Solar Energy Empowered 5G Cognitive Metro-Cellular Networks

Syed Ali Raza Zaidi, Asma Afzal, Maryam Hafeez, Mounir Ghogho, Desmond C. McLernon, and Ananthram Swami

Syed Ali Raza Zaidi, Asma Afzal, Maryam Hafeez, Mounir Ghogho, and Desmond C. McLernon are with the University of Leeds, UK.

Ananthram Swami is with the U.S. Army Research Lab, Adelphi, USA..

Mounir Ghogho is also affiliated with the International University of Rabat.

This work was supported by the U.S. Army Research Labortatory under Grant W911NF-13-1-0216.

ABSTRACT

Harvesting energy from natural (solar, wind, vibration, etc.) and synthesized (microwave power transfer) sources is envisioned as a key enabler for realizing green wireless networks. Energy efficient scheduling is one of the prime objectives in emerging cognitive radio platforms. To that end, in this article we present a comprehensive framework to characterize the performance of a cognitive metro-cellular network empowered by solar energy harvesting. The proposed model allows designers to capture both the spatial and temporal dynamics of the energy field and the mobile user traffic. A new definition for the "energy outage probability" metric, which characterizes the self-sustainable operation of the base stations under energy harvesting, is proposed, and the process for quantifying is described with the help of a case study for various UK cities. It is shown that the energy outage probability is strongly coupled with the path-loss exponent, required quality of service, and base station and user density. Moreover, the energy outage probability varies both on a daily and yearly basis depending on the solar geometry. It is observed that even in winter, BSs can run for three to six hours without any purchase of energy from the power grid by harvesting instantaneous energy.

INTRODUCTION

MOTIVATION

According to recent statistics [1], by the end of the year 2019 mobile broadband subscriptions are expected to reach 7.6 billion, accounting for 80 percent of all mobile subscriptions, compared to approximately 30 percent in 2013. Such an unprecedented incease in broadband demand will be further complemented by the exponential penetration of smart-phones, tablets, cyber-physical systems, machine-to-machine (M2M) communication devices, and mobile cloud based services. Gartner has predicted that Internet-of-Things (IoT) devices will grow to 26 billion units, representing a 30× growth compared to 2009. Similarly, Cisco Internet Business Solutions Group (IBSG) has forecasted that by the year 2020 the average number of Internet connected devices per person will amount to 6.8, compared to 1.8 in 2010, i.e. 50 billion Internet connected devices for the estimated world population of 7.6 billion. The steep ascent in demand inherently translates into a traffic explosion. The demand for mobile data traffic is expected to grow at a compound annual growth rate (CAGR) of 45 percent between 2013 and 2019. Consequently, it is predicted that while voice traffic will maintain its current trend, data traffic will grow 10 fold by the end of 2019 [1].

These formidable capacity demands have led to a so called "1000× mobile data challenge" introduced by Qualcomm. More specifically, the 1000× challenge dictates that fifth generation (5G) wireless networks, which are expected to roll out by early 2020, should be designed to be 1000 times more efficient than existing networks. In order to enable such a high level of efficiency, the architecture has to leverage three vital building blocks:

- Spectral agility.
- Network densification.
- Ultra energy efficient protocols.

While it is almost certain that the aforementioned architectural blocks should be combined in an efficient manner to address the so called "*exabyte flood*," the key question is how these blocks can be unified in a flexible architecture. Specifically, several design challenges for 5G networks are a byproduct of the trade-offs that exist in combining these architectural elements. The specific challenges addressed by each of these architectural pillars and the resulting trade-offs can be summarized as follows.

Pillar #1–Network Densification: As recognized in 3GPP LTE releases 10 and 12, network densification by small cell deployment plays an instrumental role in expanding wireless channel capacity. Intrinsically, the reduction in cell-size has a two-fold impact:

- Spatial load reduction, which is attained through both an increase in the degrees-of-freedom due to the multiplexing gain, and a reduction in the number of users per cell.
- Spectral aggregation, mainly due to the aggressive reuse of available transmission resources.

While network densification is a promising solution to improve spectral efficiency, it must be complemented with an *interference coordination* (i.e. control, mitigation, and/or avoidance) mechanism to realize its full potential. A careful design is required, as implementation of such a mechanism has its own cost in terms of both the circuit and the transmit power consumption.

Pillar #2–Spectral Agility: It is well known that the sporadic utilization of available electromagnetic spectrum induces an artificial scarcity. The impact is more pronounced in the context of 5G wireless networks, where gains of 10–100× must be realized on top of data rates supported by legacy systems. The artificial spectrum scarcity can be mitigated by provisioning dynamic spectrum access (DSA) mechanisms. Most of the existing DSA mechanism aim to exploit one or more of these parameters in an opportunistic manner to enhance spectral efficiency. While opportunism enhances spectral utilization, the price paid is increased power consumption. In particular, the operational environment awareness is driven from the inference process which consumes more energy as compared to simple radio platforms.

Pillar #3–Energy Efficient Network and Protocol Design: The issue of so called "green design" is brought into play due to a predicted high volume of Internet connected devices. Specifically, as predicted in a recent report by Ericsson [2], the CO_2 emissions due to the number of Internet connected devices will increase from 800 Mtonnes to 1200 Mtonnes by 2020. Hence, like all other sectors, ICT should significantly reduce energy consumption to operate in an eco-friendly manner.

Is Cognitive Radio a Potential Solution?

