Green Communications: A Call for Power Efficient Wireless Systems

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Abstract—**Telecommunication usage has skyrocketed in recent years and will continue to grow as developing world reaches to wireless as the communication medium of choice. The telecommunications world is only now addressing the significant environmental impact it is creating as well as the incredible cost on power usage. This realization has led to a push towards Green Communications that strives for improving energy efficiency as well as energy independence of telecommunications. A survey of existing metrics for energy efficiency is discussed with specific adaptations for a communication centric viewpoint. This paper reviews recent energy efficient advances made at specific point within the communications cycle such as components, network operation and topology, and incorporating renewable and alternative energy into base stations. We further survey several holistic approaches that illustrate the dependencies between layers of the communications stack and operation/deployment. These approaches include cross layer design, cognitive radio, and wireless distributed computing.**

Index Terms—**green communications, wireless, energy efficiency, metrics**

I. INTRODUCTION

The intersection of two undeniable trends, the escalating energy costs and the meteoric growth in communications usage, creates an urgent need to address the development of energy efficient communications. The cellular network is the largest factor contributing to the mobile industry's environmental impact [1] with the emissions from the telecommunications business sector estimated at between 0.5% [2] and 1% of the entire world's carbon footprint [3]. While this may sound paltry, the true seriousness of the issue is more apparent from the perspective of energy costs. In some telecommunications markets, energy-related costs account for as much as half of a mobile operator's operating expenses [4, 5]. The expectation that energy costs may rise three fold over the next seven years is great cause for concern [2].

Recently, the term 'Green Communications' has been marketed and sloganized as a solution to addressing the growing cost and environmental impact of telecommunications. However, there is a lack of explicit energy efficiency definitions and metrics for wireless telecommunications to provide a sound foundation for assessing overall improvement and quantifying Green Communications.

Fig. 1 highlights the relative power consumption of various components and operational aspects of a base station (BS) [6]. In this figure, the total power consumption of signal processing & control unit (30%) and RF conversion & power amplifier (70%) is used as the normalization baseline. From this figure, the top three power consuming components are feeder network, RF conversion & amplification, and climate control (e.g., air conditioning).

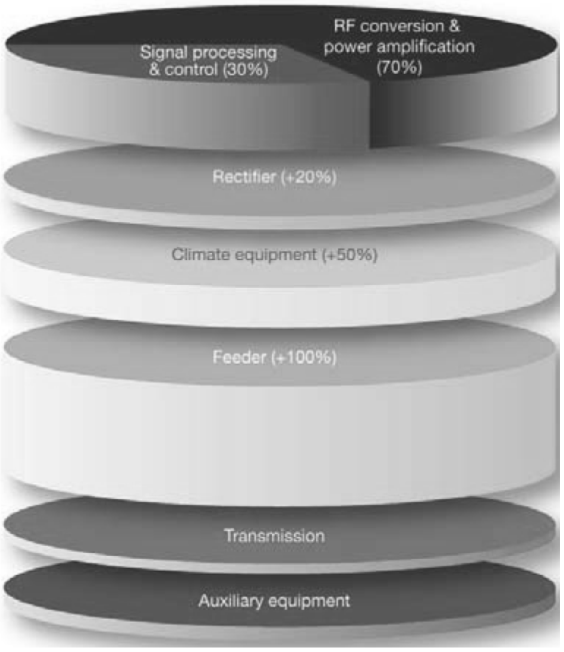

Figure 1. Energy consumption at a typical macro BS (normalized) [6].

Several hurdles must be overcome in order to significantly improve energy efficiency in communications. The current design paradigm focuses on separation between individual levels within the network protocol stack. Additionally, deployment, operations, and

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peripheral elements such as air conditioning and fuel transportation are further disconnected from the original component and system design cycle. This compartmentalized thinking severely limits truly transformational benefits. Currently, most advancements in energy efficient communications focus on a narrowly defined aspect of the communications cycle such as power amplifiers or incorporating renewable energy sources. This paper contends that energy efficient communications must be analyzed from an overall holistic system perspective rather than at singular levels.

In this paper, we strive to add a level of formalization to the term Green Communications and address fundamental hurdles to realizing overall improvements. Specifically, we survey and contrast existing definitions and metrics in energy efficiency and their applications towards communications. We collate advancements in energy efficiency from different layers within the communications cycle to provide a perspective of the current state of energy efficiency research and operations. Finally, we introduce solutions that incorporate interaction across multiple layers of the network stack and different aspects of the communications cycle. This paradigm ties together energy efficient strategies from different layers.

