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A Survey of Green Mobile Networks: Opportunities and Challenges

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Abstract The explosive development of Information and Communication Technology (ICT) has significantly enlarged both the energy demands and the CO_2 emissions, and consequently contributes to make the energy crisis and global warming problems worse. However, as the main force of the ICT field, the mobile networks, are currently focusing on the capacity, variety and stability of the communication services, without paying too much severe concerns on the energy efficiency. The escalating energy costs and environmental concerns have already created an urgent need for more energy-efficient "green" wireless communications. In this paper, we survey and discuss various remarkable techniques toward green mobile networks, to mainly targeting mobile cellular networks. We also summarize the current research projects related to green mobile networks, along with the taxonomy of energy-efficiency metrics. We finally discuss and elaborate future research opportunities and design challenges for green mobile networks.

Keywords mobile networks · energy efficiency · green technique

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1 Introduction

The rapid growth of energy consumption by user and network devices has posed serious problems [1]; for instance, the greenhouse effect has become increasingly severe, which is mainly caused by the excessive emission of Carbon dioxide (CO_2) since last century. As reported in [2–4], human industrial activities emit twice more CO_2 than natural processes can absorb at the moment. Among the energy-consuming industries, the Information and Communication Technology (ICT) industry takes 2% of global total CO_2 emissions and 3% of global energy expenditure [4, 5]. In particular, 57% of the energy consumption of the ICT industry is attributed to users and network devices in mobile and wireless networks [6], the scale of which is still growing explosively [3]. According to [7], the global mobile traffic is expected to reach 6.3 exabytes per month by year 2015, which is more than 26 times as much as the traffic load per month in 2010.

Therefore, governments and industries have recently shown keen concerns on the critical issues related to energy efficiency in the ICT area. However, as studied in the recent literature [1, 3, 4, 8, 9], most of the techniques applied to current mobile networks have been designed by taking into account non-energy-related factors, such as throughput, Quality of Service (QoS), availability, scalability, and so on. Particularly, some of the technical drawbacks of current mobile networks for moving toward "green mobile networks" [3, 8, 9] can be illustrated as follows:

- Most of the mobile communications techniques seek to maximize the performance metrics such as the throughput, QoS and reliability, paying no or little attention to the energy consumption of network devices. Devices and systems are designed in a performance oriented manner, not orienting the energy awareness or energy efficiency.
- Except for the peak time, network devices are not utilized at their full capacity, and hence normally their required level of energy is much less than the supplied power at maximum level. In such an over-provisioning condition, the electrical power cannot be dynamically adjusted depending on the networking or traffic conditions.
- The energy saving gain of most of the green techniques is achieved usually at the cost of degradation of QoS, or say "performance compromise". The tradeoff between the performance and the energy consumption should be carefully exploited.

The relation between energy and performance, can be illustrated as shown in Fig. 1 according to [10]. Many of the existing techniques did not take the energy consumption into serious consideration, but some can still reduce certain amount of energy consumption based on some performance compromise. However, we could not conserve too much energy if the performance is degraded to a unsatisfying level regarding the QoS requirement of users; this over-compromised performance with QoS sacrifice is unacceptable in commercial networks. Therefore, the green techniques should try for the perfect energy efficiency, above the satisfiable QoS level, as illustrated in shadow in Fig. 1, where performance QoS felt by users is minimally affected while energy is still saved at a certain level. Although it is challenging to design green techniques for the ideal energy efficiency, which saves much energy but still achieves equivalent performance, researchers are seeking more effective green techniques to revamp or renovate the mobile networks to realize higher and higher energy efficiency, and thus to curtail the Carbon emission.

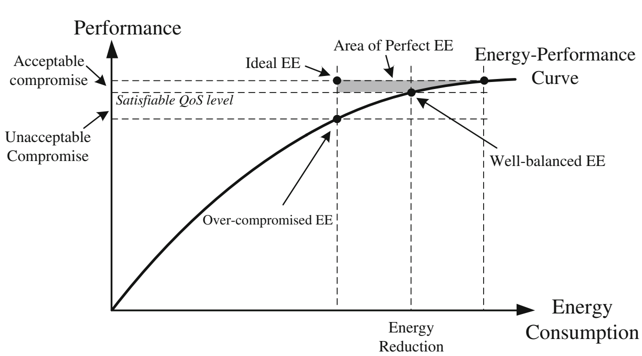

Fig. 1 Energy-performance curve of a typical mobile network system, a network device, an algorithm, or an application service etc., indicates the tradeoff between energy consumption and performance [10]. EE is the abbreviation of Energy-Efficiency

Recently, both industry and academy are paying substantial attention on the research of green mobile networks, which leads to comprehensive efforts to design new energy-efficient architectures, protocols and algorithms, targeting various types of mobile networks, e.g., mobile cellular networks, mobile ad-hoc networks, mobile sensor networks etc. In this paper, we will mainly target the infrastructure-based cellular networks,[1,2] which serve telecommunication voice call and Internet data service functionalities to mobile users, including 2G networks (e.g., GSM, CDMA), 3G networks (e.g., UMTS, CDMA2000), beyond 3G (3G+) networks (e.g., HSDPA, EV-DO, WiMAX), and 4G networks (e.g., LTE-Advanced and WiMAX 2).

Green communication techniques in mobile networks have been intensively studied across academia, industry, whilst standard bodies like IEEE, IETF and 3GPP, and ICT-related government agencies and public institutions also start the discussion on regulation and standardization of energy efficiency metrics [11–15]. We believe it is timely and desirable to compile those efforts to offer a comprehensive view on the state-of-art green techniques. In this paper, we carry out a detailed survey on current research and development efforts of green mobile networks including architectural designs, communications schemes, power-saving mechanisms and so on. In particular, the challenges, enabling technologies, and impending issues of design and deployment of emerging green mobile

[1] For simplicity, we will use "mobile networks" for the cellular networks throughout this paper

[2] More specific surveys on the latter two can be found in [16] and [17] respectively.

networks are also discussed, along with the survey of related green projects, and energy-efficiency green metrics.

The rest of the paper is organized as follows. We discuss the research efforts of green techniques to improve the energy efficiency of mobile networks in Section 2. Section 3 introduces green projects and green metrics in detail. And Section 4 outlines prospective research issues, followed by the concluding remarks in Section 5.

2 Green techniques for mobile networks

As pointed out in [18], nearly half of the operation expenditure of a typical mobile network system is for the consumed energy, so effective green techniques are important to lessen the energy consumption of the whole mobile system. Novel designs of the whole green mobile system are challenging, which require significant optimization or even reconstruction of all layers and components in the system, as stated in [19, 20] and [21]. Therefore, various research studies focus on specific aspects of the mobile networks, which are classified by the following five components, as illustrated in Fig. 2: data centers in backhaul, macrocells, femtocells, end-hosts and services. In the following, we will discuss the green techniques for the five components in detail, and categorize the techniques into three kinds: (1) processing techniques, such as resource allocation and scheduling algorithms etc., (2) communication techniques, such as power control and transmission schemes etc., and (3) system techniques, such as cooling etc., all of which are summarized in the table in Fig. 3.

