Green Networks and Communications

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KEY POINTS

- Presents the drivers and benefits of energy efficient computer networks and communications.
- Describes energy efficient networking solutions from the perspective of reduced carbon cost (of data centres, for example) and improved operational sustainability (for example, of wireless mobile devices).
- Outlines energy efficient networking objectives of green protocols and proposed green management strategies.
- Evaluates the bit count associated with traditional network protocols.
- Presents exemplar context data required for management systems with green objectives across domains.
- Illustrated with case studies, discusses the contrasting energy efficient networking requirements of UK and India.

1. INTRODUCTION

Roll-out of the Internet of Things and increase in the range of applications supported online has resulted in demands on network capacity which are greater than before. More than 70% of people with broadband at home in Britain describe it as essential and a typical consumer there spends nearly half of their time while awake using telecommunication products and services [1]. This growth can be attributed to application tailoring to meet user needs, high levels of Quality of Service (QoS) and affordability of broadband services. Continued expansion of the telecommunications market worldwide has, however, attracted concern over future network success if services continue to be provided in the current manner. 'Success' in this respect refers to a non-negative impact on the environment, continued market penetration through sustained affordability for end users and operators, and maintained levels of QoS. Already, however, there are indications of negative impact on the environment from increasing telecommunication use, reduced affordability through rising electricity cost, and potentially reduced levels of QoS through change in the devices on which applications are run and nature of service provision. In terms of the environmental consequences, the IT industry in 2009 was attributed to be responsible for approximately 10% of global electric power consumption [2]. In 2007, the ICT sector was estimated to be responsible for 2-3% of global carbon emissions [3][1]. While negative environmental impacts alone are unlikely to be the limiting force on network roll-out in the future, there are social and government-enforced obligations to prevent further damage to the environment. Optimising the efficiency of IT operational strategies has therefore become a priority to halt further damage to the environment and reputation of the Internet. There is therefore a growing need for green networking and communications.

1.1. Green Network Communications and Management: Background

The IT industry has been criticised for its contribution to carbon emissions and failure to respond to negative impact on the climate [2]. Efforts have therefore been made on this front and IT energy efficiency is now of high priority as evidenced through the publication of documents such as '*Smart 2020: Enabling the Low Carbon Economy in the Information Age*' [3] and '*Digital Britain*' [1]. Reduction in carbon emissions will occur as a result of government regulations and schemes. For instance, in the UK, The Climate Change Act 2008 [4], UK Low Carbon Transition Plan [5], Carbon Reduction Commitment (CRC) Energy Efficiency Scheme 2010 [6] and Climate Change Levy [7] are in force. In India[2], similar schemes, such as the Energy Conservation Act 2001 [8], are enforced by the Bureau of Energy Efficiency. Overall, the objective of these schemes is to minimise carbon emissions associated with all aspects of life. These schemes however, are not specific to the development or use of energy efficient IT, and for the time being, the way in which network efficiency is achieved is an independent venture and not even the responsibility of telecom regulators.

The International Telecommunication Union Telecommunication Standardisation Sector (ITU-T) standardises telecommunication operation on an international basis to build a fair and competitive environment. The UK telecommunication industry is regulated by the Office of Communications (Ofcom) who oversee operation to ensure fairness to customers by promoting competition and protecting against offensive material, governing licensing procedures, researching the market and addressing complaints in accordance with the ITU-T's requirements. In working towards the achievement of green IT, it released the report '*NGNs and Energy Efficiency*' in 2008 which recognises negative contributions of Next Generation Networks (NGNs) on climate change and examines the efficiency of telecommunication networks and applications [9]. The ITU-T has defined, '*Principles for the Management of Next Generation Networks*' [10], a key objective of which is to increase networks' autonomy to optimise performance in response to real-time dynamics and trends. While reduction of communication carbon cost is not defined explicitly as an ITU-T Management Principle, it is implied in specification of the need to meet next generation networking requirements by delivering services to, "any place, any time, and on any device, through any customer-chosen access mechanism," and assisting network operators and service providers to, "conduct their business efficiently" [10]. Solutions should subsequently be energy efficient by default in the future to meet this requirement in accordance with ITU-T objectives.

The Telecom Regulatory Authority of India (TRAI) is responsible for regulating operation of telecommunication networks in India. Sustainable services are a particular requirement of Indian networks, with the increasing roll-out of wireless technology in regions which are remote and where the terrain is harsh. Sustainability relates to energy efficiency: the financial cost to use network services for a population with lower disposable income will be less expensive if the number of bits

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[1] While this includes operation of hardware and does not necessarily refer only to network communications as is the focus of this chapter, this estimation is important to reinforce the importance of improving operational efficiency of all elements associated with the communication process, from the client device, through the access-metro-core-metro-access network to the destination.

[2] The background to the drive for energy efficient networking is explored from UK and Indian perspectives given the authors' involvement with the India-UK Advanced Technology Centre of Excellence in Next Generation Networks, Systems and Services at the University of Ulster.

associated with each transmission are reduced, and operators can provide lower cost services with reduced consumption of network resources.

1.2. The Challenge of Next Generation Networks

Next Generation Networks pose a challenge in the provision of energy efficient solutions given their transportation of data with a range of QoS requirements and tolerance of lower than optimum services. Applications which may be transmitted across NGNs include those:

1. with real-time interactivity requirements and ability to accommodate slight loss (e.g., voice);
2. with real-time interactive requirements and inability to cope with loss (e.g., online multiplayer games);
3. without real-time requirements but which cannot cope with any loss (e.g., file transfer); and,
4. without real-time requirements and ability to cope with slight loss (e.g., video download).

Energy efficient communication capabilities need to therefore support these varying QoS requirements. Furthermore, next generation networks use a range of carrier types to support the diverse range of application types, with traffic potentially traversing multiple technologies on the path between source and destination. A transmission between communicating end-points may, for example, travel between nodes connected using wired links in the data centre or network core, or across wireless links to a mobile device. QoS need therefore be supported in and redefined for environments with different levels of ability to support application requirements.

These characteristics of NGNs drive the way in which energy efficient networking solutions should be provisioned – where network intelligence occurs autonomously in response to real-time dynamics, context should be collected to drive the energy efficiency process, and assert appropriate actions in each network type and in response to the nature and requirements of the transmission being sent. Next generation green networking solutions therefore need to take into account the characteristics of client devices, networks, and applications, the configurations possible for each, level of service commonly achieved across each network portion, and ability to support application QoS requirements to optimise efficiency of operation, level of service achieved and diversity of solutions applied.

