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A survey on Green communications using Adaptive Link Rate

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Abstract The Information and Communication Technology sector is considered to be a major consumer of energy and has become an active participant in Green House Gas emissions. Lots of efforts have been devoted to make network infrastructure and network protocols power-aware and green. Among these efforts, Adaptive Link Rate (ALR) is one of the most widely discussed approaches. This survey highlights the most recent ALR approaches with a brief taxonomy and the state of the art.

Keywords Green networking · Energy efficient wired communication · Adaptive link rate

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1 Introduction and motivation

The need for energy efficient networking has become evident [57, 89, 90] due to the massive amounts of energy consumption and carbon footprints within the Information and Communication Technology (ICT) sector. Network components are designed and installed to handle peak load and tolerate faults that result in over provisioning, redundancy, and higher energy consumption [97].

Two major drivers of the energy efficient networking are: (a) high carbon footprints because of electrical energy use and (b) consumption of an enormous amount of energy by the networking equipment and the resulting high cost of energy. Consumption of electrical energy contributes to Green Houses Gases (GHG) [7]. The ICT sector is identified to be responsible for the production of approximately 0.75 million tons of CO_2 for every 1 TeraWatt hour (TWh) energy consumption [43]. Moreover, 2 % of the total CO_2 emissions are also attributed to the ICT sector [35]. The GHG emission of the ICT sector is almost equivalent to the CO_2 emissions by the aviation industry. Furthermore, an increase of approximately 6 % of CO_2 emission is expected each year until 2020 [91]. Danield et al. [27] reported that the CO_2 emissions by the ICT sector are doubling every five years. In the

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developed countries, CO_2 emission rate is even higher and reaches approximately 4 % [91]. The European Union has published a report stating the requirements to avoid the increase in the global temperature. It has been reported that to avoid an increase in global temperature less than 2°C, a decrease of 15 %–30 % in the emission rate of CO_2 is required [76].

The network components are identified to contribute 30 %–37 % [33, 91] of the GHG emission produced by the ICT sector. Personal computers account for around 48 % of the total GHG emission produced by the ICT sector [16]. Mathews et al. [66] reported that the ICT sector consumes around 30 %–35 % of the total energy consumed at an academic institution. Fouli et al. [32] observed that the bandwidth requirements double every 18 months for the new networking applications. The broadband connection offers more bandwidth for the bandwidth sensitive network applications. Such applications result in increased IP traffic and networking equipment. Therefore, increasing energy consumption of the ICT networking sector in general and networking devices, such as switches and routers in particular [9, 60, 75].

In 2006, it was estimated that the energy consumption of the Information Technology (IT) infrastructure was about 61 billion KWh [17]. The aforementioned energy consumption was more than twice the energy consumed by the IT infrastructure in the year 2000. Moreover, the energy consumption estimate of the IT infrastructure for the year 2011 are double than those of the year 2006, consuming an electricity of worth $7.4 billion each year [8]. Estimation of the worldwide energy consumption for the Internet is equal to 14 power stations [51]. About 9.4 % of the total energy produced in the US is estimated to be consumed by the Internet [73]. Network equipment consumes about 10–20 % of the total power in a data center [38]. In the year 2006, networking elements consumed more than 3 billion KWh of energy in data centers of the US [87]. Ref. [5] reported that the network infrastructure in the US consumes about 24 TWh of energy. Energy consumption of network controllers in the US for the year 2005 was estimated around 5.3 TWh [78].

Most of the network devices run at full capacity and remain underutilized most of the time [97]. The switching capacity of the backbone networks is usually more than twice the peak hour traffic volumes [15]. It has been observed that the energy efficiency of network devices has not increased following the Dennard's scaling law [12] with respect to network device capacities and traffic volumes [14]. The communication network backbone links are utilized only by 30 %–40 % or less [40, 71]. Studies [74, 78, 96] reported that the Network Interface Card (NIC) remains usually idle, and its average load is estimated around 5 % for typical computers and around 30 % for servers. It has been stated in the EnergyStar standards for the year 2009 that the idle links should operate slowly to conserve energy [71]. Therefore, most of the energy used by the networking infrastructure is wasted, and there exists strong reasons and need to save the wasted energy.

Summarizing, the effectiveness of the modern network systems from the engineering perspective deeply rates to the economical and environmental factors. The most popular and promising solutions for "Green Networking" include the following objectives:

- An utilization of the renewable energy in ICT systems,
- A design of low-power network components (keeping the sufficient level of the network performance)
- Geographical relocalization of the network resources and devices
- Fault-tolerant and secure service "migration".

The network components and devices remain idle most of the time [97]. A considerable amount of energy can be saved by using energy-effective resource management methodologies of the devices and network components [11]. To illustrate the key paradigms that may be exploited in order to reach all these objectives, we divide the existing green networking solutions into four classes, namely: (a) resource consolidation, (b) virtualization, (c) selective connectedness, and (d) proportional computing. This classification in fact sets the main research directions in green networking that may give a solid background for designing the future generation applications in device and network communication protocols.