Cognitive radios (CRs) are the key enablers for provisioning DSA. CRs are based on opportunistic exploitation of radio spectrum across one or more degrees of freedom. As observed in [3], CR-enabled DSA mechanisms can be alternatively considered as an interference management mechanism, i.e. these strategies effectively translate into interference control, shaping, and avoidance. In a nutshell, CR inspired small cellular networks are promising in terms of providing higher spectral efficiency due to tried and tested co-existence solutions. The state-of-the-art CRs naturally complement network densification by addressing the challenge posed in terms of interference coordination. Moreover, spectral agility is an intrinsic feature of the CR empowered network design. However, these intelligent radio terminals effectively trade energy efficiency for increased spectral efficiency. Consequently, this necessitates the design of next generation CRs that are capable of collectively addressing all previously stated design trade-offs. In other words, these desired design objectives serve as a blueprint for the requirement specification of the next generation of CRs.

The Second Generation CRs for 5G

Requirement Specification: For 5G wireless networks, CRs must take a leap forward in terms of opportunism providing gains both in terms of spectrum utilization and energy efficiency. Particularly, CR empowered small cells should:

- Maximize spectral efficiency by opportunistically utilizing the transmission vacancies across the spatio-temporal domain while co-existing in a heterogeneous network (HetNet) environment.
- Minimize energy consumption while opportunistically harvesting energy from ambient sources. The harvested energy will serve as a supplementary source to enable either a self sustainable eco-friendly operation or to accommodate an increasing number of users.
- Enable co-existence of small cell networks in a manner that is flexible, demand-adaptive, and self-organized. We need to enable co-existence through transmission, handover, and resource allocation coordination across different tiers and between different cells in the same tier. This may be provisioned in a distributed or centralized manner, depending on the overall architecture of network.

Small cells empowered by CRs that can combine the above mentioned attributes can be described as "second generation CRs." Contrary to the first generation CRs where exploitation of transmission opportunities was the prime objective, the second generation CRs will additionally be geared toward exploitation of energy harvesting opportunities from natural (solar, wind, vibration, etc.) and synthesized (microwave power transfer) sources.

Harvesting: Natural vs. Synthesized Sources: The key measure of the rate at which the power arrives on a unit area is termed "irradiance." Irradiance is the radiative flux measured in $^{W}/_{m^2}$. The amount of power harvested by employing a natural or synthesized source is an increasing function of irradiance experienced at the transducer. Generally, the input-output relationship of the transducer is non-linear. Thus, the output load is often matched to provide a maximum energy transfer.

Table 1 summarizes the typical values of irradiance observed at a transducer's input for various energy sources. As is clear from the table, solar and wind energy provide a minimum of 15× gain when compared with the next largest source, i.e. vibrational energy. It should be noticed that ambient RF energy has 10× lower irradiance than indoor solar irradiance. Consequently, harvesting from natural energy sources to empower self-sustainable small cellular networks seems a natural and plausible choice.

Problem Statement and Contributions

In order to explore the design space of the energy harvesting empowered CR small cellular networks, an adequate and meaningful metric is required. It is natural to assume that such a metric will be strongly coupled with both the dynamics of the energy harvester and the power consumption profile of a small cellular network. Furthermore, both of these factors are constructed by various important building blocks/parameters that jointly characterize the "*network-level self-sustainability*" (which will be defined in the subsequent discussion). Our main objective in this article is thus three fold:

- To highlight the key parameters that determine the dynamics of the harvester and shape the network-wide power consumption profile.

The amount of power harvested by employing a natural or synthesized source is an increasing function of irradiance experienced at the transducer. Generally, the input-output relationship of the transducer is non-linear. Thus, the output load is often matched to provide a maximum energy transfer.

Source	Irradiance	
Solar	Outdoor (solar noon)	100 mW/cm^2
	Outdoor (cloudy)	10 mW/cm^2
	Indoor	10–100 μW/cm^2
Wind	10 miles Class 7	12 mW/cm^2
Thermo-electric	5°C gradient	40 μW/cm^3
RF	ambient	1 μW/cm^2
Vibrations	Piezoelectric-shoe inserts	330μW/cm^3
	Electrostatic @ 105 Hz	0.021μW/mm^3
	Electromagnetic @ 10 Hz	184 μW/cm^3
	Electromagnetic @ 52 Hz	306 μW/cm^3

Table 1. Power densities of energy harvesting technologies.

- To present a new definition for a well known "energy outage probability" (EOP) metric to quantify the network-level self-sustainability. Notice that while the term EOP has been frequently used in recent harvesting literature, a statistical definition that can capture the specific dynamics for a natural energy harvesting empowered CR metro-cellular network is yet to be developed.
- To demonstrate the potential gains that can be harnessed by employing the proposed second generation CR enabled small cellular network deployments in a practical setup.

Empowering small cells with energy harvesting from a natural source such as the sun has also been solicited by Alcatel-Lucent in [4]. To this end, in this article we focus on the design space of solar energy harvesting empowered small cellular networks. As demonstrated in Fig. 1, the network level power consumption profile is a function of:

- Network architecture.
- Network wide load model.
- Desired quality of service (QoS) for mobile users (MUs).

Moreover, the dynamics of the harvester are coupled with:

- The spatio-temporal behavior of the ambient energy field.
- The properties of transducers that convert the ambient field into usable power.

Thus, to address the first objective, we highlight various design choices for the 5G metrocellular network which in turn determine the required operational power. We then identify the key parameters that dictate the characteristic of the solar energy field. We briefly outline the process of modeling the transducer, i.e. the photo-voltaic (PV) panels output in terms of the ambient input irradiance by considering an equivalent circuit model. The output power of the PV module is the key factor in characterizing the availability of energy to empower the operation of small cellular networks.