The remainder of this paper is organized as follows: Section II highlights current energy usage and costs associated with telecommunications and places these statistics into perspective by comparing to other aspects of our daily life. Section III reviews and discusses existing metrics for power and energy efficiency and identifies requirements for telecommunications specific metrics. Section IV presents advancements in energy efficiency in communications at specific levels within the communications stack and lifecycle. Section V discusses solutions that are not burdened by the status quo of existing separation among layers. Finally, the paper is summarized in Section VI.

II. THE NEED FOR GREEN COMMUNICATIONS

Information and communications technology usage has grown at a staggering rate worldwide with an estimated 6 billion subscriptions in 2010 [7]. Every year, 120,000 new BS's are deployed serving 400 million new mobile subscribers around the world [8]. Fig. 2 illustrates the growth pattern for mobile cellular subscriptions between 2000 and 2010 [7]. The developing regions are increasingly turning to wireless as a leap frog technology bypassing fixed infrastructure and the mobile subscription increases for a factor of ten. From 2000 till 2010, the mobile subscription in developed regions increases by about 200%, whereas that in developing regions increases by about 1300%. Statistics also show that in 2000 about 40% of all mobile subscriptions were attributed to the developing world and in 2009 this percentage grew to about 70% [9].

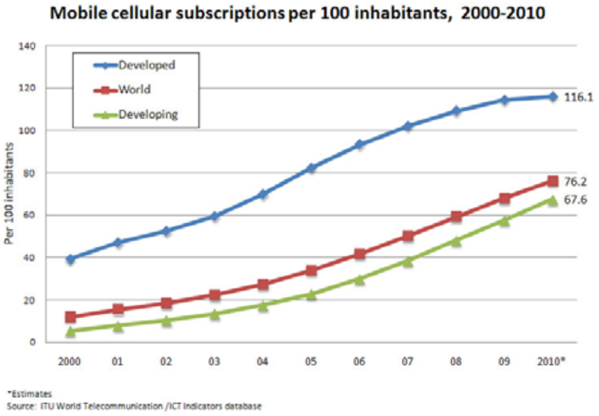

Figure 2. Mobile Cellular Subscriptions [7].

Mobile communications growth in developing countries may have a more alarming effect on carbon usage and energy costs due to the use of inefficient energy sources. Remote sites prevalent in developing regions often rely on inefficient diesel generators for power, expanding communication's carbon footprint at an even higher rate. A low power urban cell site requires 3kW of power (70-80kWh of energy for a 24-hour operation) and generates an estimated 11 tons of carbon dioxide [10]. Many rural base stations utilize significantly more power due to the larger coverage area required from each site.

At the same time, rising fuel costs are stifling service providers with energy expenditures accounting for as much as half of a mobile operator's operating expenses [4, 5]. With the strong business need to meet the rising costs, reduction of CO2 emission is becoming a dream for operators. Operators, such as Vodafone, have set goals to reduce their carbon footprint only to realize that their energy consumption has risen up by 23% [1]. In addition, the growing interest of telecom regulatory bodies on environmental and energy sustainability issues is yet another driving force for the green communication movement [11]. Table I compiled from [1], places the energy usage of cellular systems within the context of carbon footprint.

TABLE I. ENERGY USE OF TELECOMMUNICATIONS IN CONTEXT

Market	No. of Cell Sites	Energy Cost (/MWh)	Annual Operating Cost (M)	Carbon Footprint (annual CO_2 Emission)
USA	50,000	$ 54	$ 150	1.8 million tons
Europe	25,000	$ 114	$ 100-130	0.58 million tons ~121,000 midsize cars

III. DEFINING GREEN COMMUNICATIONS

Significant variance exists in the definition of Green Communications in the telecommunications community and it is most often a marketing term. Carbon footprint is often considered a metric of ‘greenness’, however telecommunications’ effect on CO2 emissions is currently under 1%. Perhaps reducing energy cost rather than CO2 maybe a more applicable metric for wireless communications.

We define Green Communications as striving to reduce energy costs while still maintaining Quality of Service (QoS) in terms of coverage needs, capacity and user needs. When comparing system designs and improvements in energy efficient components the reduction of green house gases alone is not adequate. The QoS must be considered in tandem with energy efficiency. A difficult yet maybe the most important task related to green communications is quantifying the efficiency of the alternative approaches. How can the improvements of such a broad effort be interpreted in a way that accurately reflects the savings achieved? The popular metrics covered shortly primarily focus on measuring power consumption of the system. While power consumption is certainly a major factor in reducing the carbon footprint of system operations, we also suggest metrics that take into account energy consumption. In many cases, the terms power and energy are incorrectly used interchangeably.