We present in Fig. 1 a brief characteristics and main techniques for four green networking categories. The *Resource Consolidation* approaches [10, 31, 45, 64, 81] exploit a concept of the over-provisioning of the resources to shut down underutilized devices (lightly loaded routers) and consolidate the network load and traffic on a selected cluster of active network equipment. In *Selective Connectedness* [3, 24] the idle devices are transitioned to low power or sleep modes as transparently as possible. *Interface Proxying* [1, 41, 55, 72, 80] is used in Selective Connectedness to handle network chatter (e.g., handling heartbeat messages, ARP, and unnecessary broadcasts). *Virtualization* [44, 56, 68, 70, 84] refers to operate multiple services at single piece of hardware. Virtualization intends to reduce the underutilization of resources that reduces the energy consumption. A detailed survey of virtualization techniques has been performed by Nanda et al. [70] and Kabir et al. [56].

Proportional Computing refers to the idea of consuming energy proportional to resource utilization, i.e., an idle or underutilized component or device should consume less energy. Proportional Computing methods can be classified into two main categories, namely (a) Dynamic Voltage and Frequency Scaling (DVFS) and (b) Adaptive Link Rate (ALR). The DVFS [52, 67, 79, 83, 92] techniques are mostly applied to the processors to scale the energy consumption

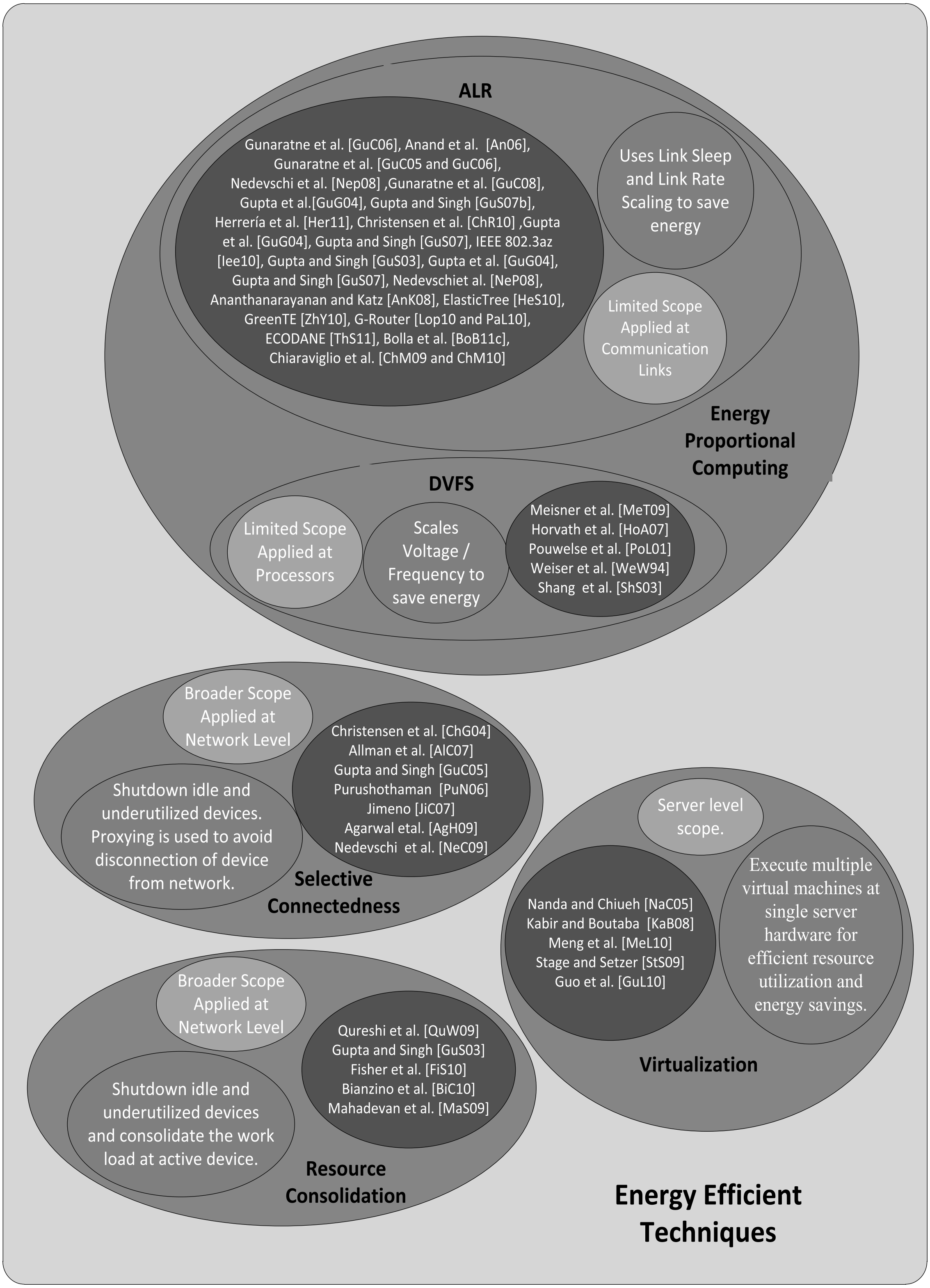

Fig. 1 The main categories of solutions for "Green Networking"