1.3. Benefits of Energy Efficient Networks

Energy efficiency strategies are subsequently being developed for use in next generation networks, and energy constraints and efficiency objectives of telecommunication operation influence the management strategies deployed. When power-saving is applied in a notebook computer, for example, the display screen backlight dims as part of a battery conservation technique. When power saving is applied in a wireless sensor network on the other hand, an intermediary node may have functionality to ‘shut-down’ so that only limited probe packets are distributed to determine its need to ‘awaken’ and become partially or fully functional. A selection of domains, illustrated in Figure 1, for which energy efficiency is a limiting force on operational ability (e.g., delay-tolerant networks), from which environmental concerns though the volume of emissions arise (e.g., data centres) and for which intelligent energy management is important (e.g., mobile devices) are considered by the authors in the provision of green networking solutions. In the case of smart homes, for example, intelligent energy management is becoming important due to the desire for ‘always-available’ services and range of devices which may be networked using the Internet Protocol. The QoS achievable will be higher when devices are available in an on-demand fashion; as a result, users may therefore be more likely to leave devices powered on (at least in standby mode) and disable low power options for convenience, presenting an opportunity for intelligent and autonomous management of devices to improve

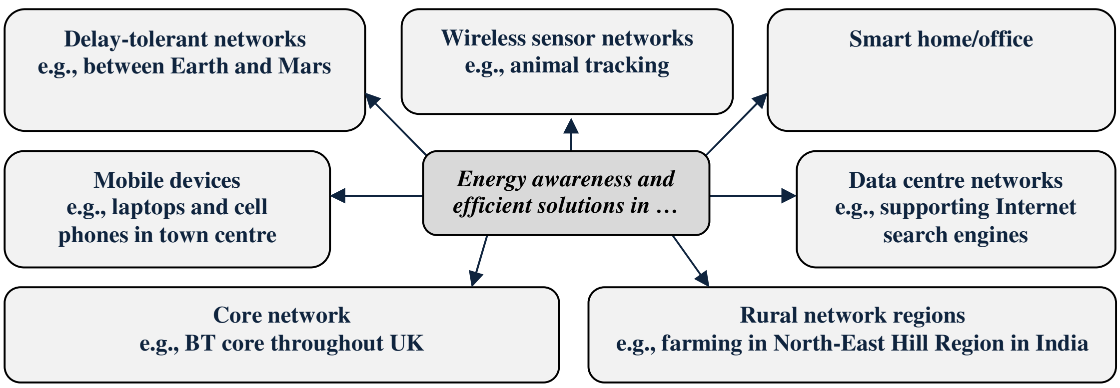

Figure 1 Domains with energy efficiency network requirements for improved sustainability and reduced cost

efficiency[3]. In a data centre on the other hand, environmental issues arise due to the volume of devices in plants which are ready to service client requests and the associated plant management costs (including lighting and air-conditioning) incurred while maintaining a suitable operating environment. Energy efficient networking is also important in rural farming regions [11]; wireless solutions are more easily deployed and less costly to roll-out in these regions. Efficient use of wireless resources helps to maximise the network's lifetime and operational ability, farmer utility received from the network and satisfaction with services provided. Drivers for improving energy efficiency within different operating environments therefore vary, while the priority and desire to reduce carbon emission remains constant between each.

1.4. Objectives of Green Networking

Across the range of domains, objectives of green network communication and management solutions include:

- Minimising the carbon footprint of delivery networks;
- Improving operational sustainability in wireless networks;
- Minimising the financial cost for operators to transmit;
- Allowing application QoS to be achieved within network resource constraints;
- Reducing load on the network and hence per transaction power consumption;
- Removal of the digital divide between urban and rural areas; and,
- Contributing to industrial standards.

Regardless of having improved sustainability, the overall requirement of green IT across domains is to decrease the number of bits per transmission so that energy demands are curtailed, power cost lowered and carbon emissions reduced. Energy efficiency objectives from this point of view therefore involves reduction of power consumption in wired networks, and in wireless networks also includes maximisation of operational sustainability. The contrasting requirements of efficiency in two exemplar domains, the data centre and wireless sensor network, are compared: in wireless sensor networks, node power resources are constrained: a study by Sensys Networks in 2007 identified that average battery lifetime is between 23 and 35 days [12]. Objectives in this scenario therefore prioritise sustainability to maximise the network's operational lifetime. In data centre networks on the other hand, there is a high degree of redundancy to minimise response time and maximise performance when responding to client requests. The carbon cost per square metre is however high, with projected server power densities of 20,000 Watts/m^2 [13]. Minimising energy consumption in this environment is therefore a core objective of next generation network equipment. Sustainability and cost reduction requirements are approached with equal importance in the development of green networking solutions, both being a consequence of more efficient operation. In improving the efficiency with which communications occur, cost per transmission will be reduced and sustainability improved.

1.5. Core Components in Green Networking Technology

To achieve sustainable and lower cost services through green technology, networks require two core capabilities (Figure 2): energy awareness and energy efficiency. Energy awareness refers to the network's ability to quantify energy cost per packet, and identify if power constraints are becoming a limiting force on ability to operate or carbon emissions are increasing above a threshold. Energy efficiency describes the network's ability to reduce carbon contributions from those incurred prior to the application of energy efficiency and extend the network's lifetime while maintaining QoS.

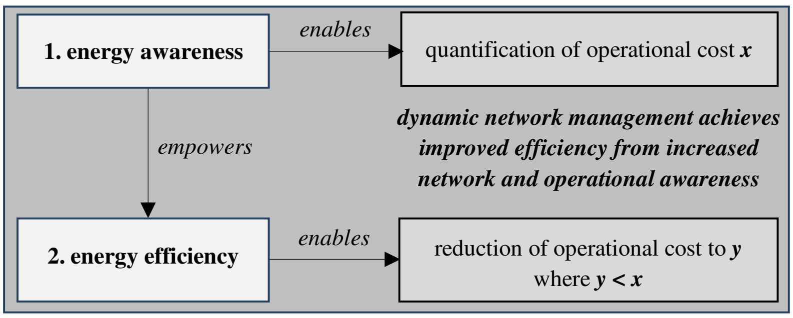

Figure 2. Components of Next Generation Green Networks

[3] While existing in a standby mode results in improved operational power efficiency, the International Energy Agency (IEA) has estimated that the standby mode of operation could be resulting in 1 per cent of world greenhouse gas emissions [Source: Climate Neutral Network, Information and Communication Technologies; Available at: www.unep.org/].