To address the second and third objectives, the solar energy harvesting model needs to be superimposed with a realistic spatio-temporal traffic and network model to characterize a network-wide performance metric. The metro-cellular networks are considered since small cell based densification by mounting platforms such as lightRadio® on the lamp posts is becoming increasingly common. We formulate the spatio-temporal model for mobile users (MUs) and metro-cellular base stations (BSs) from measurements obtained from different cities in the UK. With the help of a case study, we present:

- The modeling approach for capturing the behavior of the network load, the deployment topology, and the desired QoS for MUs.
- The gains exercised under the proposed deployment architecture.

Building Blocks for Cognitive Metro-Cellular Networks

There are several key design parameters which are crucial in characterizing the power requirements of the small cellular BS.

Deployment Mode: Metro cells can be deployed in a non co-channel or a co-channel mode. Metro cells can operate in a cognitive underlay mode where the same resource blocks are shared by the macro cells and small cells; power control at the small cells is implemented such that the MUs desired QoS requirements can always be guaranteed. An alternative phantom small cellular architecture is proposed by DOCOMO in [5, 6], where the metro cells are deployed in a non co-channel mode. Specifically, both the metro cells and the macro cells operate on different frequency bands. The architecture leverages the master-slave relationship between the macro cells and the metro cells, resulting in the separation of the control plane and the capacity plane (frequently known as the C/U plane split), thus providing support for adding capacity on-demand.

Deployment Location: Metro cells can be deployed uniformly across the macro-cellular network or alternatively on the cell edges to boost the capacity of the edge user. Even with a uniform deployment, the co-channel operation and the power control may push the operational region of the metro cells toward the edges as the interference aggregated from these edges may not deteriorate the performance of the users located toward the cell center.

Cloud vs. Traditional Radio Access Network (RAN): Cloud RAN (C-RAN) leverages its flexible architecture to provide coverage and capacity expansion in a cost efficient manner. Unlike traditional small cell networks, C-RAN architecture exploits the advantages of centralized baseband processing to address co-existence and scheduling issues. More precisely, C-RAN decouples the baseband processing unit (BBU) from the remote radio head (RRH). RRHs are connected to the cloud BBU pool via a flexible front-haul, which is usually a fiber optic cable where signaling is done using radio over fiber (RoF) or the common public radio interface (CPRI).The

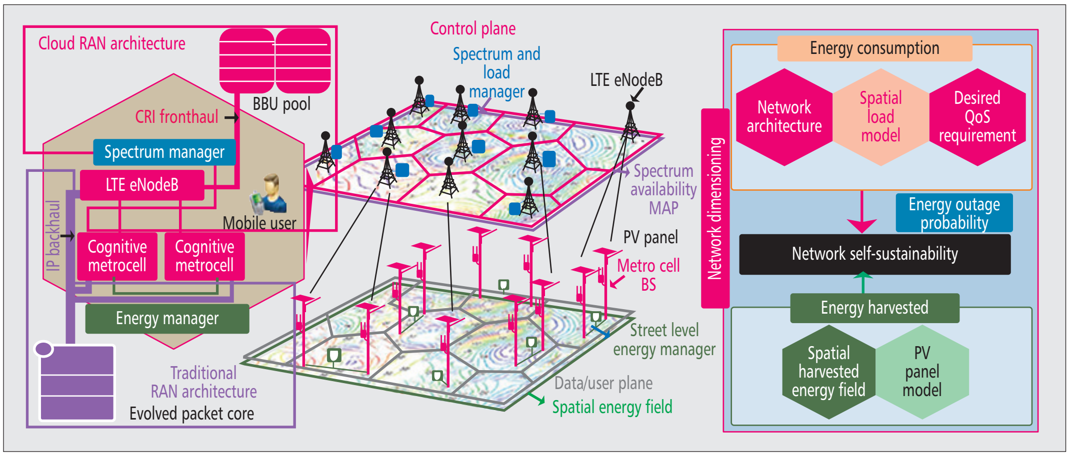

Figure 1. 5G cognitive metro-cellular network architecture.

amount of power required by the metro cell thus depends on whether the C-RAN architecture is implemented (where transmission and interference coordination provides significant gains in power reduction) or the traditional architecture is implemented.

Interference Coordination: The attainable performance of the network is mainly limited by the intra-tier and inter-tier interference. Realizing that interference is the key bottleneck, 3GPP LTE releases 10 and 11 have proposed enhanced inter-cell interference coordination (eICIC) schemes. In release 10, the concept of almost blank sub-frames (ABS) was introduced to elevate the downlink (DL) performance of a small cell user by scheduling it in the so called "blank sub-frame" of the macro cell. The concept was further extended to reduce power sub-frames (RPS) in LTE release 11 under the umbrella of further enhanced inter-cell interference coordination (FeICIC). Generally, the interference management techniques proposed under eICIC and FeICIC require either intra-tier and/or cross-tier coordination. Since the transmit power requirements are dictated by the QoS constraints expressed in the form of the desired signal-to-interference-plus-noise-ratio (SINR) threshold or throughput, the interference coordination strategy is also an important instrument in shaping the required transmit power of the metro cell.

The overall architecture of 5G cellular networks is depicted in Fig. 1. The characterization of the transmit power requirements with these architectural components will be demonstrated later with the help of a case study.

Dynamics of an Ambient Solar Energy Field and Modeling Output Power

Solar irradiance is an instantaneous measure of the energy arrival rate and thus varies across both the spatial and the temporal domains. Quantification of solar irradiance requires a comprehensive description of the underlying meteorological parameters. To this end, we provide a brief overview of these parameters. At this juncture it should be highlighted that in the recent past there has been enormous interest in studying cellular networks empowered by ambient RF energy harvesting. However, most of these studies assume stochastic/probabilistic energy arrival models. In practice, energy harvested from natural sources such as the sun have a significant deterministic component. Consequently, these models cannot accurately predict energy deficiency of power at a given time or day in a precise manner. Accurate prediction is of more interest to the cellular operator than an average performance metric.

