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Green Cooperative Cognitive Communication and Networking: A New Paradigm for Wireless Networks

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Abstract Wireless communication has nowadays become one of the major worldwide causes of energy consumption in the field of ICT, with a devastating impact in terms of pollution and energy waste. As a result, the past decade has witnessed tremendous efforts and progress made by both the industry and academia for improving energy and power efficiency in current and emerging wireless communication networks, among which cognitive and cooperative communication are proposed as key technologies to increase both spectrum and energy efficiency. In this article, we provide a comprehensive survey of the green cognitive and cooperative communication and networking techniques from its characteristics point of view to operational details in the eventual deployment. We present a systematic overview on the tools and techniques that can be used to solve problems arising in energy efficiency optimization problem in this context. The need to incorporate green concepts such as multi-input and multi-output, multi-rate, and multi-carrier systems, short-range low-power communication using small cell networks, and machine to machine communication in emerging and advanced wireless communication technologies is also addressed. Finally, we highlight design challenges and open issues in embracing green technologies in different and cross layers of communication and networking.

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1 Introduction to green communication and networking

1.1 General context

The last two decades have witnessed an unprecedented success of wireless networks due to the proliferation of inexpensive, widely available wireless devices. Such rapid development in wireless communication systems and networks is accompanied by the ever growing carbon footprint. The industry of Information and Communication Technology (ICT) as a whole accounts for about

2–4 % of global CO_2 emissions with a projection to reach 10 % in 5–10 years. Particularly, wireless and mobil communications play an important role in this process. The Smart 2020 Report [46] predicts that the footprint of wireless mobile communications would almost triple from 2007 to 2020, corresponding to more than one-third of present annual CO_2 emissions of the whole United Kingdom [46]. It is evident that limiting the energy expenditure and the resulting carbon emission has become a crucial issue for the wireless mobile communications industry.

In addition to minimizing the overall carbon footprint of wireless communications, there is a strong economic drive to reduce the energy consumption of these networks. Let us take the energy cost of the base stations as an illustrating example. Currently there are more than 4 million base stations serving mobile users, among which the number of base stations in developing regions are expected to almost double by the year 2012. Each base station consumes on average 25 MWh per year. Consequently, electricity has become a significant cost factor for both network operators and users, by accounting for up to half of the operating expense of a mobile service provider.

The ever increasing carbon footprint and energy cost of wireless communication and networking systems have led to the dedication of significant research efforts to the reduction of energy consumption in both academic and industry. Such process of reducing energy expenditure is usually referred to as the *greening* of wireless mobile networks.

1.2 Cooperative and cognitive communication for greener planet

Despite the pressing energy concerns for wireless mobile networks, existing network architecture is far from adapted from a green perspective.

- First, existing wireless communication systems are based on the conventional "command-and-control" spectrum usage model and do not support the adaptive exploitation of spectrum opportunities which can increase the energy efficiency by more effective interference management, better spatial and temporal reuse.
- Secondly, existing wireless communication systems use traditional layered approach borrowed from the wired networking paradigm. However, the need to operate the wireless medium (by nature a broadcast medium) in a manner that resembles wired links for compatibility with traditional higher-layer protocols cannot be achieved without a sacrifice of energy efficiency and communication reliability.

As a result, the past decade has witnessed tremendous efforts and progress made by both the industry and academia for improving energy and power efficiency in current and emerging wireless communication networks, among which cognitive and cooperative communication are proposed as key technologies to increase both spectrum and energy efficiency. The paradigm of cognitive and cooperative communication combines the idea of cognitive radio and cooperative communication and relay, which is summarized as follows.

Cognitive radio, first envisioned by Mitola [37] and then investigated by the DARPA XG program [9], is the key enabling technology for future generations of wireless systems that address critical challenges in spectrum efficiency, interference management, and coexistence of heterogeneous networks. The core concept in cognitive radio networks is opportunistic spectrum access, whose objective is to solve the imbalance between spectrum scarcity and spectrum under-utilization. Built upon a hierarchical access structure with primary and secondary users, opportunistic spectrum access resolves the inefficiency of the current command-and-control model of spectrum regulation while maintaining compatibility with legacy wireless systems. The basic idea is to allow secondary users to exploit instantaneous spectrum availability and communicate non-intrusively to primary users.

