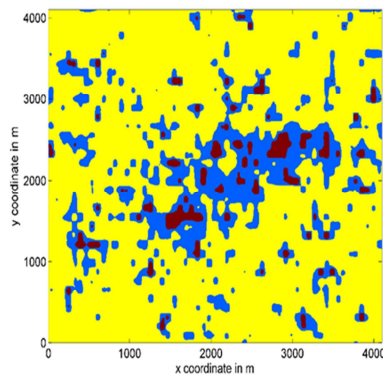
Base Station backhauling

A non-negligible power consumption is contributed by backhauling of the base stations. In the reference scenario of 2010, fiber optic point-to-point links were using 10W of power, but many cells in rural and suburban areas were connected via microwave links, consuming 145W of power.

For 2020 we apply a dedicated PON fiber optic backhauling network for the mobile access, building on the GreenTouch technology of cascaded BiPON [13]. Due to the extended optical range, this will enable backhauling with only 0.3W per attached cell. According to the power model (Figure 4), in 2020 small cells will only consume 2-7 W. Therefore, low power backhauling is key for an energy efficient deployment of small cells.

Deployment model

Beyond the separation of the network into area types, a finer granularity of traffic occurs due to urban hotspots. Operator data have been used to build a model of hotspot occurrences and their traffic level. The observed traffic inhomogeneity can be represented with central high demand areas (hot spots) and a surrounding area (hot zones) with approx. 5 times lower traffic. The remaining area bears only 1/3 of the average traffic load. Figure 5 shows a traffic measurement plot of a Western Europe dense urban area and a table with the representative model for urban hotspot traffic, as developed by GreenTouch [12] and applied in the simulations of dense urban and urban areas.



| Inhomogeneous urban traffic distribution | Traffic Modeling with 4 Hotzones/km ² according to network operator data | | Dense urban Busy Hour in 2020 | Urban Busy Hour in 2020 |
|--|---|---------------|---------------------------------|---------------------------------|
| | Area coverage | Traffic share | Traffic in Mbps/km ² | Traffic in Mbps/km ² |
| Hot spot | 3.19% | 32.0% | 7012.71 | 701.27 |
| Hotzone | 21.21% | 43.6% | 1451.75 | 145.18 |
| Non-hot area | 75.60% | 24.4% | 225.56 | 22.56 |
| area average | 100% | 100% | 702.14 | 70.21 |

Figure 5 Measured fine granularity of traffic distribution in urban areas, resolving 4 hotspots per km².

In the network scenarios, Macro BSs are evenly deployed on a regular hexagonal grid. For the 2010 reference, the network consists only of 3-sectorised macro BSs with 2x2 MIMO, an RF emission of 43dBm/sector and an inter site distance of 500m, 1000m, 1732m and 4330m (according to usual assumptions and coverage limits) for DU, U, SU and Ru areas. For 2020, the sectorisation, number of antennas, transmit power and inter site distance are chosen according to the increased traffic demand of 2020.

Four Hot Spots are inserted per km² of the simulation playground, according to the observed hotspot density of Figure 5. The traffic arrivals are distributed over the playground according to the table therein. In the 2020 scenarios, a second layer with “Small Cell BSs” can be deployed to offload traffic from the macro BSs, e.g. by placing small cells only in the hot spot areas, by a random small cell deployment over the hot zones or even by a full small cell coverage of all the playground.

A third deployment layer is proposed by the BCG² approach to provide an always-on signaling functionality by specialized Signaling Base Stations.

System simulation approach

GreenTouch used extensive simulations to assess the energy efficiency potentials. It goes without saying that the global mobile access network cannot be meaningfully represented in one simulation. Instead, the overall network is decomposed into the typical scenarios representing Dense Urban to Rural environments and different load situations over a day. Simulations use a system level approach with users statistically arriving for a service request, being served according to the received SINR (given by transmitted power, path loss, shadowing, fading, and interference of other BSs distribution), and turning idle after the transmission is completed [10][11]. As video and FTP file transfers are strongly dominant and network traffic is mainly downlink, the simulation can focus on data download, i.e. no voice service is modeled.

For the proposed GreenTouch network architecture, the types and densities of the BSs, and their bandwidth and power class can be varied freely to find an optimum deployment. Coverage limits are derived from uplink and downlink link budget considerations. Additionally, a minimum download rate is specified to model call drops and user frustration at cell edge. More details can be found in GreenTouch publications, e.g. [10][11].

The simulation playground comprises at least 7 macro BS sites of a given inter site distance, i.e. one tier of interferers, and warp around is applied. To master the complexity and the enormous amount of scenarios and technology combinations, the statistical simulations apply pre-computed performance CDFs which convert the long term SINR experienced by each user into the expectation value for the data rate of its service. These CDFs have been computed individually for the applied radio network technologies (e.g. MIMO or GTT) and aggregate the statistical effects of fast fading and 3D radio channels.

