Power-Capacity-Tradeoff for Low Energy Interference Limited Cellular Networks

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***Abstract*— This paper uses simulation results to analyze the fundamental tradeoff between the total operational power consumption and the downlink capacity in an interference limited LTE network. The paper shows that existing techniques of improving spectral and transmission energy efficiency in a fixed deployment can not reduce the total energy consumption beyond a certain limit, 35%.**

In order to achieve greater energy savings, a re-deployment of the cells is needed. The paper employs a novel power consumption vs. capacity tradeoff to assist the process of re-deployment and show that up to 75% energy can be saved. The paper considers a number of techniques and the results are derived from a dynamic multi-cell and multi-user system simulator that considers adaptive modulation and coding, as well as full interference modelling. The implication of this paper's results has a significant impact both on commercial revenue and the environment by reducing up to 24 power plants world wide.

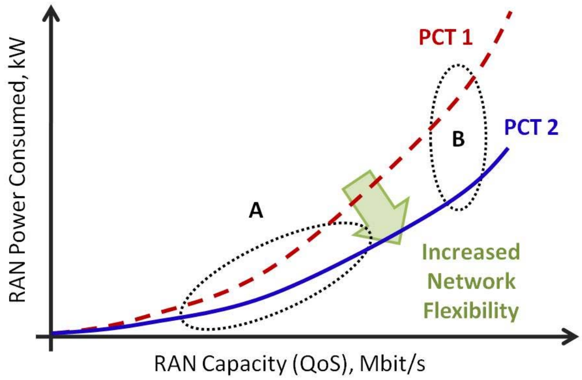

Fig. 1. Re-deployment Plot: Power-Capacity-Tradeoff (PCT) shows that by increasing the flexibility of the network, the tradeoff relationship can be improved.

I. Introduction

Conventionally, cellular networks have been primarily designed to meet the challenges of service quality. However, in the past decade, there is increasing attention on the importance of energy consumption, both from an operational expenditure (OPEX) point of view and from a climate change perspective. On average, the traffic volume has increased by more than a factor of 10 in the last five years and the associated energy consumption by 16 to 20%. The majority ($\sim$ 80%) of this energy is consumed in the base-stations and the back-haul of the radio access network (RAN).

A. Challenges

Existing work has focused on transmission techniques that improve spectral and transmission efficiency [1] [2]. For a given cell, the energy reduction this can achieve is limited by a fundamental ratio which is a function of the transmission power and the overhead pedestal power consumption. In order to achieve greater downlink capacity or lower energy consumption, the density of the cell deployment can be varied [3] [4] [5]. By increasing the cell density, both the capacity and RAN power consumption is increased. This is an **improvement** over existing work which assumes the following:

- Simplified or No interference modeling is assumed [3] [1] [4] [2]
- Neglects the overhead power of base-stations [6] [7]
- Neglects capacity saturation of realistic modulation and coding schemes [8] [2]. This not only gives over-optimistic performance results, but can yield misleading optimization results [9].

B. Proposed Solutions

The *novel* **Power-Capacity-Tradeoff (PCT)** is proposed in this paper and it characterizes a changing deployment of different cell densities. The tradeoff employs full interference modeling, a full power consumption model and realistic modulation and coding schemes. The relationship is useful for determining what the lowest energy deployment is for a given offered traffic load. In Fig. 1, the notions of the PCT tradeoff is demonstrated: increased system flexibility can improve the tradeoff characteristics (PCT 1 transforms to PCT 2). Introducing flexibility through optimizing parameters and introducing new elements, can be seen as adding extra **degrees of freedom** in the network, which is any independent parameter. The salient operating regions shown are:

- *Region A (Low Capacity)* shows that a large increase in capacity requires a small increase in Power consumed.
- *Region B (High Capacity)* shows that a small increase in capacity requires a large increase in Power consumed.

The challenge is, can we operate at a High Capacity region, but be more power efficient?

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TABLE I

SYSTEM PARAMETERS FOR VCESIM SIMULATOR.

