# Best Readings Topics on Green Communications


- Theory, modeling, analysis, and/or optimization for green and sustainable communications
- Life-cycle analysis for green communications
- Architecture, strategies, algorithms, protocols, scheduling, and/or designs for green communications
- Green software, hardware, devices, and equipment for communications
- Green wireless and/or wireline communications
- Green schedulings and allocations for communications
- Green optical devices, signal processing, and communications
- Electromagnetic pollution mitigation
- Green terminals for wireless and wireline communications
- Green data storage, data centers and cloud computing, contention distribution networks
- Green communications under delay or quality of service constraints
- Physical layer approaches for green communications and computing
- Green cognitive communications and computing
- Green smart grids
- Green Internet of Things
- Energy harvesting, storage, and recycling
- Standardization, evaluation, practice, measurement, policy and regulation for green communications
- Applications, economics, social issues, and interdisciplinary topics


## Theory, modeling, analysis, and/or optimization for green and sustainable communications

**O. Tamm, C. Hermsmeyer, A. Rush, "Eco-Sustainable System and Network Architectures for Future Transport Networks", Bell Labs Technical Journal, vol.14, no.4, p.311 2010**

This paper discusses energy consumption in core optical internet functions such as data transport, aggregation and switching. The paper addresses the fact that current internet traffic volumes are increasing rapidly, meaning that the internet is forecast to consume an increasing proportion of total energy use. The paper studies the energy consumption of internet devices as at 2008 and also forecasts energy consumption trends in these devices up until 2020.

**P. Grover, P.; K. Woyach, and A. Sahai, "Towards a Communication-Theoretic Understanding of System-Level Power Consumption," IEEE JSAC, Special Issue on Energy-Efficient Wireless Communications, vol. 29, no. 8, pp. 1744 - 1755, Sept. 2011**
The authors give a theoretical point of view on how to minimize the total power in a communication system. This article provides a well-investigated theoretical framework that considers the required decoding power as well as the transmit power. The model is examined from two perspectives – for an isolated point-to-point link, and a collection of interfering non-cooperating links.

**P. Mahadevan, P. Sharma, S. Banerjee, P. Ranganathan, "A Power Benchmarking Framework for Network Devices", Lecture Notes in Computer Science, vol. 5550, p.795, 2009**
An important property of any communications device is its capability to scale energy consumption according to the current traffic load. This paper studies a number of wired routers to assess their energy consumption properties at different traffic loads to assess their relative efficiency. The paper also defines a novel metric called energy proportionality index (EPI) which is a simple measure to show how effectively a particular device can scale its energy consumption with traffic load.

# Life-cycle analysis for green communications

**Mireille Faist Emmenegger, Rolf Frischknecht, Markus Stutz, Michael Guggisberg, Res Witschi, Tim Otto, "Life Cycle Assessment of the Mobile Communication System UMTS: Towards Eco-efficient Systems", The International Journal of Life Cycle Assessment, July 2006, Volume 11, Issue 4, pp 265-276.**
This is one of the first papers to provide a detailed life cycle assessment of wireless communications systems, based on measurements made in Switzerland. In this study both the Universal Mobile Telecommunication System (UMTS) and the older Global System for Mobile Communication (GSM). Due to the higher spectrum efficiencies of UMTS systems, it is found that its overall footprint is lower than for GSM technologies.

# Architecture, strategies, algorithms, protocols, scheduling, and/or designs for

# green communications

**B. Wang, S. Singh, "Computational Energy Cost of TCP", INFOCOM 2004, Vol.2, p.785, 2004**
The authors perform measurements on three different systems and two different platforms to study the energy cost of TCP (Transmission Control Protocol). They analyze these measurements for separate TCP functions at both the sender and receiver. Then, some software approaches are presented to re- duce the energy cost of TCP processing by between 20% and 30% in most cases. These results can be used by researchers to study node-level energy cost models and the energy consumption in wireless networks including.

**M. Gupta, S. Singh, "Greening of the Internet", ACM SIGCOMM 2003, p.19, 2003**
This paper is a premier work on studying the energy consumption of networking devices in the internet, such as Hubs, switches, and Routers, and how to modify the already deployed architectures and protocols in the internet to save energy in these devices. The authors first discuss why it is important to consider the energy consumption of networking devices in the internet. Next, identifying "sleeping" technique as the most appropriate way of energy conservation, new protocols followed by necessary architecture changes are suggested to put more networking devices into sleep at a given time.

# Green software, hardware, devices, and equipment for communications

**P. Somavat, V. Namboodiri, "Energy Consumption of Personal Computing Including Portable Communication Devices", Journal of Green Engineering, Vol.1, No.4, p.447, 2011**
This paper presents a detailed investigation of the overall energy consumption of computing devices at 2010, looking at mobile devices such as mobile phones and laptops as well as the energy consumption of network side including internet connections, data centers and desktop computers. They also discuss their results in the broader context of total energy consumption in different countries and provide recommendations for improving energy saving in future devices and networks.

**B. Puype, W. Wereecken, D. Colle, M. Pickavet, P. Demeester, "Multilayer traffic engineering for energy efficiency", Photonic Network Communications, Apr. 2011, DOI 10.1007/s11107-010-0287-6**
This paper investigates how multilayer traffic engineering helps in improving network energy efficiency, and how the power requirement in the network can be modeled for the multilayer traffic engineering (MLTE) algorithm. Then the paper discuss two case studies where the merits of MLTE for energy efficiency are shown.

**K. Hinton, J. Baliga, M. Feng, R. Ayre, R. Tucker, "Power Consumption and Energy Efficiency of the Internet", IEEE Network, March/April, p.6, 2011**

An excellent introduction and high level overview of the main energy issues for the data networks that make up the Internet including access and core technologies.