Operator sharing gains

In the 2010 reference scenario we assume four competing operators. Due to the high energy cost of network coverage (see the power characteristics in Figure 4) and the low utilization of the network at the 2010 traffic level it is easy to see that a shared infrastructure offers large saving potential. Simulations confirm savings of more than 50% in dense areas up to 75% in rural areas in 2010 (Figure 6). In general, this shows that sharing of physical infrastructure can lead to gains in energy consumption (and in capital expenditures). When the higher traffic of 2020 is applied and infrastructure sharing is combined with other energy saving techniques, it can be expected that the gains of network sharing are somewhat lower. Further, it is acknowledged that operator network sharing comes with regulation and business case issues. Nevertheless, as GreenTouch is aiming for the best technically possible solution in 2020, we always apply operator sharing for the GreenTouch optimized scenarios of 2020.

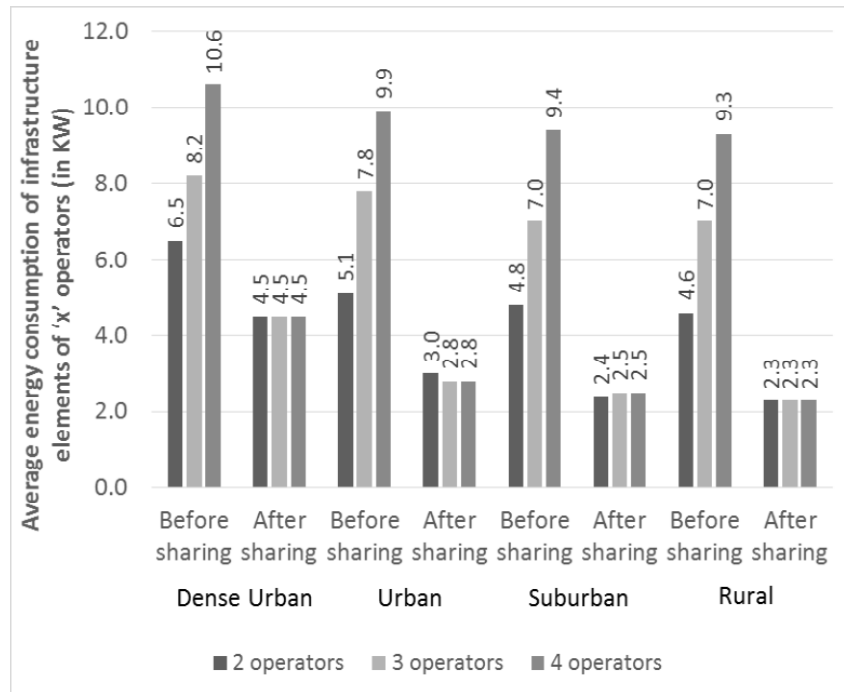


Figure 6 Simulation results for operator sharing in the 2010 reference scenario.

3. Technologies

The Mobile Working Group focused its investigations on the following technologies organized in three umbrella projects:

Beyond Cellular Green Generation (BCG²)

Advancements in transmission and hardware technologies for energy saving can provide remarkable improvements at full traffic load, as shown by the hardware evolution analysis behind the power model presented above. However, there is a non-negligible power consumption offset at low load that cannot be reduced unless the base station is switched off, or put into a sleep state. The ideal energy behavior is a power consumption of the whole system that is perfectly proportional to the traffic load, from a very low level with no traffic to a maximum value with full load (Figure 7). A network management that orchestrates base station activity and sleep periods can obtain this system behavior better than other local energy-saving features.

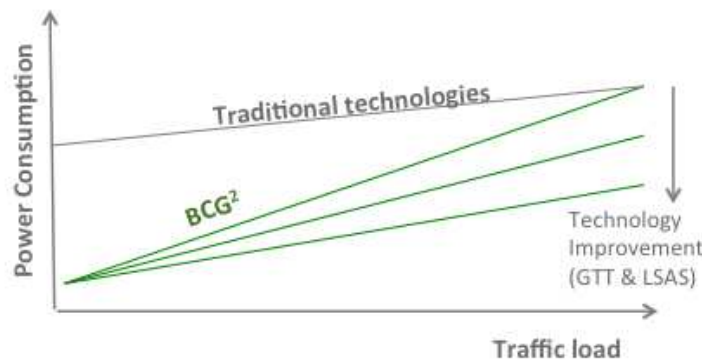


Figure 7 Load proportional energy profile

Unfortunately, energy efficiency was not taken into account when the cellular architecture was introduced. This generated severe constraints, which hamper the way towards this ideal behavior and, more in general, prevent from reaching very large cuts of the energy consumption. The cellular architecture of wireless access networks has its foundation on the concept of full coverage of the service area that ensures that user terminals can get access to the network at all times in any point of the area. Thus, a significant part of the network must be “always on” even without any traffic, resulting in unnecessary usage of resources, especially energy.

Energy saving strategies in traditional cellular networks, based on system level management of sleep periods of base stations, allow only to exploit the switch-off of redundant base stations in dense scenarios when the current traffic load is low. Previous research project and studies have shown that achievable energy savings in the current cellular architecture are in the range of 20%- 40%, depending on the considered traffic profiles and network layouts, noting that a non-negligible part of the network can never be switched off, even if there are no active users.