The information technology (IT) industry has taken a leadership role in improving energy efficiency in the information communications technology (ICT) ecosystem. The Green Grid association of IT professionals has published efficiency metrics for data centers [12] and solicited proposals for enhanced metrics [13]. The initial report proposed the metric Power Usage Efficiency (PUE) and its reciprocal, Datacenter Efficiency (DCE) to enable operators to quickly assess energy efficiency of power hungry data centers. The PUE represents a data center’s total power consumption divided by the power used only by the servers, storage systems and network equipment, as:

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power}. \quad (1)$$

A PUE rating of 1 means that all of the power for the data center is being used for the computational infrastructure and no power is being used on the non-computational infrastructure such as the air-conditioning systems. While this metric is a popular starting point, the focus is narrow and only reveals a small portion of the whole picture. The primary disadvantage is that it does not represent the efficiency of the computational equipment. Specifically for communications systems, the efficiency of the computational equipment plays a large role in energy consumption of the system.

An alternate method, perhaps more appropriate for telecommunications, strives to quantify the computational energy efficiency of a system. In this method, the ratio of energy consumption of the communications system relative to the performance of the computational system is calculated.

This may sound like an intuitive solution; however, quantifying the performance of communication is much more difficult than quantifying the performance of hardware. Typically in server farms or data centers, the performance of the hardware is measured by observing the processor utilization. For example, a typical server will consume between 60% and 70% of its total power when running at low levels of processor utilization. Increasing the processor utilization has a minimal impact on the power consumption; however, it affects the ratio of energy consumption to processor utilization significantly, thus increasing computational energy efficiency. The challenge, when applying this metric to communication systems, is how to properly quantify the performance.

In communication systems, performance comes in many different flavors. At the lowest level, the Bit Error Rate (BER) is a frequently used quantitative measure of the link. The good-put or application-level throughput measures the amount of usable bits that are received by the application. As a more strictly wireless level metric, the spectral efficiency refers to the information rate that can be transmitted over a given bandwidth, and is typically expressed as bits per second per hertz. These physical layer metrics provide an extremely low-level and detailed view of the performance of a communications system.

From a more practical and commercial focused view, an interesting metric for the cellular industry is the power utilization with respect to the number of calls or users during a specific block of time.

$$PUE_{(t_1,t_2)} = \frac{Total\ Facility\ Power}{Total\ Number\ of\ Users}. \quad (2)$$

This metric provides insight for carrier to evaluate overall economic tradeoffs in cost, coverage and cellular site planning and management.

The telecommunications industry is addressing metrics and standards related to energy efficiency specifically for cellular hardware components [14]. For example, Verizon’s Networks and Building Systems (NEBS) compliance requirements are driving the development of new metrics for evaluating energy efficiency in telecommunications systems. Their updated technical purchasing requirements define the minimum energy efficiency requirements for the purchase of new telecommunications equipments [15]. The Telecommunications Equipment Energy Efficiency Rating (TEEER) has been used by Verizon to quantify the energy efficiency of products [16]. The TEEER is defined for different types of equipments. Some sample definitions are shown in Table II, where the total power consumption P_{Total} is modeled as a weighted sum of power consumption of the equipment at different modes (full rate, $P_{\max}$, half rate P_{50} and sleep/idle mode P_{sleep}). The weights are presumably determined statistically.

$$P_{Total} = 0.35P_{\max} + 0.4P_{50} + 0.25P_{sleep}. \quad (3)$$

TABLE II. VERIZON TEEER FORMULAS [16]

Equipment Type	TEEER Formula	
Transport / Gateway	$-\log\left(\frac{P_{Total}}{Throughput}\right)$	(4)
Switch / Router	$-\log\left(\frac{P_{Total}}{Farwarding\ Capacity}\right)$	(5)
Media Gateway	$-\log\left(\frac{P_{Total}}{Throughput}\right)$	(6)
Access	$\left(\frac{Access\ Lines}{P_{Total}}\right)+1$	(7)
Power	$\left(\frac{Total\ output\ power}{Total\ input\ power}\right)\times 10$	(8)
Power Amplifier (Wireless)	$\left(\frac{Total\ RF\ Output\ Power}{Total\ Input\ Power}\right)\times 10$	(9)

From the above TEEER definition, we can see that the larger the TEEER is, the more power efficient the equipment is. The calculation of TEEER is straightforward. For example, for a router with the following specs $Forwardingcapacity = 160Gbps$, $P_{\max} = 4320W$, $P_{50} = 3000W$, and $P_{sleep} = 1500W$, its total power consumption can be calculated using (3) as $P_{Total} = 3087W$. Then, the TEEER can be calculated using (5) as $TEEER = 7.71$.

