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SERIES Y: GLOBAL INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS AND NEXT-GENERATION NETWORKS

Future networks

Measuring energy in networks

Recommendation ITU-T Y.3022

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Recommendation ITU-T Y.3022

Measuring energy in networks

Summary

Recommendation ITU-T Y.3022 describes the measurement of energy in networks and identifies the requirements for energy measurement. Based on this, a reference model, functional architecture, energy efficiency metrics and energy measurement methods are defined. To aid better understanding of energy efficiency metrics, relevant detailed equations are described in the appendices.

History

Edition	Recommendation	Approval	Study Group
1.0	ITU-T Y.3022	2013-08-13	13

Keywords

Energy efficiency metrics, energy measurement.

FOREWORD

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In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

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Recommendation ITU-T Y.3022

Measuring energy in networks

1 Scope

This Recommendation describes a reference model and methods for measuring energy in networks to reduce the operating expenditure (OPEX) of telecommunication network equipment. This Recommendation covers the following:

- requirements to measure energy consumption in networks;
- reference model and architecture to build an energy measurement framework;
- energy efficiency metrics of network elements based on a reference model;
- energy consumption measurement methods based on functional architecture.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.8013] Recommendation ITU-T G.8013/Y.1731 (2011), *OAM functions and mechanisms for Ethernet based networks*.

[ITU-T L.1310] Recommendation ITU-T L.1310 (2012), *Energy efficiency metrics and measurement methods for telecommunication equipment*.

[ITU-T X.805] Recommendation ITU-T X.805 (2003), *Security architecture for systems providing end-to-end communications*.

[ITU-T Y.2701] Recommendation ITU-T Y.2701 (2007), *Security requirements for NGN release 1*.

[ITU-T Y.3021] Recommendation ITU-T Y.3021 (2012), *Framework of energy saving for future networks*.

[ATIS-0600015.03.2009] ATIS-0600015.03.2009, *Energy Efficiency for Telecommunications Equipment: Methodology for Measurement and Reporting for Router and Ethernet Switch Products*.

[ETSI ES 203 215] ETSI ES 203 215 V1.2.1 (2011), *Environmental Engineering (EE) Measurement Methods and Limits for Power Consumption in Broadband Telecommunication Networks Equipment*.

[ETSI TS 102 706] ETSI TS 102 706 V1.2.1 (2011), *Environmental Engineering (EE); Measurement method for energy efficiency of wireless access network equipment*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 network energy efficiency [ITU-T Y.3021]: Throughput of the network divided by the power consumed.

NOTE – It is usually expressed in bps/W.

3.1.2 energy efficiency metrics [ITU-T L.1310]: Ratio between the functional unit and the energy necessary to deliver the functional unit.

NOTE 1 – Functional unit is the amount of information transmitted.

NOTE 2 – It is usually expressed in bits/Joule.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 network energy profile: Energy consumption of network elements versus offered traffic load.

NOTE – Network elements include interfaces, nodes and servers in a network.

3.2.2 power efficiency metrics: Throughput per power calculated by network energy profile.

NOTE – It is usually expressed in bps/W.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AC	Alternating Current
CDMA	Code Division Multiple Access
CPU	Central Processing Unit
DC	Direct Current
FFT	Fast Fourier Transform
GSM	Global System for Mobile communications
HPA	High Power Amplifier
ICT	Information and Communications Technology
IDC	Internet Data Centre
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
LNA	Low Noise Amplifier
LTE	Long-Term Evolution
MSPP	Multi-Service Provisioning Platform
OAM	Operation, Administration and Maintenance
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	Operating Expenditure

OXC	Optical Cross-Connect
PC	Personal Computer
PON	Passive Optical Network
RF	Radio Frequency
RLDRAN	Reduced-Latency Dynamic Random access memory
RN	Remote Node
RRH	Remote Radio Head
RSOA	Reflective Semiconductor Optical Amplifier
TCAM	Ternary Content-Addressable Memory
TDM	Time Division Multiplexing
TDM-PON	Time Division Multiplexing – Passive Optical Network
UMTS	Universal Mobile Telecommunications System
WDM-PON	Wavelength Division Multiplexing – Passive Optical Network

5 Conventions

In this Recommendation:

The keyword "**is recommended**" indicates a requirement which is recommended but which is not absolutely required. Thus, this requirement need not be present to claim conformance.

6 Overview of measuring energy consumption in networks

In response to the demands imposed by climate change, telecommunication networks should reduce energy consumption by utilizing energy saving technologies [ITU-T Y.3021]. When considering network energy consumption, network energy efficiency is an important factor. In order to calculate network energy efficiency, the total of transmitted data bits is divided by the energy consumption of the network over a specific time period. The network energy efficiency is measured and then calculated at interfaces, nodes, servers and networks as follows:

- **Energy measurement at interfaces**: The interface is the module of network equipment that enables communication via various mediums such as copper, optical fibres and air. The measurement of the energy consumption of interfaces is affected by various conditions including traffic load, interface state and packet size.
- **Energy measurement in nodes**: Nodes operate as switches or routers to exchange data in a network. Energy measurement at the node includes energy measurement at the interfaces and at the non-interfaces. The power consumption at non-interfaces such as fans, central processing units (CPUs) and alternating current (AC) to direct current (DC) converters is generally included in the measurement of energy consumption at the nodes. Depending on the power consumption of the non-interface elements within the node, energy consumption of the node varies according to the manufacturer's product characteristics.

  NOTE 1 – Routers equipped with different AC-DC power supply converters can cause the power consumption at the node to vary.

  NOTE 2 – For example, the clock rate of a CPU can be controlled at a lower traffic condition to save energy [ITU-T Y.3021].
- **Energy measurement at servers**: The energy consumption at a server is affected by equipment density and inter-operating relationships. In an Internet data centre (IDC), there are generally numerous air conditioners and dehumidifiers that enable large numbers of

servers to operate normally. These external devices operating next to servers and controlling temperature and humidity indirectly induce additional energy consumption in networks. Energy measurement at the server takes into account both energy consumption from the network equipment such as personal computer (PC)-type or rack-type servers and the non-network equipment such as air conditioners or humidifiers. The energy measurement for network equipment at the server considers processing power required to generate service traffic as well as the server interfaces.

- **Energy measurement at the network**: A network is comprised of sets of nodes and servers with interfaces. Energy measurement for networks includes the energy consumption of nodes and servers with interfaces and non-network equipment.

7 Requirements for measuring energy consumption in networks

The following are high-level requirements for network energy consumption measurement:

- It is recommended for network energy consumption measurement to measure energy consumption according to traffic load, which is dependent on interface, node and server states.
- It is recommended for network energy consumption measurement to include external devices such as air-conditioning devices operating next to network equipment as sources of energy consumption.
- It is recommended for network energy consumption measurement to include measurement time and packet size with protocols in [b-IETF RFC 1944].
- It is recommended for network energy consumption measurement to include the effects of the load distribution of routing protocols which significantly impact energy consumption.
- It is recommended for network energy consumption measurement to use all measurement functional entities to gather information on all nodes and servers in the network.
- It is recommended for network energy consumption measurement to store and manage information related to network energy profiles in a database.
- It is recommended that network energy consumption measurement be done several times in order to reduce tolerance.

8 Reference model and functional architecture for network energy consumption measurement

8.1 Reference model for network energy consumption measurement

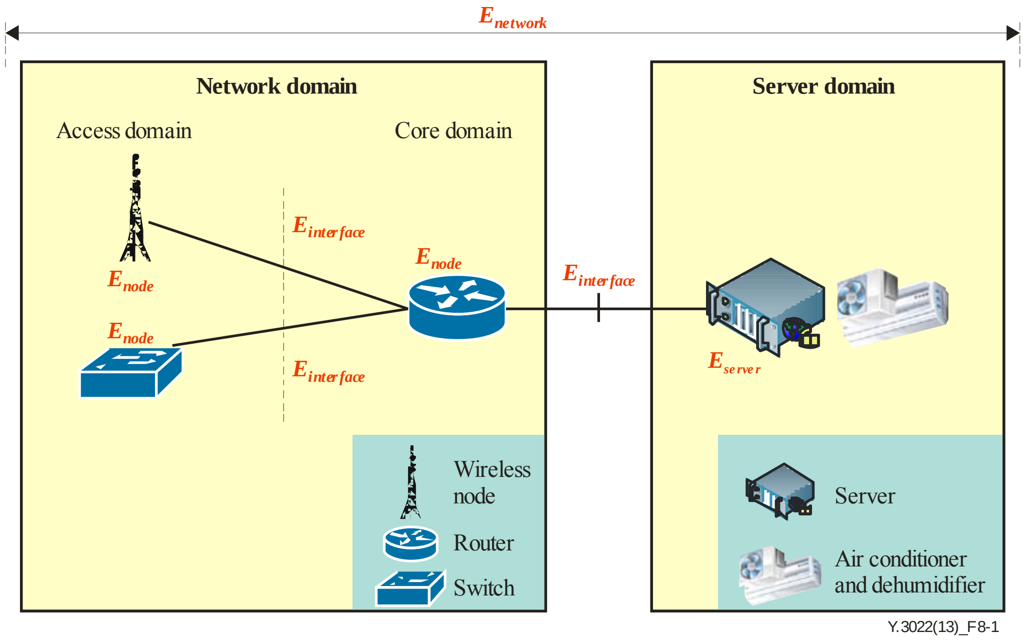

Figure 8-1 – Reference model for measuring energy consumption in networks

The reference model for network energy consumption measurement consists of the network domain and the server domain as shown in Figure 8-1.

The network domain has various nodes (e.g., a switch, a router and a wireless node) in the access domain and core domain. The nodes communicate with each other via wireless and wired interfaces. The server domain includes a number of servers and the non-network equipment. In order to measure the energy consumption of networks, it is important to be aware of network and system configurations, traffic loads of nodes and the number of interfaces both in the network domain and the server domain.