Motivated by the limitation of the traditional layered design of wireless networks, the concept of *cooperative communications* [43] has been proposed recently to take advantage of the broadcast nature of the wireless medium and provide diversity against link fades and outages on the main path, by allowing additional nodes in the vicinity of a route that overhear a transmitted signal to assist in delivering the data to its destination. Cooperative communication methods in wireless networks, ranging from relaying by a common neighbor over a single wireless hop to opportunistic routing at the network layer, have been shown in recent years to offer significant performance gains over traditional approaches that ignore the broadcast nature of the wireless medium, and are particularly valuable in environments prone to channel shadowing and fading, such as mobile ad-hoc networks.

With cognitive and cooperative communication, the use of larger spectrum band and the opportunistic adaptation of the spectrum use lead to more effective interference management, better spatial and temporal reuse, thus reducing the power consumption. Despite the ever growing interests, the research on green cognitive and cooperative communication and networking is still in its infancy. Some fundamental problems are still open and require immediate studies, for example:

- How to optimally apply cognitive and cooperative communication techniques to increase the energy efficiency without sacrificing significantly the users' enjoyed quality of service?

- How to minimize the energy consumption overhead introduced by cognitive and cooperative communication such as spectrum sensing, channel switching, cooperative relaying?

Particularly, we would like to emphasize that despite spectrum and energy efficiencies are among the most important venues for technological advances in current and emerging wireless communication networks; in many cases, they are conflicting objectives as some energy efficiency criteria are in conflict with the spectrum efficiency objectives. For example, in order to increase spectrum efficiency, a user is better off searching a wide range of spectrum; however, scanning frequency bands over a wide spectrum and switching among them incur high energy cost.

As a new technology, green cognitive and cooperative communication presents many important and pressing design challenges:

- At the algorithm level:
  - How to allocate efficiently the spectrum resources among users?
  - How to design mechanisms that allow equipment to efficiently cooperate and coordinate among them?
  - How to limit the energy cost of cognitive and cooperative communication and design energy-efficient cognitive and cooperative communication mechanisms?
- At the protocol level:
  - How to design the control channels that are necessary for node coordination and synchronization?
  - How to exchange the control information during spectrum handover?
  - How to design energy-efficient protocols and limit the energy consumption caused by protocol overhead?

Given the above research challenges, we believe that a systematical study is called for on green cognitive and cooperative communication, both at theoretical modeling, protocol design and experimental evaluation levels from the perspective of joint energy and spectrum efficiencies.

The remainder of this article is organized as follows. In Section 2, we provide a comprehensive survey of the green cognitive and cooperative communication and networking techniques from its characteristics point of view to operational details in the eventual deployment. In Section 3, we present a systematic overview on the tools and techniques that can be used to solve problems arising in energy efficiency optimization problem in this context. The need to incorporate green concepts such as multi-input and multi-output, multi-rate, and multi-carrier systems, short-range low-power communication using small cell networks, and machine to machine communication in emerging and advanced wireless communication technologies is addressed in Section 4. Finally we highlight design challenges and open issues in embracing green technologies in different and cross layers of communication and networking in Section 5.

2 Green wireless communication design and deployment

2.1 Green metrics and measurements

For designing the green wireless networks, it is necessary to investigate the energy efficiency metrics [52] to evaluate how much the wireless networks are green, which provides the objective for the energy efficiency optimization. In this way, the techniques in wireless networks could be evaluated from an energy efficiency perspective.

There have been several green metrics and measurements proposed by some international organizations and companies, as listed in Table 1. IPMVP (International Performance Measurement and Verification Protocol) [15] is proposed by IPMVP committee of Efficiency Valuation Organization (EVO). The measurement methods in IPMVP are not specified for wireless networks, but these methods could be considered as an important reference for the measurement and evaluation of energy efficiency in wireless networks. To evaluate the energy efficiency, ECR (Energy Consumption Rating) [13] proposed by ECR Initiate and TEER (Telecommunication Energy Efficiency Ratio) [5] proposed by Alliance for Telecommunications Industry Solutions (ATIS) calculate the ratio of the achieved system output to the energy consumption. TEEER (Telecommunications Equipment Energy Efficiency Ratings) [47] proposed by

Table 1 List of green metrics and measurements

Metrics and measurements	Description
IPMVP	The metrics and evaluation methods to measure the energy, conservation and the low-cost implementation of measurement.
ECR	Calculate the ratio of the energy consumption and the effective system capacity.
TEER	Calculate the ratio of the useful work to the consumed energy.
TEEER	Define the formulas of energy efficiency and provides the measurement methods at various utilization levels.

