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Reducing Energy Consumption in Access Networks
Final Report

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I would like to thank my supervisor Dr. Jennifer McManis for her direction and support during the course of this work.
I am also very grateful for the unwavering support and understanding of my wife and daughter over the past two years.

Declaration

I hereby declare that, except where otherwise indicated, this document is entirely my own work and has not been submitted in whole or in part to any other university.

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Reducing Energy Consumption in Access Networks

Walter Keating

***Abstract*—Energy consumption reduction is one of the most serious challenges facing telecommunications network operators worldwide as their networks grow in size, complexity and density with increasing energy consumption and therefore increasing energy related OPEX and environmental impact. Considering the various emerging wireless access networks standards such as LTE and LTE-Advanced, considerable attention is now being paid to the challenges of "increasing energy efficiency and reducing energy consumption in the BSS (Base Station Subsystem)" (which in the course of this paper will be collectively referred to as "Green Radio") while at the same time maintaining the higher end-user data rates and Quality of Service expected from these advanced wireless access technologies.**

Sophisticated relaying technologies that are under consideration for LTE-Advanced are expected to become key enablers for meeting some of the upcoming deployment, coverage and energy related challenges in a cost effective and energy efficient manner. This paper discusses some of the key techniques involved in Green Radio, proposes and evaluates a baseline model of energy consumption for a typical LTE Evolved Node B (ENB) Site scenario which then serves as a basis to evaluate some of the possible benefits of relaying technology in LTE networks and beyond in terms of Green Radio.

I. Introduction

Worldwide usage of mobile data services has grown in an unprecedented manner over the past 5 years, driven by evolutions in mobile access network technology such as HSDPA and HSPA+. There are presently more than 4 billion mobile phone users globally and it is expected that by 2013 mobile devices will have surpassed the Personal Computer as the most commonly used internet access device. Wireless networks are now carrying ever increasing volumes of data as improved throughput and evolved end-user services and devices have allowed the internet to become truly "mobile".

Wireless ISPs are now competing with and in many cases overtaking fixed-line internet access providers in many parts of the world as reported in [1].

As mobile access networks continue to evolve further towards real 4G services via Long Term Evolution (LTE) and LTE-Advanced, operators now face many new challenges, but probably none greater than that of growing and sustaining their networks in an energy efficient manner as regulatory demands and corporate social responsibility force them to consider the environmental and commercial impacts of their network's energy consumption trends as discussed in [2].

LTE as defined in 3GPP Release 8 [3] will support mobile data downlink speeds of up to 326.4 Mbps over scalable bandwidths of up to 20 Mhz. with a spectral efficiency of up to 15 Bps/Hertz uplink and 30 Bps/Hertz downlink. LTE will in turn be enhanced by LTE-Advanced in order to fulfill the complete requirements of IMT-Advanced for 4G [4] services as defined by the International Telecommunication Union (ITU) such as peak data rates of up to 1Gbps and much improved data rates for users at the cell edge.

Increasing energy prices mean that even to maintain current energy expenditure levels, mobile network operators must firstly look at reducing energy consumption and secondly considering the upcoming requirements to provide higher speed data services to more subscribers at higher radio frequencies and because RF free space path-loss increases with the operating frequency (most European countries have already auctioned spectrum earmarked for LTE services at 2.6Ghz.) there is obviously a very tangible requirement emerging to build denser and broader BSS networks where greatly improved energy efficiency levels will be required.

In current generation cellular networks each base station site can consume up to 2.7kW of electrical power which can lead to an energy consumption of tens of megawatts per annum for typical mobile networks as reported in [5].

Although the energy consumption of the UE (User Equipment) in the network is almost negligible [6] when compared to that of the network itself, the hard constraints imposed by the UE battery life have led to considerable and coordinated efforts to optimize and minimize UE power consumption while similar measures to drive Green Radio from the network side have only emerged quite recently. Total wireless network energy consumption is currently dominated by the BSS part [21] and in emerging and evolving wireless access technologies this will certainly continue to be the case.

The standardization processes for LTE-Advanced are already well underway and the industry is now taking this opportunity to build considerations and designs for Green Radio into the wireless access network protocols and architectures of the future. Many mobile network operators, equipment vendors and well known industry players have already begun engaging heavily in industry sponsored academic research initiatives to tackle these upcoming energy issues as they have already identified them as a becoming major limiting factor to future growth prospects in the industry.

Green Touch [7, 21] Green Touch is an Alcatel Lucent Bell Labs led privately funded consortium of ICT industry players and leading academic research resources. The goal of Green Touch is to deliver the relevant architecture, specifications and roadmaps required to enable ICT energy consumption reduction per user by a factor of 1000 from the current levels by 2015.

Earth – Energy Aware Radio and network technologies [8, 21] is a research initiative founded by partners such as Ericsson, Telcom Italia, NTT DoCoMo and ETSI seeking to achieve a 50% power consumption reduction in 4G mobile networks. The primary focus is on LTE technology and the eventual evolution to LTE Advanced.

Virtual Centre of Excellence in Mobile and Personal Communications - Mobile VCE - Green Radio [9, 21] the Mobile VCE is a consortium of industrial partners such as Vodafone, Nokia Siemens Networks and Huawei which encourages and facilitates industry steered strategic academic research initiatives with has the goal of achieving a 100 fold reduction in power consumption compared to current mobile networks levels without compromising the provided QoS or having any negative impacts on network operations.

These and other research initiatives are considering many techniques and possibilities to achieve Green Radio such as MIMO (Multiple Input Multiple Output) techniques exploiting physical layer space, time and frequency multi-diversity to enable interesting options for improved energy efficiency by using the considerable diversity gains enabled by various MIMO schemes such as outlined in [10, 21].

SON (Self Organizing Networks) based Green Radio techniques are future oriented in the sense that the operational benefits associated with SON have been already confirmed by becoming part of the LTE Standards but SON principles can also be applied to existing legacy access network technologies. In terms of Green Radio, SON is concerned with exploiting temporal and geographical patterns found through analyzing network performance data in real time and automating various control functions in the network accordingly. This is due to the fact that within a mobile network data usage patterns are spatially non uniform have a large variance over time. Some practical examples of SON are: turning off network elements during low traffic times or modifying the cell coverage dominance profiles to react to dynamically changing user requirements [21].

Various relaying techniques have been commonly deployed in legacy wireless networks to ease coverage and capacity problems in a cost effective manner, however an evolving generation of sophisticated relaying methods will play a key role in meeting many of the challenges in emerging wireless access networks. Legacy relays in 2G and 3G operate simply as layer 1

"amplify and forward" relays and have the disadvantage that noise and unwanted interference are also forwarded as outlined in [12, 13].
"Decode and Forward" relays operating at layer two and above are planned to be interference tolerant and flexible solutions to coverage issues in LTE-Advanced networks where it is required that performance for users at the edge of the cell coverage area is not perceivably worse than for users located closer to their network access point. Relays work on the simple principle that by splitting a longer and more loss prone radio link into multiple smaller hops that overall a better SINR (Signal to Noise ratio) can be achieved.
In terms of Green Radio the possible benefits of relaying techniques are wide ranging, obviously any method that extends the network coverage in a more cost effective manner than building and operating new sites with expensive backhaul links and heavy power consumption required for environmental controls as reported in [13] brings a significant Green Radio advantage.
However a trade-off inherent to relaying scenarios is that the power consumption of the Relay nodes themselves should also be taken into consideration as it is not negligible even when compared to the large power consumption of a typical BSS macro site.
This paper will assess the benefits of a Relay node deployment in a single cell environment which would of course be of much more significant magnitude if considered on the network wide macro deployment scale.

II. ENERGY MODELLING PLATFORM

"ns-3 is a discrete-event network simulator for internet systems, targeted primarily for research and educational use. ns-3 is free software, licensed under the GNU GPLv2 license, and is publicly available for research, development, and private use" [14].
The proposed ENB site energy consumption model is based on the modelling and simulation platform ns-3 [14] which in Release 3.11 (May 2011) contains bundled modules of LTE Radio Network devices (ENB and UE) and a basic network energy consumption modelling toolkit. ns-3 is based on the C++ language and provides an object oriented programming interface to define and generate models and also to define, control and execute simulations.
The ns-3 LTE modules facilitate the basic simulation of a LTE radio link with an ENB and an arbitrary number of associated UEs, the LTE modules are fully integrated with the ns-3 framework so it is possible to connect these lower layer LTE radio models with upper layer "internet" (TCP/IP or UDP/IP) stacks. The LTE modules implement the basic layers of LTE radio as defined in [3]: physical (radio spectrum), MAC (Medium Access Control), RLC (Radio Link Control), AMC (Adaptive Modulation and Coding), packet scheduling and RRC (Radio Resource Control). ns-3 LTE provides a useful framework to build models of various LTE radio link scenarios with particular focus on radio propagation and loss modelling, SINR and CQI feedback of the multiple OFDMA downlink channels.
The energy consumption modelling tools within ns-3 enable the extraction of energy consumption information from various network devices or layered protocol models. Energy source models describe basic power supplies, usually exhaustible sources such as batteries but also constant power sources such as a DC power supply which would power a typical BSS site.
Energy models describe the power consumption of the simulation objects in terms of provided parameters and use "call backs" which are hook points that can be placed in the protocol or device model code (such as the LTE spectrum model class) that call out to the energy model at various points, for example when the state model changes state (e.g. TX to IDLE) or some other defined model parameter changes. Using these basic building blocks energy consumption models were coded to model a typical LTE ENB site energy scenario albeit with many changes being necessary to the original LTE base module code to facilitate the operation of the "call backs" to the energy model class. As with the popular ns2 modelling and simulation tool, simulation traces can be evaluated by using some common regular expression driven text processing scripting tools like awk, sed or perl to extract the simulation run results from simulation run trace files, in many cases, particularly with CQI and energy parameters the model itself can be programmed to calculate desired metrics directly and export them without the need to extensively post process the trace file. More detailed descriptions of the operation of the LTE spectrum, propagation loss, LTE devices, energy source and consumption models within the ns-3 modelling and simulation tool are documented in [22].

III. LTE EVOLVED NODE B ENERGY MODEL

The overall goal of the proposed power consumption model was to develop a realistic baseline reference model which can facilitate the simulation of various ENB site power consumption scenarios and provide a means of determining and comparing the feasibility and benefits of various Green Radio techniques such as relaying and SON in an LTE radio access network.
In the 3GPP LTE Standards [3] the ENB (Evolved Node B) is defined as the node which implements the LTE air interface (Uu) and performs Radio Resource Management.
The ENB interfaces directly with the MME (Mobility Management Entity) and also with the PDN Serving Gateway, both of which are nodes within the LTE EPC (Evolved Packet Core). The proposed energy consumption model considered all standard power consuming components of an LTE ENB site.
Components with static power consumption requirements are independent of the current state or load of the ENB and as such do not vary significantly over time, there are also some components with more dynamic power consumption profiles such the output PA (Power Amplifier) [16].
Based on [15, 16] and the product descriptions and operational environment requirement datasheets of an industry leading LTE radio equipment vendor which because of non-disclosure reasons cannot be referenced in this paper, the relevant components of a typical ENB deployment site and their associated power consumptions were identified and are listed in Table 1. As shown in the Figure 1, the key component groups of an ENB site are the BBU (Base Band Unit), the RRU (Remote Radio Unit) and the Common Site Infrastructure. This is a standard LTE deployment scenario such as discussed in [17, 18] rolled out by operators with existing heterogeneous access networks. The RRU also known as the Remote Radio Head is used in LTE deployment scenarios where the BBU is actually a multi-radio SDR (Software Defined Radio) unit driving multiple RRUs to generate the output signals for 3G and LTE. As outlined in [18] the model defined represents a "distributed RBS". The BBU is responsible for interfacing with the EPC (via S1-MME and S1-U), base band signal processing, RRC, modulation and coding etc. while the RRU implements the physical radio transceiver components such as the oscillator and the RF power amplifier. CSI (Common Site Infrastructure) consists of the backhaul transmission equipment, cooling and environmental control systems, lights, AC/DC convertors, site monitoring solutions and possibly site access control systems.
The proposed model considers a homogenous LTE deployment site however it also provides a flexible framework to model any heterogeneous site technology mixes where component power consumption values are available.

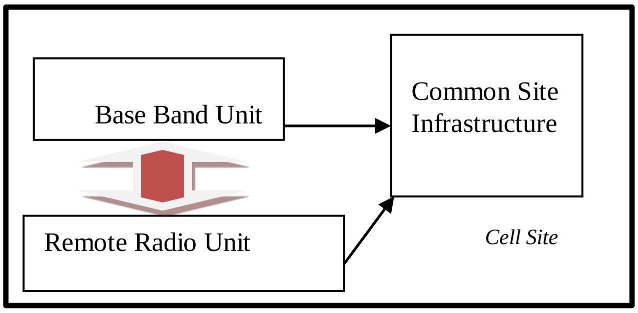

Figure 1

Model Component	Static/Dynamic	Symbol	Average Power Consumption
ENB Base band	Static	$P_{Baseband}$	200W
RRU	Dynamic	P_{RRU_Const}	100W
Cooling (CSI)	Static	$P_{Cooling}$	2000 W
Backhaul (CSI)	Static	$P_{Backhaul}$	200 W
Lighting (CSI)	Static	$P_{Lighting}$	50 W
Monitoring (CSI)	Static	$P_{Monitoring}$	50 W
Output Power per Carrier	Static	$P_{CARRIER}$	43 dBm (20 W)
Number of Sectors	Static	$N_{SECTORS}$	1
PA Efficiency Factor	Static	μ	20%

Table 1

Total Site Power Consumption and RRU power consumption were given by:

$$P_{site} = P_{Baseband} + P_{RRU} + P_{Cooling} + P_{Backhaul} + P_{Lighting} + P_{Monitoring}$$

$$P_{RRU} = P_{RRU\_Const} + \frac{P_{CARRIER}}{\mu} . N_{SECTORS}$$

From which the following model input parameters were defined:

$SitePowerW = P_{Cooling} + P_{Backhaul} + P_{Lighting} + P_{Monitoring}$
$TxPowerW = P_{Baseband} + P_{RRU}$
$RxPowerW = P_{Baseband} + P_{RRU\_Const}$
$IdlePowerW = P_{Baseband}$

Table 2

The downlink channel between the ENB and the UE was modeled to determine the variable energy consumption of the ENB RRU component serving an arbitrary number UEs each being serviced with a simple downlink packet stream. The downlink RF spectrum modeled was at 2.6 Ghz. with a total carrier bandwidth of 20 Mhz. and OFDMA physical resource blocks of 180 Khz. in the frequency domain.
The energy consumption of the BBU and the CSI were modeled as constant values over time with just the RRU energy consumption fluctuating according to the current state of the RRU physical layers (IDLE, TX or RX) which is turn determined by the number of UEs with active Radio Bearers and the currently scheduled data transmissions of the ENB packet scheduler. It was assumed that the power consumption of the BBU covers all other relevant functions of the ENB such as RRC, scheduling, MAC and ARQ functions along with all interactions with the EPC concerning the NAS (Non Access Stratum).
It was assumed that the power consumption of the RRU includes all functions necessary to generate the output signal that is delivered to the antenna feeder system. This includes all oscillation, modulation and amplification functions and the overhead due the inherent inefficiencies of the PA (Power Amplifier). Based on datasheets of industry standard RRU products, it was assumed that the total RRU power consumption required to generate a composite output signal of a particular power level will be assumed to have constant part that is independent of the output power level and a part that increases linearly up to the defined maximum output power.

$P_{CARRIER}$ is the **key variable parameter** of the proposed model, this is the output power of the RRU and variations to this will in turn cause variations to total RRU power consumption P_{RRU}.
Reductions to this output power were measured against the QoS provided to users within the cell which were determined using the CQI (Channel Quality Indicator). CQI is the most important quality measurement on the LTE radio link level which ultimately determines the QoS experienced by the user because it is derived directly from the signal strength (SINR) received by the UE on each LTE sub carrier which in turn is determined by the quality of the radio link between the ENB and the UE and invariably takes into account all loss factors which can affect the downlink power budget (free space loss, reflection, diffraction, terrain, building height, cell size, interference etc.) and therefore serves as an excellent indicator for the experienced QoS of the users within the cell.
The CQI is calculated by the UE according to the 3GPP standard predefined methods where the UE evaluates the SINR (Signal to Noise Ratio) for each OFDM sub channel and then for a given SINR the spectral efficiency is calculated for a given bit error rate. 3GPP standard defined fixed mapping tables allow the UE map the spectral efficiency to CQI values (0 to 15) ensuring a standard reporting of CQI for all compliant UEs. The reported CQI values are then interpreted by ENB which then can select the appropriate Modulation and Coding Schemes in AMC (Adaptive Modulation and Coding) to make the most efficient use of the reported radio conditions for each served UE with an active Radio Access Bearer in the cell.
Although the basic energy consumption modelling framework developed was flexible in the sense that various LTE ENB deployment scenarios and various UE mobility profiles can be modeled easily, the considered scenario focused on a macro outdoor ENB configuration considering just one active sector/cell served by a distributed RBS.
The considered LTE cell scenario involved multiple UE's (User Equipment) components which were stationary within the LTE cell at various distances from the ENB site location. Considering the surge of Fixed to Mobile Internet substitution currently within the industry it is envisaged that the majority of LTE UEs will actually have a very low mobility profile (with most LTE UEs actually being stationary USB dongles or router boxes positioned within the home [21]) the proposed scenario did not consider the UE mobility factor, but rather just the number of UEs and their (fixed) locations within the cell, however the ns-3 LTE frame work supports detailed simulations of mobility to facilitate any future work where possible UE mobility considerations might be required.

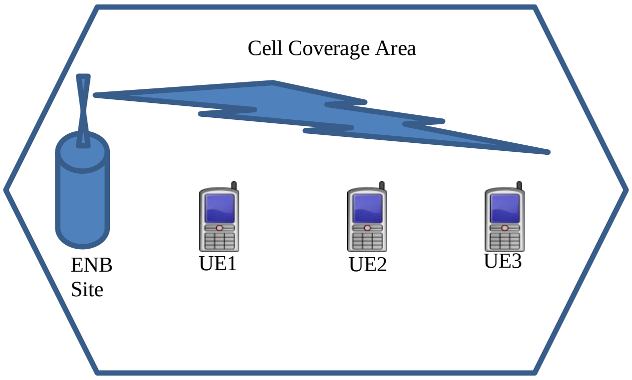

Figure 2

The **key metric** reported by the proposed model is an ECR (Energy Consumption Rate) as explained in [21], expressed in terms of Joules per transmitted downlink bit, where in the scenario under consideration the total combined downlink bitrate of the cell was determined from the simulated CQI values for the modeled UEs which were UE1 with excellent, UE2 with average and UE3 with poor reported CQI which is expected according to their relative distances from the ENB as illustrated in Figure 2.
The determination of the downlink bit rate from the simulated reported CQI values was based on assumed ideal conditions for a single LTE cell shared by 3 UEs with an assumed linear relationship between reported CQI and the total theoretical achievable throughput in Bps.
The total theoretical throughput of a single LTE Cell is **86.4 Mbps** based on the following assumptions: each LTE time slot of 0.5 milliseconds contains 7 OFDM symbols, one LTE sub-frame is made up of two time slots, giving a total of 14 OFDM symbols per sub-frame. Assuming 64QAM modulation with 6 bits per symbol, 84 bits (2 x 14) can be transmitted per 0.5 milliseconds resulting in a net throughput per LTE sub-carrier of 42000 bits per second when resource block signaling overhead is excluded. An LTE resource blocks is made up of 24 sub-carriers, therefore the throughput per resource block is 24 x 42000 bps = 1008 Kbps. Given a total carrier bandwidth of 20 Mhz. there are 100 resource blocks giving 100.8 Mbps gross per LTE Cell but that amounts to 86.4 Mbps net assuming a coding rate of 6/7 and SISO (Single Input Single Output) [19].