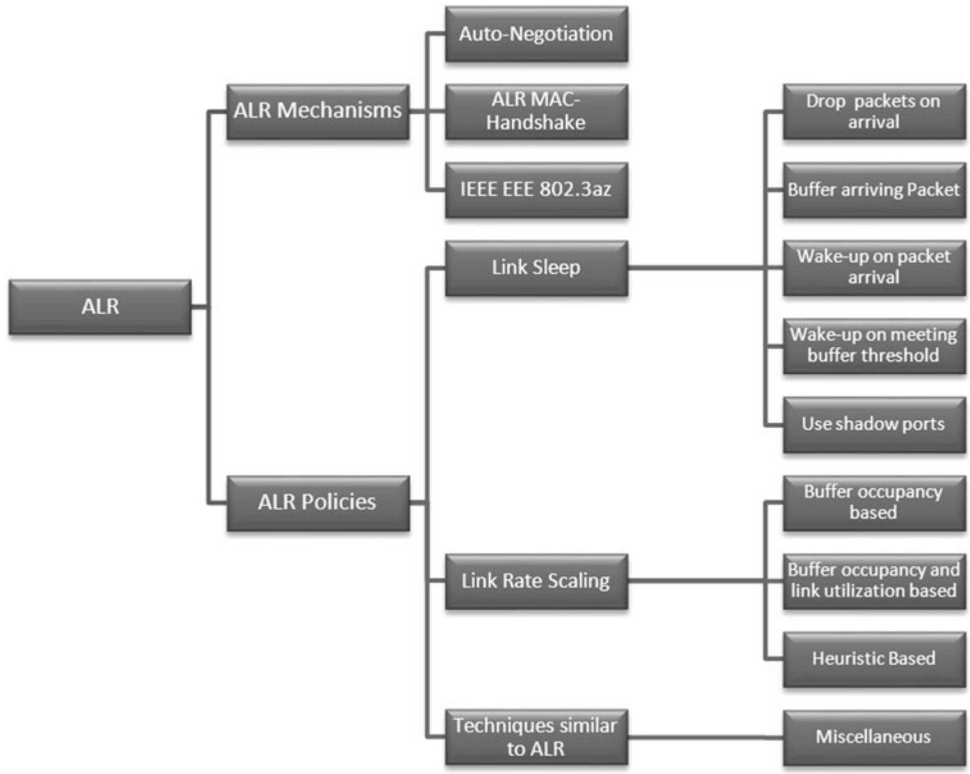

Fig. 2 ALR mechanism and policies taxonomy

power supply and frequency of the processor(-s) according to the system load. The ALR methods aim to reduce the energy states of the network interfaces by reducing their capacities as a function of the network link loads [11]. The energy consumption of links may be reduced by either: (a) scaling down the data rate of the Ethernet communication link or (b) by changing state of the communication link to sleep/Low Power Idle (LPI). As reported in several empirical studies e.g., [20, 51, 64], the Ethernet link energy consumption depends on negotiated link capacity and is largely independent of the communication link utilization. It is reported in [41] that approximately 3 W of energy can be saved by reducing the Ethernet communication link data rate from 1 Gb/s to 100 Mb/s. A working group named "IEEE 802.3az Energy Efficient Ethernet (EEE)" has been established for the ALR standardization in the year 2006. The working group's efforts resulted in IEEE STD 802.3az-2010 standard for the ALR in September 2010 [25, 28].

It has been reported that the wired Ethernet Local Area Network (LAN) in the US has more than 1 billion installed interfaces and over 3 billion worldwide [25]. Gunaratne et al. [42] reported that an energy savings of around 0.93 TWh/year is possible by operating 100 million ALR capable Ethernet links. The EEE group estimated that the energy saving of approximately $1 billion can be achieved by adapting IEEE 802.3az standard amounting to a total energy saving of 5 TWh [25]. The energy efficiency techniques in the ICT sector have received much attention in the last 10 years. Many studies have been carried out to estimate the ICT sector's energy consumption e.g., [15, 17, 61, 65, 82, 91]. Some surveys related to the energy efficient communication and networking have also been conducted that discuss the energy efficient technologies in a broad scope [6, 8, 11, 14, 58, 88, 95]. This survey on green communication using ALR narrows down the energy efficient communication domain and intends to provide a detailed discussion of existing techniques for the ALR. The survey illustrates the potential to save enormous energy savings with negligible performance degradations using the ALR techniques. The ALR and related techniques are classified and discussed in detail. The state of the art techniques for the ALR and ongoing related projects are presented. Industry and standardization body proceedings and future planning for the ALR are also highlighted. A taxonomy of the existing ALR schemes is presented in Fig. 2.

The rest of the paper is organized as follows. A detailed overview of available ALR policies and mechanisms is presented in Sect. 2. In Sect. 3 we highlight the current research trends, projects, and standards related to the ALR. We conclude the survey in Sect. 4.