2.1 Data centers in backhaul

At present, the scales of data centers (or say server farms) in the backhaul of mobile networks[3] are rapidly growing at a much faster speed than other ICT fields due to the high demands of online storage and computation [22]. Meanwhile, data centers are also gobbling up huge amount of energy for computing, storing, transmitting and cooling. In order to reduce the energy consumption and concomitantly to restrain the expenditure, many green techniques are developed targeting the **ON/OFF resource allocation** and the **virtualization technique** for the data center networks considering the dynamic use demands and traffic load.

[3] Although data centers in backhaul are used not only by mobile hosts but also by wired hosts, we still carry out discussions in this paper, as mobile devices and networks are becoming more important.

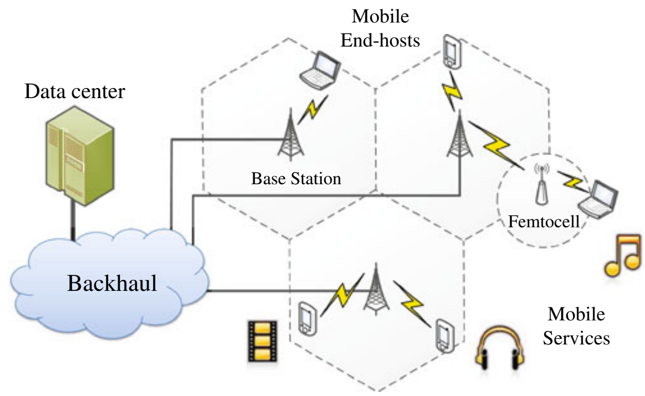

Fig. 2 A simplified structure of a mobile cellular network is illustrated, which mainly consists of five components: data centers in backhaul, macrocells, femtocells, mobile end-hosts, and various mobile services

It is observed [23] that data centers are always overprovisioned; at most time, the utilization of the data center, with respects to traffic load and the computational power, is far below the peak value. Therefore, many schemes are targeting the effective scheduling of fine-tuning or even turning off the software-level functions and hardware-level devices depending on the traffic load and user demands. The representative methods in [23, 24], and ElasticTree [25], optimally shut down idle network devices, independent cables in bundled links, unneeded links and switches to green the data center backhaul networks. The work in [24] unveils the fact that many links in core networks are actually "bundles" of multiple physical cables and line cards that can be shut down independently by linear optimization solutions. Another work, ElasticTree [25], finds minimum-power network subsets across a range of traffic patterns, and also scales up and down the network functionalities. Note that the resource adaptation problems in this direction are identified as NP-complete [24].

Furthermore, many designs rely on virtualization technique, which virtualizes a physical machine to multiple instantiations of operating systems, say virtual machines (VMs), simultaneously in order to eliminate the hardware constraints and to make the computing and storing more flexible and efficient. For instance, the VM migration in the GreenCloud [26] provides mobility for users to work on difference VMs at different times, while the live VM migration method in [27] can transfer the virtual machine workload from one physical machine to another without interrupting the services, so that the whole data center can adjust the resource dynamically to meet the elastic demands. The traffic-aware VM placement proposed in [28] considers the diversity of server capacity and user proximity

Fig. 3 We show the summarization on reviewed green techniques of all components of the mobile networks, and categorize them into three kinds: processing, communication and system

Components	Topics	Category
Data centers	• ON/OFF resource allocation: [23], [24], [25]	Processing
	• Virtualization [26], [27], [28]	Processing
	• Cooling management: [29], [30], [31]	System
Macrocells	• Dynamic scheduling: [32], [33]	Processing
	• Optimization of cell deployment: [34], [35], [36], [37]	System
	• Power saving of Power Amplifier: [38], [39], [40], [41], [42], [43]	Communication
Femtocells	• Coverage optimization and power control: [48], [49], [50], [51], [52], [53], [54], [55]	Communication & System
	• Interference avoidance: [50], [55], [56]	Processing
End-hosts	• Energy profiling: [57], [58]	System
	• Utilization of multiple radios: [59], [60]	Communication
	• Energy efficient transmissions: [61], [62], [63]	Communication
Applications & Services	• Adaptive power-saving design: [64], [65]	Processing
	• Prediction-based adaptation: [66]	Processing
	• Proxy-based caching: [67][68]	Communication
	• Energy-efficient location-based services: [70], [71], [72]	Communication & System

based on practical traffic patterns and aligns VMs optimally to improve the scalability and efficiency.

From the cooling management aspect of the data centers, besides the traditional air-side economizing methods [29], new advanced cooling methods, e.g., the chilled-liquid cooling [30], are bringing significant reduction of energy consumption to maintain low temperature for the servers in data centers. Also the wireless sensor assisted cooling method, e.g., Microsoft's Genome project [31], can help the operators conveniently monitor and improve the efficiency of cooling system of the data centers.

2.2 Macrocells

It is pointed out that, nearly 60% percentage of energy consumption of a cellular network is for operating the macrocell base stations (BSs) [18]. Therefore, the research work orienting the greenness of macrocell base stations has recently gained great momentum in the following three aspects: **dynamic scheduling of BSs**, **cell zooming** and **power-saving of power amplifiers (PAs)**.

BSs are suffering from "over-provisioning" problems [32, 33], so by tuning the BSs, on or off, based on the dynamics of traffic load, energy can be greatly saved from the view of whole mobile networks. The work in [32] utilizes a predefined sleep scheduling for BSs according to traffic variation patterns over time. Similarly, the work in [33] also targets adaptive scheduling which can optimally adjust certain low-loaded BSs while considering and evaluating the tradeoff between energy conservation and coverage guarantee of BSs, as well as the tradeoff between centralized and decentralized scheduling algorithms.

Targeting multi-user environments in specific commercial mobile networks, the work in [34] proposes the power-saving scheduling of BSs with consideration of QoS requirements (delay and jitter) of the real-time communications in WiMAX network, and the work in [35] evaluates several radio management scheduling algorithms for the LTE BSs, and effectively exploits multi-user diversity in the time, frequency and space domains for LTE networks. In all, energy-efficient scheduling of BSs relies on the awareness of the traffic load of users, and must consider the characteristics of the specific mobile system, as well as the QoS requirements in commercial services.

In practice, macrocell BSs are densely deployed to guarantee the effective coverage, but significant waste of money and energy resource are induced. Therefore the work in [36] designs efficient cell zooming strategy, which adaptively adjusts the cell size according to traffic load, user requirements, and channel conditions, and effectively leverage the trade-off between energy saving and blocking probability. Another similar proposal in [37] proposes a cell-size adjusting algorithm based on the traffic demands and rates, together with self-organization techniques, such as sleeping scheduling, location prediction and reverse channel sensing.