**J. Baliga, R. Ayre, K. Hinton, W. Sorin, R. Tucker, "Energy Consumption in Optical IP Networks", IEEE/OSA Jour. Lightwave Technol., vol.27, no.13, p.2391, 2009**
First detailed bottom up approach to understanding energy use in communication networks considering wireline networks from access to the core.

**R. Tucker, R. Parthiban, J. Baliga, K. Hinton, R. Ayre, W. Sorin, "Evolution of WDM Optical IP Networks: A Cost and Energy Perspective", IEEE/OSA Jour. Lightwave Technol. vol.27, no.3, p.243, 2009**
This paper reviewed technologies and architectures for wavelength-division multiplexing (WDM) optical IP networks from the viewpoint of capital expenditure and network energy consumption. The paper showed how requirements of the low cost and low energy consumptions could influence the choices of switching technologies.

**D. Kilper, K. Guan, K. Hinton, R. Ayre, "Energy Challenges in Current and Future Optical Transmission Networks", Proc. IEEE, vol.100, no.5, p.1168 2012**
Provides an overview of energy use in optical systems for core networks and describes trends and research related to energy and scaling of optical networks.

**A. Dejonghe, B. Bougard, S. Pollin, J. Craninckx, A. Bourdoux, L. Ven der Perre, and F. Catthoor, "Green reconfigurable radio systems," IEEE Signal Processing Magazine, vol. 24, no. 3, pp. 90-101, May 2007**
The authors present the concept of green reconfigurable radio system as a flexible energy-efficient alternative to overcome spectrum scarcity and mitigate the growing gap between the available battery energy and the rapidly increasing energy requirements of future radios. An energy-aware cross-layer radio management framework is also presented for different case studies to show the gains achieved by cross-layer optimization and problem partitioning. The Software Defined Radio and its role in enabling Cognitive Radio are also discussed.

**Amor Nafkha, Pierre Leray, Yves Louet, and Jacques Palicot, "Moving a Processing Element from Hot to Cool Spots: Is This an Efficient Method to Decrease Leakage Power Consumption in FPGAs?," the Chapter 8 of "Green Communications-Theoretical Fundamentals, Algorithms and Applications, edited by J. Wu, S. Rangan, and H. Zhang, CRC Press, September 2012**
This book chapter is dedicated to the significant implementation issue of leakage power consumption in FPGA systems. In Particular, this chapter has heavily focused on FPGA's temperature and static power consumption, possibility to move the Processing Element from a hot spot to a cooler one, and dynamic power consumption management using DPR (dynamic partial reconfiguration), so as to reduce the leakage power consumption of the FPGA systems.

# Green wireless and/or wireline

# communications

**H. Matthews, T. Morawski, A. Nagengast, G. O'Reilly, D. Picklesimer, R. Sackett, P. Wu, "Planning Energy-Efficient and Eco-Sustainable Telecommunications Networks", Bell Labs Technical Journal, vol.15, no.1, p.215, 2010**
A detailed overview of energy efficiency issues in future communications networks is described and presented. The paper addresses technical means to save energy as well as investigating alternative energy sources such as solar or wind. The paper also develops a simple business model to show the financial impact of energy savings on a network operator.

**Y. Chen, S. Zhang, S. Xu, G. Li, "Fundamental Trade-offs on Green Wireless Networks " IEEE Communications Magazine, June, p.30, 2011**
A significant work proposing a framework for green radio research and integrating the fundamental issues that are currently dispersed. Using four fundamental tradeoffs, namely deployment efficiency-energy efficiency, spectrum efficiency-energy efficiency, bandwidth-power, and delay-power tradeoffs, the authors demonstrate how key network performance/cost indicators are tied together.

**G. Auer, V. Giannini, I. Godor, P. Skillermark, M. Olsson, M. Imran, D. Sabella, M. Gonzalez, O. Blume, A. Fehske, "How Much Energy Is Needed to Run a Wireless Network? ", IEEE Wireless Communications, vol. 49, no. 6, October, 2011**
In this important work, within the Energy Aware Radio and Network Technologies (EARTH) project, a general energy efficiency evaluation framework (E3F) is developed to quantify the energy efficiency for operation of cellular radio networks. E3F stands out among existing energy efficiency evaluation schemes by taking into account various base station types, as well as long term traffic models and large scale deployment models.

**A. Fehske, G. Fettweis, J. Malmodin, G. Biczok, "The Global Footprint of Mobile Communications" The Ecological and Economic Perspective", IEEE Communications Magazine, August, p.55, 2011**
This is an important paper in which the carbon footprint of mobile communication systems is comprehensively classified and quantified. The ecological and economic implications of this carbon footprint are also discussed. It is predicted in this paper that three orders of magnitude more traffic can be supported with the same energy consumption as of today, if the technologies designed to reduce the energy consumption are implemented quickly.

**J. Baliga, R. Ayre, K. Hinton, R. Tucker, "Energy Consumption in Wired and Wireless Access Networks", IEEE Communications Magazine, vol. 49, no. 6, June 2011**
This article presents a detailed all-inclusive analysis of energy consumption in various representative wired and wireless access networks, which includes the energy consumption of DSL, HFC networks, passive optical networks, fiber to the node, point-to-point optical systems, UMTS (W-CDMA), and WiMAX. In particular, this article also points out the advantage of future optical access networks holding the potential as one of the most energy-efficient access technologies.

