Int. J. Wireless and Mobile Computing, Vol. 12, No. 1, 2017

Energy efficient networks: recent research and future challenges

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Abstract: Owing to the explosion of data and the growing need for communications, energy consumption in Information and Communication Technology (ICT) sector has shown a staggering increase these last years, making it one of the main responsible factors in climate change. The wireless industry exceeded all the expectations in terms of energy consumption, as it has to cover billions of daily users while trying to guarantee high performance communications. Traffic load keeps increasing especially with the growth of the internet of things. Despite the efforts that have been done for communication networks greening, researches in this field still encounter different issues and a considerable number of challenges need to be dealt with. In this paper, we first introduce the concept of ICT greening. After that, we introduce the recent research in this field and highlight the main used concepts. By studying the advantages and drawbacks of the latter, we aim to give some solutions and suggestions that could be helpful for the future researches in the field of energy saving in networks.

Keywords: green communications; energy efficient communications; green wireless networks; green wired networks.

Reference to this paper should be made as follows: Ameur, H., Khoukhi, L., Esseghir, M. and Boulahia, L.M. (2017) ‘Energy efficient networks: recent research and future challenges’, *Int. J. Wireless and Mobile Computing*, Vol. 12, No. 1, pp.1–15.

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1 Introduction

The environment has been subjected to harmful effects these last years, caused by non-renewable resources and CO_2 emissions. The Information and Communication Technology (ICT) sector is one of the main energy consumers and environmental polluters, as it is responsible for 2% of the world carbon emission totals (Wu, 2013) which can be compared to the airline industry. It has also been shown that carbon emission in this sector has been quadrupling over the last 20 years (Jens, 2013) owing to the rising demand for information access. Although communication devices are becoming more energy efficient, the overall communication systems still require optimisation as the actual networks are over-provisioned and not always fully used. A broad consensus to build energy efficient networks is needed by taking into account data traffic, energy use and CO_2 emission which is known as ICT greening.

Several works addressed the challenge to reduce energy consumption in ICT. However, the major concern was accorded to data-centres. Data-centres represent an important energy wasting area; but these last years, as the demand to increase wireless networks performance and capacity has risen, wireless communications has exceeded data-centres in terms of energy consumption seen that billions of daily mobile users have to be covered by the latter. A significant number of equipment manufacturers and network operators such as Orange and Vodafone strive to lower their energy consumption by 20–50 % (Wu, 2013) by implementing new transceivers design and improving cooling and power amplifier solutions.

The use of renewable energy and energy harvesting from various natural sources is increasing and has attracted the interest of some big companies. Google has launched a project called Loon in 2013 (Project Loon, 2013) aiming to ensure an internet access using solar-powered balloons which makes the communications more environment friendly.

Renewable energy includes solar, wind, geothermal, biomass, and hydropower. It has been shown that using these techniques within computer networks can be of a significant importance especially in cellular networks (Karmokar and Anpalagan, 2013). Karmokar and Anpalagan (2013) study Greenhouse Gases (GHG) emission savings and give an evaluation of the cost of several heterogeneous networks which use renewable energy sources. Green energy harvesting shows lot of variations and the energy storage can be very limited. The future green networks are expected to be hybrid, powered by multiple energy sources including on-grid energy (Han and Ansari, 2013).

Energy saving is made most of the time at the expense of Quality of Service (QoS). Many applications like VoIP and Interactive Video show a significant sensitivity to network performance and quality, which creates important challenges for green communications. Achieving a trade-off between QoS and energy consumption leads mostly to resolve hard and complex optimisation problems. Hence, the need to use heuristic and stochastic or even economic inspired models is crucial to find an acceptable solution within a reasonable delay. In this paper, we study the different techniques used for energy saving in wired and wireless communications and we highlight the main used concepts. By taking into consideration the latest research performed in this field, we study the advantages and drawbacks in order to give some solutions and suggestions that could be used to face the actual challenging problems.

The paper is organised as follows: in the first section, we summarise the state of art of the existing works by studying the related work performed in the field of energy saving and the motivation behind each one. We categorise these works according to the kind of studied networks while discussing the advantages and the drawbacks of each work. Next, we categorise the major used concepts and the way of exploiting them for energy saving. In Section 5, we address green communications under QoS constraints and point out green ICT measurements and metrics. Section 6 concludes this paper with the future prospects and research directions of green ICT.

2 Green networking in the literature

In this section, we perform a state of art of the different existing energy efficient researches. We point out the latter advances in this field for the main networking technologies including the wired and the wireless ones. By highlighting the main ideas and approaches used for the purpose of energy saving, we perform in the following sections a taxonomy as well as comparative study showing the main advantages and drawbacks which can be considered for the future researches.

2.1 Focus on wired communications

2.1.1 Green cloud computing and data-centres

Data-centres energy represented the main concern of green networking research owing to their huge energy consumption. Significant efforts have been done to reduce servers' energy cost including their cooling systems (Faraci and Schembra, 2015; Chavan et al., 2015). Researches aim also to enhance their architecture since it is known to contain redundancy. This increases fault tolerance and bandwidth which are sensitive only during high load hours. However, it can be avoided when traffic load decreases.

From the works which were interested in data-centres' architecture and reducing their redundancy, we find the work of de Sousa Araujo et al. (2015) which was motivated by the attractiveness of fat-tree architecture (Leiserson, 1985) in modern data-centres. The authors use multipath and the global view offered by software-defined networks to balance the energy efficiency, the equipment redundancy level, and the performance gain when dealing with the traffic demands.

On the other hand, Saha et al. (2012) considered different factors like servers' temperature and voltage to provide a green routing protocol based on dynamic voltage scaling, rate adaptation and any cast transmission. However, the experimentations were only based on simulations, which do not reflect the real behaviour, especially when it comes to sensitive parameters like temperature.

The latter research in this field is mostly based on virtual machines correlation (Sun et al., 2015; Lama et al., 2015) and their optimal use.

Sharma and Reddy (2015) propose an energy efficient algorithm for optimised resources allocation at data-centres using combined approach of dynamic voltage frequency scaling and genetic algorithm, while Dai et al. (2015) try to perform a balance between servers and network energy consumption in data-centres by looking for the most suitable placement of virtual machines (VMs). The purpose of this work is maximising physical servers' utilities while decreasing data transmissions within the network.

