DIMENSIONING NETWORK DEPLOYMENT AND RESOURCE MANAGEMENT IN GREEN MESH NETWORKS

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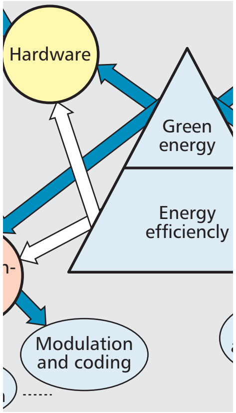

The authors argue that under the green network paradigm powered by renewable energy, the fundamental design criterion and main performance metric have shifted from energy efficiency to energy sustainability.

ABSTRACT

In this article, network deployment and resource management issues are revisited in the context of green radio communication networks with sustainable energy supply. It is argued that under the green network paradigm powered by renewable energy, the fundamental design criterion and main performance metric have shifted from energy efficiency to energy sustainability. As an effort to this end, in this article, new network solutions are proposed with an objective of improving network sustainability; the proposed solutions ensure that dynamically harvested energy can sustain the traffic demands in the network. Specifically, the placement issue of green access points (i.e., APs powered by sustainable energy sources) is investigated to meet the energy and QoS demands of mobile users; and an adaptive resource management scheme is proposed to address the unreliability of renewable energy in QoS provisioning. It is shown that by mitigating the energy depletion probability of green APs, sustainable network performance can be significantly improved.

INTRODUCTION

The unprecedented expansion of ubiquitous broadband communication networks and the increasing demand of multimedia services have led to a significant growth in the energy consumption of communication networks. Facing the fact that the cost of energy continues to rise, energy sustainability in the future has become one of the most important research directions in the information and communication technology (ICT) industry. To address this challenging issue, green radio communication networks using renewable energy sources have been emerging as a promising solution to achieve sustainable operation of communication networks.

In general, the development of a green radio communication network involves interdisciplinary research activities spanning multiple dimensions, including:

- Energy saving hardware and devices
- Energy-efficient communication techniques
- Energy-aware network architecture and protocol design
- Energy-friendly software and applications
- The development of alternative eco-friendly green energy, and so on

Figure 1 shows a block diagram of the solutions for green communication networks. First, a green communication network comprises a variety of electrical equipment, including network devices, network peripherals, customer electronics, electrical fans or other cooling systems, and more. The efficiency of the hardware devices as an organic system plays an essential role in reducing the energy consumption of the system. Furthermore, by exploiting advanced communication techniques (smart antenna, ultra-wideband communications, adaptive modulation and coding, cooperative communications, etc.), power transmission efficiency can be significantly improved. Intelligent energy management software and applications can also be developed to allow users to further optimize energy efficiency of the system, such as energy audit software and dynamic voltage control. In addition to the aforementioned, considerable energy reduction can also be achieved by upgrading the network architecture, optimizing resource allocation and network capacity planning, and improving data transmission, switching, routing protocols, and so forth. Recently, the United Kingdom's Mobile Virtual Center of Excellence (VCE) has undertaken research to improve the energy efficiency of a cellular network by reducing the number of active base stations (BSs) and reallocating their wireless users, or switching active BSs to operate at low-frequency bands [1] when the traffic load is low. It is shown that operators can achieve 70–80 percent energy savings by shifting to low-frequency operation. They also find that the deployment of power-efficient small-size femto-

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cells in a macrocellular network can greatly reduce the power consumption per user in the network [2]. Reference [3] presents a new architecture of cell zooming in mobile cellular networks. By adaptively adjusting the cell size according to the traffic loads and channel conditions of users, energy consumption of a mobile cellular network can be greatly reduced. Alternatively, [4] designs a cross-layer approach to minimize the network energy consumption by jointly considering optimal power control, link layer scheduling, and multihop routing protocols. Existing solutions largely target minimizing energy consumption to attain an energy-efficient communication network. Another important solution is using renewable and clean energy sources, such as solar or wind power, to power off-grid networks [5].

It is expected that sustainable energy sources will be applied widely to meet the growing user demands on multimedia services in future wireless networks [2]. However, it is important to note that the renewable energy harvested from such sources, although sustainable, is highly variable and often unpredictable in terms of availability and capacity, which makes the network resource management and traffic scheduling tasks very challenging when these sources of energy are applied to power the communication network. This situation dictates that the focus of the network design should shift away from minimizing the total energy consumption toward the energy sustainability of communications, that is, whether the harvested energy can sustain the traffic demands and meet the quality of service (QoS) requirements of end users in the network. To this end, it is essential to revisit the existing energy-efficient solutions under the new green communication paradigm. In summary, by recognizing the distinct dynamic and long-term inexhaustible nature of sustainable energy sources, it is beneficial to focus attention on energy sustainability by addressing relevant issues such as network architecture, deployment, capacity planning, and resource management to achieve an overall sustainable system.