**C. Jian, G. Lim, L. Cimini, G. Feng, G. Li, "A Survey of Energy-Efficient Wireless Communications", IEEE Communications Surveys and Tutorials, vol. 15, no. 1, 2013, pp. 167 - 178**
This is one of the very early introductive papers that provides a comprehensive survey covering various broad aspects of energy-efficient wireless communications and networks, which first outlines the technical roadmaps of several representative international projects for energy-efficient wireless networks and then introduces the state-of-the-art research on energy-efficient wireless networks including energy-efficiency metric, network deployment strategies, network resource management, relay and cooperative communications, MIMO and OFDM technologies, as well as cross-layer optimizations for developing energy-efficient wireless networks.

**A. Bianzino, C. Chaudet, D. Rossi, J. Rougier, "A Survey of Green Networking Research", IEEE Communications Surveys and Tutorials, vol.14, no.1, pp. 3-20, 2012**
As a comprehensive survey on green networking research, the authors focus on surveying the previous research on reducing the energy consumption in the wired networks. The article discusses four main techniques to reduce the energy waste including Adaptive Link Rate, Interface-Proxying, Energy-Aware Infrastructure, and Energy-Aware Applications. It also provides the open problems to each technique as well as a further perspective for research.

**Y. Zhang, P Chowdhury, M. Torniatore, B. Mukerjee, "Energy Efficiency in Telecom Optical Networks", IEEE Communications Surveys and Tutorials, vol.12, no.4, pp. 441, 2010**
This is a very comprehensive survey on research activities for improving energy efficiency in optical networks. It first explained the energy issues in core, metro, and access network domains and provided a survey on the standardization efforts for making optical networks be more energy-efficient. The detailed technologies for designing green core, metro and access networks were summarized afterwards. This paper is a one-stop reference for energy-efficient optical networks.

**R. Bolla, R. Bruschi, F. Davoli, F. Cucchietti, "Energy Efficiency of the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures", IEEE Communications Surveys and Tutorials, vol.13, no.2, p.223, 2011**
This paper provided a survey on existing technologies for designing energy-aware fixed network infrastructures, discussed the reasons for energy wastes in current network infrastructures, explained the concepts for low-energy networking from different perspectives, and also forecasted green technologies in future Internet.

**J. Baliga, R. Ayre, K. Hinton, R. S. Tucker, "Architectures for Energy Efficient IPTV Networks" in Proc. OFC/NFOEC, 2009**
Pioneering analysis of the energy trade-off between transport and storage in content distribution.

**L. Chiaraviglio, M. Mellia, F. Neri, "Reducing power consumption in backbone networks" in Proc. IEEE ICC 2009.**
This is an important work on reducing power consumptions in backbone networks by switching off network nodes and links strategically. The paper proved that the problem itself falls in the class of capacitated multi-commodity flow problems and proposed a few heuristics to solve it.

**D. Kilper, et al., "Power Trends in Communication Networks," IEEE J. Sel. Top. Quantum Electron., vol. 17, no. 2, p. 275, 2011.**

A detailed bottom up assessment of commercial wireline and wireless network energy trends using a transaction based service model.

**F. Richter, A. Fehske, and G. Fettweis, "Energy efficiency aspects of base station deployment strategies for cellular networks," in Proc. IEEE Vehicular Technology Conference Fall (VTC 2009-Fall), 2009**
This paper provides a detailed mathematical model that demonstrates that the choice of cell size has a significant impact on the energy consumption of a wireless network. Their results suggest that for a given network there is an optimal cell size that minimizes energy consumption.

**L. Correia, D. Zeller, O. Blume, D. Ferling, Y. Jading, I. Godor, G. Auer, and L. Van der Perre, "Challenges and enabling technologies for energy aware mobile radio networks," IEEE Communications Magazine, , vol. 48, pp. 66-72, November 2010**
This is one of the early papers presenting a holistic approach for energy efficient mobile radio networks. The authors describe a framework for energy efficiency evaluation, identifying the levels that need to be addressed, namely, component level, link level and network level.

**Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," IEEE Communications Magazine, vol. 48, no. 11, pp. 74-79, 2010**
The concept of adjusting cell sizes by varying transmission power levels to match traffic loads is investigated in this paper. The key contribution is to show that by adjusting the transmit power, a wireless network can provide good coverage for high traffic conditions and save significant energy consumption under lower traffic conditions by reducing base station transmit power or switching them off (sleep mode).

**C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. Grant, H. Haas, J. Thompson, I. Ku, C. Wang, et al., "Green radio: radio techniques to enable energy-efficient wireless networks," IEEE Communications Magazine, vol. 49, no. 6, pp. 46-54, 2011**
This is an important paper that describes the approach being taken in the Mobile VCE project to study novel approaches to reducing the energy consumption of wireless links, particularly in improving the design and operation of wireless base stations.

**B. Badic, T. O'Farrrell, P. Loskot, and J. He, "Energy efficient radio access architectures for green radio: Large versus small cell size deployment," in IEEE Vehicular Technology Conference Fall (VTC 2009-Fall), 2009, pp. 1-5, Sept. 2009**
The authors study the relation between the energy consumption performance and reducing the cell size in cellular radio access networks. Energy consumption ratio and energy consumption gain are used to evaluate this performance when the cell size is reduced for a certain user density and service area. They investigate two different architectures where sleep mode is used in one of them along with a small-cell deployment. These two architectures aim to increase the energy consumption gain and reduce energy consumption ratio while maintaining a given Quality-of-Service.

**S. Zhou, J. Gong, Z. Yang, Z. Niu, and P. Yang, "Green mobile access network with dynamic base station energy saving," in Proc. ACM MobiCom, vol. 9, 2009**

This is one of the very early papers on base station (BS) energy saving issues within the mobile cellular access networks, which deals with dynamically turning off certain BSs when the network traffic is low and implements the centralized and decentralized power saving algorithms while paying specific attention to the cellular coverage guarantee.