2.2 Focus on wireless communications

With the widespread of wireless technologies, wireless networks are considered as the major power consumers nowadays. CEET (n.d.) gives an estimated annual energy consumption of the different network technologies, and shows that mobile networks represent the higher energy consumption rate. In this section, we show up-to-date energy saving researches in cellular networks, ad-hoc networks as well as some of the existing wireless technologies. We derive from the used approaches, the advantages and drawbacks in order to perform taxonomy and a comparative study for the different approaches in Section 3.

2.2.1 Green cellular and opportunistic networks

2.2.1.1 Homogenous networks

The works studying energy consumption within cellular networks can be divided to four main areas: adjusting network density with cell zooming according to traffic load, enhancing spectrum efficiency and power allocation, using green energy and saving mobile nodes battery.

Zhang et al. (2015) consider the use of energy harvesting on relay nodes and introduce a random sleeping strategy in macro base stations as a possible method to reduce energy consumption. On the other hand, Wong et al. (2012) propose a way to tackle the problem of determining the optimal set of BSs that minimises the total energy consumption subject to users' rate requirements using by introducing an election process such as the base station having the less utility, transfers their users to its neighbouring BSs before it switches off. The utility value of a base station (BS) is based on both its provided data rate for serving users and the maximal operational power.

There are also some ideas that suggest to rethink cellular networks architecture to provide more energy saving. Capone et al. (2012) address the topic of dividing cellular networks into two separated ones: a network for data exchanges and another one for signalling. The authors think that this way of designing is one of the most promising approaches for the future cellular networks.

2.2.1.2 Heterogeneous networks

Conventional macro-cells are less efficient in terms of throughput as they are designed for large radio coverage but not for large throughput. To satisfy users' throughput needs in cellular networks, *femto-cells, pico-cells*, and *micro-cells* have been set up, allowing to reduce the distance between users and BSs, thus increasing the throughput. On the other hand, the transmission power will also decrease which means that more energy could be saved. A description of a typical heterogeneous network is presented in Figure 1.

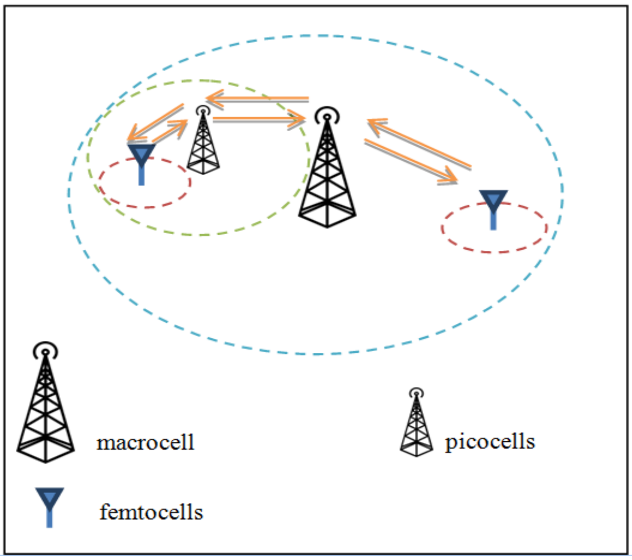
When it comes to the physical layer, Bu et al. (2015) is considered as one of the first works studying energy saving in heterogeneous networks while taking into consideration interference control, the authors propose a game-theoretical scheme using energy-efficient resource allocation and interference pricing for an interference-limited environment in heterogeneous networks.

A sleep/wake up scheme for heterogeneous networks is proposed by Ameur et al. (2015a). The authors consider a multi-tier network composed of multiple small cells and try to adapt network density to traffic load. The proposed approach is based on network state prediction and introduces a model aiming to ensure users needed capacity as well as network coverage by studying capacity distribution within the network during the switching OFF process.

Another work was interested in Media Independent Handover (MIH) (Ameur et al., 2015b). By bringing modifications into this latter, the authors aim to make this protocol collaborative for energy saving purposes. The proposed enhancements on MIH protocol allow gathering detailed information about network state and using them as statistics and indicators to manage network density according to traffic load and users location.

The authors in Arshad et al. (2012) show that in heterogeneous networks and for a given inter-site distance, pico-cell deployment improves area spectral efficiency which leads to reduce energy consumption; such as for an inter-site distance of 400 m, the introduction of 1 pico BS per cell improves the energy efficiency by 26%.

Figure 1 Typical heterogeneous network



Most of heterogeneous networks works that have been done assume that the dense deployment of low power BSs provides more energy efficiency. However, if other energy dependent resources like air cooling and power supplies are taken into account, this will involve some negative points, which leads to define some thresholds to respect while setting up these infrastructures.

2.2.1.3 Operators cooperation

In the last few years, cellular BSs number has increased in a massive rate, mainly with the appearance of the new cellular technologies like LTE advanced. The BSs deployment is redundant with the presence of more than one operator, especially when the traffic load is low.

The need for operators' cooperation to save energy is becoming crucial. Several works have been done in this context (e.g. Khan et al., 2011); however, they treated only the financial side without considering energy saving. Bousia et al. (2013) propose a game-theoretical approach to switch off base stations in multi-operator environment. These treated only the case of two coexistent operators. The growth of the cellular market and the increase of number of mobile operators need more schemes which can address more than two operators.

Tsilimantos et al. (2013) noticed the fact that all the works done in the field of sleep/wake up mode techniques did not take into account the case of different communication technologies within a network like 2G/3G. The authors took this challenge and studied the optimal active BS rate which leads to maximise the gain in terms of energy efficiency while preserving the outage probability. A transmit power threshold of the active cells was also mentioned relatively to the health effects of radiofrequency radiations as with the use of sleep/wake up techniques, some of the active cells can reach a higher output power to guarantee network coverage.

2.2.1.4 Opportunistic networks

One of the major issues that has been addressed in opportunistic networks is the communication probing, since it was found that it consumes as much energy as greedy tasks like videos and phone calls in opportunistic mobile networks (Gao and Li, 2013). A solution was provided by Xi et al. (2007) to wake up nodes only at pre-scheduled contact propping times, otherwise, nodes stay asleep. Gao and Li (2013) propose a probabilistic approach to predict the future node contacts and perform analytical balances between energy consumption and communication performance. However, opportunistic networks are known by the randomness of nodes' behaviour mainly in dense networks where inter-contact times are shorter, so more experimentations and contact prediction error schemes are needed to enhance predictions efficiency.