This article describes the characteristics of sustainable energy supplies and elaborates on the fundamental design criteria of a green mesh network in which mesh access points (APs) are powered by green energy. Based on the design criteria, we study the network deployment and resource management issues. Specifically, we first investigate how to cost-effectively deploy APs in a network and use the harvested energy to fulfill the QoS requirements of users, and then we present a resource management scheme to adaptively distribute traffic demands across the network to achieve the maximal energy sustainability of the green mesh network.

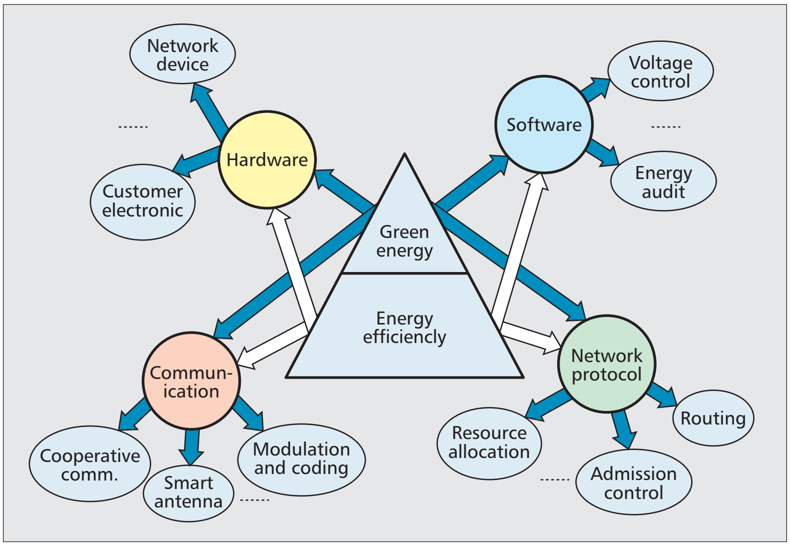

Figure 1. *Solutions for green communication networks.*

Green Energy Supply in Next-Generation Wireless Networks

Green energy, also referred to as clean or sustainable energy, is energy generated from sources such as solar, wind, tidal, and geothermal power that cause minimal pollution. Such sources are usually renewable and can be replenished without exhausting finite fuel supplies. Notably, as solar and wind energy generation are already relatively mature technologies, they are good candidates for widespread deployment in the next-generation wireless networks. It can be envisioned that green APs, powered by green energy, can be deployed to connect domestic wireless users to the Internet, for example, a home or office network where solar panels or wind turbines are installed on the roof to harvest energy and power the communications to the Internet. Furthermore, a green mesh backhaul can be formed among multiple green APs. In this case, each AP would use the recharged energy to serve the up- and downlink traffics of the domestic users and forward the traffic of other APs or wireless local area networks (WLANs) to the gateway. Therefore, mesh-connected green APs can serve as relay nodes or network portals and gateways that connect to other networks and provide ubiquitous broadband access for wireless users. With the proliferation of customer electronics and multimedia services, mobile users may carry a variety of multimedia applications with diverse QoS demands in terms of flow throughput, transmission delay, packet loss, and so on. In addition, the reception and transmission of multimedia traffic consume variable energy, which is determined by the power reception/transmission efficiency of the underlying communication techniques and the transmission environment. To provide satisfactory and continuous services to end users, green APs need to not only fulfill users' QoS requirements, but also meet the energy demands for traffic delivery.

To deploy a sustainable network, it is important to note that green energy sources are inherently dynamic and unstable; as green energy is harvested from the nearby environment such as sunlight and air currents, the underlying energy source is by nature variable and intermittent, which leads to varying power output. For instance, it is well known that a wind turbine provides intermittent and unreliable power, whereas a solar panel can supply relatively con-