While Verizon's TEEER metric focuses on the company specific purchasing decisions, the Alliance for Telecommunications Industry Solutions (ATIS) has published industry wide standards on general requirements [17], transport equipment [18], and server equipment [19] and is developing standards for routers, power rectifiers, and wireless access equipment. The Telecommunications Energy Efficiency Ratio (TEER) for network-element efficiency is introduced in the standards. Similar to the TEEER definitions, the standards are specific to equipment type, network location, and classification. Table III summarizes some performance metrics used in the standards.

TABLE III. SUMMARY OF ATIS ENERGY PERFORMANCE METRICS

Metric	Focus	Description
Power Usage Effectiveness (PUE)	Computational infrastructure power efficiency	Total facility power consumption per total equipment power consumption
Datacenter Efficiency (DCE)	Computational infrastructure power efficiency	Reciprocal of PUE
Bit Communications Energy Efficiency (BCEE)	Overall communications throughput energy efficiency	
Energy Spectral Efficiency (ESE)	Information capacity efficiency in the frequency domain	
Base Station User Energy Efficiency	Efficiency for overall hardware and communications systems	
Telecommunications Equipment Energy Efficiency Rating (TEEER)	Networks and Building Systems Compliance Purchasing Requirements	Minimum energy efficiency specifications for components for meeting purchasing requirements
Telecommunications Energy Efficiency Ratio (TEER)	Quantifies Network-element Efficiency	Specific to equipment type, network location and classification

IV. ADVANCES AT SPECIFIC POINTS IN THE COMMUNICATIONS LIFECYCLE

Researchers are addressing the need for improving energy efficiency at individual levels within the protocol stack as well as through system architecture, operational management and physical elements. This section reviews some advancements roughly defined within an elemental area of the communications cycle (shown in Fig. 3) such as the radio component, the network operation and topology, and the integration of renewable energy sources.

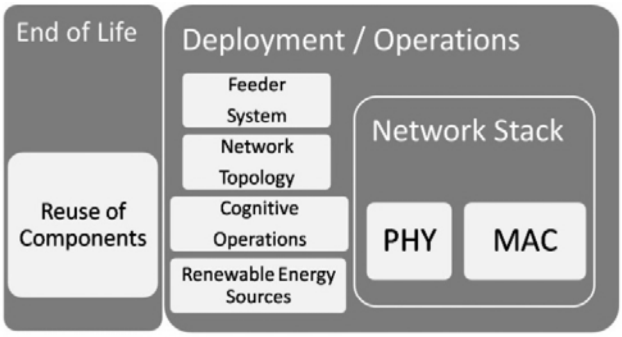

Figure 3. Communications Life Cycle.

A. Radio Component – Power Amplifier

A BS usually consists of three major components: the baseband unit, the radio and the feeder network. Among these elements, the radio accounts for around 80% of a BS' energy needs, 50% of which is consumed by the power amplifier (PA) [20-21]. Similarly, in a handheld mobile station (MS), the wireless modem consumes most of the power. The PA in the modem dominates even for computing intensive applications, such as, video conference [23].

For this reason, much emphasis has been focused on increasing PA efficiency while maintaining linearity and broadening the operating bandwidth. The PA enhances the input signal to a required output power level by converting DC power to RF AC power. However, this conversion is lossy. The characteristics of the input signal (e.g., modulation scheme) affect the PA efficiency. Non-constant magnitude modulation schemes with better spectrum efficiency have a strict linearity requirement, which usually requires a large back-off from the PA's saturation point. For example, OFDM has been exploited in many emerging wireless standards, such as, WiFi, WiMAX, and LTE, to achieve higher data rate. Its high peak to average power ratio (PAPR) is a big challenge in the PA design since large back-off is required to maintain linearity. This leads to low efficiency as the PA efficiency is maximal at its peak envelope power (PEP) and drops as its output power decreases. The improvement in PA efficiency has been achieved through new PA architecture, material, and digital signal processing algorithms.

