Energy Efficiency Metrics For Green Wireless Communications
(Invited Paper)

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***Abstract*—Recently the concern on energy efficiency in wireless communications has been growing rapidly as energy consumption increasingly becomes a global environment problem. Lots of research and development efforts have been spent in wireless industry, aiming for energy efficient solutions which lead to green wireless communications. In this paper we provide a brief overview on those efforts, with an emphasis on introducing energy efficiency metrics. Since energy efficiency metrics are indicators of efficiency, understanding those metrics provides us a better view on how energy efficiency can be achieved in wireless systems/networks. Observing energy is a concern at every corner of a wireless system/network, we describe those metrics from at**

component, equipment and system/networks level, respectively. From our observation, energy efficiency metrics for components and equipments have been well established. However, studied for system/network level solutions and metrics deserve more attention. We believe new energy efficient architecture and associated metrics will be the key for the energy consumption problem in wireless industry.

I. Introduction

The exponential growth of wireless communications calls for energy efficient solutions. According to the prediction by Gartner, the mobile will surpass the PC as the most common web access device by 2013 [1]. Consequently, more wireless infrastructure is needed, which significantly increases energy consumption of the whole wireless industry. Furthermore, the data volume of networks is expected to increase approximately by a factor of ten every five years, which associates with 16 - 20% increasing of energy consumption [2]. Applying this rate to mobile communications, it will contribute to 15 - 20% of the entire Information and Communications Technologies (ICT) energy footprint and 0.3 - 0.4% of annual world carbon dioxide emissions [2]. The wireless industry faces a sustainable development problem on energy consumption. It is critical to develop energy efficient technologies to meet this challenge and enable green wireless communications for environment protection.

Enabling energy efficient wireless communications is not a simple task. Since in the past the performance is the primary concern of communication systems, energy efficiency (EE) has been received less attention in the system design and operation. Even it is considered at the component level, to achieve EE a holistic view is necessary from the system architecture to component. It demands a clear understanding on energy consumption in current network and network elements. We expect energy efficient solutions will come from new thinking of architecture design, deployment strategies, spectrum management schemes, backhaul options, EE metrics and models.

It is important to emphasize the role of EE metrics in energy efficient communications. The concept of EE becomes meaningful only when it can be measured. Metrics then provide quantified information to evaluate efficiency. EE metrics are normally used for three purposes: to compare energy consumption performance of different components and systems in the same class; to set explicit long term research and development targets on EE; to reflect EE of certain configuration in a system/network and enable adaptation to more energy efficient configuration. Since EE can be achieved at every corner of a system/network, different metrics have been developed. Learning these metrics will help us build a better understanding on energy consumption problems.

In this article we focus on introducing the EE metrics developed at the component, equipment and system/network level. The paper is structured as follows. In Section II, we explain the importance of EE metrics. Then in the following sections, we provide an overview on metrics developed for different levels of a system/network. The conclusion is drawn in Section VI.

II. Need for EE Metrics

According to the purpose of a system, EE can be defined in different perspectives. One way is to define EE as the ratio of efficient output energy to total input energy. The other way is to define EE as the performance per unit energy consumption. The performance is referred to Floating-Point Operations Per Second (FLOPS) in digital signal processor (DSP), Million Instruction Per Second (MIPS) in computer systems, and throughput (bits/second) in communications.

EE is a concept related to comparison. The aforementioned two definitions of EE show two ways of comparison. The first one directly compares output power with input power; the second one maps energy to measurable performance and make the head-to-head comparison of similar systems possible. EE metrics are classified into two categories: absolute metrics which indicate the actually energy consumed for performance, and relative metrics which show how EE is improved. For the former, bits/Joule is the most widely used metric; for the latter,

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the ratio of output and input power in power amplifiers is an example.

The requirements of EE metrics at the component, equipment, and system/network level are significantly different. EE metrics for components are relatively straightforward to define and most of them have been well established. It is more complicated to define an EE metric for equipment and system/network. The reasons are following. Following the specifications defined in the standards, manufacturers implement equipments using competing technologies, which are different in performance, capacity, and energy consumption. Moreover, telecommunication equipments are normally operated at different loads. Energy consumption does not linearly scale with loads. The measurement method should be standardized for a metric so that the results for different systems are comparable. A measurement method describes the measurement setup, environment and procedure.