In this light, a new principle of mobile radio network architecture design, “Beyond Cellular Green Generation (BCG²)” [9] was proposed for the first time in the framework of GreenTouch in Jan 2011, targeting higher energy efficiency. The basic idea of BCG² is the concentration of control signaling in one so-called “signaling layer” (of a multi-layered network), while data transmission is served by other

layers/cells. Only the signaling cells are kept “always on”, while the data cells are available “on demand” (Figure 8). Breaking the tight coupling of data transmission and control signaling (served by the same cell) in traditional architectures, allows to overcome the limitations of cellular coverage and to manage energy in a much more flexible way.

The paradigm shift introduced by BCG² is grounded on two key points. First, not much information needs to be transmitted in order to enable ubiquitous connectivity. Basically, one only has to provide a signaling service to allow users to request a channel, when it is desired, and, in opposite direction, to enable mobile paging. Second, signaling traffic is radically different from data traffic, therefore, sharing the same network architecture and the same radio interface is not optimal in terms of energy consumption.

Radio interfaces for the signaling network can be carefully designed for long-range low-rate transmissions, while the wireless broadband data access interfaces can be designed to provide high data rates within relatively short distances using small cells. Differently from traditional Heterogeneous Networks (HetNet), BCG² layouts can be optimized considering separately the signaling and data traffic profiles and their variations over time and space so that to provide high rate and quality service while perfectly tailoring active resources to real-time needs, without any wasting. This makes viable rather extreme layouts characterized by a massive use of small cells, since base stations can be activated only when necessary to provide end users with extremely high access rates in concentrated areas. Ideally, the user is illuminated with a data service “spotlight” only where and when it is needed.

A fundamental component of the new architecture that enables the real-time activation and optimization of resources to serve user traffic requests is context information. Context information can be divided in two basic groups: network context and user context. The network context is the set of information that describes the status of the network, e.g., type and position of devices, activity status, energy consumption, capacity and current load, etc. Such information is operator-related and easily gathered via the backhauling/core network. Thus, the network context is generally assumed to be perfectly known to the resource allocation entity. The user context needed to efficiently run the resource allocation includes both the information on mobility and service requirements, needed to allocate the right amount of resources at the right moment in time, and, on the position and the quality of the available channels, which is fundamental to determine the service quality that can potentially be provided to the user.

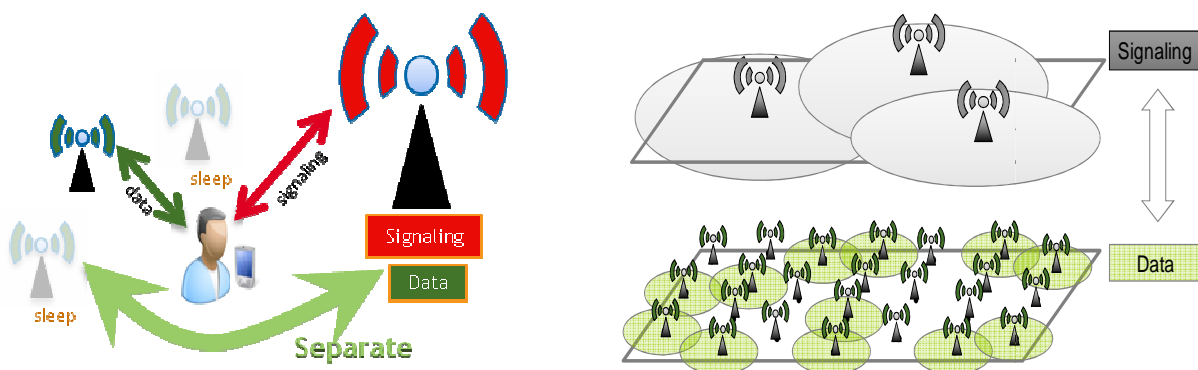


Figure 8 BCG2 architecture with separation of control and data plane functionalities. Data cells can be switched off.

GreenTouch has derived a dimensioning and the energy efficiency of the BCG² signaling layer. This layer of macro signaling-only base stations is designed to deliver common control channels (e.g. broadcast channels, synchronization signals) and data session-related L3 signaling (mainly for session setup and mobility purpose). It is noted, though, that both the signaling cells and data cells still need L1/L2 signaling for the purpose of scheduling, radio signal reception and detection. Considering the LTE radio interface as example, on average each session setup procedure consumes signaling overhead of 159 bytes [22]. The overhead of common control channels is dependent of the system bandwidth, and the number of antennas at the base stations. In the case of LTE with system bandwidth of 20MHz and 2 antennas at the base stations, about 0.33% of the radio resource is used to deliver the common control channels.

Signaling base stations only handle relatively modest amounts of signaling traffic, therefore the signaling layer can be optimized and dimensioned based on coverage-oriented link budget-based approach [10] (with a low bit rate requirement), assuming a relatively small bandwidth of e.g. 5 MHz or even 1.4 MHz. A queuing model is used to perform the downlink capacity check to ensure that the blocking probability fulfils the required threshold.