The use of high efficiency nonlinear switch-mode PA in different PA structures, such as the Doherty [24] and the out-phasing [25, 26] structures, improves its efficiency, and its linearity. For example, a multi-stage Doherty PA has shown a theoretical efficiency of 70% for Rayleigh distributed envelope signals [27]. More recently, a high power (190W PEP), 32% efficient LDMOS (lateral double-diffused metal-oxide semiconductors) Doherty PA with a more compact load network than that of a conventional Doherty PA was designed for base stations [28]. Dynamic voltage scaling and envelope tracking are two additional techniques to increase RF PA efficiency [37].

The high frequencies in wireless systems and switch-mode architectures are pushing research in the material science of transistor technology. Currently, the LMDOS technology dominates the market. However, high electron mobility transistors (HEMT's) utilizing Aluminum Gallium Nitride (AlGaN) show potential in providing higher output power as it is able to work under higher temperature and higher voltage [29-31].

Moreover, digital signal processing techniques are exploited to reduce the nonlinear effects caused by efficiency enhancement techniques [32-35]. PAPR reduction techniques, such as, clipping, windowing, interleaving, elective mapping, and polar transmission, help increase the PA efficiency for OFDM signals [36].

There are other efficiency enhancement techniques. Multi-carrier base station technology, such as GSM Quadruple Transceiver Technology using 6 carriers, can reduce maximum consumption of the PA by up to 30% [21].

B. Network Operation and Topology

Since the BS is the main power consuming component in a cellular network, a lot of efforts have been devoted to develop green BS. For example, Huawei's green GSM Base Transceiver Station (BTS) efforts address energy efficiency at several layers [38]. At the PA level, the Doherty-based technology is used to improve PA efficiency from 33% to 45%. Operation software with TRX shutdown technologies reduced static power consumption by 60%. Multi-density radio transceivers enabled a single module to support up to six carrier frequencies. This led to smaller and lighter base stations that require less cooling and auxiliary equipment.

The relative location between an antenna and radio has significant impact on energy efficiency. Traditionally, all radio equipment has been located in an enclosure at the ground level with connection to antennas through feeder cables, which could produce over 50% of loss into the system [6, 21]. Modular BS designs that locate RF transmitter closer to the antenna reduce the cable loss and maintain the same QoS at lower transmit power [39].

Topology specific design perspectives and improved planning methodologies improve power efficiency by reducing the number of sites. The smaller and more agile BS's dovetail to a distributed BS architecture, which can replace larger and more power-hungry macro BS's. Actual deployments of these more agile base stations have achieved more than a 40% power savings without affecting overall output signal power [38]. Other techniques such as transmit diversity and higher receive sensitivities can also yield power savings [21]. In addition, game theoretic principles have been used for analyzing the energy efficiency in CDMA networks [40].

Femtocell and picocell technologies have potential to reduce overall power usage while still optimizing capacity and service. A fundamental pathway to improving cellular capacity is to reduce the distance between an MS and a BS. Femtocells connect miniaturized, lower power BS's to wired backhauls such as home digital subscriber lines (DSL) or cable modems and radiate very low power compared to a full size BS. At the meantime, they can achieve improved capacity in large scale deployment [41]. Simulations have shown that joint deployment of macro BS's with publicly accessible residential picocells can reduce energy consumption up to 60% [42]. Initial research has predicted 102 million users worldwide using more than 32 million femtocells by 2011. However, early mass deployment has been delayed at least a year due to the current economic crisis [43]. While femtocells create a pathway to high capacity under low power usage, many research issues arise with regards to distributed frequency management [44, 45], Femtocell/macrocell interference [46], handover, self optimizing networks [47], security, and backhaul data load balancing.

Fluctuations in cellular usage are often spatially and temporally correlated. For example, during evening rush hour usage is high and decreases later in the night while also decreasing geographically around business districts in the evenings and weekends. BTS equipment can learn from these patterns and turn off or decrease the number of transmitting antennas and hence, reduce power consumption [39]. In addition, due to the diversity at different users, spectrum can be dynamically allocated to different users so that the overall power budget is minimized. To explore the channel fluctuation, it requires coordinated management of BS's to maintain desired capacity and customer QoS.

The green initiative also impacts the standardization process. For example, in the recently 3GPP LTE-Advanced standard release, a study item on potential solutions to energy saving has been proposed [48]. This study item includes the following use cases: intra-eNB energy saving, inter-eNB energy saving, and inter-RAT energy saving. Both user accessibility and backward compatibility are required in the evaluation of solutions. In addition, it is required that the solutions should not impact the Uu physical layer and increase the user equipment (UE) power consumption.