It is measured that 50% of the energy consumption of the radio in the BS is attributed to the PA [38], and particularly current 3G networks are mostly using the linear PAs for high bandwidth and good signal quality, at the expense of low energy efficiency inherently. Therefore the method in [39] dynamically adjusts the supply voltage of BS radio according to the output signal, so the supplying voltage margin and the power losses in the linear PA are reduced. Also, the green power amplification techniques for 3G+ networks are discussed in [40] at different levels, such as, improving the QoS to the radio frequency (RF) power radio, and scaling the energy needs with the traffic demands. Orienting the LTE BS system, the study [41] discusses the time-domain approaches, such as the optimization on the overhead of control frame and cell discontinuous transmission approach [42], frequency domain approaches, like bandwidth reduction and carrier aggregation, and spatial domain approaches, like optimal reduction of antennas and the cell-switch-off scheme [43].

Overall, the energy efficiency at BSs should be conjunctively researched with deployment strategy, associated cooperation of BSs and power-saving mechanisms of BS radios, whilst considering more practical traffic load dynamics [44].

2.3 Femtocells

Recently, together with the rapid development of WiMAX and LTE networks, the research on femtocells is becoming very hot [45–47]. For the mobile operators, the attractions of a femtocell are improvements to both coverage and capacity while optimizing the energy consumption and BS deployment cost effectively. Mobile users can also benefit from the improved signal quality within the femtocells and enjoy a potentially longer battery life. Hereby, we elaborate that green techniques for femtocells mainly fall into the topics of the **coverage optimization with power control** and the **interference avoidance**.

The work in [48] evaluates how exactly a femtocell can adjust transmission power and consume energy, and hence verifies that the power control is a "must" for balancing between the coverage and performance, and thus greening the femtocells. Also based on the modeling and prediction of outdoor and indoor user mobility, the adaptive coverage algorithm in [49] is proposed to optimize the coverage and minimize the power consumption. Meanwhile, there are many prior studies targeting practical power-saving issues for the femtocells in various commercial mobile networks, such as [50] in CDMA network, [51] in WCDMA network, [52] in HSDPA network, [48, 53, 54] in WiMAX networks and [47, 55] in LTE network etc. Particularly, for the WiMAX femtocell, the work in [53] focuses the location-aware cooperative resource management by adapting the Cognitive Radio (CR) technique to clients, femtocells, and BSs. It intelligently adjusts power, channel and computing resources to accommodate the entire network ecosystem. However the work lives in simulation stage and lacks realistic support of CR. From the practical perspective, the empirical deployment of WiMAX femtocells in Korea is introduced in [54], and the study indicates the great benefits of using WiMAX femtocells with aspects to network scalability, energy efficiency and capital expenditure. They also discover new challenges, like accurate time synchronization and adaptive auto-configuration issues.

Interference between macrocells and femtocells has become a big problem of current mobile networks, as it wastes energy unnecessarily. Therefore effective interference avoidance strategy is important, like [50], which evaluates the spectral efficiency metric defined by the number of active macrocell users and femtocells per cell-site, and analyzes the power control, path loss and shadowing effects for avoiding inter-tier and intra-tier interference in the shared spectrum of two-tier CDMA network. The work in [55] devises efficient algorithms to help LTE femtocells to choose spectrum optimally so that they can achieve high data rates without causing interference to users in the traditional macrocells. Also the power control strategy in [56] can alleviate the interference among the macrocells and femtocells based on the SINR-assisted link budget analysis. However, some unsolved issues in this direction, like the hidden terminal problem [55], are still open for further research.

2.4 End-hosts

Mobile end-host devices have evolved from simple phones to high-end computing and communication devices, e.g., smartphones and tablet PCs. The fast development of global market of end-host device and the increasing demands of the computational power of various mobile services are driving researchers to consider more severely about the power-saving issues of the end-host devices. Most of the green techniques for end-hosts are within following three directions, **energy profiling**, **utilization of multiple radios** and **effective transmissions**.

While implementing green techniques at the end-hosts, comprehensive and accurate knowledge of all energy demands, local resources, traffic pattern and user behaviors of the mobile end-host system, called energy profiling, is of significant importance [57]. For instance, the work in [58] focuses on the pattern of traffic load and energy consumption of 3G smartphones in order to profile the relationships among smartphone traffic, contents, energy consumption and radio power management. In this study, the power consumption of radio is expected to be able to shrink significantly (up to 35%) if the device functions are tuned adaptively and the sleep timers are adjusted optimally. The energy profiling assisted predictions on the user demand and resources utilization will effectively help the energy conservation of end-hosts.

Most current end-host devices are equipped with multiple radios, e.g. bluetooth, WiFi and 3G, with different magnitudes of energy-consumptions [59], while users utilize different interfaces for data communication in different environments and conditions. Targeting those multi-radio smartphones, the work in [60] quantitatively measures and estimates the power consumption of devices with different radios for various network activities and application contents, and then devises algorithms to learn and predict available network resources in order to automatically switch to a proper radio interface for each condition.

Transmission is the most energy-consuming mode of end-hosts as measured in [57], so energy-efficient transmission schemes are highly needed to prolong the battery life of end-hosts, while the QoS should be maintained at an acceptable level. The work [61] discussed the tradeoff between QoS and delay of data transmission for mobile end-hosts, and presents an online optimization algorithm to decide whether and when to defer a transmission by considering the deadline boundary of tolerance of transmission requirements and adapting to channel condition and location information. Another energy-efficient transmission scheme, Catnap [62], exploits the bottlenecks of wireless and wire links, and utilizes an application proxy to decouple data unit into segments, schedule the segments to be transferred in a burst with high speed but short time, and merge tiny gaps between packet transmissions into meaningful sleep intervals, so the device can "rest" during data communication, while delays for each segment won't affect the total delay of unit transmission. However the scheme requires a modification on the network gateway (e.g. AP in WiFi, BS in cellular network). A more practical piece of work, Bartendr [63] demonstrates the fact that strong signal reduces energy cost from empirical measurement, and then develops energy-aware scheduling algorithms for different workloads (background synchronization traffic and video stream traffic) based on the signal prediction by location and history.

Conclusively, most of the proposals for green end-hosts achieve remarkable improvement of energy-efficiency, but they always rely on dense deployment of heterogeneous mobile networks, or focus on the particular delay requirements of services. Also not only the QoS but also the Quality of Experience (QoE) for users should be minimally affected by radio switching, which still remains challenging.