For the considered baseline energy consumption model scenario, simple IP based streaming services running at the speeds outlined in Table 3 were deployed, with the streaming clients attached to the IP stacks of the UEs and for simplification purposes the streaming server attached to the IP stack directly at the ENB because simulating the LTE EPC connection and internet links to the streaming server was beyond the scope of this model and for the purposes of ENB site power consumption analysis also quite irrelevant.

Based on the considered ns-3 ENB site energy model input parameters, the baseline simulation results for the proposed scenario were observed using a constant RRU output carrier power of 43 dBm are detailed in Table 3.

	UE1 (400M) from ENB	**UE2 (800M) from ENB**	**UE3 (1200M) from ENB**
Average CQI (0-15)	14.92	7.89	3.97
Theoretical Throughput per UE	57.6 Mbps	19.2 Mbps	9.6 Mbps

Table 3

Total ENB Site Energy Consumption = 2696.8 Joules per second (Watts)
ENB Site Energy Consumption Rate = 31.2 microJoules/bit

This is the simulated ECR for a typical LTE ENB site scenario according to the component power consumption values as detailed in Table 1 and the user data throughput for three UEs sharing a single cell utilizing the maximum theoretical throughput possible for the reported CQI values.
Considering the flexibility of the model implementation in ns3 it would be possible to consider many different site component power consumption scenarios to serve as baselines against which to measure the ECG [21] of possible Green Radio proposals for LTE and to gauge their possible benefits.

IV. Relaying Techniques in Green Radio

Relaying is one of the most exciting enabler technology topics under consideration in LTE-A, with wide ranging applications foreseen in meeting the requirements of improved cell edge throughput rates and facilitating more efficient use of network resources while extending coverage and capacity particularly within buildings and difficult urban areas as a more cost effective and faster option than building new sites as has already been confirmed by comprehensive studies such as [20].

Building on the LTE ENB site energy consumption model presented already in this paper and extending and enhancing this baseline energy consumption model to facilitate the operation of a Relay node, an assessment of the impacts of relay technology in terms of Green Radio was possible.

It was expected that with a Relay node deployment, the radiated output power of the ENB can be reduced significantly while maintaining an acceptable CQI for the end-users, especially for those end-users located towards the cell edge compared to those closer to the ENB. In the proposed scenario, the power consumption of the Relay node itself was not considered, however it should be noted that Relay nodes are planned to be relatively small, simple and robust nodes with low power consumption, which offer flexibility in terms of positioning, therefore the power consumption of a Relay node deployment site is considered to be quite low when compared to an ENB site.

Although the ECG of a Relay node assisted ENB site over an ENB site without a relay may be quite small on the micro/cell level, on the macro/network level it can sum up to be quite considerable and coupled with the numerous benefits offered by Relay nodes in terms of efficient coverage extension, relay technology appears to have many distinct advantages and use-cases for enabling Green Radio within emerging radio access networks.

Relays can operate at various levels of the LTE access stratum protocol stack as shown in Figure 3. The Relay node operation mode considered in the proposed model was the “decode and forward” mode at the MAC/RLC layer which has the distinct advantage that it “terminates” the radio link at layer two and any noise or interference from layer 1will not be forwarded on via the next hop, however this also brings with it a tradeoff against increased processing delays and therefore increased end to end latency of the system.

An interesting feature of “decode and forward” Relay nodes in LTE is the concept of the “in-band backhaul”, which means that unlike an ordinary ENB which has a microwave or optical transmission backhaul link, an “in-band backhauling” relay is connected to the host ENB via the standard LTE radio interfaces meaning the Relay node must support the LTE radio interface protocols towards the ENB like a “normal” UE would do.

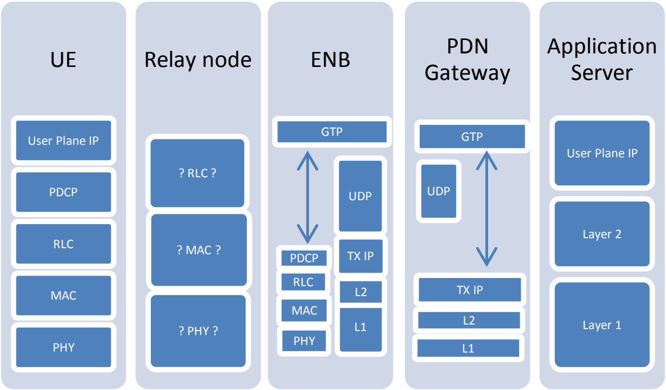

Figure 3

The general ENB site power consumption model parameters as defined in Table 1 are also applicable in this relay enhanced scenario. The power consumption of the Relay node itself was not considered in this model however based on the assumption that Relay nodes will be small, compact nodes deployed on the side of buildings or street corners without the need for dedicated backhaul and site environmental control and the associated power consumption it was assumed that the power consumption of a Relay node site is will be orders of magnitude smaller than that of a typical ENB site.

Based on the product datasheets of a commercially available LTE “decode and forward” relay from a leading mobile network equipment vendor which cannot be referenced in this work due non-disclosure reasons, the power consumption of typical Relay node components was investigated and are detailed in Table 4 and was estimated to be approximately 220W at running at full output power, assuming 43dBm total output carrier power.

Relay Component	**Static/Dynamic**	**Symbol**	**Average Power Consumption**
Relay Base Unit	Static	$P_{Baseband}$	120W
Relay Output Power per Carrier	Static	$P_{CARRIER}$	43 dBm (20 W)
Number of Sectors	Static	$N_{SECTORS}$	1
PA Efficiency Factor	Static	μ	20%

Table 4

As shown in Figure 4 the proposed relay scenario was concerned with a simple model of a single LTE cell with one UE and one Relay node with the Relay node being located equidistant to the serving ENB and the served UE. From the point of view of the ENB, the Relay node was seen as a UE and from the point of view of the UE the Relay node was seen as an ENB.

For the considered scenario, only the downlink direction from the ENB towards the UE was considered, with a single radio bearer supporting a simple downlink steaming service operating at the maximum theoretical cell capacity (86.4 Mbps) to the UE.

The model of the relaying scenario proposed focused on the CQI reported by the UE, again using the assumption that the CQI provides the best estimator of perceived radio channel quality and can be directly correlated with the throughput rates and QoS that the UE would actually experience in the cell.

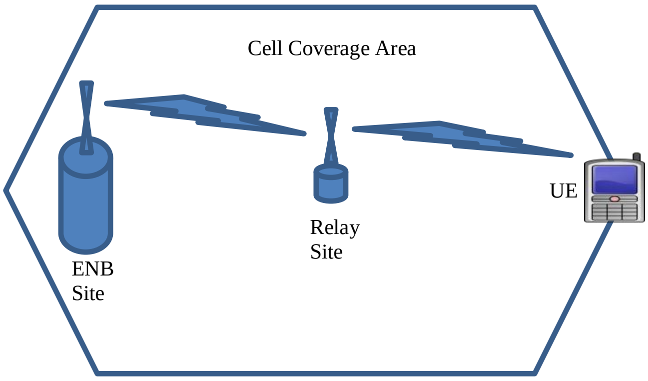

Figure 4

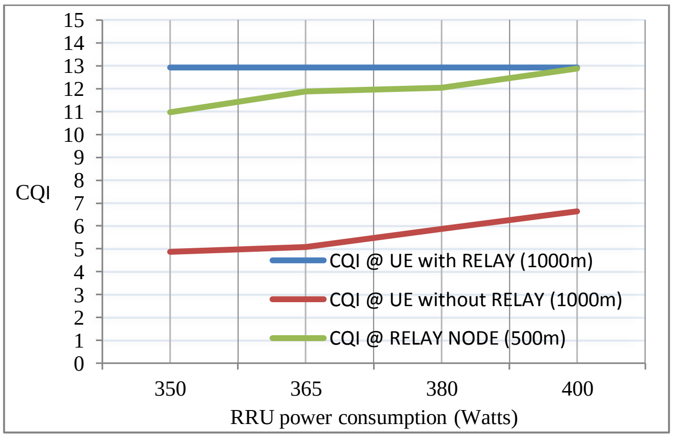

Figure 5

ENB Site ECR *with* Relay [LS] = 28.9 microJoules/bit for CQI = 15 @ UE 1000m from ENB (ENB site power consumption was 2497.5 Watts)

ENB Site ECR *without* Relay [LS] = 33.5 microJoules/bit for CQI = 15 @ UE 1000m from ENB (ENB site power consumption was 2897.1 Watts)

$$ECG_{Relay} = \frac{ECR_{WithRelay}}{ECR_{WithoutRelay}} = 0.863$$

Considering the results shown in Figure 5 and the calculated ECG of the relay enhanced ENB site, the simulations carried out clearly confirmed the positive effect of a relay deployment on the baseline ENB site power consumption in terms of RRU power consumption while maintaining a specific Quality of Service to the served UEs within the cell.

One of the most important criteria in a successful Relay node deployment strategy is the positioning of the Relay node within the cell, while practical deployment scenarios may be bound by geographical constraints and commercial or planning related issues, the simulations carried out based on the proposed Relay node deployment scenario were used to explore not only the possible benefits in terms of Green Radio and the QoS experienced at the UE but also the CQI reported by the Relay node itself for the downlink channel from the ENB (the "first hop" link), which is obviously plays an important role in deciding where to position the relay. The trade-off to be found here is between extending the total cell range as far as possible and maintaining an acceptably high radio channel quality between the Relay node and the ENB otherwise there is a risk that this link will become a capacity bottleneck within the end to end communications system.

Considering Figure 6 it can be noted that depending on the specific propagation conditions in the cell, generally positioning the Relay node closer than 400m to the ENB site is not advantageous while positioning it further away than 750m would force the CQI to drop below 10, where according to the defined 3GPP CQI to AMC scheme mapping tables [3], operation in the higher order modulation schemes would no longer be possible and significant throughput reductions on the ENB to Relay node link would be experienced.

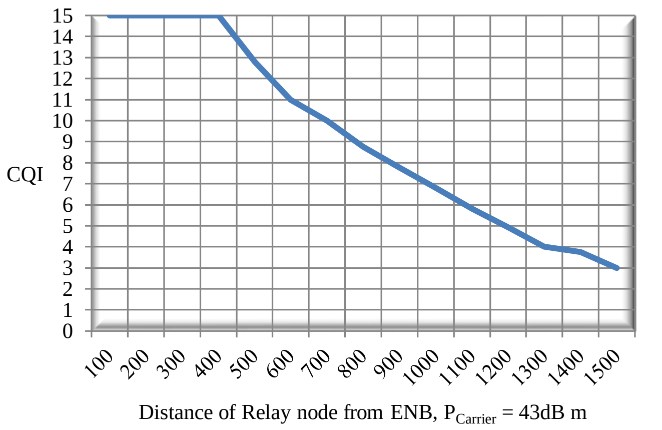

Figure 6

V. CONCLUSIONS

In this paper the background of Green Radio was explained in the context of current and projected energy consumption trends in wireless access networks and the associated upcoming energy challenges brought by new and emerging standards such as LTE and LTE-A which will enable higher throughput speeds and lower latencies for end-users but will also bring new requirements for denser networks and improved coverage.

Having discussed some general methods and techniques involved in Green Radio a power consumption model for an LTE ENB site scenario was developed, modelling in detail both the static and dynamic power consumption profiles of the various components of a typical LTE ENB site as identified by previous studies and the datasheets of a market leading LTE network equipment vendor. Using this model an Energy Consumption Rate for a typical LTE Site scenario was measured by simulation.

Using the open source modelling and simulation tool ns-3, a convenient and flexible model was constructed to allow simulations of baseline power consumption rates for given LTE site component power requirements.

The key function of the model was to capture the dynamic power profile of the ENB reflecting the total carried user service load along with the radio channel conditions experienced by the users in the radio cell, utilizing the radio propagation and CQI calculation models of ns-3.

Smart Relay nodes are expected to play a key role in solving both coverage and throughput challenges in LTE Advanced networks, as part of heterogeneous network deployments strategies where smaller and energy efficient nodes can be deployed easily without expensive site and backhaul requirements, to complement existing macro cell site deployments.

The ECG simulation based on the considered relay enhanced ENB site component power consumption scenario indicated that the ENB site power consumption required for a particular QoS level with a Relay node deployment equidistant to the ENB site and the UE location is considerably less than that required without a Relay node, approximately14% less.

If the power consumption of a typical compact next generation LTE relay site is assumed to be considerably lower than that of typical ENB site then the ECG of a relay enhanced system would still be quite significant.

Considering the improved coverage profile, the enhanced throughput for users at the edge of the cell and the positive effect on the ENB site power budget the possible benefits of relaying technology are compelling.

The model developed in the course of this work should provide a flexible tool for simulating various Green Radio techniques with particular potential to enable future work in the area of assessing SON based power saving schemes and various other coverage enhancement methods.

As this work has highlighted, ongoing Green Radio research initiatives are numerous and varied, as are the energy challenges facing mobile network operators. It will be necessary to compare, contrast and combine different Green Radio methods in order to develop strategies to tackle these challenges in a holistic manner so that wireless access networks of the future can be operated in a commercially viable but also environmentally responsible and sustainable manner while fulfilling the promised quality and performance levels of evolving radio access technologies.

ACKNOWLEDGEMENTS

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Appendix A

A Survey of Reducing Energy Consumption in Access Networks

Abstract

Reducing energy consumption is one of the greatest challenges facing telecommunications network operators worldwide.
For mobile networks operators in particular, reducing energy consumption and increasing energy efficiency are key requirements to enable their future growth and sustainability particularly when one considers the large increase of mobile internet data traffic that has been witnessed over the past years, increasing energy and infrastructure costs and the growing awareness of the need for environmentally responsible and sustainable telecommunications networks.

This report details the results of a literature survey undertaken to assess relevant published research and information on methods to enable energy consumption reduction and increase energy efficiency in wireless access networks with particular focus on emerging future standards and technology such as LTE and LTE Advanced.

With relevant background information on wireless network energy consumption trends, details of relevant energy consumption metrics, through to detailed research on initiatives focusing on the dominant future wireless access network standards, the literature survey drew on published research and literature from academia, industry and worldwide standards bodies.

Based on the findings of the literature survey a specific area of interest was identified and discussed along with presenting the motivation to study this topic in detail within scope of the ongoing Master of Engineering research project.

Chapter 1 - Introduction

This section provides a detailed introduction to the “Energy consumption reduction Problem” and sets the scene with background information based on previously published research and energy consumption studies describing and justifying why this is such an important issue for the mobile telecommunications industry, not just for various social/corporate responsibility and environmental protection reasons but also because of very tangible operational and financial reasons. The key ongoing industry backed academic research initiatives in this area are also presented.

The energy consumption of cellular networks worldwide has become a major obstacle to the continued future development of mobile data services, considering that the number of mobile phone users worldwide has already surpassed 4 billion and as the near exponential increase of data traffic carried over mobile networks continues, mobile network operators are faced with rapidly increasing energy costs and regulatory pressures to reduce their carbon footprint to operate more “green” networks.

Gartner Research [1] reported that by 2013, web browser equipped cellular devices will exceed 1.82 billion units and that the mobile phone will overtake the Personal Computer as the most popular internet access device worldwide.
The information and communication technology (ICT) industry’s total contribution to global greenhouse gas emissions is forecast to double over the next ten years [1].

The global telecommunication industry was responsible for 183 million tonnes or approximately 0.7% of the total greenhouse gas emissions in 2006 and this is increasing rapidly [2, 3]. The energy needed by a major mobile network operator in Italy as reported in [7] was more than 2 TWH a year, corresponding to approximately 1% of Italy’s total national energy demand.

Long Term Evolution (LTE) represents the next major upcoming advance in mobile radio telecommunications, introduced as Release 8 in the Third Generation Partnership Project (3GPP) [4]. The goal of LTE is to reduce packet delays (improve latency), increase throughput speed, improve spectrum flexibility and reduce the cost of ownership and operations for the network operators and the end users. Orthogonal Frequency Division Multiple Access (OFDMA) has been selected as the downlink radio access technology for 3GPP LTE.
Before the large scale commercial roll outs of LTE have even started to gather pace, the 3GPP is already working on standardising Long Term Evolution - Advanced (LTE-A) which will again deliver a major performance enhancement to 3GPP Release 8 LTE. LTE-A is required to fulfil the overall requirements of IMT-Advanced for the future generation of wireless broadband technologies because LTE does not actually meet all the IMT Advanced requirements for 4G services (also known as IMT Advanced) as defined by the International Telecommunication Union (ITU), such as peak data rates of up to 1 Gbps.

The scale of the challenge facing the mobile telecommunications industry is quite immense.
Increasing penetration of mobile data services, rapidly increasing throughput and data rates and higher quality of service demands are weighing against factors such as the fact that Average Revenue per User (ARPU) is increasing at much smaller rate or even decreasing compared to the volume of traffic that is carried and the very urgent need to reduce energy consumption both for environmental protection and operational cost reduction reasons.

It was found in [5] that 57% of the total energy consumed in cellular networks is in the radio access network, with the majority being consumed by the base stations and their associated site infrastructure (power amplifiers, cooling, backhaul transmission equipment).
The energy consumption of both the User Equipment (UE) and of the server farms in the core network infrastructure (including Billing, CRM, web portals etc.) was found in [6] to be approximately four to five times smaller than the total energy consumption of the base station subsystem (BSS).
Currently even for the world's largest network operators, UE energy consumption is only a fraction of the energy consumption of the whole network, while base stations within the radio access network are the major energy consumers and therefore the part of the mobile network with greatest potential to contribute towards increased energy efficiency in the future [7,8].
The energy efficiency of mobile terminals has been extensively researched is already highly optimized due to the tight and hard boundary constraints of the available battery power supply, until recently power consumption of base stations in the access network has been largely ignored.
At the heavyweight Japanese mobile network operator NTT DoCoMo with 52 million customers, [6] claimed that in 2006 120Wh per customer was consumed daily in the entire network infrastructure (wireless access, core network, IT, Office, Shops etc.) but just 0.83Wh was consumed by the UE of each customer daily. This indicates that the total energy consumption of User Equipment is negligible in comparison to that of the network itself.

Another major upcoming challenge is that operators will be under considerable pressure to expand and build network infrastructure to cope with the higher cell/base station density that will required by emerging radio access network technologies at higher frequencies, which obviously will require a huge increase in overall energy consumption.
This poses the more complicated problem that methods which just focus on reducing energy consumption alone will not suffice, as mobile access networks continue growing in size and density they must also become more energy efficiency.

Recently, mobile telecommunication operators worldwide have been becoming increasingly aware of these existing and upcoming energy challenges and have begun to study and research an area that has now been coined "Green Radio" - techniques and solutions which can be employed to improve the energy efficiency of the Mobile Access Network. In many cases consortia have been formed with academic institutions and telecommunications network equipment vendors to foster and promote research in this area.

Here is an overview of the most relevant recent and ongoing “Green Radio” research initiatives.

Earth – Energy Aware Radio and network technologies [9] is a research initiative founded by partners such as Ericsson, Telcom Italia, NTT DoCoMo and ETSI seeking to achieve a 50% power consumption reduction in 4G mobile networks. The primary focus is on LTE technology and the eventual evolution to LTE Advanced.
The objective is to raise the importance of energy efficiency considerations in the standardisation process while seeking solutions using a holistic approach to energy efficiency. The various work packages that have already been defined are researching a wide variety of energy efficient techniques such as relaying, cooperative base stations, energy aware network re-configuration Self Organising Networks (SON) and advanced radio transmission techniques focusing energy efficiency instead of just on spectral efficiency improvements.