Energy awareness empowers networks with capabilities, absent previously, for efficiency objectives. Empowering this ability enables reorganisation of the way in which communication occurs, including the operations at each stack layer and management function in general. Network communication protocol standards traditionally focus on achievement of reliability for applications with stricter QoS requirements or a faster response time for those without. Mechanisms for improved efficiency should however be incorporated in a cross-layer approach in Next Generation Green Networks (NGGN) such that these objectives may continue to be achieved in parallel with optimised operation.

2. Objectives of Green Network Protocols

In empowering the network with energy awareness and efficiency ability, it is necessary to understand protocol overhead in terms of mandatory fields in packet headers and control packets currently used to manage transmissions. The objective of this section is therefore to gain an appreciation for the way in which protocols may be optimised while application QoS is maintained, and to understand mandatory content carried within protocol headers. This leads to identification of ways in which protocols may be optimised such that their degree of reliability is maintained while the number of bits associated with each, the cost of which to transmit may be incurred during any transaction, is reduced and hence energy efficiency improved.

2.1. Energy-optimising Protocol Design

Network efficiency can be enhanced by the design of protocols used. Reducing the number of bits associated with a transmission and minimising network load will optimise communication efficiency. Where fewer bits are transmitted, less processing operation will be required at nodes, fewer finite power resources will be consumed during transmission, less carbon emitted, less congestion in the network, fewer retransmissions and an overall more optimised process. From the point of view of network protocols, the number of bits involved can be reduced by:[4] 1) minimising the number of overhead packets per protocol, 2) minimising the number of mandatory bits per protocol, 3) minimising retransmission attempts, and 4) maximising the number of successful data packets sent. These four objectives of optimisation are as follows:

Objective 1: minimising the number of overhead packets *O* per protocol:

$$\underset{n \in N^{*(i,j;G)}}{minimise} \quad O \tag{1}$$

where O represents the number of overhead packets associated with a transmission, pushed from each node n where $n \in N^{*(i,j;G)}$ is the set of all nodes traversed across sub-links on path (i,j) between source and destination devices in network G. Overhead in this case refers to control and management packets transmitted across the network in support of the protocol design. In the case of the Ad hoc On-Demand Distance Vector (AODV) protocol [14], for example, a broadcast packet is sent when a connection between nodes which wish to communicate is needed. Intermediary nodes forward the message towards the destination; when the message is received at a node with a route to the destination, it communicates this detail with the source node, which subsequently begins to use the route. In minimising the number of overhead packets used to support protocol operation, optimisation in power requirements can be achieved.

Objective 2: minimising the number of mandatory *M* bits per protocol:

$$\underset{n \in N^{*(i,j;G)}}{minimise} \quad M \tag{2}$$

where M is the number of mandatory bits associated with a protocol for packets pushed from each node n using the protocol where $n \in N^{*(i,j;G)}$ is the set of all nodes traversed across sub-links on path (i,j) between source and destination devices in network G. Mandatory bits include those transmitted alongside application data in packets encapsulated at each stack layer. (For more detail on mandatory bits applied in encapsulated packets for a selection of protocols, see Section 2.2.) In minimising the number of mandatory bits associated with a protocol, fewer resources will be required to support packet transportation, leading to an overall more optimised, and subsequently efficient, communication.

In parallel with optimising the number of bits associated with a network transaction, sufficient detail and capability should be maintained such that operational performance is achieved. Further objectives in the design of energy efficient protocols therefore include:

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[4] To set the context for which protocol costs are being considered: A network can be considered as a graph G=V(E) composed of V:=V(G) nodes and E:=E(G) links. A path p between communicating end points is composed of one or more sub-paths $(v,i)(i,j),\ldots(k,h)$ between a source v and destination h. Path $p_{i,j}$ represents all sub-links of this path, connected by intermediary nodes. The transmission will pass through zero or more intermediary nodes n while traversing sub-links on the end-to-end path (i,j).

Objective 3: minimising retransmission attempts *R*:

$$\underset{n\in N^{*(i,j;G)}}{minimise} \; R \tag{3}$$

where R is the number of retransmission attempts associated with a transmission pushed from each node n where $n \in N^{*(i,j;G)}$ is the set of all nodes traversed across sub-links on path (i,j) between source and destination devices in network G. Retransmissions refer to data packets sent more than once through the network when reliable protocol mechanisms have been applied in the instance that application packets have been lost or received incorrectly. One or more retransmissions may be sent in response.

Objective 4: maximising the number of successful data packet sends *S*:

$$\underset{n\in N^{*(i,j;G)}}{maximise} \; S \tag{4}$$

where S is the number of packets sent successfully from each node n where $n \in N^{*(i,j;G)}$ is the set of all nodes traversed across sub-links on the end-to-end path (i,j) within network G.

Objectives 1 and 2 can be influenced by protocol design. Network costs in general, are calculated as a function of the traffic volume passing across links, nodes, and client devices. This volume varies in relation to the number of active ports at nodes on the end-to-end path, residual node memory resources, reliability mechanisms associated with protocols carrying traffic through nodes and overhead required to enable the protocol to achieve its control and management function. Ideally, the objectives defined in equations (1) to (4) will be achieved simultaneously. This requirements set presents a *constrained optimisation challenge* however, due to attempts to achieve minimisation across competing parameters simultaneously. Minimising the volume of protocol overhead (using approaches defined in equations (1) and (2)), may impact the number of successful data packet sends and subsequent number of retransmissions. It will therefore not be possible to achieve minimisation and maximisation of all characteristics as outlined in equations (1) to (4). Due to this constrained optimisation challenge, objectives defined in equations (1) and (2) should therefore be prioritised in the design of a protocol optimised for energy purposes while objectives defined in equations (3) and (4) are maintained at least above a threshold.