In the network domain, the energy consumption of the interface ($E_{interface}$) and the energy consumption of the node (E_{node}) are measured and calculated from their network energy profiles and traffic loads.

In the server domain, the energy consumption of the server (E_{server}) is measured and calculated according to server configuration, including the non-network equipment (e.g., an air conditioner and a dehumidifier). The server domain may have a centralized or distributed configuration. For example, distributed servers incorporating the cloud computing concept can be configured at the server domain. The energy consumption of a network ($E_{network}$) is the combined energy consumptions of all interfaces, nodes and servers within the defined area of the network.

8.2 Functional architecture for measuring energy consumption in networks

Functional architecture for network energy consumption measurement consists of energy measurement functions and transport functions as shown in Figure 8-2. Transport functions include both domains of the reference model for network energy consumption measurement shown in Figure 8-1.

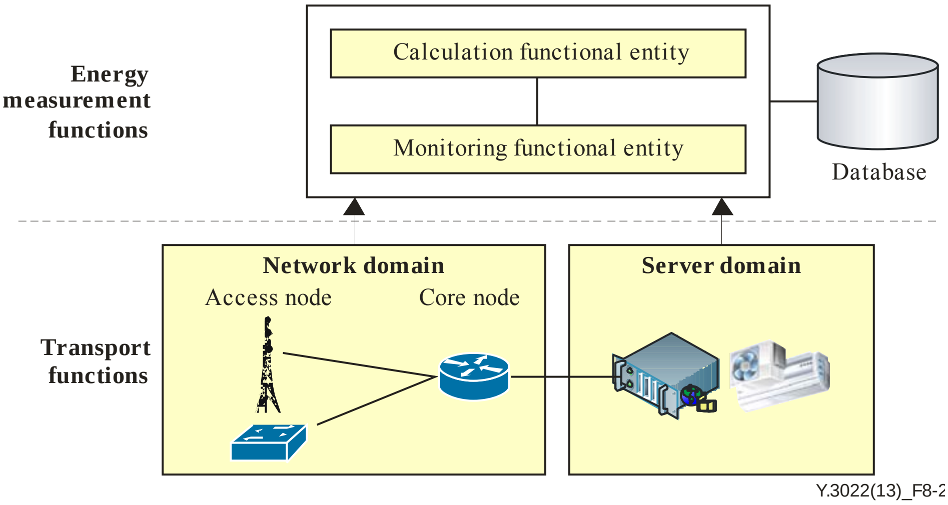

Figure 8-2 – Functional architecture for measuring energy consumption in networks

The network energy consumption measurement functions include two functional entities. The functional entities interact with each other for network energy consumption measurement as follows:

- **Monitoring functional entity**: This functional entity monitors required information about networks as follows:
  - Traffic load, which can be obtained from transport functions in nodes and servers.

  The monitoring functional entity performs measurement of energy consumption such as interface states (e.g., on, off and sleep) and packet size on each interface, node and server when traffic load reaches a target value, such as 0%, 10% or 100%, which can be decided by the network manager. The monitoring functional entity delivers information such as throughput, state and packet size on each interface, node and server to the calculation functional entity. In order to calculate the energy consumption and the network energy efficiency, the monitoring functional entity operates in association with the calculation functional entity.

  NOTE – If a node is turned on and a port cable is connected to an interface of the node, the interface's state is on. If a node is turned on and traffic load is zero (0%), the interface's state is changed to sleep as a power saving mode. If a port cable is disconnected, the interface's state is off, regardless of whether the node is turned on or off.

- **Calculation functional entity**: This functional entity calculates the energy consumption and network energy efficiency by using traffic load and network energy profiles, which contain the measured information in a database. The energy consumption can be calculated according to measurement time and power consumption. This functional entity operates in association with the monitoring functional entity and database.

  A database stores the network energy profiles, which combine the energy consumptions of interface, node and server in both the network domain and the server domain.

9 Energy efficiency metrics

To determine network energy consumption, various input parameters should be calculated. Input parameters consist of traffic load, environmental and electrical conditions and system and operating conditions. Figure 9-1 shows network energy consumption, which is calculated according to several input parameters and network energy profiles.

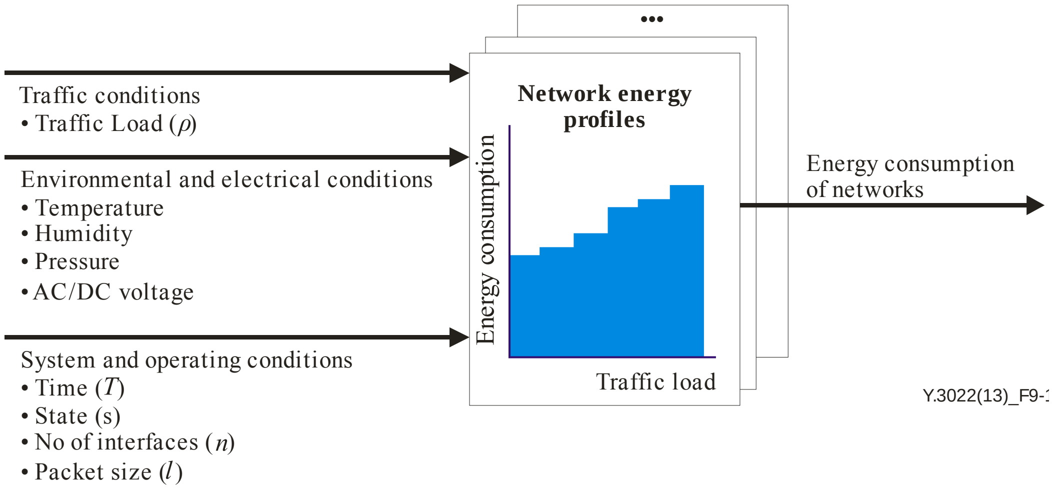

Figure 9-1 – Measuring energy consumption in networks according to input parameters and energy profiles

When calculating network energy consumption, the following input parameters are taken into account:

- **Traffic conditions**: Traffic load (ρ) can be measured actively or passively at interface, node and server level. Traffic can be measured by hand-shaking or management protocols. It can be passively calculated by counting the number of packets during a time period. In addition, traffic for operation, administration and maintenance (OAM) functions can be measured in terms of traffic load (ρ) [ITU-T G.8013].
- **Environmental and electrical conditions**: The environmental and electrical conditions relating to energy consumption are described in [ITU-T L.1310]. Temperature, humidity, air pressure and AC/DC voltage are used to calculate energy consumption for each server. Energy consumptions for networks are calculated differently depending on higher and/or lower temperature conditions.
- **System and operating conditions**: In order to calculate energy consumption, system and operating conditions should be provided in terms of measurement time (*T*), operating state (*s*) of interfaces, nodes and servers, the number of interfaces (*n*) and packet size (*l*). For the measurement time (*T*), the periodical behaviour of input traffics may be considered. The busy hours or off-peak hours are also a factor in measurement time. The operating state (*s*) assumes that the interfaces, nodes and servers are in on/off/sleep states reflecting operation modes. The number of interfaces (*n*) is used to provide information on the topological configuration and functional modularity of the interfaces, nodes and servers. Also it is useful to calculate energy consumption at the corresponding links or in an end-to-end manner. Generally, measurement time *(T)* can be the same as reporting frequency. However, depending on the characteristics of traffic or energy consumption, measurement time and reporting frequency can be differentiated.

In Figure 9-1, the network energy profiles are described in terms of energy consumption versus traffic load. All interfaces, nodes and servers have their own network energy profiles depending on the network, system configuration and functional modularity. In addition, the operating modes depending on environments and application protocols are dynamically changed for network energy efficiency. At the off-peak hours, the functional module running on high-layer protocols may go into sleep mode while only the reception module is on. The network energy profiles are reflected in the implementation or operating algorithm of interfaces, nodes and servers for network energy efficiency.

The energy consumption of networks is calculated with input parameters obtained from traffic conditions, environmental and electrical conditions and system and operating conditions. In addition, the network energy profiles of each interface, node and server are also used to calculate the network energy consumption.

In general, the power efficiency metrics ($P_{metrics}$) are formulated as follows:

$$P_{metrics} = Power\ efficiency\ metrics\ \left(\frac{bps}{Watt}\right) = \frac{Average\ data\ rate\ during\ measurement\ period\ of\ T}{Average\ power\ consumption\ during\ measurement\ period\ of\ T}.$$

Also, the energy efficiency metrics ($E_{metrics}$) are formulated as follows:

$$E_{metrics} = Energy\ efficiency\ metrics\ \left(\frac{bits}{Joule}\right) = \frac{Total\ length\ of\ data\ bits\ during\ measurement\ period\ of\ T}{Accumulation\ of\ power\ consumption\ during\ measurement\ period\ of\ T},$$

where $E_{metrics} = \int_0^T P_{metrics} dt$.

NOTE 1 – Each numerator of power/energy efficiency metrics is required to calculate average data rates and total length of data bits at interfaces, nodes and servers. Average data rates required to calculate power consumption metrics are calculated from throughput multiplied by traffic load through network energy profiles during measurement time. In addition, total length of data bits required to calculate energy efficiency metrics is calculated from throughput multiplied by measurement time.

NOTE 2 – Examples for the calculation process for energy consumption at interfaces are shown in Appendix I.

NOTE 3 – Examples for the calculation process for energy consumption at nodes are shown in Appendix II. The node includes a switch, router and optical equipment as well as a wireless node such as at a base station.

NOTE 4 – Examples for the calculation process for energy consumption at servers are shown in Appendix III. In addition, it includes energy consumption with consideration of environmental conditions.

NOTE 5 – Examples for the calculation process for network energy consumption are shown in Appendix IV. Using typical access domain network elements, the examples for the calculation process for energy consumption for passive optical networks (PONs) are shown in Appendix IV.

NOTE 6 – Energy management levels on restricted electricity supply are shown in Appendix V.

NOTE 7 – Energy consumption in relation to functional operations is described in Appendix VI.