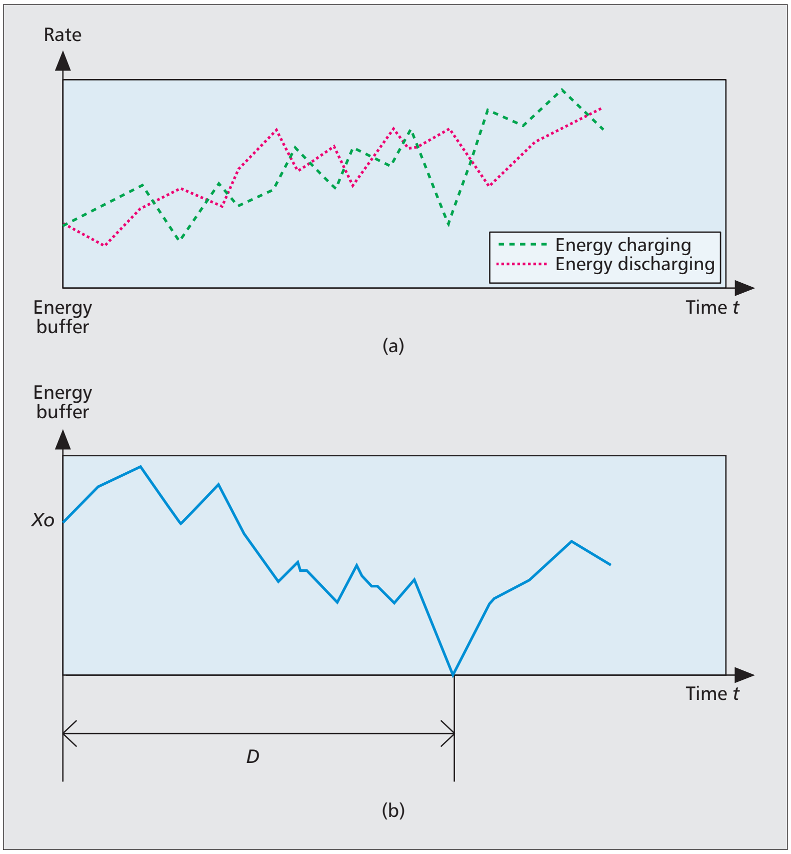

Figure 2. *Energy buffer of a green AP: a) energy charging and discharging processes; b) energy buffer evolution.*

tinuous power with varying output throughout the day and through the seasons. To combat the intermittent and variable nature of the green energy supply, a battery to store the harvested electric power for future use is desirable. That is to say, a practical solution to the usage of green energy in future wireless networks is to combine green energy technology with large-capacity rechargeable batteries to provide a reliable and sustainable power supply. In this context, the research emphasis is on managing the dynamically charged energy in the battery (or energy buffer) to support the application requirements of mobile users.

From the perspective of applications, it is well known that multimedia traffic flows typically exhibit bursty characteristics, and the energy used for multimedia transmissions is therefore also a dynamic process. Note that the energy consumption of each node includes the energy used for receiving a message, processing it, and forwarding it to the next hop. Usually the receiving and processing energy can be considered to be constant while the transmission energy can be adapted to ensure a desirable bit error rate at the receiver when adaptive coding and modulation are used. That is, for a given signal-to-noise ratio requirement, the minimal energy used for transmitting one bit, denoted e^t, should be proportional to the path loss, $e^t \propto d^\alpha$, where d is the transceiver distance and α is the path loss exponent. Without loss of generality, in this article we model the energy buffering (or battery) as a $G/G/1$ queue with arbitrary arrivals (charge) and departures (consumption) of unit energy. The energy buffering evolution is thus a random process determined by both energy charging, $C(t)$, and discharging, $D(t)$, processes, as shown in Fig. 2a. When the energy charging rate is larger than the discharging rate, $C(t) > D(t)$, the length of the energy buffer increases, and vice versa. The energy buffer evolution is shown in Fig. 2b. When an AP depletes its energy (i.e., the energy buffer reaches 0), the AP becomes temporarily out of service until it is replenished. A simple but coarse design criterion to ensure the sustainable performance of a green mesh network is $E[C(t)] > E[D(t)]$; that is, the average charging rate over time should be greater than the average energy consumption rate so that all traffic can be served eventually with the harvested energy at the AP. However, because of the random dynamics in both the energy charging and discharging processes, APs may deplete or drain the energy and go out of service from time to time, even if the long-term recharged energy is higher than the energy demands from users. Unavailable APs due to energy depletion are not able to serve the traffic demands with intolerable transmission delays and severe packet losses, and finally degrade the QoS performance of mobile users. Therefore, in a green mesh network, it is necessary and important to ensure a low energy depletion probability of APs, and provide mobile users consistent and guaranteed services.

