Introducing Energy Awareness in the Cognitive Management of Future Networks

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Abstract

The current circumstances on a worldwide level urgently impose to exploit technology in order to reduce environmental pollution, CO$_2$ emissions and waste. The current technologies and the provisioned evolution steps take into consideration these facts and contribute to achieve greener footprint. This paper describes technologies as important elements in the design of Energy-aware Future Networks. They comprise Energy-aware Opportunistic Networks and Traffic Engineering schemes that can be seen as two major extensions towards future networks in the wireless infrastructure-less and wired backhaul/core segments, respectively. In parallel, the role of Cognitive Management Systems for enhancing these technologies with intelligent features that can assist in the optimization of network performance goals, including green targets, is also pointed out. Several simulation results evince how the proposed schemes can contribute in achieving greener footprint in the context of Future Networks.

Keywords: cognitive management, energy-aware, green footprint, opportunistic networks, traffic engineering, future networks.

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1 Introduction

Networking systems and user devices have become in the past decade an integral tool of people every day lives; in personal professional and leisure activities. Therefore, it is essential to evolve not only the devices themselves, but also the networks, in order to meet both people needs with respect to applications, as well as to the way and the quality of provisioning of these applications for the users. Consequently, certain technological requirements emerge; Personalization, context awareness, always best connectivity, ubiquitous service provision and seamless mobility are some of the high priority requirements [1–4]. Most importantly, current socio-economic circumstances in Europe and worldwide impose immediate actions with respect to achieving pollution reduction, environmental-friendly behaviour and adaptation to every aspect of peoples’ routine [5, 6]. To this end, green aspects must be considered towards the evolution of the networking solutions so as to satisfying today’s needs while preparing for tomorrow, future networks.

Obviously, addressing such requirements and ever increasing complexity with the goal to select the ideal operating state of networks, is a very difficult task to achieve, considering the huge number of controllable parameters and different network performance objectives. Cognitive Management Systems (CMSs) have been proposed as a promising technology towards this direction. In general, CMSs are characterized by their ability to empower networks with advanced, intelligent processing and decision making e.g., based on learning and reasoning so as to dynamically adapt to varying network conditions in order to optimize performance.

Framed within the above, in this paper we advocate that Energy-aware Opportunistic Networks and Traffic Engineering can be seen as two major extensions towards future networks in the wireless access and wired/core segments, respectively. At the same time they render a fruitful landscape for naturally evolving the Cognitive Management Systems (CMSs) developed as part of the cognitive research findings within the FP7 European project End-to-End Efficiency (E³) [1] and most importantly, further elaborated and specified in the Reconfigurable Radio Systems (RRS) Technical Committee [15] of ETSI standardization body.

More specifically, the OneFIT [20] research project has recently proposed and started working on a solution that comprises Opportunistic Networks (ONs), CMSs and control channels. Differentiating to what has been described so far [7], ONs can be seen here as temporary extensions to the infrastructure, which are dynamically built, based on connectivity oppor-
tunities and by exploiting flexible spectrum management [1] and ad-hoc networking technologies. Four basic technical challenges need to be addressed with respect to these ONs; the determination of the suitability of the appropriate circumstances to proceed with their creation, their creation per se, the maintenance of the offerings that they were created for and their release, as long as they have fulfilled their goal. In this context, the paper describes the five technical scenarios related to ONs that are used in [20] so as to leverage the arising challenges and the evolved management systems that need to be developed for addressing them. In addition, we also demonstrate how the management decisions made by these cognitive systems can result in higher green footprint, mainly in terms of lower electrical energy consumption (lower transmission powers,) and less investments in and accordingly deployment of hardware.