LTE System Parameters		
Parameter	**Symbol**	**Value**
LTE Operating Frequency	f_{LTE}	2600MHz
LTE System Bandwidth	BW_{LTE}	**5MHz**, **20MHz**
Subcarrier Size	BW_{sc}	15kHz
HSPA System Parameters		
HSPA Operating Frequency	f_{HSPA}	2200MHz
HSPA System Bandwidth	BW_{HSPA}	**5MHz**
HSPA Chip Rate	$BW_{HSPA,CR}$	3.84Mc/s
Deployment Parameters		
Cell Radius	r_{cell}	200-1500m
Cell Max. Tx Power	P_{cell}	varies (6 to 40W)
No. of sectors per cell	N_K	1,3,6
No. of antennas per sector	N_A	1,2
Cell Antenna Pattern	A	(1)
Cell Antenna Down-tilt	T	0-20 degrees
Cell antenna Height	H_{cell}	10-35m
Relay Receiver Sensitivity	S_{relay}	5dB
Relay Max. Tx. Power	P_{relay}	1W
Relay antenna Height	H_{relay}	5m
Common Parameters		
Propagation Model	λ	WINNER II Urban [12]
Pathloss Exponent	α	2.2 to 3.7 [12]
Pathloss Constant	K	4.6×10^{-4}
Offered Traffic Rate	$R_{traffic}$	6-120 Mbit/s/km^2
Traffic Load	L	Full Buffer ($L = 1$)
UE Downlink QoS	R_{QoS}	1Mbit/s
UE antenna Height	H_{UE}	1.5m
AWGN	n_0	4×10^{-21} W/Hz
UE Noise Figure	n_{UE}	6dB
Mobility Model	$Mobility$	Brownian Motion

TABLE II

POWER CONSUMPTION FOR MACRO TO PICO-CELLS AND RELAYS (2010) [14] [15]

Power Consumption per Antenna (Full Load)				
	Macro	Micro	Pico	Relay
Cell Radius, m	>1000	400-1000	<400	N/A
Max. Tx Power, P_{cell}^{max}	40W	20W	6W	1W
RF Efficiency, μ_Σ	0.25	0.25	0.18	0.1
Radio-head Power, P_{cell}^{RH}	160W	80W	33W	10W
Overhead Power, P_{cell}^{OH}	84W	68W	40W	10W
Operational Power, P_{cell}^{OP}	244W	148W	73W	20W
Sleep Mode Power, P_{cell}^{Sleep}	42W	34W	20W	5W

II. SYSTEM MODEL

A. System Simulator

The system simulator is the **VCESIM**, which is a proprietary LTE dynamic system simulator developed at the University of Sheffield for industrial and academic members of the Mobile Virtual Centre of Excellence (MVCE). The combined system and link performance is validated against results in [10] and the parameters are given in Table I.

The associated antenna patterns employed are as follows. In the case when the cell-sites have a single omni-directional antenna, the antenna gain is unity. In the case when the cell-sites each have 3 or 6 horizontal sectors, the antenna gain (dB) is [11]:

$$\begin{aligned} A_{cell} &= A_{bs} - \min[-A_a(\theta_a) - A_e(\theta_e)] \\ A_a(\theta_a) &= \min[12(\frac{\theta_a}{\theta_{3dB,a}})^2, 25] \\ A_e(\theta_e) &= \min[12(\frac{\theta_e}{\theta_{3dB,e}})^2, 20], \end{aligned} \quad (1)$$

for an angle θ_a on the azimuth and an angle θ_e on the elevation plane from the bore-sight direction. The bore-sight gain is $A_{bs} = 17.6dBi$. For a 3 sector antenna, $\theta_{3dB,a} = 75$ degrees and $\theta_{3dB,e} = 20$ degrees. For a 6 sector antenna: $\theta_{3dB,a} = 60$ degrees and $\theta_{3dB,e} = 20$ degrees.