Table 1 Acronym table

Term	Acronym
Adaptive Link rate	ALR
Dynamic Voltage/Frequency Scaling	DVFS
Dynamic Voltage Scaling	DVS
Dual-Threshold Policy	DTP
Green House Gas	GHG
Energy Efficient Ethernet	EEE
Hardware Assisted Sleep	HAS
Hardware Assisted Buffer Sleep	HABS
Information and Communication Technology	ICT
Information Technology	IT
Low Power Idle	LPI
Link Layer Discovery Protocol	LLDP
Management Data Input Output	MDIO
Medium Access Control	MAC
Network Interface Card	NIC
Physical layer	PHY
Type Length Values	TLV

2 Adaptive link rate

2.1 Overview

The ALR-based technologies aim to reduce the energy consumption of network components through adapting the Ethernet link data rate in accordance with the link utilization. The key issues of ALR are: (a) to define effective mechanisms for a fast modification (and negotiation) of the link data rates (ALR Mechanisms) and (b) to create policies for controlling the link date rate switching (ALR Policies) [96]. We present a simple taxonomy of the recent ALR solutions in both mechanisms and policies areas in Fig. 2. We divided the ALR Policies into three categories, namely: (a) link sleep, (b) link rate scaling, and (c) energy efficient ALR related techniques. The link sleep based ALR schemes are further categorized in terms of link reactivity on the packet arrival during the sleep state. The link rate scaling schemes are classified on basis of the metrics that are considered in taking the decision to initiate the link rate switching. The acronyms of the most important techniques surveyed in this paper are listed in Table 1.

In Sect. 2.2 we discuss the main ALR mechanisms for link rate negotiation and synchronization. Section 2.3 is dedicated to the ALR policies. The techniques to change the link state to sleep/LPI mode are discussed in Sect. 2.3.1. The policies for scaling down link data rate are presented in Sect. 2.3.2. A brief characteristics of the methods that use the same concept as ALR (link scaling or link sleep) for energy saving is provided in Sect. 2.3.3.

2.2 ALR mechanisms

The ALR mechanisms allow the changes in data rates and link resynchronizations for the network devices. A positive response to the data rate change request results in data rate switching (rate transition) and resynchronization of the link [43]. Changing the link data rate may introduce a non-negligible delay in communication. Therefore, the effectiveness of an ALR policy depends on an efficient ALR mechanism [96].

The Auto-Negotiation protocol [19] enables the network devices to choose common parameters (e.g., speed, flow control, and mode) for communication. The same can also be used to change link data rate [19, 42]. The Auto-Negotiation protocol usually requires from 256 ms to several seconds for a 1000 BaseT implementation [42, 43]. Any delay in this process may fill up the device buffer that leads to buffer overflow and increased packet delay [43, 96]. Therefore, the Auto-Negotiation protocol is not a suitable mechanism for the data rate change in ALR schemes.

The "ALR Medium Access Control (MAC) frame handshake" mechanism was proposed for fast data rate switching [4, 42]. The authors reported a two way MAC handshake mechanism in which:

(i) The communication link that determines the need for change in the data rate sends an ALR MAC REQUEST frame.
(ii) The receiver sends an acknowledgment as either: (a) an ALR ACK (agreeing at the requested link rate) or (b) ALR NACK (discarding the request for link rate change).

Gunaratne et al. [42] estimated the time needed for handshake and physical rate change as less than 100 μs for 1 Gb/s links. The result and presented methodology were further discussed and improved in [43]. An effective "Rapid PHY Selection (RPS)" ALR mechanism has been proposed by IEEE 802.3az. Zhang et al. [96] implemented a hardware prototype for a real-time ALR system to address MAC and Physical layer (PHY) synchronization challenges by directly configuring the control registers of PHY. They measured the time and power consumed during the link rate switching. The real time prototype revealed that the rate switch time was reported at least 70 times lower in previous studies (e.g., [4, 42, 43]). In order to force the link rate switching, Zhang et al. [96] proposed to transmit Management Data Input Output (MDIO) frame to PHY. The real-time prototype results revealed that most of the time is utilized in PHY resynchronization. The "Minimum Time to Stay in Low Rate" (MTSLR) was calculated based on the transition times and the power utilized by the MAC and PHY for rate switching. To get maximum benefits of the ALR techniques, Zhang et al. proposed that the time to stay in either switched state must be greater than the MTSLR to avoid frequent link switch oscillations and energy waste in switching.

The IEEE 802.3az Energy Efficient Ethernet (EEE) standard was approved in September 2010 [25, 28]. The energy efficient operation in the Ethernet is enabled by changing the existing PHY and introduction of the LPI mode [28]. The standard also discusses the communication mechanism and the management of entering into and exiting out of the LPI mode. New Type Length Values (TLVs) are defined for Link Layer Discovery Protocol (LLDP) to negotiate parameters related to energy efficiency. The idea behind the LPI is to go into sleep mode when there is no traffic to transmit and resume active state and start transmission on traffic arrival. It takes 2.88 μs to put link in LPI, and 4.48 μs to reactivate the link for 10 Gb/s link. The estimated energy consumption of the link in the LPI mode is estimated to be around 10 % of the energy consumption in the active mode [25]. *The EEE only defines a mechanism for handshake and link state change. The decision to go into and exit out of the LPI mode depends on implementation policy and is beyond the scope of the standard* [28]. We will discuss the ALR implementation policies in next section.