2.5 Applications and services

The key mission of mobile networks is to offer satisfying services to mobile users, such as, video casting, VoIP calls, web surfing, online gaming, file sharing etc. As predicted in [7], in 2015, the mobile applications and services will generate 26 times more traffic load than that in 2010, so they should be designed with more serious concerns to the energy efficiency. In one word, they must be able to work adaptively based on the dynamics of wireless links and user demands, while the mobile network systems, at not only end-host side but BS side, should also be able to optimally tune system and hardware parameters to offer proper support to deal with the dynamics of service activities. From related work, we can summarize three directions for designing the "green" applications and services, including **inherent power-saving design**, **predication-based adaptation**, and **proxy-based caching**. Also we will discuss the energy efficiency of the Location-Based Services (LBSs), as they are one of the representative services in current 3G/4G networks.

The fundamental approach to green the mobile applications and services is to introduce specific power-saving designs inherently. Targeting particular service types, e.g. video transmission and voice call, the work in [64] introduces an adaptive approach to reduce power consumption of multimedia transmissions over wireless channels by selecting proper source compression, coding and transmission strategy subject to a required end-to-end source distortion, depending on the varying channel quality. Also there is another work [65] discussing the energy efficiency of VoIP service, but more work about reducing energy waste for mobile VoIP is still pending.

Another direction of designing energy-efficient applications is based on the prediction of application activities by learning the historical pattern. For instance, targeting the mobile gaming service, the proposal in [66] carries out measurement, modeling and prediction of gaming actions, to dynamically limit and adjust the low-layer functions of mobile end-hosts (e.g., power control and coding schemes) for saving energy while still preserving the user experience. However, it is still complicated to learn and predetermine game actions, especially in a real-time manner, which is the drawback of these prediction-based approaches.

Distributed proxy-based caching servers will both significantly help the energy conservation of end-hosts and improve the performance, especially for heavy-loaded services, since the most energy-consuming task, downloading transmission, will be done by dedicated proxy servers, and then whole content will be transferred to a mobile end-host intensively in a short time. With respect to the P2P transmission service, Cloud-Torrent [67, 68] analyzes and evaluates the energy efficiency of BitTorrent service for mobile phones by utilizing distributed proxy servers from cloud service. However, proxy-based schemes highly rely on remote servers, which will bring more deployment cost in practical, and moreover, how to inherently reduce energy consumption for P2P protocols (or other content sharing protocols) for mobile environment is still unexplored and challenging.

Recently, a myriad of LBSs have become popular on mobile end-hosts over the past several years. Excessive use of LBSs can however drain out the device battery, owing to their power-intensive localization operations. Therefore, different from traditional accuracy-oriented localization mechanisms, such as GPS and Skyhook [69], various novel energy-efficient localization schemes are proposed recently, like Entracker [70], EnLoc [71] and A-Loc [72]. Entracker [70] schedules localization updates to both minimize energy consumption and ensure robustness, based on the estimation and prediction of system conditions and mobility. Similarly, the EnLoc framework [71] characterizes the optimal localization accuracy for a given energy budget, a nd develops a prediction-based heuristic algorithm for real-time localization. Furthermore, based on two investigations that mobile services always do not require high-precision accuracy in practice, and the required localization accuracy normally varies with LBS environment, A-Loc [72] automatically determines the accuracy requirement for specific mobile applications, and continually tunes the energy budget on localization sensing so that the appropriate accuracy can be guaranteed.

3 Green projects and metrics

Within recent year, a growing number of green projects are funded to facilitate the research, experiment, deployment and evaluation of green techniques for mobile networks. In this section, we present a summarization of research projects on green mobile net-

Project	Organizer	Region	Participants	Targets	Working Emphasis
EARTH	European Commission FP7 IP (3 years / 15 million €)	Europe	European main mobile operators and research organizations	Mobile networks	• energy aware radio and network technology • energy-efficient deployment, architecture, adaptive management • multi-cell cooperation
Green IT	METI & JEITA (Japan)	Japan	Over 100 companies, institutes and organizations	IT	• power efficiency at data centers, networks, displays • policy and mechanisms to encourage green IT • collaboration of industry, academia and government
GreenTouch	GreenTouch Consortium	Global	Experts form industry and academia	Telecom networks and mobile networks	• reinvention of telecom networks • sustainable data networks • optical, wireless, electronics, routing, architecture, etc.
OPERA-Net	CELTIC / EUREKA (3 years / 5 million €)	Europe	European main mobile operators	Mobile networks	• heterogeneous broadband wireless network • mobile radio access network • link-level power efficiency, amplifier, test bed
GREEN-T	CELTIC (3 years / 6 million €)	Europe	European main mobile operators	Mobile networks (particularly 4G)	• multi-standard wireless mobile devices • cognitive radio and cooperative strategies • QoS guarantee
GreenRadio	MVCE (3 years)	UK	UK universities	Base station and handsets of mobile data service	• power amplifier, power efficient processing • backhaul redesign, multi-hop routing, relaying, • resource allocation, dynamic spectrum access
Cool Silicon	Silicon Saxony Management	Global	Over 60 global ICT companies and institutes	ICT	• micro-/nano-technology • media communication • sensor newtork.
Green Grid	8 Main Contributor Companies	Global	Global ICT Companies	Data centers	• data center energy efficiency (design, measurement, metrics)
GSMAMEE	GSM Association Congress	Global	Over 800 mobile operators and 200 companies	Mobile networks	• benchmarking of mobile energy efficiency networks
Green500	Virginia Tech	US	Virginia Tech	Supercomputer	• benchmarking of greenest & fastest supercomputers
Cool IT	GreenPeace	Global	GreenPeace	IT	• leaderboard of IT brands on the contributions to the green IT