B. Link Level Capacity

For an OFDMA system (such as LTE), the downlink received SINR ($\gamma_{s,i}$) in a sub-carrier s in cell i is calculated as a function of the transmit power (P_s), antenna gain (A), interference cells j, AWGN (N_0), log-normal shadowing ($\mathcal{S}$) and multipath fading gain (h):

$$\gamma_{s,i} = \frac{|h_k|^2 \lambda_i 10^{\frac{S_i + A}{10}} P_{s,i}}{n_0 n_{UE} + \sum_{j=1, j\neq i}^{N_{cell}} |h_i||h_j| \lambda_j 10^{\frac{S_j + A}{10}} P_{s,j}}, \quad (2)$$

where the parameters values are defined in Table. I and the pathloss component as a function of distance (d) is $\lambda(d) = Kd^{-\alpha}$. Log-normal shadow fading is defined as $\mathcal{S} = \mathcal{N}(0, \sigma^2_{shadow})$. The paper employs the appropriate adaptive modulation and coding scheme given by internal link level simulators and verified against [13].

C. Energy Consumption

A general cell-site power consumption model for N_K sectors and N_A transmit antennas per sector is:

$$P_{cell}^{OP} = N_K N_A (\frac{P_{cell}^{out}}{\mu_\Sigma} L + P_{cell}^{OH}) + P_{BH}, \quad (3)$$

where μ_Σ largely depends on the power-amplifier efficiency, and the radio-head power can be defined as: $P_{cell}^{RH} = \frac{P_{cell}^{out}}{\mu_\Sigma} L$, and the backhaul power consumption per cell is $P_{BH} = 50W$. The power consumption of different cell sizes is presented in Table. II.

Consider a RAN with users demanding a traffic load of M bits of data over a finite time duration of T_{RAN}^{OH}. In order to compare two systems, a useful metric is the Energy Reduction Gain (ERG), which is the percentage reduction in energy consumption when a test system is compared with a reference system [16]:

$$\begin{aligned} \text{ERG}_{RAN}^{OP} &= 1 - \frac{E_{RAN,test}^{OP}}{E_{RAN,ref.}^{OP}} \\ &= 1 - \frac{\sum_n^{N_{test}} P_{n,test}^{RH} \frac{R_{traffic}}{R_{RAN,test}} + P_{n,test}^{OH}}{\sum_n^{N_{ref.}} P_{n,ref.}^{RH} \frac{R_{traffic}}{R_{RAN,ref.}} + P_{n,ref.}^{OH}}, \end{aligned} \quad (4)$$

where the capacity of the system is defined as $R_{RAN,i} = M/T_{RAN}^{RH,i}$, which is greater or equal to the offered load: $R_{traffic} = M/T_{RAN}^{OH}$.

The term $\frac{P_n^{RH,i}}{R_{RAN,i}}$ in (4) is an indication of the average radio transmission efficiency, which does not consider the overhead energy. This is commonly used to measure energy consumption in the literature [6], and is known as the Energy-Consumption-Ratio (ECR). **This shows how existing work, which only considers transmission energy, can be encompassed into the full energy metric.**

D. Constant Deployment Upper Bound

For a given deployment, by improving the transmission energy efficiency, the greatest energy reduction that can be achieved from (4) is therefore:

$$\mathrm{ERG}_{RAN}^{\text{RH Limit}} = 1 - \frac{\sum_n^{N_{test}} P_{n,test}^{OH}}{\sum_n^{N_{ref.}} P_{n,ref.}^{RH} \frac{R_{traffic}}{R_{RAN,ref.}} + P_{n,ref.}^{OH}}. \quad (5)$$

That is to say, given the power consumption values presented in Table. II, if the capacity or transmission efficiency improvement was infinite and subsequently reduced the radio-head power consumption to zero, only 50 to 65% operational energy reduction gain can be achieved. In reality the overall energy savings achieved by a single technique is significantly less and in order to increase the saving, a redeployment is needed.

III. Homogeneous Network

A. LTE vs. HSPA

The paper first establishes a reference HSPA system, which is currently deployed in many countries. The HSPA system is a tri-sectorized deployment employing 2x2 SFBC MIMO. We compare this with an LTE baseline system that employs a similar deployment. Our results agree with existing literature that LTE can improve the capacity by an average of 55% compared to LTE for micro-macro cell densities and more for higher cell densities [10]. The resulting **constant deployment energy reduction is 35%**.