Since the value of a metric is obtained from measurement, a metric comes with accuracy, which reflects the averaging done in the course of measurement and fluctuations within the device. The former is related to sampling frequency during the test, and the latter is related to technological deviations, which reflect the tolerance of components in the system. Accounting for metrology errors and platform variations, a difference of 10% or higher is possible. The accuracy of a metric should be taken into account in comparison.

In remainder of the paper, we will provide an overview on the typical EE metrics used by components, equipments and systems/networks.

III. Component Level

According to the purposes and architecture, there are different types of wireless systems/networks. Some of them work in an ad hoc way and others rely on infrastructure. For wireless ad hoc networks they may only consist of wireless equipments. Here we use the wireless equipment as a general term referring to any devices with air interfaces, which could be radio BSs (RBS) or wireless terminals. For infrastructure based wireless networks, such as cellular networks, both wireless and wired equipments are integrated part of the network. We only discuss the components in a typical wireless equipment in this article.

We use a general EE model, as shown in Fig. 1, for different types of wireless equipments. As wireless equipments share key common components, this common model is sufficient to understand EE at the component level. However, we should note that wireless equipments may have difference on components. The building blocks of a typical wireless equipment are shown in Fig. 1. They include antenna(s), radio frequency (RF) frontend, baseband processor, support system, power supply, and optional components like the climate control. A RF frontend consists of transmitting and receiving chains. The power amplifier in the transmitting chain is explicitly drawn in the figure since it has a significant impact on EE of a wireless equipment. The support system implements link to higher layer protocol stack, performs control functions, and provides interface to other network elements. The power source in power supply can be alternating current (AC) power supply or battery. Finally, optional components, such as air condition for the climate control, may be equipped in large equipments like RBSs. In the following, we describe the energy efficiency metrics of components in details.

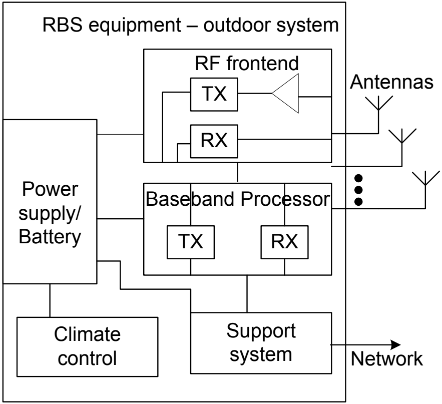

Fig. 1. Building blocks of a wireless equipment.

The efficiency of an antenna is related to the input power to the antenna and the power radiated by the antenna. A high efficiency antenna has most of the input power at the antenna radiated away, while a low efficiency antenna has most of the power absorbed as losses within the antenna. The losses associated with an antenna are typically the conduction losses and dielectric losses. Sometimes efficiency is defined to also include the mismatch between an antenna and the transmission line. The efficiency can be written as the ratio of the radiated power to the input power of the antenna:

$$\eta_{Ant} = \frac{P_{radiated}}{P_{input}} \tag{1}$$

The other way to describe the efficiency of an antenna is the antenna gain, which tells how much power is transmitted in the direction of peak radiation to that of an isotropic source which equally radiates in all directions. The antenna gain takes into account the efficiency of the antenna as well as its directional capabilities. It is more commonly quoted in a real antenna's specification. The antenna gain is expressed as:

$$Gain = 4\pi \frac{\text{Radiation indensity}}{\text{Antenna input power}} \tag{2}$$

In a RF frontend or even an equipment, the power amplifier is the main source of power consumption. The study showed the power amplifiers in a GSM BS turns 22% of total input energy into heat [3]. The efficiency of power amplifier is defined as the ratio of effective output power to input power, shown as follows:

$$\eta_{PA} = \frac{P_{output}}{P_{input}} \tag{3}$$

It is important to solve the EE problem caused by the power amplifier. A straightforward approach is to improve the efficiency limit of the power amplifier. In RF power amplifiers, special design techniques are used to improve efficiency. Doherty designs, which use a second transistor, can lift efficiency from the typical 15% up to 30-35% in a narrow bandwidth. Envelope Tracking designs are able to achieve efficiencies of up to 60%, by modulating the supply voltage to the amplifier in line with the envelope of the signal. Moreover, digital-pre-distortion (DPD) techniques can help maximize power amplifier efficiency, increase reliability, and reduce operating costs. A system level approach is to shut down a power amplifier when the transmitter is idle. This is currently under intensive study in the 3rd Generation Partnership Project (3GPP) standard body [4].