2.2. Bit Costs associated with Network Communication Protocols

Reducing the overhead costs associated with protocols will improve their energy efficiency. Minimum costs of network protocols and typical overhead volumes associated with packets sent using each protocol are therefore explored in this section to highlight the network resources required for protocols to operate and lead to optimisation of their design through identification of inefficiencies.

1. Internet Protocol v4 (IP) cost

Mandatory bits included in Internet Protocol (IP) packet headers according to Request for Comments (RFC) 791 [15] are shown in Table 1. Application data is appended to this IP control information, with the volume of data being 1<>MTU, restricted by the Maximum Transmission Unit (MTU) of the link to which the node is attached. Additional field options may be appended to IP packets on a transmission-specific basis to supplement the information available, as shown in Table 2.

Table 1. IPv4 packet header format

Field	**Number of bits**
Version	4
Internet Header Length	4
Type of Service	8
ID	16
Flag	3
Fragment Offset	13
Time to Live	8
Protocol	8
Checksum	16
Source Address	32
Destination Address	32
Options	*variable* (zero or more options)
Padding	*variable*

Table 2 Optional IPv4 packet header fields

Optional IP Packet field	**Number of bits**
End of Option List	-
No Operation	-
Security	16
Compartments	16
Handling Restrictions	16
Transmission Control Code	24
Loose Source and Record Route	*variable*
Strict Source and Record Route	*variable*
Record Route	*variable*
Stream Identifier	4
Internet Timestamp	*variable*

The overall minimum cost of IP packets is therefore the sum of those in Table 1, and will be incurred by all packets on the end-to-end path passed between communicating nodes. IP modules implement the Internet Control Message Protocol (ICMP) defined in Request for Comments 792 [16] and ICMP messages are sent using the IP packet header (with an IP header Protocol field value of 1). ICMP reports problems with IP packet processing and can therefore send a range of error-reporting packets. This includes a Destination Unreachable Message (packet type 3), with fields included shown in Table 3:

Table 3. ICMPv4 Destination Unreachable Message packet header format

Field	**Number of bits**
Type	8
Code	8
Checksum	16
Internet Header + 64 bits of Original Data Datagram	64

Other ICMP packet types include: Time Exceeded Message (type 11), Parameter Problem Message (type 12), Source Quench Message (type 4), Redirect Message (type 5), Echo (type 8) or Echo Reply Message (type 0), Timestamp (type 13) or Timestamp Reply Message (type 14), and Information Request (type 15) or Information Reply Message (type 16). The sizes of each of these packets are constant, with the code and type field varying as a function of the message type. Taking into account the packet header structure used by IPv4 and ICMPv4 protocols, *there is a minimum of 144 bits in an IPv4 packet before application traffic is encapsulated and 96 bits in an ICMPv4 packet.*

While IPv4 continues to be the most widely-used version of the Internet Protocol, IPv6 [17] is used to support the rapid growth in the number of Internet users. In addition, IPv6 demonstrates a greater level of efficiency in its design, with the header fields restricted to those shown in Table 4:

Table 4. IPv6 packet header format

Field	**Number of bits**
Version	4
Traffic Class	8
Flow Label	20
Payload Length	16
Next Header	8
Hop Limit	8
Source Address	128
Destination Address	128

IPv6 supports flexibility in its operation through use of an Options header (which contains the fields: Option Type (8 bits), Option Data Length (8 bits), and Option Data (variable)). Option types include those which are read on a hop-by-hop manner and those read at the destination node only (both containing the fields Next Header (8 bits), Header Extension Length (8 bits) and Options (variable)). ICMPv6 [18] also demonstrates improved efficiency. Packets are divided into error and informational messages: the number of error messages is reduced from those provisioned in ICMPv4, and include only: Destination Unreachable (type 1), Packet Too Big (type 2), Time Exceeded (type 3), and Parameter Problem (type 4) packets. Fields included within the Destination Unreachable packet, for example, include those used by ICMPv4. It is therefore through reduction in the number of packets used which improves its operational efficiency. With all header fields being mandatory, *there is therefore a minimum of 320 bits in an IPv6 packet before application traffic is encapsulated and 96 bits in an ICMPv6 packet*.

While IP is the common protocol used across all Internet communication, a selection of others, with their costs explored below, may be applied at the other stack layers:

2. Routing Information Protocol (RIP) cost

At the network layer, mandatory fields associated with packets transmitted using the Routing Information Protocol (RIP) according to Request for Comments 2453 [19] include: Command (8 bits), Version (8 bits), and RIP Entry (between 1 and 25 entries). The RIP Entry is composed of the following fields: Address Family Identifier (16 bits), Route Tag (16 bits), IPv4 Address (32 bits), Subnet Mask (32 bits), Next Hop (32 bits) and Metric (32 bits). With each attribute being mandatory in all packets and the RIP Entry of variable length (with the potential of an array of information), *there is a minimum of 176 bits of overhead in RIP packets.*

3. AODV

The routing protocol AODV [14] supports a number of packet types, which include the Route Request, Route Reply, Route Error and Route Reply Acknowledgement. With regard to the Route Request message as an example, packet fields include: Type (8 bits), Flags including Join, Repair, Gratuitous Route Reply (RREP), Destination Only, and Unknown Sequence Number (all 1 bit), Reserved (11 bits), Hop Count (8 bits), Route Request (RREQ) ID (32 bits), Destination IP Address (32 bits), Destination Sequence Number (32 bits), Originator IP Address (32 bits), Originator Sequence Number (32 bits). With all attributes being mandatory in each packet, *there is therefore 192 bits of overhead in the AODV Route Request message.*

4. User Datagram Protocol (UDP) cost

At the transport layer of the stack, mandatory fields of User Datagram Protocol (UDP) packets according to Request for Comments 768 [20] include: the Source Address (16 bits), Destination Address (16 bits), Length (16 bits), and Checksum (16 bits). The volume of application data appended to each packet is controlled by the MTU of the link to which the node is attached. As each attribute is included in all packets transmitted using UDP, *there is therefore 64 bits of overhead in UDP packets prior to the encapsulation of application data.*