In addition, the idea of ONs and the QoS-demanding applications that will need to support, unavoidably leads to more traffic that must be served by the infrastructure-based backhaul/core network. This also leads to increased power consumption and complexity in terms of required configuration/management complexity. Therefore, it is essential to reconsider the design and the management of this part of Future Networks, as well. An important goal in this direction is to achieve the best ratio of performance to energy consumption and at the same time assure manageability. To this effect, an Energy-Aware Traffic Engineering (ETE) scheme is proposed for the core/backhaul segments of a future network, providing balanced, congestion free, energy-aware and operator governed network operation. Once again, it is envisaged that mixing such schemes with CMSs and self-x capabilities will also empower Future Networks with the capability to adapt their behavior in an autonomous manner using learning and knowledge sharing.

Accordingly, the rest of this paper is structured as follows: Section 2 focuses in the need for Cognitive Management systems and their role in the emerging wireless world through the prism of ETSI RRS. Section 3 focuses on the OneFIT solution that is based on ONs, describes the tackled scenarios and shows how the latter can be exploited so as to increase energy-awareness in future networks. Section 4 complements the puzzle by discussing challenges and proposing energy-aware schemes related to the infrastructure-based core/backhaul parts of the network. Finally the paper is concluded in Section 5.
2 Cognitive Management Systems

As already stated, CMSs have the ability to empower networks with advanced, intelligent processing and decision making. Particularly CMSs incorporate self-management and learning mechanisms in order to overcome the complexity of the infrastructure and the wireless access [8].

Self-management enables a system to identify opportunities for improving its performance and adapting its operation without the need for human intervention. Learning mechanisms are important so as to increase the reliability of decision making. They also enable proactive handling of problematic situations, i.e. identifying and handling issues that could undermine the performance of the system before these actually occur.

Generally a CMS enables a system to identify opportunities for improving its performance and adapting its operation without the need for human intervention. CMSs make and enforce decisions by taking into account the context of operation (environment requirements and characteristics), goals and policies, profiles (of applications, devices and users), and machine learning (for managing and exploiting knowledge and experience). Learning mechanisms are important so as to increase the reliability of decision making. They also enable proactive handling of problematic situations, i.e. identifying and handling issues that could undermine the performance of the system before these actually occur.

Actually, there has been a lot of research in the field of cognitive networks and their management; it spans physical layer [9–11], network layer [12] and application layers [13, 14]. The FP7/ ICT E3 project [1] also worked towards integrating cognitive wireless systems in the Beyond 3G (B3G) world, evolving current heterogeneous wireless system infrastructures into an integrated, scalable and efficiently managed B3G cognitive system framework. The delivered result comprises a set of entities that exhibit cognitive functionality and interfaces for introducing cognition in the wireless world. In addition and more importantly, the ETSI RRS TC [15] delineated the standardisation roadmap of these functional entities and interfaces as a hallmark certifying their timeliness and importance for emerging networks. A graphical representation of the current view of the wireless world as formed by ETSI TC RRS is given in Figure 1. In this figure, the Cognitive Control Network (CCN) on the one part and the Composite Wireless Network (CWN) on the other part, need to collaborate in order to efficiently provide the requested applications/services to both emerging (multiradio) and legacy user devices. As far as CCN is concerned, the management relies on autonomic/cognitive
Challenges arising with respect to the above include:

- Potentials for efficient FI application provisioning.
- Improved resource utilisation and “green footprins” with respect to reduced costs (Capital Expenditures – CAPEX, Operational Expenditures - OPEX, total cost of ownership).
- Dynamic spectrum management, ad-hoc network operation.
- Standardization activities (evolved ETSI TR102.682 [16], ETSI TR102.683 [17], IEEE Std 1900.4-2009 [18]).
- Coordination with CWN.

On the other hand, the characteristics of CWNs are the following:

- They comprise a set of radio networks, heterogeneous or not.
- Each CWN is operated by a single Network Operator (NO).
- The network management system is common for all the radio networks in CWN.