C. Incorporation of Alternative Energy

Several cellular operators are experimenting with the use of alternative energy sources such as fuel cells, wind, and solar for BS operation. These alternative energy sources can provide an energy efficient alternative to 'dirtier' and more expensive fuel sources such as diesel and strive towards energy independence. In addition to the cost of the fuel itself, energy can be saved from minimizing the transportation and storage of the fuel, especially for remote sites. Similarly, energy harvesting techniques such as solar, thermal, optical and kinetic energy (vibration and biochemical) [49] can replace or complement batteries in mobile handsets.

While traditional radio design is based on consistently available power supply, green radios are expected to maintain the same QoS even when the power supply stochastically varies in space and time, thereby experiencing outages not only in the channel but also in the system itself. The design objectives also differ from extending the system lifetime to maximizing the system availability. Additionally, the overall network design should include redundant energy sources and neighboring BS's should be able to compensate for BS's that go down due to insufficient power.

In Namibia, the Mobile Telecommunications Limited (MTC) of Namibia, the GSMA Development Fund, and Motorola initiated a 90 day trial in 2007 to evaluate the use of solar and wind as a feasible cost-effective energy source for a cellular base station [50]. This trial utilized a 6kW wind turbine and 28kW solar panels combined with battery capable of supporting 60 hours of operation. The system provided an average of 198kW of power per week which was 10kWh more than necessary for regular operations. MTC calculated a return on investment of 3 years and reduction of approximately 4,850kg of CO2 annually compared to a typical electrical grid installation. Additional reduction of 649.25kg CO2 annually could be achieved by eliminating the diesel generators.

A startup company, on the request of Ericsson, has developed a BS that runs on wind and solar power [51]. Currently, over 40,000 BS's operate in Africa with most running on diesel power consuming almost 20,000 liters of diesel per year per BS. According to the manufacturer, Flexenclosure, the cost of running a diesel base station exceeds $30,000 per year. Potentially, $120,000 to $150,000 in operation cost can be saved over a five-year period using the alternative energy.

In addition to the above areas where power efficiency improvement can lead to great overall power reduction, power efficiency improvement of any other individual element in the wireless network will also lead to power reduction. Nowadays, many of the research results have seen their adoption in actual product design. And the benefit achieved using the new technologies stimulates and accelerates further research on improving power efficiency of elements in the network.

V. HOLISTIC SOLUTIONS

Simply combining the power efficiency improvement technologies developed for single element might not lead to optimal power reduction. Instead, a holistic strategy that explores the synergy between various technologies may optimize overall power performance. This section presents a couple of approaches under this strategy, including cross-layer design method, cognitive approach, and radio coordination approach.

A. Cross Layer Design for Power Efficiencies

Communication networks have traditionally followed a layered architecture where specific functional are completely separate. This modular architecture simplifies overall design and development. On the other hand, a cross-layer design method can obtain performance gains by designing protocols with interaction between different layers [52]. Energy efficiency and security are examples of aspects that could benefit from a cross-layer design strategy that ties the PHY layer to the MAC layer or other networking functions.

Cross-layer design for resource allocation has been applied to 3G networks for optimizing radio resource allocation with a BER constraint [53]. The information exchange across protocol layers shows better performance especially with heterogeneous data and video services. QoS and capacity are evaluated outside the protocol stack, while energy efficiency is measured within the PHY layer. Various QoS constraints are studied with the goal of minimizing energy consumption [54].

QoS metrics such as average conditional expectation of delay is typically correlated with channel gain. If delay is constrained to a fixed level across all channel gains then average power can be minimized subject to a specific delay constraint. By imposing this tighter delay constraint, power savings can be achieved through cross-layer design and source-channel coding as opposed to the typical power control methodology [55].

B. Cognitive Radio for Power Optimizaiton

Cognitive Radio (CR) is a relatively new research area in communications that incorporates environment observation, decision making and learning, and radio reconfiguration to improve the performance of communication systems [56, 57]. CR springboards off of the successful adoption of software radio platforms and has shown promise in military [58] and public safety [59] domains. The concept of cognitive systems has great promise towards Green Communications. Leveraging the advancements in the capability of environment observation, realizable learning and decision making algorithms can be applied in a cellular network. Environment observation includes traditional RF metrics such as signal to noise ratio (SNR), channel occupancy as well as application QoS requirement. Additionally, observing the power usage of base stations and manipulating interaction with the underlying electrical system has significant potential to contributing towards a smart grid capable of more balanced energy delivery.