Fig. 4 Summarization of green mobile networks projects

Metrics	Full Names	Creator	Targets	Calculation	Units	Remarks
PUE	Power Usage Effectiveness	Green Grid	Data Center	$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment Power}$	Ratio	Ranging from 1 to infinite
DCiE	Data Center infrastructure Efficiency	Green Grid	Data Center	$DCiE = \frac{1}{PUE} = \frac{IT\ Equipment\ Power}{Total\ Facility\ Power} \times 100\%$	Percentage	Ranging from 0 to 100%
DCP	Data Center Productivity	Green Grid	Data Center	$DCP = \frac{Userful\ Work}{Total\ Facility\ Power}$	Ratio	Ranging from 1 to infinite
ECR	Energy Consumption Rating	ECRInitiate, (IXIA, Juniper)	ISP, ICT enterprises	$ECR = \frac{Energy\ Consumption}{Effective\ System\ Capacity}$	Watt / Gbps	Energy normalized to capacity
ECRW	ECR-Weighted	ECRInitiate, (IXIA, Juniper)	ISP, ICT enterprises	$ECRW = \frac{(0.35 \times E_f + 0.4 \times E_h + 0.25 \times E_i)}{T_f}$	Watt / Gbps	E_f, E_h and E_i are the energy consumption in full-load, half-load and idle modes respectively. T_f is the effective throughput.
TEER	Telecommunications Energy Efficiency Ratio	ATIS	General, Server, Transport	$TEER = \frac{\sum_{i=1}^{n} D_i}{\sum_{j=1}^{m} \left(\frac{P_{0j} + P_{50j} + P_{100j}}{3} \right)}$	Gbps / Watt	D_i is the data rate of each interface i; P_{0j}, P_{50j}, and P_{100j} are the power of module j at data utilization of 0%, 50% and 100% respectively
TEEER	Telecommunications Equipment Energy Efficiency Ratio	Verizon NEBS	Transport, Switch, Router, Access, Amplifier	$TEEER = \log \left(\frac{0.35 \times P_{MAX} + 0.4 \times P_{50} + 0.25 \times P_{sleep}}{Throughput} \right)$	log (Watt / Gbps)	Referring from ECRW and TEER, P_{MAX}, P_{50} and P_{sleep} are the power consumption at 100%, 50% and 0% load utilization. (Formula may change based on different types of devices)
CCR	Consumer Consumption Rating	Juniper	Consumer network devices	$CCR = \frac{E}{\sum A(j)}$	rad(dimensionless)	E is power rating of a consumer network device; A is energy allowance per function; j is the set of all allowances claimed. Value 1 matches an average device.
EPI	Energy Proportionality Index	HP Labs	Network Devices	$EPI = \frac{PM - PI}{PM} \times 100\%$	Percentage	PI is the power consumption at idle mode, PM is the power consumption at maximum workload
WattsPerVLL	Watts Per VLL	Ericsson	IP Networks	$WattsPerVLL = \frac{Power\ Consumption}{Number\ of\ VLLs}$	Watt / line	Used for *Virtual Leased Line* (point-to-point Ethernet-line) services based on the *Number of VLLs*
WattsPerMAC	Watts Per MAC port	Ericsson	IP Networks	$WattsPerMAC = \frac{Power\ Consumption}{Number\ of\ MAC\ ports}$	Watt / port	Used for *MAC address* (multipoint Ethernet-LAN) services based on the *Number of MAC ports*
P_{BBline}	Power consumption per line of Broadband	ETSI	Broadband telecommunication networks equipment	$P_{BBline} = \frac{P_{BBeq}}{No.Of\ Sub\ Lines}$	Watt / subscriber line or Watt / port	P_{BBeq} is the Power consumption of fully equipped broadband equipment, *No.Of Sub Lines* is the maximum number of subscriber lines supported
NPC	Normalized Power Consumption	ETSI	Broadband telecommunication networks equipment	$NPC = \frac{1000 \times P_{BBline}}{Bit\ Rate \times Line\ Length}$	Watt / (Mbps x km)	Normalized power consumption per line for broadband network equipment based on the line length

Fig. 5 Taxonomy of green metrics

works from governments, academies, operators and vendors, and also we compare most of the green metrics proposed for evaluating energy efficiency of network system in recent literature. Note that we summarize and compare the green projects and metrics in the tables in Figs. 4 and 5 respectively.

3.1 Projects of green mobile networks

Governments have funded and developed a series of directives aimed at obligating corporations to become more energy-efficient, using greener techniques and thereby reducing CO_2 emissions. As a pioneer of the revolution on green mobile networks, the Framework Programme 7 by the European Commission has pushed several long-term research projects [73], for instance the *EARTH* project [74], which is a highly ambitious and unique project for investigating the energy efficiency of mobile communication systems. It will mainly investigate the theoretical and practical energy-efficiency limitations of current mobile networks, while developing new generation of energy efficient equipments, comprising components, deployment strategies and network management solutions, but still maintaining high capacity and un-compromised QoS. Practically, *EARTH* mainly focuses on mobile cellular systems of LTE and LTE-Advanced, but it will also consider 3G (UMTS/HSPA) technology for immediate impact.

Japan government also shows great interests to the green networking technology, and establishes the *Green IT* [75] targeting the power efficiency techniques of data centers, networks and displays, while setting related policies to encourage the collaboration of industry and academia for greening the networks and computers.

The dramatically increasing pressure to ICT companies to develop green techniques has driven their international cooperation widely, and the activities among leading industry entities in form of associations and organizations will perform key role to help reducing the emission of CO_2 eminently. For instance, the *GreenTouch* [76] is a consortium of about 30 global leading ICT companies and research institutes dedicated to fundamentally transforming communications and data networks, and significantly reducing the Carbon footprint of ICT devices, platforms and networks. Their goal is to increase network energy efficiency by a factor of 1000 from current levels until 2015.

The *OPERA-Net* project [77] and the *GREEN-T* project [78], managed by a European Consortium composed of global ICT companies, both desire to overcome the energy trap of emerging mobile systems by investigating and demonstrating energy saving technologies. They mainly focus on the holistic approaches to optimize power efficiency in heterogeneous mobile broadband networks (4G) by addressing multiple objectives, like radical improvement in energy efficiency at system, infrastructure and terminal level, new metrics for evaluating energy efficiency, cooperative cognitive radio, data rate and QoS support etc.

The Mobile Virtual Center of Excellence (MVCE) core 5 programme of *Green Radio* project [6, 79] is a 3-year industry-government funded research program started in 2009, focusing on designing new green architectures and reducing energy consumption in individual base stations and handsets, with respects to power amplifier, processors, sleep modes, backhaul, multi-hop, relaying, resource allocation and dynamic spectrum access.

Cool Silicon Cluster [80] in Germany, with more than 60 global companies and research institutions, has shown their emphasis on energy-efficient innovations, and has tried to contribute to a reduced time-to-market for innovative products, processes and services of green ICT. *Cool Silicon* focuses on three key projects: cool computing for seeking top performance and high energy-efficiency for micro- and nano-technologies, cool reader for reducing energy consumption in media communication systems, and cool sensor networks for developing special energy autarkic sensors.

The *Green Grid* consortium [81] consisting a number of global IT companies seeks to unite global industry efforts to standardize on a common set of metrics, processes, methods and new technologies for green data centers and business computing ecosystems. Particularly, *Green Grid* has already announced two important evaluation metrics for energy efficiency of data centers, Power Usage Effectiveness (PUE) and Data Center infrastructure Efficiency (DCiE) [82].

Benchmarking and ranking services are also effective to promote and encourage the revolution of green mobile networks. The Mobile Energy Efficiency Network Benchmarking Service offered by *GSM Association* [83] helps mobile network operators benchmark and then lower their energy costs. The *Green500* [84] maintains a global rank on the energy-efficient super-computing systems, and furthermore, the *Cool IT* leader-board [85] calls on leading IT companies to collaborate for green techniques by regularly tracking the greening progress of the IT brands. The ranking will mainly consider three key aspects: the efforts to offer world-wide technological climate solutions that contribute to global greenhouse gas reductions, the initiatives to reduce their own global warming emissions, and the active engagement in political advocacy and support for science-based climate and energy policies.

