Capacity-Energy-Cost Tradeoff in Small Cell Networks

Weisi Guo, Tim O'Farrell
Department of Electronic and Electrical Engineering
University of Sheffield, United Kingdom
Email: {w.guo, t.ofarrell}@sheffield.ac.uk

***Abstract*— Wireless communications has been recognized as a key enabler to the growth of the future economy. There is an unprecedented growth in data volume and the associated energy consumption in the Information and Communications Technology (ICT) infrastructure. The challenge addressed in this paper is how to meet the growth in data traffic, whilst reducing both the cost and energy consumed. The paper shows that small cell deployments can significantly reduce energy consumption (30%), but increase the network cost (14%). The novel characterization of the tradeoff between Capacity, Energy and Cost (CEC) is of importance to researchers and operators.**

I. Introduction

Over 1.4 billion users are connected to the cellular network with over 3 million base-stations. Globally, this infrastructure consumes approximately 0.5% of the worlds total energy, as shown in Fig. 1. Roughly 70% of this energy is consumed by the outdoor base-stations and this value has risen by at least 20% over the past 5 years [1]. The global cellular RAN consumes 60TWh of electricity, which is the equivalent output of 3-4 2000MW power plants and the consumption level of 20 million developed world households. The utility bill for the network operators stands at over $10 billion in 2010-11.

In the face of increasing data demand and uncertain revenue trends, operators are looking at ways to reduce the running costs in order to improve their competitiveness [2] [3]. Many operators are also pledging to reduce carbon emissions, i.e., Vodafone aims to reduce CO_2 emissions by 50% in developed markets by 2020 [4].

A. Small-Cell Networks

There is a trend of increased urbanization in the world, with a global average of 50% and a developed world average of 80% of population living in cities. The paper will focus on how to reform the cellular network in urban environments, which typically have a dense number of users with a low mobility speed. Traditionally, the network deployment is fairly homogeneous and the reference deployment is typically 500m radius sectorized micro-cells with a density of 2 cell-sites per sq km. By deploying a denser number of pico-cells at 10 cell-sites per sq km, the capacity can be improved significantly, this is known as **Small-Nets**. What has not been considered is what the relationship between capacity, energy consumption and total cost of a deployment is.

Existing work published in [3] [5] [6] [7] has considered the economic cost of various 3G, 802.11 and 4G deployments.

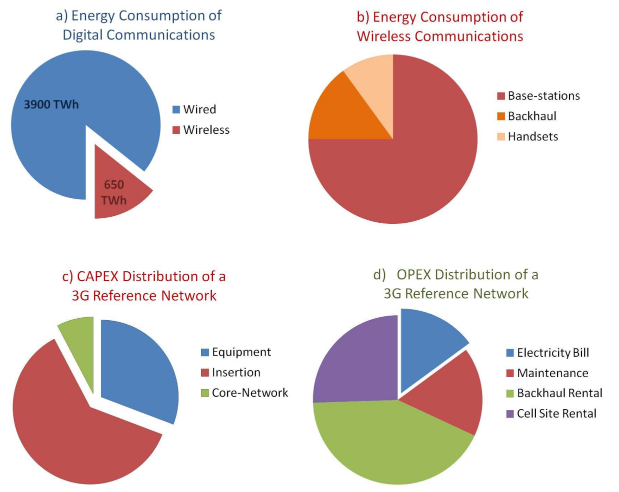

Fig. 1. Energy Consumption of a) ICT and b) Wireless Communications as of 2008-2010. A single UK cellular network typically consumes 40MW. Cost Distribution for a typical 3G Network: c) CAPEX, d) OPEX.

The cost saving has been conducted in terms of achieving a certain capacity and minimizing the deployment-operation cost. Regarding the energy efficiency of cellular networks, this has been extensively studied both theoretically [8] and through simulations [9]. However, existing literature often over-simplifies the role of capacity saturation, interference [8] [10] and energy-cost models [3]. This can lead to misleading optimization results, as shown in [11].

B. Proposal

Global annual electricity bills ($10 billion) make up approximately 45% of the operational and maintenance (O&M) bills ($22 billion), which excludes rental and spectrum payments (Fig. 1). Therefore, examining the relationship between reducing energy consumption and cost levels, for a given offered traffic load is important and novel. The paper first considers the body of investigation in Section II and introduces the energy and cost consumption models in Sections III and IV. The proposal is to first examine the small cell network deployment that can achieve a certain required offered traffic load. The energy consumption and cost analysis is then performed. The results showing capacity, energy efficiency and cost efficiency is then analyzed and optimized in Section V, and the Capacity-Energy-Cost (CEC) Tradeoff is considered in Section VI.