5. Transmission Control Protocol (TCP) cost

Mandatory bits associated with Transmission Control Protocol (TCP) packets according to Request for Comments 793 [21] include: the Source Port (16 bits), Destination Port (16 bits), Sequence Number (32 bits), Acknowledgement Number (32 bits), Data Offset (4 bits), Reserved (6 bits), Control (6 bits), Window (16 bits), Checksum (16 bits), Urgent Pointer (16 bits), and the variable-sized fields Options and Padding. As in the case of the IP and UDP protocols, the volume of application data appended to each packet is controlled by the MTU of the link to which the node is attached. With the header fields included in all packets transmitted using TCP, *there is therefore a minimum of 160 bits in TCP packet headers prior to encapsulation of application data.*

6. RTP

The Real-Time Protocol (RTP) packet header according to Request for Comments 3550 [22] contains the fields: Version (2 bits), Padding (1 bit), Extension (1 bit), Contributing source (CSRC) Count (4 bits), Marker (1 bit), Payload Type (7 bits), Sequence Number (16 bits), Timestamp (32 bits), Synchronisation source identifier (32 bits) and Contributing Source Identifier (0-15 items, 32 bits each). With each attribute being used in all RTP packets, *there is therefore a minimum of 96 bits in RTP packets prior to the encapsulation of application data.*

2.3. Objectives of Green Network Protocols

Through exploring the range of header fields in a selection of commonly-used protocols at different stack layers, potential opportunities to improve their efficiency have been identified. In the development of green network protocols, objectives therefore include:

1. Improving utilisation of cross-layer detail between protocols unpacked at different stack layers;
2. Minimising or eliminating redundancy in header detail; and,
3. Optimising the protocols in their design through removal of support for older versions.

A cross-layer approach promises the greatest improvements in energy efficiency [23], allowing problems and/or inefficiencies at each layer to be tackled in a consistent manner. When a protocol header is adapted cross-layer compatibility will ensure that any attributes removed are not needed at other layers. Similarly, attributes incorporated for improved energy intelligence should be utilised at a maximum number of layers for optimum efficiency.

To improve their efficiency, these objectives are applied to protocols evaluated in Section 2.2 as follows:

Meeting Objective 1

- Header detail may be better re-used between stack layers in the case of the Internet Protocol. The *Time to Live* (*TTL*) field is applied by the Internet Protocol but not by other routing protocols, demonstrating possible cross-layer reliance on use of this protocol standard in all network communications. On the other hand, the *Time to Live* (*ToS*) field is included in the IPv4 header and also in the RSVP header, for example. As the network layer is traversed at each node, the attribute need therefore not be included in all headers but only in those used lower in the stack, and appended when being unpacked at the previous header layer.

Meeting Objective 2

- Inclusion of the *ToS* field in the IP header may be considered unnecessary at this layer. It describes the packet's precedence, acceptable delay, volume of throughput and degree of reliability required. This detail may instead be gleaned from the *TTL* attribute which is also included in the header by default in an approach optimised for energy efficiency. On the other hand, the *TTL* can be captured from the *ToS* field and it need not be appended to the header instead. The nature of detail retained in these fields means that only one, and not both, attributes are needed.
- The need to include *Source and Destination Addresses* in a range of packet headers used at different stack layers may also be questioned. Source and destination addresses are included, for example, in MAC, IP, AODV, UDP, TCP and SNMP packet headers, for example. Optimised UDP may however, omit source and destination addresses from the packet header. This detail will be carried by the routing protocol and need therefore not also be replicated at the transport layer.
- The inclusion of a *Checksum* within each protocol header can also be reconsidered for improved efficiency. Determined on an application-specific basis, it may be possible to optimise the inclusion of a checksum in all protocol headers, particularly in the case where the application can cope with a small degree of error, for the objective of optimising communication energy efficiency.
- There may be redundancy in the header fields provisioned for IPv6. The *Hop Limit* field, for example, may be replaceable with the *Traffic Class* field only. The traffic class field can be used to indicate the acceptable delay associated with a packet stream (traffic classes remain undefined in RFC 2460), thereby removing the need to include both fields in the packet header.
- In the case of ICMPv6, there may be an opportunity to reduce the amount of redundancy associated with the protocol: while there are fewer error message types used by this protocol in relation to those used by ICMPv4, it may be possible to restrict the range of error codes. With regard to the Destination Unreachable message, for example, there are seven optional error codes for reasons why the destination is unreachable. Three of these may however, not be needed, including the options 'Beyond scope of source address', 'Address unreachable', and 'Reject route to destination', which could instead be replaced with the single error code, 'No Route to Destination'.

Meeting Objective 3

- With regard to provision for support of updated versions of the protocol, this is the case with the Internet Group Management Protocol (IGMP) Version 3 defined in RFC 3376 [24] which also supports packet types associated with older versions of the protocol.

3. Green Network Protocols and Standards

Minimum costs associated with a selection of network protocols incurred through their encapsulation of application data with mandatory header detail was explored in Section 2. The management function of protocols represents overhead in the sense that all packets sent do not contain application traffic and all data in packets is not application traffic. As they are additional expenses incurred during network communications, they represent potential avenues where optimisation may be achieved. This section therefore acts as a bridge between identification of protocol cost and approaches proposed by the authors to provision green networking solutions, and involves discussion of state-of-the-art in green communication protocols and operational management. Through exploration in this section, the current research gap with regard to energy efficient networking standards can be defined.

3.1. Strategies to Reduce Carbon Emissions

The Business for Social Responsibility (BSR) suggests strategies to reduce carbon emissions at all stages of the business life cycle in general, from product manufacture to distribution [25]. They suggest that carbon reductions are achievable by:

1. Enabling cleaner sourcing/manufacturing;
2. Lowering emissions in transit;
3. Enabling cleaner warehouse operations;

4. Reducing transit distances;
5. Removing nodes/legs;
6. Reducing total volume and/or mass shipped;
7. Consolidating movements;
8. Contributing to reductions elsewhere; and,
9. Increasing recycling/re-use.

These techniques to reduce carbon emissions are not specific to telecommunication networks and consider carbon emitted during physical transportation of resources, development and production costs, and on site day-to-day operation. While applied generically across businesses irrespective of their domain, we relate these to NGGN state-of-the-art strategies to demonstrate their versatility with regard to reducing carbon emissions in general, with processes involved during the communication of data having the same (albeit scaled-down) energy-associated impact.