Network Deployment in a Green WLAN Mesh Network

In general, the development of a green communication network involves network architecture planning, network deployment, and resource management issues. The main focus in network planning and deployment is the implementation cost of the network infrastructure because radio network controllers (RNCs, i.e., BSs, APs, etc.) are usually much more expensive and consume far more power than nomadic and mobile users. Thus, the foremost issue is how to economically deploy RNCs (e.g., APs) to meet the QoS demands of mobile users with the minimum physical investment. The conventional AP placement problem can typically be modeled as an optimization problem: to find an optimal set of APs with the minimum deployment cost to provide full coverage radio access for all users and fulfill their QoS demands. Most previous works on the issue of AP placement mainly focus on minimizing the total placement cost and/or provisioning biconnectivity between APs and users without considering the energy efficiency of the system [6, 7]. Some recent studies jointly consider energy-efficient RNC placement and power control to minimize the total network energy consumption by covering mobile users in a given area [8]. As discussed above, when sustainable green energy is used to power APs, we need to revisit the AP placement problem under the new energy sustainability constraint [9]. Our focus is no longer on minimizing the energy consumption of APs, since green energy is renewable and sustainable with no extra expense. Instead, we need to minimize the investment cost of APs, because a green AP, by employing green energy technologies, is typically more expensive than a traditional one. That is, we need to place a minimal number of APs and allocate appropriate network resources to meet the QoS requirements of mobiles users, including both the bandwidth and energy requirements. A mobile user is associated with a green AP if and only if the AP can allocate its required bandwidth and use the harvested energy to transmit the downlink and uplink traffic to and from the mobile user. Let $\mathbb{U}$ denote the set of mobile users and $\mathbb{A}$ denote the candidate locations where APs can be deployed. Overall, the green AP placement problem can be formulated as the following minimization problem:

$$
\begin{aligned}
\text{Minimize}: & \sum_i I\left(\sum_j x_{ij}\right) & \\
\text{Subject to}: & \sum_i x_{ij} = 1 & \forall j \in \mathbb{U} \\
& R_j \geq \hat{R}_j & \forall j \in \mathbb{U}, \\
& \sum_i x_{ij} E_j \leq E_i^+ & \forall j \in \mathbb{A}, \\
& P(0; x_0) < \varepsilon & \forall j \in \mathbb{A}, \\
& x_{ij} \in \{0,1\} & \forall j \in \mathbb{A}, \forall j \in \mathbb{U}
\end{aligned} \quad (1)
$$

where the indicator $I(x)$ equals 1 if $x > 0$ and 0 otherwise. The binary variable x_{ij} equals 1 when user j is associated with AP i, and 0 otherwise. R_j denotes the achieved flow throughput of user j, which should be greater than or equal to the demanded throughput $\hat{R}_j$. E_j is the energy demand of user j, and E_i^+ is the energy charging capacity of AP_i. $P(0; x_0)$ is the energy depletion probability of a green AP with initial energy x_0, which indicates how likely a green AP will deplete its energy and become unavailable.

In Eq. 1, the objective function is to find a minimal number of green APs deployed in the network. The first constraint shows that each user should be associated with only one AP. The second constraint specifies the QoS demand of every user should be satisfied. The following two constraints stipulate that the demanded energy consumption of all users served by a green AP should not exceed its charging capability, and the energy depletion probability of each AP should be maintained at a low level, respectively. Notice that each AP can also adjust its transmission power to achieve different transmission rates with different coverages for a given transmission bit error rate requirement. In this case, the achieved user throughput R_j, the consumed energy to serve each user E_j, and the network topology will change accordingly, which results in a different optimal placement setting $\{x_{ij} | i \in \mathbb{A}, j \in \mathbb{U}\}$. The formulated problem in Eq. 1 is a mixed integer nonlinear programming problem (MINLP) which is known to be NP-hard. As there is no efficient polynomial time solution for NP-hard problems in general, we need to apply heuristic algorithms to address the green AP placement problem.

Adaptive Green Resource Management

Resource management plays a prominent role in improving utilization efficiency of the network resources and enabling QoS provisioning. Bandwidth and energy are two important network resources. As mentioned earlier, most previous works on resource management have been concerned with minimizing the energy consumption on the basis that the energy supply is a fixed and limited network resource. In a green mesh network in which the energy source is inexhaustible in the long term but dynamic and unreliable in the short term, the objective of resource allocation should also shift to address these fundamental properties of the green network paradigm. Similar to the energy sustainability constraint defined in network deployment, we study how to adaptively distribute the network traffic across the network to ensure that the harvested energy of green APs can sustain the traffic demands with a minimal energy depletion probability. We assume that an ideal medium access control protocol is in place for both inter- and intra-WLAN communications so that all active nodes are scheduled for data transmissions in a contention-free manner. As the network capacity is inherently bounded, we propose a distributed admission control strategy to strike a balance between the high resource utilization and desirable energy sustainability performance.