The baseband processor in a wireless equipment is normally a digital baseband, which relies on DSP for processing. EE of a DSP is measured by performance per unit energy consumption. The widely used performance metrics for a DSP is FLOPS, which measures the floating point performance of the processor. The EE metric for a DSP is then FLOPS/watt or Million FLOPS (MFLOPS)/watt. Similarly, the support system running protocols and control functions also uses performance per unit energy consumption. As the support system is more like a computer system, MIPS is normally used as the performance metric. MFLOPS and MIPS are not interchangeable. Both types of operations, however, require processor clock cycles, allowing one to express demand in a common measure of millions of operations per second (MOPS) where an operation is the amount of work that can be accomplished by a given resource in a single clock cycle of a standard width. Using this measure, required MIPS and MFLOPS can both be expressed in MOPS. A general EE metric for the baseband DSP and the support system is then MOPS/watt. Note that Input/Output (I/O) and memory access affect the performance of a DSP and computer system. The capacity of a baseband processor and support system may become the bottleneck of the whole equipment, which in turn limits the capacity and EE performance of the equipment.

As the function of a power supply is to provide energy to a equipment, its EE is measured by effective output power to input power. Normally an AC power supply has an efficiency of 85% or higher [3].

From the equipment viewpoint, optional components like the climate control turns all input energy into heat. We normally do not evaluate EE of the climate control in a communication system, but simply reduce its consumed energy as much as possible. There is a new design trend to apply passive cooling techniques in the equipment. That totally avoids energy used by the climate control.

IV. Equipment Level

It is hardly to classify wireless equipments due to the diversity of equipments. To understand the EE problem, however, we roughly divide wireless equipments into RBSs and wireless terminals. A RBS here refers to a cellular BS or wireless access point, while a wireless terminal refers to a user terminal equipped with wireless interfaces. The justification for such a classification is that RBSs and wireless terminals are most used wireless equipments.

The standard body European Telecommunications Standards Institute (ETSI) defined the metrics and methods to evaluate EE of RBSs in [5]. The current technical specification [5] covers three systems: GSM/Enhanced Data-rates for Global Evolution (EGDE), Wideband Code Division Multiple Access

(WCDMA), and Worldwide Inter-operability for Microwave Access (WiMAX). EE for 3GPP Long Term Evolution (LTE) system will be included in the new version.

The ETSI document [5] specifies the standardized energy consumption measurement for a RBS equipment and a RBS site. A site normally includes a RBS equipment, rectifiers, climate control, power distribution loss between units, and other auxiliary equipments and cabinets. A reference model for a RBS site is shown in Fig. 2. Note that the figure only shows the outdoor reference model. For the indoor reference model the climate control is not used.

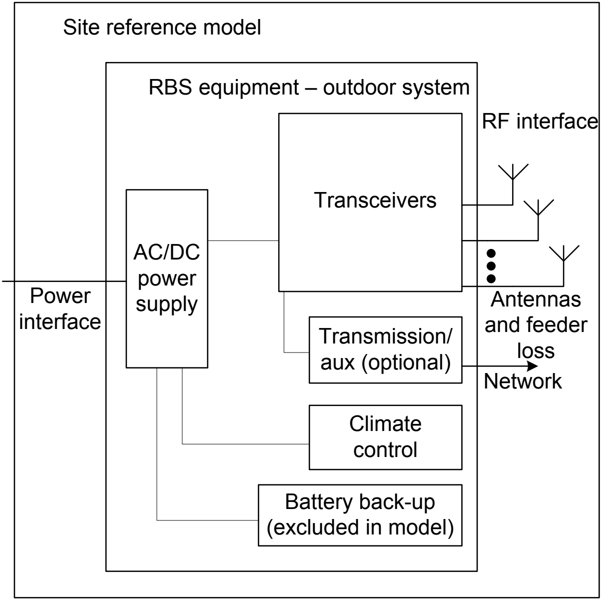

Fig. 2. RBS site reference model, source [5].

