# Towards Taxonomy of Telecommunication Network Metrics

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***Abstract*—The metrics and measurements play a crucial role in the whole lifecycle of telecommunication networks. The number of metrics being considered for modern telecommunication systems supporting digital or computing infrastructures has grown exponentially. It requires sophisticated systems for the metrics management which are under development by the industry consortia. For many research tasks, it would be sufficient to identify a relatively small number of recommended metrics to achieve more consistent evaluations of the system performance. There are still many unsolved problems in this area including defining the optimum modeling strategies and the metrics optimality. This paper explores a landscape of the most commonly used telecommunication and computing metrics to illuminate what metrics are available.**

***Keywords*–key performance indicator; metric; measurement; performance; telecommunication network**

## I. Introduction

Numerous metrics are routinely used to design, deploy and manage telecommunication systems and services. The metrics to accomplish specific objectives are often referred to as key performance indicators (KPIs), and they are intended to drive the system and service adoption rates. The metrics included in service level agreements (SLAs) define contractual agreements between the service providers and the service consumers. Some metrics have been standardized to support objective comparison and regulatory compliance of products and services from different vendors and providers. In general, metrics describe how the physical infrastructure and dynamic processes are perceived by various stakeholders. In that sense, metrics represent simple models or abstractions of otherwise rather complex systems.

As the complexity of systems is increasing over time, and as the system design objectives get updated, the metrics need to evolve correspondingly. For example, today's wireless networks assume multiple design and operational objectives to deliver services in the desired quality and quantity while the system resources are optimized to be used efficiently. Some metrics are phased out or modified, and the new metrics are introduced constantly. It is often difficult to know beforehand what assumptions need to be satisfied in order for the metric to be meaningful. Hence, the subject of metrics and measurements is a complex matter, and it deserves more systematic study and understanding. At minimum, there is a need to establish rules how to define the optimum metrics and their measurement conditions for the system and tasks considered. The selection of metrics should assist to achieve the desired objectives such as making operational decisions. The proper interpretation of measurements is equally important.

Several sources of metrics can be identified. The largest number of metrics can be found in the technical literature. Some of these metrics are used much more often than the others. Many metrics in the literature are a result of mathematical analysis, so they are concise representations of the system model considered. The regulatory bodies and industrial consortia are another important source of metrics. The previously published papers on metrics either focus on some specific metrics, or they survey the metrics defined for a particular objective. In this paper, our aim is to look at the landscape of metrics for telecommunication networks more broadly. We reviewed over 400 papers, technical reports and online articles concerned with different problems in telecommunications networks, so the references included in this paper should only be considered as illustrative examples. This effort allows us to understand how the network metrics are being used. We identified the following groups of metrics for telecommunication networks which appear to be used most widely: fairness, energy and power, quality-of-service (QoS), quality-of-experience (QoE), robustness and resilience, and security metrics. We also consider metrics for emerging digital systems such as computing platforms and websites, metrics used specifically to characterize broadband networks and Internet traffic, and metrics used for machine learning from big data. Other important metrics not included in this paper are, for example, the metrics related to users behavior (e.g., social metrics), and the metrics to quantify the financial and business aspects of telecommunication networks. Moreover, we did not summarize any metrics which are used to evaluate the performance at the physical layer (e.g, probability of outage, and spectral efficiency).

## II. Metrics Selection

The metrics represent simplified models of systems by transforming possibly complex systems into simpler observations. Such compression of the system complexity can create another problem of how to interpret these measurements. This leads to two fundamental scenarios depicted in Fig. 1. In the reverse data-driven modeling of systems, the available measurements constrain possible applications to define system model and the corresponding metrics. This strategy of defining the system model and its metrics is used when there is uncertainty about the exact functions or services the system will be offering such as the case of self-learning systems utilizing the artificial intelligence. However, in a purpose-driven engineering design, the forward data-driven system modeling is usually preferred. In this case, we determine what measurements are needed for a given application and for given observation metrics.