Verizon establishes more detailed energy efficiency formulation and measurement at various utilization levels. These metrics are applicable to broadband, video, datacenter, network and customer-premises equipments. They are provided to the manufacturers for energy efficiency improvement.

Most of the existing energy efficiency metrics are designed for parts of wireless networks rather than the entire networks. In addition, they are not primarily designed considering various factors in different environments, e.g., interference environment, traffic load. Due to the above two issues, the following aspects should be taken into account when designing the future green metrics and measurements for wireless networks [48].

- The green metrics are reflected by the carbon emission eventually, rather than just the energy efficiency, especially for the cases evaluating the green property of entire networks. Actually, the carbon emission is not simply linear to the energy consumption, because consuming the energy from various sources causes totally different carbon emission. Therefore, towards the green wireless networks, the metrics should include the carbon emission as an important factor, which is directly related to how much the networks are green.
- The conventional per-bit energy consumption from the information theoretic perspective does not always represent the energy efficiency in practical wireless networks. The green performance has close relationship to the specified situation, e.g., interference environment, traffic load. For example, some protocols and algorithms achieve mentionable energy efficiency with light traffic load, but their green performance degrades quickly with the increasing load. Therefore, it is necessary to evaluate the energy efficiency based on typical scenarios for providing more practical energy efficiency performance evaluation.
- For green measurement, the modules for predicting, monitoring, evaluating the green metrics and finally decision making should be deployed in the equipments including core network, base station, relay node and user equipments. The corresponding signaling is also necessary for exchanging the energy information and control information between equipments in the networks. In the layered protocol architecture, the new modules should be compatible to the existed protocols well, which would become a major property of green wireless networks. By collecting the related information, the green equipments can predict the energy consumption caused by different strategies and make the decision for improving the energy efficiency of entire networks.

2.2 Green network deployment

Different wireless networks have different properties and requirements, so it is difficult to find a general green deployment approach for all kinds of wireless networks. In this part, we investigate cellular networks, sensor networks and machine-to-machine networks, respectively, to provide an insight on green network deployment.

1) Green Cellular Networks

In cellular networks, the principle method to reduce the energy consumption significantly is turning off some base stations, which could be considered as the dynamic adjustment of network planning. According to its traffic distribution, the base station of this cell can be turned off for saving energy consumption. In order to avoid the coverage hole after turning off some base stations, the base stations nearby should be reconfigured to compensate the coverage hole [20]. In addition, the neighbor relation needs to be updated to decrease the handover delay.

For heterogeneous cellular networks, the macrocell base station guarantees the coverage in the cell, while several small cells are deployed to increase the capacity at hot spots. In that case, the coverage areas of multiple base stations are overlapped. If the traffic load of a small cell is relatively light, it is possible to turn off the base station of this small cell for saving energy consumption without causing coverage holes. The energy conservation is maximized, because all the energy that was supposed to be consumed by the base stations is saved by turning off the base stations.

2) Green Sensor Networks

In sensor networks, the energy consumption is a crucial issue, since the sensor energy is supplied by battery in most applications. When the number of sensors is more than required, some sensors could sleep and just remain the minimum necessary functions to reduce the energy consumption. In [12], all the sensors are divided into multiple disjoint sets, which sleep in turn for saving energy. Only the sensors in one of the sets work at an instant. Furthermore, the slot-based sleeping strategies TRAMA [18] and SERENA [36] schedule the nodes into sleeping according to the traffic.

There are two green approaches for data transmission in wireless sensor networks. One is reducing the energy consumption during transmission. In [45], the route with the lowest energy consumption is selected, and in [35], the route with the largest residual energy is selected. Considering both energy consumption and residual energy, the tradeoff between the above two factors is balanced in [44]. The other is decreasing the transmitted information. LEACH [6] and MLDA [39] are the classic data aggregation approaches in wireless sensor networks. LEACH aggregates data based on clustering, in which the data from the whole cluster are aggregated at the cluster head. MLDA establishes a tree for determining the data aggregation strategy.