RBSs defined in [5] are divided into concentrated RBSs and distributed RBSs. The difference is that a concentrated RBS puts all but antenna element in the same location, while a distributed RBS uses the remote radio head (RRH) close to the antenna element to reduce feeder loss. The measurement takes power consumption samples at different load conditions, i.e. busy hour load, medium term load and low load. The duration in each load condition is denoted as t_{BH}, t_{Med}, t_{Low}, respectively. For a concentrated RBS, assuming the average power consumption measured in each load conditions is P_{BH}, P_{Med}, P_{Low} respectively, the average power consumption in watt is defined as:

$$P_{equipment} = \frac{P_{BH}t_{BH} + P_{Med}t_{Med} + P_{Low}t_{Low}}{t_{BH} + t_{Med} + t_{Low}} \tag{4}$$

For a distributed RBS, the power consumption for RRH and the elements in the central location are measured separately. Using the equation similar to Eqn. 4, we can get the power consumption of RRH and central elements P_{RRH} and P_C. The total average power consumption of a distributed RBS is:

$$P_{equipment} = P_C + P_{RRH} \tag{5}$$

The power consumption of a site takes into account power consumed by power supply, cooling and other auxiliary equipments. Two correction factors are applied in the power consumption of the RBS equipment to get the power consumption of a site: the power supply correction factor, denoted as PSF, and the cooling factor, denoted as CF. Both two factors are unit less and the values are related to the specific system. The average power consumption for concentrated RBS is defined as:

$$P_{site} = PSF \cdot CF \cdot P_{equipment} \tag{6}$$

For a distributed RBS site, the specific correction factors for central elements and RRH are applied separately, and the power consumption of the site is obtained by getting the sum.

The FLexi EDGE Base Station from Nokia Siemens Networks is announced as the first one to be measured following the ETSI technical specification [6]. In a typical configuration of 3 sectors and 4 carriers per sector, the average power consumption of a Flexi EDGE Base Station is 978 watts . By using energy saving features, it can be reduced to 562 watts in some instances.

In current version of the ETSI document [5] no EE metric is proposed for the RBS equipment. However, with the average power consumption, we can use the metrics proposed by the Energy Consumption Rating (ECR) Initiative [7]. The basic form of ECR is:

$$ECR = \frac{E}{T} \tag{7}$$

where E is the energy consumption in watts and T is the effective system throughput in bits per second. The effective system throughput counts the frame overhead from the physical and link layer.

In a wireless terminal, communications is normally just a function to support applications. To study EE of a wireless terminal, the whole functions of a terminal should be taken into account. Typical wireless terminals are mobile phones, mobile computers, such as netbooks and notebooks, and other user equipments. Taking the mobile phone as an example, the measurement shows that wireless modem in Nokia 6630 consumes 1.2 out 3 watts [8]. The other 1.8 watts are used by applications and other peripherals. Since mobile devices are normally energy constrained, EE is one of primary design targets. The de-facto standard to measure EE of a mobile phone is the talking time and stand-by time by a fully charged battery. If those data are normalized by the capacity of battery, we can get EE metrics of a mobile phone. For netbooks and notebooks, since the communication function is just an option, when referring to EE, the focus is more on the application level. The ENERGY STAR, an international standard initialized by US government, specifies the EE requirements for computers, which include notebooks [9]. The current standard for computers is Energy Star Version 5.0. Note that the edge between a mobile phone and a mobile computer become blur. A unified approach to evaluate EE of both categories may need in the future.

V. System/Network Level

Wireless systems/networks can be roughly divided into four classes. The first and oldest one is the class of cellular networks. Cellular networks are normally deployed with careful network planning, and rely on RBSs to provide access services. The second class of wireless network is wireless local area networks (WLAN). The IEEE 802.11 standard series is the de-facto standard for WLAN. For a WLAN to offer wireless access services to wireless stations, it is more like a simplified version of a cellular network, where an access point acts as a RBS. Different from a cellular network, no network planning is required to deploy access points. The third class refers to those using satellite links. Since satellite communications only occupies a small portion in the whole wireless industry, we do not discuss EE of satellite communications in this article. The fourth class is wireless ad hoc networks, which refer to self-organizing wireless networks without the support of infrastructure. Note that WLAN has different forms, in which some forms can be regarded as wireless ad hoc networks. In this article, we narrow WLAN to the network using access points. EE is one of primary concerns in wireless ad hoc networks, since nodes in such a network normally use battery. The wireless sensor network is considered as a special case of wireless ad hoc networks. Energy consumption problem is more critical in wireless sensor networks as the battery of a sensor may not be charged or replaced.