2.3 The ALR policies

2.3.1 The ALR policies using link sleep

Under such a policy, the link can be in either of two states: (a) idle/sleep state or (b) active state. The sleep state may further be categorized based on the link reactivity on packet arrival as follows: (a) drop packet in sleep mode [47, 48, 50], (b) fully awake on packet arrival [28, 45], (c) wakeup on meeting the buffer threshold [47, 48, 71], (d) buffer the packets to process them in the active state [25, 46–48], and (e) use shadow ports to service the packets on behalf of cluster of sleeping ports [5].

Link transitioning to sleep mode to conserve energy is extensively studied in wireless networks. Some of the examples to use link sleep to save energy in wireless networks are [21, 36, 39, 59, 62, 94].

Gupta and Singh [45] proposed a strategy to change the state of network interfaces and other networking devices to sleep. The authors discussed the energy consumption details and energy conservation issues. They proposed two policies for sleep decision: (a) a coordinated scheme, where traffic is aggregated in a few routes by the routing protocol and (b) an isolated scheme for making sleep decision by calculating the inter-packet arrival delays. The link state is switched into a "sleep" mode, if the inter-arrival time is above a defined threshold. The sleep state is advertised to the neighbors. A wakeup packet (to transit from sleep to active state) by the neighbors is used before transmission of actual data. The authors also discussed the impact of sleep decision on the network protocols and described the changes that are required in protocols for the feasibility of the sleep mode.

The same group of authors in [46] proposed ALR policies that exploit the sleep timer programmable ability to shut down links. They assumed that both the sender and receiver interfaces are either in the sleep or active mode. In the sleep mode, the packets to send are buffered at sender. Three policies were suggested for the sleep decision:

(a) on/off-1: This policy runs at the link's upstream (sender) interface and is invoked when the buffer occupancy falls below a threshold value,
(b) on/off-2: This is an extended version of the on/off-1, in which if the buffer is empty, then the upstream interface is remains in sleeping state,
(c) disabling IEEE 802.3 Auto-Negotiation protocol after the transition of link to active state by assuming that no changes have occurred in the link type and data rate.

The authors evaluated the algorithms using the campus LAN traces and concluded that even for high-traffic bursts, it is possible to conserve energy by shutting the links down.

Gupta and Singh in [47] reported a policy termed DELS. In DELS, the decision to place the link to the sleep mode was based on the buffer occupancy and mean of arrival times of recently received packets. The sleep timer was set based on the estimation of the number of packets that will arrive in the buffer during the sleep state. This calculation was based on the assumption that the packet inter-arrival timings are exponential random variables having a gamma distribution. When the sleep feasibility conditions are met, the upstream (transmitting interface) sends a frame to the downstream interface for sleep transition. If send buffer remains empty then the upstream interface might stay in sleep state. The downstream interface awakes when the sleep timer expires and if no signal is detected at the link for a specified time interval, the downlink interface resumes sleep. If the number of packets in buffer exceeds a defined threshold, an unscheduled wakeup at the upstream interface will occur. The upstream interface will become active and starts sending signals at the link forcing the downstream to become active.

Gupta et al. [48] performed a feasibility study to illustrate the energy saving that can be achieved by placing components of a switch to sleep. Inter-activity time of the packets received from the wire or other ports was calculated. The calculations showed that the interactivity time during the low network activity period was greater than 20 seconds for 60 % of the time. This value was 10 % for high activity periods. The interactivity time greater than 1 second during high activity period was 80 % of the time. The aforementioned results clearly demonstrated the feasibility for the sleep mode in switch ports. The authors proposed three ALR sleep policies named the: (a) simple sleep policy in which switch interface goes to the sleep mode for a specified time and all traffic arriving at the interface is discarded,

(b) Hardware Assisted Sleep (HAS) policy in which the interface wakes up by an incoming packet, however the packet is not transmitted, and (c) the Hardware Assisted Buffered Sleep (HABS) policy, to buffer the incoming packets while interface is in the sleep mode.

The concept of using the shadow ports to assist the sleeping interfaces has been discussed by Ananthanarayanan and Katz in [5]. The ingress packets are discarded in the sleeping state of the interface. The authors suggested the use of a shadow port that receives an incoming packet on behalf of a sleeping port. The shadow port was attached to a cluster of switch ports. It was estimated that it is possible to achieve the energy efficiency even if two ports in the port cluster remain in sleep state.

Herrería et al. in [50] enhanced the policies proposed by Gupta and Singh [46] and suggested an opportunistic policy for link sleep. The authors proposed to transition the interface to a complete shutdown state with no ability to sense traffic to maximize the energy savings. The authors considered four states: (a) active sate, (b) idle state, (c) sleep state, and (d) transition state. Transition state performs all of the tasks required to wake up the interface from the sleep state. Interface is not transitioned to sleep until the buffer is empty. The aforementioned was done to extend the sleep duration. Moreover, the wakeup timer starts when the first packet is received and wakeup decision is based on either: (a) timer expiry or (b) queue length. The experimental results show that around 75 % of energy savings may be achieved by using power-aware Ethernet link.

2.3.2 The ALR policies using link rate scaling

The energy efficiency can also be achieved by scaling down the link speed. The network components are designed to bear the peak load. Therefore, links remain underutilized most of the time [97]. Gunaratne et al. [41] revealed that there is a considerable difference in power consumption when links are operated at lower rates. Multiple power states and link rates are already supported by ADSL and are recommended for home users in Europe [34].