The resulting signaling network applies 3-sectorised macro BS with 4x2 MIMO and 35dBm transmit power per antenna. Depending on the area type, the most efficient inter-site distance of signaling cells is 2km (DU) to 6.6km (Rural). However, the power consumption per bit for these signaling base stations is relatively high, comparable with conventional macro base stations. But, this energy cost gets more than compensated by the gains achieved through the sleeping data cells. Thanks to the context knowledge of the signaling layer and its taking care of all the common control channels and L3 signaling traffic, the data cells obtain more chances to enter into deeper sleeping mode.

For DU areas, the total BCG² system efficiency improves by a factor of 2 over the performance of a Green HetNet (i.e. a LTE compliant HetNet, with small cells in Hotzones and energy-optimised RF powers and inter-site densities of the macro cells) (Figure 9). A detailed analysis shows that in the Green HetNet scenario the largest power contribution is from the many low loaded small cells in Hot Zones which can be operated in deep sleep mode using the BCG² technologies.

The BCG² project has compared different implementations scenarios of the data layer in the new architecture, from full area coverage by small cells to only macro cells. For the signaling, all these cases are applying the macro signaling-layer described above. Simulation results show that in DU areas a full data coverage with small cells is most efficient, while in rural areas only macro data cells should be deployed. In medium traffic areas (U, SU) a HetNet is best for the data layer. The best achievable efficiencies for BCG² are listed in Table 3.

Finally, it is very interesting to observe that the BCG² approach with the separated layer of signaling macro cells can be combined with the advanced transmission and antenna technologies in the data cells. This has been done by the GTT and LSAS projects obtaining even higher efficiencies, as applied in the following chapters.

BCG² Power Consumption in DU Areas BCG² with only small cells in the data layer, at 2020 traffic level

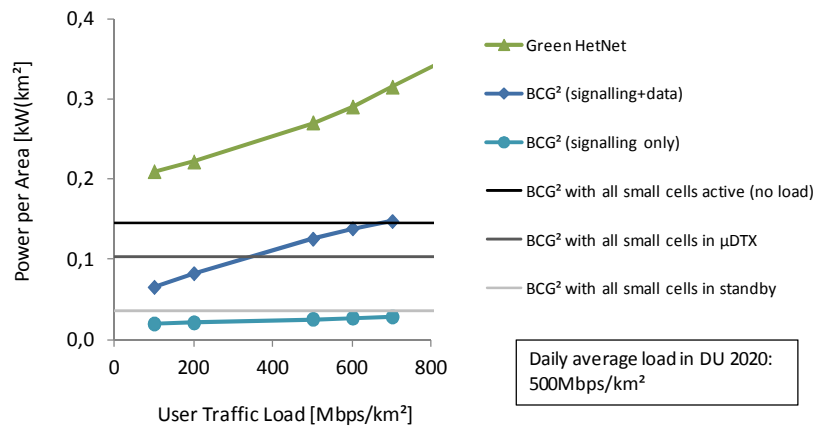


Figure 9 Area power consumption of a DU HetNet and a BCG² deployment, indicating that most small cell can be in standby.

Large Scale Antenna Systems (LSAS)

Large Scale Antenna Systems (generically known as Massive MIMO) is a promising candidate technology for 5G on account of its extraordinary spectral efficiency and its ability to deliver uniformly good service everywhere in the cell [16]. The emphasis of the GreenTouch LSAS project has been somewhat different: to maximize total energy efficiency subject to stipulated service requirements for a range of defined scenarios.

Figure 10 illustrates the downlink operation of LSAS: an array of physically small, low power, individually controlled antennas simultaneously (over the same time/frequency resources) directs data-bearing beams to a multiplicity of single-antenna users (terminals) utilizing directly measured channel characteristics.

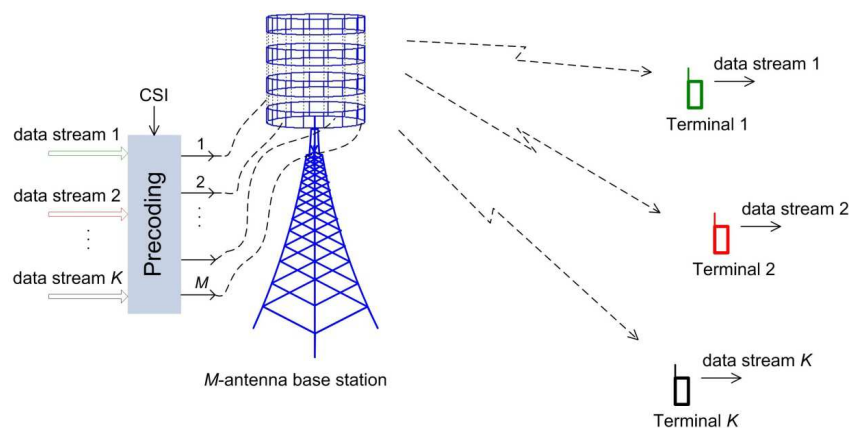


Figure 10 The LSAS array uses directly measured channel characteristics to transmit selective data-bearing beams to the users.