Particularly, CWNs’ management relies on a set of specified functional entities, namely 3GPP Self Organizing Network (SON) (self-
management/planning, 3GPP use cases), JRRM (Joint Radio Resource Management), DSONPM (Dynamic Self-Organized Network Planning and Management) and DSM/FSM (Dynamic/Flexible Spectrum Management) [15]. JRRM is an entity that enables management of composite radio resources and selection of radio access technologies for user traffic connections. DSM provides long and medium term recommendations for the (technically and economically) available amount of spectrum introducing flexible spectrum management scheme. Finally, DSONPM caters for the medium and long term management decision of reconfigurable network segments, realizing the management domain.

The challenges also arising for CWN include:

- QoE/QoS, cost efficiency (OPEX, CAPEX).
- End-to-end perspective: evolution, intelligence embodiment, federation for end-to-end optimality.
- Efficient validation (simulation, prototyping, experiments, trials, pilots).

Consequently, based on the emerging wireless world (ETSI RRS view), the proposed scheme with ONs [20] can be seen as a solution to address challenges appearing in CCN, while Traffic Engineering can resolve problems arising in the area of CWN [21].

Despite the extended research that has been done in the field of cognitive management technologies, it is necessary to further evolve the aforementioned concepts. This means that they need to be adjusted to the current needs of users, as well as to the needs imposed by the society as a whole. As mentioned before, the need to protect the environment and investigate ways to consume less energy and create environment friendly technologies has emerged, more compelling than ever. The following sections present the current technology evolution in these research fields, highlighting their green footprint perspective.

3 Opportunistic Networks

3.1 The Idea of Opportunistic Networks

ONs have been defined in [20] as coordinated extensions of the infrastructure networks and they are operator-governed as far as resources management, policies, and information/knowledge are concerned. They are dynamically created based on the operators’ spectrum/ policies/ information/ knowledge, in places and times that efficient service provisioning to mobile users is needed. They can comprise network elements of the infrastructure as well
as terminals/devices, potentially organized in an infrastructure-less (ad-hoc) mode and they are created and “live” for a particular time interval that needed for setting up and providing QoS demanding applications (Video Streaming, VoIP, IPTV, etc.) to users in the most efficient manner.

As an extension to ETSI RRS specified CMSs described above, two types of systems are envisaged, called “Cognitive systems for Managing the Opportunistic Network” (CMONs) and “Cognitive management Systems for Coordinating the Infrastructure” (CSCIs). The main idea in the aforementioned schemes is to provide the means to facilitate close cooperation between the infrastructure and the ONs, as depicted in Figure 2. Such collaboration is essential for ensuring viability, deployment and value creation for all the stakeholders. In addition, the “Control Channels for the Cooperation of the Cognitive Management System” (C4MS) is introduced in order to coordinate the functionality of the previous entities.

In this context, five technical scenarios are considered and related to the management of ONs. They are used to describe the arising challenges (including the green footprint) which will be addressed by the development of
cognitive management systems as part of the ongoing work in this effort. The scenarios are as follows:

1. Opportunistic coverage extension (Figure 3).
2. Opportunistic capacity extension (Figure 4).
3. Infrastructure supported opportunistic ad-hoc networking (Figure 5).
4. Opportunistic traffic aggregation in the radio access network (Figure 6).
5. Opportunistic resource aggregation in the backhaul network (Figure 7).

In the following subsection the above-mentioned scenarios are described and the green footprint of each scenario is presented, accordingly.
3.2 Green Footprint of ONs

In this subsection, the five scenarios are presented in more detail, depicting the different facets of the ON-based solution along with its potential for contributing in a “greener” footprint.

1. Opportunistic coverage extension

In this scenario the ONs are used for enabling the devices to communicate over infrastructure networks, even if there is no direct connection to an infrastructure network. This may be occurring as the user’s device supports the air interface of the infrastructure, but is out of its coverage or has bad coverage. Another reason is that the user’s device may be in the coverage of
In this scenario, ONs are used to resolve the capacity/congestion issues in mobile (infrastructure) networks. In other words, the ON is used in order to redirect the access route and avoid connecting to a congested network infrastructure with questionable offered QoS levels.