Solar Insolation

The radiation intensity at the sun's surface is 6.33×10^7, $^W/_{m^2}$. The earth revolves around the sun in an elliptical orbit with the mean separation $r_{SE} = 1.496 \times 10^8$km (also known as 1 AU (astronomical unit)). Due to the distance squared spread of the radiant power, the amount of solar energy received outside the earth's atmosphere is reduced to $I_{SC} = 1367 ^W/_{m^2}$. The constant I_{SC} is frequently referred to as the 'solar constant'. The irradiance measured outside earth's atmosphere is generally called the extra-terrestrial (ET) solar irradiance. The energy that passes through the atmosphere and strikes the surface of a PV module is referred to as insolation. A number of astronomical and geometrical factors govern the amount of insolation, e.g. declination angle, zenith angle, latitude, longitude, day number, and atmospheric conditions [7]. Figure 2 provides a graphical illustration of these geo-physical parameters.

Using decades of past insolation and weather forecast data, numerous analytical models have been formulated taking all the above mentioned factors into account in order to characterize the direct and diffuse components of solar energy received by a PV module (see [7] for details). For the purpose of dimensioning a metro-cellular network, a simple yet accurate Hottell's clear day model [8] can be adapted to characterize the global horizontal irradiance in the absence of cloud cover. More sophisticated models can be employed to capture the randomness induced by cloud cover and aerosol absorption.

In practice, energy harvested from natural sources such as the sun have a significant deterministic component. Consequently, these models cannot accurately predict energy deficiency of power at a given time or day in a precise manner. Accurate prediction is of more interest to the cellular operator than an average performance metric.

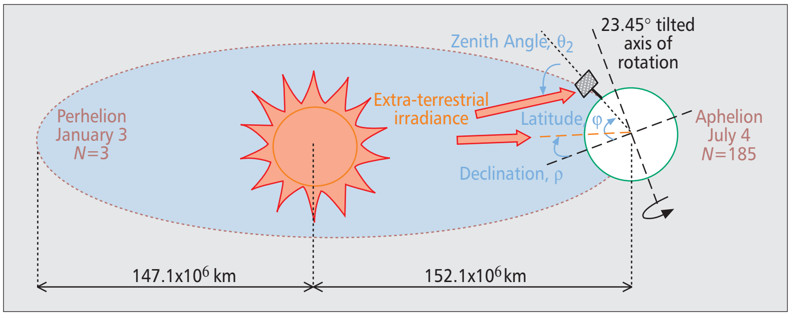

Figure 2. Illustration of the geophysical parameters controlling irradiance.

Harvested Solar Energy

Solar panels are comprised of PV cells made with various different materials such as mono-crystalline, polycrystalline, thin-film, or amorphous silicon. The underlying material determines the overall cost, panel efficiency, and power rating. In practice, the maximum output power is extracted by adjusting the cell load. The maximum extracted power is obtained by maximizing the output power with respect to the output voltage. Given the value of insolation at a particular time, the harvested power can be calculated using a well known single diode model for a PV module [9]. This computation requires a set of various parameters, such as: short circuit current; open circuit voltage; maximum power point voltage; and maximum power point current. These parameters can be individually expressed as a function of ambient temperature, insolation, and other constants that are specific to the panel itself and can be easily found in the panel's data sheet, such as voltage, current, and insolation values at standard temperature conditions (25°C). A detailed characterization of the output power (P_{PV}) in terms of these parameters is presented in [7]. The output power of the PV module (P_{PV}) can be compared with the power requirement of a metro-cellular BS to determine the network-wide self-sustainability.

Feasibility Study for Metro Cells Deployed on Lamp Posts in the UK

In this section we investigate the feasibility of deployment of solar energy powered metro-cellular networks in the UK. We build our case study by selecting worst-case features from the previously discussed network architecture for a power consumption profile. The relevant assumptions and considerations are presented in a subsequent discussion.

Assumptions and Considerations

Choice of Network Architecture and the PV Panel: We assume a two-tiered C/U plane split small-cellular network supported by the traditional IP back-hauling. Moreover, to simplify the analysis, we do not consider any intra-tier interference coordination mechanism. For the purpose of this case study, we focus on the DL operation of the considered cellular network. It is assumed that each CR metro-cellular BS is furnished with a PW1650-24V solar panel (as in [7]).

Network Deployment: Lamp posts can serve as ideal candidates for ultra dense outdoor BS deployment. To evaluate the effectiveness of metro cell deployment on lampposts, we obtained their coordinates from various cities in the UK including Nottingham, Winchester, Southampton, Basingstoke, and Salford. We also acquired the measured data for solar radiation from the British Atmospheric Data Centre (BADC). Our objective is to quantify the time for self-sustainable operation of metro cells with and without the presence of an energy storage device such as a battery. If the available energy is unable to satisfy the minimum rate requirements of the user, the network is said to be in energy outage. Thus, as implied by the name, EOP is the probability that the energy harvested from solar panels is not sufficient to fulfill consumer demands and thus additional energy has to be procured from the grid. Consumer demand can be adequately captured by the QoS parameters such as desired DL transmission rate and link reliability guarantees. In what follows, we present a relationship between the energy outage and the spatio-temporal dynamics of metro cells, user traffic, and the solar radiation for the above mentioned cities in the UK.