2.2.2 Green ad-hoc and sensor networks

In addition to the need for reducing energy consumption in ad-hoc and sensor networks, these face another challenge which consists of prolonging network lifetime by distributing the workload. High loaded nodes quickly lose their energy and cause network destabilisation. There are two classes of energy-efficient topology control algorithms to prolong networks lifetime (Wang et al., 2013): algorithms that aim to minimise nodes transmission power (Wang and Liang, 2015) and others that look for the minimum energy paths in network topology (Sah et al., 2015).

Energy consumption in these networks can be achieved in different ways. Zhu and Towsley (2011) proposed an original opportunistic routing protocol which does not specify any path to forward data packets. The main idea is the use of back-off windows such as the higher node priority has the smaller windows time to forward the packets without designating a forwarder. This approach reduces redundant packets transmission which results in less energy consumption.

In ad-hoc and sensor networks, a significant energy saving is done during nodes' sleep time since energy consumption in sleep mode is much less than any other mode. However, switching between sleep and transmit mode may be achieved with additional cost (Jahanet and Narayanan, 2013).

Two options are considered in sleep/wake up modes: in the first one, the transmit node wakes up in the same time with the receiver and switches repeatedly to sleep mode, until it has delivered the packets to all the receivers, several works make this assumption to estimate the energy costs of their algorithms (Hong et al., 2010; Wang and Liu, 2009). In the second one, the node stays awake until it has delivered the packets to all the receivers and comes back after that to sleep (Sun et al., 2009); this option shows the best energy saving in dense networks where there are only few slots between active times.

Jahanet and Narayanan (2013) worked on decreasing the time units of nodes' wake up time in order to achieve the broadcast operation, by finding a minimum energy broadcast tree. While this approach reduces the average of additional active time units, which means saving more energy, it increases the average forwarding delay. Finding an efficient distributed algorithm remains an interesting topic for the future works to decrease the forwarding delay.

Many researches have been done to ensure network coverage in Mobile Wireless Sensor Networks (MWSNs). Among these works, we mention the model proposed by Torbey (Chen et al., 2015). In this model it would be more interesting if the energy constraint had been considered to control nodes movements. Choudhury et al. (2012) show a cellular automaton model to decrease the amount of nodes movements while maintaining network coverage. Decreasing nodes' movement leads to a significant energy saving. More studies can be done in this area while focusing on merging conventional energy-efficient model and nodes' mobility.

Although there are lots of researches to improve wireless networks' energy efficiency, the current results need more realistic experimentations and more challenges remain to be investigated. For instance, interferences and handoffs management in heterogeneous cellular networks need to get more interest as they are more frequent owing to the high number of access points.

It is also worth noting that energy consumption needs more studies in MIMO technologies, like the use of adaptive MIMO to make a trade-off between performance improvement and energy saving, and some examples of adaptive MIMO technologies for energy saving are given in Kim et al. (2009).

3 Green ICT paradigms

To decrease energy consumption in network infrastructures, some core concepts have been considered. These concepts lead to show that energy saving can be achieved either by adjusting resources density while driving their usage to its highest rate, or by building energy efficient devices in such a way that their energy consumption will be proportional to their utilisation.

We can express these paradigms as follows: (1) resource consolidation in which we find virtualisation and dynamic infrastructures, (2) selective connectedness, and (3) energy-proportional design that requires a significant improvement in the energy usage profile of devices components.

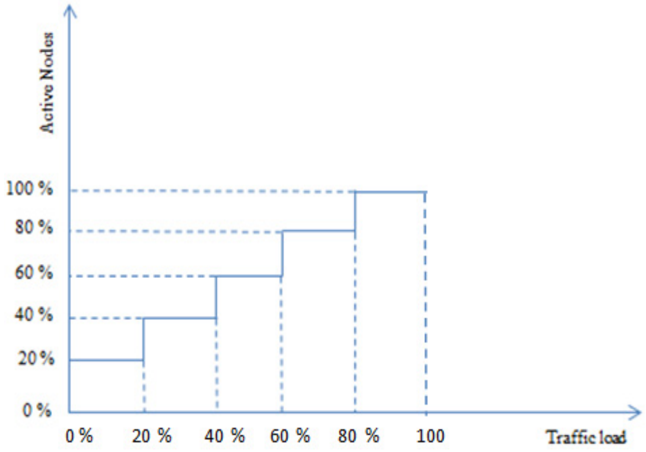
These paradigms can be expanded and adapted to the different kinds of networks, namely cellular networks, core networks and mobile ad-hoc networks (MANETs).

3.1 Resource consolidation

3.1.1 Dynamic infrastructures

Existing computing servers do not show proportionality in terms of energy consumption subject to the workload. Hence, a significant amount of power is consumed even at their lower levels of utilisation. To tackle this problem, several approaches were proposed in the literature in order to estimate the resources requirements and adjust dynamically the network infrastructure (Han et al., 2012; Balasubramaniam et al., 2013). Figure 2 shows an example of an adaptive infrastructure which reduces the number of network active nodes by switching them off depending on defined traffic rate thresholds.

Figure 2 Adaptive network infrastructure according to traffic load



As it can be seen in Figure 4, the remaining active nodes will be high loaded and then more efficient; the overall network energy consumption decreases as there will be more nodes which are likely to be switched off. In some cases, where network nodes are energy constrained, the workload must be distributed by taking into account battery residuals or the type of the used energy (Wang et al., 2013; Wang et al., 2015).

Figure 3 Active node efficiency while using adaptive network infrastructure (see online version for colours)

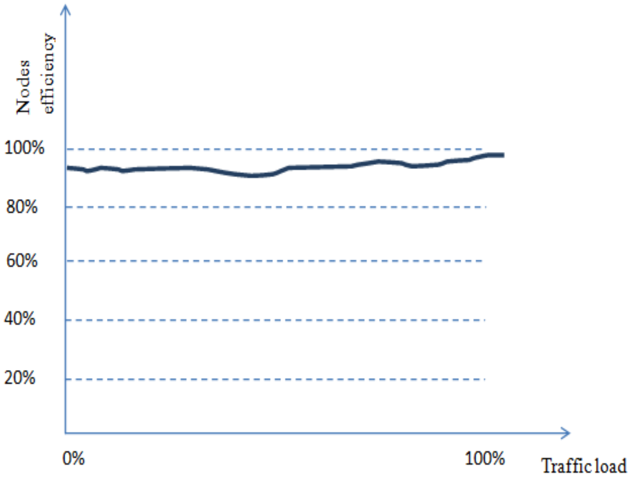
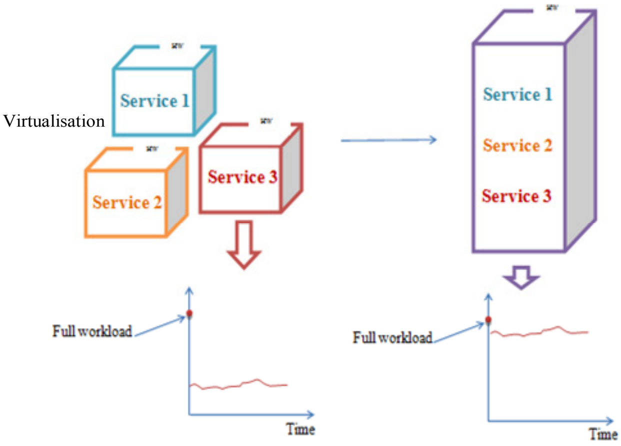