In this scenario the claim that the ONs influence the green footprint is strengthened, as they contribute to the reduction of the transmission power and consequently lead to lower electrical energy waste. Higher bit-rates are also possible, while capacity extension leads to less investment in infrastructure and consequently less hardware deployed. This means that lower OPEX, as well as CAPEX are achieved.

3. Infrastructure supported opportunistic ad-hoc networking
ONs are also used along with the local Peer-to-Peer (P2P) communications paradigm, so as to enable the optimization of resource usage and the...
provision of new services in a localized manner. The ON created is completely infrastructure-less, but still operator-governed through the provision of resources and policies. The rationale is to exploit the fact that often the end-points of an application are physically close devices at any given time (e.g., attendees to a conference or concert, travellers in the same bus or train etc.) so that traffic exchange can be limited within its scope.

The green footprint of this scenario is also proved by the energy consumption diminishment that is achieved through the localization of application provisioning. Higher bit rates are possible, as well.

4. Opportunistic traffic aggregation in the Radio Access Network
In this case the ONs are used for enabling the optimization of resource usage and QoS provision in the Radio Access Network (RAN). This is achieved by “forcing” a limited sub-set of the ON terminals to exchange data with the infrastructure; these terminals aggregate/ distribute data from/ to all the other terminals in the ON. This situation improves the degree of traffic aggregation and caching, which is useful for the overall network performance improvement.

Obviously, in this case the green footprint is achieved by succeeding to support limited ON terminals, fact that leads to lower electrical energy consumption.

5. Opportunistic resource aggregation in the backhaul network
Lastly, the ONs and multipath routing are used for enabling the optimization of backhaul resource usage in the infrastructure network. In this case, the ON is created over access points rather than user terminals. It thus offers a new focus on system performance improvement.

In this scenario, capacity extension leads to less investment in infrastructure and consequently less hardware deployed, which consequently results to higher green footprint and lower CAPEX.

3.3 Performance Evaluation
This section discusses on the simulations we have conducted for two of the aforementioned scenarios in order to investigate the green benefits and the overall network performance from the creation of the ON. We will also study performance metrics in order to assure that the achievement of greener footprint does not negatively affect the overall network efficiency in the application provisioning.
3.3.1 Test Case 1 – Coverage Extension

A set of test cases were executed in the simulation environment, which was based on the widely used NS-2 simulator [24] and ran on an Intel Core i5 2.3 GHz with 4 GB of RAM and a 64-bit Operating System.

Without loss of generality, the topology comprises a single AP supporting IEEE 802.11 g technology with a maximum offering data rate at 54 Mbps. A set of 12 mobile terminals (MTs) are supported within the range of the AP, the four of which are selected to be the application consumers. VoIP application, based on the G.711 [25] voice encoding scheme for both the caller and the callee, is considered in the simulation test cases exhibiting stringent resource requirements and real time sensitivity.

Describing the test cases depicted in Figure 8, four phases (steps) are considered, each one corresponding to a specific percentage of the initial TRx power of the AP/MTs, namely: 100% (initial)/100% (initial), 80%/100%, 60%/100% and 60%/60%, thus resulting in ranges R0/T0, R1/T0, R2/T0 and R2/T1, respectively. In general, during the reduction of the AP’s TRx power, some of MTs are left out of the APs’ range. These MTs are then supposed to create ONs with intermediate MTs in an ad-hoc manner and operate in WLAN 802.11g, as well. In particular, the initial transmission power of the AP and MTs is set equal to 0.03 W and 0.02 W, respectively.
Furthermore, each phase evolves also sub-phases depending on the mobility level of the intermediate MTs that are inside a predefined mobility domain using a random waypoint mobility model. We assumed 7 mobility levels (0 m/sec–15 m/sec), with the same maximum speed for all the MTs that are inside this domain and pause times equal to 1 sec. Finally, for completion reasons, we also experiment with the routing protocols [26] namely, DSR, AODV, OLSR and GRP, which will be used to route traffic to MTs that are found out of range during the AP’s and MTs’ transmission power reduction.