OPERA-Net–Optimising Power Efficiency in mobile Radio Networks [10] is an EU sponsored project led by France Telecom (Orange) along with several industrial and academic research partners with the goal of consolidating the response of the mobile telecommunications industry to Climate change trends and meeting the relevant EU objectives for improving energy efficiency by 20% before 2020.
OPERA-Net is researching areas such as defining KPIs for energy efficiency, radio link performance and energy efficiency using various MIMO methods, relaying and multi-hop scenarios, various SON techniques (such as sleep mode management) and defining relevant upper and lower bounds for energy efficiency.

Green Touch [11] Green Touch is an Alcatel Lucent Bell Labs led privately funded consortium of ICT industry and leading academic research resources including Dublin City University.

“As researchers in the area of ICT, we have a social responsibility to improve the energy efficiency, and reduce the carbon footprint of the networks we design. At Dublin City University, we are very excited to be part of this ambitious initiative and we look forward to lending our expertise towards bringing about significant change in the ICT industry; change which will enable the internet's continued growth with a dramatically reduced impact on our planet.”

-Dr. Frank Smyth, Radio and Optical Communications Group, Research Institute for Networks and Communications Engineering, School of Electronic Engineering, Dublin City University

The stated goal of Green Touch is to deliver the architecture, specifications and roadmap required to reduce energy consumption per user by a factor of 1000 from the current levels by 2015. Green Touch is focussing on ICT in general not just mobile access networks however significant related research is being carried out in the areas of MIMO and smart antenna technology such as Large Scale Antenna Systems which was recently presented in London [February 2011] as a first tangible result of Green Touch’s research.
A notable academic member of the Green Touch consortium is Professor Rodney Tucker, a renowned expert on energy and environmental issues associated with broadband access, particularly in the optical communications area.

Virtual Centre of Excellence in Mobile and Personal Communications - Mobile VCE - Green Radio [12] the Mobile VCE is a non-profit consortium of industrial partners such as Vodafone, Nokia Siemens Networks and Huawei which is seeking to encourage and facilitate industry steered strategic academic research initiatives which will deliver significant contributions to the positive development and growth of the mobile telecommunications industry generally and provide solutions to the key energy consumption challenges which it's members are facing.

Started in 2009, the Green Radio programme of the Mobile VCE set the goal of achieving a 100 fold reduction in power consumption compared to current mobile networks without decreasing the provided QoS or having any negative impacts on network operations. Achieving this goal will be enabled by defining optimal network architectures with reduced energy consumption patterns and by developing new techniques to reduce the power requirements of wireless communications in future generations of wireless access networks such as LTE and LTE Advanced.

Chapter 2 - Energy Architectures and Techniques

This section describes the main architectures and techniques which have been considered in various “Green Radio” research projects.
Several broad research areas are discussed focussing mainly on the key future wireless access network technologies such as LTE and LTE-Advanced and in what way these various techniques may contribute to generally reducing energy consumption and increasing energy efficiency as discussed in [13].

Multiple Input Multiple Output MIMO Resource allocation strategies

Resource allocation is the mechanism used by the eNodeB or BTS to make decisions on exactly how and when to transmit data over the air interface to users in the downlink direction.
Resource allocation techniques that are designed with the goal to make the most efficient user of the transmitter RF Power amplifier can contribute very significant improvements to the overall energy efficiency of the eNodeB or BTS.

MIMO techniques can be used to leverage the gain of multiuser diversity to increase the overall system capacity by employing opportunistic resource scheduling and allocation strategies i.e. scheduling downlink transmissions to users when they are at or near their best radio channel conditions and exploiting the diversity arising from the assumption that with multiple users in a cell at any given time there will always be at least one user experiencing their best possible radio conditions.
Interesting recent area such as [14, 15] in this area have focussed on finding the best methods to combine scheduling techniques to handle varying cell traffic patterns from the energy efficiency perspective in LTE networks.

Self Organising and Optimising Networks SON

Large reductions in energy consumption and increased energy efficiency can be achieved as discussed in [16] by reacting to and exploiting changing traffic patterns not just on the radio link or the cell level but also on the network level. The SON principles that are introduced in LTE as described in [40] will facilitate optimising key operational tasks in the network such as automatic neighbourhood planning and electrical down-tilt adjustment and such techniques which are based on automated and intelligent decisions with associated actions according to evaluation of performance data received from the network can also be applied to help achieve energy consumption reduction goals in a cellular networks.
In Chapter 9 of [17] it is claimed that on average in the daily busy hours approximately 90% of end user traffic originates from just roughly 40% of the cells in a mobile network meaning techniques that can exploit this geographical and temporal imbalance that seem to be prevalent in many networks can contribute to energy consumption reductions and as these traffic patterns are certainly not constant but fluctuate both within and across different networks any such schemes must be autonomous and self directing in the manner prescribed for SON.
Research initiatives such as [18, 19] already undertaken in this area combined with the already wide ranging and diverse possible use cases for various SON techniques within LTE make this is an interesting avenue of research with good prospects for practical applications already in the short to medium term within the “Green Radio” area.

Relaying and Multi-hop cellular

The use of relays to transmit information between the eNodeB and the UE within an LTE radio access network has been shown in [20, 49] to be a very effective technique to enable increased energy efficiency due the fact that because the distance from the UE to the Relay is much shorter when compared to the distance between the UE and the eNodeB meaning reductions in transmission energy requirement on both sides are possible.
There are many different relay deployment strategies with fixed, mobile and the so called mechanical Store and Carry Forward (SCF) relays all providing interesting opportunities for various use cases.
An interesting approach which is presented in [20] considers the Store and Carry Forward concept, which can be used to trade energy efficiency for extra delays in data delivery in services where an increased delivery delay is acceptable to the end user application.

Efficient power amplifiers and RF power delivery

Great potential exists for increasing energy efficiency by improving the basic amplifier efficiency of the RF power amplifiers which amplify the output RF signal of the eNodeB or BTS before applying it to the sector antenna.
Efficiency gains may be also achieved by moving the power amplifiers closer (mast head PA) to or even integrating them, as part of the antenna itself [21, 22, 23]

Spectrum Management

Many mobile network operators have licensed spectrum in several frequency bands ranging from the old per 2G allocations for analogue services around 400 Mhz. up to the recently auctioned allocations at 2.6 GHz. for LTE services.
Through understanding and leveraging statistical differences between traffic profiles and the service mix provided to particular customer groups in different frequency bands it may be possible to make significant energy consumption reductions by moving particular users and services between different radio access network technologies and frequency bands and identifying the most energy efficient use of the available spectrum [21, 22, 23]. There is considerable scope in this area to enable and expedite the decommissioning of older and less energy efficient network infrastructure.
Many European countries with highly developed and well established mobile telecommunications markets where mobile broadband access penetration is quite advanced are considering allowing operators to consolidate and to reorganise their sometimes scattered and fragmented 2G licensed frequency assignments around 900 Mhz. to achieve the larger contiguous blocks of spectrum required for OFDMA in LTE. This process is known as “re-farming” and the benefits of this were outlined and discussed in [24].
Due to greatly reduced wireless path loss at and around 900 Mhz. compared to around 2.6 GHz. such an approach would facilitate larger cell sizes and therefore facilitate the provisioning of 4G services in a more energy efficient manner especially in rural or lowly populated areas.

Chapter 3 – Energy consumption and efficiency metrics

This section describes relevant energy efficiency and consumption metrics along with discussing power consumption models that are required to understand, characterise and contrast the challenges, opportunities and benefits associated with various techniques and relevant research initiatives in the “Green Radio” arena.

A very important factor associated with reducing energy consumption in wireless access networks is to be able to have an understanding of how energy consumption is characterised and measured, because only with an established and agrees baseline of appropriate metrics and evaluation methods and tools can various energy consumption reduction and efficiency improvement techniques be effectively analysed, compared and contrasted with one another. Energy consumption metrics and evaluation methods have been specified in order to adequately compare different techniques and systems and to evaluate their relevant efficiency and identify where such solutions may be deployed together and to quantify what tradeoffs are involved.

Many energy consumption metrics have already been defined in order to quantify the energy consumption of telecommunications equipment.
Generally such metrics define the energy consumption normalized per some quantity or per network entity, for example the energy consumption can be normalized by the average data throughput rate, peak data throughput rate, spectral efficiency in Bps/Hz, the number of subscribers or even the coverage radius per cell.

The standardized energy metrics are usually based on two basic definitions: the Energy Consumption Ratio (ECR) as presented in [25, 26] and the Telecommunications Energy Efficiency Ratio (TEER) as presented in [25, 27]. The ECR metric is defined as the ratio of the peak power (measured in Watts) to the peak data throughput rate in bits per seconds and therefore can measure the consumed energy per bit of information transported which is then expressed in units of joules per bit.

$$\mathrm{ECR} = \frac{\mathrm{POWER}}{\mathrm{DATA\ RATE}} = \frac{\mathrm{Watt}}{\mathrm{Bps}} = \frac{\mathrm{Joule}}{\mathrm{bit}}$$

The TEER metric is a more generic metric than ECR and is defined the ratio of useful work done to the total power consumed.
The units of TEER depend on the specific quantity that one wished to consider as being useful work, for which there are many possibilities in a mobile network environment or even with the BSS.
The Energy Consumption Gain (ECG) metric is the ratio of the measured ECR metrics of two different systems which are under comparison, usually a reference system as the baseline and a system to which a different energy efficiency technique has been applied against which a comparison is required.

The deployment strategy of base station sites within a wireless access networks is typically optimized and designed to provide the legally required population coverage as defined in conditions of the operator's license.
This means wireless access networks are normally planned and designed without energy efficiency a key design consideration or criteria, meaning many of the deployed base stations are just serving to provide coverage while operating at less than full load even during peak traffic hours, which means very poor energy efficiency is achieved and the situation is even worse when one considers low traffic times as presented in [13].
With these considerations in mind a useful energy consumption metric based on energy consumption per coverage area [W/m^2] was presented in [13], this is an important metric used to relate energy consumption to coverage, and indeed coverage (and by association the delivered quality of service) is one of the main areas where trade-offs are must be met to achieve increased energy efficiency.

Several studies have proposed various models for base station power consumption such as presented in [13, 21, 29, 30].
An interesting finding of the model developed in [13] are that the power consumption of a base station site running with zero traffic load (meaning no user data is being transported) is still 50 percent of the peak power consumption while running at full traffic load.
Also in [13] a model of the base station power consumption based just on output RF power without considering power supply and environment controls can be up to 400 W lower than the actual total power consumption of the whole BTS site, therefore energy efficiency metrics for wireless access networks cannot simply just consider the output RF power of the base stations, as this captures only a small percentage of the overall required "power budget" of a base station site.

A base station in wireless access network can be defined as all equipment needed to communicate with the mobile stations and with the backhaul transmission network including the equipment necessary to facilitate and support the operating environment at the base station's location as described in [13]. Several elements are per cell/sector such as the power amplifier and other elements are common for the whole site such as air conditioning.

For example consider a LTE eNodeB sector (cell) operating with a radio spectrum bandwidth of 20 MHz having an average spectral efficiency of 1.5 Bps/Hz, giving an average data rate over all users in sector of 30 Mbps. If the eNodeB PA delivers 8 Watts of RF power to the sector antenna then the ECR of the sector is 0.267 microJoules/bit.
Now consider if the total input consumed power budget of the same eNodeB site including all relevant site environmental power requirements was measured to be 600 Watts and assuming the eNodeb is running three sectors then the ECR value per sector would increase to 6.7 microJoules/bit.

The key issues to consider when developing an effective model for a wireless access network are how to model the base station as accurately as possible using manufacturer data sheets for all site components required to deliver the service and then defining how to aggregate the consumption model of each base station up to the network level.

ETSI has published a standardised [27] method to analyse the energy efficiency of wireless access network equipment to make it easier to compare energy efficiency performance of different vendor's equipment with the goal of reducing energy consumption and increasing energy efficiency. This standard method defines a common reference configuration under which average power consumption can be measured along with a common network level energy efficiency KPI in terms of power consumption required to achieve a specific degree of coverage. Although the scope of the standard is limited to GSM/EDGE, WiMAX and WCDMA, the principles can also be applied to LTE and other wireless access network technologies. This standard only considers the energy efficiency metrics on a network element component level rather than the whole network (holistic end-to-end, including Microwave and Optical backhaul, Core etc.). Also no KPIs for Quality of Service at specific energy efficiencies levels have been defined.

Once the relevant power consumption model has been defined, and the relevant components identified, a set of methods and tools can be developed for each component to reduce energy consumption and therefore increase the overall energy efficiency of the system and the ECR or ECG metric can be used to gauge the degree of success achieved and characterise the overall feasibility of the various methods and tools.

Chapter 4 – Energy Consumption Reduction Techniques

In this chapter published research on key energy consumption reduction and improved energy efficiency techniques in 4G LTE wireless access networks are discussed.

MIMO (Multiple Input Multiple Output) describes a set of techniques to improve the quality (BER), throughput (bps) and spectral efficiency (bps/Hz) of radio communications systems and which thereby can potentially contribute to reducing energy consumption and increasing energy efficiency by generally leveraging the many beneficial properties of deploying multiple transmit and multiple receive antennae [31, 32].

SISO (Single Input Single Output) Systems deploy just one transmit and one receive antenna meaning that no diversity at all is employed whereas SIMO (Single Input Multiple Output) systems which are already quite common in UMTS for example, where the Node-B /BTS receiver has two separate receive antennae (diversity paths) and the UE just one transmit antenna [14, 16, 31].

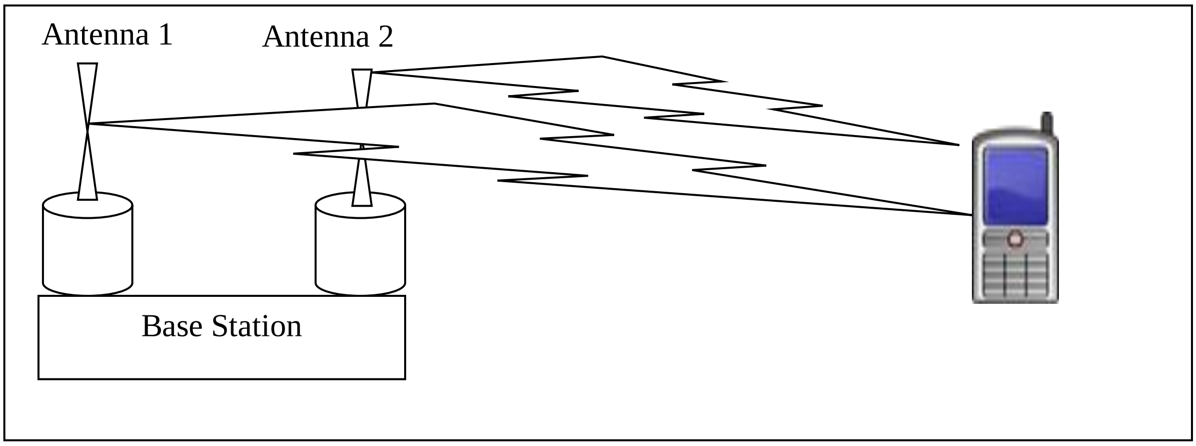

Figure 1

There are three main types of MIMO techniques considered for the OFDM radio access technology of 3GPP LTE [4] networks, these are: ***Diversity Gain***, ***Array Gain*** and ***Spatial Multiplexing***.

Considerable industry driven academic research such as [14, 34, 35] has already been carried on these techniques as they promise extremely valuable improvements in spectral efficiency and ECR even at the lower orders of MIMO (2x2, 2x1) that are will most probably be deployed in LTE networks.
Because MIMO techniques can offer such potentially large efficiency improvements while not requiring extra RF spectrum explains why these were considered as key design elements of LTE, enabling the realisation of many of the ambitious performance goals.

The two types of MIMO ***Diversity Gain*** (single-user and multi-user) differ in that single-user refers to multiple antennae of one UE receiving the same information across the multiple diversity paths, whereas with multiuser MIMO different information is transmitted and received by different users over the multiple diversity paths

Space Time Block Coding and Space Frequency Block Coding refer to MIMO ***Diversity Gain*** techniques where the same signal is transmitted over multiple antennae but either at different frequencies or different times as explained in [36]. The receiver is then able to combine both streams to achieve higher quality (meaning lower BER (Bit Error Rate)) and with a better SNR (Signal to Noise Ratio).

Array Gain or *Precoding* (also referred to as *Beamforming*) is a MIMO technique where the same signal is transmitted from each of the transmitter antennae but with predetermined phase (time) and/or gain (amplitude) shifts (known as coding) over the different transmission paths in order to maximize the signal strength and quality at the receiver. Beamforming increases the received signal strength in the multipath environment by making the diverse multipath signals combine constructively at the receiver. In order to achieve dynamic and constructive Beamforming gain, the precoding process requires feedback from the receiver to the transmitter providing important information about the received signal quality (describing the radio channel conditions) in order for the transmitter to adjust and improve the "beam" in the direction of that user [31, 33, 36, 37].

Spatial multiplexing involves splitting a high bit rate stream into several lower bit rate streams, each of which is transmitted via a different transmitter antenna but all over the same frequency channel, if the multiple signals arrive at the receiver with large spatial differences, the receiver can separate the streams orthogonally. Spatial multiplexing increases capacity and improves the signal-to-noise ratio and offers overall greater spectral efficiency [31, 33, 36, 37].

Considering [14] where the energy efficiency performance of various MIMO transmission and precoding schemes are compared to the basic SU-SISO as a reference, the important role that the concept of multi-user diversity plays in LTE MIMO techniques is highlighted. Multi-user diversity builds on that principle that all users in a cell channel will generally experience radio channel quality fluctuations due to fading at various times and to varying degrees, this diversity can be exploited by tracking and predicting the channel quality experienced by the users and scheduling their transmissions at times when their channel quality is at or near the best possible values.

Through various simulations of possible spectral efficiency MU-MIMO (Spatial Division Multiple Access (SDMA)) and Layered Random Beamforming (LRB) are found to be the most energy efficient and fairest schemes but with the tradeoff that they incur a greater feedback overhead.

Power reduction through the increased spectral efficiency offered by MIMO techniques is considered in [14] through modelling and comparing the power efficiency of each considered MIMO technique with a cost metric which sums the total power required to reach a particular spectral efficiency.

An important trade off that is identified in [10] and [34] is that between power efficiency and user fairness, highly power efficient MIMO techniques tend to favour users with better radio conditions (experiencing little or no fading) at the expense of users with poorer radio conditions. A Power Fairness Index is defined to compare MIMO schemes in terms of power efficiency and fairness and to quantify this important trade off.

The results presented indicate that compared to SISO, selected MIMO schemes like MU-MIMO (STDMA) and LRB can offer up to double the spectral efficiency and a performance gain of 7dB to 10dB. It should however be noted that the feedback overhead is not considered or the extra energy requirements to actually build and operate a MIMO enabled eNodeB.

The proposed scheduling algorithms for MIMO try to ensure fairness (equal access to resources and equal fulfilment of the requested QoS) across all users while maximising the overall system gain [34]. Various scheduling algorithms for LTE MIMO are presented and investigated through simulation in [34] where several opportunistic algorithms such as the Greedy Algorithm (GA) and Proportional Fair Algorithm (PFA) are shown to deliver significantly better throughput than deterministic and simpler algorithms like plain Round Robin scheduling. This is reflected in the Energy Consumption Ratio (ECR) model of the scheduling algorithms which indicates that while the Greedy Algorithm is by far the most energy efficient it fairs badly on the fairness index, again highlighting the known tradeoff between improved energy efficiency and lower fairness in the MIMO area.