NOTE 8 – Based on measurement of power consumption and calculation of network energy profiles, the energy efficiency rating of network equipment is provided in Appendix VII, which is in accordance with [ITU-T L.1310].

NOTE 9 – Appendix VIII shows methods for adjusting the energy consumption measurement time.

10 Energy consumption measurement methods

10.1 Measurement methods at an interface

This clause defines measurement methods at an interface. Input parameters for energy consumption at an interface are listed in Table 10-1.

Table 10-1 – Measurement methods at an interface

Measurement point	Input parameters	Measurement methods	
		References	**Descriptions**
Interface	Traffic load	[ATIS-0600015.03.2009]	Target values required to monitor traffic load
		[ITU-T G.8013]	Method to measure traffic load
	Environmental and electrical conditions	[ITU-T L.1310]	Specific operation conditions such as temperature, humidity, air pressure, and AC/DC
		[ETSI TS 102 706]	
	Measurement time	[ATIS-0600015.03.2009]	Configuration for measurement time
	State	[ITU-T L.1310]	Measurement methods for active (on), low power (sleep) or idle (off or non-traffic) mode based on traffic load
	Number of interfaces	[ETSI TS 102 706]	Intuitive (wired) or number of connected user terminals (wireless)
	Packet size	[ATIS-0600015.03.2009]	Various packet sizes required to be measured
NOTE – In the case of a base station, 'number of interfaces' can substitute 'number of connected user terminals'.			

10.2 Measurement methods at a node

This clause defines measurement methods at a node. The power consumption of a node consists of power consumption at non-interfaces and the summation of power consumption at interfaces. The power consumption at an interface refers to Table 10-1. Power consumption of the non-interface at a node such as a switch, a router, optical equipment or a base station is described in Table 10-2. Figure 10-1 shows a block diagram for power consumption of a node. The power consumption of the non-interface at a node is variable according to the manufacturer's product characteristics.

NOTE 1 – The power consumption of the non-interface at a node is measured when traffic load is 0% and all interfaces are in an off state.

NOTE 2 – The non-interface at node includes the AC/DC module, fan, switching and processing.

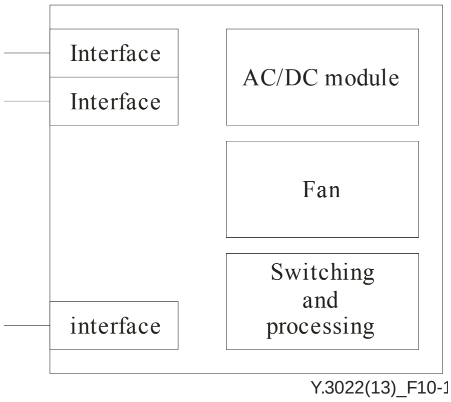

Figure 10-1 – Block diagram for energy consumption of a node

Table 10-2 – Measurement methods at a non-interface of a node

Measurement point	Input parameters	Measurement methods	
		References	**Descriptions**
Non-interface at a node	AC/DC module	[ITU-T L.1310]	Specific operation conditions such as temperature, humidity, air pressure and AC/DC
		[ETSI TS 102 706]	
	Fan	[b-EMERSON-White]	Measurement for fan's power consumption in a large IDC
		[ETSI ES 203 215]	Power consumption inside a rack cooling system needs to be taken into account
		[ETSI TS 102 706]	Air fan based cooling solution needs to be compensated for in consumption.
	Switching and processing	[b-Rob]	Processing energy calculation via packet header

10.3 Measurement methods at a server

This clause defines measurement methods at a server. The power consumption of a server consists of power consumption at non-interfaces, summation of power consumption at interfaces and non-network equipment. The power consumption at interfaces is described in Table 10-1. Power consumption of the non-interface at the server and the non-network equipment is described in Table 10-3. Figure 10-2 shows a block diagram for the energy consumption of a server.

NOTE – The power consumption of the non-interface at a server is measured when traffic load is 0% and all interfaces are in an off state.

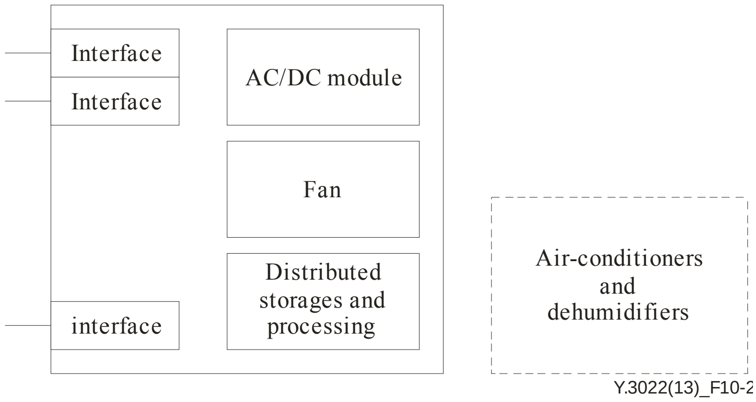

Figure 10-2 – Block diagram for energy consumption of a server

Table 10-3 – Measurement methods at non-interface of a server and non-network equipment

Measurement point	**Input parameters**	**Measurement methods**	
		References	**Descriptions**
Non-interface at server	AC/DC module	[ITU-T L.1310]	Specific operation conditions such as temperature, humidity, air pressure and AC/DC
		[ETSI TS 102 706]	
	Fan	[b-EMERSON-White]	Measurement of fan's power consumption in a large IDC
		[ETSI ES 203 215]	Power consumption inside rack cooling system needs to be taken into account
		[ETSI TS 102 706]	Air fan based cooling solution needs to be taken into account in consumption
	Distributed storages and processing	[b-Zhu]	Power consumption of a large storage cache in a storage system such as an IDC
		[b-Rob]	Processing energy calculation via packet header
Non-network equipment	Air conditioners and dehumidifiers	[ITU-T L.1310]	Specific operation conditions such as temperature and humidity
NOTE – Specific profiles of power consumptions for non-network equipment are supplied by manufacturers.			

10.4 Measurement methods at a network

This clause defines measurement methods at a network. The power consumption of a network consists of the power consumption of nodes, power consumption of servers and power consumption of non-network equipment. Power consumptions of nodes and servers are calculated in accordance with clauses 10.1 to 10.3. In addition, the power consumption of devices present due to environmental and electrical conditions such as air conditioners is optionally calculated by using profiles supplied from manufacturers.

11 Security considerations and requuirements

These security considerations and requirements are based on security architecture for systems providing end-to-end communications [ITU-T X.805], the security requirements for NGN release 1 [ITU-T Y.2701] and a framework for energy saving in future networks [ITU-T Y.3021]. Because cyclic interactions among functional entities for energy consumption measurement of networks in dynamic technologies [ITU-T Y.3021] may provide security risks, the operation parameters of the cyclic interactions should be carefully selected.

Appendix I

Calculation process for energy consumption at an interface

(This appendix does not form an integral part of this Recommendation.)

A node consists of various types of interfaces such as uplink/downlink and multiple links. In an interface, state (e.g., on, off or sleep) and utilization are used for measurement. At an interface of each node, there is a consumption of power when transmitting and receiving traffic depending on traffic load and states. Generally, as utilization increases, energy consumption also increases. The following equation for interface energy consumption is considered for traffic load and interface states:

$$E_{interface} = \sum_{0}^{T} \sum_{i} P_{interface,i}(\rho, s, n, l)$$

where $P_{interface}(\rho, s, n, l)$ is power consumption dependent on the node features, ρ is a traffic load, *s* is state, *n* is the number of interfaces with *s* state, *l* is packet size and *T* is a measurement time.

I.1 Switch

The switch conceptual diagram consists of a processor, a buffer, a module and a fan. Figure I.1 shows a module configured with a physical interface, a processor to process the incoming packet, a buffer for temporary data storage and a fan for maintaining the proper temperature. More specifically, the module features each individual operation for energy saving.

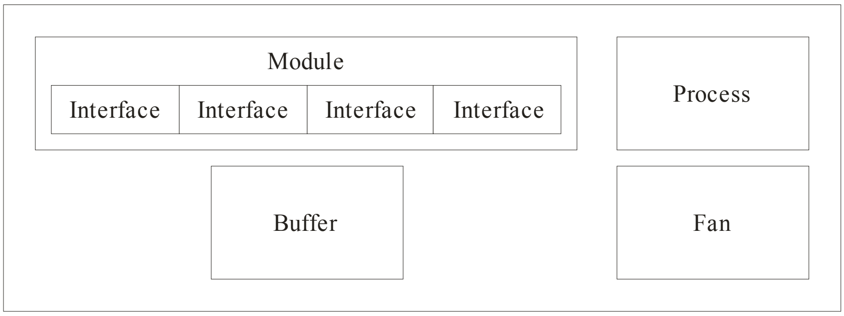

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Figure I.1 – Conceptual diagram of a switch

The energy consumption of a switch can be determined from the processor, buffer, module and fan. The energy consumption of interfaces in a switch is shown in Figure I.2.