Figure 9 depicts the total power consumption that is required for supporting the data traffic in the test case prior to (phase 1) and after the formation of the ON (phase 2–4). All the nodes in the network and the infrastructure element (AP) are considered in the computation of the total energy consumption. As depicted, the formation of the ON can result in a reduction of 40% of the initial transmission power. This result supports our initial claims of better use of resources in terms of energy consumption.

In the sequel, we also focus on specific QoS metric, which is used to evaluate conditions and assist in coming up with useful recommendations with respect to the creation of the ONs networks with the possible green gains. We focus herewith on performance metric associated with the QoS levels that the applications will be provided through the ON(s), namely Application Delay (sec).

Figure 10 depicts the end-to-end delay that VoIP suffers averaged on the application MTs. The single dotted line corresponds to the maximum accept-
able delay. Generally, as the mobility level increases, the overall delay also increases. This is due to the fact that the mobility in the intermediate nodes, can significantly impact the performance of the ad-hoc routing protocols, including the packet delivery ratio, the control overhead and the data packet delay [27].

Moreover as the number of intermediate nodes increases, while the AP’s range is shrinking, the overall delay also increases since more MTs participate in routing and forwarding of the received packets. In the same figure, the existed solutions in terms of mobility level are depicted with the anticipated green benefits. In phase 2 and 3, it is observed that all mobility levels has acceptable values and can result to a 20 and 40% reduction of transmission power, respectively.

On the other hand in phase 4 there are only three acceptable solutions (0–1.5 m/sec) and can result in a reduction of 40% of the required transmission power. Therefore, there is some degree of freedom regarding the creation of the ON to be applied, which can vary depending on the level of emphasis given to specific target QoS levels and aimed savings in transmission power.

In general, as simulations showed, AP/MTs transmission power reductions of 60% can be obtained without impacting too much the service provisioning. This means that the supported application remains at acceptable QoS levels with less AP/MT power resources. Therefore this reduction will result important savings in the total transmission power in the network.
3.3.2 Test Case 2 – Opportunistic Traffic Aggregation in the Radio Access Network

Focusing on the traffic aggregation scenario described above, there may be users that face poor channel quality towards the infrastructure, because they may residing at the edge of the AP and at the same time very good channel quality towards some of their neighbours. It is obvious that users with poor channel quality, compared to those with better quality, need more resources (e.g., power, time) to transmit the same amount of data. After the creation of the ON, users with good channel conditions towards the infrastructure will be responsible for forwarding traffic to those that have poor channel conditions, through their direct interfaces. Therefore, the ON will increase the overall system capacity and resource utilization, and offer a service in an energy efficient manner.

For the simulations, a set of four nodes set-up direct connections (via cellular interfaces) with a network in order to transmit data packets of the size of 1 MB each. It is assumed that users’ devices are equipped with 3G interfaces (for the connection with the AP) and with IEEE 802.11g interfaces for the peer-to-peer connections among them. At some point in time the quality of the nodes’ connections significantly drops, thus the connection throughput is limited for three of them to 0.5 Mbps. At the same time, these nodes maintain very good channel quality towards some of their neighbours, offering a rate of 54 Mbps by using IEEE 802.11g interface. The AP in collaboration with the nodes, detects that situation, and initiates the process for the creation of an ON. They jointly determine one or several nodes, with high channel conditions to aggregate and/or relay traffic of other users, which have poor channel conditions towards the infrastructure.