Transient Evolution of Energy Buffer

To well understand the impact of dynamic energy charging and discharging processes on the energy sustainability performance of APs, we resort to a diffusion or Brownian motion approximation to analyze the transient behavior of the energy buffer. Diffusion approximation allows us to approximate the discrete energy buffer size by a continuous process such that the incremental change in the energy over a small interval is normally distributed [10] with the mean and variance determined by the charging and discharging processes of the energy in the energy buffer. Provided the initial energy buffer size, x_0, and the mean and variance of the energy charging and discharging processes, μ_a, v_a, and μ_s, v_s, respectively, the conditional energy depletion probability, $P(0; x_0)$, can be represented as [11]

$$
P(0; x_0) = \begin{cases} 1, & \text{for } \beta \leq 0, \\ \exp\left(-\dfrac{2x_0\beta}{\alpha}\right) & \text{otherwise}, \end{cases} \quad (2)
$$

where

$$
\begin{cases} \alpha = v_a / \mu_a^3 + v_s / \mu_s^3, \\ \beta = 1/\mu_a - 1/\mu_s. \end{cases}
$$

α and β are referred to as diffusion and drift diffusion coefficients, respectively. Here, Eq. 2 indicates that the energy buffer depletes with probability 1 when the energy charging rate is smaller than or equal to the energy consumption rate. However, even if the mean energy charging rate is larger than the mean energy discharging rate, it is still possible that the energy buffer

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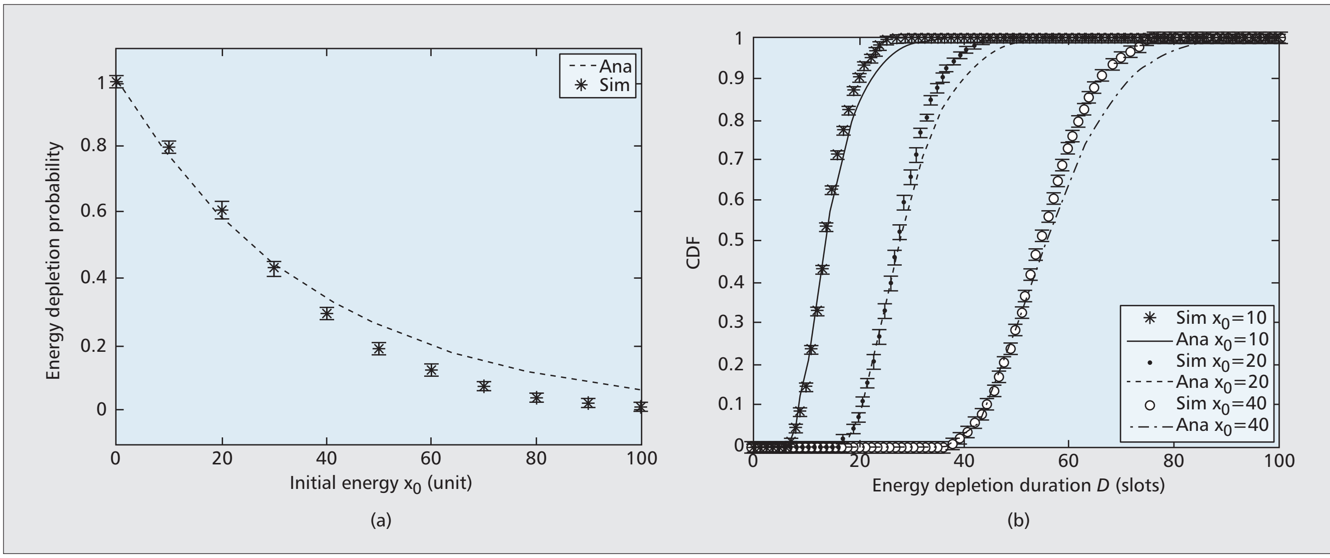

Figure 3. *Energy buffer analysis (μ_a = 2.75, v_a = 1.09, μ_s = 11.1, v_s = 11.1): a) Energy depletion probability $\mathcal{P}(0; x_0)$; b) CDF of $\mathcal{D}$.*

depletes to 0 due to the variance in energy charging and discharging processes. Figure 3a plots the energy depletion probability of an energy buffer when the charging rate is higher than the discharging rate. The energy charging intervals are randomly selected from $\vec{t_a}$ = {1, 2, 3, 4} (in units of time slots) with a given probability p_{ta} = {0.15, 0.25, 0.3, 0.3}; thus, the mean and variance of the charging interval are μ_a = 2.75 and v_a = 1.09, respectively. The inter-traffic arrivals of a flow are exponentially distributed with mean and variance $\mu_s = v_s$ = 11.1. The buffer depletion probability is determined by gradually adding 12 flows and collecting the results. To compute $\mathcal{P}(0; x_0)$ in the simulation, we collect the number of runs until the energy buffer of a node reaches 0 when the simulation runs 6000 time slots, and divide it by the total number of runs (i.e., 1000), and plot the results in Fig. 3a. It can be seen that $\mathcal{P}(0; x_0)$ decreases with the initial energy x_0. As the simulation is only conducted over a limited duration, the simulation results are conservative and slightly lower than the analytical results (which converge as time goes to infinity).