3) Green Machine-to-Machine Communications

Machine-to-machine (M2M) communications [2] is an emerging technique towards the Internet of Things. According to the properties of M2M communications, i.e., large number of devices, light traffic load for each device and infrequent transmission, it is necessary to take energy consumption into consideration in the scenario with a large number of devices. The energy efficiency can be increased by adjusting the transmission power to the minimal necessary level and designing green distributed protocols, e.g., routing protocols, sleeping scheduling algorithms [34].

Furthermore, the M2M devices can decrease their measurements during sleeping. In the sleep state, the M2M devices does not communicate, but they should measure neighbours cells at least once per Discontinuous Reception (DRX) period. The conventional cellular devices perform multiple idle measurements during a DRX period to provide better mobility support. As M2M devices do not require active mobility support, the implementation can be relaxed to reduce power consumption. If the DRX period is extended to a longer value, the average idle power consumption decreases dramatically.

2.3 Cross-layer approach to green cooperative cognitive communication and network design

For achieving high energy efficiency in the Green Cooperative Cognitive Communication and Networking (GCCCN), the algorithms and protocols in different layers should be designed and optimized jointly. In GCCCN, both cooperative communications and cognitive radio are the key techniques towards green communications. Here, considering the characteristics of both techniques, we discuss the green design issues in different layers in Table 2.

To achieve better performance, two or more schemes in the above table can be designed jointly. By cognitive radio, the nodes sense the channels by spectrum sensing to find out the available channels. The number of signal samples affects the sensing accuracy and the energy consumption during spectrum sensing. The accurate sensing results provides a large amount of available spectrum resource, which improves the energy efficiency. By cooperative communications, the energy efficiency is improved because the node cooperation essentially increases the utilization of given resources, e.g. more power, more space freedom, etc. For improving the transmission and energy efficiency, the user transmits the information by not only itself but also the nearby users. The channel gain and the interference on different channels are not the same, so the cooperation partner selection should be considered with channel allocation together. The dynamic channel availability leads to the necessity of modifying the current transport layer, in which the lower layer information should be obtained to adjust the congestion control scheme, and the interaction between transport layer and lower-layer parameters is a plus.

Table 2 Green design in different layers

Layer	GCCCN design
Physical layer	modulation & coding selection due to cooperation, sampling rate during spectrum sensing, power control
Link layer	spectrum sensing duration adjustment, channel allocation for each link, dynamic channel access
Network layer	cooperation partner selection, interference-avoid routing
Transport layer	TCP congestion window adjustment

2.4 Energy-performance tradeoff in GCCCN

According to Shannon capacity formula, it is easy to obtained that the energy consumption decreases with the decreasing data rate for a given mount of data. There exist the packet delay constraints in some cases, especially for the real-time services. In that cases, the data rate could not be too slow. It is obvious that there is a tradeoff between energy consumption and transmission performance. One of the methods to balance the tradeoff is adopting as slow data rate as possible on the condition that the delay requirement of the traffic is satisfied. The analysis is, however, just for point-to-point communications. Here, we discuss the new energy-performance tradeoffs brought by cooperative communications and cognitive radio, respectively.

Cooperative communications In order to minimize the energy consumption, one or more appropriate nodes are selected for node cooperation, and the transmit data rates between nodes are adjusted for load balancing. The energy consumed by nodes is composed by two parts. One part is the energy used for data transmission, which is related to the data rate. The other part is consumed by the equipment circuit and control signaling exchange. Even if the node does not transmit any data, the latter part of energy can not be saved. In that case, although more nodes participating the cooperation can achieve better transmission performance, it is not always a good choice to utilize all the available nodes for cooperation. Appropriate number of collaborate nodes should be optimized to balance the tradeoff between energy consumption and transmission performance.

Cognitive radio It is necessary to investigate the energy consumption of sensing, reporting and transmission jointly with cognitive radio. The performance of cooperative spectrum sensing depends on the cooperation strategies, which affects the energy consumed during cooperative spectrum sensing. The merit of cooperative spectrum sensing mainly lies in the sensing diversity gain provided by multiple users. With the increasing number of cooperative users, the sensing performance is improved, which means that the environment information can be provided more accurately to discover more spectrum opportunities. In this case, the energy consumption of transmission can be saved when more spectrum bands are available. On the other hand, the cooperative spectrum sensing with a large number of users induces a lot of extra communication overhead that causes more energy consumption. In multi-channel cases, there also exists another similar tradeoff on the number of exploited channels.