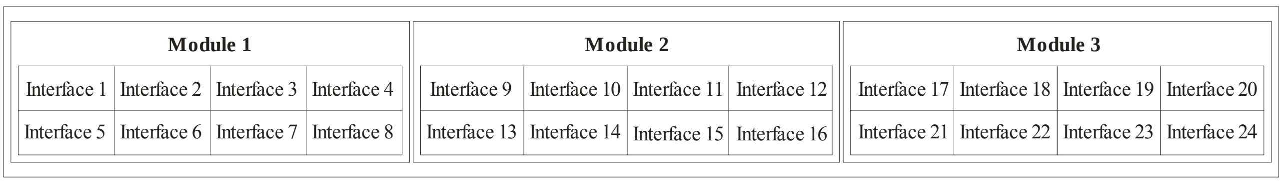

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Figure I.2 – Conceptual diagram on modules and interfaces in a switch

Interface groups are divided into modules. The energy measurement of module is the summation of interfaces in a switch as shown in the following equation:

$$E_{module} = \sum_{i} E_{interface,i}$$

Examples of energy consumption in an interface are shown below:

- Case of using two interfaces in one module
  - In this case, a switch uses the two interfaces in one module. During this period, two other unused modules can be turned off for energy saving. Energy consumption of the interface in a switch $E_{interface}$ is:

$$E_{interface} = \sum_{0}^{T} \left\{ P_{processor}(\rho_{interface\_1} + \rho_{interface\_2}) + P_{module} \times 1 \right\}$$

- Case of using each interface in two modules, respectively
  - In this case, it is assumed that the switch uses interface 1 and interface 9, which are in different modules, module 1 and module 2, respectively. Energy consumption of the interface in a switch $E_{interface}$ is:

$$E_{interface} = \sum_{0}^{T} \left\{ P_{processor}(\rho_{interface\_1} + \rho_{interface\_9}) + P_{module} \times 2 \right\}$$

I.2 Router

The energy consumption of a router interface is shown in the following equation:

$$E_{interface,i} = \sum_{0}^{T} P_{interface,i}\,(\rho, l, s, c)$$

where $P_{interface,i}$ is the function that provides the energy consumption of an interface, T is the measurement time, ρ is the traffic load on an interface, l is the packet size, s is the status of the interface and c is the computing factor which relates to the power consumption overhead by routing protocols or other unique functions of each router device [b-Kerry].

The computing factor c depends on the routing technology in the router. If this technology includes traffic processing operations such as traffic aggregation, multi-path routing and network coding, this computing factor will differ from conventional store-and-forward based routing technology.

The energy consumption of an interface in a router is the energy consumed in handling the packet arriving at an interface. Since a router implements the header processing and the packet transfer of incoming packets [b-Rob], the energy consumption of an interface is distinct from the energy consumption for the header processing and the packet transfer. According to [b-Rob], the energy consumption of an interface in a router is shown in the following equation:

$$P_{interface,i} = P_{HP,i} + P_{PT,i} = \left(E_{HP} \times \frac{\rho \times R_i}{l} \right) + \left(E_{PT} \times \rho \times R_i \right)$$

where $P_{HP,i}$ is the packet header processing power, $P_{PT,i}$ is the packet transfer power, E_{HP} is the packet header processing energy, ρ is the traffic load on the interface, R_i is the throughput of the i-th interface, E_{PT} is the per bit transfer energy, and l is the packet size. The energy consumption of the router interface is shown in the following equation:

• Single packet size case

$$E_{interface,i} = \sum_{0}^{T} P_{interface,i}\ (\rho, l, s, c)$$

$$= \sum_{0}^{T} s \times \left(E_{HP,i} \times c \times \frac{R_i \times \rho}{l} + E_{PT,i} \times \frac{R_i \times \rho}{l} \times l \right) = \sum_{0}^{T} \rho \times s \times R_i \times \left(E_{HP,i} \times \frac{c}{l} + E_{PT,i} \right)$$

where $P_{interface,i}$ is the function that shows the power consumption of the i-th interface and T is the measurement time.

NOTE 1 – s is equal to 1 if the status of the interface is on, and s is equal to 0 if the status of the interface is off.

NOTE 2 – R_i, $E_{PT,i}$, and $E_{HP,i}$ depend on the interface type.

• Multi-packet size case

$$E_{interface,i} = \sum_{0}^{T} \left(\sum_{k=1}^{n} P_{interface,i} \left(\rho_k, l_k, s, c \right) \right)$$

$$= \sum_{0}^{T} \left[\sum_{k=1}^{n} \left\{ s \times \left(E_{HP,i} \times c \times \frac{R_i \times \rho_k}{l_k} + E_{PT,i} \times \frac{R_i \times \rho_k}{l_k} \times l_k \right) \right\} \right]$$

$$= \sum_{0}^{T} s \times R_i \times \sum_{k=1}^{n} \left\{ \rho_k \times \left(E_{HP,i} \times \frac{c}{l_k} + E_{PT,i} \right) \right\},$$

where $P_{interface,i}$ is the function that provides the power consumption of an interface, T is the measurement time, l_k is the k-th packet size, ρ_k is the traffic load of the packet size l_k, and n is the number of packet sizes. $\sum \rho_k$ is the total traffic load during the measurement time.

NOTE 3 – ρ_k is the multiplication of ρ and the percentage of the packet size l_k in the traffic load.

NOTE 4 – The Simple IMIX packet size mixtures are used *58 bytes* (*7%* in traffic load), *594 bytes (56%)*, and *1518 bytes (37%)* in L2 packet size. [b-Spirent]. It is assumed that s is equal to 1 which means the interface is on, ρ is *10%*, R_i is equal to *1 Gbps*, $E_{HP,i}$ is $1.1 \times 10^{-6} J$, T is *100 s*, $E_{PT,i}$ is $0.2 \times 10^{-8} J$, and c is equal to *0.03*, then,

Table I.1 – An example of IMIX packet size for traffic load

Traffic load **Packet size**	**1 (100%)**	**0.1 (10%)**
ρ_1 (p_1 = 58 bytes)	0.07 (7%)	0.007 (0.7%)
ρ_2 (p_2 = 594 bytes)	0.56 (56%)	0.056 (5.6%)
ρ_3 (p_3 = 1518 bytes)	0.37 (37%)	0.037 (3.7%)

and

$$
\begin{aligned}
E_{interface,i} &= s \times R_i \times \sum_{0}^{100}\left[\sum_{k=1}^{n}\left\{\rho_k \times \left(E_{HP,i} \times \frac{c}{l_k} + E_{PT,i}\right)\right\}\right] \\
&= 1 \times 1\ \text{Gbps} \times 100\ \text{sec} \\
&\times \left\{\begin{aligned}
&0.1 \times 0.07 \times \left(1.1 \times 10^{-6}\, J \times \frac{0.03}{58\, bytes} + 0.2 \times 10^{-8}\, J\right) \\
&+0.1 \times 0.56 \times \left(1.1 \times 10^{-6}\, J \times \frac{0.03}{594\, bytes} + 0.2 \times 10^{-8}\, J\right) \\
&+0.1 \times 0.37 \times \left(1.1 \times 10^{-6}\, J \times \frac{0.03}{1518\, bytes} + 0.2 \times 10^{-8}\, J\right)
\end{aligned}\right\} \\
&= 21.47\, J
\end{aligned}
$$

Appendix II

Calculation process for energy consumption at a node

(This appendix does not form an integral part of this Recommendation.)

A network contains various types of nodes for delivering traffic (e.g., switch, router, gateway base station, etc.). Node energy consumption contains the summation of interface energy consumption and environment energy consumption (e.g., cooling) during measurement time. Environment energy consumption is an input parameter known to a network management administrator. For example, chiller-based cooling is responsible for a 30-70% of overhead in energy usage. The following equation for node energy consumption is considered for the energy consumption of a common module and interfaces:

$$E_{node} = E_{common} + \sum_i E_{interface,i}$$

The following energy consumptions for a node are based on various mediums.

II.1 Energy consumption for wired nodes

II.1.1 Switch

The calculation for the energy consumption of a switch is shown in the following equation:

$$E_{switch} = \sum_{0}^{T} \left(P_{common} + \sum_{i} P_{Module,i} \right)$$

$$P_{module} = \sum_{i} P_{interface,\, i}$$

$$P_{common} = P_{buffer} + P_{fan}$$

$$P_{fan} = \left\{ P_{processor}(\rho) + P_{module} \times n + P_{buffer} \right\} \times \eta$$

where E_{switch} is energy consumption, T is measurement time, $P_{processor}$ is power consumption to process traffic volume, ρ is traffic volume, P_{buffer} is power consumption per buffer, P_{module} is power consumption of the module, n is the number of modules in use and η is power consumption for cooling the heat dissipated by *1 W* (case of efficient cooling system: P_{fan} is approximately *0.358 W* in [b-CISCO-White]). Energy consumption indicates on and off state (s) according to the number (n) of interfaces and modules.

II.1.2 Router

The calculation for the energy consumption of a router is shown in the following equation:

$$E_{router} = E_{common} + \sum_i E_{interface,i}$$

where E_{common} is the energy consumption of the router when no port connects to the Internet. $E_{interface,i}$ is the energy consumption of packet processing in i-th interface.

The calculation for the energy consumption of the router when no port is connected is shown in the following equation:

$$E_{common} = \sum_{0}^{T} P_{common}$$

where:

$$P_{common} = P_{chassis} + \sum_i P_{routing\,engine,\,j} + \sum_k P_{power\,supply\,unit,k} + \sum_l P_{line\,card,l}$$

here P_{common} is the power consumption of the router when there is no port connected to a router and T is the measurement time. $P_{chassis}$ is the power consumption of chassis including the power for operating internal temperature moderation components, $P_{routing\ engine,j}$ is the power consumption of j-th routing engine module, $P_{power\ supply\ unit,k}$ is the power consumption of k-th power supply unit and $P_{line\ card,l}$ is the power consumption of lth line card [b-Kerry].

II.1.3 Optical equipment

A passive optical network (PON) system combines both time division multiplexing (TDM)-PON and wavelength division multiplexing (WDM)-PON.

II.1.3.1 Energy consumption of an OLT and an ONU in TDM-PON

An optical line terminal (OLT) has a transmitter, a receiver and a common module in a PON system. These OLT components are always on, so the energy consumption by all the components in an OLT is given by:

$$E_{OLT} = \sum_0^T \{P_{OLT-CM} + P_{OLT-Tx}(\rho_{DL}, n) + P_{OLT-Rx}(\rho_{UL}, n)\}$$

Here, $P_{OLT\text{-}CM}$ is the power consumption of the common module of OLT, $P_{OLT\text{-}Tx}$ is the power consumption of the OLT transmitter, and $P_{OLT\text{-}Rx}$ is the power consumption of the OLT receiver. ρ_{DL} is the downlink traffic load to optical network units (ONUs) and ρ_{UL} is the uplink traffic load from ONUs. $P_{OLT\text{-}TX}$ and $P_{OLT\text{-}RX}$ are the related downlink/uplink traffic load and number of ONUs. Here, T is the measurement time of energy consumption and n is the number of ONUs served by the OLT.