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TABLE I
SYSTEM PARAMETERS FOR VCESIM SIMULATOR.

LTE System Parameters		
Parameter	**Symbol**	**Value**
LTE Operating Frequency	f	2600MHz
LTE System Bandwidth	BW	20MHz
Subcarrier Size	BW_{sc}	15kHz
Base-station Antenna Power	P_{cell}	6 to 40W
Common Parameters		
Cell Radius	r_{cell}	200-1500m
Inter-cell-site Distance	d_{cell}	$1.5r_{cell}$
UE antenna Height	H_{UE}	1.5m
UE Speed	v_{UE}	2m/s
Cell antenna bore-sight	A_0	17.6dBi
Cell antenna Height	H_{cell}	10-35m
Antenna patterns	A	Fig. 2
Antenna Down-tilt	T	0-20 degrees
AWGN (1 sided PSD)	n_0	4×10^{-21} W/Hz
UE Noise Figure	n_{UE}	6dB
Offered Traffic Rate	$R_{traffic}$	30-120 Mbit/s/km^2
UE QoS	R_{QoS}	1Mbit/s
Pathloss Model	λ	WINNER II
Shadow Fading standard deviation	σ_{shadow}	4,8dB
Theoretical Parameters		
Pathloss Exponent	α	3.7
Pathloss Constant	K	4.6×10^{-4}

II. BODY OF INVESTIGATION

The experiment is conducted using a proprietary simulator (VCESIM) developed at the University of Sheffield for the Mobile Virtual Centre of Excellence (MVCE)s industrial and academic members. The simulator considers: multiple user mobility, multiple cells with antenna patterns, full interference modeling, scheduling, modulation and coding schemes, and realistic cell power consumption and economic cost models. The simulation and theoretical parameters are given in Table I, the antenna pattern used in simulations is given in Fig. 2. The power consumption and economic cost models are given in Fig. 4 and Table II respectively, which will be explained in more detail later on. Furthermore, the simulation results are reinforced with a novel theoretical framework.

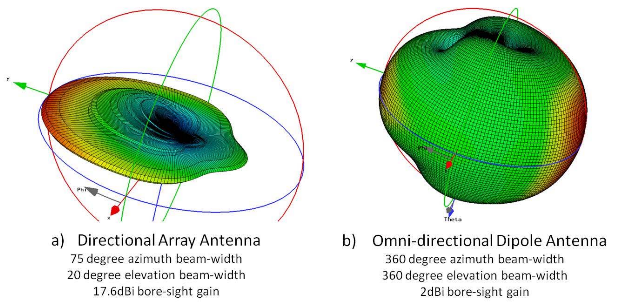

Fig. 2. 3D Antenna Plots for a) Directional sectorized-cell antenna and b) Omni-directional cell antenna.

III. ENERGY AND CAPACITY MODELS

A. Capacity Theory

The paper now introduces the theory of how the capacity and energy savings can be calculated theoretically to yield an approximate notion. Accurate simulation results are presented

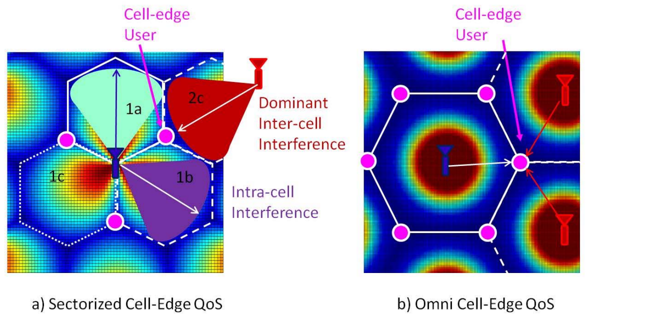

Fig. 3. The downlink QoS is defined by the cell edge performance. The dominant inter and intra-cell interference is illustrated with the average received SINR map for: a) Reference Sectorized Deployment; b) Small-Net Omni-directional Deployment.

later on in the paper, and are shown to match these theoretical estimates. A theoretical azimuth antenna pattern is defined, whereby for an angle of θ from the antenna bore-sight, the antenna gain is given by:

$$A(\theta) = A_{bs} - 12(\frac{\theta}{\theta_{3dB}})^2, \tag{1}$$

where the beam-width is defined by the 3dB angle ($\theta_{3dB} = 75^o$), the antenna bore-sight gain is $A_{bs} = 17.6dBi$ and the elevation antenna pattern is ignored. This pattern matches the realistic antenna patterns shown in Fig. 2.