3.2 A taxonomy of green metrics

Recently research efforts devoted towards the evaluation of the energy efficiency of mobile network systems and particular devices have been proliferated, and hence various energy-efficiency metrics, say green metrics, are proposed. The green metrics can be mainly categorized as two types [86], **equipment-level metrics** and **facility-level metrics**. The equipment-level metrics account for the lower-level energy efficiency rating of an individual piece of mobile network equipment with specific functionality, in a micro perspective, such as Energy Consumption Rating (ECR) [87], Consumer Consumption Rating (CCR) [88], Telecommunications Energy Efficiency Ratio (TEER) proposed by the Alliance for Telecommunications Industry Solutions (ATIS) [89–91], Telecommunications Equipment Energy Efficiency Rating (TEEER) by Verizon NEBS Compliance [92], Normalized Power Consumption (NPC) [93], PBBLine [87] etc. And the facility-level metrics are related to high-level energy efficiency of a consolidated system consisting of interconnected devices and networks, in a macro perspective, such as data center metrics, including PUE, DCiE and Data Center Productivity (DCP) designed by Green Grid [82].

Green metrics at early stage is normally calculated by the energy consumption of the network or consumer equipment normalize by the performance, or by provisioned total power (or the reciprocal of either), such as, PUE, DCiE, DCP, ECR, NPC etc. Particularly, PUE is defined as the ratio of total facility power used by data centers to the total power that delivered to the equipments, DCiE is a reciprocal of

PUE times 100, and DCP is the productive useful workload normalized to the total facility power. Recent green metrics are applying more adaptive evaluation considering the effective load (traffic load or computing load) of specific type of devices or system functions (e.g., general devices, network servers, transport devices etc.), normally in three utilization cases, idle, half-load and full-load, such as, TEER, TEEER, ECR-Weighted (ECRW) [87] etc. Those green metrics can estimate and unveil a more valuable and practical reference to guide the industry to determine equipment's energy efficiency, and thus to design new green techniques.

Due to space limitation, we list details of the metrics as shown in the table in Fig. 5. In the future, more effective designs of green metrics can target how much percentage of power can be further saved under the technique or standard, or how much CO_2 emission can be converted and generated in relation to delivered QoS and system utilization efficiency. Forceful definition of green metrics will not only help network vendors and mobile service operators to quickly estimate the energy efficiency of their equipments and systems, but also further accelerate the standardization and then the integration of various green techniques.

4 Impending research issues

Green mobile networking technology will play an important role in enabling the new stage of energy-efficient ICT industry, but many impending and challenging issues still remain to be addressed, as summarized in this section as following.

4.1 Green communication techniques

4.1.1 How green are 4G networks?

The proposal of next generation (4G) mobile networks are discussed and then finalized by two class of standards, LTE-Advanced and WiMAX 2 (based on 802.16 m). The greenness of ICT in the next decade will highly depend on the the energy-efficient techniques of these two standards. However, in current stage, they both mainly emphasize the spectrum efficiency and performance capacity, with no or limited consideration on energy saving issues. Researchers are still facing to many remained challenges for further greening 4G networks as suggested in following:

- Both 4G standards utilize Multi-Input and Multi-Output (MIMO) technique for high carried throughput, which also significantly swallows huge amount of energy [94]. This energy-consuming issue becomes more serious when utilizing multiuser-MIMO technique. More efforts should be paid on the concerns of the processing complexity, the power consumption of the tight channel synchronization, and the energy cost of channel characterization with respect to the mobility of devices and link dynamics of outdoor environment. Also from the MAC layer, MIMO-oriented energy efficient MAC protocol is also highly needed to adaptively utilize necessary number of antennas by balancing the reliability level and multiplexing gain, and also by reducing frame overhead. Furthermore, the Large-Scale Antenna System (LSAS) [95], an extended MIMO system with hundreds of antenna elements, each of which consumes smaller amount of energy, is recently designed to bring tremendous improvement of energy efficiency for the mobile networks. In LSAS, the radiated power consumption can be reduced as the number of antenna elements is increased, and LSAS avoids the dissipated signal radiation in broadcasting manner but forces it directly to point at the mobile user. More practical research and experiments for multi-user LSAS are imperative.
- When an end-host roams near the edges of cells, 4G networks support coordinated multi-point communication with intra-site and inter-site modes to overcome the weak signals and cell interference. By the edges, the end-host always consumes higher power to communicate with BSs, therefore, energy-efficient algorithms for coordinated multi-point communication are needed, while the QoS guarantee becomes more challenging.
- Handovers of the end-host from current BS to a better BS take certain amount of time and energy by ranging and associating behaviors. Therefore, more effective and adaptive handover schemes will be needed for both homogeneous and heterogeneous mobile networks, e.g. [96].
- Although many operators, e.g. Vodafone, AT&T, Sprint, KT, Verizon etc., have already launched femtocell services, researchers are still tuning the femtocell systems regarding the energy-efficiency by putting more efforts into the tradeoff between the size of femtocell coverage and usage demands in homogeneous and heterogenous mobile networks [97]. Future challenges still fall within the traffic load sensitivity, the optimization adjustment of the femtocell power due to the dynamics of users and environments, and the interference avoidance along with the hidden terminal problems.

4.1.2 Tethering and multi-hop

The hierarchy infrastructure of mobile cellular networks omits the potential connectivity and interactions among end-hosts. The host-to-host modes supported in the 3G, 3G+ and 4G networks, such as **tethering** and **multi-hop**, will possibly improve the scalability and the energy efficiency of mobile networks [98, 99]. The tethering-mode [98] enables the direct data communication among a group of end-hosts in the ad hoc manner while the tethering gateway end-host will share the Internet access to other devices based on striping transmission schemes. Also multi-hop routing and transmission among tethered end-hosts, are attractive but challenging. Although [99] proposes an opportunistic relay selection method for the greenness of multi-hop transmission in cellular networks, due to lack of practical implementation, many crucial issues are still unexplored, including the efficient pre-fetching and caching algorithms, the balancing problems of energy and traffic load among tethered end-hosts, as well as the pricing and security issues.

4.1.3 Cognitive radio

One big problem of current telecommunication system is that most users are congested in very limited RF spectrum, while many of the spectrums are not utilized optimally. The cognitive radio (CR) technique [100], allows a network system or a wireless node to change the transmission or reception parameters thus to tune and to communicate via various RF spectrums dynamically to avoid interference with concurrent users. Therefore it enables efficient share of spectrums, and hence brings significant improvement of green mobile networks, but it consumingly relies on the active monitoring to maintain the awareness of user behaviors and link conditions in the internal and external radio environments. The CR technique brings opportunities and benefits to green both mobile service providers and end-hosts [53, 101], but due to the limitation of practical CR hardware development, most of current work stays at literature and simulation. In future, three important directions of utilizing CR techniques will be probably the intelligent spectrum sensing for mobile users [101], dynamic spectrum allocation for targeted QoS requirement, and the reliable spectrum management in mobility race condition.