ETSI defines two network level EE metrics for the GSM system in [5]. The network level EE considers not only energy consumed by the RBS site, but also the features and properties related to capacity and coverage of the network. In rural areas, the network is seldom fully loaded. The coverage area is used in EE metric to reflect energy to achieve coverage. The EE metric for rural area is define as:

$$PI_{rural} = \frac{A_{coverage}}{P_{site}} \tag{8}$$

where $A_{coverage}$ is the RBS coverage area in km^2, and P_{site} is the average site power consumption. The coverage area is calculated based on uplink and downlink system values.

In urban areas, the traffic demand is often larger than the capacity of the RBS. The capacity, instead of the coverage, is reflected in the EE metric. The metric for urban area is defined as:

$$PI_{urban} = \frac{N_{BH}}{P_{site}} \tag{9}$$

in which N_{BH} is the number of subscribers based on average busy hour traffic demand by subscribers and average RBS busy hour traffic.

Referring to the area spectral efficiency [10], Richter et al. proposed the concept of the area power consumption for cellular networks [11]. The metric for the area power consumption is defined as:

$$\rho = \frac{P_C}{A_C} \tag{10}$$

where P_C is the power consumption of a cell site, and A_C is the coverage area in km^2 of the cell. The area power consumption reflects the power consumption of cellular cells at different site density. Note that this metric is the inversion of Eqn. 8.

As we can see, the aforementioned metrics are not directly related to the throughput performance of the system. The reason is that for the GSM and WCDMA system the main service is voice, the performance of which is not measured by the data rate. However, in fourth generation cellular systems, all services are carried by packets. It provides a possibility to measure the performance of the system by throughput represented by the data rate. Bit/Joule is expected as the basic EE metric for fourth generation cellular systems and beyond.

EE of WLAN has been intensively studied, mostly focus on the performance of medium access control (MAC) protocol [12][13]. The sleep mode has been introduced into the IEEE 802.11 standards for energy saving. The idea is that a station which has nothing to send or transmit can temporarily shut down its transceiver and wakes up periodically to transmit or receive buffered messages. The metric used to evaluate energy saving of the sleep mode is normally the ratio of saved power to the power without the use of the sleep mode. Studies showed the energy saving performance is affected by the size of the Announcement Traffic Indication Message (ATIM) window, which is a repeated time period that a sleeping station has to wake up and listen to the channel. Algorithms are proposed to adapt the ATIM windows to network conditions [12]. The average throughput/Joule is proposed by [12] as an EE metric. The unit of this metric is bits/Joule. IEEE 802.11 standard also introduced dynamic frequency selection (DFS) and transmit power control (TPC) in IEEE 802.11h to solve the interference problem with satellites and radio at 5 GHz frequency band [14]. It is clear that the power control will have positive impact on energy consumption. However, fewer studies have been found on this topic. The EE metric for power control in IEEE 802.11 can be the same as used in the sleep mode.

The EE studies in wireless ad hoc networks have spanned all layers of the network protocol stack. The energy saving in wireless ad hoc networks can be achieved by the following methods: collision avoidance; the sleeping mode; radio turnaround reduction; channel and battery aware schedule; adaptive Automatic Repeat-reQuest (ARQ) and Forward Error Correction (FEC); EE routing; topology aware power control; application aware power saving. In the following, we describe the main methods used from MAC to transport layer and the associated EE metrics.

At the MAC layer, the energy saving is achieved mainly by collision avoidance and sleep mode. For instance, Singh et al. proposed the Power Aware Multi-Access protocol with Signalling (PAMAS) for energy saving in ad hoc networks [15]. They introduced a separate signalling channel to exchange Request to Send (RTS)- Clear to Send (CTS) messages and send busy tones to resolve the hidden terminal problem. Their approach enables nodes in the network to avoid collision and determine when and for how long they can power themselves off. The power saving metric used in [15] is the ratio of saved power to the consumed power without using power aware algorithm. By simulation, the power saving of 10%-70% was reported. In [16], the S-MAC protocol is proposed for wireless sensor networks. Like in PAMAS, the sleep mode is the main method to achieve energy saving, but it only uses one channel for data and signalling. Moreover it uses message passing to divide a long packet to small segments for transmission so that the retransmission overhead is reduced. The EE metric used by S-MAC for comparison with other MAC protocols is Joule.