An ONU has a transmitter, a receiver and a common module in a PON system. These ONU components are always on, so the energy consumption by all the components in an ONU is given by:

$$E_{ONU} = \sum_0^T \{P_{ONU-CM} + P_{ONU-Tx}(\rho_{DL}) + P_{ONU-Rx}(\rho_{UL})\}$$

Here, $P_{ONU\text{-}CM}$ is power consumption of the common module of an ONU, $P_{ONU\text{-}Tx}$ is the power consumption of transmitter of an ONU and $P_{ONU\text{-}Rx}$ is the power consumption of receiver of an ONU. ρ_{DL} is the downlink traffic load to an ONU and ρ_{UL} is the uplink traffic load from an ONU.

NOTE 1 – An ONU and an OLT of a PON have T_x and R_x as pairs of an interface.

NOTE 2 – Optical equipment such as optical cross-connect (OXC) multi-service provisioning platform (MSPP) can be included as an optical node.

ITU-T has introduced sleep mode to save on the power consumption of ONUs [b-ITU-T G.Sup45]. Therefore, to calculate the energy consumption of an ONU, it is necessary to consider the ONU sleep mode mechanism. Overall the ITU-T introduced two kinds of sleep mode. These two sleep modes are doze mode and cyclic sleep mode.

- **Formulating energy consumption when an OLT uses doze mode**: In doze mode, an ONU only shuts down its *Tx* and keeps the *Rx* always on. As a result, the OLT can send downstream traffic to the ONU whenever the OLT receives packets. When uplink traffic arrives, an ONU should turn on the transmitter and transmit to the OLT during a dedicated uplink transmission slot. As the receiver and CM are always on when doze mode is used, the energy consumption of all the components except the transmitter is obtained. In doze mode, energy consumption by the transmitter mainly depends on uplink traffic load ρ_{UL}, packet size l_{size} and state (i.e., doze mode) s_{Doze}. Then the energy consumption of an ONU in doze mode states is as follows:

$$E_{ONU} = \sum_{0}^{T} \{P_{Rx} + P_{CM} + P_{Tx}(\rho_{UL}, l_{size}, s_{Doze})\}$$

where P_{Tx} is the power consumption of the transmitter of an ONU, P_{Rx} is the power consumption of the receiver of an ONU, and P_{CM} is power consumption of the CM of an ONU.

- **Formulating energy consumption when an OLT uses cyclic sleep mode**: In cyclic sleep mode, an ONU periodically wakes up by turning on both *Tx* and *Rx* to check whether it has any traffic to receive or not, as shown in Figure II.1.

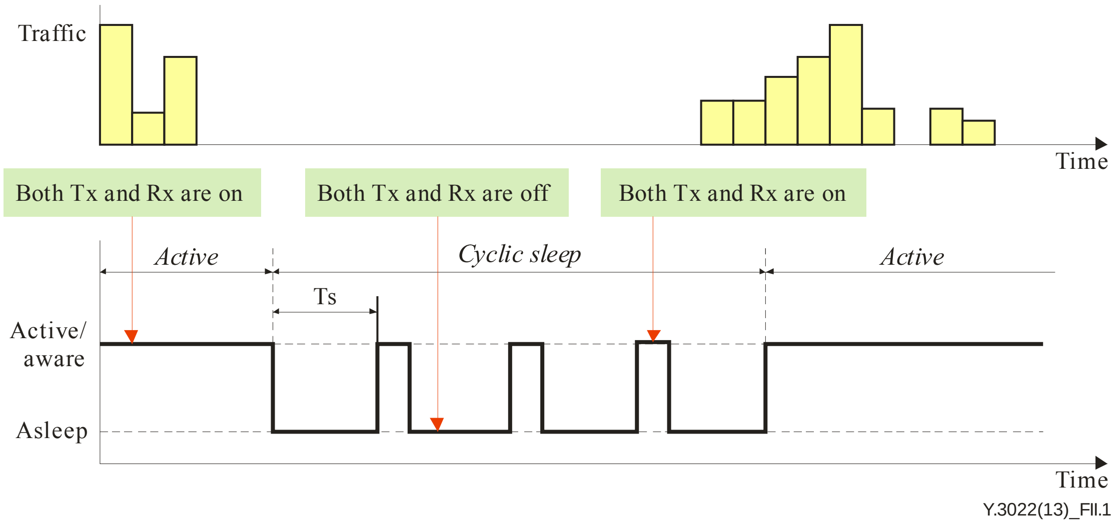

Figure II.1 – Cyclic sleep mode

To measure energy consumption, the following steps must be considered.

– **STEP 1**: Consider the parameter T_s (length of sleep interval). The smaller the size of T_s assigned, the more energy an ONU consumes.

– **STEP 2**: Consider both uplink and downlink arrival. The more traffic arrives at an ONU, the more an ONU stays in active mode.

– **STEP 3**: Consider the signaling messages that are used in this cyclic sleep mode.

In this case, this model considers that the *CM* is always on. However, *Tx* and *Rx* are periodically turned on at the end of every T_s. Therefore, the energy consumed solely by these two modules depends on the arrival of ρ_{DL}, ρ_{UL} and the length of the sleep interval. Then the energy consumption of an ONU in cyclic sleep mode states is as follows:

$$E_{ONU} = \sum_{0}^{T} \{P_{CM} + P_{Tx}(\rho_{UL}, l_{size}, T_s, s_{CycleSleep}) + P_{Rx}(\rho_{DL}, l_{size}, T_s, s_{CycleSleep})\}$$

II.1.3.2 Energy consumption of an OLT in a WDM-PON

- **Formulating energy consumption when an OLT uses active mode**: The energy consumption of an OLT and ONUs in a WDM-PON during the measurement time *T* can be summarized as follows:

$$E_{OLT} = \sum_{0}^{T} P_{OLT-CM} + \sum_{i} \left\{ \sum_{0}^{T} P_{OLT-Tx,i} + \sum_{0}^{T} P_{OLT-Rx,i} \right\},$$

$$E_{ONU,i} = \sum_{0}^{T} P_{ONU-CM,i} + \sum_{0}^{T} P_{ONU-Rx,i} + \sum_{0}^{T} P_{RSOA,i}$$

where $P_{OLT\text{-}CM}$ is power consumption by the CM of an OLT, $P_{ONU\text{-}CM,i}$ is power consumption by the CM of an ONU_i, $P_{OLT\text{-}Tx,i}$ is power consumption by the *i*-th *Tx* of OLT, $P_{OLT\text{-}Rx,i}$ is power consumption by the *i*-th *Rx* of an OLT, $P_{ONU\text{-}Rx,i}$ is power consumption by a *Rx* of ONU_i and $P_{RSOA,i}$ is power consumption by a RSOA of an ONU_i.

This WDM-PON architecture with centralized light sources also has a critical power consumption problem. Without the downstream signal, the ONU cannot send the upstream signal. Thus even if no traffic is on the line, the OLT has to send the downstream signal all the time and cannot switch to the sleep mode.

- **Formulating energy consumption when an OLT uses sleep mode**: [b-Tatsuya] uses a polling scheme of a supervisor transceiver in WDM-PON. If a Tx_i of the OLT has no downstream traffic, then the Tx_i interface state is changed to sleep mode, which stops the transmission of downstream signals. If an ONU_i has upstream traffic, then the ONU_i sends a "recovery request" signal using the optical source of the supervisor. After the supervisor transceiver receives the request signal, it awakens Tx_i of the OLT from sleep mode.

Using the sleep mode in WDM-PON, the total energy consumption of this WDM-PON during the measurement time *T* can be summarized as follows:

$$E_{OLT} = \sum_{0}^{T} P_{OLT-CM} + \sum_{0}^{T} P_{Supervisor-TRx} + \sum_{i} \left\{ \sum_{0}^{T} P_{OLT-Tx,i}(T_s) + \sum_{0}^{T} P_{OLT-Rx,i}(T_s) \right\}$$

$$E_{ONU,i} = \sum_{0}^{T} P_{ONU-CM,i} + \sum_{0}^{T} P_{ONU-Rx,i} + \sum_{0}^{T} P_{RSOA,i}$$

where $P_{supervisor\text{-}TRx}$ is the power consumption of the transceiver of a supervisor in the OLT. The other notation is explained in the clause above.

NOTE – The length of the sleep interval T_s in sleep mode of a WDM-PON is variable. However, T_s is fixed in the cyclic sleep mode of the TDM-PON.

In sleep mode, the CM and a supervisor transceiver of the OLT are always on, however if some of *Tx* and *Rx* in the OLT have no traffic (down/up), then *Tx* and *Rx* switch to sleep mode.

II.2 Energy consumption for wireless nodes

II.2.1 Base station

A typical base station consists of a baseband processing unit, a radio frequency (RF) power amplifier unit, a power supply unit and a climate control unit. Figures II.2 and II.3 show simplified base stations with these units. Figure II.2 shows a conventional base station and Figure II.3 shows a remote radio head (RRH)-based distributed base station architecture. The amount of energy consumption of units can vary over time according to resource allocation, data rates and baseband signal processing.