3 Select tools and techniques for green communication

Most of the the green effort so far in the wireless communication research can be divided into four broad categories: those that address the efficiency of the power amplifiers in the base stations [23], those that seek to increase the efficiency of these amplifiers by their on/off behavior [53], studies that focus on the energy efficiency of the data transmissions [8, 17, 21, 29, 30, 51, 54, 55], and those that study the placement of the base stations and/or relays to improve coverage efficiency [4, 32]. A considerable fraction of these efforts are simulation studies [28, 31, 41]. Another fraction deals with ad-hoc protocols that does not require any analytical methods. Others require only the analytical tools that are already familiar to a typical communication engineer or researcher, such as convex optimization. This article concentrates on green initiatives seeking to reduce the carbon foot-print, that require techniques that a communication engineer may not readily know. These include fractional programming [31, 41, 42], Charnes-cooper transformation [42], Dinkelbach method [11], multi-objective optimization [10], and evolutionary algorithms [14].

Energy efficiency (EE) can be an appropriate metric in green communication as discussed before. Let us consider the OFDMA based transmissions from a base station. The total energy efficiency in terms of bits/Joule of the transmissions is defined by the total number of information bits transmitted (throughput) per Joule of energy used. The energy includes any static energy consumed by the transmit power amplifier. The difficulty with this metric is that it is not concave in the powers. If we include the sub carrier allocation in the optimization problem it becomes formidable hard, because we know that the subcarrier allocation that maximizes even the throughput is NP-hard.

One way to get around these difficulties is to use the Charnes-Cooper Transformation [42], to convert the optimization problem into a concave problem. After solving the power allocation problem for a fixed subcarrier assignment, use any insights gathered to solve the subcarrier assignment problem using evolutionary algorithms [14]; and finally perform the power allocation over the subcarrier assignment thus obtained.

Another metric is a weighted average of the normalized throughput and one minus the normalized total energy. In a world where companies have to pay for the environmental harm they are causing, there will be a cost to the company via something similar to a carbon tax that increases with the energy used. In such a situation, it is easily seen that the above expression represents the revenue of the company. The weights will depend on the revenue from the data transmissions and the cost due to carbon tax. However, optimizing a linear combination of two functions does not always produce a solution that is at the exact ratio dictated by the coefficients of the linear combination. However, by normalizing the two functions, as suggested by multi-objective optimization [10], we can overcome this difficulty. In the following we describe the tools in details that can be used to overcome the difficulties mentioned previously.

3.1 Concave fractional program

Finding the power allocation that maximizes the EE for pre-assigned subcarriers is difficult because the EE is not concave in the powers. However, this belongs to a class of optimization problems called *Concave Fractional Programs* [42]. Furthermore, a concave fractional program with an affine denominator can be transformed into a concave program using a transformation proposed by Charnes and Cooper [42].

Throughout this section, we use bold letters to represent vector variables. Consider an optimization problem where we want to maximize the quotient $N(\mathbf{x})/D(\mathbf{x})$ subject to the constraints $M_i(\mathbf{x}) \geq 0, i = 1, 2, ..., k$. Here, $N(\mathbf{x})$, $D(\mathbf{x})$, and each $M_i(\mathbf{x})$ are scalar functions of vector variable $\mathbf{x}$. The following theorem summarizes the essence of the Charnes-Cooper Transformation.

Theorem 1 *The concave fractional program* $max\{N(\mathbf{x})/D(\mathbf{x}) | M_i(\mathbf{x}) \geq 0, i = 1, 2, ..., k\}$ *can be reduced to the concave program* $max\{tN(\mathbf{y}/t) | tM_i(\mathbf{y}/t) \geq 0, i = 1, 2, ..., k, tD(\mathbf{y}/t) = 1, t > 0\}$, *by using the transformation* $t = 1/D(\mathbf{x}), \ \mathbf{x} = \mathbf{y}/t$.

Proof Please see Avriel, Chapter 7, page 216 [42]. □

3.2 DinkelBach method

Now that we have reduced our original optimization to a concave fractional program, one way to solve it is to use an algorithm known as the DinkelBach method [11], which finds the maximum value of the fraction $N(\mathbf{x})/D(\mathbf{x})$.