Traffic Load Distribution

Based on the transient energy buffer analysis, an adaptive resource management scheme is proposed in this section. To improve the network sustainability, the network traffic should be appropriately distributed over multiple relay paths across the network so as to avoid overloading some of the mesh APs and ensure that the probability that APs deplete their energy is minimized. Toward this goal, in what follows we design a relay path selection metric based on the instantaneous energy level, energy charging capability, and existing traffic demands at each AP. We also present a distributed admission control strategy to further guarantee the energy sustainability of a green mesh network.

In a green mesh wireless network, multihop relaying is required when a mobile user communicates with another mobile user associated with different APs. In this case, to ensure the energy sustainability and network connectivity, the traffic should be scheduled on a relay path along which the APs have the minimum probability of being out of service (i.e., of depleting their energy and becoming temporarily unavailable). Based on the analysis, we proceed with the relay path selection as follows. A source user first floods a request that includes the destination user and the estimated first and second order statistics of the traffic demands of the flow. When the destination AP receives the request, it will first calculate the probability of energy depletion, $\mathcal{P}(0; x_0)$ in Eq. 2, based on its current energy level and the accumulated traffic demands. Notice that $\mathcal{P}(0; x_0)$ is 1 when $\beta \le 0$, implying that the AP will eventually deplete its energy by relaying this flow. Therefore, to differentiate their weights for path selection, the APs need to further evaluate whether their current energy level can sustain the flow demand within a finite duration. Denote the energy depletion duration $\mathcal{D}$ and the survival time of a traffic flow T; that is, the flow is expected to survive in the network in the subsequent T time slots. The AP updates its weight according to the flow request as

$$
\begin{aligned}
w_v &= \mathcal{P}(0;x_0) + \Delta(\beta \le 0) F_{\mathcal{D}}(T;x_0), \\
&= \mathcal{P}(0;x_0) + \Delta(\beta \le 0) \int_0^T f_{\mathcal{D}}(T;x_0)\,dt, \qquad (3)
\end{aligned}
$$

where the indicator $\Delta(\cdot)$ equals 1 if condition $(\cdot)$ is true and 0 otherwise, and where $F_{\mathcal{D}}(T; x_0) = \int_0^T f_{\mathcal{D}}(t; x_0)dt$ is the probability that an AP depletes its energy before the flow survival time T expires. $F_{\mathcal{D}}(T; x_0)$ indicates how likely it is that a green AP can sustain the traffic demand before T expires. The closed-form density function $f_{\mathcal{D}}(T; x_0)$ can also be obtained from the diffusion equation as a function $f(x_0, \alpha, \beta)$ [11]. Figure 3b plots the CDF of the energy depletion duration. Basically, for a smaller x_0, an AP is more likely to deplete its energy in the near future; thus, the CDF curve shifts to the left.

The destination AP then attaches its weight in the reply packet backward to the source user. Upon receiving the reply message, each mesh AP also updates its weight in Eq. 3, based on the accumulated load energy consumption over each link. The path with the minimum energy depletion probability (MEDP), $\sum_v w_v$, is then selected for the requested flow. In a multihop network, the data buffer of the relaying AP may absorb the traffic variance to some degree, and the output traffic characteristics may vary. If the estimated traffic demand changes during time duration T, APs should update the traffic parameters and the remaining survival time T, and repeat the aforementioned path selection process. It is also possible that a mesh AP may need to retransmit a packet after a random period if its next hop mesh AP is currently out of service, which may change the energy consumption statistics of the ongoing flow. In case $\mathcal{P}(0; x_0)$ is large, energy consumption statistics may vary hop by hop, and mesh APs need to update the energy consumption statistics and recalculate $\mathcal{P}(0; x_0)$. However, by minimizing the energy depletion probability and ensuring a sufficiently large depletion duration, the probability that an AP is out of service can be reduced to a negligible level.

Figure 4 compares the network lifetime of three schemes, defined as the maximum duration that all APs are available until one of the APs depletes its energy. The minimum energy (ME) scheme selects a relay path with the minimum energy consumption. The minimum path recovery time (MPRT) chooses the path with the minimum cumulative recovery time such that the total consumed energy can be recovered in the shortest duration. Thus, MPRT is more likely to select the path with a higher charging rate. The proposed MEDP distributes traffic along a path to maintain the minimized energy depletion probability. It can be seen that the sustainable performance of ME is lower than those of MPRT and MEDP as it does not consider the energy charging capability. The proposed MEDP outperforms MPRT as the latter considers only the charging capability of mesh APs, neglecting the traffic demands and variations in both charging and discharging processes.