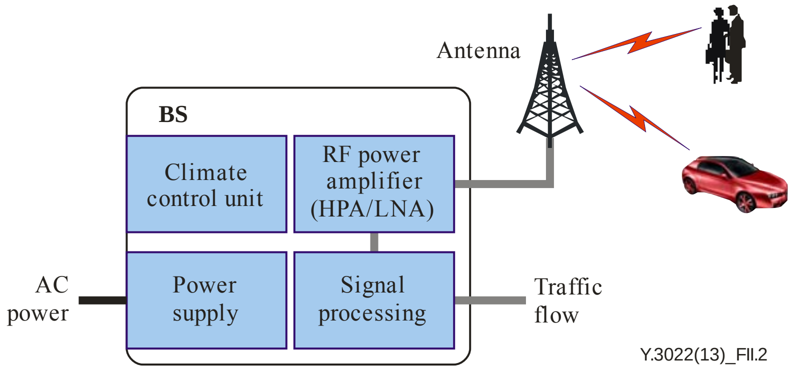

Figure II.2 – Conventional base station architecture

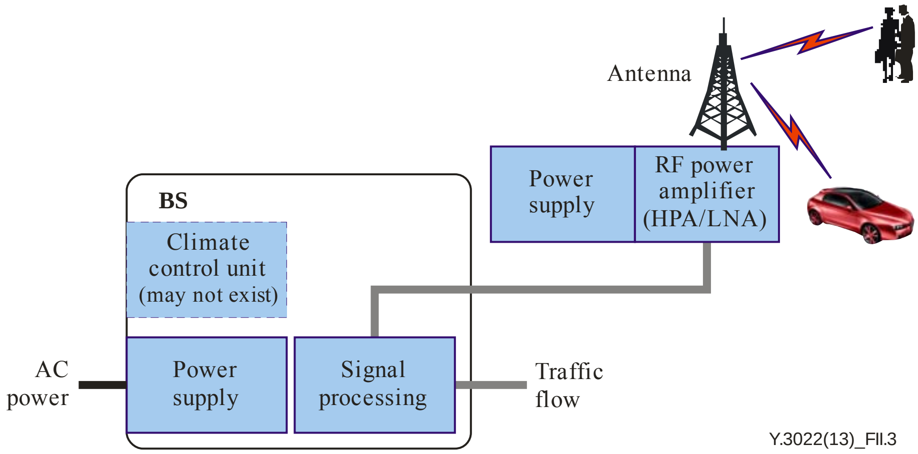

Figure II.3 – Distributed RRH-based base station architecture

P_{SP}, P_{PA}, P_{PS}, P_{CC} and P_{ckt} represent the power consumptions of the signal processing unit, the RF power amplifier unit consisting respectively of the high power amplifiers (HPAs) and low noise amplifiers (LNAs), the power supply unit with AC power input, the climate control unit and the energy management unit with power circuit. The signal processing unit contains wireless signal processing blocks for baseband processing, precoding, subcarrier mapping, fast fourier transform (FFT) and inverse fast fourier transform (IFFT). The climate control unit can be optionally removed to improve energy efficiency when used in a distributed RRH-based base station architecture. With the energy consumption models, the conventional base station architecture is modeled as shown in Figure II.4 and distributed (RRH-based) base station architecture as shown in Figure II.5. Each sector is assumed to have K antennas for transmission.

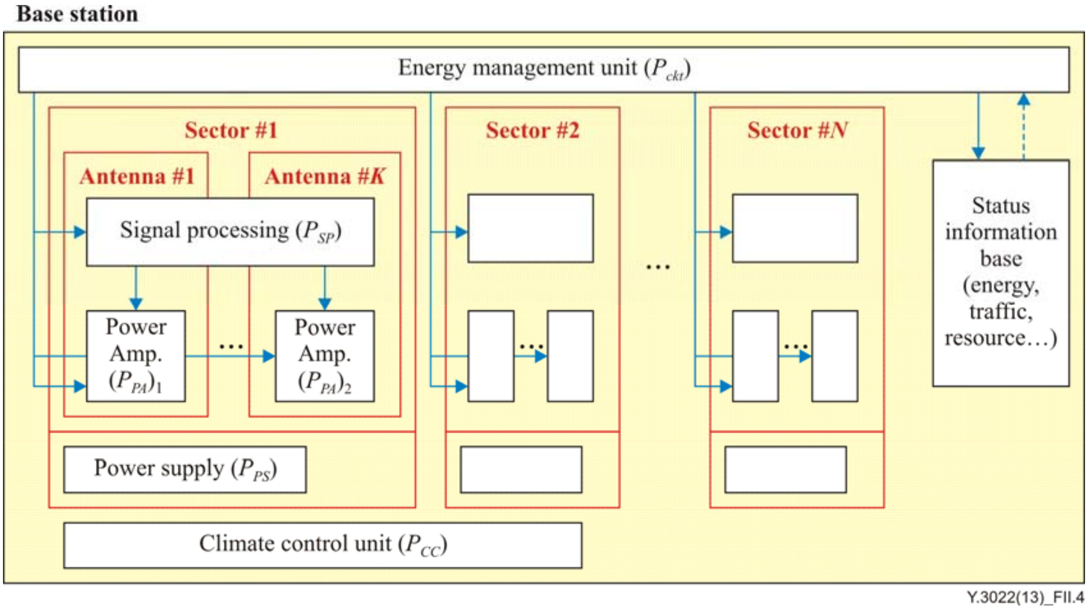

Figure II.4 – A conventional base station architecture

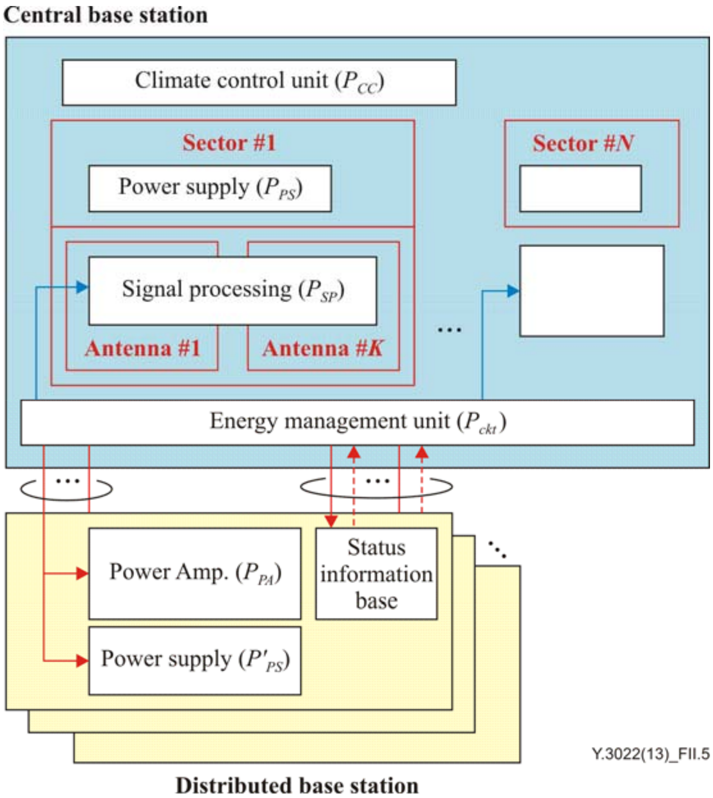

Figure II.5 – A distributed RRH-based base station architecture

The energy consumption of a base station is summarized in the following equation:

$$E_{BS} = \sum_{0}^{T} P_{BS} \approx \sum_{0}^{T} \alpha_{conv} P_{BS.tx} + P_{BS.other}$$

where T is the measurement time and P_{BS} is the power consumption of the base station. In the above equation, E_{BS} is the integration of interface power consumption during the measurement time T. $P_{BS.tx}$ is the sum of the transmission power of the base station's antennas and α_{conv} is the power conversion efficiency accounting for the power amplifier efficiency, feeder loss and extra loss.

$P_{BS.other}$ is the sum of the power consumptions of the other components such as signal processing, battery backup and the base station's cooling. In the above equation, E_{BS} is the sum of node power consumption during the measurement time T. The P_{BS} is measured from a conventional base station and a distributed or RRH-based base station. In wireless system technologies such as global system for mobile communications (GSM), code division multiple access (CDMA), universal mobile telecommunications system (UMTS) and long-term evolution (LTE), RRH-based base stations are deployed.

The power consumption of the conventional base station can be modelled as follows:

$$P_{BS\_CONV} = P_{ckt} + P_{CC} + \sum_{i=1}^{N_{sector}} \left[\sum_{j=1}^{N_{TXi}} P_{PAij} + P_{SPi} + P_{PSi} \right], \qquad \text{(II.1)}$$

where N_{sector} and N_{TXi} represent respectively the number of sectors in a base station and the number of transmit/receive antennas in the i-th sector. P_{PAijk} represents the power consumption of the power amplifier unit in the j-th antenna of the i-th sector. P_{SPi} and P_{PSi} respectively represent the power consumptions of signal processing and power supply, in the i-th sector. Similarly, the power consumption of the distributed RRH-based base station can be modeled as follows:

$$P_{BS\_RRH} = P_{ckt} + P_{CC} + \sum_{i=1}^{N_{sector}} \left[\sum_{j=i}^{N_{TXi}} P_{PAij} + P_{SPi} + P_{PSi} \right] + \sum_{k=1}^{N_{RRH}} P'_{PSk} \qquad \text{(II.2)}$$

where N_{RRH} represents the number of remote radio heads and P'_{PSk} denotes the power consumption of the power supply unit in the k-th remote radio head. Even the same parameters in equations II.1 and II.2 have different values due to different base station architectures.

The power consumption of each unit can be measured for varying resource utilizations (or traffic loads). Using these results, it is possible to characterize the relationship between the resource utilization and the power consumption of each unit.

Appendix III

Calculation process for energy consumption at a server

(This appendix does not form an integral part of this Recommendation.)

In the case that a server within an IDC exists, energy consumption of network air conditioners is considered as $E_{environment}$. The following equation for server energy consumption is defined as the sum of common energy consumption, interface energy consumption and the energy environment:

$$E_{server} = \sum_{0}^{T} P_{server} = \sum_{0}^{T} \left\{ P_{common} + \sum_{i} P_{interface,i} + (P_{environment}) \right\}.$$

$E_{environment}$ is optionally added in the case of an IDC. The energy consumption at a server is affected by the environment conditions as well as the operation state, such as an idle or a peak mode of a server. The idle mode of a server indicates power consumption when the traffic load is 0%. The peak mode of a server indicates power consumption when the traffic load is 100%. The server's power consumption generally increases with utilization and has linear characteristics in utilization between idle load power (e.g., traffic load 0%) and peak load power (e.g., traffic load 100%).

$$P_{common} = P_{server_{idle}},$$

$$\sum_{i} P_{interface,i} = (P_{server_{Peak}} - P_{server_{Idle}}) \times u_{server}$$

where $P_{server_{idle}}$ is the server power consumption when traffic load is 0%, $P_{server_{Peak}}$ is the server power consumption when traffic load is 100%, and u_{server} is normalized traffic load between 0 and 1.