A Framework for Characterizing EOP

The quantification of power requirements for the CR metro-cellular network requires the spatio-temporal models for the MUs and the metro cells. It should be noted that the required power has a stochastic nature due to fading experienced on the communication links between an MU and its serving metro cell. The required transmit power is coupled with the desired data rate requirements (which forms the QoS constraint).

Spatial Model for Metro Cells: In the recent past, stochastic geometry has been used extensively for analyzing the performance of large scale cellular and ad hoc networks. Most of the studies assume that the spatial distribution of the BSs follows a homogeneous Poisson point process (HPPP). The key advantage of employing the HPPP based models is the analytical tractability of performance metrics such as coverage and ergodic rate. In [7] we used the nearest neighbor statistic for testing complete spatial randomness using the Clark-Evans test and showed that the spatial distribution of lamp posts in central Nottingham can be approximated by a HPPP. We conducted the same test for various cities in Hampshire county and the city of Salford. It was observed that the HPPP approximation also holds for these cities. The validity of HPPP based modeling can be intuitively explained by the fact that there is still sufficient randomness in deployment topology embedded due to the urban geometry even though the lamp posts exercise some degree of repulsion and regularity (as compared to the HPPP). Consequently, it is safe to capture the spatial configuration of the lamp posts by a HPPP with intensity λM for the purpose of this study.

Spatio-Temporal Model for MUs: In DL operation of the metro cells, the power required to serve MUs directly depends on the number of MUs in a cell. The number of active users changes with time, and their average density in a cell is known to vary according to a half sine model with respect to the number of hours of the day. The sinusoidal variation of mean density has been derived from empirical traffic measurements collected from operational cellular networks. On a typical day user density has a predictable pattern, i.e. it reaches a minimum value around 4-5 a.m., rising steadily thereafter to a peak value in the evening and declining afterward. The distribution of the number of active users may change drastically for weekdays and weekends and also depends on the rate requirements.

Besides modeling temporal variations of MU, an accurate spatial distribution is also required to develop the load/activity model for small cellular networks. It has been demonstrated in the past that the active DL users are distributed according to a HPPP. Since the active users at a certain time in a cell are also the number of users distributed across space, the HPPP based modeling of MUs can be quite reasonable. Association of MUs with a serving metro cell can range from the nearest neighbor criterion to a more complex function of SINR in the presence of channel state information. For simplicity, we assume that an active user associates itself to the nearest BS, resulting in a Voronoi tessellation of metro-cellular BSs.

Quality of Service and Transmit Power Selection: The criteria for successful DL communication for CR small-cellular BSs is satisfied when a certain fraction of metro cell BSs in the network are able to meet the minimum rate demand for the active users. Mathematically, the probability of successful DL communication is given as

$$\mathbb{P}_{suc}^{MU} = \Pr\{f(SINR) > R_o\} \geq \rho_{th}, \tag{1}$$

where R_o is the MU's desired DL rate, ρ_{th} is the link reliability constraint, and f(SINR) is the instantaneous rate. For the purpose of this study, it is assumed that the minimum rate requirement is the same for all users. The minimum transmit power required (P_{MC}) to serve an MU such that its QoS requirements are satisfied can be established by quantifying P_{suc}^{MU} and then inverting the inequality in Eq. 1. The total power requirement to simultaneously serve all users in an arbitrary cell is $N_u(t)P_{MC}$, where $N_u(t)$ is the number of active DL users in an arbitrary metro cell.

Energy Outage Probability (EOP): When the metro cells operate without a battery, the user demand is met only when the instantaneous harvested energy is sufficient. In this case, the instantaneous EOP of the metro-cellular network is mathematically characterized as

$$\mathbb{P}_{out}^{E} = \Pr\{N_u P_{MC} > P_{PV}\}. \tag{2}$$

The above equation implies that the instantaneous EOP is distributed according to the spatial distribution of the number of active users in a cell. Network-wide self-sustainability can be characterized in terms of the average number of hours for which $\mathbb{P}_{out}^{E}$ is below a certain pre-specified threshold E_{out}. When the cognitive metro-cellular BSs employ P_{MC} to serve each active user, the average number of self-sustainable hours of operation per month are depicted in Fig. 3. As expected, during the summer the maximum harvested energy is significantly higher than in the winter. Consequently, the CR enabled metro-cellular network is self-sustainable for 10 to 12 hours on average during the summer for the considered set of parameters. Nevertheless, even during the winter approximately three to six hours of operation can be guaranteed by instantaneous expenditure of harvested solar power. The self-sustainable number of hours are also coupled with λ_U (user density). More specifically, it decreases with an increase in the mean number of peak hour users per cell. In this paper we consider $\lambda_U = \lambda_M N_s$ where $N_s = 6$ is considered.