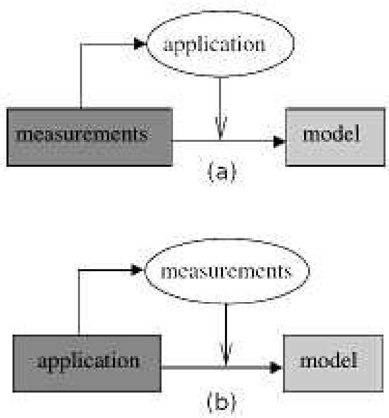


Figure 1. Reverse (a) and forward (b) data-driven modeling.

In general, the more complex system we are dealing with, the more opportunities there are to define different perspectives, models and metrics for that system. Zachman framework is commonly used in the industry to manage this complexity [1]. In particular, the interests of different stakeholders are represented in a two dimensional table the rows correspond to stakeholders, and the columns are system attributes. The stakeholder perspectives correspond to contextual, conceptual, logical, physical, and out-of-context views of the system, or equivalently, to scope, business, system, technology, and detailed representation of the system, respectively. For metrics, the columns in Zachman framework matrix could be interpreted as:

- data model of measurements (the what);
- flow of measurements (the how);
- location of measurements (the where);
- interaction with the network operators (the who);
- time-scale ofmeasurements (the when);
- converting measurements to decisions (the why).

In telecommunications, we can identify the following stakeholders: equipment manufacturers and subcontractors, infrastructure providers, service providers, content providers, network operators, end-users, government, and regulatory bodies. Table I highlights different interests of telecommunication stakeholders assuming the energy consumption, the services quality, and the costs involved. The stakeholders create the whole ecosystem of telecommunication services and markets with complex mutual interrelations. Since the stakeholder interests may be conflicting, it is important to manage their competing goals, and to carefully define the trades-off among multiple performance objectives. For instance, the total energy consumption in telecommunication sector is relatively small, however, the energy consumption is vital for network operators to reduce their operational expenses.

Table I
Interests of Different Stakeholders

| | **Energy consumption** | **Services** | **Costs** |
|---|---|---|---|
| **Equipment manufacturers** | embodied energy | KPIs | production cost |
| **Infrastructure providers and network operators** | deployment and operational energy | SLAs | CAPEX and OPEX |
| **Content and service providers** | operational energy and battery lifetime | QoS and QoE | infrastructure rent cost |
| **Regulatory bodies** | spectral RF mask | KPIs and SLAs | fairness of fees |
| **Government** | sector energy consumption | availability and accessibility | GDP creation |
| **End-users** | battery life time | QoE | monthly fee |

In general, selecting appropriate or even optimum metrics is crucially dependent on who is going to use these metrics (different stakeholders have different goals and needs), time-scales, measurement location, assumptions, system model adopted, and the scenario considered. The following characteristics can guide the metrics selection:

- accuracy: measurement errors and biases need to be within acceptable limits;
- validity: measurements and their evaluations need to be checked for correctness;
- feasibility: measurements are collected as necessary;
- robustness: measurement quality must not be affected by changing conditions of the system or environment;
- efficiency: measurements should not consume too much of the system resources;
- desirable: measurements collected are required for the system design or operation;
- viable: measurements being collected can clearly provide the measurable benefits.