DinkelBach Algorithm

1. Choose an arbitrary $\mathbf{x} \in S$ and let $q = N(\mathbf{x})/D(\mathbf{x})$
2. Solve the problem $f(q) = \max\{N(\mathbf{x}) - qD(\mathbf{x}) | \mathbf{x} \in S\}$ and denote the solution as $\mathbf{x}^*$.
3. Unless the convergence criterion is satisfied let $q = N(\mathbf{x}^*)/D(\mathbf{x}^*)$ and go to step 2.

3.3 Multi-objective optimization

Consider a situation where we have two different conflicting objectives that depend on the same decision variables. An example would be maximizing the throughput R and minimizing the CO_2 emissions V. Suppose that we are interested in finding a trade off between these two objectives. First, minimizing V is equivalent to maximizing $-V$. This way, we have two maximizing objectives. We can now maximize a linear combination of the two, where the coefficients, or the weights, represent the relative importance we give to each objective.

An important step here is to make sure that both objective functions have the same range. Otherwise the "solution" of the optimization problem will not produce the objective values in the ratios of the weights. We make assure that they have the same range by normalizing each objective function by dividing it by its maximum possible value. That is, we work with $R_1 = R/R_{\max}$ and $V_1 = 1 - V/V_{\max}$. We maximize $\alpha R_1 + \beta V_1$ where α and β are the desired weights. In an example, they will be determined by the relative values of the revenue from the throughput and the penalty or tax payable due to the CO_2 emmissions.

3.4 Genetic and EDA algorithms

The computational complexity of solving the subcarrier and relay assignment problems in cooperative communication using analytical methods is often too high to be of any use in real time applications [38]. If we are willing to settle for near optimal solutions, evolutionary algorithms can be of great use. In what follows, we describe two evolutionary algorithms: the genetic algorithm (GA) and the estimation of distribution algorithm (EDA).

Both GA [40] and EDA [33–38] are sophisticated search methods that avoid intractability by getting rid of points in the solution space that are unlikely to yield the optimal solution. In both methods, points in the solution space are represented by individuals, or more precisely, by their chromosomes. The objective function of the optimization problem is often referred to as the fitness function. Each iteration of the algorithm corresponds to one generation of individuals. The algorithm starts with the creation of a number of individuals or chromosomes that represent a random selection of points in the solution space. During each iteration, the fitness of the individuals are evaluated by computing the objective function. Only a fraction of the individuals whose fitness evaluation are the highest are allowed to pass information in their chromosomes to the next generation of individuals. GA and EDA differ in how the chromosomes of a new generation are created. In what follows we will first explain GA using a specific example.

Consider the subcarrier assignment problem with 64 subcarriers and 16 users, where the objective of the optimization problem is to maximize the throughput. The subcarrier assignments can be stored in a 1×64 array whose cells represent the subcarriers, as shown in Fig. 1b. The cells in the array can hold a number between 1 and 16, which indicates the user to whom that subcarrier is assigned. For example, in Fig. 1b, cell number 5 contains number 7, indicating subcarrier 5 is assigned to user 7. This array represents a chromosome or an individual. The subcarrier assignment represented by this chromosome will give a particular throughput. The higher that throughput is the better this chromosome is. The steps involved in the GA are shown in Fig. 1a. Steps 1 through 5 are self-explanatory.

In step 6, each of the 2P individuals is married to a randomly chosen individual. The chromosomes of the couples is split at a randomly chosen but identical location as shown in Fig. 1c, and the pieces are swapped to create two new chromosomes, or children. In order to prevent the algorithm from converging to a local maximum, occasionally we are mutating the chromosomes at birth. This occurs at step 8, but the algorithm executes this step only rarely. The chromosome of the individual with the best fitness evaluation in the last generation gives the near optimal solution to the problem.

There are many variations in GA that the readers can experiment with. For example, the Elites can be divided into two groups, the super Elites and regular Elites and the super Elites can be allowed to have more children than the regular ones. The chromosomes can be created using two-point crossovers. The only limit is the imagination.