Figure 4 Nodes efficiency with and without virtualisation (see online version for colours)



3.1.2 Virtualisation

Virtualisation consists of allowing the same resources to run different applications or services. With virtualisation, the number of physical devices will be reduced while the utilisation of the existing ones is improved (cf. Figure 3).

It is obvious that the higher the IT equipment utilisation is, the higher the network energy efficiency would be, in the case of non-proportional devices (Wu, 2013).

Virtualisation is widely used in cloud computing and data-centres, as the hardware in this area is much powerful. For example, servers in data-centres have many cores, and a significant number of applications do not require such high performance. So, virtualisation allows consolidating several

VMs running different applications on the same server, to take full advantage of it. In Wu (2013), it has been shown that even if the CPU utilisation is 10% in a server, its energy consumption is about 60% of that at full utilisation. Virtualisation can be achieved at different levels: server, storage, network and middleware. Storage virtualisation and network virtualisation are as efficient as server virtualisation and can reach the same results in terms of energy efficiency, while middleware virtualisation can show more improvements in data-centres efficiency compared to the other techniques. For example, in server virtualisation, a VM running an application which requires 4GB memory needs to allocate an additional memory space within the physical server to handle the peak resource usage, and this will be the case of each VM.

3.2 Selective connectedness

Selective connectedness aims to save energy by reducing the workload of edge resources within a network, since they are known as greedy in terms of used energy. Selective connectedness allows switching edge devices to idle state for a period of time or until there will be tasks with high processing requirements. During the idle periods, edge nodes identity will be faked by other devices in order to avoid disturbing the QoS of the network. Figure 5 shows an example of a selective connectedness. In this case, the node with the highest energy consumption switches into sleep mode while its identity is faked by another one (a proxy system for example) (Da Costa et al., 2009). The node will wake up only when high processing is required for some tasks.

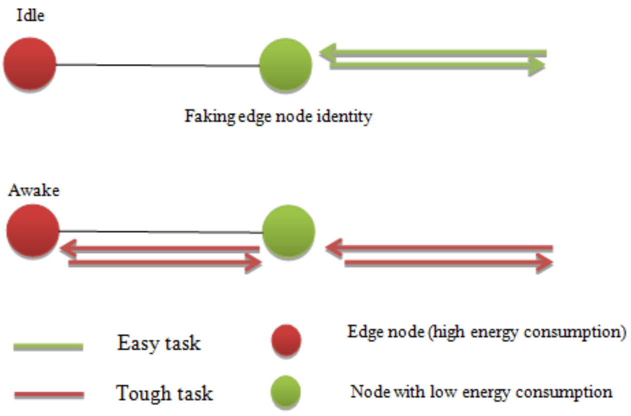
3.3 Energy-proportional design

Another useful figure of merit for energy-saving is the dynamic range for power proportional computing (Barroso and Hölzle, 2007).

Energy proportional designs have been proposed to achieve a significant saving in energy consumption within network infrastructures and data-centres. Big companies like Google, for instance, show a big interest to these technologies as they set up several calls to support industry and researchers in order to develop high efficient energy proportional systems.

In an ideal energy proportional system, no energy will be consumed when this one is on idle state, while energy consumption grows linearly with the amount of computational resources. However, such systems do not exist yet.

Figure 5 Faking edge node identity by a proxy node to process easy tasks



A proportional system can be expressed as shown in Figure 6 (the relationship is not necessarily linear). We can see that even when there is no workload, energy is consumed due to the baseline power which is about 50% of the maximum power (Barroso and Hölzle, 2007).

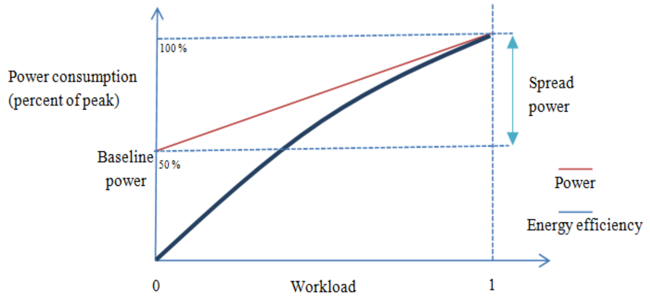
The device is then less energy efficient during low workload periods. Energy efficiency increases with the growing workload, as the ratio workload to power consumption increases.

The principles of the paradigms mentioned above can be combined within the same infrastructure to give more energy efficiency. To show the features as well as the common points of these paradigms, we summarise their main characteristics in Table 1.

Table 1 The major characteristics and common points of green communication paradigms

		Resource consolidation		*Selective connectedness*	*Energy-proportional design*
		Dynamic infrastructures	*Virtualisation*		
Resource consolidation	Dynamic infrastructures	Shutting down lightly loaded nodes		Allowing equipment to go idle for a period of time	Adapting over-provisioning and resource load level based on statistical behaviour changes
	Virtualisation		Multiple services run on the same hardware	Faking the identity of idle devices	
Selective connectedness				Only edge resources of the network can go idle	
Proportional computing					Proportionality of hardware energy consumption according to its utilisation rate

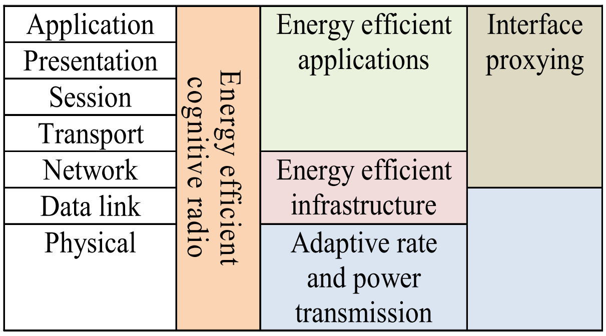
Figure 6 Power consumption of energy proportional devices according to the workload



4 Energy efficient methods according to layers-based design

In this section, we address in more details the existing green methods by categorising them according to the network layer in which they operate. Each one of the following methods belongs to one of the main defined paradigms in the previous section. Figure 7 shows these classes according to their network layer.