**E. Oh, B. Krishnamachari, X. Liu, and Z. Niu, "Toward dynamic energy-efficient operation of cellular network infrastructure," IEEE Communications Magazine, vol. 49, no. 6, pp. 56-61, 2011**
This is a significant work which discusses how dynamic operation of base stations can contribute to significant energy savings in cellular networks. The idea is to turn off redundant base stations when they are under low traffic condition. Some open issues associated with implementing energy efficient dynamic operation of base stations are also discussed.

**Z. Hasan, H. Boostanimehr, and V. Bhargava, "Green cellular networks: A survey, some research issues and challenges," IEEE Communications Surveys Tutorials, , vol. 13, no. 4, pp. 524-540, 2011**
This is a premier work identifying the methods to improve the power efficiency of cellular networks while also exploring some research issues and challenges and suggesting techniques to enable an energy efficient or “green” cellular network. The authors also present a research vision to make future technologies such as cognitive radio and cooperative relaying more energy efficient.

**M. Marsan and M. Meo, "Energy efficient management of two cellular access networks ," ACM SIGMETRICS Performance Evaluation Review, vol. 37, no. 4, pp. 69-73, 2010**
The article addresses an interesting energy-aware cooperative management technique for two-operator cellular access networks. It proposes to switch off the networks whose traffic is very low while allowing their users to use one of the cooperating networks as roaming customers. The authors show that with different switching patters a substantial amount of energy could be saved.

**K. Chen, C. Cui, Y. Huang, and B. Huang, "C-RAN: A Green RAN Framework ," the Chapter 11 of "Green Communications-Theoretical Fundamentals, Algorithms and Applications, edited by J. Wu, S. Rangan, and H. Zhang, CRC Press, September 2012**
From industrial perspective, this book chapter introduces the motivation, the concept, advantages, challenges, framework, architecture, and up-to-date research and deployment status of C-RAN (Centralized processing, Cooperative radio, Cloud, and Clean infrastructure Radio Access Network) approaches, first announced by China Mobile Communications Corporation in April 2010. C-RAN offers a new paradigm in base stations architecture that aims to reduce the number of cell sites while increasing the base station deployment density. The C-RAN concept lowers operating expenses and simplifies the deployment process. By centralizing all the active electronics of multiple cell sites, at one location, energy, real-estate and security costs may be minimized.

**P. Rost and G. Fettweis, , “Green communications in cellular networks with fixed relay nodes,” Chapter 11 in "Cooperative Cellular Wireless Network," Cambridge, 2011.**
This is a leading work which identifies relaying technique as a candidate to increase the spatial frequency reuse in cellular networks in order to meet higher data rate demands while reducing

the energy consumption level.

**R. Bolla, F. Davoli, R. Bruschi, K. Christensen, F. Cucchietti, and S. Singh, "The potential impact of green technologies in next-generation wireline networks: Is there room for energy saving optimization?," IEEE Communications Magazine, vol. 49, no. 8, pp. 80-86, August 2011**
According to results from ECONET European project, this paper analyzes the feasibility of energy efficiency improvements in green wireline networking through adapting the performance and energy absorption to meet actual workload and operational requirements.

**K. Son, H. Kim, Y. Yi, and B. Krishnamachari, "Base station operation and user association mechanisms for energy-delay tradeo s in green cellular networks ," IEEE Journal on Selected Areas in Communications, vol. 29, no. 8, pp. 1525-1536, 2011**
Facing the ever-growing energy-efficiency challenge of wireless cellular networks, a theoretical framework for base-station (BS) energy saving has been thoroughly developed in this paper, which integrates the dynamic BS operation mechanisms with the relevant mobile terminal/user association processes, in order to realize a total network cost minimization allowing for a flexible tradeoff between the low-level performance and the energy consumption while obtaining optimal energy-efficient user association.

**G. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient wireless communications: tutorial, survey, and open issues," IEEE Wireless Communications, vol. 18, pp. 28-35, December 2011**
An analysis of the basic mathematical trade-offs concerning energy efficiency are explored and discussed. The paper also studies how multiple antenna links and cooperative or relay communications can improve the energy efficiency of wireless communications systems.

**I. Humar, X. Ge, L. Xiang, M. Jo, M. Chen, and J. Zhang, "Rethinking energy efficiency models of cellular networks with embodied energy," IEEE Network Magazine, vol. 25, no. 2, pp. 40-49, March-April 2011**
Unlike most of research in literature, which only considers the operating energy, the authors discuss the effect of embodied energy on the energy efficiency of cellular networks. It is shown that the embodied energy accounts for a significant amount of the energy waste and cannot be neglected when compared to the operating energy. This encourages researches, operators, and manufacturers to reconsider their models for base station energy consumption.

**Tomas Edler and Susanne Lundberg, "Energy efficiency enhancements in radio access networks", Ericsson Review, No 1, 2004**
One of the first publications to study the energy consumption of wireless radio base stations. It drew attention to the inefficiencies in base station design and to the importance of modeling of base station components.

**Meshkati, F., Poor, H.V. ; Schwartz, S.C, "Energy-Efficient Resource Allocation in Wireless Networks", IEEE Signal Processing Magazine, May 2007, vol 24, no. 3, pp 58-68.**
This paper explores energy efficient resource allocation strategies with a focus on the uplink from mobile terminals to base stations. The paper considers a variety of resource allocation and power

control strategies, including those based around game theory concepts.

**C.E. Jones, K.M. Sivalingam, P. A. Agrawal and J.Y.H. Cheng Chen, "A Survey of Energy Efficient Network Protocols for Wireless Networks", Wireless Networks 7, 343–358, 2001**
As one of the pioneering works on energy efficiency in wireless networks, [8] provides a comprehensive survey of recent research in energy efficient and low-power design within all layers of the protocol stack of the wireless networks. Besides the energy savings at the physical layer, the article focuses on the higher layers (starting from the data link layer up to the application layer). The article shows the importance of focusing on all the protocol layers instead of the typical power conservation research at the physical layer only in which most of energy savings have been already achieved.