The following institutions are issuing standards and recommendations about the metrics and measurement procedures:

| | |
|---|---|
| 3GPP(2): | 3rd Generation Partnership Project |
| ATIS: | Alliance for Telecomm. Industry Solutions |
| ETSI: | European Telecomm. Standards Institute |
| IEEE-SA: | IEEE Standards Association |
| IETF: | Internet Engineering Task Force |
| ITU: | The International Telecomm. Union |
| TIA: | Telecomm. Industry Association |

## III. Metrics Classification

By reviewing hundreds of technical reports and papers to survey the metrics which are used for telecommunication networks, we discovered two things. First, the number of the metrics is enormous, so collecting all of them would be impractical. Many of these metrics are used for specific purposes, and their general applicability is rather limited. In addition, very few papers in telecommunication engineering are specifically devoted to metrics; instead, most of these papers assume a small number of specific metrics to quantify how well the used method achieves a given performance objective. Second, if we restrict our attention only to the metrics which are used most frequently, several distinct categories of metrics readily emerge:

1. General aspects of network metrics: [2], [3]
2. Energy and power metrics: [4]
3. Quality-of-service (QoS): [5]
4. Quality-of-experience (QoE): [6]
5. Combining QoS and QoE: [7]
6. Throughput and delay metrics: [8], [9]
7. Failures and robustness metrics: [10], [11]
8. Security metrics: [12]

The commonly used metrics for telecommunication networks are summarized in Table V at the end of this paper.

### A. *Energy and power metrics*

These metrics are used to reduce the operational cost, extend the battery lifetime, and to some extent, to reduce the environmental footprint. The main challenge is to reduce energy consumption without sacrificing other performance metrics, especially the level service provided. Alternatively, we can intentionally trade-off energy consumption with other performance parameters. For example, the delay-tolerant networking is a very efficient method to reduce the energy consumption. There are two main reasons why some of these metrics have been standardized (e.g., by ITU, ETSI and ATIS). First, these metrics represent an important differentiating factor for telecommunication equipment from the different vendors. The network infrastructure providers as well as the end-users prefer to use equipment delivering the same utility, but having smaller energy consumption. Second, defining the energy or power measurement procedures is non-trivial.

The total energy consumed is a sum of the embodied and operational energy over the whole life-cycle of a telecommunication product. The operational energy can be further decomposed into the baseline energy which is expended even when the equipment does not produce any useful work (e.g., when the network traffic load is zero), and the energy which is proportional to the useful work (e.g., the network traffic load). Many papers on telecommunication networks assume only this latter energy while ignoring the baseline energy which is difficult to quantify without considering specific equipment from a vendor. Another typical case which may lead to misleading conclusions is to only assume the energy required for the transmission while completely ignoring the baseline energy consumption during the receiving and idle modes of the transceiver.

### B. *QoS metrics*

The QoS metrics are probably among the most used in telecommunication engineering. Many QoS metrics have relatively simple definitions, however, specifying their measurement conditions may be challenging. For instance, the users of broadband services are subscribing to monthly plans with defined connection speeds usually expressed in Mbit/s. Such data rate can mean a peak value, an average value, or the value which is achievable most of the time. In addition, the data rate can be measured to a specific end-point, e.g. the first router, it can be averaged across many connections, and so on.

The QoS requirements are specified in SLAs, in standards, and they are key items included in most product specifications. They play a key role in the real-time management of telecommunication networks. Maintaining the required QoS can be challenging under the network dynamic conditions. It is possible to define QoS classes in order to support differentiated services (e.g., IntServ and DiffServ). The QoS metrics can be also classified as application-oriented (AQoS) and network-oriented (NQoS). The former are concerned with the end-to-end quality of real-time applications such as voice and video, and they focus on the user satisfaction. The latter consider the quality of traffic delivery through the network equipment.

In Table V, we classify the QoS metrics as error rate metrics, throughput metrics, delay metrics and availability metrics. The latter category received a lot of attention in the context of self-healing networks and their ability to recover from the hardware and software (hard) failures, and the temporal link (soft) failures due to time-varying propagation conditions. It should be noted that provisioning of the QoS in wired and wireless networks is fundamentally different. For instance, using TCP/IP in wireless networks is much less efficient than in the wired networks.