As shown in Fig. 3b, the **reference** Quality-of-Service (QoS) is based on the cell-edge downlink throughput of a cell, which can be written as:

$$\begin{aligned} C_{cell,3} &\approx 3\text{BW}\log_2(1 + \frac{F10^{\frac{A(60)}{10}}(\frac{r_{cell}}{2})^{-\alpha}}{10^{\frac{A(0)}{10}}r_{cell}^{-\alpha} + 10^{\frac{A(60)}{10}}(\frac{r_{cell}}{2})^{-\alpha}}) \\ &= 3\text{BW}\log_2(1 + 0.67\frac{9.8(0.5)^{-\alpha}}{57.5 + 9.8(0.5)^{-\alpha}}) = 1.64\text{BW}, \end{aligned} \tag{2}$$

where BW is the bandwidth available in a cell-sector, and r_{cell} is the radius of the cell. In order to avoid over-optimistic results and biased optimization [11], the term $F = 0.67$ is an adjustment factor for LTE [12]. The AWGN is assumed to be negligible in comparison with interference and all cells transmit at the same power level. A similar expression for 1 sector omni-directional pico-cells can be written as:

$$\begin{aligned} C_{cell,1} &\approx \text{BW}\log_2(1 + \frac{F(r_{cell})^{-\alpha}}{2(r_{cell})^{-\alpha}}) \\ &= \text{BW}\log_2(1 + 0.67\frac{1}{2}) = 0.4\text{BW}. \end{aligned} \tag{3}$$

B. Power Consumption Model

The theoretical framework employs a novel power consumption expression that vary with cell size and load. As shown in Fig. 4, based on data from [13], the **power consumption** model for a cell with N_a antennas is:

$$\begin{aligned} P_{cell} &= N_a(\frac{P_{max}}{\mu_{RH}}L + P_{cell}^{OH}) + P_{BH} \\ &\approx N_a(0.1r_{cell}L + r_{cell}^{0.62} + 50), \end{aligned} \tag{4}$$

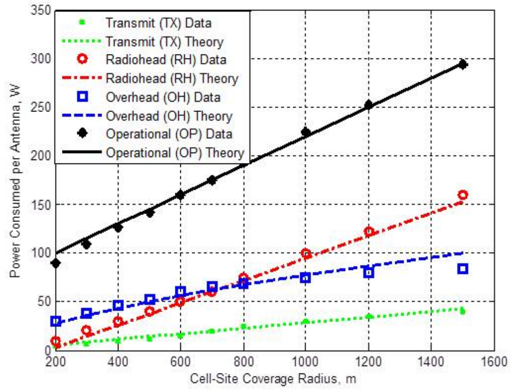

Fig. 4. Power Consumption Data variation with cell size, data from [13] and theory from expression (4).

, which has been further improved as a function of cell size (r_{cell}) to fit empirical data from [13], as shown in Fig. 4. The parameter $P_{max} \approx \frac{r_{cell}}{35}$ is the maximum transmit power. The load of the cell is defined as the ratio between the instantaneous offered traffic in the cell and the maximum capacity of the cell: $L = \frac{R_{\text{traffic}}}{R_{\text{cell}}}$. The radio-head power can be defined as: $P^{RH}_{cell} = \frac{P_{max}}{\mu_{RH}} L$ and the backhaul power consumption per cell is $P_{BH} = 50W$.

C. Energy Saving Bounds

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 RAN is compared with a reference RAN:

$$\text{ERG}_{RAN} = 1 - \frac{N_{cell,test} P_{cell,test}}{N_{cell,ref.} P_{cell,ref.}}. \tag{5}$$

There are **two fundamental energy saving limits** that can be achieved owing to either:

- **Fixed Deployment:** whereby the cell-sites have already been deployed and energy can only be saved through improving each cell's capacity and energy efficiency. That is to say, only the load dependent part (radiohead) of the energy consumption is reduced. The ERG upper-bound of this can be shown to be:

$$\text{ERG}^{fixed}_{RAN} \to \frac{E_{\text{Radiohead}}}{E_{\text{Total}}} \simeq 40\%, \tag{6}$$

  which depends on the cell technology and size.
- **Re-Deployment:** whereby the cell-sites can be re-deployed and energy can only be saved through either deploying fewer larger complex cells (Large-Net) or more smaller simpler cells (Small-Net). This is done whilst keeping the load constant at unity. The ERG upper-bound of this can be shown to be:

$$\text{ERG}^{small}_{RAN} \to 1 - \frac{N_{small}}{N_{ref.}} \left(\frac{E_{\text{Backhaul}}}{r_{ref.}}\right) \simeq 60\%, \tag{7}$$

That is to say, fixed deployment can only hope to achieve a 40% ERG by decreasing the load part of energy consumption, whereas changing the deployment can achieve 60% ERG without considering further improvements to load reduction.

TABLE II
ANNUAL CAPEX AND OPEX COST VALUES FOR A RAN.

Shared Parameters		
Parameter	**Symbol**	**Value**
Interest Rate	i	5%
Loan Duration	Y	15 years
Electricity Price	$\wp_{\text{bill}}$	$0.05-0.5 (mean: $0.2)
Carbon Emission Ratio	Ω	0.52-0.64 kg/kWh
CAPEX-IMPEX (per cell)		
Core Network	$\wp_{\text{core}}$	$5k
Macro-cell Equipment	$\wp_{\text{macro}}$	$50k
Micro-cell Equipment	$\wp_{\text{micro}}$	$20k
Pico-cell Equipment	$\wp_{\text{pico}}$	$5k
Macro Build Insertion Cost	$\wp_{\text{macro,insert}}$	$120k
Micro Build Insertion Cost	$\wp_{\text{micro,insert}}$	$15k
Pico Build Insertion Cost	$\wp_{\text{pico,insert}}$	$3k
OPEX (per cell)		
Maintenance Cost Ratio	η	0.04
Backhaul Rental	$\wp_{\text{BH}}$	$10k
Macro-cell Site Rental	$\wp_{\text{macro,rent}}$	$6-10k
Micro-cell Site Rental	$\wp_{\text{micro,rent}}$	$1-6k
Pico-cell Site Rental	$\wp_{\text{pico,rent}}$	$1k
Number of Backhaul	N_{BH}	1-4
Energy Consumption (per cell)		
Macro Cell Operational Energy	E_{macro}	17.5MWh
Micro Cell Operational Energy	E_{micro}	4-12MWh
Pico Cell Operational Energy	E_{pico}	1MWh

IV. ECONOMIC COST MODELS

A. Cost Data

The paper in this section introduces the economic cost of deploying and running a radio-access-network (RAN), which can be generally broken down into the following categories [9]:

- Capital and Implementation Expenditure (CAPEX includes IMPEX): one off insertion costs that include: planning, equipment and installation costs.
- Operational Expenditure (OPEX): maintenance and operational costs that occur over a period of time.

The initial CAPEX-IMPEX per cell ($\wp$) can be broken down into that owing to: cell-site and the core-network:

$$\text{CAPEX} = \wp_{\text{cell}} + \wp_{\text{insert}} + \wp_{\text{core}}, \tag{8}$$

where $\wp_{\text{cell}}$ and $\wp_{\text{insert}}$ are the equipment and the insertion building cost of a cell-site respectively; and $\wp_{core}$ is the core network cost on a per cell basis. Fig. 8a shows the CAPEX for a dense urban 3G network.

The annual OPEX per cell includes the costs associated with marketing and billing, electricity bills, site leasing costs, backhaul rental, hardware and software maintenance:

$$\text{OPEX} = \wp_{\text{cell,rent}} + N_{\text{BH}} \wp_{\text{BH}} + E_{\text{cell}} \wp_{\text{bill}} + \eta \text{CAPEX}, \tag{9}$$

where $\wp_{\text{cell,rent}}$, $\wp_{\text{BH}}$, and $\wp_{\text{bill}}$ are the cell site rental, backhaul rental, and electricity utility costs respectively. The annual operational costs attributed to marketing and upgrades can be represented as a function of the initial CAPEX-IMPEX costs, whereby the parameter η is the factor by which a percentage of the CAPEX is used to maintain the RAN. The values for the OPEX and CAPEX are given in Table II, with data drawn