Figure 7 Energy efficient method classes according to network layers (see online version for colours)



4.1 Adaptive rate and transmission power

Energy efficiency can be achieved by re-engineering approaches which introduce new technologies like modern silicon based memories. It can also be realised by dynamically adaptive solutions, such as adapting rate or transmission power according to the current load. This class may be presented in the shape of link rate switching, dynamic power management or sleep/wake up mode.

4.1.1 Link rate switching

This method is designed most of the time for Ethernet networks since they are known for their low traffic periods especially in local area networks (LANs). Several works show that the energy consumption of LANs is independent of their utilisation due to connectivity and synchronisation traffic which are periodically exchanged even when no data are sent (Christensen et al., 2004). Adaptive Link Rate (ALR) allows Ethernet links to change dynamically their data rate according to the traffic level. However, it shows some difficulties such as defining an effective mechanism for a fast modification (negotiation) of the link data rate and creating policies for controlling the link rate switching (Bilal et al., 2013).

4.1.2 Adaptive power management

A good example of this method is the transmission power regulation in WSNs MAC layer (Wang and Liang, 2015) or cellular networks (Balasubramaniam et al., 2013), which is known as cell zooming. Adaptive transmission power allows energy saving not only by reducing the voltage of devices but also by reducing interferences in wireless networks since a smart adjustment of the transmit power leads to minimise interferences probability, thus less errors will occur and then less retransmissions.

4.1.3 Sleep/wake up mode

Some works propose to switch on or off base stations rather than achieving load balancing techniques as this latter does not show a significant energy saving due to the load-independent components and the presence of pilot channels (Xi et al., 2007). However, switching a device into idle state leads often to connectivity loss and to a reconnection process that is performed when it wakes up. Hence, a significant amount of energy is wasted.

New approaches have to deal with the trade-off between the sleeping/wake up decisions and reconnection process energy cost. For example, Bolla et al. (2013) address this problem by using network proxying, such as a proxy takes charge of the host network presence during its sleeping time (more details are given in Subsection 4.3).

It is obvious that with sleep/wake up mode or adaptive rate, the system response time will be more important. Thus, a trade-off between performance and energy saving must also be done, by for example evaluating users requirements. It is also worth noting that switching between sleep and wake up mode is not without cost. Jahanet and Narayanan (2013) show that at a low traffic load, consumed energy for switching can dominate the energy required for transmission.

Figure 8 Illustration of sleep mode and rate adaptation (squares represent load while shadings represent the operating rate)

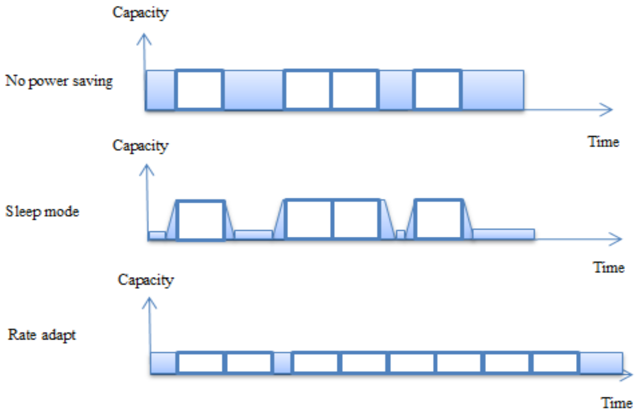


Figure 8 shows an example of the operating rate (less operating rate means less energy consumption) and loads management in the case of no power saving mode, sleep/wake up mode and rate adaptive mode.

Choosing between sleep/wake up and adaptive rate modes varies according to the network infrastructure and devices technology; for example, Wu (2013) specifies that in optical transceivers there is a little gain in power by reducing the rate, while sleep/wake up mode presents more promising results.

4.2 *Energy efficient applications*

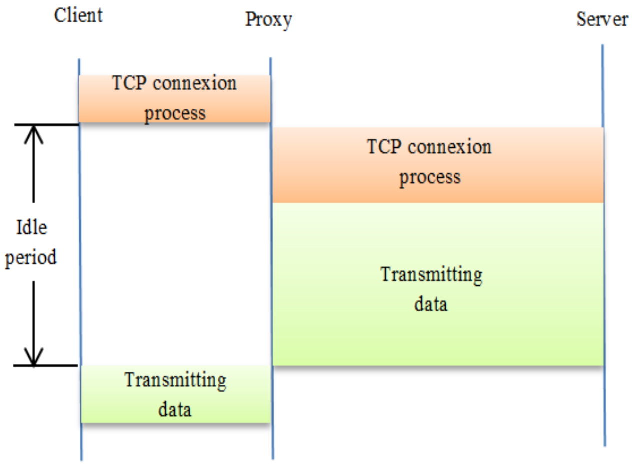
These approaches operate at the higher network layers and focus on software design. Optimising energy consumption differs depending on software level; it can be planned for a high level software (user level) or low level software. Few works have addressed user level software. We mention among these ones, the green version of telnet (Galanopoulos et al., 2015). Low level software optimisation is deeper and therefore affects the general aspects of computing architectures such as operating systems kernel. TCP greening is a good example of this kind of design. Decreasing TCP connection lifetime or TCP losses and retransmissions should improve energy saving and communications performance simultaneously; Bruschi et al. (2013) studied dynamic TCP congestion control since it reduces losses and retransmissions, allowing to save more energy. Bruschi et al. (2013) demonstrate also that the use of active windows management (some examples are given in Lombardo et al., 2010), which aims to control the queue length in network routers, helps to reduce losses while maximising network utilisation.

4.3 *Proxying*

In the current internet network, the nodes are assumed to be always available, the current services and applications are also designed to be fully available. The network nodes receive traffic at any time which prevents them to be idle; otherwise, if nodes switch to idle mode, then packets may be lost. Proxying allows network nodes to be idle while another device delegates them and performs their processing tasks. The proxy can be within the same communication device such as network interface controllers (NIC) (Agarwal et al., 2009); this is known by internal proxying or within the network equipments such as switches or servers which creates an external proxy.