Figure 11, depicts the anticipated average delivery latency prior to and after the formation of ON. It corresponds to the one-way time (in seconds) from the source sending a packet to the destination receiving it. With direct links, it is observed that the average delivery latency is around 13 sec, while the deployment of the ON yields a significant drop of this metric to 2.3 sec.

Moreover, Figure 12 depicts the total power consumption that is required for the traffic of the test case prior and after the creation of the ON. It considers again all nodes in the range of the AP and the infrastructure element. As Figure 12 depicts, the creation of the ON can result in a reduction of 22% of the required transmission power, which can be justified by the shorter direct links that are used for forwarding traffic within the ON. This result in this test case also proves our claims of better use of resources in terms of energy consumption. Finally, the CMSs can ensure fast and reliable establishment of
ONs and perform well when facing same situations, thus resulting in faster reductions of the energy consumption, achieving efficiently green targets.
4 Infrastructure Networks

4.1 Future Core/Backhaul Networks

As mentioned before, the current network infrastructures face problems in keeping up with the requirements of their growing ecosystem and increased QoS demanding wireless/mobile access segment, mainly due to the inability of their management systems to deal with current challenges. An efficient management system would require operators to be able to manage and to control their networks both effectively (reducing human intervention whilst optimizing resource usage, reducing costs through energy-efficient solutions, etc.) and flexibly.

However, typical management systems are designed in a bit-centric fashion offering reasonably stable bandwidth pipes to their customers, whereas the demands of today and tomorrow call for a service centric fashion which puts a strong focus on end-user satisfaction and energy efficiency, too. Currently, Operators and ISPs are far from being able to respond to the aforementioned demands since management and operational costs represent the majority of the total cost of ownership of networks, permitting only a limited amount of investment into new infrastructure and facilities.

One of the main characteristics in the era of Future Networks will be the growth of QoS-demanding applications that need to be supported. Unavoidably, this leads to increased traffic that has to be served by the deployed networks.

Figure 13 depicts the expected growth of traffic that has to be supported by the Future Networks in order to provide efficient service provisioning [22]. In addition, this also leads to increased power consumption and configuration/management complexity.

Recently, due to the increased energy prices, the growth of costumer population and the expanding number of services being offered by operators and ISPs, the energy efficiency issue has become a high-priority objective for the Future Networks. The continuously rising demands in network energy consumption essentially depend on new services that must be supported by the future infrastructures. Figure 14 depicts the Global e-Sustainability Initiative (GeSI) report [23]: In 2002, network infrastructures for mobile communication and for wired narrowband access caused the most considerable greenhouse contributions, since each of them weighs for more than 40% upon the overall network carbon footprint. The estimation for 2020 says that mobile communication infrastructures will represent more than 50% of network CO₂ emissions.
4.2 Green Footprint of Core/Backhaul Networks

The concept of “Future Internet Networks” is globally emerging as a federation research theme with the objective of overcoming the structural and cost limitations of the telecommunication infrastructures (mainly at the core level) and their management systems. Using Future Internet systems, Operators and ISPs should be able to manage their ever more pervasive and sophisticated networks, enabling:

- Dynamic, efficient and scalable support of a multiplicity of applications across federated administrative and technology domains.
- Light operations and migration to cost effective, secured, and manageable networking functionality.
- Autonomic management procedures in order to achieve the best ratio of performance to energy consumption and assure manageability.

Focusing basically on the last two objectives that are related to the green footprint of the Future Core/Backhaul Networks, we must highlight that given the high heterogeneity of networks and technologies, architectures, and operational constraints of protocols applied at different layers, the most efficient way to develop novel energy saving mechanisms is to concentrate on specific scenarios, investigate their demands on energy saving and design
specific energy-efficient protocols. Thus, the researchers must try to find specific solutions/mechanisms that will have negligible impact on the network level performance: Energy-efficient router operation and switch architectures must be concerned. Moreover, new approaches must be investigated that will provide efficient and energy-aware network operation through sophisticated traffic engineering mechanisms. These energy-efficient traffic engineering schemes must allow the operators to balance the load and avoid failures, increasing in this way the reliability and improving the network performance.