The MIMO beamforming scheme proposed in [20] is quite interesting because it explores the concept of actually inducing random fading to radio environments where it does not occur naturally (which is quite often the case for LTE mobile data networks where the UE is a stationary indoor dongle or router, experiencing radio conditions that do not vary significantly over time) therefore this a more realistic MIMO approach, this induction process is known as “Opportunistic Beamforming”.
Opportunistic Beamforming as described in [38] is considered in [39] with the “dumb antenna” technique which is actually a very simple MIMO method to implement.
It requires no additional MIMO processing at either the eNodeB or the UE because from the point of view of the UE the second diversity path is completely transparent, the same Pilot signal (Cell Specific Reference Signal) is sent over both paths so the UE must not be concerned with taking care of any additional higher level MIMO processing requirements. The UE simply feeds back the CQI (Channel Quality Information) the eNodeB which schedules the transmissions to the UEs according on their instantaneous reported radio channel conditions.
It was found in [38] that this scheme provides a solution that achieves a good tradeoff between fairness and spectral efficiency (and therefore also energy efficiency) with an approximately 28% improvement in fairness and 10% improvement in spectral efficiency possible when compared to normal Alamouti Space Time Coding (STC) based MIMO as proposed for baseline 3GPP LTE.

An investigation of the affects of MIMO on energy efficiency in LTE is presented in [29] where 4x4 MIMO is compared to SISO using simulation models. The results showed that for LTE networks introducing MIMO actually increases the total power consumption of the individual eNodeB but as then in total less eNodeBs are then needed to provide the required coverage levels to the same area a lower Power Consumption Rate per area covered can be achieved (approximately 74% less when compared to standard SISO operation).
The power consumption of all base station site equipment is modelled in [29] based on manufacturer data sheets, combined with a link budget to determine path loss and therefore the achieved cell radius to determine the number of base stations required to provide the required coverage and QoS to a particular geographical area and combining these to then calculate the Power Consumption per covered area in W/m^2.
The practical issues of this approach, particularly concerning the large cell size (which generally means more users per cell) are unproven but the idea of a tool evolving from this to aid network operators to plan an LTE radio network according to energy efficiency goals is interesting.

SON (Self Organising/Optimising Networks) (as discussed in [16, 41]) methods and their applications in the development of LTE standards contain interesting use cases and techniques for energy consumption reduction. Specifically SON describes automatic and intelligent methods to change certain characteristics of the eNodeB's operation that can be leveraged to reduce the total energy consumption of the BSS.

3GPP TSG RAN is the main standardisation technical specialist working group within the 3GPP responsible for the definition of the functions, requirements and interfaces of the UTRA/E-UTRA network and was therefore also tasked with developing associated energy consumption reduction techniques within the framework of the standards body.
The TSG RAN working group consists of nominated experts from all major radio network equipment vendors and key network operators worldwide.
As outlined in [41, 42, 43], 3GPP TSG RAN identifies SON techniques as being key elements in achieving significant energy savings within wireless access networks.
"As an essential feature of Self-Organization Network (SON), the topic on energy saving for LTE has been discussed in a number of 3GPP working groups in 2009. For example, energy savings by switching on and off LTE cells has been studied in both RAN3 and SA5, with RAN3 focusing on eNodeB based solutions and SA5 focusing on the OAM based solution" [43].

Considering [45] where a model and simulation results were presented showing how changing handover thresholds dynamically according to user load can be used to shrink the coverage area of overloaded cells, move the excess traffic on to less loaded cells and therefore achieve savings in eNodeB deployment density and the associated energy consumption while maintaining the required QoS.
This approach is a simplified model which assumes there will be varying temporal traffic profiles in neighbouring cells at certain hours due to user behaviour and mobility (higher traffic load from business areas during the day/weekdays and from residential areas during the night time/weekend.) In [45] the energy consumption of the eNodeB was modelled based on manufacturer datasheets, including all peripheral site and environmental equipment and this was extrapolated over the whole network. A notable tradeoff of this solution is the complexity and overhead required to implement the scheme against the size of the actual area where the prevailing traffic profiles may be favourable.

An interesting energy efficient sleep mode design was presented in [18] based on switching the eNodeB transmitter (and RF Power Amplifier) off during particular OFDMA sub frames (within the time domain) and is was claimed that energy reductions of up to 90% are possible during low traffic times but possible gains decreasing rapidly with increasing traffic loads. This research is noteworthy because makes user of DTX/DRX (Discontinuous Transmit, Discontinuous Receive) techniques which up until now were usually just considered for achieving power savings on the UE side.

An approach to increasing energy efficiency was presented in [41] involving so called "hotspots" (areas of high traffic density with a very pronounced temporal traffic profile.) The approach discussed has two parts involving the automatic adjustment of the antenna electrical down-tilt and the transmitted pilot power to influence the coverage area – basically sending an LTE cell into hibernation once the performance statistics show that a particular traffic threshold has been reached in cell the and moving service to a neighbouring cell by increasing the dominance area of the neighbouring cell by boosting the transmitted Pilot Power. In this study the power consumption per eNodeB was modelled, including all peripheral site and environmental equipment and extrapolated over the complete “hotspot” target area considered and it was estimated that total power savings of approximately 13% are realisable.

The considerable focus that has been given to SON techniques in TSG RAN as shown in [42, 43] confirms the importance and relevance of research in this area and the input of equipment vendors such as Huawei and network operators like NTT DOCOMO gives a good insight into the practicalities of such schemes. While recognising the potential of such techniques (switching off eNodeBs and PAs would clearly bring huge energy savings) they also considered issues such as backwards compatibility and the effects that suddenly changing the network configuration could have on the users, recognising that some short service interruptions will be unavoidable when new energy optimising configurations are loaded.

An important tradeoff to consider with the various Self Organising/Optimising schemes is that there is a certain overhead and complexity associated with such schemes in terms of signalling overhead and processing/decision making work, this overhead must be balanced against the energy efficiency gain that such a scheme might achieve.

SON is an area of considerable promise for energy savings as it relies on a self optimization process that is playing an increasing role in LTE and emerging radio network standards generally and applying these methods to the energy efficiency problem is really a logical evolution. Much more research is required on the effects that automatic changes to the network configuration and coverage profiles would have on services and users, specifically affects on the delivered QoS and coverage to users at the edges of coverage areas of eNodeBs that are hibernating or operating in some reduced capacity and also the effects of pilot pollution on neighbouring cells which are not involved in the self optimization due to the expansion of the pilot dominance area of nearby cells involved in a self optimization energy saving scheme.

Relay Node (Multi-Hop) Compared to the traditional cellular network scenario where the UE communicates directly with the eNodeB within a Relay assisted cellular network the UE can communicate directly with the dominant eNodeB or via an intermediate relay station.

The use of a Relay station between UE and eNodeB enables various performance improvements and energy saving as reported in [46].

Relaying generally splits longer (and therefore more loss prone) radio paths into multiple shorter path segments thereby reducing the total path loss due to the non-linear relationship of path loss to path distance as shown in [47]. Replacing longer and more loss prone radio links with shorter and more robust radio links can have a positive effect on the overall radio link power budget.

Analogue repeaters which amplify and forward the received signal without decoding it are already known to be cost effective solutions for solving localised or indoor coverage issues but provide no real benefit in terms of link budget or energy efficiency.

In contrast to analogue repeaters which are already widely deployed in GSM and UMTS networks, Relay stations that operate in decode and forward mode, decoding and regenerating the received signal before passing it on ensure that the effects of noise and loss on a particular path are not propagated any further.

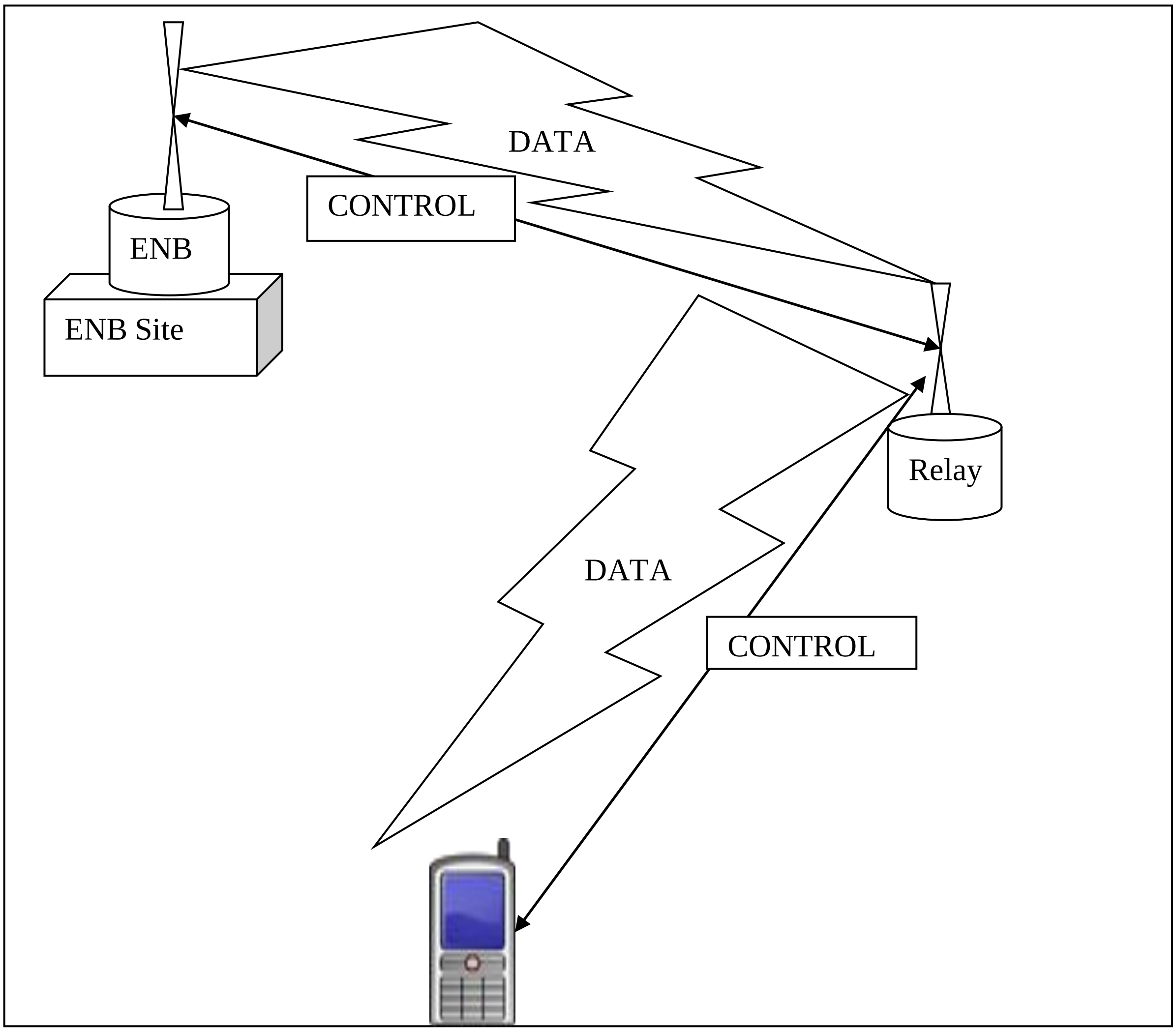

Figure 2

The placement strategy of Relay stations within a cell is a key design factor in reducing energy consumption with such multi-hop schemes but there is a also clear tradeoff present here between the cost of deploying the extra relay stations (including their own power non-negligible consumption) and the overall power consumption reduction they can provide. Higher relay density means increased network infrastructure costs as mentioned in [48] meaning an optimal number of relays must be deployed in order to achieve the specified QoS requirement. As decode and forward Relay stations use an in-band backhaul to the eNodeB there is no transmission power required for microwave backhaul at a relay location and because Relays would be smaller and more robust, even portable compared to an eNodeB there would be much less cooling required at a Relay site as was reported in [48].

Standardisation processes to include multi-hop relaying technologies in future cellular networks standards such as LTE-Advanced (LTE-A) have already commenced and the 3GPP has already identified relaying as a very important technique for improving radio coverage and throughput in LTE-A networks [49].
The increasing importance being associated with cellular relay technology is due to the fact that most mobile network operators already have an existing network of site locations built that have been rolled out with GSM/EDGE, 3G UMTS and now starting with LTE but as the frequency of assigned spectrum increases (UMTS at 2 GHz. and LTE at 2.6Ghz) radio link path loss becomes larger and therefore cell sizes will have to become smaller to provide the same coverage and the required QoS meaning a higher site density and the requirement to build out new sites but well established mobile operators will generally not be able to build a significant amount of new sites due to budgetary constraints due to the fact that along with the explosion of mobile data throughput, ARPU and the price per MB transported is decreasing.
In this paradigm, the role of relay technology could play an important role although in some European countries with well developed 3G infrastructure there are counter measures underway to “re-farm” 2G frequencies for LTE.
Relay stations at temporary hotspot locations such as shopping centers, business centers or airports could provide a cost effective and energy efficient coverage and capacity boost while maximising the utilisation of existing site assets.

Techniques based on mobile mechanical relaying in wireless access networks were presented in [49] focusing on the benefits that can be achieved in terms of overall energy consumption.
The term mechanical relaying means to Store and Carry the information received before Forwarding (SCF) which is ideal for supporting delay tolerant or “elastic” services.
In [20] several types of prevalent internet service traffic which by their nature would lend themselves quite easily to being transported via SCF relays have been identified such as Peer to Peer (P2P), SMTP, POP, RS, updates/status reports for various social networking applications and even a significant share of HTTP traffic. An interesting point discussed in [20] is that in the mobile relay scenario, considerable reductions in energy consumption can be achieved by delaying transmission until the relay station is at a location with more favourable radio conditions, it was suggested according to simulation results that savings of several orders of magnitude are possible.

The techniques described in [20] are based on mobile relay stations operating across cell borders in contrast to a lot of earlier research initiatives on multi-hop cellular systems which were limited to relay systems operating within one cell.
It was reported in [20] that this network level diversity introduced by the mobility of relay stations enabled a lot of very promising factors such as neighbourhood interference

reduction and spatial capacity gain all facilitating significant improvements in energy and spectral efficiency by exploiting the numerous benefits that arise due to the fact that transmissions from mobile relay stations generally occur closer to the eNodeB and further from the cell edge.

The concept of using mobile relay stations to provide coverage to users in low utilization cells that have been already switched off or degraded in some way as part of a SON energy consumption optimisation process is also a very promising area of future research.
Although the benefits of mobile relay stations in the context as described in [20] are well proven, the scenarios presented are probably not very common in real networks, the magnitude of gain due to mobility of users within a cell that can be exploited will very much depend on the mobility profile and when considering the context of mobile broadband users with stationary dongles/routers in the home, the mobility of users would be quite low.

Research initiatives into various facets of multi-hop cellular access have been ongoing for quite some time now for example in [50, 51] but decode and forward or mechanical relaying techniques have not been introduced to wireless access networks in any meaningful manner.
Ongoing research with the renewed focus on the energy efficiency use case and importance assigned to cellular multi-hop techniques in the standardisation processes may change this.
With LTE-A the present focus is on using relays for extending the coverage area however studies such as [49] indicate the potential of relay technology to improve energy efficiency in LTE-A networks.

In a simulation of a LTE-A environment in [49] a power reduction of up to 50% was simulated depending on the path loss experienced using Fixed Relay nodes however this study was just concerned with UE power consumption as in [52] where various routing protocols for cellular multi-hop are analysed in terms of their possible energy efficiency gains.

Apart from [20] where the focus is on mobile SCF relay stations in a multi-cell environment there has been no significant research published to date on the effects of cellular multi-hop/relaying on the eNodeB/BSS network level side power consumption.
In [49] interest was focused generally on the benefits of fixed relays in LTE in terms of coverage and throughput and simulation results show that with optimal use of relays energy consumption (TX power) of the eNodeB can reduced and cell throughput and coverage can be increased, of course with the caveat that the relay nodes themselves also consume energy which is not negligible.

Ideally a combined strategy of fixed and mobile relay stations would seem to offer the best tradeoffs of performance against complexity over varying mobility and traffic profiles while bearing in mind that the mobile relay station may not be applicable in every locations, however the fact that they can operate across cell borders and the benefits they bring in terms of spatial diversity, interference reduction and the role they could play to empower various SON schemes to switch off eNodeBs with low utilization means they worth consideration and further research.

Chapter 5 - Conclusions and Project Outline

Considering the important role that relay and multi-hop cellular techniques will play in future mobile access network standards such LTE-Advanced and the fact that research to date indicated that the potential of such approaches to deliver significant energy efficiency increases is considerable, continued and detailed research in this area is required.

As already mentioned, the benefits of relaying techniques in terms of UE power consumption, coverage and spectral efficiency have been studied in great detail, relatively little research has been done into employing these techniques to the problem of increasing energy efficiency on the eNodeB (network side).

To characterise, quantify and understand the applications of relaying techniques in the context of energy consumption reduction and energy efficiency and to determine what limitations, drawbacks and tradeoffs are associated with them, it is proposed to initially develop a power consumption simulation model of the LTE E-UTRAN interface between an eNodeB and a UE using a network simulation tool where various service, load, propagation and mobility scenarios can be analysed in terms of ECR to establish a baseline scenario for energy consumption.

The power consumption simulation will be developed utilising the LTE simulation modules of the NS-3 [53] network simulation tool and will allow power consumption metrics to be gathered from the simulations along with relevant QoS related metrics such as throughput and delay.
This should prove be a useful tool in general for studying network energy consumption in LTE environments and will allow simulations based on typical link power budget information obtained from network equipment vendors datasheets including the complete site power budget.

Building on the initial simulation, models of relay stations will be introduced into these scenarios to simulate, understand and quantify the ECG of decode and forward fixed relay node deployments in an LTE cell compared to the baseline scenario, also with the particular focus on QoS for UEs towards the cell coverage borders compared to the baseline scenario.

The final goals of the simulation will be to determine for a single user (UE) towards the edge of the cell coverage how the deployment of decode and forward fixed relay nodes can improve the overall energy efficiency of the eNodeB while maintaining a given QoS for the UE and to determine which relay deployment strategies are the most energy efficient in terms of positioning and deployment density because this will be a key factor in the success of relay technology as there will certainly be an important tradeoff in the cost/benefit ratio to be found.