**Arnold, O., Richter, F. ; Fettweis, G. ; Blume, O., "Power consumption modeling of different base station types in heterogeneous cellular networks", Future Network and Mobile Summit, 2010, 16-18 June 2010, pp 1-8.**
Modelling the relationship between transmitted radio frequency power and the overall power consumption of radio base stations is important for analyzing the overall energy consumption of wireless networks. This is an important paper that studies these issues in detail and proposes realistic power consumption models.

**L. Le, D. Niyato, E. Hossain, D. Kim, D. Hoang, "QoS-Aware and Energy-Efficient Resource Management in OFDMA Femtocells," IEEE Transactions on Wireless Communications, vol. PP, no. 99, pp.1-15, 2013**
As one of the premier works on energy-efficient design of two-tier cellular wireless networks, the authors develop a unified mathematical model to solve the problem of cross-layer resource allocation and admission control for OFDMA-based two-tier femtocell networks. In the presence of both co-tier and cross-tier interferences, this model considers the Quality-of-Service requirements of the macrocell and femtocell users in terms of average data rates and blocking probabilities. They propose a distributed power adaptation algorithm that improves the energy efficiency of the system.

**Hoydis, J.; Kobayashi, M.; Debbah, M., "Green Small-Cell Networks," IEEE Vehicular Technology Magazine, vol. 6, no. 1, pp.37-43, March 2011**
As a more economical and energy-efficient alternative to increasing the density of base stations to meet the expected traffic demands in future networks, the authors introduce the concept of green small-cell networking. The challenges related to the optimal system design and a large system analysis are presented in this article. This is an important work in the area of green cellular wireless networks.

**Fallahi, A.; Hossain, E., "Distributed and Energy-Aware MAC for Differentiated Services Wireless Packet Networks: A General Queuing Analytical Framework," IEEE Transactions on Mobile Computing, vol.6, no.4, pp.381-394, April 2007**
The authors develop a novel analytical model to analyze the trade-off between the Quality-of-Service and the energy efficiency of a distributed and energy-aware wireless medium access control (MAC) protocol considering ser- vice differentiation between two different types of services. They take the impact of non-ideal wireless channel condition as well as the bursty traffic

arrival process and non-saturation MAC buffer state into account. For this general model, the authors present some applications to integrate more realistic considerations into it.

**Tao Chen, Yang Yang, Honggang Zhang, Haesik Kim, and Kari Horneman, "Network Energy Saving Technologies for Green Wireless Access Networks," IEEE Wireless Communications, Feature Topics Issue on Green Radio Communication Networks, vol. 18, no. 5, pp. 30-38, October 2011**
This article presents a timely overview of the network energy saving studies within the framework of 3GPP LTE standardization activities. In particular, by classifying the network energy saving technologies into the time, frequency, and spatial domains, this article strengthens the whole-scale networking solutions involving multiple networks/systems as the most promising technologies toward green wireless access networks.

**S. Aleksic, "Analysis of Power Consumption in Future High-Capacity Network Nodes ", IEEE/OSA Journal of Optical Communications and Networking, vol. 1, no. 3, pp. 245-258, August 2009**
As an important work on improving energy-efficiency in wireless networks, the authors address the significance of exploiting the dependencies between different protocol layers of ad hoc wireless networks in designing these layers when there is a constraint on the energy. The challenges and applications of ad hoc wireless networks as well as cross-layer design are also presented. The article summarizes the design issues at the radio link, network, and application layers.

**A. J. Goldsmith and S. B. Wicker, "Design challenges for energy constrained ad hoc wireless networks," IEEE Wireless Communications. Mag., vol. 9, no. 4, pp. 8–27, Aug. 2002.**
As an important work on improving energy-efficiency in wireless networks, the authors address the significance of exploiting the dependencies between different protocol layers of ad hoc wireless networks in designing these layers when there is a constraint on the energy. The challenges and applications of ad hoc wireless networks as well as cross-layer design are also presented. The article summarizes the design issues at the radio link, network, and application layers.

**E. Jorswieck, H. Boche, S. Naik, "Energy-Aware Utility Regions: Multiple Access Pareto Boundary," IEEE Trans. Wireless Communications, vol. 9, no. 7, pp. 2216-2226, July 2010**
Based on the difference of the individual capacity and a weighted power penalty term, this paper puts forward a novel definition and the relevant model of energy-aware utility function for energy-efficient resource allocation and transmit optimization in the multiuser communication systems, for which the energy-aware utility region and the closed form expression for its Pareto boundary, the maximum sum utility problem in MIMO multiple-access channel, and the relevant efficient algorithm have been theoretically analyzed.

**J. Wu, "Green wireless communications: from concept to reality," IEEE Wireless Communications, vol. 19 , no. 4,, August 2012**
From industry perspective, this article provides a concise and high-level overview in green wireless communications on the relevant statuses and recent advances of the research and

development, which not only summarizes the broad topics in general green wireless communications but also systematically covers various typical aspects of energy-efficient cellular system infrastructure, energy efficiency approaches for base station equipment and environmental temperature control, as well as state-of-art energy efficiency efforts in industrial sectors like 3GPP and Cloud RAN.