Ding et al. (2012) aim to improve the use of Power Saving Mode (PSM) using external proxying. PSM mode presents some weaknesses in its classical application (e.g. energy saving causes extra delays on data transfer). The authors engaged a web proxy behind the Access Point (AP) to split TCP flows. The proxy intercepts TCP connections from the client and establishes a new connection with the server while relaying client requests, allowing the client node to switch into PSM until the proxy recuperates all the required data. The low delay between the proxy (AP) and the client node allows this latter to minimise its activity period and to stay for a longer time in PSM mode, as shown in Figure 9. Thus, more energy will be saved.

Figure 9 Using a web proxy to recuperate data while client switch into idle mode



4.4 *Energy saving via cognitive radio*

There is a direct relationship between bandwidth and power (energy efficiency). According to Shannon's law (Shannon, 1998), the capacity increases linearly with the increasing bandwidth, but only logarithmically with the increasing power. Thus, the capacity could be improved with less energy consumption by a good use of the spectrum.

Cognitive radio is a communication system which is aware of the environment for more efficient and conscious use of the spectrum. By sharing and managing the spectrum intelligently, cognitive radio leads to interferences reduction while enhancing the bandwidth usage, so it plays a major role in green communications and it is a subject of interest for several wireless communications researches. A significant number of works have been done recently in this field (Eryigit et al., 2013; Huang and Tugnait, 2013; Wildemeersch et al., 2013). For example, Eryigit et al. (2013) aim to minimise sensing duration as well as channel switching in cognitive base stations. The authors proposed a scheduling scheme to discover the appropriate set of secondary users for each frequency while trying to find the optimal order of channels to sense, in such a way to minimise channel switching cost. Cognitive radio allows saving energy. The techniques used are known to operate on different network layers and collect the maximum possible parameters to improve spectrum prediction, like considering user's location, which makes these algorithms more complex.

4.5 *Energy efficient infrastructure*

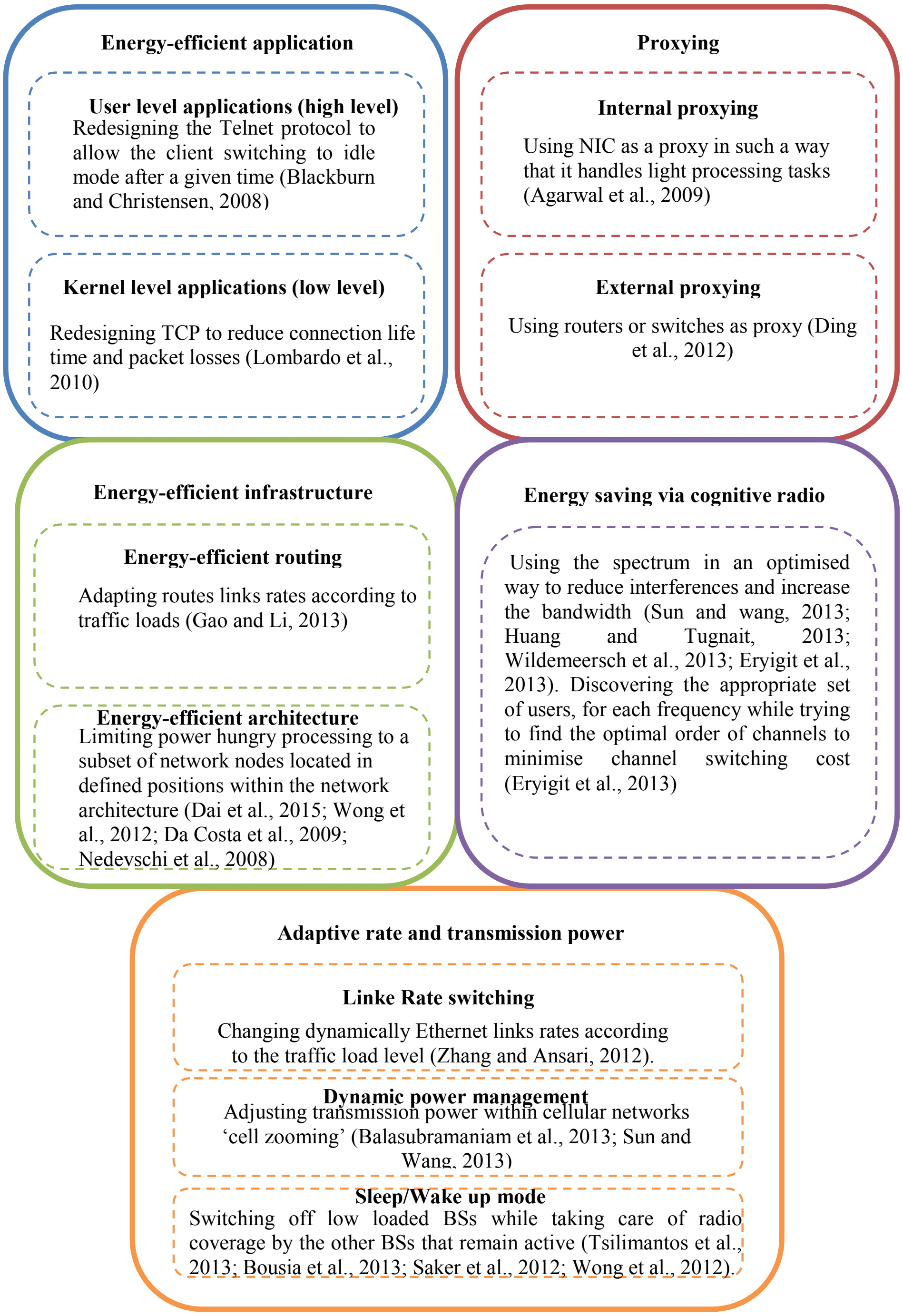
Most of the methods showed previously can be used with a global vision within a network by taking into account the relationship between nodes and how this relationship can impact energy saving as well as network performance.

Networks are mostly over-provisioned, so a high amount of energy is wasted in low traffic load periods; thus, some researchers suggest performing energy aware routing by shutting off some nodes or adapting routes links rates in low traffic load periods (Xi et al., 2007).

Energy saving can also be done within the network design, as it can be designed in such a way to consume less energy, like limiting power-hungry processing to a subset of network nodes which are located in defined positions. Bianzino et al. (2010) have considered two main energy-efficient network architecture approaches. The first one is incremental (Da Costa et al., 2009; Nedevschi et al., 2008) and can be built over an existing architecture, while the second is a clean slate approach in which a complete redesign of the network is required. Most of the clean state approaches promote the use of optical switching and consider this technology as promising to reduce significantly energy consumption in future core networks (Fiorani et al., 2013).