Leveraging advances in emerging CR technologies, we have proposed a power optimization framework using CR, as shown in Fig. 4, to dynamically implement favorable trade-offs in radio parameters to minimize power consumption for the required QoS for a particular application and radio environment [60]. In this framework, the solid lines with arrows and the blocks in solid boundaries are existing components in conventional wireless communication devices. The dashed lines with arrows and the cognitive engine (CE) block are new components enabling CR capability in conventional systems. The bidirectional dashed lines between the CE and various building blocks enable the CE to learn the characteristics and the capabilities of the building blocks and control/configure the blocks based on its decision for different application and environment.

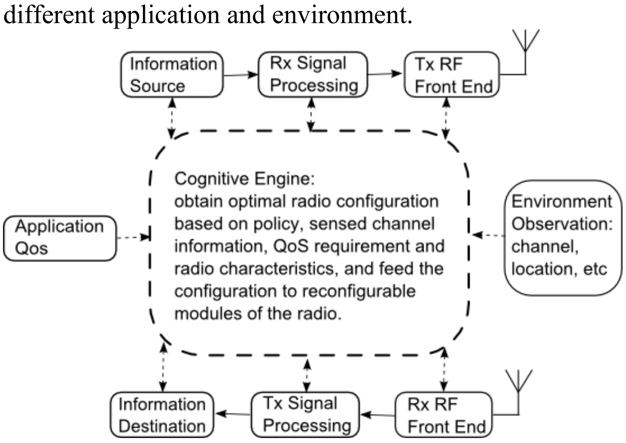

Figure 4. Cognitive Radio Framework for Power Optimization [60].

A general active process starts with CE receiving a service request along with the QoS requirement, it then queries the radio platform for platform capabilities and characteristics and environment information. The CE uses the obtain information to determine a favorable radio configuration that satisfies the application QoS and optimizes some radio performance metrics. For green communications purpose, these performance metrics can include power consumption.

This framework can be applied to radio systems with different technologies. For example, for a conventional single input single output system, two levels of operation, adaptive transmission with component knowledge and adaptive transmission with component adaptation, have shown significant energy savings (up to 75%) compared to conventional adaptive transmission [60, 61]. This work has been extended to multiple input multiple output (MIMO) systems [62]. Conventionally, various power and bit allocation schemes were proposed to tradeoff total radiated power and capacity. Leveraging the knowledge on the platform (component) characteristics learned by the CR, system power consumption, instead of radiated power, can be minimized for given target rate. Simulation results show up to 75% of power savings for a 4 by 4 MIMO system using Class A PA's.

In addition to hardware power consumption, resource consumption of digital signal processing can also play a significant role in system power consumption. [63] investigates the use of real-time resource monitoring to reduce the computational complexity of the baseband processor. Specifically [63] demonstrates by minimally scarifying physical layer system performance, computational complexity can be significantly reduced without compromising the QoS of the application. Supervised intelligent heuristic-based learning algorithms are used to achieve this resource management. These learning algorithms optimize energy and processing efficiencies in dynamic spectrum environments using software-level feedback of the radio's active resource consumption.

C. Coordinated Approach to Improving Efficiency

In a wireless network, while each node might have a selfish goal of improving performance in capacity, QoS or power, the needs of the overall system must be balanced with the goals of each node. In addition, each node is also a power hungry citizen of the overall power grid network. Coordinated management and load balancing among nodes underneath an overall smart grid has positive impact on energy consumption without adversely affecting QoS and capacity. Recent developments in wired distributed computing theory [64, 65] provide initial models for its application to wireless networks and the interaction between different nodes and between the entire telecommunication network and the electrical grid network.

It is challenging to apply similar concepts in a wireless environment due to disruptive characteristics of the wireless channels, such as varying channel conditions, a shared medium, and drastically different power-costs of communication. The Wireless Distributed Computing (WDC) system design tradeoffs involve cross-system interaction between the computation subsystem (or application layer where the computing process is executed) and the communication subsystem (or underlying networking, radio access and physical layers). Consequently, new methodologies have been proposed to as performance in terms of range, power efficiency and scalability is greatly influenced by the underlying radio environment [66]. The new methodologies try to develop protocols, service architecture, resource allocation and computational load balancing, and power consumption minimization algorithms.