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Appendix B

An Overview of ns-3 Modelling and Simulation for ENB Site Energy Consumption and Relaying in LTE

ns-3 general overview

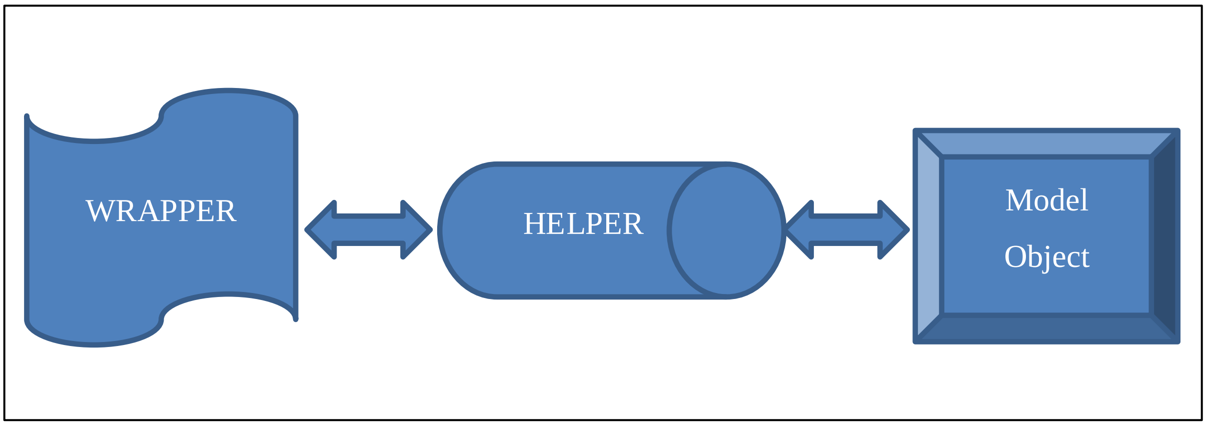
ns-3 is a discrete event simulation tool available for research and educational purposes and is maintained, developed and distributed by the ns3 open source project.

ns-3 is in some ways a follow on effort from the very popular ns-2 tool but does not yet contain all the modules that are available in ns-2 but it does have some advantages like support for multiple interfaces per node and much better modelling of IP and internet protocol stacks. The modules within ns-3 are strongly object oriented, written in C++ while scripting tasks such as generating and running simulations can also be done in the Python scripting language.

Within the scope of this work, ns-3 version 3.11 was used as the modelling framework. This version of ns-3 contains contributed modules for simulating LTE radio network nodes and also some basic energy consumption modelling tools that would allow developers to design and build functions for energy consumption modelling into simulations of various network model scenarios in the context of ns-3.

Modules within ns-3 are normally designed and implemented in two parts, the module itself containing all object classes and the logic defining the interactions between these and other object classes, and also “helper” classes, which are classes that provide a simple interface to the internal objects of the model allowing developers to create, initialise, parameterise and terminate the objects of the required models in a comfortable fashion without any need to be concerned with the actual workings of the model, this makes it convenient to utilise the many existing modules within the open source project.

Simulations within ns-3 are defined in “wrapper” programs which can either be implemented in C++ or with Python scripts. Wrappers use helpers to set up and configure the model including activating various tracing groups that are coded in the model.



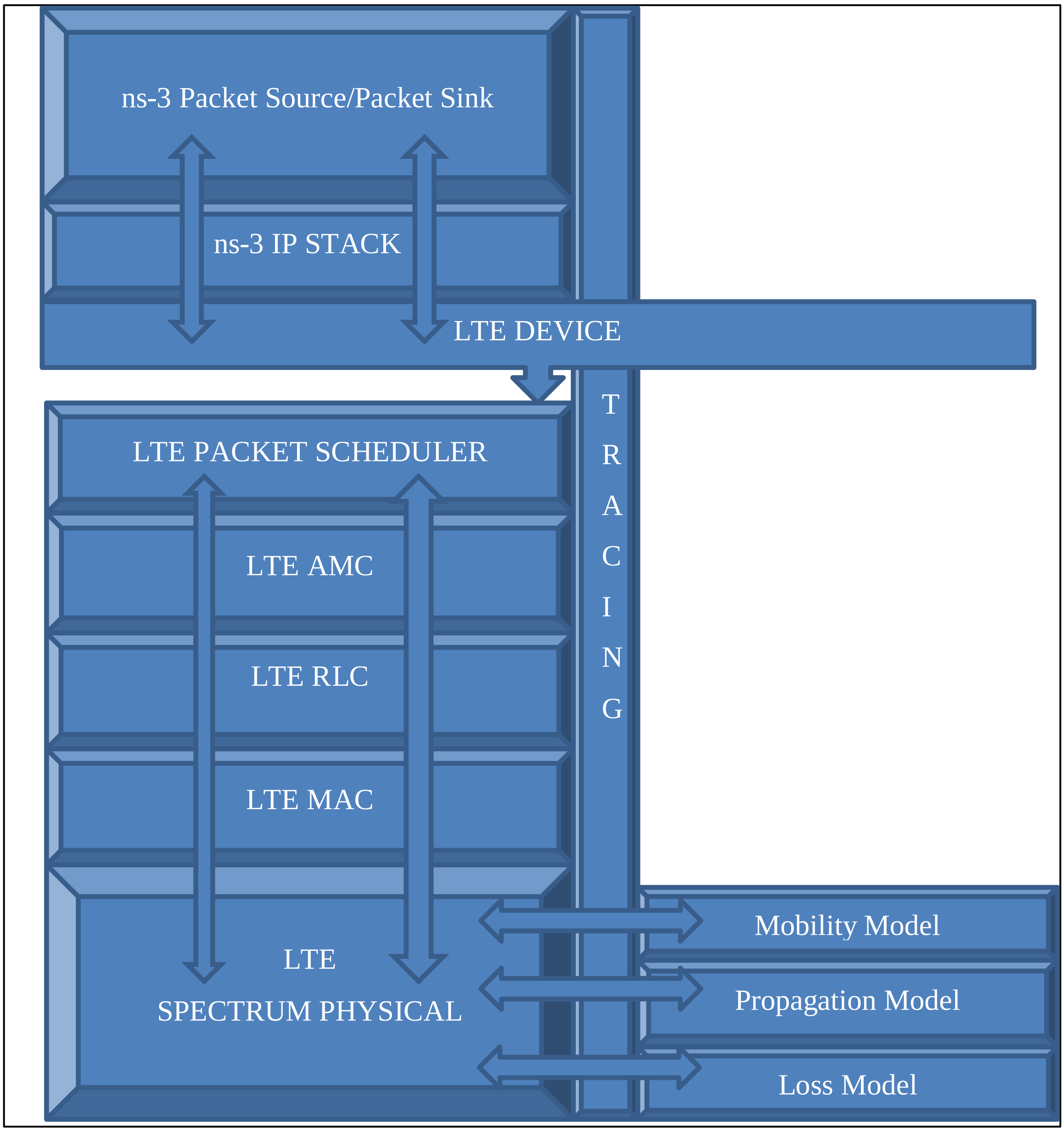
ns-3 simulation tool logical structure

ns-3 lte overview

The contributed LTE modules contained within the ns-3 3.11 release of May 2011 facilitate the simulation of LTE radio network devices and protocols, specifically an ENB and UE and the LTE Uu control and user plane protocol interfaces between them.

The LTE modules of ns-3 use spectrum channel simulation classes contained within the ns-3 project to model the physical radio interface in terms of propagation, loss, and throughput.

A LTE device model class creates a channel realisation of the radio link and combines this with models of the other layers of the LTE Uu interface such as MAC, RLC, RRC and AMC.



ns-3 LTE Model logical structure

The various components of the LTE modules are made available to wrappers via an LTE helper which provides interfaces to integrate and use the LTE objects within a given simulation instance.

LTE objects may be configured as ENBs or UEs, which can then be attached to the configured joint spectrum channel implementation (both for the uplink and for the downlink).

LTE Device object classes within a spectrum channel are assigned to a mobility model which dictates their relative grid position in relation to each other and also their movement patterns if mobility modelling is required.

The ns-3 propagation model classes are used by the channel to calculate the total losses that occurs due to propagation of the radio signal including path loss, fading loss, penetration loss, and shadowing loss.

The LTE Packet Scheduler class connects to the IP stack model in ns-3 and allows interaction with TCP or UDP packets sources or sinks to simulate user plane IP services being carried over the lower layers of LTE. The AMC class generates and process the UE CQI feedbacks and determines which modulation and coding scheme should be used for a particular LTE sub channel based on the calculated Signal to Noise Ratio, which in turn is calculated by applying the relevant loss and mobility models to the signal parameters.

More detailed documentation of the LTE modules of ns-3 can be found at the following link http://www.nsnam.org/docs/release/3.11/doxygen/group__lte.html.

ns-3 energy modelling overview

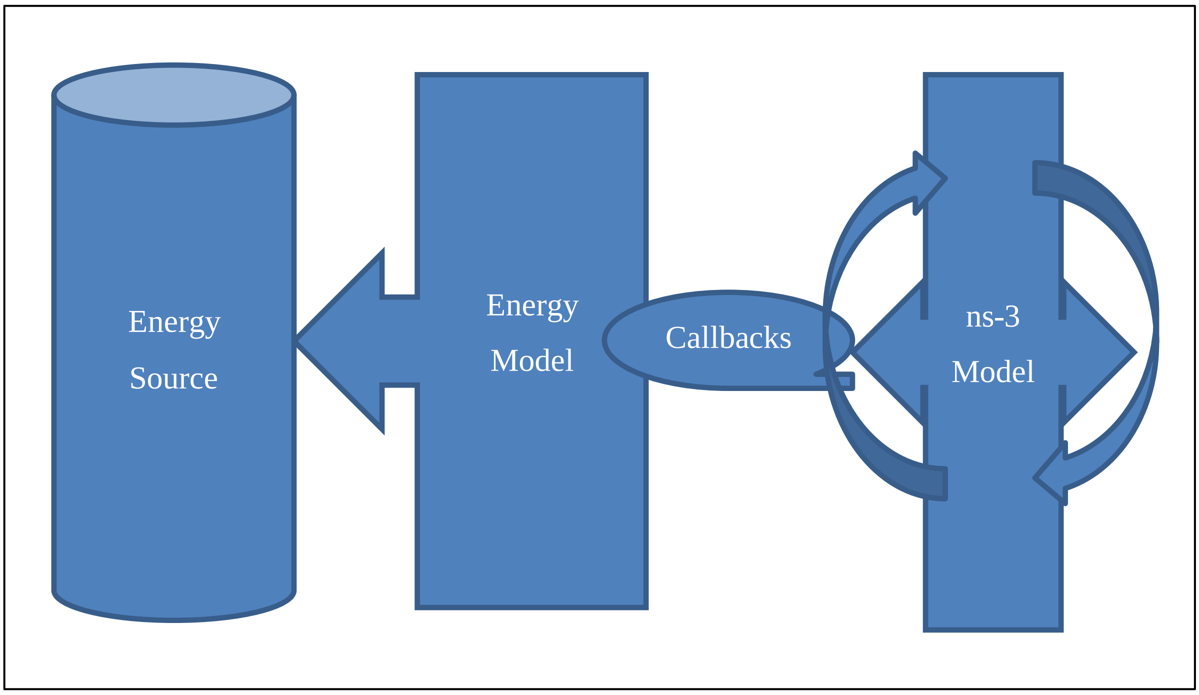
The ns-3 modelling and simulation framework offers model developers a useful toolkit to build energy consumption considerations into the many communications protocol and device scenarios that can be simulated within the extensive network scenarios that may be modelled with the tool.

The ns-3 framework does not offer solutions to all energy modelling requirements but rather allows designers of new modules a common method to design and build models of energy sources and energy consumers into their simulation code.

Within the ns-3 energy framework an energy "helper" class can be defined which offers a set of interfaces to create, install and configure energy source and consumer object classes and to extract traces from the simulations which are enriched with this energy consumption dimension.

An energy source class object represents an energy source that can be configured with a specific initial amount of energy that is then depleted by interactions with the associated energy model during the course of a simulation run, normally an energy source represents a battery that is powering a mobile device like a WIFI card for example, however energy sources can also be configured as constant power sources that never deplete such as the behaviour of a constant DC power source.

The energy model object within the ns-3 framework models the energy consumption behaviour of a system with ns-3, it basically gets state change information from the object class that is being modelled by injecting "energy call-back" hook functions into the code of the target objects which "call-back" out to the energy model whenever there is a state change. The energy model tracks the state of the target object and knows how much time it has spent in a particular state and coupled with appropriate configuration information supplied in the simulation wrapper about how much power is consumed in a particular state, it can calculate the energy consumption of the target object and then deplete this amount of energy from the associated energy source.

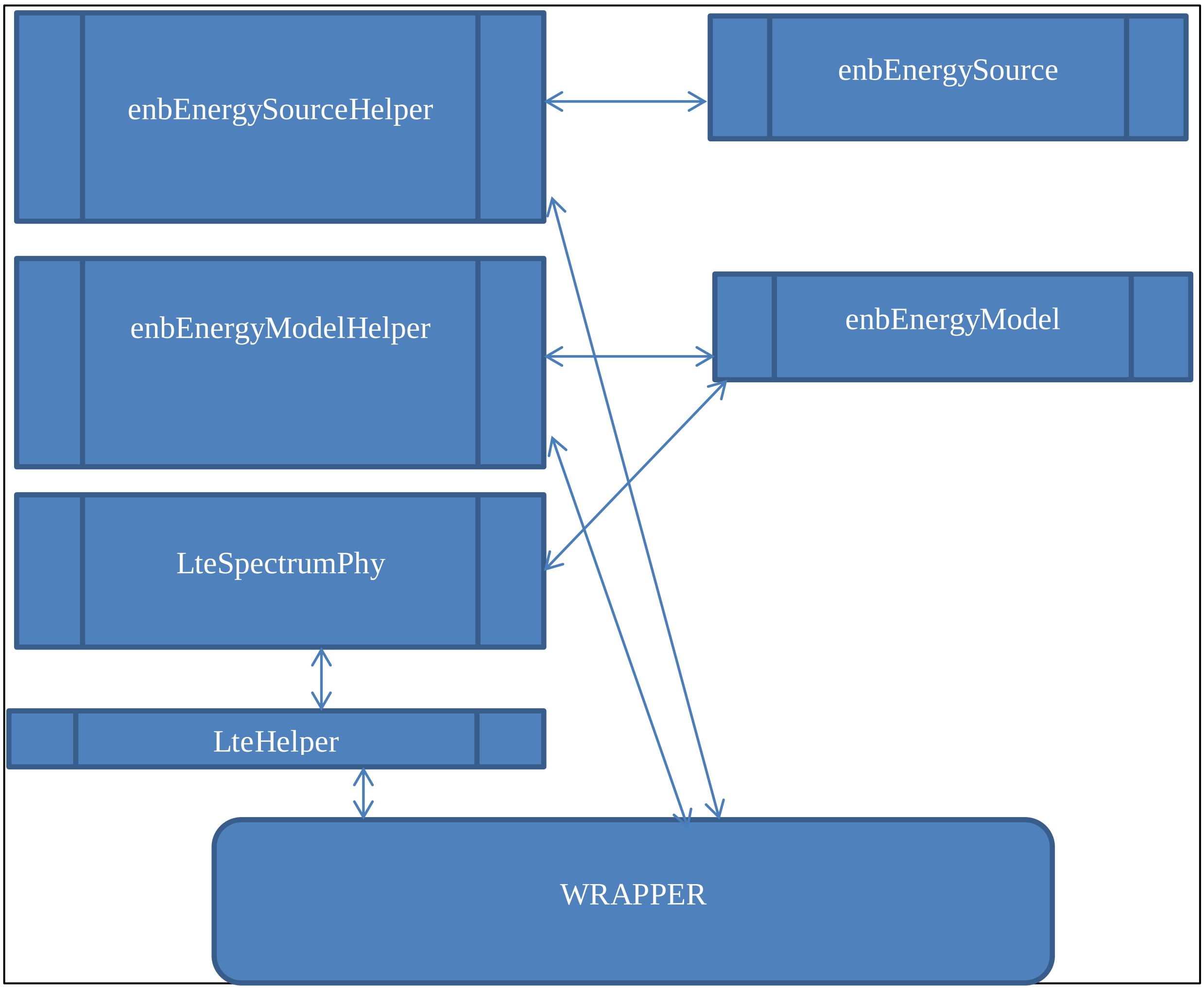


ns-3 energy framework logical structure

LTE ENB Site energy modelling design

In order to introduce energy modelling functionality into the ns-3 lte modules several distinct steps were necessary.

1. Definition of the ENB energy source class and the associated helper class.
2. Definition of the relevant call back points within the LTE Spectrum Physical class which defines the current state of the LTE physical layer and allows it to be utilised by upper layers with the model.
3. Definition of the ENB energy model class and the associated helper class and parameterisation with the relevant variables to facilitate power consumption modelling in the identified states of the energy consuming object.
4. Definition of the appropriate trace call-out points and algorithms to extract information from the energy model to the ns-3 trace files.
5. Testing with various site component power consumption scenarios and service mixes.



ns-3 LTE Energy Model logical structure

The key parameters that are necessary to drive the model are passed into the model via the energy model helper: TxPowerW, IdlePowerW, RxPowerW and SitePowerW which were all defined according to the power consumption assessment of a typical ENB site and were identified as the power consumption metrics of all key components of a typical ENB site during the various operational states of the site equipment.
The ENB energy source was defined as being a constant DC power supply delivering -48V DC which is the standard voltage required by telecommunications equipment which would be deployed on a typical ENB site location. The current draw from the energy source power supply is calculated from the power consumption metrics of the various components which are passed into the model
The Energy modeling frame work for LTE was designed to plug into the LTE model according to the defined frameworks of ns-3 and was applied generically to the LTE spectrum model states, this means that UE LTE devices can also be easily bound into this framework and the their power consumption also parameterized and modeled.