The ALR policies using link rate scaling can further be categorized on the basis of: (a) buffer occupancy [4, 42], (b) buffer occupancy and link utilization [41, 42, 71], and (c) heuristics [43]. Some related studies for scaling the link rate to save energy are discussed in following paragraphs.

The possibility of using low link rates for reduced energy consumption was presented by Gunaratne et al. [41]. The authors discussed different techniques for energy efficiency, including variable link transmission rates [41]. The authors depicted that there is a significant difference in power consumption among different link data rates. The authors reported that the energy consumption is 3 W less in switching from 1 Gb/s link speed to 100 Mb/s at NIC, and about 1.5 W less at switch interface. The power consumption of 10 Gb/s link was estimated to increase by 18 W. Gunaratne et al. proposed an ALR policy based on buffer queue length and link utilization for link rate adaptation. The authors analyzed the effect of link rate scaling by using a packet trace of the busiest user in University of South Florida (USF) campus network for 30 minutes duration. The simulation results depicted the possibility to place the busiest user in low data rates, i.e. 10 Mb/s, with a negligible increase in the packet delay.

Gunaratne et al. [42] found that 99 % of the time links can be operated at 10 Mb/s, without any perceivable delay by users. To increase efficiency of the ALR policy, the authors suggested the ALR MAC handshake mechanism for negotiation and rate switching [42, 43]. A Markov model for Poisson arrivals was developed to have an insight of the effects on the packet delay and energy savings. Gunaratne et al. proposed a: (a) dual threshold policy and (b) link utilization based policy. It was observed that the dual threshold based policy may lead to link switch oscillations. Therefore, to minimize the link switch oscillations and maximize the energy conservations, a second policy based on link utilization with dual buffer threshold was discussed. The link rate switch decision is based on the dual threshold policy in addition to counting the number of transmitted bytes (t_n) in time (t_{util}). If t_n is less than the defined threshold, then the link rate switch process is invoked. The authors computed the value of t_{util} and the threshold by using the central limit theorem for Poisson arrivals. It was reported that for up to 5 % link utilization, links can be operated at low link rates for more than 80 % of the time, with less than 0.5 ms delay. The above techniques are also referred as ALR Dual-Threshold Policies (DTPs). However, the main limitation of such models is that it in fact they do not take into account the link rate switching times and, in the consequence, the packet losses, which may increase significantly the energy consumed by the system. The improvement of the Markov-based DTP models has been recently proposed by Callegari et al. in [18]. They re-defined the previous model and added the rate switching times and the NIC buffer size as new criteria.

Another analysis and improvement of the DTPs models has been provided by Anand et al. in [4]. The authors observed that if low and high threshold values of buffer are adjusted 50 % and 80 % respectively, then the link can be operated in the low link rate almost 100 % of time with negligible packet delay.

Counting the number of bytes require extra hardware, such as accumulators and registers that increase the ALR hardware complexity. Therefore, Gunaratne et al. [43] discussed an adaptive heuristics based policy termed as "ALR timeout based threshold policy". Two time intervals were defined, one each for the low and high link rate. The link rate must stay in high data link rate for a specified interval of time before switching to low link rate regardless of the buffer occupancy. The policy was adaptive and the time interval to remain in high rate was doubled when the time interval to remain in low link rate has not expired before switching to high link rate. The authors estimated a saving of around $300 million by the ALR schemes adaptation.

Nedevschi et al. [71] discussed the energy savings achieved by the use of protocols based on power management enabled hardware. Two policies were proposed: (a) a policy that enables the hardware to remain in sleep mode for a short interval of time and incoming packets are buffered for sending, and (b) a policy for link rate adaptation based on the buffer queue length and link utilization. Nedevschi et al. analyzed both the aforementioned policies and compared the results for different parameters including QoS, energy saving, packet delay, and packet loss rate. A comparison of link sleep and rate adaptation was also performed. The simulation results demonstrated that sleep state is more feasible when the link utilization is low. A comparison of the rate adaptation and the sleep mode was disused [67, 93] for processors and servers, and the sleep mode was found to be a better choice. In the following section we present some of the related techniques that use same fundamental concept as ALR.

2.3.3 Techniques similar to ALR

In this section we discuss some techniques that are in close resemblance to the techniques that use the ALR methodology.

Shang et al. in [83] discussed the feasibility of using Dynamic Voltage Scaling (DVS) within the communication fabric. The authors used the workload history to predict the future traffic. Based on the predicted workload assumptions, DVS was applied at the communication links.

Heller et al. proposed in [49] the ElasticTree, an energy efficient network-level energy optimizer. This method is based on a fat-tree topology [2, 69] and exploits the over provisioning of network paths in the fat-tree topology to switch off the idle links. The ElasticTree monitors the network and indicates a cluster of the network devices that are required to remain active to meet the traffic needs. The ElasticTree consists of three modules: (a) optimizer, (b) routing, and (c) power control. The optimizer finds a minimal network cluster that is must remain active. The routing module defines the paths for all flows and the power control shut down the idle links, line cards, or switches. The ElasticTree is estimated to provide around 50 % of energy savings in the data center networks.