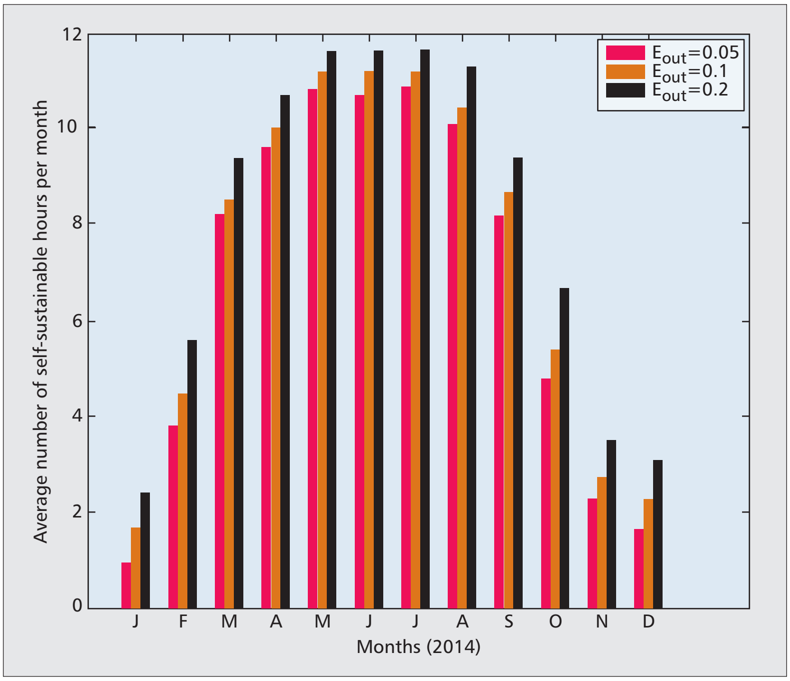

Figure 3. Energy outage probability of a metro-cellular network for λ_U (user density) = $6\lambda_M$ (metro-cell density), $\varepsilon = 0.02$, $\alpha = 4$, $\lambda_{LP} = 0.48 \times 10^{-3}$ (Nottingham City) and $\sigma^2 = -90$ dB/Hz.

With a practical solar energy storage system, performance can be improved significantly as the surplus energy during afternoons can be used in the evenings. Moreover, employing an appropriate sizing of the battery, continuous self-sustainability can be realized. An example of this would be to select a trickle charge battery to avoid the negative effects of over-charging in summers and have dimensions such that a metro cell can utilize battery reserve for a number of consecutive overcast days. We conducted a simplified analysis to quantify the energy deficit when the metro cell BS is equipped with a battery. We considered a 12v, 1 ampere hour battery attached to a metro cell BS and compared the average daily energy demand with the average daily harvested energy, each multiplied with the number of days in a particular month. Neglecting the charging and discharging inefficiencies, the average battery state for a particular month is simply considered to be the difference between the demand and supply, as shown in Fig. 4. The results in Fig. 4 show that a battery operated metro-cellular network may never go into outage for the entire year except in the month of January.

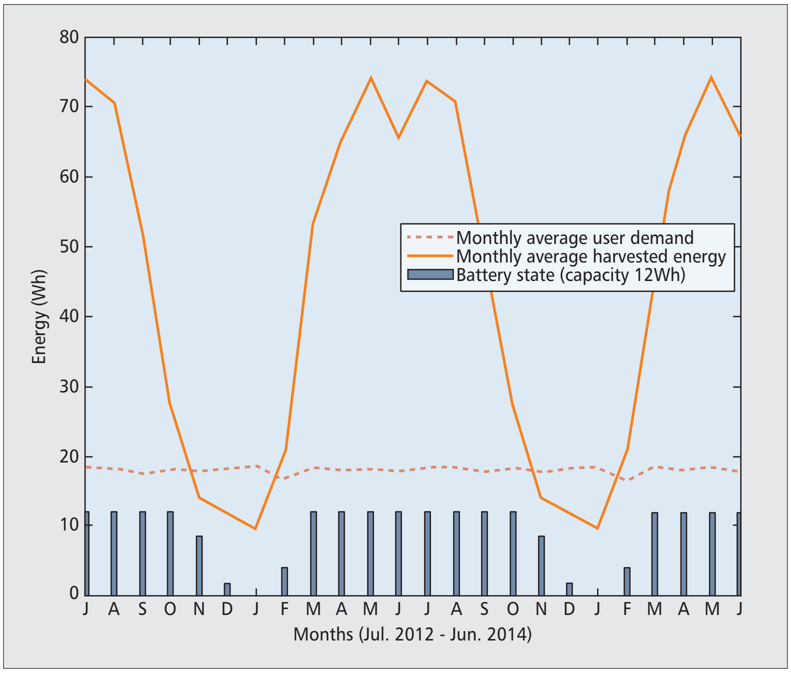

Figure 4. Average daily harvested energy and user demand aggregated over a month and the corresponding average battery state. λ_U (user density) = $6\lambda_M$ (metro-cell density), $\alpha = 4$, $\lambda_{LP} = 0.48 \times 10^{-3}$ (Nottingham City) and $\sigma^2 = -90$ dB/Hz.

Open Issues and Future Directions

There are several important open design issues that need to be considered to explore the design space and full potential of CR empowered metro-cellular networks. Due to space limitation, we only highlight the most important and promising research directions.

Energy Storage: Dimensioning of energy storage, design of online prediction algorithms, and optimal trading of energy with the grid still remain open issues. With the advent of smarter grid infrastructure, energy trading and sharing on the micro level for self-sustainable network deployment will become possible in the near future. However, the impact of such an evolution when communication networks are empowered with green renewable sources has not yet been fully investigated.

Energy Aware Load Balancing: Tiered structures with heterogeneous small cells, relays, and distributed antenna systems are envisioned to be the key enabler toward addressing the 1000× challenge. In HetNet deployments, the transmit power of each child tier is generally lower than its parent tier. Thus, received signal strength based association may overload the parent tier due to higher transmit power. In order to circumvent this problem, 3GPP standards have introduced the concept of "biased-association." In particular, a range extension bias (REB) is introduced in received signal strength to determine the tier that will serve the MU. Due to the introduction of such bias, the MUs may experience high interference as they may be associated with a sub-optimal serving BS. However, performance can be elevated through inter-tier interference coordination. We advocate that for a 5G cognitive metro-cellular network, load balancing should be complemented with energy balancing, i.e. REB should designed such that the energy burden can be shared across the network. Specifically, due to the highlighted variations in both energy field and user traffic across space and time, association criterion should be adaptive.