In the IDC, it is important to consider the environment power consumption of air conditioners and dehumidifiers. Though this equipment functions separately from network equipment, it is essential for operating networks normally. This environment power consumption at the IDC is obtained using the following equation:

$$P_{environment} = P_{chiller} + P_{dehumid}.$$

- $P_{chiller}$ is power consumption from all of the air conditioners in an IDC
- $P_{dehumid}$ is power consumption from the all of the dehumidifiers in an IDC

$P_{chiller}$ = *(number of air conditioners) x standard power consumption of an air conditioner*

$P_{dehumid}$ = *(number of dehumidifiers) x standard power consumption of a dehumidifier*

To obtain E_{server}, the environment power consumption for one server is calculated as there are a number of servers in the IDC. The environment power consumption per server ($P^{*}_{environment}$) is calculated using the following equation:

$$P^{*}_{environment} = \frac{P_{environment}}{number\ of\ servers}.$$

The equation for $E_{environment}$ is shown as follows:

$$E_{environment} = \sum_{0}^{T} P^{*}_{environment},$$

where T is measurement time and $E_{environment}$ is environment energy consumption per server during T.

Appendix IV

Calculation process for energy consumption at a network

(This appendix does not form an integral part of this Recommendation.)

The network energy consumption is the sum of the energy consumption of nodes contained in the network. The general energy consumption ($E_{Network}$) is described by the following equation:

$$E_{network} = \sum_{i} E_{node,i} + \sum_{j} E_{server,j} + E_{environment}$$

Energy consumption ($E_{Network}$) optionally consists of the sum of $E_{node,i}$ or the sum of E_{server} and $E_{environment}$.

One of the representative access networks can become a PON. A typical PON system consists of an OLT, a remote node (RN) and ONUs. The RN is either a passive power splitter or an arrayed waveguide grating that has no energy consumption. The energy consumption of a PON is shown in the following equation:

$$E_{PON} = E_{OLT} + \sum_{i} E_{ONU,i},$$

where E_{OLT} is the energy consumption of an OLT and $E_{ONU,i}$ is the energy consumption of the ONUs.

For greater understanding the following description of PON energy consumption includes TDM-PON and WDM-PON.

IV.1 Energy consumption of TDM-PON

TDM-PON is the more conventional optical access network compared to the WDM-PON system because of ease of implementation, low cost, etc. In this clause, the energy consumption of a TDM-PON is introduced as one of the PON system models.

The TDM-PON system consists of an OLT and ONUs. The block diagram of the TDM-PON system is shown in Figure IV.1.

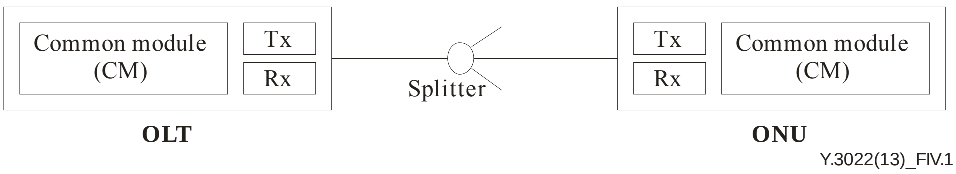

Figure IV.1 – Block diagram of TDM-PON system

The energy consumption of the TDM-PON system can be summarized as follows:

$$E_{TDM-PON} = E_{OLT} + E_{ONUs}.$$

IV.1.1 Formulating energy consumption in doze mode

$$E_{TDM-PON} = \sum_{0}^{T} \{P_{OLT-CM} + P_{OLT-Tx}(\rho_{DL}, n) + P_{OLT-Rx}(\rho_{UL}, n)\}$$

$$+ \sum_{i=1}^{n} \sum_{0}^{T} \{P_{ONUi-CM} + P_{ONUi-Rx} + P_{ONUi-Tx}(\rho_{UL}, l_{size})\}$$

IV.1.2 Formulating energy consumption in cyclic sleep mode

$$E_{TDM-PON} = \sum_{0}^{T} \left\{ P_{OLT-CM} + P_{OLT-Tx}\left(\rho_{DL}, n\right) + P_{OLT-Rx}\left(\rho_{UL}, n\right) \right\}$$

$$+ \sum_{i=1}^{n} \sum_{0}^{T} \left\{ P_{ONUi-CM} + P_{ONUi-Rx}\left(\rho_{DL}, l_{size}, T_s, s_{CycleSleep}\right) + P_{ONUi-Tx}\left(\rho_{UL}, l_{size}, T_s, s_{CycleSleep}\right) \right\}$$

IV.2 Energy consumption of a WDM-PON

WDM-PON is a promising access network technology developed to meet increasing traffic due to its capacity for huge bandwidth compared to TDM-PON. In this clause, the energy consumption of a WDM-PON is introduced as a PON model.

Recently, the WDM-PON architecture with centralized light sources at the OLT has emerged as an attractive solution for low-cost implementation. The architecture of WDM-PON with centralized light sources is shown in Figure IV.2.

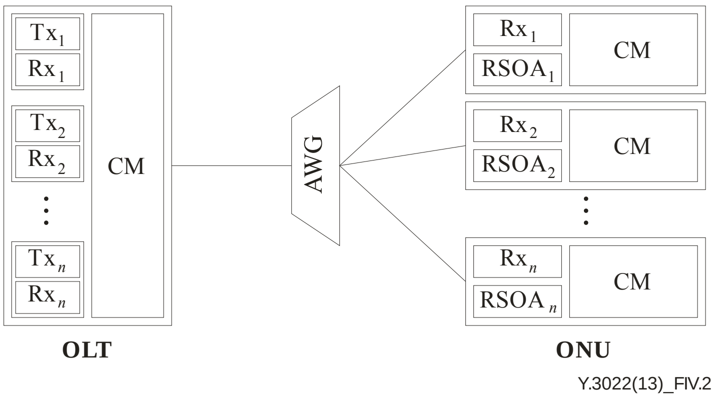

Figure IV.2 – Block diagram of WDM-PON

In this WDM-PON, an OLT has a number of n transmitters (Tx) and n receivers (Rx) which use different wavelengths and each ONU has a receiver and a reflective semiconductor optical amplifier (RSOA). Each ONU does not have a light source because an ONU can transmit upstream signals by reusing downstream signals from an OLT light source using RSOA. Otherwise, an arrayed waveguide grating (AWG) in a remote node does not include power consumption because it is a passive component.

IV.2.1 Formulating energy consumption for active mode

The total energy consumption of this WDM-PON during the measurement time T can be summarized as follows:

$$E_{WDM-PON(on)} = E_{OLT} + \sum_i E_{ONU,i}$$

$$= \sum_{0}^{T} P_{OLT-CM} + \sum_i \left\{ \sum_{0}^{T} P_{OLT-Tx,i} + \sum_{0}^{T} P_{OLT-Rx,i} \right\}$$

$$+ \sum_i \left\{ \sum_{0}^{T} P_{ONU-CM,i} + \sum_{0}^{T} P_{ONU-Rx,i} + \sum_{0}^{T} P_{RSOA,i} \right\}.$$

where $P_{OLT\text{-}CM}$ is the power consumption by the CM of the OLT, $P_{ONU\text{-}CM,i}$ is the power consumption by the CM of an ONU_i, $P_{OLT\text{-}Tx,i}$ is the power consumption by the i-th Tx of the OLT, $P_{OLT\text{-}Rx,i}$ is the power consumption by the i-th Rx of the OLT, $P_{ONU\text{-}Rx,i}$ is the power consumption by a Rx of ONU_i and $P_{RSOA,i}$ is the power consumption by a RSOA of an ONU_i.

IV.2.2 Formulating energy consumption for sleep mode

Using clause II.1.3.2, the total energy consumption of this WDM-PON during the measurement time T can be summarized as follows:

$$E_{WDM-PON(sleep)} = E_{OLT} + \sum_i E_{ONU,i}$$

$$= \sum_0^T P_{OLT-CM} + \sum_0^T P_{Supervisor-TRx} + \sum_i \left\{ \sum_0^T P_{OLT-Tx,i}(T_s) + \sum_0^T P_{OLT-Rx,i}(T_s) \right\}$$

$$+ \sum_i \left\{ \sum_0^T P_{ONU-CM,i} + \sum_0^T P_{ONU-Rx,i} + \sum_0^T P_{RSOA,i} \right\},$$

where $P_{supervisor\text{-}TRx}$ is the power consumption for the transceiver of a supervisor in the OLT.

In sleep mode, the *CM* and a supervisor transceiver of the OLT is always on, however if some of *Tx* and *Rx* in the OLT have no traffic (down/up), then *Tx* and *Rx* switches to sleep mode.

Appendix V

Energy management levels on restricted electricity supply

(This appendix does not form an integral part of this Recommendation.)

Rising energy prices and pollution credit policy on carbon emissions are encouraging governmental and industrial movement to agree on enhancing energy related goals and energy management practices. Energy regulation in the ICT industry would be active and restrictive. Consequently, possible levels are presented for the near future.

In the case of disruption of energy supplies, electricity suppliers would recommend a network provider to reduce energy usages. For example, network providers operate their own networks on best effort mode for energy consumption or for the specific energy consumption usage.

For example, a network can be operated on the following energy levels.

- **Level 0**: Full capacity level

  In level 0, a network utilizes its full bandwidth regardless of energy consumption.

- **Level 1**: Tolerant level

  In level 1, a network conditionally reduces energy consumption levels when network energy consumptions exceed the thresholds.