The following is the source code for the ENB Energy Source helper class:

```
/*
 *     Author: Walter Keating
 *         ID: 95421262
 * Description: ENB Energy Source helper class
 */

#include "enb-energy-source-helper.h"
#include "ns3/energy-source.h"

namespace ns3 {

EnbEnergySourceHelper::EnbEnergySourceHelper ()
{
  m_enbEnergySource.SetTypeId ("ns3::EnbEnergySource");
}

EnbEnergySourceHelper::~EnbEnergySourceHelper ()
{
}
void
EnbEnergySourceHelper::Set (std::string name, const AttributeValue &v)
{
  m_enbEnergySource.Set (name, v);
}

Ptr<EnergySource>
EnbEnergySourceHelper::DoInstall (Ptr<Node> node) const
{
  NS_ASSERT (node != NULL);
  // check if energy source already exists
  Ptr<EnergySource> source = node->GetObject<EnergySource> ();
  if (source != NULL)
    {
      NS_FATAL_ERROR ("Energy source already installed!");
    }
  source = m_enbEnergySource.Create<EnergySource> ();
  NS_ASSERT (source != NULL);
  source->SetNode (node);
  return source;
```

```
}

}
```

The following is the source code for the ENB Energy Source class:

```
// namespace ns3
/*
 *     Author: Walter Keating
 *         ID: 95421262
 * Description: ENB Energy Source class */

#include "enb-energy-source.h"
#include "ns3/log.h"
#include "ns3/assert.h"
#include "ns3/double.h"
#include "ns3/trace-source-accessor.h"
#include "ns3/simulator.h"

NS_LOG_COMPONENT_DEFINE ("EnbEnergySource");

namespace ns3 {

NS_OBJECT_ENSURE_REGISTERED (EnbEnergySource);

TypeId
EnbEnergySource::GetTypeId (void)
{
  static TypeId tid = TypeId ("ns3::EnbEnergySource")
    .SetParent<EnergySource> ()
    .AddConstructor<EnbEnergySource> ()
    .AddAttribute ("EnbEnergySourceInitialEnergyJ",
                   "Initial energy stored in enb energy source.",
                   DoubleValue (10),  // in Joules
                   MakeDoubleAccessor (&EnbEnergySource::SetInitialEnergy,
                                       &EnbEnergySource::GetInitialEnergy),
                   MakeDoubleChecker<double> ())
    .AddAttribute ("EnbEnergySupplyVoltageV",
                   "Initial supply voltage for enb energy source.",
                   DoubleValue (48.0), // in Volts
                   MakeDoubleAccessor (&EnbEnergySource::SetSupplyVoltage,
                                       &EnbEnergySource::GetSupplyVoltage),
                   MakeDoubleChecker<double> ())
    .AddAttribute ("PeriodicEnergyUpdateInterval",
                   "Time between two consecutive periodic energy updates.",
                   TimeValue (Seconds (0.1)),
                   MakeTimeAccessor (&EnbEnergySource::SetEnergyUpdateInterval,
                                     &EnbEnergySource::GetEnergyUpdateInterval),
                   MakeTimeChecker ())
    .AddTraceSource ("RemainingEnergy",
                     "Remaining energy at EnbEnergySource.",
                     MakeTraceSourceAccessor (&EnbEnergySource::m_remainingEnergyJ))
  ;
  return tid;
}

EnbEnergySource::EnbEnergySource ()
{
  m_lastUpdateTime = Seconds (0.0);
}
```

```
EnbEnergySource::~EnbEnergySource ()
{
}

void
EnbEnergySource::SetInitialEnergy (double initialEnergyJ)
{
  NS_LOG_FUNCTION (this << initialEnergyJ);
  NS_ASSERT (initialEnergyJ >= 0);
  m_initialEnergyJ = initialEnergyJ;
  m_remainingEnergyJ = m_initialEnergyJ;
}

void
EnbEnergySource::SetSupplyVoltage (double supplyVoltageV)
{
  NS_LOG_FUNCTION (this << supplyVoltageV);
  m_supplyVoltageV = supplyVoltageV;
  m_TotalConsumedEnergyJ = 0;
}

void
EnbEnergySource::SetEnergyUpdateInterval (Time interval)
{
  NS_LOG_FUNCTION (this << interval);
  m_energyUpdateInterval = interval;
}

Time
EnbEnergySource::GetEnergyUpdateInterval (void) const
{
  return m_energyUpdateInterval;
}

double
EnbEnergySource::GetSupplyVoltage (void) const
{
  return m_supplyVoltageV;
}

double
EnbEnergySource::GetInitialEnergy (void) const
{
  return m_initialEnergyJ;
}

double
EnbEnergySource::GetRemainingEnergy (void)
{
  NS_LOG_FUNCTION (this);
  // update energy source to get the latest remaining energy.
  UpdateEnergySource ();
  return m_remainingEnergyJ;
}

double
EnbEnergySource::GetEnergyFraction (void)
{
  NS_LOG_FUNCTION (this);
  // update energy source to get the latest remaining energy.
  UpdateEnergySource ();
```

```
  return m_remainingEnergyJ / m_initialEnergyJ;
}

void
EnbEnergySource::UpdateEnergySource (void)
{
  NS_LOG_FUNCTION (this);

  // do not update if simulation has finished
  if (Simulator::IsFinished ())
    {
      return;
    }

  m_energyUpdateEvent.Cancel ();

  CalculateRemainingEnergy ();

  m_lastUpdateTime = Simulator::Now ();

  m_energyUpdateEvent = Simulator::Schedule (m_energyUpdateInterval,
                                             &EnbEnergySource::UpdateEnergySource,
                                             this);
}

/*
 * Private functions start here.
 */

void
EnbEnergySource::DoStart (void)
{
  NS_LOG_FUNCTION (this);
  UpdateEnergySource ();  // start periodic update
}

void
EnbEnergySource::DoDispose (void)
{
  NS_LOG_FUNCTION (this);
  BreakDeviceEnergyModelRefCycle ();
}

void
EnbEnergySource::HandleEnergyDrainedEvent (void)
{
  NS_LOG_FUNCTION (this);
  NS_LOG_DEBUG ("EnbEnergySource:Energy depleted!");
  NotifyEnergyDrained (); // notify DeviceEnergyModel objects
  m_remainingEnergyJ = 0; // energy never goes below 0
}

void
EnbEnergySource::CalculateRemainingEnergy (void)
{
  NS_LOG_FUNCTION (this);
  double totalCurrentA = CalculateTotalCurrent ();
  Time duration = Simulator::Now () - m_lastUpdateTime;
  NS_ASSERT (duration.GetSeconds () >= 0);
  // energy = current * voltage * time
  double energyConsumedJ = totalCurrentA * m_supplyVoltageV * duration.GetSeconds ();
```

```
  NS_LOG_DEBUG ("EnbEnergySource:Previous Total Consumed Energy = " <<
m_TotalConsumedEnergyJ);
  m_TotalConsumedEnergyJ += energyConsumedJ;
  NS_LOG_DEBUG ("EnbEnergySource:Additional Consumed Energy = " << energyConsumedJ);
  NS_LOG_DEBUG ("EnbEnergySource:New Total Consumed Energy = " << m_TotalConsumedEnergyJ);
  NS_LOG_DEBUG ("EnbEnergySource:Duration = " << duration.GetSeconds ());
  NS_LOG_DEBUG ("EnbEnergySource:Currrent = " << totalCurrentA);
  NS_LOG_DEBUG ("EnbEnergySource:Voltage = " << m_supplyVoltageV);

}

} // namespace ns3
```

The following is the source code for the ENB Energy Model helper class:

```
/*
 *     Author: Walter Keating
 *         ID: 95421262
 * Description: LTE Energy Model class helper
 */

#include "enb-energy-model-helper.h"
#include "ns3/basic-energy-source-helper.h"
#include "ns3/lte-spectrum-phy.h"
#include "ns3/lte-net-device.h"
#include "ns3/config.h"
#include "ns3/names.h"
#include "ns3/log.h"
#include "ns3/simulator.h"
#include "ns3/packet.h"
#include "ns3/log.h"
#include "ns3/pointer.h"
#include <string>


NS_LOG_COMPONENT_DEFINE ("EnbEnergyHelper");


namespace ns3 {

EnbEnergyModelHelper::EnbEnergyModelHelper ()
{
  m_enbEnergy.SetTypeId ("ns3::EnbEnergyModel");
}

EnbEnergyModelHelper::~EnbEnergyModelHelper ()
{
}

void
EnbEnergyModelHelper::Set (std::string name, const AttributeValue &v)
{
  m_enbEnergy.Set (name, v);
}
```

```
/*
 * Private function starts here.
 */

Ptr<DeviceEnergyModel>
EnbEnergyModelHelper::DoInstall (Ptr<NetDevice> device,
                                 Ptr<EnergySource> source) const
{
  NS_ASSERT (device != NULL);
  NS_ASSERT (source != NULL);
  // check if device is EnbNetDevice
  std::string deviceName = device->GetInstanceTypeId ().GetName ();
  if (deviceName.compare ("ns3::EnbNetDevice") != 0)
    {
      NS_FATAL_ERROR ("NetDevice type is not EnbNetDevice!");
    }
  Ptr<Node> node = device->GetNode ();
  Ptr<EnbEnergyModel> model = m_enbEnergy.Create<EnbEnergyModel> ();
  NS_ASSERT (model != NULL);
  // set node pointer
  model->SetNode (node);
  // set energy source pointer
  model->SetEnergySource (source);
  // get phy layer
  Ptr<LteNetDevice> enbDevice = DynamicCast<LteNetDevice> (device);
  Ptr<LtePhy> enbPhy = enbDevice->GetPhy ();
  Ptr<LteSpectrumPhy> enbDlSpecPhy = enbPhy->GetDownlinkSpectrumPhy();
  Ptr<LteSpectrumPhy> enbUlSpecPhy = enbPhy->GetUplinkSpectrumPhy();
  // add model to device model list in energy source
  source->AppendDeviceEnergyModel (model);
  // set node pointer
  source->SetNode (node);
  // create and install energy model callback
  DeviceEnergyModel::ChangeStateCallback cb_dl;
  DeviceEnergyModel::ChangeStateCallback cb_ul;
  cb_dl = MakeCallback (&DeviceEnergyModel::ChangeState, model);
  cb_ul = MakeCallback (&DeviceEnergyModel::ChangeState, model);
  enbDlSpecPhy->SetEnergyModelCallback (cb_dl);
  enbUlSpecPhy->SetEnergyModelCallback (cb_ul);

  return model;
}

} // namespace ns3
```

The following is the source code for the ENB Energy Model class:

```
/*
 *     Author: Walter Keating
 *         ID: 95421262
 * Description: LTE Energy Model class
 */
```

```
#include "ns3/log.h"
#include "ns3/double.h"
#include "ns3/simulator.h"
#include "ns3/trace-source-accessor.h"
#include "ns3/energy-source.h"
#include "ns3/lte-spectrum-phy.h"
#include "ns3/lte-net-device.h"
#include "enb-energy-model.h"

NS_LOG_COMPONENT_DEFINE ("EnbEnergyModel");

namespace ns3 {

NS_OBJECT_ENSURE_REGISTERED (EnbEnergyModel);

TypeId
EnbEnergyModel::GetTypeId (void)
{
  static TypeId tid = TypeId ("ns3::EnbEnergyModel")
    .SetParent<DeviceEnergyModel> ()
    .AddConstructor<EnbEnergyModel> ()
    .AddAttribute ("TxPowerW",
                   "The Enb Tx power in Watts",
                   DoubleValue (0),
                   MakeDoubleAccessor (&EnbEnergyModel::SetTxPowerW,
                                       &EnbEnergyModel::GetTxPowerW),
                   MakeDoubleChecker<double> ())
    .AddAttribute ("RxPowerW",
                   "The Enb Rx power in Watts",
                   DoubleValue (0),
                   MakeDoubleAccessor (&EnbEnergyModel::SetRxPowerW,
                                       &EnbEnergyModel::GetRxPowerW),
                   MakeDoubleChecker<double> ())
    .AddAttribute ("IdlePowerW",
                   "The Enb Idle power in Watts",
                   DoubleValue (0),
                   MakeDoubleAccessor (&EnbEnergyModel::SetIdlePowerW,
                                       &EnbEnergyModel::GetIdlePowerW),
     MakeDoubleChecker<double> ())
    .AddAttribute ("SitePowerW",
                   "The Enb Site background power consumption in Watts",
                   DoubleValue (0),
                   MakeDoubleAccessor (&EnbEnergyModel::SetSitePowerW,
                                       &EnbEnergyModel::GetSitePowerW),
                   MakeDoubleChecker<double> ())
    .AddTraceSource ("TotalEnergyConsumption",
                     "Total energy consumption of the Enb Site.",
                     MakeTraceSourceAccessor (&EnbEnergyModel::m_totalEnergyConsumption))
  ;
  return tid;
}

EnbEnergyModel::EnbEnergyModel ()
{
  NS_LOG_FUNCTION (this);
  m_currentState = LteSpectrumPhy::IDLE;
  m_lastUpdateTime = Seconds (0.0);
  m_node = 0;
  m_source = 0;
}
```

```
EnbEnergyModel::~EnbEnergyModel ()
{
}

void
EnbEnergyModel::SetNode (Ptr<Node> node)
{
  NS_LOG_FUNCTION (this << node);
  NS_ASSERT (node != 0);
  m_node = node;
}

Ptr<Node>
EnbEnergyModel::GetNode (void) const
{
  return m_node;
}

void
EnbEnergyModel::SetEnergySource (Ptr<EnergySource> source)
{
  NS_LOG_FUNCTION (this << source);
  NS_ASSERT (source != 0);
  m_source = source;
}

double
EnbEnergyModel::GetTotalEnergyConsumption (void) const
{
  NS_LOG_FUNCTION (this);
  return m_totalEnergyConsumption;
}

double
EnbEnergyModel::GetTxPowerW (void) const
{
  NS_LOG_FUNCTION (this);
  return m_txPowerW;
}

void
EnbEnergyModel::SetTxPowerW (double txPowerW)
{
  NS_LOG_FUNCTION (this << txPowerW);
  m_txPowerW = txPowerW;
}

double
EnbEnergyModel::GetRxPowerW (void) const
{
  NS_LOG_FUNCTION (this);
  return m_rxPowerW;
}

void
EnbEnergyModel::SetRxPowerW (double rxPowerW)
{
  NS_LOG_FUNCTION (this << rxPowerW);
  m_rxPowerW = rxPowerW;
}
```

```
double
EnbEnergyModel::GetSitePowerW (void) const
{
  NS_LOG_FUNCTION (this);
  return m_sitePowerW;
}

void
EnbEnergyModel::SetSitePowerW (double sitePowerW)
{
  NS_LOG_FUNCTION (this << sitePowerW);
  m_sitePowerW = sitePowerW;
}


double
EnbEnergyModel::GetIdlePowerW (void) const
{
  NS_LOG_FUNCTION (this);
  return m_idlePowerW;
}

void
EnbEnergyModel::SetIdlePowerW (double idlePowerW)
{
  NS_LOG_FUNCTION (this << idlePowerW);
  m_idlePowerW = idlePowerW;
}


int
EnbEnergyModel::GetCurrentState (void) const
{
  NS_LOG_FUNCTION (this);
  return m_currentState;
}

void
EnbEnergyModel::ChangeState (int newState)
{
  NS_LOG_FUNCTION (this << newState);
  // NS_ASSERT (IsStateTransitionValid ((EnbState) newState));

  Time duration = Simulator::Now () - m_lastUpdateTime;
  NS_ASSERT (duration.GetNanoSeconds () >= 0);

  // energy consumed = current * voltage  (watts) * time
  double energyConsumed = 0.0;
 // double supplyVoltage = m_source->GetSupplyVoltage ();
  switch (m_currentState)
    {
    case LteSpectrumPhy::TX:
      energyConsumed = duration.GetSeconds () * (m_txPowerW + m_sitePowerW) ;
      break;
    case LteSpectrumPhy::RX:
      energyConsumed = duration.GetSeconds () * (m_rxPowerW + m_sitePowerW);
      break;
    case LteSpectrumPhy::IDLE:
      energyConsumed = duration.GetSeconds () * (m_idlePowerW + + m_sitePowerW) ;
      break;
```

```
    default:
      NS_FATAL_ERROR ("EnbEnergyModel:Undefined radio state!");
    }

  NS_LOG_INFO("Previous Total Energy Consumed: " << m_totalEnergyConsumption );

  // update total energy consumption
  m_totalEnergyConsumption += energyConsumed;


  NS_LOG_INFO("Update Additional Energy Consumed: " << energyConsumed );



  // update last update time stamp
  m_lastUpdateTime = Simulator::Now ();

  // notify energy source
  m_source->UpdateEnergySource ();

  // update current state & last update time stamp
  SetEnbState (newState);

  // some debug message
  NS_LOG_INFO ("EnbEnergyModel:Total energy consumption at node " <<
               m_node->GetId () << " is " << m_totalEnergyConsumption << "J");
}

void
EnbEnergyModel::HandleEnergyDepletion (void)
{
  NS_LOG_FUNCTION (this);
}


/*
 * Private functions start here.
 */

void
EnbEnergyModel::DoDispose (void)
{
  NS_LOG_FUNCTION (this);
  m_node = 0;
  m_source = 0;
}

double
EnbEnergyModel::DoGetCurrentA (void) const
{
  NS_LOG_FUNCTION (this);

  double supplyVoltage = m_source->GetSupplyVoltage ();
  NS_ASSERT (supplyVoltage != 0.0);
  double stateCurrent = 0.0;
  switch (m_currentState)
    {
    case LteSpectrumPhy::TX:
      stateCurrent = (m_txPowerW + m_sitePowerW) / supplyVoltage;
      break;
    case LteSpectrumPhy::RX:
```

```
      stateCurrent = (m_rxPowerW + m_sitePowerW) / supplyVoltage;
      break;
    case LteSpectrumPhy::IDLE:
      stateCurrent = (m_idlePowerW +  m_sitePowerW) / supplyVoltage;
      break;
    default:
      NS_FATAL_ERROR ("EnbEnergyModel:Undefined state!");
    }

  NS_LOG_INFO("Device Current is: " << stateCurrent);

  return stateCurrent;
}

bool
EnbEnergyModel::IsStateTransitionValid (const int destState)
{
  NS_LOG_FUNCTION (this << destState);
  return true;
}

void
EnbEnergyModel::SetEnbState (const int state)
{
  NS_LOG_FUNCTION (this);
  if (IsStateTransitionValid (state))
    {
      m_currentState = state;
      std::string stateName;
      switch (state)
        {
        case LteSpectrumPhy::TX:
          stateName = "TX";
          break;
        case LteSpectrumPhy::RX:
          stateName = "RX";
          break;
        case LteSpectrumPhy::IDLE:
          stateName = "IDLE";
          break;
        }
      NS_LOG_INFO ("EnbEnergyModel:Switching to state: " << stateName <<
                   " at time = " << Simulator::Now ());
    }
  else
    {
      NS_FATAL_ERROR ("EnbEnergyModel:Invalid state transition!");
    }
}

} // namespace ns3
```

Relay energy modelling design

The basic ENB site energy consumption modelling functionality developed the ns3 LTE modelling environment to facilitate the investigation of the effects of relaying technology on the ENB site power consumption.

Introducing the relay node into ns-3 LTE was possible with major modifications to the existing ns-3 LTE code to facilitate the new device type RN (relay node) and to define the functional interaction the RN model with the ns-3 LTE UE and ENB models.

To achieve this integration several distinct steps were necessary.

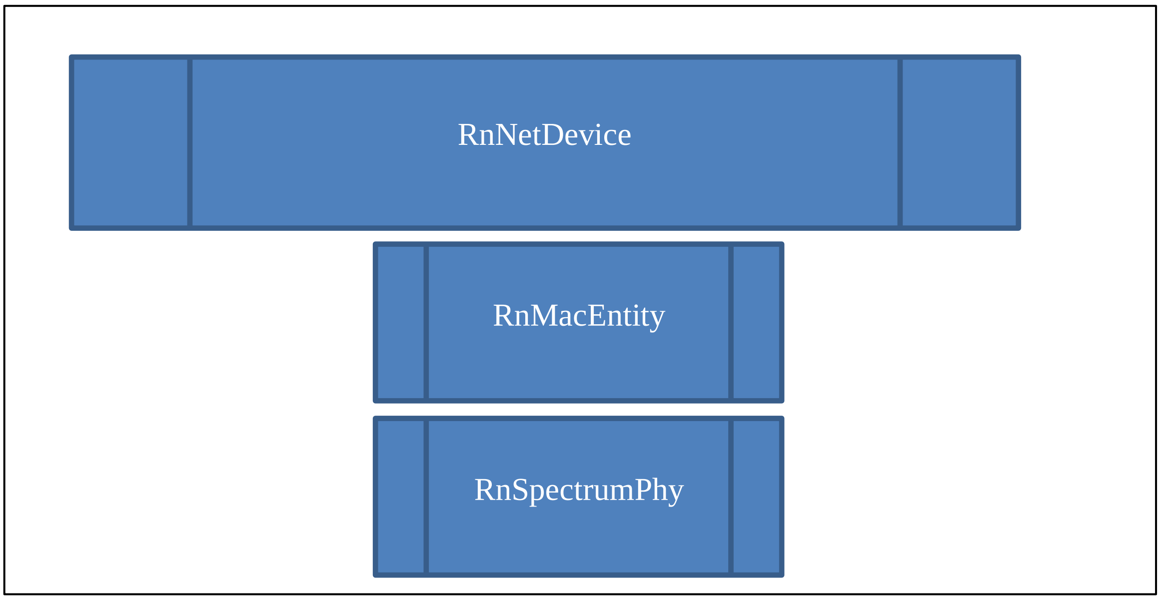
1. Definition of the RN device type model class.
2. Definition of the RN spectrum physical model class.
3. Definition of the RN MAC entity model class
4. Adaptation of the of the UE model class to interact with the RN model object
5. Adaptation of the of the ENB model class to interact with the RN model object
6. Adaptation of the AMC model class to interact with the RN model object
7. Adaptation of the LTE helper class to facilitate creating and parameterising the RN object.

Functionally the RN could be described as a combination of the ns-3 LTE UE and the ns-3 LTE ENB basically operating in parallel with direct interaction between the co-existing components above the MAC/RLC level.