3.2. Contributions from the EMAN Working Group

The Energy Management (EMAN) Working Group is involved in conversion of 'work in progress' Internet Drafts (their primary contributions are summarised in Table 5) into formal Request for Comments (RFC) documents. In general, these drafts define Management Information Base (MIB) structures designed to empower networks with energy awareness such that efficiency may be achieved. In '*MIB for Energy, Efficiency, Throughput and Carbon*' [26], for example, calculation of carbon emissions includes energy consumption, operational efficiency and utilisation of each device attributes. Detail in '*Requirements for Power Monitoring*' [30] supplements that in [26] by defining requirements to perform energy calculations. This involves ensuring that all network components are monitored and that attributes collected include the current state and time spent in each state, total energy consumed at a device and since the last monitoring interval, and current battery charge, age, state, and time when last used. The '*Energy Monitoring MIB*' collects attribute details which include power cost per packet, duration of power demand intervals and maximum demand in a window [28].This Internet Draft also considers compliance with MIB monitoring processes, with support for both reading and writing context from and to MIBs. Modes of improved operational efficiency are also suggested in this standard and twelve power states may be applied to nodes in response to collected context. When related to the BSR's principles, these strategies can be compared to enabling cleaner warehouse operations by improving understanding of the real-time environment and enforcing timely and appropriate actions to it.

Table 5. Contributions of 'work in progress' Internet Drafts

'Work in Progress' Internet Draft	Contribution
MIB for Energy, Efficiency, Throughput, and Carbon Emission [26]	Defines MIB attributes required to calculate the carbon emission of network elements, with attributes including power consumed while performing packet throughput when idle, when operating with full power, and to operate with half power.
Definition of Managed Objects for Energy Management [27]	Defines MIB structures required to appreciate the energy characteristics associated with network transactions, including a Power State MIB, Energy MIB, and Battery MIB.
Energy Monitoring MIB [28]	Defines a number of non-operational and operational states which nodes can exist in to optimise energy efficiency, including standby, ready, reduced power, and full power modes.
Benchmarking Power Usage of Networking Devices [29]	Defines a power usage calculation for network devices, with attributes including the number of active ports and their utilisation.
Requirements for Power Monitoring [30]	Defines requirements when calculating the energy consumption cost of network devices, which includes consideration for monitoring granularity and information required (state, state duration, and power source).

3.3. Contributions from Standardisation Bodies

The European Telecommunications Standards Institute (ETSI) Environmental Engineering group defines techniques to monitor and control telecommunication infrastructure in response to collected context and pre-defined alarm conditions. Their drafts therefore define alarms, events and measurements necessary to provide the level of management required. In [31], '*AC Monitoring Diesel Back-Up System Control and Monitoring Information Model*,' for example, the minimum range of events which should be monitored on a back-up generator are defined, with alarms being raised if an undefined stop, start failure, fuel leakage or battery charger failure occurs. In [32], the monitored attributes of a DC power system control are defined. Alarms are raised when conditions include testing for battery failure, battery over-temperature and low voltage output. These drafts further highlight the range of context which must be collected on an application-specific approach and the tailoring of alarms in relation to the domain in which management is applied. When compared to the BSR's strategies, integration of alarms such as those proposed by ETSI relate to lowering emissions in transit by suspending operations when environment conditions are insufficient to support it.

The IEEE 802.3 Study Group on Energy Efficient Ethernet (EEE) is actively involved in reduction of power required to operate Ethernet technology. Primary contributions in the IEEE Standard 802.3az include a low power state for activation during idle periods and times of low utilisation (Low Power Idle (LPI)). This mode is applied in relation to link status and observed traffic flow. The standard also includes an alert signal which can be used to awaken those connections which have been sent to the sleep state when data arrives for transmission across an Ethernet link. When compared to the strategies proposed by the BSR, EEE relates to consolidating movements across primary links while suspending those across links which are not used as frequently.

3.4. Context Detail to Drive Energy Efficiency

The EMAN working group has proposed MIB structures specific to the challenge of improved communication efficiency; ETSI defines alarms and measurements to control operation of power systems; and the IEEE defines strategies to optimise the power required to operate Ethernet technology. In addition, independent researchers propose solutions for application in individual domains and/or in response to a specific operational challenge at a specific stack layer, as in [33] [34].

Table 6 Domain-specific context data required to achieve energy efficiency

Network Domain	**Context used in each domain (per node)**	**Context used in each domain (in the wider environment between client and destination devices)**
Data centre	*At an individual server within the data centre, context includes*: Server utilisation, packet arrival rate (packets/second), power consumption rate (Watts/second), job completion rate (seconds), operational state (per node and per port), processing delay (seconds), page faults (faults/page)	Bandwidth availability (bits per second), temperature (°C), power consumption rate (Watts per second), operational state of neighbours (per node and per port)
Delay-tolerant network	*At an individual spacecraft deployed in deep space, context includes*: Tilt of solar panel (degrees), propagation distance from neighbours (seconds), critical activities, temperature (°C), line of sight connectivity with neighbours (true/false), residual battery capacity (units), received signal strength (dB), operational state (per node and per port)	Wind speed (miles/hour), location of neighbours (x, y, z co-ordinates), residual battery capacity at neighbours (units), strength of signal arriving at neighbours (dB), operational state of neighbours (per node and per port), time of day, time of year, bit error rate (packets/second), bandwidth availability (bits/second)
Mobile device	*For a mobile phone or laptop, context* includes: Backlight (% brightness), residual battery capacity (units), application type of service, device type, memory capacity (bits), device critical activities, packet sending rate (packets/second), location (x, y, z co-ordinates)	Time of day (hours, minutes, seconds), bandwidth availability (bits/second), location of neighbours (x, y, z co-ordinates)
Core	*At an individual router/switch in the network core, context includes*: Throughput (bits/second), utilisation (%), operational state (per node and per port), energy cost per packet (Watts), packet processing delay (seconds), packet arrival rate (packets/second)	Bandwidth availability (bits/second), retransmission count at neighbours (packets/second), residual memory capacity at neighbours (bits), bit error rate (packets/second)
Rural region	*At an individual networked device (client device or intermediary router), context includes*: Residual battery capacity (units), location (x, y, z co-ordinates), retransmission count (packets/second), packet transmission rate (packets/second), power cost per packet (Watts/packet), packet arrival rate (packets/second)	Temperature (°C), bandwidth availability (bits/second), residual battery capacity at neighbours (units), time of day (hours, minutes, seconds)
Smart home and office	*At an individual networked device, context includes*: Use of solar panel (true/false), device critical activities, operational state (per node and per port), time spent in state, energy cost per packet (Watts), time of last node sleep (hours, minutes, seconds), sleep duration (seconds),	Bandwidth availability (bits/second), time of day (hours, minutes, seconds), location of nodes (x, y, z co-ordinates), operational state of neighbours (per node and per port)
Wireless sensor network	*At an individual sensor, context includes*: Residual battery capacity (units), node location (x, y, z co-ordinates), operational state (per node and per port), propagation distance from neighbours (metres), temperature (°C), retransmission count (packets/second), residual node memory (bits)	Temperature (°C), time of day (hours, seconds, minutes), location of neighbours (x, y, z co-ordinates), residual battery capacity at neighbours (units), residual memory capacity at neighbours (bits)