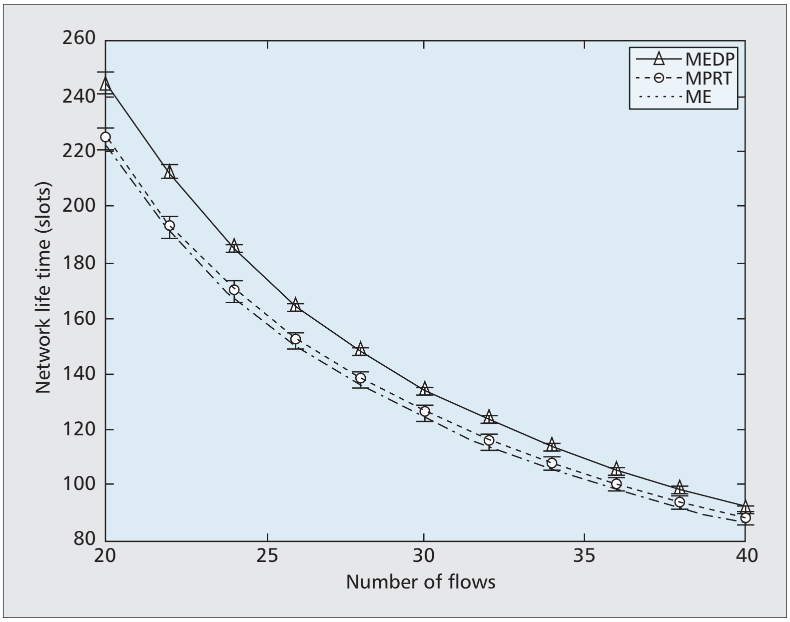

Figure 4. *Network life time comparisons of three schemes.*

Distributed Call Admission Control

Facing the limited network capacity, call admission control (CAC) plays a critical role in provisioning satisfactory QoS to the existing users [12]. In general, admission control is designed to strike a trade-off between the resource utilization and QoS provisioning. For instance, when more users are admitted to the network, they can exploit more network resources to achieve higher network throughput and utilization. Corresponding to that, the network resources are consumed much faster, making the residual energy of mesh APs deplete quickly and some APs become unavailable. As a direct result, individual users would encounter long service delays, intensive jitter, and packet losses. Therefore, an effective admission control strategy is necessary to ensure high resource utilization and at the same time provide satisfactory energy sustainability performance of the network.

In wireless networks, strict QoS provisioning is often very difficult and not resource efficient. Thus, we propose a stochastic QoS provisioning method to ensure a prescribed level of service for admitted users by ensuring that the energy depletion duration, $\mathcal{D}$, is larger than the longest survival time of traffic flows, $\hat{\mathcal{D}}$, with a high probability,

$$Pr(\mathcal{D} \le \hat{\mathcal{D}}) = \int_0^{\hat{\mathcal{D}}} f_{\mathcal{D}}(t; x_0)\,dt < \varepsilon, \qquad (4)$$

where $0 < \varepsilon \ll 1$ is an adjustable parameter that reflects the energy sustainability condition level. A smaller ε implies a stricter energy sustainability constraint for admitting a new flow. As such, according to the estimated flow statistics in the request, each mesh AP verifies its energy sustainability to decide whether its energy level can sustain the requested traffic demand based on Eq. 4, given its current residual energy level x_0. An AP only relays and responds to a message when its energy sustainability condition satisfies Eq. 4. If the source AP cannot establish a valid relay path to the destination from the received response messages, which implies that one or more APs' energy supply cannot sustain the demands of the traffic flow, the source AP will reject the flow request from the end user. By upper bounding the energy depletion probability, satisfactory sustainable network performance can be achieved.

Figure 5 shows the network lifetime, which is defined as the maximal duration that all APs are available until one of the APs depletes its energy, with and without CAC, respectively. Without CAC deployed, when more flows join the network, the increased traffic loads will deplete the energy of APs, and the network lifetime degrades significantly. By using the proposed CAC, some flow requests are rejected to guarantee the QoS provisioning of the existing users as the current energy level of green APs cannot sustain more traffic demands. Therefore, the existing traffic demands in the network are maintained at a certain level to achieve a desirable network sustaining performance.