The key changes the LTE channel realisation model involved allowing a RN node to be connected to four channels simultaneously (uplink from UE, uplink to ENB, downlink from ENB and downlink to UE). The flexible definitions of channels and spectrums via the LTE helper allowed the definition of the required multiple radio channels and then accordingly configured and assigned to the nodes appropriately.

Existing propagation and path loss models along with the LTE mobility framework were applied directly to the RN without any changes being necessary due to the fact that the RN LTE network device could inherit the characteristics of the base LTE network device class just as the ENB and UE devices and could therefore interact with standard ns-3 model stacks inherently.

Due to the considerable complexity of the ns-3 LTE models it was decided to construct a separate LTE Helper class to deal with the relaying scenario and the complexities of constructing the relay model, so in this case it is not possible to mix relay and non-relay based scenarios within the context of one LTE Cell Simulation run within the ns-3 environment.



Here is the code of the modified LTE Helper Class code that allows wrappers create, configure, and steer the various LTE relay simulation model components.

```
#include "lte-helper.h"
#include "ns3/simulator.h"
#include "ns3/packet.h"
#include "ns3/log.h"
#include "ns3/pointer.h"
#include <string>
#include "ns3/config.h"
#include "ns3/single-model-spectrum-channel.h"
#include "ns3/lte-spectrum-phy.h"
#include "ns3/enb-lte-spectrum-phy.h"
#include "ns3/rn-lte-spectrum-phy.h"
#include "ns3/ue-lte-spectrum-phy.h"
#include "ns3/ue-net-device.h"
#include "ns3/enb-net-device.h"
#include "ns3/rn-net-device.h"
#include "ns3/ue-manager.h"
#include "ns3/spectrum-propagation-loss-model.h"
#include "ns3/lte-propagation-loss-model.h"

NS_LOG_COMPONENT_DEFINE ("LteHelper");

namespace ns3 {

LteHelper::LteHelper (void)
  : m_downlinkChannel (CreateObject<SingleModelSpectrumChannel> ()),
    m_uplinkChannel (CreateObject<SingleModelSpectrumChannel> ()),
```

```
    m_downlinkChannel_rn_ue (CreateObject<SingleModelSpectrumChannel> ()),
    m_uplinkChannel_rn_ue (CreateObject<SingleModelSpectrumChannel> ())
{
  Ptr<LtePropagationLossModel> model = CreateObject<LtePropagationLossModel> ();
  m_downlinkChannel->AddSpectrumPropagationLossModel (model);
  Ptr<LtePropagationLossModel> model_rn_ue = CreateObject<LtePropagationLossModel> ();
  m_downlinkChannel_rn_ue->AddSpectrumPropagationLossModel (model_rn_ue);
}

LteHelper::~LteHelper (void)
{
  m_downlinkChannel = 0;
  m_uplinkChannel = 0;
  m_downlinkChannel_rn_ue = 0;
  m_uplinkChannel_rn_ue = 0;

}


Ptr<LtePhy>
LteHelper::CreatePhy (Ptr<SpectrumChannel> dlChannel, Ptr<SpectrumChannel> ulChannel, NetDeviceType
t)
{
  Ptr<LtePhy> phy;
  Ptr<LteSpectrumPhy> dl;
  Ptr<LteSpectrumPhy> ul;

  if (t == LteHelper::DEVICE_TYPE_ENODEB)
    {
      phy =  CreateObject<EnbLtePhy> ();

      dl = CreateObject<EnbLteSpectrumPhy> ();
      ul = CreateObject<EnbLteSpectrumPhy> ();
    }


  if (t == LteHelper::DEVICE_TYPE_USER_EQUIPMENT)
    {
      phy =  CreateObject<UeLtePhy> ();

      dl = CreateObject<UeLteSpectrumPhy> ();
      ul = CreateObject<UeLteSpectrumPhy> ();
    }

  phy->SetDownlinkSpectrumPhy (dl);
  phy->SetUplinkSpectrumPhy (ul);

  if (t == LteHelper::DEVICE_TYPE_ENODEB)
    {
      dl->SetChannel (dlChannel);
      ul->SetChannel (ulChannel);

      m_downlinkChannel->AddRx (dl);
      m_uplinkChannel->AddRx (ul);
    }

  else if (t == LteHelper::DEVICE_TYPE_USER_EQUIPMENT)
    {
      dl->SetChannel (dlChannel);
      ul->SetChannel (ulChannel);
```

```
    m_downlinkChannel->AddRx (dl);
  }
 else
  {
    NS_FATAL_ERROR ("LteHelper: Invalid Device type");
  }

 return phy;

}

Ptr<LtePhy>
LteHelper::CreatePhy (NetDeviceType t)
{
 Ptr<LtePhy> phy;
 Ptr<LteSpectrumPhy> dl;
 Ptr<LteSpectrumPhy> ul;

 if (t == LteHelper::DEVICE_TYPE_ENODEB)
  {
    phy =  CreateObject<EnbLtePhy> ();

    dl = CreateObject<EnbLteSpectrumPhy> ();
    ul = CreateObject<EnbLteSpectrumPhy> ();
  }

  if (t == LteHelper::DEVICE_TYPE_DFRN)

  {
   phy =  CreateObject<RnLtePhy> ();

    dl = CreateObject<RnLteSpectrumPhy> ();
    ul = CreateObject<RnLteSpectrumPhy> ();
  }

 if (t == LteHelper::DEVICE_TYPE_USER_EQUIPMENT)
  {
    phy =  CreateObject<UeLtePhy> ();

    dl = CreateObject<UeLteSpectrumPhy> ();
    ul = CreateObject<UeLteSpectrumPhy> ();
  }

 phy->SetDownlinkSpectrumPhy (dl);
 phy->SetUplinkSpectrumPhy (ul);

 if (t == LteHelper::DEVICE_TYPE_ENODEB)
  {
    dl->SetChannel (m_downlinkChannel);
    ul->SetChannel (m_uplinkChannel);

    m_downlinkChannel->AddRx (dl);
    m_uplinkChannel->AddRx (ul);
  }

else if (t == LteHelper::DEVICE_TYPE_DFRN)
  {

   dl->SetChannel (m_downlinkChannel);
    ul->SetChannel (m_uplinkChannel);
```

```
    m_downlinkChannel->AddRx (dl);
    m_uplinkChannel->AddRx (ul);



   }

  else if (t == LteHelper::DEVICE_TYPE_USER_EQUIPMENT)
   {
    dl->SetChannel (m_downlinkChannel);
    ul->SetChannel (m_uplinkChannel);

    m_downlinkChannel->AddRx (dl);
   }
  else
   {
    NS_FATAL_ERROR ("LteHelper: Invalid Device type");
   }

  return phy;
}

Ptr<UeLtePhy>
LteHelper::CreateUePhy (void)
{
  Ptr<UeLtePhy> phy = CreateObject<UeLtePhy> ();

  Ptr<UeLteSpectrumPhy> dl = CreateObject<UeLteSpectrumPhy> ();;
  Ptr<UeLteSpectrumPhy> ul = CreateObject<UeLteSpectrumPhy> ();;

  phy->SetDownlinkSpectrumPhy (dl);
  phy->SetUplinkSpectrumPhy (ul);

  dl->SetChannel (m_downlinkChannel_rn_ue);
  ul->SetChannel (m_uplinkChannel_rn_ue);

  m_downlinkChannel_rn_ue->AddRx (dl);

  return phy;
}

Ptr<EnbLtePhy>
LteHelper::CreateEnbPhy (void)
{
  Ptr<EnbLtePhy> phy = CreateObject<EnbLtePhy> ();

  Ptr<EnbLteSpectrumPhy> dl = CreateObject<EnbLteSpectrumPhy> ();;
  Ptr<EnbLteSpectrumPhy> ul = CreateObject<EnbLteSpectrumPhy> ();;

  phy->SetDownlinkSpectrumPhy (dl);
  phy->SetUplinkSpectrumPhy (ul);

  dl->SetChannel (m_downlinkChannel);
  ul->SetChannel (m_uplinkChannel);

  m_downlinkChannel->AddRx (dl);
  m_uplinkChannel->AddRx (ul);

  return phy;
}
```

```
Ptr<RnLtePhy>
LteHelper::CreateRnPhy (void)
{
  Ptr<RnLtePhy> phy = CreateObject<RnLtePhy> ();
  Ptr<RnLteSpectrumPhy> dl = CreateObject<RnLteSpectrumPhy> ();;
  Ptr<RnLteSpectrumPhy> ul = CreateObject<RnLteSpectrumPhy> ();;
  phy->SetDownlinkSpectrumPhy (dl);
  phy->SetUplinkSpectrumPhy (ul);
  m_downlinkChannel->AddRx (dl);
  m_uplinkChannel->AddRx (ul);

  return phy;
}

Ptr<RnLtePhy>
LteHelper::CreateRnRelayPhy (void)
{
  Ptr<RnLtePhy> phy = CreateObject<RnLtePhy> ();

  Ptr<RnLteSpectrumPhy> dl = CreateObject<RnLteSpectrumPhy> ();;
  Ptr<RnLteSpectrumPhy> ul = CreateObject<RnLteSpectrumPhy> ();;

  phy->SetDownlinkSpectrumPhy (dl);
  phy->SetUplinkSpectrumPhy (ul);

  dl->SetChannel (m_downlinkChannel_rn_ue);
  ul->SetChannel (m_uplinkChannel_rn_ue);

  m_downlinkChannel_rn_ue->AddRx (dl);
  m_uplinkChannel_rn_ue->AddRx (ul);

  return phy;
}
void
LteHelper::AddMobility (Ptr<LtePhy> phy, Ptr<MobilityModel> m)
{
  phy->GetDownlinkSpectrumPhy ()->SetMobility (m);
  phy->GetUplinkSpectrumPhy ()->SetMobility (m);
}


NetDeviceContainer
LteHelper::Install (NodeContainer c, NetDeviceType type)
{
  NetDeviceContainer devices;
  for (NodeContainer::Iterator i = c.Begin (); i != c.End (); i++)
    {
      Ptr<Node> node = *i;
      Ptr<LteNetDevice> device;
      Ptr<LtePhy> phy;

      if (type == LteHelper::DEVICE_TYPE_ENODEB)
        {
          Ptr<EnbLtePhy> p = CreateEnbPhy ();
          Ptr<EnbNetDevice> dev = CreateObject<EnbNetDevice> (node, p);

       p->GetUplinkSpectrumPhy ()->SetGenericPhyRxEndOkCallback (MakeCallback
(&LteNetDevice::Receive, dev));

          device = dev;
          phy = p;
```

```
      }

 else   if (type == LteHelper::DEVICE_TYPE_DFRN)
      {
        Ptr<RnLtePhy> p = CreateRnPhy ();
        Ptr<RnLtePhy> p_relay = CreateRnRelayPhy ();
        int t = 1;

        Ptr<RnNetDevice> dev = CreateObject<RnNetDevice> (t, node, p, p_relay);

        p->GetDownlinkSpectrumPhy ()->SetGenericPhyRxEndOkCallback (MakeCallback
(&LteNetDevice::Receive, dev));
        p->GetUplinkSpectrumPhy ()->SetGenericPhyRxEndOkCallback (MakeCallback
(&LteNetDevice::Receive, dev));

        device = dev;
        phy = p;

        p_relay->SetDevice (device);
        p_relay->GetDownlinkSpectrumPhy ()->SetDevice (device);
        p_relay->GetUplinkSpectrumPhy ()->SetDevice (device);
        p_relay->GetDownlinkSpectrumPhy ()->SetGenericPhyRxEndOkCallback (MakeCallback
(&LteNetDevice::Receive, dev));
        p_relay->GetUplinkSpectrumPhy ()->SetGenericPhyRxEndOkCallback (MakeCallback
(&LteNetDevice::Receive, dev));
      }

 else     if  (type == LteHelper::DEVICE_TYPE_USER_EQUIPMENT)
      {
        Ptr<UeLtePhy> p = CreateUePhy ();
        Ptr<UeNetDevice> dev = CreateObject<UeNetDevice> (node, p);

        p->GetDownlinkSpectrumPhy ()->SetGenericPhyRxEndOkCallback (MakeCallback
(&LteNetDevice::Receive, dev));

        device = dev;
        phy = p;
      }

     else
      {
        NS_FATAL_ERROR ("LteHelper: Invalid Device type");
      }

     device->SetAddress (Mac48Address::Allocate ());
     phy->SetDevice (device);

     phy->GetDownlinkSpectrumPhy ()->SetDevice (device);
     phy->GetUplinkSpectrumPhy ()->SetDevice (device);

     device->Start ();
     node->AddDevice (device);
     devices.Add (device);
    }
  return devices;
}

void
LteHelper::RegisterUeToTheEnb (Ptr<UeNetDevice> ue, Ptr<EnbNetDevice> enb)
{
  ue->SetTargetEnb (enb);
```

```
  enb->GetUeManager ()->CreateUeRecord (ue, enb);

}

void
LteHelper::RegisterUeToTheRn (Ptr<UeNetDevice> ue, Ptr<RnNetDevice> enb)
{
  ue->SetTargetEnb (enb);
  enb->GetUeManager ()->CreateUeRecordRn (ue, enb);

}

void
LteHelper::RegisterRnToTheEnb (Ptr<RnNetDevice> rn, Ptr<EnbNetDevice> enb)
{
  rn->SetTargetEnb (enb);
  enb->GetUeManager ()->CreateRnRecord (rn, enb);

}

void
LteHelper::AddDownlinkChannelRealization (Ptr<MobilityModel> enbMobility, Ptr<MobilityModel>
ueMobility, Ptr<LtePhy> phy)
{
  Ptr<LtePropagationLossModel> model = m_downlinkChannel->GetSpectrumPropagationLossModel ()-
>GetObject<LtePropagationLossModel> ();

  model->CreateChannelRealization (enbMobility, ueMobility);

  //initialize multipath model
  Ptr<JakesFadingLossModel> m = model->GetChannelRealization (enbMobility, ueMobility)-
>GetJakesFadingLossModel ();
  m->SetPhy (phy);
}

void
LteHelper::AddRelayDownlinkChannelRealization (Ptr<MobilityModel> rnMobility, Ptr<MobilityModel>
ueMobility, Ptr<LtePhy> phy)
{
  Ptr<LtePropagationLossModel> model_rn_ue = m_downlinkChannel_rn_ue-
>GetSpectrumPropagationLossModel ()->GetObject<LtePropagationLossModel> ();

  model_rn_ue->CreateChannelRealization (rnMobility, ueMobility);

  //initialize multipath model
  Ptr<JakesFadingLossModel> m = model_rn_ue->GetChannelRealization (rnMobility, ueMobility)-
>GetJakesFadingLossModel ();
  m->SetPhy (phy);
}

void
LteHelper::EnableLogComponents (void)
{
  LogComponentEnable ("LtePhy", LOG_LEVEL_ALL);
  LogComponentEnable ("EnbLtePhy", LOG_LEVEL_ALL);
  LogComponentEnable ("UeLtePhy", LOG_LEVEL_ALL);

  LogComponentEnable ("LteSpectrumPhy", LOG_LEVEL_ALL);
  LogComponentEnable ("EnbLteSpectrumPhy", LOG_LEVEL_ALL);
  LogComponentEnable ("UeLteSpectrumPhy", LOG_LEVEL_ALL);
```

```
 // LogComponentEnable ("LtePropagationLossModel", LOG_LEVEL_ALL);
 // LogComponentEnable ("LossModel", LOG_LEVEL_ALL);
 // LogComponentEnable ("ShadowingLossModel", LOG_LEVEL_ALL);
 // LogComponentEnable ("PenetrationLossModel", LOG_LEVEL_ALL);
 // LogComponentEnable ("MultipathLossModel", LOG_LEVEL_ALL);
 // LogComponentEnable ("PathLossModel", LOG_LEVEL_ALL);

  LogComponentEnable ("RrcEntity", LOG_LEVEL_ALL);
  LogComponentEnable ("MacEntity", LOG_LEVEL_ALL);
  LogComponentEnable ("EnbMacEntity", LOG_LEVEL_ALL);
  LogComponentEnable ("UeMacEntity", LOG_LEVEL_ALL);
  LogComponentEnable ("RlcEntity", LOG_LEVEL_ALL);
  LogComponentEnable ("RadioBearerInstance", LOG_LEVEL_ALL);
  LogComponentEnable ("LteMacQueue", LOG_LEVEL_ALL);

  LogComponentEnable ("LteNetDevice", LOG_LEVEL_ALL);
  LogComponentEnable ("UeNetDevice", LOG_LEVEL_ALL);
  LogComponentEnable ("EnbNetDevice", LOG_LEVEL_ALL);

  LogComponentEnable ("UeManager", LOG_LEVEL_ALL);
  LogComponentEnable ("UeRecord", LOG_LEVEL_ALL);

  LogComponentEnable ("PacketScheduler", LOG_LEVEL_ALL);
  LogComponentEnable ("SimplePacketScheduler", LOG_LEVEL_ALL);
}

} // namespace ns3
```

Appendix C

Testing and Tracing of ns-3 Simulations of ENB Site Energy Consumption and Relaying in LTE

ns-3 tracing overview

ns-3 offers a simple yet flexible framework to integrate logging and tracing functions into simulation models and to extract the contents of key model variables from various objects within the simulation environment.

Model designers can create tracing functions within their code which can registered with the ns-3 tracing subsystem and allows trace content for specific modules to be enabled or disabled within the overall simulation wrapper context.

The key parameters to be extracted from the LTE Energy model were the total power consumption reported by the energy source in joules and the CQI reported by LTE UE objects which were enabled and extracted from the trace output produced by the simulation run instances.

The following example of the ns-3 trace format is for the LTE ENB site energy consumption model:

```
0s 3 EnbEnergySource:CalculateRemainingEnergy(0x95bdcb8)
0s 3 EnergySource:CalculateTotalCurrent(0x95bdcb8)
0s 3 EnbEnergyModel:DoGetCurrentA(0x95be0a8)
0s 3 EnbEnergyModel:DoGetCurrentA(): Device Current is: 52.0833
0s 3 EnbEnergySource:CalculateRemainingEnergy(): EnbEnergySource:Previous Total Consumed Energy = 0
0s 3 EnbEnergySource:CalculateRemainingEnergy(): EnbEnergySource:Additional Consumed Energy = 0
0s 3 EnbEnergySource:CalculateRemainingEnergy(): EnbEnergySource:New Total Consumed Energy = 0
0s 3 EnbEnergySource:CalculateRemainingEnergy(): EnbEnergySource:Duration = 0
0s 3 EnbEnergySource:CalculateRemainingEnergy(): EnbEnergySource:Currrent = 52.0833
0s 3 EnbEnergySource:CalculateRemainingEnergy(): EnbEnergySource:Voltage = 48
0s 3 MapScheduler:Insert(0x95ba0f8, 0x95c7130, 5f5e100, 27)
0s 3 MapScheduler:RemoveNext(0x95ba0f8)
```

The following example of the ns-3 trace format is for the LTE UE CQI reporting model:

```
002s 0 AmcModule:GetCqiFromSpectralEfficiency(): 11
0.002s 0 AmcModule:GetCqiFromSpectralEfficiency(): 12
0.002s 0 AmcModule:GetCqiFromSpectralEfficiency(): 13
0.002s 0 AmcModule:GetCqiFromSpectralEfficiency(0x95baf70, 5.53534, 14)
0.002s 0 AmcModule:CreateCqiFeedbacks(0x95baf70, channel_id = , 100, sinr = , 23.9951, spectral efficiency =, 5.53534,  ---- CQI = , 14)
0.002s 0 AmcModule:CreateCqiFeedbacks(0x95baf70, ----AVG CQI = , 14.27)
0.002s 0 LtePhy:GetDownlinkSubChannels(0x95ba620)
0.002s 0 LtePhy:GetDownlinkSubChannels(0x95ba620)
```

ns-3 Energy Model Testing

Using flexible ns-3 wrapper programs it was possible to make automated runs through multiple testing loops while varying the key parameters of interest within the model for example, the RRU transmission power as such as the test runs detailed below.