Energy Aware Interference Coordination: As mentioned earlier, inter-tier and intra-tier interference coordination are important features of small cellular networks. As discussed earlier, EICIC or FeICIC are employed to manage inter-tier interference when co-channel deployment is the preferred option. The duty cycle of almost blank subframes or reduced power subframes is designed to optimize the throughput. However, in an energy harvesting empowered network, we suggest that the design of duty cycles should consider the natural variations in energy states. BSs with lower residual energy may increase blank subframe duty cycle to reduce co-channel interference while harvesting energy. The duty cycle should be optimized for throughput whenever sufficient energy is available at BSs to schedule transmissions. Optimal duty cycling for interference coordination in an energy aware manner has not yet been explored.

Conclusion

In this paper we presented a framework to investigate the performance of a solar empowered metro-cellular network. We depart from the traditional definition of cognition which focuses on spectral efficiency performance; rather, we characterized cognition in terms of energy efficiency. It is demonstrated that both temporal and spatial dynamics of the solar energy field and mobile user traffic are critical in shaping the network-wide energy requirement. The energy demand of a metro-cellular BS is also strongly coupled with the QoS desired by MUs. It is shown that a metro-cellular network is self-sustainable in terms of energy for approximately three to 12 hours of a day depending upon the time of the year. Finally, it was argued that the dynamics and randomness in energy state can be exploited in the future to attain energy aware load balancing and interference coordination.

References

[1] A. Ericsson, "Traffic and Market Data Report — On the Pulse of the Networked Society," 2014.
[2] —, "Ericsson Energy and Carbon Report: On the Impact of Networked Society," 2013.
[3] S. Zaidi, D. McLernon, and M. Ghogho, "Breaking the Area Spectral Efficiency Wall in Cognitive Underlay Networks," *IEEE JSAC*, vol. 32, no. 11, Nov. 2014, pp. 2205–21.
[4] A. Lucent, "Alternative Renewable Power Concepts for Alcatel-Lucent Outdoor Wireless Small Cell Solutions," 2011.
[5] H. Ishii, Y. Kishiyama, and H. Takahashi, "A Novel Architecture for LTE-B: Cplane/u-Plane Split and Phantom Cell Concept," *IEEE Globecom Wksps.*, 2012, pp. 624–30.
[6] S. Mukherjee and H. Ishii, "Energy Efficiency in the Phantom Cell Enhanced Local Area Architecture," *IEEE Wireless Commun. and Networking Conf. (WCNC)*, 2013, pp. 1267–72.
[7] S. Zaidi *et al.*, "Energy Harvesting Empowered Cognitive Metro-Cellular Networks," *IEEE 1st Int'l. Wksp. Cognitive Cellular Systems (CCS)*, 2014, pp. 1–5.

[8] W. B. Stine and M. Geyer, Power from the Sun. powerfromthesun.net, 2001.
[9] A. Bellini *et al.*, "Simplified Model of A Photovoltaic Module," *IEEE Applied Electronics*, 2009, pp. 47–51.

Biographies

Syed Ali Raza Zaidi (s.a.zaidi@leeds.ac.uk) is currently a research fellow at the University of Leeds on the U.S. Army Research Lab funded project, "Cognitive Green Wireless Communication–A Network Science Perspective." He received his B.Eng degree in information and communication system engineering from the School of Electronics and Electrical Engineering, NUST, Pakistan in 2008, and a Ph.D. from the University of Leeds in 2013. He was awarded the University of Leeds F. W. Carter prize for best Ph.D. thesis, and NUST's most prestigious Rector's gold medal for his final year project. From September 2007 to August 2008 he served as a research assistant in the Wireless Sensor Network Lab on a collaborative research project between NUST, Pakistan and Ajou University, South Korea. In 2008 he was awarded an overseas research student (ORS) scholarship along with Tetley Lupton and Excellence Scholarships to pursue his Ph.D. at the School of Electronics and Electrical Engineering, University of Leeds, U.K. He was also awarded with COST IC0902, DAAD, and Royal Academy of Engineering grants to promote his research. He was a visiting research scientist at the Qatar Innovations and Mobility Center from October to December 2013. He has served as workshop chair for IEEE VTC 2015 DCS, IEEE IWCMC 2015 ReAP, CROWNCOM 2015 and IEEE CAMAD 2015 ReAP. He has served as an invited reviewer for IEEE flagship journals and conferences. Over the past few years he has served as TPC member for IEEE WCNC 12-15, IEEE VTC 10-15, EUSIPCO 11-15 and SPAWC 10. He is also the lead guest editor for the *IET Signal Processing Journal* SI on signal processing advances for 5G. His research is focused toward the design and analysis of large scale ad-hoc wireless networks by employing tools from stochastic geometry and random graph theory.

Asma Afzal (elaaf@leeds.ac.uk) received the B.E. and M.S. degrees in electrical engineering from the National University of Sciences and Technology (NUST), Islamabad, Pakistan, in 2011 and 2013, respectively. She is currently working toward the Ph.D. degree in electrical engineering from the University of Leeds, Leeds, U.K. During her masters she worked as a lab engineer at NUST on a collaborative project with Cypress Semi-Conductor, San Jose, CA, USA. Her research interests are in stochastic modeling and analysis of future generation wireless networks with energy harvesting.