**Q. Zhao and L. Tong, "Energy Efficiency of Large-scale Wireless Networks: Proactive Versus Reactive Networking", IEEE JSAC, vol. 23, no. 5, May 2005**
This paper presents an analytic approach to characterize energy consumption of large-scale wireless networks including ad-hoc sensor networks, focusing on the total energy consumption of two representative networking scenarios (i.e. proactive and reactive networking), and specifically taking into account the energy consumption of nodes at various operating states like transmitting, listening, and sleeping mode.

# Green schedulings and allocations for communications

**L. Wang, Y. Xiao, "A Survey of Energy-Efficient Scheduling Mechanisms in Sensor Networks", Mobile Networks and Applications October 2006, Volume 11, Issue 5, pp 723-740**
This is a comprehensive survey on power consumption and energy saving issues in the field of sensor networks, with specific emphasis on various energy-efficient scheduling mechanisms. Corresponding to different typical sensor networking scenarios under the constraints of energy saving and limited lifetime, this survey provides in-depth yet panoramic description on a number of key aspects within sensors networks like sensors detection model, sensing area, transmission range, failure model, time synchronization, ability to obtain location and distance information, distributed non-hierarchical/hierarchical networks structure and sensor deployment strategy.

**Devarajan, R.; Jha, S.C.; Phuyal, U.; Bhargava, V.K., "Energy-Aware Resource Allocation for Cooperative Cellular Network Using Multi-Objective Optimization Approach," IEEE Transactions on Wireless Communications, vol.11, no.5, pp.1797-1807, May 2012**
This is a pioneering work to use multi-objective optimization approach to jointly optimize and keep a balance between the power consumption and throughput in a multiuser, multi-relay cooperative cellular system. In this paper, quality-of-service for the end users is guaranteed in terms of end-to-end signal-to-noise ratio using more realistic channel model assuming the presence of channel estimation errors. The authors also proposed an algorithm to enhance fairness among end users.

# Green optical devices, signal processing, and communications

**D. Miller, "Device Requirements for Optical Interconnects to Silicon Chips", Proc. IEEE, vol.97, no.7, pp. 1166 - 1185, 2009**
A clear and thorough analysis of the scalability and energy efficiency requirements for board and chip level interconnects and the corresponding targets for and potential of optical technologies.

**R. Tucker, "The Role of Optics and Electronics in High-Capacity Routers" Jour Lightwave Technol. vol.24, no.12, pp. 4655 - 4673, 2006**
This paper discussed the designing of high-capacity routers with the emphasis on the usages of optics and electronics. It also covered the energy-consumption problem and provided some ideas on how to improve the energy-efficiency of high-capacity routers.

**R. Keys, "Power Dissipation in Information Processing", Science, vol.168, p.796, 1970**
An early classic paper comparing electronic processing energy limits with optics, pneumatics, and neurons.

**U. Lee, I. Rimac, D. Kilper, V. Hilt, "Toward Energy-Efficient Content Dissemination ", IEEE Network, March/April, vol. 25, no. 2, pp.14-19, 2011**
A review of content dissemination networks and analysis of the potential energy efficiency benefits.

**R. Tucker, K. Hinton, "Energy Consumption and Energy Density in Optical and Electronic Signal Processing", IEEE Photonics Journal, vol.3, no.5, p.812, 2011**
This paper compared the energy consumption and energy density in optical and electronic signal processing, and provided some practical models for future research in these areas.

**K. Hinton, G. Raskutti, P. Farrell, R. Tucker, "Switching Energy and Device Size Limits on Digital Photonic Signal Processing Technologies", IEEE Jour. Quantum Electron., vol. 14, no. 3, pp. 938 - 945, 2008**
This paper derived the relationship between the device size and power consumption of photonic signal processing devices through using device-specific models for photonic signal processing using semiconductor optical amplifiers, periodically poled lithium niobate, and highly nonlinear fibers.

**R. Tucker, "Green Optical Communications -- Part I: Energy Limitations in Transport ," IEEE J. Sel. Top. Quantum Electron., vol. 17, no. 2, pp. 261-274, 2011.**
A detailed analysis of energy limitations for transport in optical communications considering key practical and fundamental constraints. First of a two part analysis that is essential reading for understanding energy limitations in optical networks.

**R. Tucker, "Green Optical Communications -- Part 2: Energy Limitations on Networks ," IEEE J. Sel. Top. Quantum Electron., vol. 17, no. 2, p. 261, 2011.**
A detailed analysis of energy limitations for optical networks considering key practical and fundamental constraints. Second of a two part analysis that is essential reading for understanding energy limitations in optical networks.

**K.-L. Lee, B. Sedighi, R. S. Tucker, H. Chow, and P. Vetter, "Energy efficiency of optical transceivers in fiber access networks," J. Opt. Comm. Netwking, vol. 4, no. 9, pp. 59-68,**

**2012.**
This paper proposes a model on the power consumptions of different transceivers and demonstrates how various electronic and photonic technologies could help improve the energy efficiencies. Then it shows how the energy efficiency is related to the network topology.

**A. V. Krishnamoorty, et al., "Progress in Low-Power Switched Optical Interconnects ," IEEE J. Spec. Top. Quantum Electron., vol. 17, no. 2, pp. 357-376, 2011**
A comprehensive review of the key progress and targets for optical devices and interconnects in terms of energy, bandwidth, and footprint.

**A. Morea, et al., "Power management of optoelectronic interfaces for dynamic optical networks," in Proc. European Conference on Optical Communications, Geneva, 2011.**
This paper proposed a protocol enhancement to manage the power state of optoelectronic interfaces in automatically reconfigurable optical networks. This paper proposed an enhancement of current GMPLS signaling protocol enabling the dynamic power management of optoelectronic devices in the optical layer.

**K. Guan, D. C. Kilper, G. Atkinson, "Evaluating the energy benefit of dynamic optical bypass for content delivery," in Proc. IEEE INFOCOM Green Communications Workshop, 2011**
Establishes the potential and metrics for using dynamic optical bypass to achieve energy efficiency including the trade-off between transmission and content storage.