The activity of doubling the number of antennas enables the total radiated power to be reduced by a factor of two with no reduction in the quality of the received signals. Thus one could make the radiated energy efficiency as great as desired by increasing the number of antennas without limit. However, increasing the number of antennas increases the internal power consumption: every antenna has its own electronics chain, and the power required for signal processing computations increases. Thus, to maximize total energy efficiency, there is a trade-off between minimizing radiated power and minimizing internal power consumption.

The various contributions to internal power consumption (r.f. generation, electronics chains, and computing) are captured in a power model. Semi-analytical simulations are used for evaluating total energy efficiency, and numerical procedures perform system optimization for each of the four scenarios. The simulations correspond to a 49-cell system with wrap-around. A number of effects are accounted for including: pilot overhead, inter-cell interference (both non-coherent and coherent), channel estimation error, power control, and the imperfections of conjugate beamforming multiplexing. Two approaches for system optimization are taken: a non-adaptive algorithm provides equal (and minimum required) throughput simultaneously to each user [17], while an adaptive algorithm seeks further energy efficiency by optionally providing variable levels of service through adaptive scheduling [18].

The pertinent power model parameters used in the simulation are: 50% efficient r.f. generation, 150 mW per antenna internal power consumption, and 12.8 Gflop/W computational energy efficiency. For all simulations the spectral bandwidth is 40 MHz (TDD), the maximum number of antennas per base station is 600, and the maximum radiated power per antenna is 200 mW. LSAS base stations are deployed with optimized inter-site distance of 2.0km in dense urban to 6.7 km in rural areas.

Table 2 displays LSAS daily energy efficiencies relative to the 2010 reference for the four major scenarios for both non-adaptive and adaptive scheduling.

| | Dense Urban | Urban | Suburban | Rural |
|---------------------|-------------|--------|----------|-------|
| Non-Adaptive | 11,700 | 5,640 | 1,980 | 1,380 |
| Adaptive | 14,200 | 10,600 | 2,540 | 1,640 |

Table 2 Total energy efficiency gain of LSAS, relative to the 2010 reference.

Gains in total energy efficiency range from 1,600 for rural deployments to 14,000 for Dense Urban. The greater efficiency gains in the latter scenario can be attributed to smaller path loss because of the reduced size of the cell, and denser traffic which better exploits the multiplexing capabilities of LSAS. Adaptive resource allocation shows its greatest gain over non-adaptive in the Urban scenario.

Green Transmission Technologies (GTT)

Shannon's ground breaking capacity theorem suggests that there is a fundamental tradeoff between energy efficiency (EE, defined in bits per second per Watt) and spectrum efficiency (SE, defined in bits per second per Hertz). The theory suggests adapting the system's operating point from the high SE region to the high EE region whenever possible while satisfying the quality-of-service of all users. Though straight-forward in concept, it is not trivial to implement in practice. Transmit power is only a part of the total power consumption in real systems and the power required for baseband processing and the radio frequency chains needs to be taken into account. A large number of users are sharing all the resources such as bandwidth, power, time, antennas, etc., and interfering with each other, which makes the EE oriented optimization flexible but complex. Smart integration of the various proposed solutions becomes a challenging task.

In a bandwidth-rich environment, bandwidth expansion has been shown to lead to a corresponding reduction in the transmit power but it pushes the system to work in very low SNR conditions. Dedicated signal processing algorithms to maintain the stability and reliability for such transmissions are one of the key breakthroughs of the Green Transmission Technologies (GTT) project. On the other hand, in bandwidth limited situations, the network EE optimization problem is formulated under the EE-SE tradeoff framework and various GTT solutions are proposed to best utilize all available resources. These strategies include Dynamic MIMO with antenna sleeping which selects between single-user beamforming and multi-user multiplexing with the optimal number of active antennas. Interference alignment is another technology that is investigated to eliminate the strongest interference produced by a large set of neighboring base stations. Finally at the network architecture level, a collaborative distributed antenna system is considered that enables low interference virtualized access through intelligent clustering and optimal power allocation.

The GTT project has developed a methodology and a unified simulation platform to integrate all the different technologies. Hierarchical modeling with two layers is used to decouple the network layer deployment with the physical layer transmission technology design. Each (combined) solution gives a physical-to-network performance mapping curve and the best solution is selected for any given environment. Together, the GTT technologies offer an improvement in energy efficiency between 5200x (for rural environment) and 7300x (for urban environment) compared to the 2010 GreenTouch reference architecture. Additional gains can be achieved when the GTT technologies are coupled with the Beyond Cellular Green Generation (BCG²) concept of separating the control and data plane functionalities.