### C. *QoE metrics*

The QoE metrics are used to measure and express, preferably as a numerical value, the experience or perception of the users with a telecommunication service. These metrics explore the user satisfaction, and possibly also their response to the service. The mutual interactions of users also influence their perceptions of the service quality. The challenge in defining these metrics is a lack of commonly accepted models of the human perception, and the difficulty to precisely define the measurement context. The situation is even more complicated in heterogeneous networks where the QoE is influenced by the content type, service type, pricing policy and other psychological characteristics.

The QoE metrics are rapidly evolving, partly to account for the new multimedia services being introduced such as the immersive reality. The QoE metrics can be associated with both subjective and objective quality needs, and they go beyond just complementing the technical QoS performance indicators. Using the QoE rather than the QoS may lead to better economic returns for the service providers by optimizing the service pricing plans. However, improving the QoS (e.g., by a technical upgrade) may deteriorate the QoE, and thus, lower the user satisfaction. Nevertheless, the mappings of QoS values to QoE values are often considered in practice.

The QoE can be assessed using either subjective or objective metrics. The subjective metrics involve either qualitative (surveys and interviews) or quantitative (statistical measurements) methods, but their disadvantage is that they are not suitable for real-time monitoring. On the other hand, the objective QoE metrics mathematically infer the user satisfactions from the QoS measurements using full, partial or no-reference data. The challenge is to define appropriate non-linear and time-varying models of the human perception. These metrics are now used extensively by network operators and application developers.

### D. Robustness and resilience metrics

A common strategy to assess the network robustness and resilience is to explore the network topology. The traditional analysis of network topology is known as the social network analysis (SNA). The key idea is to infer the network functionality or other characteristics (e.g., the robustness against attacks or faults) from its structure. The original methods of Network Science have been devised for the networks in the nature which are large scale, and are governed by complex and often unknown interactions. The man-made networks such as those in telecommunications are comparably much smaller, and their internal interactions are well defined. The network services are defined at a macroscopic level. If we have sufficient number of network measurements, it may be possible to infer its internal topology, or the values of hidden parameters which is sometime referred to as a network tomography.

The connectivity in wireless networks is affected by the broadcasting nature of wireless transmissions and the protocols used. The connectivity is an integral quantity, so it can only be defined over a finite time interval. The connectivity may indicate the network functionality. For instance, knowing the structure and function of network A, we can infer the function of network B by comparing its structure with the network A. There is a lot of research interest in transforming network models to equivalent smaller graphs.

In general, the topology metrics can be local or global, and defined for the network nodes or the network edges (links). In telecommunications, the path metrics are more important. The topology metrics for binary networks (i.e., the links exist or not) are well defined whereas metrics for the general weighted networks have not been widely adopted yet. Moreover, defining topology metrics for time-varying (e.g. mobile) networks is a very active area of research.

### E. Security metrics

The security metrics rely extensively on assessment of the security risks, threats and vulnerabilities. This is challenging due to lack of data, lack of suitable models, rapidly evolving technologies, and the involvement of the human factors. It is usually easier to evaluate the relative security improvement compared to a reference system. The security strategies are often developed and visualized with the help of attack graphs. A common vulnerability scoring system (CVSS) is becoming accepted as the industry standard on describing and evaluating the system security. However, majority of security metrics are still being defined and evaluated in the research papers. Among those, the VEA-bility (vulnerability, exploitability, attackability) security metric attracted wider attention.

## IV. Metrics for Broadband Networks

The broadband networks are a backbone of the Digital Economies. They have direct and measurable impact on the economic development of countries and regions. Many countries have introduced mandatory minimum broadband connections to be provided in all households. OECD recommends to consider the following 4 categories of metrics: broadband availability and mappings, broadband infrastructure investment, broadband performance, and broadband competition. The most important broadband metrics are listed in Table II.

The access speed is either the speed advertised by the network providers to the subscribers, or it is the speed which is actually measured. The measured values can vary significantly over the day, and they are dependent on the application, traffic shaping used (e.g., a fair use policy), and on sharing the single outgoing connection among multiple devices or households. For small data transfers such as websites, the TCP rate control may not reach the maximum data rate.