# Electromagnetic pollution mitigation

**P. Venkatapathy, J. Jena, A. Jandhyala, "Electromagnetic Pollution Index - A Key Attribute of Green Mobile Communications," in Proc. IEEE Green Technologies Conference, April 2012**
This paper is a pioneer effort to quantify electromagnetic pollution (EMP) from the mobile communications perspective. Such an objective measure may be a prerequisite to model, measure, monitor and manage EMP. In this paper, the authors propose electromagnetic pollution index (EPI) as the product of normalized polluted area and polluting energy in a cell. This paper also proposes a model for EPI and derive the relevant relationships to understand the fundamental factors contributing to EPI.

# Green terminals for wireless and wireline communications

**A. P. Azad, S. Alouf, E. Altman, V. Borkar, and G. S. Paschos, "Optimal Control of Sleep Periods for Wireless Terminals," IEEE JSAC, Special Issue on Energy-Efficient Wireless Communications, vol. 29, no. 8, pp. 1605-1617, Sept. 2011**

Power consumption of pervasive mobile terminals is fundamentally significant, which however has been lacking of solid theoretical model to be characterized. As one of the key power consumption control methods, optimal sleep mode for wireless terminals has been theoretically investigated in this paper, with focus on how to optimally schedule shutting off terminal's transceiver and how to control off-times duration (periods of inactivity), response delaying and cost of "waking-up" activities.

# Green data storage, data centers and cloud computing, contention distribution networks

**X. Fan, W. Weber, L. Barroso, "Power Provisioning for a Warehouse-sized Computer ", Proc. ACM International Symposium on Computer Architecture, ISCA, 2007**
This paper presents in-depth investigation and analyses on the basic characteristics of aggregate power usage in the scenario of large collections of computing servers for different classes of applications, which highlights the potential opportunities for maximizing the deployed power capacity usage within datacenters and provides power management schemes to reduce peak power and energy consumption.

**A. Berl, E. Gelenbe, M. di Girolamo, G. Giuliani, H de Meer, M. Dang, K. Pentikousis, " Energy-Efficient Cloud Computing", The Computer Journal, vol. 53, no. 7, p. 1045, 2010**
This paper describes cloud computing as an inherently energy-efficient ICT technology for achieving significant energy savings, especially taking into account various key aspects of computing hardware, system operation and networking infrastructure in the context of cloud computing while identifying the relevant arising research challenges when such energy-saving techniques are applied in cloud computing environments.

**J. Baliga, R. Ayre, K. Hinton, R. Tucker, "Green Cloud Computing: Balancing Energy in Processing, Storage, and Transport" Proc. the IEEE, vol. 99, no. 1, pp. 149-167, 2011**
Seminal work analyzing the balance of network processing, storage, and transport from an energy perspective. Identifies key issues and determines metrics for energy efficient cloud computing.

# Green communications under delay or quality of service constraints

**M. Gursoy, D. Qiao, and S. Velipasalar, "Analysis of energy efficiency in fading channels under QoS constraints," IEEE Transactions on Wireless Communications, vol. 8, no. 8, pp. 4252-4263, August 2009.**
This paper employed the effective capacity formulation, rather than the Shannon capacity, to fundamentally analyze the spectral efficiency-bit energy tradeoff in the low-power and wideband regimes under QoS constraints.

# Physical layer approaches for green communications and computing

**S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," IEEE J. Selec. Areas Commun., vol. 22, pp. 1089-1098, August 2004.**
This important paper is one of the first to consider the energy efficiency of multiple antenna transmission and reception techniques in low power sensor networks. The paper studies both radio frequency transmission power and crucially circuit power consumption in sensors.

# Green cognitive communications and computing

**D. Grace, J. Chen, T. Jiang, and P. Mitchell, "Using cognitive radio to deliver 'green' communications," in Proc. International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2009. CROWNCOM '09. 4th , June 2009**
This is the first paper concretely investigating various effective approaches of realizing green cognitive radio concept and functionalities. In particular, this paper is dedicated to exploiting the basic trade-off of spectrum (bandwidth) availability and power(energy) efficient modulation by introducing greater intelligence into the devices for a balance of spectrum-efficiency and energy-efficiency, meanwhile reducing the complexity overall of cognitive radio systems during spectrum sensing by virtue of reinforcement based learning.

**J. Palicot, "Cognitive radio: an enabling technology for the green radio communications concept," in Proc. the 2009 ACM International Conference on Wireless Communications and Mobile Computing: Connecting the World Wirelessly, IWCMC '09, pp. 489-494, 2009**
As the very first work on proposing cognitive radio approaches for meeting green communications concept and needs, this paper not only deals with the applications of cognitive radio functionalities to various scenarios of energy-efficient networks, protocols, devices and energy management, but also addresses the potential electromagnetic waves pollution and the corresponding threat to sustainable development considering human aspects both from the social and the health point of views.

**G. Gur and F. Alagoz, "Green wireless communications via cognitive dimension: an overview," IEEE Network, vol. 25, no. 2, pp. 50-56, 2011**
This is the first comprehensive overview on cognitive green wireless communications, which especially highlights the two fundamental features of cognitive radio systems in the context of green communications, namely: taking advantage of cognitive radio functionalities for improving energy-efficiency and cognitive radio self-operation with energy-efficiency.