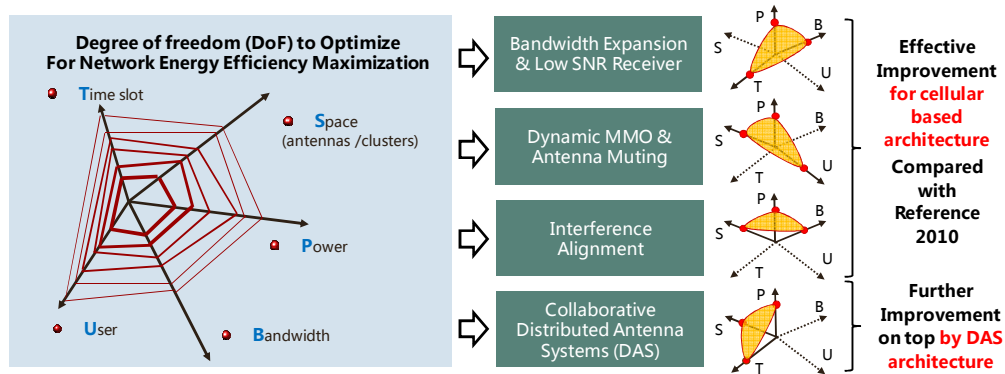


Figure 11 Major component of Green Transmission Technologies

Low SNR receiver

To achieve minimum energy-per-bit, the wireless system should work at low SNR region. A practical low-SNR receiver is needed that can perform critical initialization and tracking tasks that allow for proper data demodulation. These include carrier and clock recovery, channel equalization, and time/frame synchronization at low SNRs. This is difficult because the performance of each function is dependent on SNR. Poorer performance at the receiver front end will contribute to an even lower SNR before error-control decoding. This performance needs to be quantified and taken into account when applying various code types, lengths, and rates for bandwidth expansion. Low SNR receiver has been developed for point-to-point single-carrier and multiple-carrier transmissions in a physical demonstration.

Interference Management

The fundamental challenge for a multi-cell scenario is the mitigation of inter-cell interference, especially when the frequency is in full reuse. The EE and SE will be significantly degraded by inter-cell interference, especially for cell edge users. Reducing interference can be achieved by proper static or dynamic resource allocation over cells providing a significant EE gain. However, most of these techniques rely implicitly on reducing the bandwidth available for each BS, thus introducing an SE loss, and the global trade-off is then shifted.

When full feedback is available, the multi-cell scenario becomes equivalent to a single-cell MIMO scenario and the optimal performance may be achieved by employing joint transmission and reception of multiple cells. To reduce the amount of backhaul transmissions and cooperation requirements, interference alignment is attractive because it requires only information exchange relative to channel states, each mobile being associated with only one BS. However, the performance of interference alignment is limited by imperfect channel estimation and time variations. Interference alignment can also be designed with limited feedback. Indeed, the local choice made by a transmitter should be restricted to not affect the interference perceived by neighbour receivers. The effects of interference alignment on the energy efficiency have been shown by a physical demonstration.

The interference management is further investigated in the heterogeneous networks (HetNets). As different tiers of BSs coexist in the same coverage area, tackling the cross-tier interference and co-tier interference has become a major challenge and a bottleneck towards improving network performance. To achieve the desired performance, many interference management methods can be employed as part of the HetNets design: calibration of small cell's downlink transmit power to limit interference to the macro network while providing good coverage for the small cell users; transmit beamforming as an efficient solution for managing interference; adaptive UL attenuation at the small cell to mitigate interference caused by a nearby interfering macro and/or small cell user not controlled by the small cell; carrier selection for small cells combined with inter-frequency handover for macro cell users to avoid co-tier and cross-tier interference.

Distributed Antenna Systems

The distributed antenna systems (DAS) take advantages of distributed antennas, MU-MIMO [24] and water-filling UE power allocation to increase energy efficiency. The distributed antennas are connected with centralized processor via low delay links. UEs are served by nearby antennas. The BS and UE power consumption can be decreased due to less loss in signal strength over the air. The ZF MU-MIMO to cancel out intra-system interference is followed by a simple wait-and-go (first-in-first-out) scheduler. The limitation of maximum number of allowable UEs decreases the power consumption of signal processing. Multiple antennas jointly transmit one stream to an UE with allocated transmit power. The limited power resource can thus be utilized in an efficient way. Both MU-MIMO and UE power allocation

increase the system SE. From the simulation results, regarding the 5%ile of data rate, the centralized antenna system and equal power allocation (CEP) methods requires 80, 250, 390 and 450 antennas to achieve the same performance as GTT DAS with 16, 24, 24 and 28 antennas in dense urban, urban, suburban and rural scenario, respectively.

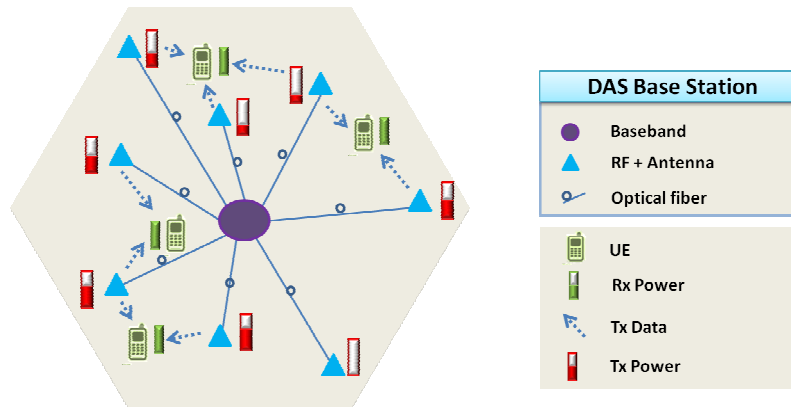


Figure 12 Illustration of GTT-DAS, characterized by distributed antennas, MU-MIMO and power allocation

4. Mobile Network Architecture

Combined solutions

All proposed network technologies of section 3 are applied to all scenarios described in section 2. For each of the network areas a different architecture can be chosen and over the time of a day management techniques can be applied to adapt this network to the load situations. The final GreenTouch mobile network architecture is selected from the most efficient solution per area.