4.2.1 Green Traffic Engineering

Following up on our previous discussion we focus on traffic engineering and investigate ways of introducing energy-awareness in the network. Traffic engineering receives huge attention as one of the most important mechanism seeking to optimize network performance and traffic delivery. Wang et al. [28] gave an overview of the traffic engineering approaches that emerged the last years and placed focus on two major issues: quality of service (QoS) and network resilience. They provide a general classification of these traditional-objective traffic engineering approaches: intradomain vs. interdomain [29], MPLS-based vs. IP-based [30, 31], offline vs. online [32, 33], unicast vs. multicast [34, 35]. The work in this paper is inspired by these traditional traffic engineering approaches.
A challenging task is to identify the main parts of the Internet that dominate its power consumption and investigate methods for improving energy consumption [36]. Moreover, the authors in [37] discuss the idea of dynamically turning part of the network operations into sleeping mode, during light utilization periods, in order to minimize the energy consumption. Recently, routing, rate adaptation and network control are mobilized towards energy-efficient network operation [38, 39]. Unfortunately, none of these approaches provide a general problem formulation in the direction of “coupling” the traditional traffic engineering objectives with the modern objectives (like energy-awareness). This paper is an attempt to “modernize” the research in this field.

We present below a distributed Energy-Aware Traffic Engineering (ETE) mechanism. We consider a network model, as depicted in Figure 15, where each ingress router may have traffic demands for a particular egress router or set of routers. We use multiple paths (MPLS tunnels) to deliver traffic from the ingress to the egress routers. We must mention here that traffic is split among the available paths at the granularity of a flow, to avoid re-ordering TCP packets or similar effects that lead to performance degradation (using efficient traffic splitting approaches, like [40]). In addition, we consider that the paths are computed and re-computed (if it is necessary) offline by the operator, since most of the operator’s networks work in this way.
Table 1 Variables.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>Set of links in the network</td>
</tr>
<tr>
<td>$IE$</td>
<td>Set of Ingress to Egress node pairs</td>
</tr>
<tr>
<td>$el$</td>
<td>Energy consumption of the port connected to link $l$</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Set of paths of Ingress to Egress node pair $i$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Traffic demand of Ingress to Egress node pair $i$</td>
</tr>
<tr>
<td>$a_l$</td>
<td>Binary variable: 0 if link $l$ is sleeping, 1 if link $l$ is active</td>
</tr>
<tr>
<td>$u_l$</td>
<td>Utilization of link $l$</td>
</tr>
<tr>
<td>$c_l$</td>
<td>Capacity of link $l$</td>
</tr>
<tr>
<td>$x_{ip}$</td>
<td>Fraction of traffic of Ingress to Egress node pair $i$, sent through the path $p$</td>
</tr>
<tr>
<td>$r_{ip}$</td>
<td>Traffic of Ingress to Egress node pair $i$, sent through path $p$</td>
</tr>
<tr>
<td>$P_l$</td>
<td>Set of paths that go through link $l$</td>
</tr>
<tr>
<td>$L_i$</td>
<td>Set of links that are crossed by the set of paths $P_i$</td>
</tr>
<tr>
<td>$E$</td>
<td>Demand of the operator in energy consumption</td>
</tr>
</tbody>
</table>

The main “cornerstones” in the proposed mechanism are the following low-complexity and distributed algorithms (Table 1 contains the definitions of the variables used):

- **Load Balancing**: Given the $a_l$ values for the links in the network, find the corresponding $x_{ip}$ values that provide balanced network operation in terms of link utilization. In order to provide an efficient solution we investigate for each ingress-egress node pair the paths that goes through the maximum utilized link. Then, we “relieve” this link by moving a portion of traffic $\Delta x$ and provisioning it proportionally to the rest paths (inverse procedure of progressive filling that leads to optimal load balancing based on [41]). This procedure continues till convergence to the optimal $x_{ip}$ values.