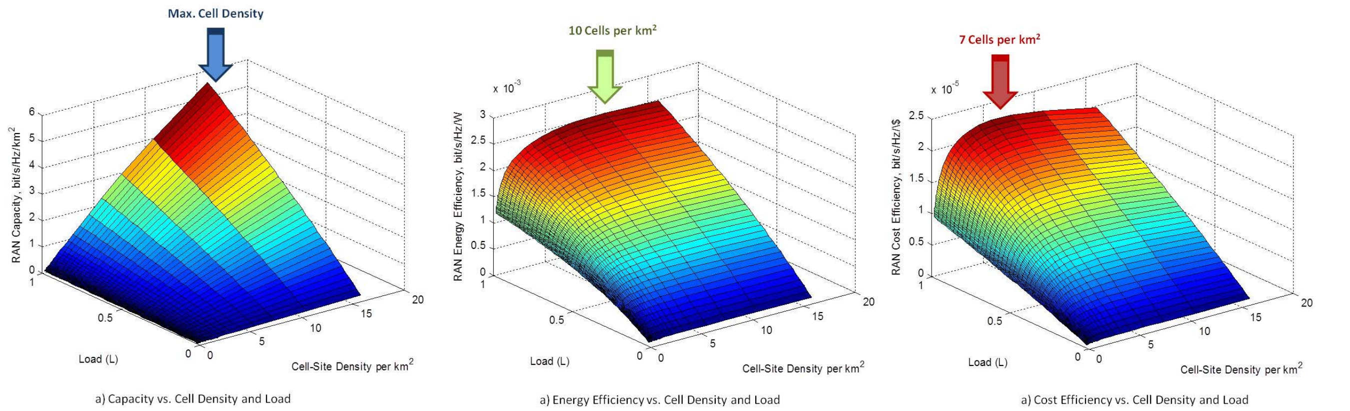

Fig. 5. Simulation Results for Small-Net Deployment with varying Cell Density and Load (L): a) Capacity Density; b) Energy Efficiency; c) Cost Efficiency.

TABLE III

NETWORK DEPLOYMENT PERFORMANCES WITH SAVINGS CALCULATED WITH RESPECT TO THE LTE **REFERENCE** WITH 20MHZ BAND, SATISFYING A SIMILAR OFFERED LOAD.

Deployment	**Cell Density**	**Cell Radius**	**Capacity Density**	**Power Density**	**Cost Density**	**Energy Saving**	**Cost Saving**
Reference Deployment							
High Capacity LTE	4.2/km^2	350m	120 Mbit/s/km^2	2700 W/km^2	211k $/km^2	N/A	N/A
Medium Capacity LTE	3/km^2	420m	79 Mbit/s/km^2	2100 W/km^2	150k $/km^2	N/A	N/A
Low LTE	2/km^2	500m	50 Mbit/s/km^2	1600 W/km^2	105k $/km^2	N/A	N/A
Small-Net Deployment							
Small-Net: Max. Capacity	>16/km^2	<150m	>125 Mbit/s/km^2	>2500 W/km^2	330k $/km^2	7%	-56%
Small-Net: Max. Energy Eff.	10/km^2	200m	75 Mbit/s/km^2	1500 W/km^2	180k $/km^2	29%	-20%
Small-Net: Max. Cost Eff.	7/km^2	240m	54 Mbit/s/km^2	1100 W/km^2	120k $/km^2	31%	-14%

from [4][5][6][7][9]. Fig. 1c & d show the CAPEX and OPEX respectively for a typical dense urban 3G network.

B. Total Cost Calculation

The paper assumes that the CAPEX amount needed was raised by paying a loan at an annual interest rate i over Y years. The annual total cost of a RAN with N_{cell} cells, is therefore the sum of the CAPEX repayment and OPEX costs:

$$\wp_{\text{Total}} = N_{\text{cell}}[\text{CAPEX}\frac{i(1+i)^Y}{(1+i)^Y-1} + \text{OPEX}]. \qquad (10)$$

Using the data given in Table II, expression (10) yields that the global energy consumption of 3.5 million cell-sites is 60TWh and costs over $200 billion. The results are inline with the Annual Financial and Attainability Reports [4] published in 2011 for Vodafone.