P CARRIER dBm	**P Carrier Watts**	**P RRU CONST**	**P RRU**	**TxPowe rW**	**CQI @ UE with Relay (1000m)**	**CQI @ UE without RELAY (1000m)**	**CQI @ RELAY NODE (500m)**
40	10	100	150	350	12.92	4.88	10.96
41	13	100	165	365	12.92	5.08	11.88
42	16	100	180	380	12.92	5.88	12.04
43	20	100	200	400	12.92	6.64	12.88

P CARRIER dBm	**P Carrier Watts**	**P RRU CONST**	**P RRU**	**TxPowe rW**	**CQI @ UE with Relay (800m)**	**CQI @ UE without RELAY (800m)**	**CQI @ RELAY NODE (400m)**
40	10	100	150	350	14.96	6.96	13
41	13	100	165	365	14.96	7.6	13.84
42	16	100	180	380	14.96	7.96	14.72
43	20	100	200	400	14.96	8.64	14.92

The following is an example of the ns-3 wrapper code that creates, configures, and steers the LTE simulation model components and the traces the energy model components for a basic LTE simulation without relaying functionality.

```
//     +-----+    +-----+    +-----+
//     | UE0 |    | UE1 |    | UE2 |
//     +-----+    +-----+    +-----+
//    10.1.1.1   10.1.1.2   10.1.1.3
//     --------  --------    -------
//       ((*))    ((*))       ((*))
//
//                        1200m
//              800m
//
//       400m
//
//              10.1.1.4
//            +------------+
//            |eNB         | ==((*))
//            +------------+

#include "ns3/core-module.h"
```

```
#include "ns3/network-module.h"
#include "ns3/applications-module.h"
#include "ns3/mobility-module.h"
#include "ns3/config-store-module.h"
#include "ns3/internet-module.h"
#include "ns3/lte-module.h"
#include <iostream>
#include "ns3/global-route-manager.h"
#include "ns3/energy-module.h"

NS_LOG_COMPONENT_DEFINE ("lte-device");

using namespace ns3;

/// Trace function for total energy consumption at LTE ENB  Site.
void
TotalEnergy (double oldValue, double totalEnergy)
{
  NS_LOG_UNCOND (Simulator::Now ().GetSeconds ()
              << "s Total energy consumed by ENB Site= " << totalEnergy << "J");
}

int main (int argc, char *argv[])
{
  // default values
  int nbUE = 3;

  LteHelper lte;

  //lte.EnableLogComponents ();
 // LogComponentEnable ("UdpClient", LOG_LEVEL_INFO);
 // LogComponentEnable ("UdpServer", LOG_LEVEL_INFO);
 // LogComponentEnable ("EnergySource", LOG_LEVEL_DEBUG);
  LogComponentEnable ("EnbEnergySource", LOG_LEVEL_DEBUG);
 // LogComponentEnable ("DeviceEnergyModel", LOG_LEVEL_DEBUG);
  LogComponentEnable ("EnbEnergyModel", LOG_LEVEL_INFO);

  // CREATE NODE CONTAINER AND CREATE LTE NODES
  NodeContainer ueNodes;
  NodeContainer enbNodes;
  ueNodes.Create (nbUE);
  enbNodes.Create (1);

  // CREATE DEVICE CONTAINER, INSTALL DEVICE TO NODE
  NetDeviceContainer ueDevs, enbDevs;
  ueDevs = lte.Install (ueNodes, LteHelper::DEVICE_TYPE_USER_EQUIPMENT);
  enbDevs = lte.Install (enbNodes, LteHelper::DEVICE_TYPE_ENODEB);

  /** Energy Model **/
  /*************************************************************************/
  /* energy source */
  EnbEnergySourceHelper basicSourceHelper;
  // configure energy source
  // install source
  EnergySourceContainer sources = basicSourceHelper.Install (enbNodes);
  /* device energy model */
  EnbEnergyModelHelper enbEnergyHelper;

  enbEnergyHelper.Set("TxPowerW",DoubleValue (400));
  enbEnergyHelper.Set("IdlePowerW",DoubleValue (200));
  enbEnergyHelper.Set("RxPowerW",DoubleValue (300));
```

```
enbEnergyHelper.Set("SitePowerW",DoubleValue (2300));

// configure ENB Site energy model
// install LTE device model
DeviceEnergyModelContainer deviceModels = enbEnergyHelper.Install (enbDevs, sources);
/***************************************************************************/

// INSTALL INTERNET STACKS
InternetStackHelper stack;
stack.Install (ueNodes);
stack.Install (enbNodes);
Ipv4AddressHelper address;
address.SetBase ("10.1.1.0", "255.255.255.0");
Ipv4InterfaceContainer UEinterfaces = address.Assign (ueDevs);
Ipv4InterfaceContainer ENBinterface = address.Assign (enbDevs);

// MANAGE LTE NET DEVICES
Ptr<EnbNetDevice> enb;
enb = enbDevs.Get (0)->GetObject<EnbNetDevice> ();

Ptr<UeNetDevice> ue[nbUE];
for (int i = 0; i < nbUE; i++)
  {
    ue[i] = ueDevs.Get (i)->GetObject<UeNetDevice> ();
    lte.RegisterUeToTheEnb (ue[i], enb);
  }

// CONFIGURE DL and UL SUB CHANNELS
// Define a list of sub channels for the downlink
std::vector<int> dlSubChannels;
for (int i = 0; i < 100 ; i++)
  {
    dlSubChannels.push_back (i);
  }
// Define a list of sub channels for the uplink
std::vector<int> ulSubChannels;
for (int i = 50; i < 100; i++)
  {
    ulSubChannels.push_back (i);
  }
enb->GetPhy ()->SetDownlinkSubChannels (dlSubChannels);
enb->GetPhy ()->SetUplinkSubChannels (ulSubChannels);

for (int i = 0; i < nbUE; i++)
  {
    ue[i]->GetPhy ()->SetDownlinkSubChannels (dlSubChannels);
    ue[i]->GetPhy ()->SetUplinkSubChannels (ulSubChannels);
  }

// CONFIGURE MOBILITY
Ptr<ConstantPositionMobilityModel> enbMobility = CreateObject<ConstantPositionMobilityModel> ();
enbMobility->SetPosition (Vector (0.0, 0.0, 0.0));
lte.AddMobility (enb->GetPhy (), enbMobility);

 float distance=0;

  for (int i = 0; i < nbUE; i++)
  {
    distance = (i+1)*300;
    Ptr<ConstantPositionMobilityModel> ueMobility = CreateObject<ConstantPositionMobilityModel> ();
    ueMobility->SetPosition (Vector (distance, 0.0, 0.0));
```

```
    lte.AddMobility (ue[i]->GetPhy (), ueMobility);
    lte.AddDownlinkChannelRealization (enbMobility, ueMobility, ue[i]->GetPhy ());
  }

  /** connect LTE energy tracing sources **/
 /***************************************************************************/
 // all sources are connected to the LTE ENB node
 // energy source
 Ptr<EnbEnergySource> basicSourcePtr = DynamicCast<EnbEnergySource> (sources.Get (0));
 // device energy model
 Ptr<DeviceEnergyModel> basicEnbModelPtr =
   basicSourcePtr->FindDeviceEnergyModels ("ns3::EnbEnergyModel").Get (0);
 NS_ASSERT (basicEnbModelPtr != NULL);
 basicEnbModelPtr->TraceConnectWithoutContext ("TotalEnergyConsumption", MakeCallback
(&TotalEnergy));
 /***************************************************************************

 //******* FLOW  to UE 1 @ 57.6Mbps *********
 UdpServerHelper udpServer_1;
 ApplicationContainer serverApp_1;
 UdpClientHelper udpClient_1;
 ApplicationContainer clientApp_1;

 udpServer_1 = UdpServerHelper (100);
 serverApp_1 = udpServer_1.Install (ueNodes.Get (0));
 serverApp_1.Start (Seconds (0.00));
 serverApp_1.Stop (Seconds (2));

 udpClient_1 = UdpClientHelper (UEinterfaces.GetAddress (0), 100);
 udpClient_1.SetAttribute ("MaxPackets", UintegerValue (7200));
 udpClient_1.SetAttribute ("Interval", TimeValue (Seconds (0.0001)));
 udpClient_1.SetAttribute ("PacketSize", UintegerValue (1000));
 clientApp_1 = udpClient_1.Install (enbNodes.Get (0));
 clientApp_1.Start (Seconds (0.00));
 clientApp_1.Stop (Seconds (2));

 //******* FLOW  to UE 2 @ 19.2Mbps *********
 UdpServerHelper udpServer_2;
 ApplicationContainer serverApp_2;
 UdpClientHelper udpClient_2;
 ApplicationContainer clientApp_2;

 udpServer_2 = UdpServerHelper (100);
 serverApp_2 = udpServer_2.Install (ueNodes.Get (1));
 serverApp_2.Start (Seconds (0.00));
 serverApp_2.Stop (Seconds (2));

 udpClient_2 = UdpClientHelper (UEinterfaces.GetAddress (1), 100);
 udpClient_2.SetAttribute ("MaxPackets", UintegerValue (2400));
 udpClient_2.SetAttribute ("Interval", TimeValue (Seconds (0.0001)));
 udpClient_2.SetAttribute ("PacketSize", UintegerValue (1000));
 clientApp_2 = udpClient_2.Install (enbNodes.Get (0));
 clientApp_2.Start (Seconds (0.0));
 clientApp_2.Stop (Seconds (2));

 //******* FLOW  to UE 2 @ 9.6 Mbps *********
 UdpServerHelper udpServer_3;
 ApplicationContainer serverApp_3;
 UdpClientHelper udpClient_3;
 ApplicationContainer clientApp_3;
```

```
  udpServer_3 = UdpServerHelper (100);
  serverApp_3 = udpServer_3.Install (ueNodes.Get (2));
  serverApp_3.Start (Seconds (0.0));
  serverApp_3.Stop (Seconds (2));

  udpClient_3 = UdpClientHelper (UEinterfaces.GetAddress (2), 100);
  udpClient_3.SetAttribute ("MaxPackets", UintegerValue (1200));
  udpClient_3.SetAttribute ("Interval", TimeValue (Seconds (0.0001)));
  udpClient_3.SetAttribute ("PacketSize", UintegerValue (1000));
  clientApp_3 = udpClient_3.Install (enbNodes.Get (0));
  clientApp_3.Start (Seconds (0.0));
  clientApp_3.Stop (Seconds (2));

  std::cout << "Starting ENB Site Energy simulation.." << std::endl;
  Simulator::Stop (Seconds (1.0));

  Simulator::Run ();
  Simulator::Destroy ();
  std::cout << "Done." << std::endl;
  return 0;
}
```

The following is an example of the LTE wrapper code that creates, configures, and steers the LTE simulation model components and the traces the energy model components for a basic LTE simulation including relaying functionality.

```
//              +-----+
//              | UE1 |
//              +-----+
//             10.1.1.0
//             --------
//              ((*))
//
//
//            +------------+
//     ((*))== |RN         | ==((*))
//            +------------+
//
//
//               10.1.1.1
//            +------------+
//            |eNB         | ==((*))
//            +------------+

#include "ns3/core-module.h"
#include "ns3/network-module.h"
#include "ns3/applications-module.h"
#include "ns3/mobility-module.h"
#include "ns3/config-store-module.h"
#include "ns3/internet-module.h"
#include "ns3/lte-module.h"
#include <iostream>
#include "ns3/global-route-manager.h"
#include "ns3/energy-module.h"
NS_LOG_COMPONENT_DEFINE ("lte-device");

using namespace ns3
```

```
void
ReceivePacket (Ptr<Socket> socket)
{
  Ptr<Packet> packet;
  Address from;
  while (packet = socket->RecvFrom (from))
    {
      if (packet->GetSize () > 0)
        {
          InetSocketAddress iaddr = InetSocketAddress::ConvertFrom (from);
          NS_LOG_UNCOND ("--\nReceived one packet on socket: "<< iaddr.GetIpv4 ()
                                                << " port: " << iaddr.GetPort () << " at time = " <<
                        Simulator::Now ().GetSeconds () << "\n--");
          (void) iaddr;
        }
    }
}

// Trace function for total energy consumption at LTE ENB node.
void
TotalEnergy (double oldValue, double totalEnergy)
{
  NS_LOG_UNCOND (Simulator::Now ().GetSeconds ()
               << "s Total energy consumed by eNodeB site = " << totalEnergy << "J");
}

int main (int argc, char *argv[])
{

  LteHelper lte;

 // lte.EnableLogComponents ();
 // LogComponentEnable ("UdpClient", LOG_LEVEL_INFO);
  //LogComponentEnable ("UdpServer", LOG_LEVEL_INFO);
 // LogComponentEnable ("lte-device", LOG_LEVEL_INFO);
 // LogComponentEnable ("LteSpectrumPhy", LOG_LEVEL_INFO);
 // LogComponentEnable ("EnbLtePhy", LOG_LEVEL_INFO);


  // CREATE NODE CONTAINER AND CREATE LTE NODES

  NodeContainer enbNodes;
  NodeContainer ueNodes;
  NodeContainer rnNodes;
  enbNodes.Create (1);
  rnNodes.Create (1);
  ueNodes.Create (1);


  // CREATE DEVICE CONTAINER, INSTALL DEVICES TO NODE
  NetDeviceContainer ueDevs, enbDevs, rnDevs;
  enbDevs = lte.Install (enbNodes, LteHelper::DEVICE_TYPE_ENODEB);
  rnDevs = lte.Install (rnNodes, LteHelper::DEVICE_TYPE_DFRN);
  ueDevs = lte.Install (ueNodes, LteHelper::DEVICE_TYPE_USER_EQUIPMENT);



/** Energy Model **/
  /*****************************************************************************/
  /* energy source */
  EnbEnergySourceHelper basicSourceHelper;
```

```
// configure ENB Site energy source
// install source
EnergySourceContainer sources = basicSourceHelper.Install (enbNodes);
/* device energy model */
EnbEnergyModelHelper enbEnergyHelper;
enbEnergyHelper.Set("TxPowerW",DoubleValue (200));
enbEnergyHelper.Set("IdlePowerW",DoubleValue (200));
enbEnergyHelper.Set("RxPowerW",DoubleValue (300));
enbEnergyHelper.Set("SitePowerW",DoubleValue (2300));
// configure radio energy model
// install device model
DeviceEnergyModelContainer deviceModels = enbEnergyHelper.Install (enbDevs, sources);
/*****************************************************************************/
// INSTALL INTERNET STACKS
InternetStackHelper stack;
stack.Install (ueNodes);
stack.Install (enbNodes);
Ipv4AddressHelper address;
address.SetBase ("10.1.1.0", "255.255.255.0");
Ipv4InterfaceContainer ENBinterface = address.Assign (enbDevs);
Ipv4InterfaceContainer UEinterfaces = address.Assign (ueDevs);

// MANAGE LTE NET DEVICES
Ptr<EnbNetDevice> enb;
Ptr<RnNetDevice> rn;
Ptr<UeNetDevice> ue;


enb = enbDevs.Get (0)->GetObject<EnbNetDevice> ();
rn  = rnDevs.Get (0)->GetObject<RnNetDevice> ();
ue  = ueDevs.Get (0)->GetObject<UeNetDevice> ();

lte.RegisterUeToTheRn (ue, rn);

lte.RegisterRnToTheEnb (rn, enb);

// CONFIGURE DL and UL SUB CHANNELS
// Define a list of sub channels for the downlink
std::vector<int> dlSubChannels;
for (int i = 0; i < 25; i++)
  {
    dlSubChannels.push_back (i);
  }
// Define a list of sub channels for the uplink
std::vector<int> ulSubChannels;
for (int i = 50; i < 100; i++)
  {
    ulSubChannels.push_back (i);
  }

enb->GetPhy ()->SetDownlinkSubChannels (dlSubChannels);
enb->GetPhy ()->SetUplinkSubChannels (ulSubChannels);

rn->GetPhy ()->SetDownlinkSubChannels (dlSubChannels);
rn->GetPhy ()->SetUplinkSubChannels (ulSubChannels);

rn->GetRelayPhy ()->SetDownlinkSubChannels (dlSubChannels);
rn->GetRelayPhy ()->SetUplinkSubChannels (ulSubChannels);

ue->GetPhy ()->SetDownlinkSubChannels (dlSubChannels);
ue->GetPhy ()->SetUplinkSubChannels (ulSubChannels);
```

```
  // CONFIGURE MOBILITY
  Ptr<ConstantPositionMobilityModel> enbMobility = CreateObject<ConstantPositionMobilityModel> ();
  Ptr<ConstantPositionMobilityModel> rnMobility = CreateObject<ConstantPositionMobilityModel> ();

  enbMobility->SetPosition (Vector (0.0, 0.0, 0.0));
  rnMobility->SetPosition (Vector (1000.0, 0.0, 0.0));

  lte.AddMobility (enb->GetPhy (), enbMobility);

  lte.AddMobility (rn->GetPhy (), rnMobility);
  lte.AddMobility (rn->GetRelayPhy (), rnMobility);

    Ptr<ConstantPositionMobilityModel> ueMobility = CreateObject<ConstantPositionMobilityModel> ();
    ueMobility->SetPosition (Vector (1000.0, 0.0, 0.0));

    lte.AddMobility (ue->GetPhy (), ueMobility);

     lte.AddDownlinkChannelRealization (enbMobility, rnMobility, enb->GetPhy ());
     lte.AddRelayDownlinkChannelRealization (rnMobility, ueMobility, rn->GetRelayPhy ());

  /**************************************************************************/
  // all sources are connected to node 1 which is the ENB
  // energy source
  Ptr<EnbEnergySource> basicSourcePtr = DynamicCast<EnbEnergySource> (sources.Get (0));
  // device energy model
  Ptr<DeviceEnergyModel> basicEnbModelPtr =
    basicSourcePtr->FindDeviceEnergyModels ("ns3::EnbEnergyModel").Get (0);
  NS_ASSERT (basicEnbModelPtr != NULL);
  basicEnbModelPtr->TraceConnectWithoutContext ("TotalEnergyConsumption", MakeCallback
(&TotalEnergy));
  /**************************************************************************/

    //CREATE A DOWNLINK RADIO BEARER (RAB)
  Ptr<RadioBearerInstance> bearer = CreateObject<RadioBearerInstance> ();
  bearer->SetBearerDirection (RadioBearerInstance::DIRECTION_TYPE_DL);
  bearer->SetBearerType (RadioBearerInstance::BEARER_TYPE_DRB);

  IpcsClassifierRecord *ipcs = new IpcsClassifierRecord (UEinterfaces.GetAddress (0),
                                         "255.255.255.0",
                                         ENBinterface.GetAddress (0),
                                         "255.255.255.0",
                                         100, 100, 0, 10000, 17, 1);
  bearer->SetIpcsClassifierRecord (ipcs);

  enb->GetRrcEntity ()->AddDownlinkNgbrBearer (bearer);

  bearer = 0;

    /** simulation setup **/

  Simulator::Stop (Seconds (1.00));
  Simulator::Run ();
  Simulator::Destroy ();

  delete ipcs;

  return 0;
}
```