The paper now considers the re-deployment of the cell-sites in Fig. 2a. The **re-deployment energy reduction is 50%**, primary due to the increased spectral efficiency of LTE, which allow fewer cell-sites required for a given area. The energy saving can be further reduced by jointly optimizing the antenna height and tilt, to produce around 3 to 8% operational energy reduction.

B. Sectorization and Frequency Reuse

Whilst approximately 50% energy can be saved by deploying LTE instead of HSPA, it is less clear what the low energy architecture for LTE is. The paper now considers what combination of sectorization and frequency reuse pattern can yield the lowest energy consumption architecture for a variety of targeted RAN capacity levels. The combinations investigated are as follows:

- 1, 3 and 6 Horizontal Sectors per Cell-site with Frequency Reuse Pattern 1 and 3
- 2 Vertical Sets of 3 Horizontal Sectors with Frequency Reuse Pattern 1, 3, VS1 and VS3,

where frequency patterns VS2 and VS6 mean that each vertical set employs an orthogonal reuse pattern of 1 and 3 as shown in Fig. 3a.

The key **re-deployment** results are as follows with 3 sectors (reuse 1) as reference network [10]:

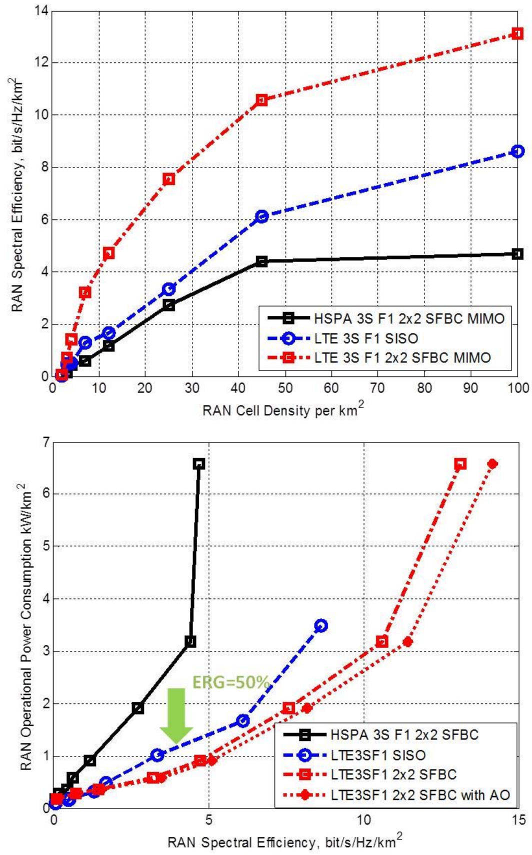

Fig. 2. a) Capacity vs. Cell Density graph and b) Power-Capacity-Tradeoff (PCT) graph for HSPA and LTE deployments. Nomenclature for graphs are as follows: 3S refers to 3 sectors, 1F refers to frequency reuse pattern 1, and AO refers to antenna parameter optimization.

- Re-deploying to a **denser** deployment of omni-directional single sector pico cell-sites can yield 10 to 30% lower energy consumption across different loads.
- Re-deploying to a **sparser** deployment of macro cell-sites, increased vertical sectorization can yield 15% lower energy consumption at high loads.
- Re-deploying to a **sparser** deployment of macro cell-sites, increased horizontal sectorization can yield 35% higher energy consumption at high loads.

In summary, the denser deployment of single sector 2x2 SFBC cell-sites will yield the lowest energy RAN across a variety of targeted downlink capacities. It has also shown that increased vertical sectorization is more energy efficient than increased horizontal sectorization. Without re-deployment, it is difficult to yield meaningful energy savings when the overhead power consumption is included.