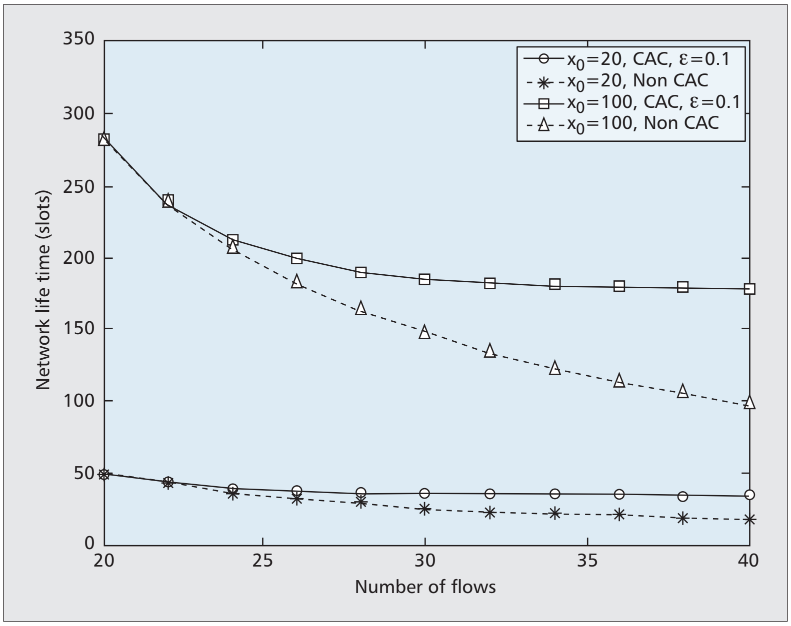

Figure 5. *Network lifetime with and without CAC.*

Conclusion and Future Research

In this article, we have studied network resource deployment and management in a green mesh network where APs are powered by renewable green energy. We first formulate an AP placement optimization problem under the energy and QoS constraints. We then propose an adaptive resource management scheme to improve the energy sustainability of the green mesh network, considering variable energy charging capabilities of APs.

With the advances in green energy technologies, it can be envisioned that green energy will power more network devices and end-user electronics in the near future. The distinct characteristics of green energy supplies (i.e., inexhaustible in the long term and unstable in the short term) will shift the emphasis of network design from the requirement of energy efficiency to energy sustainability. From this perspective, a revisit of the existing energy efficiency and management solutions in different areas, as shown in Fig. 1, is therefore necessary with changes in the fundamental network paradigm. Along this vein, there remain many open issues that deserve in-depth investigations.

Energy Sustainable Software Defined Radio

Software defined radio (SDR) is a promising emerging green technology that allows users to use one hardware to adaptively and opportunistically access multiple radio access networks. Note that the network designers have incorporated SDR platforms in the BSs to provide multiple radio accesses to end users. While previous works mainly focus on energy efficiency in SDR configurations at both the user's end and BSs, the impact of sustainable energy sources has not yet been seriously investigated in SDR configuration. The dynamic availability and capacity of the sustainable energy supply will result in different spectrum sensing and channel access strategies as different frequency bands exhibit different propagation characteristics and achieve diverse power transmission efficiency. Thus, based on the statistics of the energy supply and the current energy storage, energy-aware SDR design and radio access technology should be jointly considered to ensure sustainable operation of the network and achieve high throughput performance.

Energy-Sustainable Network Deployment and Resource Management

The use of low-power, inexpensive, and small-size femtocells or picocells has attracted increasing attention in the wireless community. A femtocell operating in a licensed band typically uses low transmission power to avoid severe co-channel interference with other licensed users, and thus achieve enhanced energy efficiency and capacity. While the deployment of femtocells in a range of network scenarios is ongoing, the development of green femtocells with a sustainable energy supply is still in its infancy. With different deployment locations, the harvested energy would exhibit different statistics. As such, the placement of green femtocells should not only cater to the downloading demands of users, but also consider the sustainability of the network energy supply. While our article sheds light on the deployment issue of green APs in a wireless mesh network, there remain significant challenging issues in different networks like femtocell networks. For example, when femtocells are powered by sustainable energy with diverse amplitudes, it is important to determine the appropriate femtocell size and adapt it to the varying charging rate of energy and traffic demands to ensure high energy sustainability in the network. In a macrocell with multiple green femtocells, it is also important to revisit spectrum allocation, power management, CAC, and QoS management to attain high-performance sustainable self-organized femtocells.

Cross-Layer Approach for a Sustainable System

Improving the overall system performance of future green communication networks is inherently a cross-layer design problem that should be addressed by applying techniques across the protocol stack, ranging from hardware implementation, software design, and energy-efficient signal processing to communication techniques, including link-layer scheduling, medium access control, network layer routing, transport layer flow control, and the upper-layer applications, as shown in Fig. 1. It is important not only to optimize the parameters residing in different networking components and protocol layers, but also to study the interactions among different functions. For example, energy audit software provides energy usage statistics, which can be utilized for energy management, resource allocation, power control, and sleep scheduling of green stations, and so on. On the other hand, when a set of green stations are powered off or use different power levels for communication, the network topology changes, which results in different user energy demands, multihop routing, and end-to-end QoS performance of mobile users. In this case, a cross-layer solution to improve overall system reliability and sustainability is an interesting yet challenging issue.

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Improving the overall system performance of future green communication networks is inherently a cross layer design problem that should be addressed by applying techniques across the protocol stack.