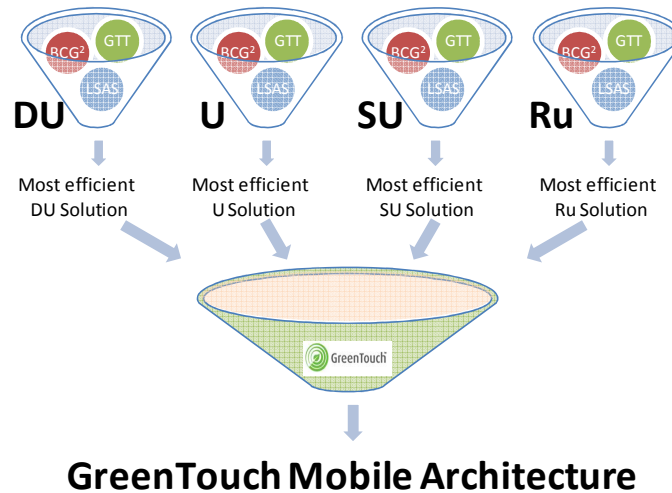


Figure 13 Combination of solutions for final GreenTouch Mobile Architecture.

Architecture selection

The table below summarizes the energy efficiency of the different scenarios and network architectures. The values are averaged over the daily load cycle. It can be seen that already for the Evolution scenario the overall efficiency (over DU, U, SU and Ru scenarios, weighted according to the served traffic) grows by a factor of 100.

Much higher efficiency gains and energy savings are achieved by a dedicated green network architecture. The LTE compliant Green HetNet scenario performs 40 times more efficient than the Evolution scenario. Even higher gains are possible when taking into account the beyond-LTE techniques studied in GreenTouch. The table reveals that for the highest traffic density (i.e. DU) LSAS provides superior energy efficiency, for all other areas the GTT technology is best. In both cases an overlaying signaling network (BCG² architecture) is required. With the optimum choice (printed in bold in the table) gains between 7400 and 14,000 over the 2010 reference are achieved.

| Technology | Daily energy intensity [J/Mb] | | | |
|----------------------------------|-------------------------------|--------------|--------------|-------------|
| | DU | U | SU | R |
| 2010 Reference | 1989 | 5528 | 6126 | 10849 |
| Evolution according to trend | 20.4 | 53.6 | 60.0 | 104.4 |
| Green HetNet (LTE compliant) | 0.55 | 1.25 | 1.52 | 2.82 |
| BCG | 0.24 | 0.6 | 2.33 | 2.74 |
| GTT | 0.37 | 0.75 | 0.88 | 2.08 |
| GTT with BCG ² Layer | 0.26 | 0.39 | 0.50 | 1.47 |
| LSAS with BCG ² Layer | 0.14 | 0.52 | 2.41 | 6.62 |
| Improvement | 14000 | 14000 | 12000 | 7400 |

Table 3 Energy efficiency gains for different deployment environments and different mobile architectures and technologies

Final results and outlook

The GreenTouch Mobile Working Group has studied the performance and energy consumption of mobile data communications and, in unique modelling depth, assessed the efficiency gains of the leading research approaches over the 2010 reference. The reference scenario assumes a synthetic broadband LTE deployment for the developed markets of North America, Western Europe and Japan. The average efficiency of this scenario amounts to 5850J/Mb. This yields an energy consumption of 25TWh/year, which is well in line with the global electricity consumption of wireless networks of 88TWh/year, as reported [19] by GSMA for 2010.

Assuming only the historic hardware improvement trends of 5% CAGR, the energy efficiency of mobile networks will improve 100 times between 2010 and 2020. Considering the 89-fold traffic increase, this still yields a 12% energy saving. This result proves the simplistic argument wrong, that the observed traffic growth inevitably drives the energy consumption into unsustainability.

Much higher efficiency gains and energy savings can be achieved when the mobile networks of 2020 are strictly redesigned for maximum efficiency, applying the best of the studied approaches for each of the area types. The overall performance then is 10000 times more efficient than in 2010 and thus allows to reduce the energy consumption below 1% of the 2010 reference – at the 89-fold traffic!

An interactive tool [3] has been provided to visualize the effect of the individual technologies and of the integrated architecture on energy efficiency, energy consumption and carbon footprint of mobile access networks in 2010 and 2020.

These results of the Mobile working Group of GreenTouch demonstrate that from research perspective a network layout for 2020 can be proposed that is not just keeping energy consumption flat but reducing the energy consumption by two orders of magnitude, way beyond the original aspiration of GreenTouch. To realize these gains, however, the current 2G and 3G deployments need to be discontinued and the latest 2020 hardware needs to be deployed with a different set of Base Station sites than in 2010.

GreenTouch strongly encourages to apply the methodology and findings documented in the White Paper for the ongoing standardization of the 5th generation of mobile networks.