EDA does not use crossovers or mutations to create new chromosomes. When creating a new chromosome, EDA uses a probability distribution that predicts the likelihood of finding a particular chromosome in fit individuals. For example, we can consider the Elites as the fit individuals and ask the question what is the probability of finding a par-

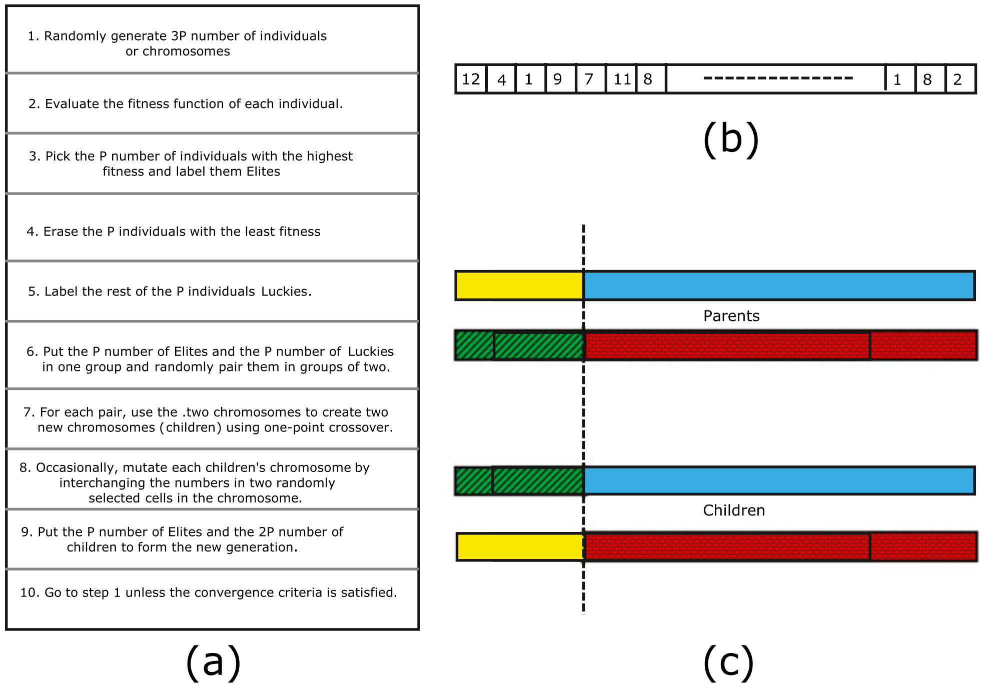

Fig. 1 **a** The genetic algorithm. **b** The chromosome. **c** One-point crossover (Reproduced with permission from [40])

ticular chromosome among the Elites. Usually, determining this probability distribution is extremely expensive computationally. In practice, a number of simplifying assumptions are used, and a variety of probability distributions have been derived. We mention here, only the simplest of such probability distributions. Naturally, the simplest distribution comes from the strongest assumption, which is, that the contribution of a single cell to the fitness of the complete chromosome is independent of the contribution of other cells. This assumption allows us to work with probability distributions for individual cells.

As an example, consider the 5th cell. It can contain any integer from 1 to 16. We now examine the 5th cell of all the chromosomes of the Elites during a particular generation and form a frequency table. Suppose there are 100 Elites and the number 13 appears 23 times in the 5th cell of the Elites. This suggests that we should assign the number 13 to the 5th cell with probability 0.23. Each cell of the chromosome of a new generation can be decided based on a frequency table for that cell obtained from the chromosomes of the Elites of the previous generation.

4 Challenges and future research directions in emerging green networks

It is challenging to design multihop cognitive radio networks due to multiple entities and operations in the network. The routing is a fundamental issue to be addressed in the multi-hop scenario. In [16], the authors argue that in multi-hop cognitive radio environments, adaptive routing solution should be provided with respect to the radio environments. The authors provide some guidelines in designing good routing algorithm. In [3], the authors proposed a tree-structure based routing protocol for multi-hop cognitive radio networks, which can reduce the network delay and improve the system throughput. The authors in [7] consider the joint design of routing and spectrum assignment, which can be basically categorized to QoS driven routing. In [50], the authors use the graph model to investigate the routing selection for multi-hop cognitive radio networks and in [27], a probabilistic based routing approach is proposed to achieve opportunistic routing performance.

4.1 Multi-rate networks

Muti-rate wireless networks have been extensively studied in recent years. The modulation adaption at the physical layer can provide the wireless networks with multiple transmission rates. The transmission rates can also impact the bit error rates at the physical layer. Therefore, the challenging of multi-rate networks is how to choose the multi-rates based on dynamic channel conditions and network topologies making it a cross layer design. In paper [49], a design guideline of multi-channel and multi-rate wireless networks has been studied. Especially in mobile wireless networks, the rate design is significantly related to the energy consumption of each network node when the communication energy consumption is dominated in the wireless networks. The energy and multi-rate optimization at the physical layer has been investigated in [1]. The cross-layer design approaches are dominated in the design of multi-rate networks. Many cross-layer design frameworks [19] are proposed. However, the challenges still remain when the overheads must be added for the message exchanges among multiple layers.