Taking into account developments in the field which provision information with regard to the nature of context required, the way in which it should be monitored, relevant evaluations and actions which may be applied, there is a research gap in that solutions have been provided in an ad hoc manner. In response to this, we have suggested that there are benefits to be achieved through application of domain–specific solutions applied to the collection and monitoring of context, evaluation and application of optimisation strategies. Referring to Figure 1 which shows a range of domains that could benefit from improved efficiency networking solutions due to a desire to improve sustainability and/or reduce operational costs due to a currently high volume of carbon emissions, the range of context which may be required in a solution applied across domains to drive the optimisation process is presented in Table 6. Context attributes are collected to drive intelligent decision-making in terms of detail required on each individual node within the domain and also across the network within the wider environment. In exploring the problem domain in this way, optimisation solutions in a range of environments which use different context and to which a range of contrasting evaluations should occur and actions can be applied are realised. Furthermore, in extension to standalone solutions identified in the literature, an integrated context-aware management solution which is cross-layer compatible across domains can also be developed (such as that proposed by the authors, the energy aware and efficient Context-Aware Broker (e-CAB) [35]), with a potential deployability and sustainability improvement in an approach similar to the TCP/IP and Open Systems Interconnection (OSI) protocol stacks upon which the Internet's success to date has been built.

Conclusion

Energy efficient networking is explored in this chapter from the perspectives of reducing the energy cost to communicate, and improving device sustainability when operation is supported by finite-resource technology. These requirements are approached with equal priority in the development of energy efficient network solutions, allowing improved efficiency to be achieved for both wired and wireless communications. Exploration from this perspective takes into account the range of domains in which energy efficient networking solutions can be applied to improve performance in terms of both application Quality of Service and user Quality of Experience. Energy efficient networking solutions are explored in this chapter from the perspective of reduced carbon cost and improved operational sustainability.

Green network protocols transmit fewer bits than standard default protocols developed with reliability as opposed to energy efficiency as core operational objectives. Green networking includes selection of least cost paths in terms of node number queuing delay, carbon and financial cost, maximisation of node and link resources and use of optimised protocols. We have described the energy efficient design that includes optimisation of the number of overhead packets which control protocol operation and the number of mandatory management bits associated with each packet sent using the protocol.

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Further reading & Useful websites

- Bureau of Energy Efficiency: www.bee-india.nic.in
- Energy Management Working Group mailing list: eman@ietf.org
- European Telecommunications Standards Institute (ETSI) Environmental Engineering: http://www.etsi.org/WebSite/technologies/EnvironmentalAspects.aspx
- IEEE P802.3az Energy Efficient Ethernet Task Force: grouper.ieee.org/groups/802/3/az/public/index.html
- International Telecommunication Union Telecommunication Standardisation Sector (ITU-T): www.itu.int/ITU-T/

- The Office of Communications: www.ofcom.org.uk
- Telecom Regulatory Authority of India (TRAI): www.trai.gov.in/

Review questions

1. Why do Next Generation Networks make the need for energy efficiency more important than in network operation previously?
2. How does the drive for reduced carbon cost and improved operational sustainability relate to the common objective of energy efficient networking?
3. What are the two main strategies which can be applied to reduce the operational cost associated with network communications?
4. What is the constrained optimisation challenge which arises in response to achieving the objectives of energy efficient network communications?
5. Which are exemplar domains that can benefit from the application of energy efficient networking due to either reduced carbon cost or improved operational sustainability?
6. What are the objectives of green networking and communication which can benefit user and operator needs alike?
7. What are the outstanding research issues which remain with regard to achieving green networking and communication?
8. In the protocols evaluated in Section 2, which has the greatest number of minimum mandatory bits included in its packet header?
9. What have been the contributions from the Working Group involved in the field of Energy Management?
10. Why is energy efficient networking important in light of the increased number of renewable power plants?

Discussion questions

1. Why have energy optimising approaches to date primarily concentrated on switching nodes or ports on a node to exist in a sleep state as opposed to optimising the structure and/or operation of network communication protocols within the stack as a whole?
2. Is it too big a task to begin to reorganise the network protocol stack and design of protocols operating within it for improved energy efficiency purposes given its successful operation for forty years since the Internet was first established?
3. In what way should standards currently under review by the Energy Management Working Group be extended/supplement to provide improved energy management functionality as opposed to simply definition of MIB structures?
4. Energy management is important in delay-tolerant networks where the sustainability of expensive missions could be improved to maximise scientific discovery. Autonomic energy efficiency in this domain has, to date, not been a key research focus. Why?
5. Integration of energy modelling and enforcing efficiency practices is relatively limited in the network management software available to date. Why is this the case given the volume of research currently on-going in this field?

REFERENCES

[1] Department for Culture, Media and Sport & Department for Business, Innovation and Skills, "Digital Britain Final Report," Jun. 2009, pp. 1-245; Available [Accessed: Dec. 2011]: http://www.official-documents.gov.uk/.
[2] A. Phippa, "Who Makes IT Professionals Environmentally Aware?" *European Community in Information Technology (ERCIM) News 79*, Special Theme: Towards Green IT, Oct. 2009, pp. 16.
[3] The Climate Group, "Smart 2020: Enabling the Low Carbon Economy in the Information Age," 2008, pp. 1-87.
[4] Department of Energy & Climate Change, "The Climate Change Act 2008," 2008; Available [Accessed: Dec. 2011]: www.decc.gov.uk/.
[5] HM Government, "The UK Low Carbon Transition Plan: National Strategy for Climate and Energy," Jul. 2009, pp. 1-220; Available [Accessed: Dec. 2011]: http://www.decc.gov.uk/.
[6] Department of Energy & Climate Change, "The CRC Energy Efficiency Scheme Order 2010," 2010.