A power-aware traffic engineering technique was proposed in [97] in order to redirect the network's traffic. Some links become idle and can be placed into sleep mode by using traffic redirection. Over provisioned and redundant nature of network links were exploited to free some of the network links by transferring their traffic to other links. Zhang et al. showed in [97] that 27 %–42 % of energy savings can be achieved when maximum link utilization is less than 50 %.

Lombardo et al. proposed in [63, 77] G-Router, a measurement mechanism for an autonomous adaptation of the power consumption of access nodes. The power consumption of an access node can be aligned according to the: (a) user traffic requirements or (b) end-to-end path available network capacity. The authors discussed their approach for link rate adaptation and network congestion control. The access node estimates the maximum traffic demands of the user and the minimum available capacity in the end-to-end path. The access node then adjusts the link rate to one of aforementioned parameters that has minimum of estimated value, to provide the QoS and conserve energy.

Thu et al. [53] designed a network control system to optimize the network power consumption in ECODANE project. The ECODANE is based on the fat-tree topology [2, 69] and uses the ElasticTree [49] to find a subset of network for the traffic flow. The authors implemented the "topology-aware heuristics" [49] and the emulation results demonstrated an energy saving of 10 %–30 %.

Bolla et al. [13] discussed the concept of standby mode in the backbone devices, to conserve substantial amount of energy. The authors estimated that the energy consumption of the telecom core network can be reduced to half by using aforementioned approach. The idea works by reconfiguring the nodes and links to meet traffic demands, reliability, QoS, and stability. The authors exploited two features largely available in present network and devices: (a) resource virtualization and (b) modular architecture. Decoupling of physical elements from resource virtualization provides an opportunity to migrate virtual resources. The authors discussed the idea of transitioning idle or lightly loaded components of the network devices to sleep and migrate the virtual processes of an idle component to an active physical element of the same device. The authors introduced the Network Control Unit (NCU), a dedicated node to collect the traffic loads from different routers and apply traffic engineering criterion to reconfigure the virtual resources. The NCU uses a threshold based policy to decide on the transitioning of device elements to sleep or wakeup. The threshold values are decided on the basis of traffic volume profiles. The simulation results depicted that up to 51 % of savings can be achieved by introducing the sleep mechanism.

Chiaraviglio et al. [22] evaluated the possibility of turning the links off in a Wide Area Network (WAN) while considering QoS and connectivity constraints. The authors discussed heuristics based algorithms to turn the node or links

Table 2 Summary of ALR policies

			Description	Pros & Cons	Reference
ALR Policies	Link Sleep Based	Drop arriving packets	The policies that discard any incoming packet during sleep state.	Link can be transitioned to full sleep mode saving maximum energy. May lead to increased packet loss and packet delay, low throughput.	[47, 48, 50]
		Awake at packet arrival	The policies that transition to active state when a packet arrives during sleep state.	Packets are not delayed or stored in buffer. May result in frequent link state switching oscillation, consuming more time and energy. Link remains in partial sleep mode saving less energy.	[28, 45]
		Buffer incoming packets	The policies that buffer the incoming packets in sleep state to process later when link becomes active.	Link remains in sleep state for specified interval of time saving more energy. Increased packet delays as packets remains in buffer unprocessed for specified sleep time interval. Packets may drop in case of buffer overflow leading to increased packet loss.	[25, 46–48]
		Wake-up on meeting buffer threshold	Packets are buffered for later processing during sleep state. The link is transitioned to active state either on sleep interval timeout, or when number of incoming packets increases a threshold.	Prevent packet loss due to buffer overflows during sleep state. More energy savings as link remain in sleep state for specified interval. Increased packet delays because of packet buffering during sleep state.	[47, 48, 71]
		Use shadow ports	The policy use dedicated port (Shadow port) for a cluster of sleeping ports to process packets on behalf of the sleeping ports.	Few ports need remain active during low activity period. Shadow ports process packets on behalf of sleeping ports, leading to more energy savings and less packet delays. Require changes at hardware and protocol level.	[5]
	Link Rate Switching Based	Buffer occupancy	The policies that consider the buffer occupancy to transition the link to low data rate and vice versa.	Buffer occupancy based policies are simple. Buffer occupancy based policies may lead to link rate switching oscillations, that may cause packet delay and packet loss. Performance is dependent on defined buffer threshold values for switching decision. These policies do not take into account the link rate switching time.	[4, 42]
		Buffer occupancy and link utilization	To prevent the switching of data rates based on buffer occupancy, these policies also consider link utilization along with buffer occupancy.	Using link utilization in collaboration with buffer occupancy prevents frequent link data rate switch oscillations and more energy savings. The performance and energy savings are dependent on threshold values for buffer and link utilization.	[18, 41, 42, 71]
		Heuristics	The policies that use heuristics to determine the time to remain in a switched state and data rate switch.	Eliminate the data link rate switch oscillations and need for counting transmitted bytes. Adaptively change the time duration to remain in low or high data rate. Link data rate is restricted to remain in one state for specified interval that may cause low energy savings in case of high data rate state, and packet delay and loss in low data rate state.	[43]

off to save energy. Simulation results showed the possibility to turn off around 30 %–50 % of the nodes and links. Chiaraviglio et al. [23] extended their work and discussed a new scheme to conserve energy in a real Internet Service Providers (ISPs). The authors considered a real traffic profile of an IP backbone network and evaluated the energy costs. The authors improved the idea presented in Ref. [22] by sorting the devices based on energy consumption. The intuition behind the new heuristic scheme was to prioritize power off the devices that consumes more energy, resulting in higher savings. The scheme works by powering off the node and checking whether QoS and connectivity constraints are fulfilled or otherwise. The simulation results depicted that around 23 % of energy can be saved. Next section presents a few ALR related industry and academic projects and outline future expectations. A summary and comparison of the discussed ALR policies is demonstrated in Table 2.