Measurements of Internet traffic is used for real-time network management such as to optimize the network resources, and to identify anomalies and security issues. For longer-term network planning, knowing the traffic statistics is important for network dimensioning, and to set fair service pricing. The measurements can be across whole flows, or at the level of individual packets. The challenge is to link data from multiple paths and connections corresponding to the same application flow, and to deal with protocol encapsulation.

Table II
METRICS FOR BROADBAND NETWORKS

| |
|---|
| **Demand-side metrics**<br>• connection speed, penetration and adoption rates, number of connections, traffic volume, monthly allowance<br>• applicaiton usage: patterns, pricing, performance and security |
| **Supply-side metrics**<br>• speed tiers, capacity, availability/coverage, access speed<br>• competition and market share<br>• upload and download speed, round-trip time (RTT) delay/latency, delay jitter, packet loss, DNS failure rate, DNS resolution, web browsing speed, avg. daily disconnection, distance from exchange |
| **Broadband adoption metrics**<br>• service penetration rate (SPR), busy hour service attempt (BHSA), concentration factor of service attempt (CSA), monthly service activity (MSA), service holding time (SHT), service throughput per usage (STPU), time interval of serv. attempts (TISA), net data rate (NDR) |
| **Internet traffic attributes**<br>• service tier, content provider, OS, browser, website<br>• IP addresses, MAC addresses, client device, client device type<br>• app./transport/session protocol, media stream type<br>• video codec, audio codec, media container, video resolution |
| **Quality of broadband (QoB)**<br>• ITU-T Y.1540 standardized metrics: IP packet transfer delay (IPTD), IP packet delay variations, (IPDV), IP packet loss ratio (IPLR), IP packet error rate (IPER), IP packet reordered ratio (IPRR), spurious IP packet ratio (SIPR), IP packet severe loss block ratio (IPSLBR), IP packet duplicate ratio (IPDR), replicated IP packet ratio (RIPR), service availability<br>• IETF standardized metrics: link/path bandwidth capacity, bulk transport capacity, one-way and two-way packet losses and connectivity, one-way and two-way packet delay, delay variation, number of packet reordering and duplicated packets |

## V. METRICS FOR DIGITAL SYSTEMS

The digitalization is going to profoundly transform the telecommunication industry. It will completely change how the telecommunication services are provided. In particular, the new solutions encompasses centralized platforms such as clouds where the content and service producers meet the consumers. The network operators are loosing their revenues due to the new over-the-top (OTT) service providers (e.g., Google and Facebook), so they have to change their business strategies to remain competitive. It is not only the network infrastructure which need to be managed by the operators, but also the underlying operation and business support systems (OSS and BSS). The business-to-business markets (B2B) require new metrics as indicated in Table III.

Table III
METRICS FOR DIGITAL SYSTEMS

| |
|---|
| **Computing systems**<br>• digital maturity model<br>• service and system availability, response reliability, response time/latency, throughput/bandwidth<br>• computing and storage capacity, usage capacity, maximum utilization, scalability, elasticity<br>• cost per request, return on invested capital (ROIC), OpEx, CapEx, market share<br>• security threats and incidents |
| **Website metrics**<br>• web traffic, traffic sources, bounce rate, number of shares, visit duration, click through, exit page rate<br>• conversion rate, value per visit, cost per conversion |

The big data not only in telecommunications are enabled by ML algorithms. These algorithms are particularly useful for solutions which can be learned from in-flow of data. For instance, the networks can forecast the congestion as well as faults, so they can become self-healing and self-configuring. Some of the ML metrics are provided in Table IV. However, the ML algorithms do not provide any intuitive explanation of their outcomes, so justifying the ML decisions can be problematic. Due their nature, the ML based metrics are significantly specialized for the system where they are used which complicates their general validity and acceptance.