[7] HM Revenue & Customs, "Climate Change Levy"; Available [Accessed: Dec. 2011]: customs.hmrc.gov.uk/.
[8] Ministry of Power, Government of India, "The Energy Conservation Act 2001"; Available [Accessed: Dec. 2011]: www.powermin.nic.in/.
[9] International Telecommunication Union, "NGNs and Energy Efficiency, ITU-T Technology Watch Report #7," Aug. 2008.
[10] International Telecommunication Union Telecommunication Standardisation Sector, "Series M: Telecommunication Management, including TMN and Network Maintenance; Series Y: Global Information Infrastructure, Internet Protocol Aspects and Next-Generation Networks – Principles for the Management of Next Generation Networks," 2006, pp. 1-64.
[11] S. Singh, "Selected Success Stories on Agricultural Information Systems," *Asia-Pacific Association of Agricultural Research Institutions*, Sep. 2006, pp. 1-40.
[12] Sensys Networks, "Measurement of Sensys^{TM} Wireless Sensor Battery Life," 2007, pp. 1-8; Available [Accessed: Dec. 2011]: http://www.sensysnetworks.com/.
[13] R. R. Schmidt, C. Belady, A. Classen, T. Davidson, M. K. Herrlin, S. Novotny, and R. Perry, "Evolution of Data Center Environmental Guidelines," *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)*, Vol. 110, Part 1, 2004, pp. 559-566.
[14] C. Perkins, E. Belding-Royer, and S. Das, "Ad hoc On-Demand Distance Vector (AODV) Routing," Network Working Group Request for Comments 3561, Jul. 2003, pp. 1-36.
[15] J. Postel, "Internet Protocol," *Internet Engineering Task Force Request for Comments 791*, Sep. 1981.
[16] J. Postel, "Internet Control Message Protocol," *Internet Engineering Task Force Request for Comments 792*, Sep. 1981.
[17] S. Deering and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification," *Internet Engineering Task Force Request for Comments 2460*, Dec. 1998.
[18] A Conta, S. Deering, and M. Gupta, "Internet Control Message Protocol (ICMPv6) for the Internet Protocol Version 6 Specification," *Internet Engineering Task Force Request for Comments 4443*, Mar. 2006.
[19] G. Malkin, "RIP Version 2," *Internet Engineering Task Force Request for Comments 2453*, Nov. 1998.
[20] J. Postel, "User Datagram Protocol," *Internet Engineering Task Force Request for Comments 768*, Aug. 1980.
[21] J. Postel, "Transmission Control Protocol," *Internet Engineering Task Force Request for Comments 793*, Sep. 1981.
[22] H. Schulzrinne, S. Casner, R. Frederick, and V. Jacobson, "RTP: A Transport Protocol for Real-Time Applications," *Internet Engineering Task Force Request for Comments 3550*, Jul. 2003.
[23] K. Almi'ani, S. Selvakennedy, and A. Viglas, "RMC: An Energy-Aware Cross-Layer Data-Gathering Protocol for Wireless Sensor Networks," *in Proc. 22nd IEEE Int. Conf. on Advanced Information Networking and Applications*, Mar. 2008, pp. 410-417.
[24] B. Cain, S. Deering, I. Kouvelas, B. Fenner, and A. Thyagarajan, "Internet Group Management Protocol, Version 3," Network Working Group Request for Comments 3376, Oct. 2002.
[25] Business for Social Responsibility, "Value Chain Approaches to a Low Carbon Economy: Business and Policy Partnerships: A Discussion Paper for the World Business Summit on Climate Change in Copenhagen," May 2009, pp. 1-13.
[26] S. Sasidharan, KP. Bhat, and S. Shreekantaiah, "MIB for Energy, Efficiency, Throughput and Carbon Emission," *work in progress as an IETF Internet Draft*, Jan. 2010.
[27] J. Quittek, R. Winter, T. Dietz, and D. Dudkowski, "Definition of Managed Objects for Energy Management," *work in progress as an IETF Internet Draft*, Apr. 2010.
[28] B. Claise, M. Chandramouli, J. Parello, and B. Schoening, "Energy Monitoring MIB," *work in progress as an IETF Internet Draft*, Jul. 2011.
[29] V. Manral, "Benchmarking Power Usage of Networking Devices," *work in progress as an IETF Internet Draft*, Jan. 2011.
[30] J. Quittek, R. Winter, T. Ditz, B. Claise, and M. Chandramouli, "Requirements for Power Monitoring," *work in progress as an IETF Internet Draft*, Jul. 2010.
[31] European Telecommunications Standards Institute (ETSI), "Environmental Engineering (EE); Monitoring and Control Interface for Infrastructure Equipment (Power, Cooling and Building Environment Systems used in Telecommunication Networks); Part 5: AC diesel back-up generator system control and monitoring information model," *ETSI Standard ES 202 336-5 v1.1.1*, Jan. 2010, pp. 1-18.
[32] ETSI, Environmental Engineering, "Environmental Engineering (EE); Monitoring and Control Interface for Infrastructure Equipment (Power, Cooling, and Environment Systems used in telecommunication networks): Part 2: DC power system control and monitoring information model," *ETSI Standard ES 202 336-2 v1.1.1*, Mar. 2009, pp. 1-26.
[33] W. Ye, J. Heidemann and D. Estrin, "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE/ACM Transactions on Networking*, Vol. 12, No. 3, Jun. 2004, pp. 493-506.
[34] I. Rhee, A. Warrier, M. Aia, and J. Min, "Z-MAC: a Hybrid MAC for Wireless Sensor Networks," *ACM SenSys*, Nov. 2005, pp. 1-12.
[35] C. Peoples, G. Parr, and S. McClean, "Context-Aware Characterisation of Energy Consumption in Data Centres," in *Proc. 3rd IFIP/IEEE International Workshop on Management of the Future Internet*, May 2011, pp. 1250-1257.