**Hasan, Z.; Bansal, G.; Hossain, E.; Bhargava, V., "Energy-efficient power allocation in OFDM-based cognitive radio systems: A risk-return model," IEEE Transactions on**

**Wireless Communications, vol.8, no.12, pp.6078-6088, December 2009**
This is one of the first papers to address energy efficiency of cognitive wireless networks. The authors propose an energy-efficient power allocation scheme to maximize the expected transmission rate for OFDM-based cognitive radio systems while taking into account the reliability of the available sub-bands, sub-band power constraints, and total allowed interference limit to the adjacent primary user bands.

# Green smart grids

**B. Heile, "Smart grids for green communications," IEEE Wireless Communications, vol. 17, pp. 4-6, June 2010**
The author states some of the work done to manage the smart grids effectively to meet the targeted carbon footprint. This is an important work from industrial point of view.

**H. Farhangi, "The path of the smart grid," IEEE Power & Energy, vol. 8, no. 1, pp. 18-28, Jan. 2010**
This paper provided a precise high level view and roadmap of the transition from traditional power grids to smart grids as well as the strong impact and relevance to the ICT. The author described the current status and limitations of conventional power grids and looked forward to the potential enhancements through the evolution of smart grid technologies and relevant standardizations. The author also pointed out the challenges and potential problems to be combated during the global transitions to smart grids.

# Green Internet of Things

**H. Chao, Y. Chen, J. Wu, "Power saving for machine to machine communications in cellular networks", in Proc. IEEE Globecom International Workshop on Machine-to-Machine Communications, Dec. 2011**
This paper is a pioneer work in systematically proposing efficient power saving mechanisms on simultaneously considering all three aspects machine-to machine devices, radio access networks and core networks for machine-to-machine communications in cellular systems. With the significant power savings in the machine-to-machine communications and the minimal impact in legacy human-to-human communications, the new proposal in this paper includes the new sleep state, the new three-layer machine-to machine paging solution, and the modified signaling flow for the core network. The authors have provided both qualitative and quantitative analysis for the proposed comprehensive solutions.

# Energy harvesting, storage, and recycling

**Aman Kansal, Jason Hsu, Sadaf Zahedi, Mani B. Srivastava, "Power management in energy harvesting sensor networks", ACM Transactions on Embedded Computing Systems, vol. 6, no. 4, September 2007**

This paper discussed issues in power management for energy-harvesting sensor networks. The authors pinoeerly developed abstractions to characterize the complex time varying nature of such sources with analytically tractable models and use them to address key design issues. The authors also develop distributed methods to efficiently use harvested energy.

**Chin Keong Ho, Rui Zhang, "Optimal Energy Allocation for Wireless Communications With Energy Harvesting Constraints", IEEE Transactions on Signal Processing, vol. 60, no. 9, pp. 4808-4818, Sept. 2012**
In this paper, the authors considered maximizing the throughput through the the energy allocation over a finite horizon. Two types of side information (SI) on the channel conditions and harvested energy are assumed to be available: causal SI (of the past and present slots) or full SI (of the past, present and future slots). Through the use of dynamic programming and convex optimization techniques, the structural results for the optimal energy allocation were obtained. In the case of the unlimited energy storage and the full SI, the authors prove the optimality of a water-filling energy allocation solution where the so-called water levels follow a staircase function.

**S. Sudevalayam, P. Kulkarni, "Energy Harvesting Sensor Nodes: Survey and Implications ", IEEE Communications Surveys & Tutorials, vol. 13, no. 3, Third Quarter 2011 pp. 443 - 46**
In this paper, the authors have made a timely survey on various aspects of energy harvesting sensor systems- architecture, energy sources and storage technologies. This paper also has investigated some insights into implications of recharge opportunities on node-level operations and design of sensor network applications and solutions.

**J.P. Barton, D.G. Infield, "Energy storage and its use with intermittent renewable energy ", IEEE Transactions on Energy Conversion, vol. 19, no. 2, pp. 441-448, June 2004**
This paper discusses on the connection of wind generators at locations where the level of embedded renewable generation (ERG) would be limited by the voltage increase. Short-term storage offers only a small increase in the amount of electricity that could be absorbed by the network. Storage over periods of up to one day delivers greater energy benefits, but is significantly more expensive. This paper compare different feasible electricity storage technologies for their operational suitability over different time scales. This paper also investigate the value of storage regarding to the power rating and energy capacity so as to adapt appropriate sizing.

# Standardization, evaluation, practice, measurement, policy and regulation for green communications

**Greenhouse Gas Protocol (GHG Protocol)**
Guidelines from leading environmental and telecom organizations on how to account for greenhouse gas emissions in telecom networks.

**K. Christensen, P. Reviriego, B. Nordman, M. Bennett, M. Mostowfi, and J. A. Maestro, "IEEE 802.3az: The Road to Energy Efficient Ethernet," IEEE Communications Magazine, vol. 48, no. 11, pp. 50-56, November 2010**
The IEEE 802.3az Energy Efficient Ethernet standard is a quite successful example of green standardizations not only in the standardization process but also in the relevant practical applications. In this article, the authors described the development of the EEE standard and how energy savings resulting from the adoption of EEE may exceed $400 million per year in the U.S. alone (and over $1 billion worldwide). The authors also presented the energy efficiency of EEE through a simulation-based performance evaluation. The author also explore the coalescing effects with EEE on TCP/IP through a simulation evaluation. This article would encourage more and more efforts on green standardizations.

# Applications, economics, social issues, and interdisciplinary topics

**The Climate Group, "SMART 2020: Enabling the low carbon economy in the information age," Global e-Sustainability Initiative (GeSI), 2008.**
This report summarizes the relations among ICT industry, global energy consumptions, human activities, and economy issues, and discusses existing and potential enabling actions to reduce the energy consumptions of ICT, reduce the energy consumptions using ICT, and achieve sustainable development for human beings and the environments. This report also provides some roadmap and summary of global green ICT efforts.

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