3 The ALR current trends and the future

Underutilization and over provisioning of network links and devices, and the need for green technologies have started their impact on the industries and standardization bodies. IEEE has already approved EEE standard for network devices to work in LPI mode. ECONET project [85], a combined effort of academicians, device manufacturer groups, and Telecom Operators is dedicated to develop device prototypes for wired networks to adopt power consumption according to resource utilization. The resulting network devices will use rate adaptation and standby primitives to conserve energy and ensure that the energy consumption is proportional to the usage. The NeTS-FIND [86] project by USF and Berkley is dedicated to explore "selectively-connected" [54] project in Japan aims to develop energy-efficient standards and energy efficient metrics for networking equipment for access networks. The New Energy and Industrial Technology Development Organization (NEDO) [37] has started several projects aimed at design of energy efficient electronics and IT. The AIM project [30] is focused on designing autonomous and self-configurable mechanisms for power consumption management of the devices. The EnergyWise project [26] by CISCO facilitates to measure and tune power utilization of network devices. EnergyStar has included the ALR in their Tier-2 requirements [29].

The trend of research in the field of green communication using ALR as the core technology from the year 2003 to the year 2011 is reported in Fig. 3. The histogram in Fig. 3 depict a remarkable growth-trend in terms of the papers published during the nine years period (The histogram only reports the work that has been cited in this survey. However, the work reviewed during this survey is thorough and complete to best of our knowledge). The histogram depicts the growing interest of researchers in the ALR and energy efficient communication. Moreover, the major standardization bodies (IEEE and EnergyStar) are also taking interest in energy efficient communication using the ALR and have approved the energy efficient standards using the ALR. Academia and research groups are also working on projects (discussed in above paragraph) using ALR and related techniques.

Constantly growing energy demands of the ICT sector, increased energy costs, and energy proportional computing clearly call for energy efficient solutions. The ALR techniques are able to provide promising energy efficient solutions by exploiting over provisioning and idleness of network devices. The access network devices are estimated to consume 70 % of total energy used by the network [14]. The average link utilization of typical computers is estimated to be only around 5 % [74, 78, 96]. The ALR techniques can exploit the aforementioned facts of access network devices and the extent of idleness all of which lead to saving of many terawatts of energy and billions of dollars. Although, the EEE 802.3az standard has been approved, the standard only provides an ALR mechanism for LPI mode. The ALR policies are yet to be devised that can exploit the EEE 802.3az LPI mode. The ALR polices would be the key drivers of the EEE 802.3az LPI mode, and extent of energy savings and performance would be dependent upon the ALR policies. Much work is expected to appear by utilizing EEE 802.3az standard to save energy after appearance of compatible devices in market.

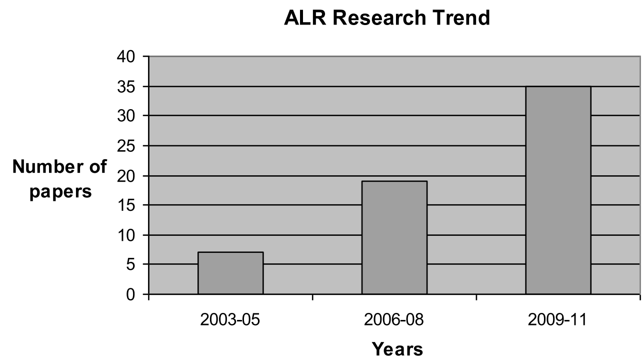

Fig. 3 ALR research trend

4 Conclusions

From the literature review presented in this paper, the immense need for energy-aware network infrastructure and protocols is obvious. It is clear from the discussion that there exists much potential to save energy using the ALR due to the over provisioning and idleness of the communication links. Green networking research is in its infancy, but realization of its need has started its impact on industry and standardization bodies. The IEEE 802.3az standard defined a low power sleep mode for the Ethernet devices. The IEEE 802.3az compliant devices are expected to appear in 2011. However, the IEEE 802.3az standard only defines the mechanism for the sleep mode that is implementation policy dependent. Therefore, new ALR policies based on IEEE 802.3az are required to be devised to exploit the LPI mode defined in IEEE 802.3 standard for substantial energy savings. Use of the energy-aware green network infrastructure and protocols can help in saving billions of dollars and terawatts of energy in coming years.

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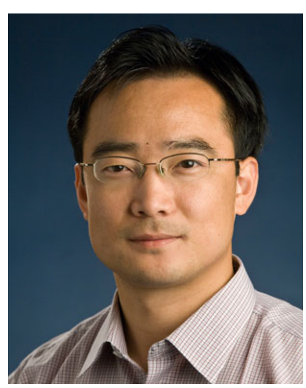

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