4.1.4 Green mobile sensor networks

Towards to the coming heterogenous environment of mobile communication, the integration of mobile sensor networks and other network systems, e.g. mobile cellular networks, will bring ubiquitous and intelligent services to users anytime and anywhere. For mobile sensor networks, the power consumption issue becomes more serious for a sustainable deployment. Although various green schemes are proposed to improve the energy efficiency of the mobile sensor networks, from the aspects of compressed data aggregation [102], sensing dispatch [103], sensor visualization [104], diagnosis [105] and so on, more efforts are still desired for deeper investigation among the factors of energy-awareness, mobility-awareness, QoS requirements and deployment cost.

Also large-scale deployment of green sensor networks targeting the climate surveillance will significantly help to monitor the greenness of the ICT industry and the earth. For instance, the GreenOrb project [106, 107], has tailored a highly capable wireless sensor network in wild environment for the purposes of canopy closure estimates, forestry fire evaluation, wild succor and so on. Apparently, more efforts of bringing academic proposals to practical surveillance applications in this direction are encouraged.

4.1.5 Mobile M2M communication and Cyber-Physical System (CPS)

The Machine-to-Machine (M2M) communication technique enables intelligent [108] interconnecting of physical objects, and particularly the cellular-based M2M [109], will further realize the wireless talks among terminal things in a wider range, to support more dynamic services, like telematics, smart metering, automation etc. The energy-efficient mobile M2M communication faces to many obstacles, like the sustainable power supply for mobile artificial machine and energy-efficient strategy for peer-to-peer communication protocol etc.

Based on the sensor, M2M and energy scavenging techniques, the concept of Cyber-Physical System (CPS) [110] is proposed to tightly combine, and coordinate between, the system's computational and physical elements, targeting the monitoring and controlling of the physical processes with feedback loops, where physical processes affect computations and vice versa. While carrying out extensive research topics on the structural designs, reliability, and security of CPSs, the energy efficiency issue will be critical due to the limited power supply of the cyber sensors and physical actuators. Especially in mobile CPSs, e.g., aerospace, automotive and health care applications [111], the balance among performance, safety and energy-efficiency of CPSs should be seriously considered. Future research topics on how to integrate CPS with mobile cellular networks for ubiquitous services will be with great importance and interest.

4.2 Green service techniques

4.2.1 Cloud computing for mobile networks

Cloud computing [112] transits most computations from personal clients and enterprize servers to dedicated remote "clouds" (data centers) through network communications effectively. It is expected that the cloud computing will make significant contributions for green ICT industry [113] and thus cut the global Carbon emissions [114] effectively. Especially, mobile devices with limited power supply and computational capacity will have increasing opportunities and advantages to benefit from the cloud computing in mobile space, with respect to not only cloud storage and computing but also ubiquitous mobile services.

However, practical analysis in [115] indicates that cloud services at current stage are mainly targeting the performance of storage, processing and transportation, and are taking less care of the energy-efficiency. So researchers should pursue more green techniques and more practical efforts to further develop the mobile cloud computing in a greener way [116]. As learned from a prototype of cloud-based mobile service, the Stratus [117], a bundle of energy-efficient techniques are strongly required but still in suspense [118, 119], such as, data aggregation to bunch up sporadic transmissions, asymmetric dictionary-based compression, and efficient algorithms for cloud selection and service replica sharing. Also in order to balance the tradeoff between communication energy and computing energy, more challenges are yet impending [114], like the effective estimation of computational requirements and QoS demands, energy-aware middleware for automatic decision between local and cloud processing, and the adaptive provisioning considering the dynamics of wireless links and user activities.

4.2.2 Tradeoff between "Greenness" and "QoS"

Many of the green techniques gushing into the field of mobile networks may achieve the energy efficiency based on certain sacrifice of system performance as discussed in Section 1 and illustrated in Fig. 1. For instance, the work in [60] and [70] reduce power consumption based on mobility prediction, but the prediction fails in worst cases, which may lead to seriously degraded performance. So despite the efforts in the design of green techniques, it is imperative to develop appropriate techniques by jointly considering the network capacity, energy consumption, and adequate QoS.

There are several critical issues for balancing "greenness" and "QoS" which still require further investigation. We detail several potential research trends as follows:

– **Balancing in the heterogeneity**: The mobile devices have different storage capacity, power consumption limits, and QoS requirements. This heterogeneity makes the design of a comprehensive and QoS supportive architecture difficult.
– **Profiling and scheduling:** Profiling of various services and accurate predictions will help the network system to carry out effective scheduling methodology to improve energy efficiency and satisfy users. Also multi-profile based managements will definitely offer high flexibility for mobile networks to serve the various types of users and services with different QoS requirements.
– **Multi-radio performance and QoS:** When designing those scheduling and optimization of multi-radio end-hosts [60, 61], continuity QoS and QoE of applications should not be affected due to radio interface scanning and switching. Effective solutions are still remained open.

4.2.3 Prediction-based green techniques

In practical, energy can be wasted for many unnecessary behaviors in mobile networks, like overprovisioned resource allocation, failed routing in mobility rush case, and so on. Therefore, accurate prediction of traffic dynamics and user activities based on human-oriented activity model and mobility model will prevent the waste and improve the energy-efficiency of mobile service. For instance, the handover scheme for integrated WiMAX and WiFi networks in [96] avoids unnecessary handovers intelligently and increases the probability of associating with properly predicted network accesses based on the accurate model of historical handover patterns to conserve handover energy. There are some energy-aware scheduling algorithms, like Bartendr [63], based on the signal prediction by location and history modeling as well.

Although prediction-assisted green techniques can be widely applied, they strongly rely on collecting much geographical and activity information while bringing more industrial expense and energy consumption. Also, how to overcome the prediction failures caused due to the worst cases, and how to reduce the computation complexity of learning and prediction in real-time manner are challenging problems still.

4.2.4 Energy-efficient mobile P2P sharing

Legacy P2P sharing (i.e., BitTorrent) generates huge amount traffic load in the Internet, and the same thing is happening in mobile environment [7]. Much more energy will be consumed if legacy P2P protocol is directly applied into mobile applications, because frequent signal fluctuations and link disconnections will make the P2P protocol work inefficiently thus achieve poor performance as pointed out in [120, 121].

Distributed proxy and cache servers will highly help the energy reduction of end-hosts and improve the performance of heavy-loaded P2P transmission, as analyzed by CloudTorrent [67, 68]. More research efforts on energy-efficient mobile P2P sharing are highly encouraged. Even breaking up legacy P2P protocols, researchers are also facing to opportunities of inventing new efficient and green content sharing protocol for mobile network.