A group of collaborating radios offers several benefits over a lone radio, such as: (1) enabling lower power consumption per node and, under certain conditions, lower power consumption for the whole network; (2) allowing matching between power demand and supply; (3) meeting high computing and latency requirements by leveraging the computing resources in the network; and (4) simplifying small form factor node designs with lower computing and power resources per node.

Minimizing energy consumption in WDC networks through optimal computational workload allocation has been discussed in [67]. In a WSC network the communication subsystems connect the computation subsystems on various nodes through wireless links, disseminate the computational workload, pass inter-process messages, and collect processing results. For example, in a broadcast network, a master node distributes its computational load among several slave nodes. The slave nodes process their share of the workload and return the results to the master node. The master node then fuses the results from participating slave nodes.

In WDC, the savings in computational power consumption are partially negated by the overhead of communication power consumption. In addition, the improvement in the computational power savings with an increase in the number of collaborating nodes is countered by an increase in the overhead of power consumption for communication between the nodes. Thus, as shown in Fig. 5 [66], a breaking point may exist, beyond which WDC is not power efficient as compared to on-board processing.

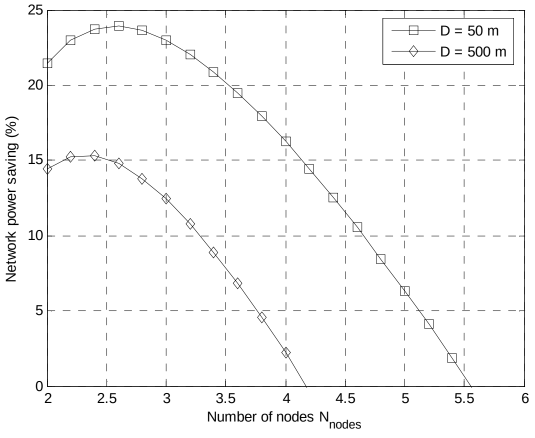

Figure 5. Network power savings achieved by distributed computing for various network sizes and network ranges [66].

A similar idea, called Coordinated Multipoint Transmission (CoMP), has been recently proposed in the 3GPP LTE-Advance standardization process [68]. This technology coordinates transmission among multiple cells and reduces the interference from other cells thus reduces the power required to maintain certain QoS.

VI. CONCLUSIONS

There is no doubt that the explosive growth in voice and data usage and the rising energy costs are leading to significant impact in the carbon emission and the operation expense. In this paper, we present some initial efforts in Green Communications to compensate these effects. A few efficiency definitions that can be used to evaluate different approaches are discussed first. We then review the existing developments within singular aspect of the communication life cycle, including network components, network operation and topology, and integration of alternative energy in the network. Finally, we present several holistic approaches that incorporate multiple aspects in the communication life cycle. These approaches include cross-layer design, cognitive radio approach, and wireless distributed computing solution.

As we can see from the existing work, researchers are creating novel solutions to the energy problem faced by the wireless industry by employing and combining existing technologies developed for related issues in wireless domain as well as in other domains. As the advancements in designing power efficient network components, a framework, which is aware of the capabilities and characteristics of each component, can further optimize the network operation for various goals given the application QoS requirement and operation environment. For this scenario we think a cognitive radio based framework can be of great help. This is reflected in the development of emerging wireless standards. For example, the new universal mobile telecommunications system (UMTS) proposals advocate self-configuring and self-organizing wireless networks [69]. The self-organizing networks can automatically optimize wireless network operation, e.g., potentially reducing power consumption given QoS requirements and channel conditions. A cognitive radio based solution is favorable through online learning and monitoring of network operation, integration of learned knowledge about network operation in network optimization, and dynamic reconfiguration of network to improve network efficiency.

As we move down the path to greener communications, we will identify new useful technologies developed in related areas. The capability of integrating new technologies into an existing system becomes crucial in developing a future-proof green communication solution. The success of this green endeavor defends on the synergy gained from the cooperation of researchers from many disciplines, some of which may seem to be quite remote from today's review point.

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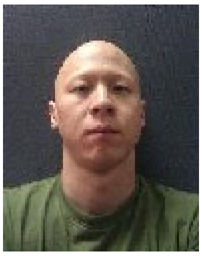

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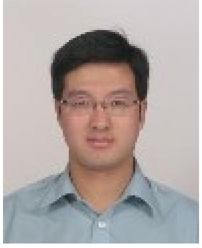

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