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Contact and Further Information

For further information, please visit the GreenTouch web page at www.greentouch.org

References

- [1] "GreenTouch Final Results from Green Meter :Reducing the Net Energy Consumption in Communications Networks by up to 98% by 2020 ",GreenTouch White Paper, Version 1.0, June 18, 2015,
www.greentouch.org/uploads/documents/GreenTouch_Green_Meter_Final_Results_18_June_2015.pdf .
- [2] www.greentouch.org
- [3] G.W.A.T.T. : "Global 'What if' Analyzer of neTwork energy consumpTion", Online visualisation tool of GreenTouch results and network configurations: <http://gwatt.greentouch.org>
- [4] GreenTouch Green Meter Announcement, May 2013
<http://www.greentouch.org/index.php?page=press-releases>
- [5] "GreenTouch Green Meter Research Study: Reducing the Net Energy Consumption in Communications Networks by up to 90% by 2020.", GreenTouch White Paper, Version 1.0, June 26, 2013
http://www.greentouch.org/uploads/documents/GreenTouch_Green_Meter_Research_Study_26_June_2013.pdf.
- [6] B. Debaillie, C. Desset, E. De Greef, "Power model for today's and future base stations"; online Web-tool of the GreenTouch power model, <http://www.imec.be/powermodel>
- [7] C. Desset, B. Debaillie, and F. Louagie, "Modeling the hardware power consumption of large scale antenna systems," Invited, at IEEE OnlineGreenComm, Nov. 2014.
- [8] B. Debaillie, C. Desset, and F. Louagie, "A flexible and futureproof power model for cellular base stations," in Vehicular Technology Conference (VTC), May 2015.
- [9] A. Capone, A. Fonseca dos Santos, I. Filippini, and B. Gloss, "Looking beyond green cellular networks," in Conference on Wireless On-demand Network Systems and Services (WONS), Jan. 2012, pp. 127–130.
- [10] R. Litjens, Y. Toh, H. Zhang, and O. Blume, "Assessment of the energy efficiency enhancement of future mobile networks," in IEEE Wireless Communications and Networking Conference (WCNC), April 2014.
- [11] O. Blume, A. Ambrosy, M. Wilhelm, and U. Barth, "Energy efficiency of LTE networks under traffic loads of 2020," in International Symposium on Wireless Communication Systems (ISWCS), Aug. 2013.
- [12] H. Klessig, V. Suryaprakash, O. Blume, A. Fehske, and G. Fettweis, "Spatial analysis of mobile traffic hot spots," in IEEE Wireless Communication Letters, 2014, vol. 3, pp. 537–540.
- [13] P. Vetter, D. Suvakovic, H. Chow, P. Anthapadmanabhan, K. Kanonakis, K.L. Lee, F. Saliou, X. Yin, and B. Lannoo, "Energy efficiency improvements for optical access," IEEE Communications Magazine, April 2014.

- [14] O. Blume, D. Zeller, U. Barth, "Approaches to energy efficient wireless access networks", 4th International Symposium on Communications, Control and Signal Processing (ISCCSP), Limassol, 2010
- [15] Y Chen, O Blume, A Gati, A Capone, "Energy saving: Scaling network energy efficiency faster than traffic growth", IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Shanghai, 2013
- [16] Marzetta, T.L., "Massive MIMO: An Introduction", Bell Labs Technical Journal (Volume 20), March 2015, pp. 11 – 22.
- [17] H. Yang and T. L. Marzetta, "Total energy efficiency of cellular large scale antenna system multiple access mobile networks", 2013 IEEE OnLineGreenComm Conference, pp. 27-32, Oct 2013.
- [18] W. Pramudito, E. Alsusa, D. So and K. Hamdi, "Load aware adaptive scheduling for energy efficient suburban Massive MIMO networks," 2015 IEEE Global Communications Conference (GLOBECOM), 6-10 Dec. 2015.
- [19] "Mobile's Green Manifesto 2012", GSMA, June 2012
<http://www.gsma.com/publicpolicy/public-policy-resources/mobiles-green-manifesto>
- [20] "Environmental engineering (EE); principles for mobile network level energy efficiency," ETSI TR103117, pp. 40–44, Nov. 2012.
- [21] "How Much Energy is Needed to Run a Wireless Network ?", G. Auer, V. Giannini, I. Gódor, P. Skillermark, M. Olsson , M.A. Imran, D. Sabella, M.J. Gonzalez, C. Desset, O. Blume, A. Fehske. IEEE Wireless Communications Magazine, 18(5), pp. 40 – 49, Oct 2011
- [22] 3GPP TR 36.822, "LTE Radio Access Network (RAN) enhancements for diverse data applications".
- [23] Y Chen, O Blume, A Gati, A Capone, "Energy saving: Scaling network energy efficiency faster than traffic growth", IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Shanghai, 2013
- [24] J. Li, X. Su, J. Zeng, Y. Zhao, S. Yu, L. Xiao, and X. Xu, "Codebook Design for Uniform Rectangular Arrays of Massive Antennas," in Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, June 2013, pp. 1-5.