We represent, in Figure 10, a hierarchical representation of green networking classes as well as some typical examples.

Figure 10 Hierarchical representation of green networking classes



Energy-efficient application

User level applications (high level)
Redesigning the Telnet protocol to allow the client switching to idle mode after a given time (Blackburn and Christensen, 2008)

Kernel level applications (low level)
Redesigning TCP to reduce connection life time and packet losses (Lombardo et al., 2010)

Proxying

Internal proxying
Using NIC as a proxy in such a way that it handles light processing tasks (Agarwal et al., 2009)

External proxying
Using routers or switches as proxy (Ding et al., 2012)

Energy-efficient infrastructure

Energy-efficient routing
Adapting routes links rates according to traffic loads (Gao and Li, 2013)

Energy-efficient architecture
Limiting power hungry processing to a subset of network nodes located in defined positions within the network architecture (Dai et al., 2015; Wong et al., 2012; Da Costa et al., 2009; Nedevschi et al., 2008)

Energy saving via cognitive radio

Using the spectrum in an optimised way to reduce interferences and increase the bandwidth (Sun and wang, 2013; Huang and Tugnait, 2013; Wildemeersch et al., 2013; Eryigit et al., 2013). Discovering the appropriate set of users, for each frequency while trying to find the optimal order of channels to minimise channel switching cost (Eryigit et al., 2013)

Adaptive rate and transmission power

Linke Rate switching
Changing dynamically Ethernet links rates according to the traffic load level (Zhang and Ansari, 2012).

Dynamic power management
Adjusting transmission power within cellular networks 'cell zooming' (Balasubramaniam et al., 2013; Sun and Wang, 2013)

Sleep/Wake up mode
Switching off low loaded BSs while taking care of radio coverage by the other BSs that remain active (Tsilimantos et al., 2013; Bousia et al., 2013; Saker et al., 2012; Wong et al., 2012).

5 Quality of Service and green ICT metrics

5.1 *Green communications under Quality of Service constraints*

Realising green communications may be done at the expense of systems performance. The challenge is to perform energy saving methods and techniques as transparently as possible. Despite the efforts to design adequate green communication systems with respect to QoS, energy saving and QoS trade-off remains a critical issue and requires more investigations. Realising the previously mentioned energy saving approaches can be more complicated in some cases, such as in heterogeneous infrastructures where QoS requirements and device parameters are different. Many applications like VoIP and Interactive Videos show also a significant sensitivity to network performance which creates important challenges for green communications. Achieving a trade-off between QoS and network performance leads mostly to resolve complicated optimisation problems. Some researches propose stochastic or heuristic models to optimise this trade-off, like Zhang and Wang (2013) which designs a semi-Markov decision process. Although the significant efforts that have been carried out to optimise the trade-off between energy efficiency and QoS, this field still remains challenging; we also highlight that QoE (Quality of Experience) must also be considered, as most of the existing works neglect it.

5.2 *Measurement and metrics of green ICT*

In this section, we focus on benchmarking methodologies and efficiency metrics. In order to compare in an objective way the energy efficiency level among the different types of devices, some standards have been proposed. We mention by way of example ECR (Energy Consumption Rating) (HUPO, 2015) and Alliance for Telecommunication Industry Solutions (ATIS).

ECR standard introduces tests to determine the energy efficiency of packet-based networks as well as telecommunication equipments, while ATIS introduces a methodology to calculate the energy efficiency of enterprises and service providers' chain including routers and Ethernet switches. We note that both of the two mentioned standards use constant bit rate (CBR) traffic during tests, so they do not represent the real behaviour. Although ECR tests can be automated and performed in a faster way, they are done with a fixed packet size which is far from being realistic. Unlike ECR, ATIS tests are performed using Internet Mix (IMIX) traffic which is considered as closer to the real behaviour.

The green metrics can be categorised into three types: equipment level metrics, facility level metrics and network level metrics.

Equipment level metrics are defined to express the energy efficiency of individual equipment; thus, they reflect the equipment design performance. Facility level metrics express energy efficiency of high level systems like data-centres, to take into account additional energy requirements like cooling and lightning, while network level metrics assess equipments' energy efficiency as well as features and properties related to capacity and coverage of the network.

A good example of network level metrics is PI_{rural} (Performance Indicator in rural areas) and PI_{urban} (Performance Indicator in urban areas) which consider network coverage and capacity, respectively.

We highlight among the power consumption measures, PUE (Power Usage Effectiveness), this metric which is an ISO standard and it is generally accepted as the international measure of energy efficiency in data-centres (Wu, 2013). The significance of PUE is how much energy is consumed in the IT equipment among the total power consumption. Hence, in order to reduce PUE, the reduction of air conditioners and supply systems power is also needed. We summarise in Table 2 some of green metrics as well as their targets and calculation.

Table 2 Some of green ICT metrics

Metrics	*Full name*	*Target*	*Calculation*	*Level*	*Comment*
PUE	Power Usage Effectiveness	Data-centres	$PUE = \frac{Total\,Facility\,Power}{ITE\,quipement\,Power}$	Facility level	
DCIE	Data Centre infrastructure Efficiency	Data-centre	$DCIE = \frac{1}{PUE}$	Facility level	
ECR	Energy Consumption Rating	ICT enterprises	$ECR = \frac{E_{100}}{T_f}$	Equipment level	E_{100}, E_{100}, E_{100}, E_{100}: power consumption measured at 100% T_f T_f: effective throughput
ECRW	ECR-weighted	ICT enterprises	$ECRW = \frac{0.35.E_f + 0.35.E_h + 0.35.E_i}{T_f}$	Equipment level	E_f, E_h and E_i are the energy consumption in full-load, half-load and idle modes, respectively. T_f: effective throughput

Table 2 Some of green ICT metrics (continued)