V. SMALL-NET DEPLOYMENT

A. Deployment and Capacity

In this section, the paper introduces the Small-Net heterogeneous architecture. For a given offered traffic load to satisfy, a dense number of *low-power* 1-sector omni-directional pico-cells are deployed. Depending on the mobility profile of users, a macro-cell overlay is usually required. This is compared against a **reference** LTE homogeneous deployment of 3-sector 2x2 SFBC co-frequency micro-cells, typically with 500m radius (2 cell-sites per km^2). The reference network's capacity is 50 Mbit/s/km^2 for a 20MHz band. In the Small-Net deployment, as the cell-density increases from 1 to 16 cell-sites per km^2, the capacity density improves, as shown in Fig. 5a. A single sector macro-cell overlay is deployed to cover a small percentage of high mobility users in the urban environment.

B. Energy and Cost Efficiency

Fig. 5a & b demonstrate that maximizing capacity doesn't maximize operational energy efficiency. The traffic load (L) can change throughout the day and Fig. 5b shows that the most energy efficient operating region is always at when a deployment is operating at peak load ($L = 1$) and when the cell-density is a value that is not maximum nor minimum, and in this particular case: 4.5 cells per km^2 (300m radius). The relationship between load, cell density and energy efficiency can be shown to be **convex** and is outside the scope of this paper.

From expressions (9) and (10), it can be seen that the energy consumption is linked with the total cost of the RAN. Results in Fig. 5c show the cost efficiency of the network for different cell densities and loads. It shows that the most cost efficient deployment is approximately 2.5 cell-sites per km^2 (400m radius). The results are summarized in Table III. The results show that the Small-Net architecture can save up to 31% operational energy by deploying a higher density of smaller and lower power cell-sites. However, this doesn't

$$E_{RAN} = 8.76\frac{R_{\text{traffic}}}{\log_2(1+\frac{F}{2})}\{0.1L(\frac{2\log_2(1+\frac{F}{2})}{3\sqrt{3}R_{\text{traffic}}})^{0.5} + (\frac{2\log_2(1+\frac{F}{2})}{3\sqrt{3}R_{\text{traffic}}})^{0.315} + 50\} \quad (11)$$

,

$$\begin{aligned}\wp_{\text{Total}} =& \frac{R_{\text{traffic}}}{\log_2(1+\frac{F}{2})}\{[\eta + \frac{i}{1-(1+i)^{-Y}}](\wp_{\text{cell}} + \wp_{\text{insert}} + \wp_{\text{core}}) \\ &+ \wp_{\text{cell,rent}} + N_{\text{BH}}\wp_{\text{BH}} + 8.76\wp_{\text{bill}}[0.1L(\frac{2\log_2(1+\frac{F}{2})}{3\sqrt{3}R_{\text{traffic}}})^{0.5} + (\frac{2\log_2(1+\frac{F}{2})}{3\sqrt{3}R_{\text{traffic}}})^{0.315} + 50]\}\end{aligned} \quad (12)$$

necessarily translate into a cost saving, at least incurring 14% extra cost. That is to say, there is a tradeoff between reducing energy consumption (and CO_2 emissions) and operating costs.

VI. Capacity-Energy-Cost (CEC) Tradeoff

The paper now uses the theoretical expressions for capacity (3), energy consumption (4) and total cost (10) to formulate their mutual CEC relationship. The annual energy consumption of the RAN (kWh) is shown in (11). An estimation of the CO_2 emissions or carbon footprint, can be made by using the Carbon Emission Ratio factor (Ω), which varies between 0.52-0.64 kg/kWh in developed nations.

The total cost of the RAN can be expressed as a function of the offered traffic load (R_{traffic}, bit/s/Hz) that needs to be satisfied, and the instantaneous load offered (L) and is given in expression (12). The relationships are given for the omni-directional Small-Net deployment, but a similar set of relationships for sectorized cells can also be found using the capacity expression (2) and modifying the coverage area per cell-site appropriately. The CEC relationship is useful for network operators and researchers to gauge whether reductions in energy consumption and CO_2 emissions balance the changes in CAPEX-OPEX costs [4].

VII. Conclusions

The paper has shown that balancing a cellular network's capacity, energy and cost is not straightforward. The paper has presented a novel Capacity-Energy-Cost (CEC) Tradeoff, both in the form of realistic simulation results and a theoretical framework. The results show that the greatest capacity deployment doesn't mean it is the most energy efficient, and neither of them are necessarily the most cost efficient solution. Whilst the proposed Small-Net architecture can reduce energy consumption and CO_2 emissions by up to 31%, they incur a higher running cost of at least 14%. Cellular operators need to balance the data demand, their emission obligations and total operating costs in order to achieve maximum market competitiveness.

Acknowledgement

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