C. Sleep Mode

The paper also considers a conventional sleep mode scheme whereby cell-sites are switched off when no users are attached, and a proportion of the overhead power remains active [16]. The resulting improvement depends on the ratio between the user density and the cell density. The results show that as the load decrease and as the cell density increases, sleep mode

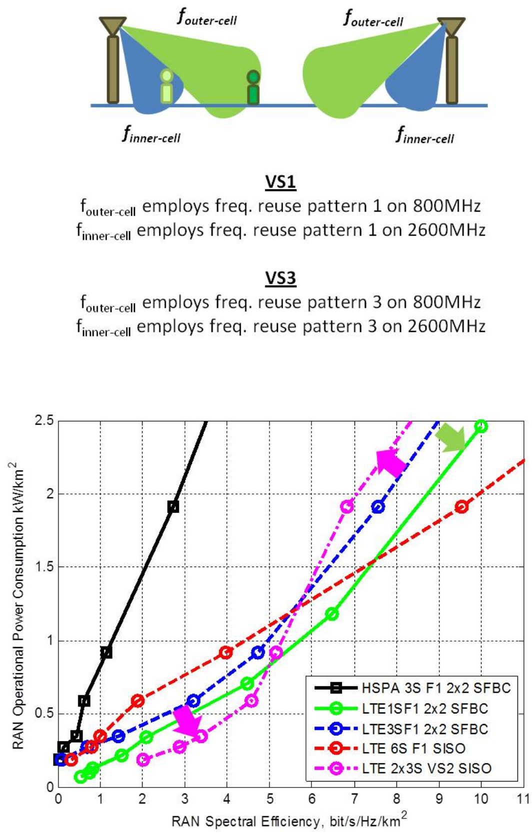

Fig. 3. a) Vertical Sectorization Frequency Reuse Pattern and b) Power-Capacity-Tradeoff (PCT) graph for HSPA and LTE deployments with different sectorization and frequency reuse patterns.

becomes more effective. The results in Fig. 4 show that the energy saved can be up to 25% for a dense deployment of cells that satisfy a high load, but experience a low load. However, generally speaking the energy reduction is around 1 to 3% for a fully loaded deployment.

IV. Heterogeneous Network with Relays

In an interference limited network, the cell-edge users receive the lowest downlink throughput. This often leads to the greatest contributor to transmission energy inefficiency, as a large number of resource blocks is dedicated to satisfying the cell-edge Quality-of-Service (QoS). This part of the paper compares wireless relay deployment against 2x2 SFBC MIMO deployment. Specifically, we consider the following scenarios:

- A dense deployment of Omni-directional single sector cell-sites with either 2x2 SFBC MIMO or 3 Directional Relays per cell-site deployed on the cell-edge.
- A sparse deployment of Tri-sector cell-sites with either 2x2 SFBC MIMO or 6 Omni-directional Relays per cell-site deployed on the cell-edge.

A. Wireless Relay Deployment

We consider co-frequency wireless decode-and-forward (DF) relays, where the capacity of the relay-UE channel is

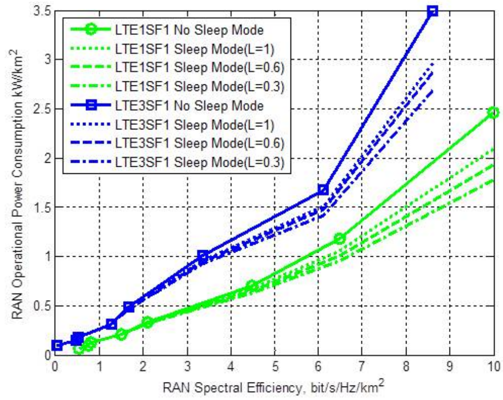

Fig. 4. Power-Capacity-Tradeoff (PCT) graph for LTE deployments with sleep mode for different loads.

limited by the minimum of the capacity between the cell-relay and relay-UE channel [17]:

$$C_{\text{relay}} = \min(C_{\text{cell-relay}}, C_{\text{relay-UE}}). \tag{6}$$

The tradeoff is that the conventional cell-edge performance is improved, but the consequence is that new cell-edge zones are created between the relays and the cell-sites. The location of the relays are deployed to complement the cell-edges that arise from both intra and inter-cell interference. As shown in Fig. 5a, up to 3 directional relays per cell-site is needed to cover the hexagonal shaped cell-edge of an omni-directional cell. For tri-sector cell-sites with frequency reuse 1, up to 6 omni-directional relays are required to cover the cell-edges.