4.2 MIMO and multi-carrier systems

A significant advance in multi input multi output (MIMO) have significant improved the throughput of wireless networks, and helped to resist the wireless channel noise. Diverse channel coding schemes and modulation schemes have been extensively studied for the MIMO and multi-carrier systems. To achieve MIMO, numerous techniques [22–24] have been extensively studied: beamforming, space-time coding/processing, SDMA, spatial multplexing and cooperation. There is also significant research on the combination of two or more of them to achieve high MIMO system performance. Cooperative MIMO, also known as Net-MIMO can improve the MIMO system by introducing multiple antenna advantages such as diversity, beamforming and multiplexing. The technique is useful for the future cellular networks which consider wireless mesh networking or wireless ad-hoc networking.

4.3 Femto and small cell networks

Next generation network includes femto, pico, microcells. These small cell networks are gaining momentum and popularity. The small cells can operate in licensed and unlicensed spectrum that have range of 10–200 m. These techniques are mainly used to support mobile data offloading with the growth of mobile phones and traffic. The femto and small cell networks can provide the wireless services in-building and outdoor. The future small cell will be integrated with LET networks. Although in 3G networks, the small networks can be regarded as an offloading technique. The small cell networks will be fully development and can be integrated with layers of small and large cells. The significant challenges of femto and small cell networks is how to integrate these types of networks and services with existing 3G or 4G wireless networks seamlessly, and the challenges with cooperative and cognitive radio networks would be enormous.

4.4 Green multimedia communication

Multimedia such as 3D video are large sized data. The transmission of these large size data requires high communication bandwidth. Many source coding techniques have been significantly studied in the past to reduce the size of multimedia but also keep the quality the transmitted multimedia. For the multimedia over mobile devices, both the source coding and transmission will consume the energy of the devices, and produce CO_2 in the air. Especially, when the ubiquitous multimedia services are everywhere, it is important to develop green multimedia communication techniques to overcome the energy issues of wireless mobile devices. In the multimedia communication research field, cross-layer design such as joint design of source and channel coding are dominated. In [25–26], both the cognitive radio techniques and scalable video coding have been applied to improve the media quality and network throughput. In the near future, with the growth of 3D video applications, developing energy efficient multimedia communication techniques is becoming more and more critical.

4.5 Field trials and testbeds

All the techniques mentioned above have been or are being implemented in the real network system such as 4G networks. The scalability of the green networks is becoming a significant challenges for the field trials. Therefore, the large size network modeling is required to evaluate the performance of the emerging wireless networks. In addition, how to design an effective network measurement system and collect the network information from heterogeneous future network will be a difficult task. The testbeds should include both prototype tested in the academic institute and research labs, but also include the large scale testbed from the major telecommunication industry. Significant collaborations among these organizations will push the emerging network forward. In addition, many industry standards should be developed for realizing the future emergent green networks. IEEE standard organization and America FCC have drafted and modified a number of standards to support the future emerging green networks.

5 Conclusion

Green cooperative, and cognitive communication and networking (GCCCN) brings about many benefits such as savings in power budget, efficient utilization of scarce radio frequency resources, expanded coverage benefiting in terms of quality of services, to name a few. However, due to the complexities involved in combined technologies, there are many challenges to be tackled by system designers in order to understand fully how the GCCCN performs. This article reviewed GCCCN from its characteristics point of view to operational details in the eventual deployment. Also we presented some tools and techniques that can be used to solve problems arising in energy efficiency optimization problem in GCCCN design. The need to incorporate green concepts such as multi-input and multi-output, multi-rate, and multi-carrier systems, short-range low-power communication using small cell networks, and machine to machine communication in emerging and advanced wireless communication technologies was also addressed. Future research embracing green technologies in different and cross layers of communication and networking was discussed. The next generation of wireless communication technologies are expected to be energy-smart while providing rich multimedia contents to the end-users, and the industry and academia is expected to play a major role in achieving this goal.

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