Maryam Hafeez (elmh@leeds.ac.uk) received a B.Eng. in information and communications systems engineering from the School of Electrical Engineering and Computer Sciences (SEECS), National University of Science and Technology (NUST), Pakistan in 2008. Throughout her undergraduate degree she was awarded the SEECS prestigious merit scholarship. NUST's most presitigous Rector's gold medal was awarded to her final year project. From 2008 to 2009 she served as a research assistant in the Wireless Sensor Network (WiSNET) Lab on a collabrative research project between Ajou University, South Korea and the NUST, Pakistan. Her research is geared toward design and analysis of protocols for next generation green intelligent wireless networks by employing tools from game theory and stochastic geometry

Mounir Ghogho (m.ghogho@leeds.ac.uk) received the M.Sc. degree in 1993 and the Ph.D. degree in 1997 from the National Polytechnic Institute of Toulouse, France. He was an EPSRC research fellow with the University of Strathclyde, Glasgow (Scotland), from September 1997 to November 2001. He joined the school of Electronic and Electrical Engineering at the University of Leeds (UK) in December 2001, where he currently holds a chair in signal processing and communications. He is also currently a research director at the International University of Rabat (Morocco). He is currently an associate editor of *IEEE Signal Processing Magazine*. He served as an associate editor of *IEEE Transactions on Signal Processing* from 2005 to 2008, *IEEE Signal Processing Letters* from 2001 to 2004, and the Elsevier *Digital Signal Processing* journal from 2011 to 2012. He is currently a member of the IEEE Signal Processing Society SAM Technical Committee. He served as a member of the IEEE Signal Processing Society SPCOM Technical Committee from 2005 to 2010, and as a member of the IEEE Signal Processing Society SPTM Technical Committee from 2006 to 2011. He was the general chair of the 11th IEEE Workshop on Signal Processing for Advanced Wireless Communications (SPAWC'2010), general chair of the 21st edition of the European Signal Processing Conference (EUSIPCO 2013), the technical co-chair of the MIMO symposium at IWCMC 2007 and IWCMC 2008, and a technical area co-chair of EUSIPCO 2008, EUSIPCO 2009, and ISCCSP'05. His research interests are in signal processing and communication networks. He has published three book chapters, more than 75 journal papers and 150 conference papers. He is the EURASIP liaison in Morocco. He was awarded the prestigious and highly competitive five-year UK Royal Academy of Engineering Research Fellowship in September 2000. He is also one of the recipients of the internationally competitive 2013 IBM Faculty award. He has held invited scientist/professor positions at many institutions, including the US Army Research Lab (USA), TÉlÈcom Paris-Tech (France), the National Institute of Informatics (Japan), the University Carlos Third of Madrid (Spain), ENSICA (France), the Technical University of Darmstadt (Germany), the University of Minnesota (USA), Beijing University of Posts and Telecommunication (China), and the University Mohamed V (Morocco).

Desmond C. McLernon (d.c.mclernon@leeds.ac.uk) received the B.Sc. in electronic and electrical engineering and the M.Sc. in electronics from Queen's University of Belfast, N. Ireland. He then worked on the research and development of radar systems with Ferranti Ltd. in Edinburgh, Scotland, and later joined Imperial College, University of London to obtain the Ph.D. degree in signal processing. After first lecturing at South Bank University, London, UK, he moved to the School of Electronic and Electrical Engineering at the University of Leeds, UK, where he is currently a reader in signal processing. His research interests are broadly within the domain of signal processing for wireless communications systems (in which discipline he has published more than 270 international journal and conference papers). He is the associate editor of the UK IET journal *Signal Processing*. He has been a member of various international conference organizing committees, more recently the IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2010, Marrakech), European Signal Processing Conference (EUSIPCO) 2013, IET Conference on Intelligent Signal Processing (London, 2013 and 2015), and IEEE Globecom 2014 and 2015, Workshop on Trusted Communications with Physical Layer Security (Austin, Texas).

Ananthram Swami (a.swami@ieee.org) received the B.Tech. degree from the Indian Institute of Technology (IIT), Bombay, the M.S. degree from Rice University, Houston, TX, and the Ph.D. degree from the University of Southern California (USC), Los Angeles, all in electrical engineering. He has held positions with Unocal Corporation, USC, CS-3, and Malgudi Systems. He was a statistical consultant to the California Lottery, developed a Matlab-based toolbox for non-Gaussian signal processing, and has held visiting faculty positions at INP, Toulouse, France. He is with the U.S. Army Research Laboratory (ARL), where he is the ST for Network Science. His work is in the broad area of network science, with an emphasis on wireless communication networks. He was the co-editor of *Wireless Sensor Networks: Signal Processing & Communications Perspectives* (New York: Wiley, 2007). He is a member of the IEEE SPS Technical Committee on Sensor Array and Multi-Channel systems, and serves on the Senior Editorial Board of the *IEEE Journal on Selected Topics in Signal Processing*. He is an ARL Fellow. He has served as an associate editor for *IEEE Transactions on Signal Processing*, *IEEE Signal Processing Letters*, *Signal Processing Magazine*, *IEEE Transactions on Circuits and Systems II*, *IEEE Transactions on Wireless Communications*, and as guest editor for the *IEEE Journal on Selected Areas in Communications*. He was a tutorial speaker on "Networking Cognitive Radios for Dynamic Spectrum Access" at ICASSP 2008, DySpan 2008, MILCOM 2008, and ICC 2010. He received the best conference paper award at IEEE Trustcom 2008, and was co-Organizer and co-Chair of three IEEE workshops related to signal processing and communications, including IEEE SPAWC'10.

We advocate that for a 5G cognitive metro-cellular network, load balancing should be complemented with energy balancing, i.e. REB should designed such that the energy burden can be shared across the network. Specifically, due to the highlighted variations in both energy field and user traffic across space and time, association criterion should be adaptive.