B. Relay vs. MIMO Results

The re-deployment results in Fig. 5b show that only the 3-Sector deployment benefits from relays, and single-sector cell-sites save more energy from MIMO transmission. The key results are:

- For a dense deployment of single sector cell-sites, employing 2x2 SFBC MIMO consumes 50% less energy than deploying relays.
- For a sparse deployment of 3-sector cell-sites, employing relays consumes 15% less energy than 2x2 SFBC MIMO.
- A sparse deployment of 3-sector cell-sites with relays has a similar Power-Capacity-Tradeoff to a dense deployment of single sector cell-sites employing 2x2 SFBC MIMO.

V. Discussion

The results of this paper has shown that there is a fundamental limit to the achievable energy saving for a constant deployment. Whilst this value is theoretically 50 to 65%, it would require a near infinite improvement in spectral efficiency. In reality only approximately 35% energy saving can be achieved. However, re-deployment by changing the cell density to achieve the same capacity but with different number and configuration of cell-sites can achieve greater energy reductions. Through re-deployment, LTE can consume 50% less energy than HSPA, and furthermore two low energy LTE architectures have emerged:

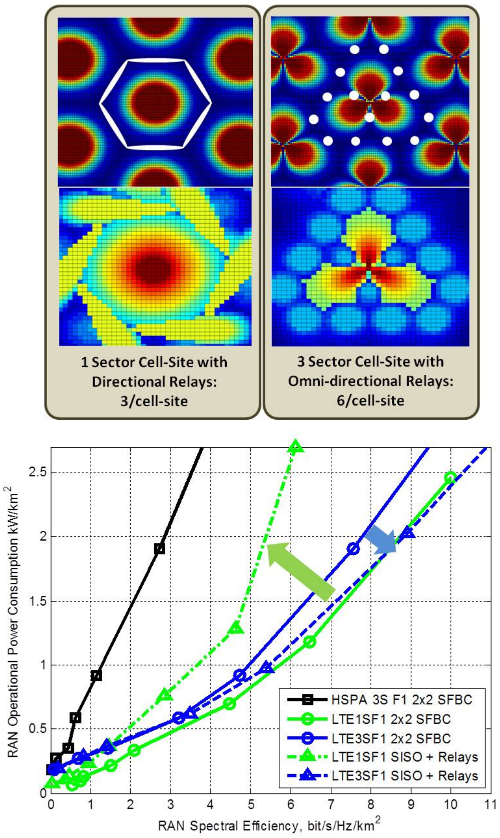

Fig. 5. a) Relay Deployment Pattern and b) Power-Capacity-Tradeoff (PCT) graph for HSPA and LTE deployments with different sectorization and frequency reuse patterns.

- A dense deployment of low power single sector cell-sites employing 2x2 SFBC MIMO
- A sparse deployment of high power tri-sector cell-sites employing cell-edge wireless relays

Their energy saving compared to the reference LTE deployment is 30% and HSPA deployment is 65%. If re-deployment is not considered, the energy reduction is not greater than 35 to 40%.

In our previous work [16], a comprehensive sensitivity analysis was made, which considered: power amplifier efficiency, transmit power, mobility model, interference and pathloss models. It was found that each one of these parameters can have up to 100% effect on the energy saving obtained. In particular, power amplifier efficiency and interference modeling can affect the results the most.

VI. Conclusions

This paper has shown that for a given deployment, existing techniques that improve spectral and transmission energy efficiency can only reduce the overall operational energy consumption by 35 to 40%. However, by re-deploying the cell-sites the energy saving can be increased significantly. This can be done with the aid of the Power-Capacity-Tradeoff (PCT) plots, which has been shown for a variety of techniques. The combined energy saving for deploying a low energy LTE architecture compare to the HSPA baseline is 65%. Scaling this energy saving globally leads to a reduction of 24 2000MW power plants.

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