The error control and correction at the link layer have impact on energy consumption. There are two types of error correction mechanisms: ARQ and FEC. The former uses retransmission to guarantee the order delivery of messages, while the latter adds redundancy at a message to help the decoding even some errors are detected in the message. For ARQ, the unnecessary retransmission will waste energy when the channel is in deep fading. Zorzi et al. [17] studied this problem and developed an adaptive ARQ algorithm to freeze ARQ process when the channel condition is bad. An EE metric is proposed to evaluate the energy saving performance, which is:

$$\lambda = \frac{\text{total amount of effective data delivered}}{\text{total energy consumed}} \tag{11}$$

For FEC, energy is wasted if the channel condition is good since redundant information is not necessary to be used. The combination of ARQ and FEC to conserve energy was studied in [18], which used ARQ retransmission for short packets and FEC for long packets. The EE metric used in [18] is:

$$E_t = \frac{P}{C} \tag{12}$$

where P is the transmitter power, and C is the bit rate of the channel.

At the network layer, EE is mainly concerned in routing. It should be noted that EE in wireless ad hoc network has an additional meaning. That is not only energy saving but also network partition avoidance are considered as EE. Network partition happens when the use of some routing metrics, e.g. the short path routing metric, leads to some nodes in the network being frequently chosen for routing so that their batteries are depleted quickly, consequently affecting the connectivity of the network. To mitigate network partition, the routing protocol should take into account the residual energy of nodes when establishing a routing path. Therefore in addition to those EE metrics to evaluate the energy saving performance, energy aware routing metrics are also considered as EE metrics. Two parameters are normally considered in energy aware routing metrics: energy cost of a link, and the residual battery level of a node. The link energy cost is a function of distance between two neighboring nodes [19]. The residual battery level is mapped into a cost function, where the cost is inversely proportional to the battery level. In [19], three routing algorithms are proposed according to the metrics based on these two parameters: the power efficient algorithm chooses a link with minimum energy cost to establish the route; the cost efficient algorithm selects nodes with more battery level as routing nodes; the power-cost efficient algorithm considers a tradeoff between the link energy cost and the battery level of a node. Combining the link energy cost and the battery level of the node as a routing metric is also considered in [20]. In addition to unicasting, applications may also use broadcasting and multicasting in wireless ad hoc networks.

Energy efficient broadcasting and multicasting involve the building of broadcasting and multicasting trees, which is studied in [21]. The idea is to develop an energy efficient metric to evaluate total energy cost of the tree.

At the transport layer, EE of Transmission Control Protocol (TCP) is studied in [22], where EE is defined as the average number of successful transmission per unit energy. It showed EE is sensitive to TCP versions. TCP is originally designed to use packet loss as a trigger for congestion control, while in wireless networks packet loss is normally caused by the bad channel condition. The use of wrong trigger will degrade the TCP throughput. Tsaoussidis et al. proposed a TCP probing mechanism to improve it EE in wireless networks [23]. In TCP probing, data transmission is suspended and a probe cycle is initiated when a data segment is delayed or lost, rather than immediately invoking congestion control. The metric energy expenditure ratio is used to evaluate EE. It is defined as total overhead bytes generated by original TCP divided by overhead bytes generated by the proposed protocol. Simulation results indicate that TCP probing achieves higher throughput rates while consuming less energy.

VI. Conclusion

This article provides an overview on EE metrics used by wireless systems at the component, equipment, and system/network level. Those EE metrics fall into two categories: those used for energy performance comparison, and those used to configure system for better EE. We notice that EE metrics at the component and equipment level are well developed, while those for system/network need more attention. To achieve the long term EE goal for the sustainable growth of wireless industry, the answer may exist in new EE technologies and architecture, and especially the energy efficient architecture that uses relay, cooperation and cognitive radio technologies for capacity performance and EE.

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