- **Level 2**: Best effort level

  In level 2, a network reduces energy consumption with best effort. It is similar concept to the best effort delivery of an Internet protocol (IP) network.

- **Level 3**: Delayed transfer level

  In level 3, a network is forced to reduce energy consumption to meet the specific energy consumption level. Delayed transfer can be implemented to reduce the energy consumption level.

Appendix VI

Energy consumption in relation to functional operations

(This appendix does not form an integral part of this Recommendation.)

This appendix presents elements of energy consumption defined by functional operations as follows:

- **Wired/Wireless selection**: The IP sharing equipment consists of common modules, wired modules and wireless modules. The energy consumption in the IP sharing equipment varies according to operating modules. For example, if there is no user using wireless modules, the IP sharing equipment turns off the power for wireless modules or enters the sleep state for energy saving. Also, if there is no user using wired modules, the sharing equipment enters the sleep state for energy saving. In this way, the power consumption may be different according to operating modules. Each module respectively operates independently.
- **Modularization**: The network equipment consists of several modules for carrying out various functions. The module usage is determined according to whether each function is used or not. Network systems are commonly available in both fixed and modular form. The energy consumption can be directly measured by adding or removing the module from the network equipment. In the latter case, the systems can be variably configured, which may affect their efficiency ratings. Whenever a telecom system can be equipped with diverse modules to a degree that they form different classes (e.g., separate packet switching and TDM switching modules), such system may obtain two or more ratings within the appropriate product classes.
- **Memory technology**: Choosing a memory system is one of the biggest technology challenges when designing a modern router. Progress in memory channel bandwidth has trailed Moore's law, while Internet bandwidth has grown much faster than Moore's law. This has created a significant discrepancy between the demand for memory throughput and the technology that is actually available. Thus, hardware engineers face hard choices between cost, speed, energy efficiency and the general availability of prospective memory technologies. The trade-off for hardware engineers is whether to heavily optimize memory access algorithms to retain flexibility and programmability, or to remove certain features like flexibility and power efficiency in favor of more complex (and limited) linear models such as reduced-latency dynamic random access memory (RLDRAN) or non-linear memory structures, such as ternary content-addressable memories (TCAMs) that feature deterministic prefix matching speeds and thus can significantly relax processing requirements in the forwarding path. In fact, some contemporary router designs use TCAM for the execution of both forwarding and filtering, thus effectively freeing packet processors to perform only service differentiation and generic lookup tasks. TCAM technology allows for lower-grade packet processing designs without complex memory lookup algorithms. But while both linear and content-driven lookup approaches are proven in the context of large lookup structures and are widely used, prefix tree-based lookup is generally more efficient with respect to energy.

Appendix VII

Energy efficiency rating for network equipment

(This appendix does not form an integral part of this Recommendation.)

This appendix describes other methods for measuring the efficiency of energy consumption of a network. It shows how well an input power is used without directly being affected by data transmission of network equipment. This value is EER_{NE}.

$$EER_{NE} = \frac{\sum P_{wi}}{P_{ingress}}$$

- $P_{ingress}$ is energy consumption provided from the power supply of an item of network equipment
- $P_{wi} = a \times P_{\rho 1} + b \times P_{\rho 2} + c \times P_{\rho 3}$
  - $\rho_1 \sim \rho_3$ is system utilization (traffic load)
  - a, b and c are weighted factors ($a+b+c=1$)

Where, $P_{\rho 1}$, $P_{\rho 2}$, and $P_{\rho 3}$ are the energy consumption when they operate at each system utilization level (e.g., 0%, 10% and 100%). P_{wi} is the modular weighted energy consumption at i-th interface. To obtain this value, a decision on weighted factors is required. These weighted factors (a, b, c) are decided as different values per item of equipment because they usually operate at different system utilization levels. This parameter is indicated in [ITU-T L.1310].

$\sum P_{wi}$ means energy consumption only consumed by data transmission at network equipment. Therefore, EER_{NE} presents the ratio of energy consumption for transmission to input power. High EER_{NE} means that network equipment largely contributes its energy consumption to data transmissions.

The energy efficiency of networks is calculated as the following equation:

$$EER_{total} = \alpha_1 \times EER_{NE,1} + \alpha_2 \times EER_{NE,2} + \ldots + \alpha_i \times EER_{NE,i}$$

where

- $\alpha_1, \alpha_2, \cdots, \alpha_i$ and weighted factors ($\alpha_1 + \alpha_2 + \ldots + \alpha_i = 1$),
- $EER_{NE,i}$ is a value of EER_{NE} at i-th network equipment.

Each weighted factor ($\alpha_1, \alpha_2, \cdots \alpha_i$) is decided by a given power. This is obtained via the following equation:

$$\alpha_i = \frac{P_{ingress,i}}{\sum P_{ingress,i}}$$

Appendix VIII

Methods for adjusting the energy measurement time

(This appendix does not form an integral part of this Recommendation.)

This appendix explains the methods for adjusting the energy measurement time.

VIII.1 Framework of adjusting the energy measurement time

This clause describes the framework for adjusting the energy measurement time. Figure VIII.1 shows the general framework for adjusting the energy measurement time. Each node can include the four functions: alarm functional entity, measurement functional entity, calculation functional entity and adjusting functional entity of measurement time for adjusting the energy measurement time.

- **Alarm functional entity**: This functional entity can set an alarm flag when traffic congestion occurs at a node. At the same time, this functional entity can send the alarm to the calculation functional entity for adjusting the energy measurement time.
- **Monitoring functional entity**: This functional entity can measure the energy consumption of a node during the energy measurement time. In addition, this function can operate in association with the calculation function in order to adjust the energy measurement time.
- **Calculation functional entity**: This functional entity can calculate the energy measurement time considering the variation of traffic volume or energy consumption, traffic volume and the alarm flag.
- **Adjusting functional entity of measurement time**: This functional entity adjusts the energy measurement time based on the results of the calculation functional entity.

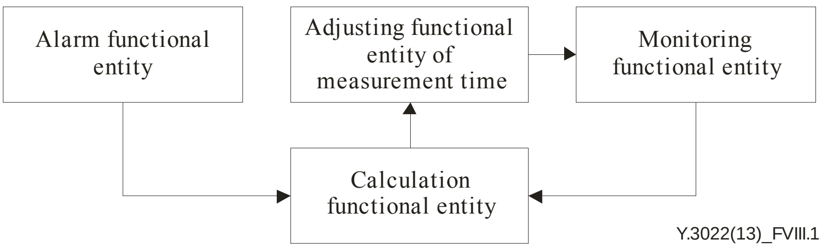

Figure VIII.1 – Framework for adjusting the energy measurement time

VIII.2 Variation of traffic volume-based adjusting method for the energy measurement time *T*

This clause explains the adjusting method for the energy measurement time based on the variation of traffic volume. The energy measurement time can be changed by variations in traffic volume, as in the traffic congestion situation using equation VIII.1. When the variation in traffic volume ΔL is higher than the arbitrary value M, the energy measurement time decreases by a specific time α. On the other hand, it increases by α when ΔL is lower than M. If ΔL is equal to zero, the energy measurement time is not changed. In addition, the energy measurement time is the threshold value $T_{threshold}$ if the alarm is on. Through the adjustment of the energy measurement time, the network providers can efficiently measure energy consumption.

$$T = \begin{cases} T_{prev} + \alpha, & if\ \Delta L > M \\ T_{prev} - \alpha, & if\ \Delta L < M \\ T_{prev}, & if\ \Delta L = 0 \\ T_{threshold}, & if\ alarm\ is\ on \end{cases} \quad \text{(VIII.1)}$$

where T_{prev} represents the energy measurement time at the previous time. α represents the standard value of the energy measurement time to evaluate whether T is increased or not. M represents an arbitrary value, the network provider can randomly set this value. ΔL represents the variation of traffic volume during the measurement time. $T_{threshold}$ represents the threshold value of the energy measurement time for the traffic congestion situation.

VIII.3 Variation of energy consumption based method for adjusting the energy measurement time *T*

This clause explains the method for adjusting the energy measurement time based on the variation of energy consumption. The energy measurement time can be changed by a variation in energy consumption according to the traffic congestion situation using equation VIII.2. If ΔL is equal to zero, the energy measurement time is not changed. In addition, the energy measurement time is the threshold value $T_{threshold}$ if the alarm is on. Except for the previous two cases, if ΔL is changed, the energy measurement time is T divided by k, which is the slope of the energy profile function ($= f_l()$) shown in Figure VIII.2,

$$T = \begin{cases} T_{prev}, & if\ \Delta L = 0, \\ T_{threshold}, & if\ alarm\ is\ on \\ T/k, & otherwise \end{cases} \quad \text{(VIII.2)}$$

where $f_l()$ represents the energy profile function of link l according to the normalized traffic load. Therefore, $f_l(L)$ represents the normalized energy consumption at the normalized traffic load L according to the energy profile function.

NOTE – The energy profile function can be also termed as a mathematical formula.

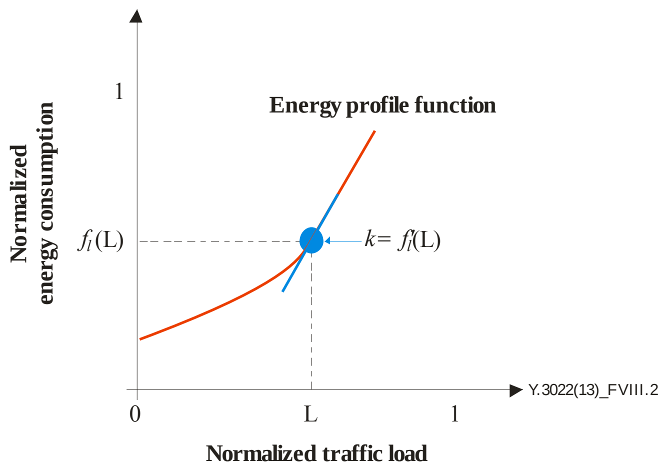

Figure VIII.2 – The energy profile function

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