- **Energy Saving**: Given the $x_{ip}$ values resulted from Load Balancing, find the maximum set of links that could be turned into sleeping mode. For each ingress-egress node pair we find the routers that are part of the active routes and turn the lines of their network card that are not used (by any path in the network) into sleeping mode.

The proposed approach (Figure 16) receives as input the operator request, as far as the energy consumption is concerned ($E$). Then, **Load Balancing** and **Energy Saving** are applied, by each ingress-egress node pair $i$ in order to balance the link utilization in their paths and put the links that are not utilized into sleeping mode. Next, the new energy consumption level is compared to $E$ in order to realize if we have reached the desired state. If not, the heuristic mechanism continues by excluding the path $p$ with the minimum $x_{ip} T_i$ (light-
The heuristic mechanism iterates based on the updated $P_i$ values, optimizes $x_{ip}$ and $a_l$ values $\forall p \in P_i, l \in L_i$, and finally, stops when the operator’s energy consumption goal is achieved.

We must highlight that ETE can be executed in an autonomous/cognitive manner using monitoring and knowledge sharing (Figure 16). In other words, the status of the system is continually monitored in order to apply ETE when needed. Moreover, knowledge (related to configuration actions and different states of the system) is stored for increasing reliability and automation of the system reactions. In this way there is no need for execution of the proposed heuristic mechanism when a “known” event happens in the network (e.g., new request with specific characteristics).

We present now the evaluation study of the proposed scheme. In order to provide realistic simulation results, we use real ISP topologies and traces provided by Rocketfuel tool [42]. In our simulation, we consider Tiscali (3257) traces and a network topology consisted of 18 routers and 77 links. We compare the performance of ETE to OSPF-TE [43] that was applied in Tiscali network when the traces were collected.
Figure 17 depicts the utilization of the links in the network when ETE and OSPF-TE are applied. We observe that ETE is able to keep the link utilization at low levels using the minmax link utilization policy that is adopted. On the other hand, OSPF-TE uses a dynamic procedure to calculate the link weights in order to route the traffic efficiently, which could lead to link overutilization.

Then, we plot the percentage of the initially consumed energy that is saved when ETE is applied. Similar to the previous test case, we consider Tiscali traces in order to build a relationship between the load of the traffic that must be supported in the network and the energy saving that could be achieved by ETE. Figure 18 visualizes that when the maximum link utilization is low, the energy saving is close to 50%. The percentage of saved energy continually drops while the traffic in the network grows and therefore the utilization of the links is becoming high.

Finally, Table 2 presents the existing tradeoff between the energy consumption and the maximum link utilization in the network. The first column contains the operator’s request, as far as energy saving is concerned. In addition, in the next two columns we observe the percentage of the links that must be turned into sleeping mode and the routes that will be excluded in order to approach the corresponding $E$ values. The last column presents the balanced link utilization that is achieved by ETE for each desired $E$ level. It is obvious
that there is an important tradeoff between the balanced and energy-aware network operation which is handled by ETE, based on the operator’s goals.

5 Conclusions

In this paper we described several technologies envisioned as important elements in the design of Energy-aware Future Networks. Energy-aware Opportunistic Networks and Traffic Engineering schemes are presented as two major extensions towards Future Networks in the direction of introducing energy-awareness in the operation of wireless infrastructure-less and wired backhaul/core segments, respectively. Moreover, the role of Cognitive Management Systems for enhancing these technologies with intelligent features is also investigated in the paper. The simulation results depict the greener footprint that is achieved in the context of Future Networks by the proposed approaches. Future directions include: extended cognit-
ive/autonomous functionality enhanced with learning and autonomic features and implementation/deployment using commodity hardware.

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References

Energy Awareness in the Cognitive Management of Future Networks


**Biographies**

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