4.2.5 Energy-efficient LBSs

As described in Section 2.5, localization methods of LBSs rely on costly GPS or other embedded functions, which consumes a high amount of energy. In order to improve the energy efficiency of current localization schemes, the substitution, suppression, piggybacking, and adaptation of localization sensing requests to conserve energy are more promising and practical as discussed in [122]. Following some innovations of localization methodology, such as the accelerometer-based location estimation [123], and the distributed human-assisted localization in [124], more efforts should be contributed to help LBSs grow green. Practically, the localization is just a referencing joint between the users and LBSs, which can be transparent, therefore it doesn't always require too high accuracy [72]. So it is better to obtain or estimate the accuracy requirement for specific LBSs, and then to carry out adaptive location sensing based on the energy budget. The balancing among the energy efficiency, localization accuracy and response time, is still unexplored as an open issue.

4.3 Other issues

4.3.1 Standardization of green mobile networking

Great efforts have been put into the research of green techniques for mobile networks, but standardized rules are also required to explicitly identify *what is green* and *how it is green*. Currently IEEE is developing specifications for energy-efficient networking techniques while the IETF is specifying energy consumption monitoring requirements [12] and managed objects [13] for creating interoperable standards for green networks. In the meantime, 3GPP has been working on energy saving initiatives and green standards targeting current 3G networks architectures, like TSG RAN WG3 for energy saving of UMTS and LTE [14, 15], and the WiMAX forum is carrying out phase 2 standardization work on femtocell techniques as well [46]. Future standardization work will have to target the diverse requirements, flexible methodologies, vendor-independent attributes, and so on, considering the heterogeneity of the emerging mobile networks.

4.3.2 Pricing in green mobile networks

One more critical issue for greening the mobile networks is the effective pricing scheme. Traditional pricing schemes [125, 126] mainly focus the service bandwidth and contents. Therefore, the community currently still lacks of a set of representative green pricing policies, and there are only a few related research proposals, such as the compensation-based pricing model in [127] considering the QoS service degradation due to energy conservation and resource limitation of mobile virtual network operators, and the strategies in [128] and [129] to combine user pricing, network expenditure, and power control jointly for network-centric and user-centric radio resource management.

In the future, researchers must deliberate effective pricing strategies attending to the encouragement of greening the mobile networks, along with the QoS guarantee, for those users who take trails of green devices and applications, in order to push the mass to pay more attention to and thus transit to green mobile networks, from a long-term perspective to reduce the global CO_2 emission. Also pricing schemes for the tethering and multi-hop mode of commercial 3G, 3G+ and 4G mobile networks and those for the cognitive radio based mobile networks, are with great importance inevitably, but still unexplored.

4.3.3 New energy & materials for mobile networks

While countless efforts are put into power-saving communication techniques, research activities on discovering new energy source are strongly inspired in recent years, which can dramatically push forward the development of green mobile networks [130]. Efficient adoption of new power resource such as wind and solar to assist current mobile networks can be one promising direction. For instance, over 1 year, 1 m^2 solar panel can produce enough energy for 10% of the power requirement of a 3G macrocell BS, and it is also announced

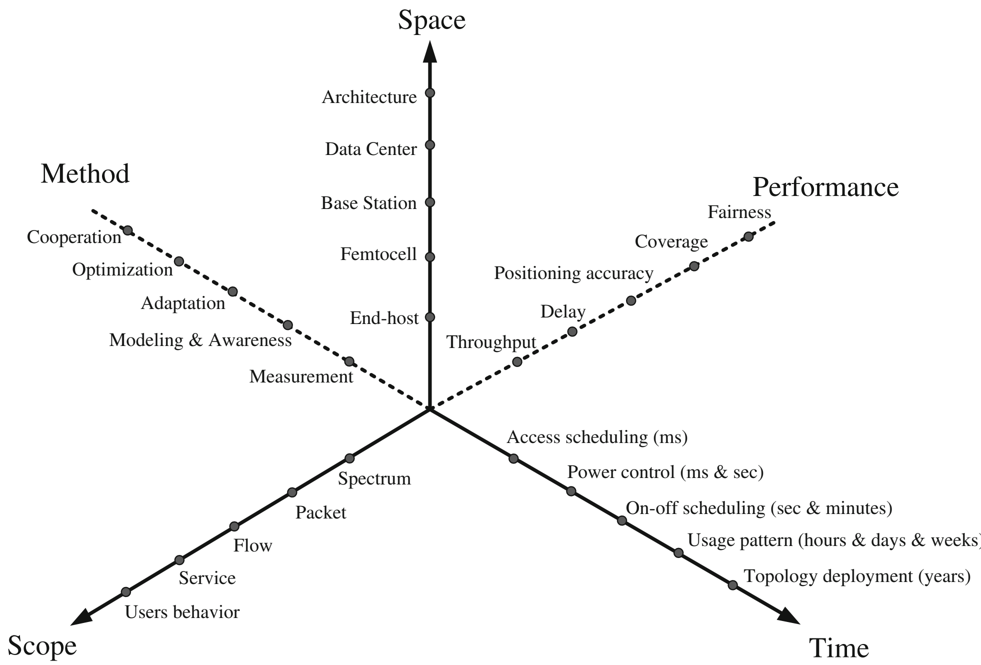

Fig. 6 Multiple dimensions of green techniques of mobile networks: space, time, and scope (method and performance dimensions are illustrated as *dashed lines*, because the factors of both are with no explicit sequence or direction)

that about 335,000 cellular base stations will include solar power by 2013 [130]. Furthermore, pioneer companies, such as Samsung, LG, Sharp, ZTE etc., have developed solar-driven smartphones already. However researchers are still dedicating to increasing the convert efficiency of those new energy. Also utilizing of renewable materials and recycling wasted materials can also contributing for the green ICT, and new methods of energy harvesting for mobile device, like the movement-driven and sound-wave-driven power supply, as well as the biology energy, will lead to new stages of green mobile networks.

5 Conclusions

In this paper, we have presented a comprehensive survey of current green techniques for mobile networks with their merits and demerits. Also we summarized recent essential research projects for green mobile networks and showed a taxonomy of green metrics. However, there are still many challenges that need to be addressed, especially on emerging green communication techniques and green service techniques, as well as standardization and pricing issues.

Conclusively, we further illustrate the Fig. 6 based on [10] to summarize the multiple dimensions of various critical factors for designing the green mobile networks, in terms of space, time, and scope. Space and time dimensions indicate where and when to apply the techniques, while the scope dimension shows the applied level or layer. Moreover, we draw the performance dimension identifying the QoS and fairness requirements, whilst general methodologies are listed in method dimension. Effective green techniques for mobile networks must rely on the consideration and balance among those factors.

Making the mobile networks green could not only have a tangible positive impact on saving the energy, but also help to achieve a long-term profitability of mobile service operators and sustainability of the environment. The revolution of green mobile networks will need not only the widespreaded acceptance but also great efforts and collaboration from the cellular service providers, device vendors, governments and the mass. Moreover, non-technical factors, such as, pricing and marketing strategy, law establishment, service affordability and user friendliness, would also play important roles in the success of the green mobile networking technology.

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