Metrics	*Full name*	*Target*	*Calculation*	*Level*	*Comment*
TEER	Telecommunications Energy Efficiency Ratio	General, server	$TEER = \frac{\sum_{i=1}^{n} D_i}{\sum_{j=1}^{m}\left(\frac{P_{0j}+P_{50j}+P_{100j}}{3}\right)}$	Equipment level	D_i: the data rate of each interface *i* P_{0j}, P_{50j}, and P_{100j} represent the power of module j at data utilisation of 0%, 50% and 100%, respectively
PI_{rural}	Performance Indicator in rural areas	Cellular networks	$PI_{rural} = \frac{A_{coverage}}{P_{site}}$	Network level	$A_{coverage}$ is the RBS coverage area [km^2] for rural area
P_{site}: power consumed at the site					
PI_{urban}	Performance Indicator in urban areas	Cellular networks	$PI_{urban} = \frac{N_{busy\_hour}}{P_{site}}$	Network level	N_{busy_hour} is the number of subscribers
P_{site}: power consumed at the site					

5.3 Heterogeneous networks vs. homogenous networks

Heterogeneous networks can guarantee significant throughput efficiency to users, as the distance between these and micro BSs will decrease. However, micro BSs should be deployed carefully, given that they are impacted by inter-site distance as well as the average number of micro-cells per cell. Choosing between heterogeneous and homogenous deployment may also depend on target area throughput. The pure deployment of macro BSs is more efficient in low area throughput (Wu, 2013), such in rural areas while the use of heterogeneous cellular networks may be more efficient in urban areas.

5.4 Incremental vs. clean slate approaches

Saving energy within network architecture can be done either by incremental or clean slate approaches; many debates have been done on this topic and the points of view differ from the ones that support building energy efficient models over the existing networks (Da Costa et al., 2009; Nedevschi et al., 2008) and those that prefer redesigning the overall network architecture (Fiorani et al., 2013). With the success of internet network nowadays, implementing clean slate networking may seem superfluous, but the massive energy consumption in the actual architectures which require some fundamental changes pushes the green ICT community to rethink these aspects and pave the way for clean slate approaches which enable computer networking to mature by using the performance of the latest existing technologies.

Despite the efforts that have been done for energy saving in communication networks, this topic still remains challenging. Several points must be reconsidered such as switch mode-based protocols, since switching off nodes leads to a loss of connectivity which requires a reconnection process, without forgetting that switching nodes state isn't without cost and can contribute sometimes in energy wastage rather than saving it (when the idle periods aren't long enough). More works are needed to define the appropriate moment to switch nodes states as well as trying to consider their connectivity during idle states in order to avoid the reconnection process.

The right choice of the energy saving approach must be studied according to the network infrastructures and devices technology, as way of example, it has been shown that using sleep/wake up mode rather than adaptive rate is more promising for optical transceivers and cellular networks.

Resource consolidation in data-centre networks, like the use of virtual machines, can show more energy saving by putting them in the more suitable placements such as the overall data-centre utility will be increased while decreasing network transmissions. Optical bypass is also a promising technology in backbone networks as it has the ability to reduce the number of routers and then energy consumption.

In cellular networks several points still need reconsideration, like energy efficiency evaluation process which should consider users devices energy consumption within a specific cellular network infrastructure. Some researchers believe that the dense deployment of low power BSs provide more energy saving while it prolongs users devices battery life. However, other factors must also be taken into account like air cooling and power supplies; it is also worth noting that in heterogeneous and dense cellular networks, interferences and handoffs are more frequent which needs more investigations to define some thresholds and efficient interference management models considering energy constraint in such situations.

In a later research (Capone et al., 2012), the authors are convinced that a new cellular architecture is needed to face the energy issue and that by dividing cellular infrastructures into two layers, signalling networks and data networks, this will be possible by dedicating some BSs for signalling while the others will be used for data communications. For future green cellular networks, operators' cooperation is crucial as the actual networks become more and more redundant.

The contribution of the application level protocols should not be underestimated and needs more efforts; protocols like TCP, which is used with most internet traffic, need more improvements to minimise losses and retransmissions as well as the connection lifetime.

In addition to communication network optimisation for energy saving, renewable energy is also an interesting area. A major interest must be given to energy harvesting and solar panels efficiency improvement.

While WSNs remains an interesting tool for decreasing energy consumption in several fields, the need for more energy efficient WSNs is always wanted, more routing and communication protocols are needed to consider different factors such as the environmental ones.

Users are likely to be demanding which still remains a key issue for green networking to provide energy-efficient communications with respect to QoS and QoE degradations.

6 Conclusion

The evolution of the ICT sector has pushed carbon emission to quadruple in the last 20 years and the environmental degradation has become more and more severe. Owing to the spreading of wireless technologies, these show as much energy consumption as data-centres and ICT greening research studies have become wider. We addressed in this paper the major concerns of green communications in both wireless and wired networks from different angles. We discussed the paradigms and the major concepts to be considered in green communications; we gave also a closer vision of the existing methods as well as the latest researches in this field.

Conclusively, we summarised the different green networking researches in Table 3 while classifying these ones according to the green techniques categories presented above in this paper. Care has also been taken to mention the kind of network for which these researches were intended, whether wired or wireless.

In summary, greening ICT is one of the major concerns that will have a straight impact in our future environment and the way that the next generation technologies will operate. Researches in this field still encounter issues and challenges, since a considerable number of problems should be dealt with.

In addition to technical greening solutions, other factors may have a positive impact on saving energy in ICT sector, such as marketing strategies and users' awareness.

Table 3 Taxonomy of green networking research

		Adaptive rate and transmission power	*Proxying*	*Energy efficient infrastructure*	*Energy efficient application*	*Energy saving via cognitive radio*
Wired networks		Zhang and Ansari (2012), Nedevschi et al. (2008), Faraci and Schembra (2015), Chavan et al. (2015), Gattulli et al. (2014)	Bolla et al. (2013), Ding et al. (2012)	Saha et al. (2012), Dai et al. (2015)	Blackburn and Christensen (2008), Ding et al. (2012), Bruschi et al. (2013), Lombardo et al. (2010)	
Wireless networks	Cellular networks	Tsilimantos et al. (2013), Wong et al. (2012), Balasubramaniam et al. (2013), Han et al. (2012), Bousia et al. (2013), Saker et al. (2012), Gattulli et al. (2014), Galanopoulos et al. (2015)		Capone et al. (2012), Sun and Wang (2015)		Sun and Wang (2013), Eryigit et al. (2013), Huang and Tugnait (2013), Wildemeersch et al. (2013), Zhao et al. (2015)
	Ad-hoc and sensor networks	Jahanet and Narayanan (2013), Hong et al. (2010), Wang and Liu (2009), Sun et al. (2009)		Wang et al. (2013), Sah et al. (2015), Choudhury et al. (2012), Zhu and Towsley (2011)		

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