Table IV
METRICS FOR DATA PROCESSING

| |
|---|
| **Bid data metrics**<br>• 5 V's: volume, velocity, variety, veracity, value |
| **Machine learning metrics**<br>• estimation/prediction: variance and bias, mean squared error, scoring function<br>• classification: evaluate loss, score and utility functions<br>• binary classification: false-positives, false-negatives, sensitivity, specificity<br>• regression: mean absolute error, r2 score<br>• clustering: similarity metrics, distance metrics |

## VI. DISCUSSION

As the complexity of telecommunication networks has grown substantially, the number of metrics defined, or required is enormous. This problem is already addressed by some industry consortia which are developing the metrics management and database systems to more systematically and consistently define and manage a large number (typically, 1000's) of system metrics. Developing a relatively simple framework of, say, about 100 most commonly used metrics for telecommunication networks would be very useful, and likely appreciated by the research community. For 100 metrics, Zachman framework can be sufficient whereas for 1000's of metrics used in the industry, a lot more sophisticated approaches are required. The problem of metrics optimality appears not to have been defined yet, even though it is closely related to the optimum system modeling.

The energy and power metrics are still important, but they are now less actively researched. The QoE is gaining considerable interest from the operators as they align network performance with the user experience. There are a few security metric frameworks, but most security metrics are still user defined. Unlike QoE which can be inferred from QoS, this strategy is not viable in security context. Using metrics from Network Science to solve Network Engineering problems is not convincing, since the man-made networks are both weighted and dynamic. The emerging networks and digital technologies rely on advanced techniques which either renders many traditional metrics inadequate, or they have to be re-validated to verify that they are still relevant.

Machine learning and the analytics based on big data are a promising avenue. However, it is difficult, if at all possible, to guarantee privacy, to validate these algorithms, and to justify their decisions. These are some of the present very active research areas in ML. More traditional problems in ML involve automating systems and processes.

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Table V
COMMON NETWORK METRICS

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|---|
| **Fairness**<br>• Jain's index, max-min fairness, proportional fairness |
| **Energy and power metrics**<br>• total energy consumed<br>• embodied energy: life-cycle assessment, environmental KPI, ecological footprint analysis<br>• operational energy: energy consumption rating (ECR), variable load ECR, energy efficiency rate (EER), ECR for radio access networks, key power indicator<br>• ATIS and ITU standardized metrics<br>• other metrics: area to power density, subscribers to power density, Tx/Rx/idle/sleep power |
| **Quality-of-service (QoS) metrics**<br>• Error rate metrics: bit/frame/packet error rate (BER/FER/PER)<br>• Throughput metrics: link bit rate, packet delivery ratio (PDR), network sum rate<br>• Delay metrics: data transmission time, processing and queuing delays, propagation delay, average end-to-end delay (AED), delay jitter statistics<br>• Availability metrics: mean time to failure (MTTF), mean time to repair (MTTR), impacted user minutes (IUM), defects per million (DPM), mean time between failures (MTBF) quality of recovery (QoR), point and average uptime availability steady state availability, inherent/achieved/operational availability |
| **Quality-of-experience (QoE) metrics**<br>• subjective QoE metrics: mean opinion score (MOS), double stimul. cont. quality scale (DSCQS), double stimulus impairment scale (DSIS), single stimulus (SS), single stimul. cont. quality evaluation (SSCQE), absolute category (ACR), ACR hidden ref. removal (HRR), just noticeable difference (JND) scale, maximum likelihood difference scale (MLDS)<br>• objective QoE metrics: e-modeling, perception evaluation of speech quality (PESQ), application performance index (APDEX), MOVIS model peak signal-to-noise ratio (PSNR), moving picture quality metric (MPQM), motion-based video integrity evaluation (MOVIE), structural similarity index (SSIM), video quality metric (VQM), pseudo subjective quality assess.(PSQA), context-aware, state-space models, user satisfaction index (USI) |
| **Robustness and resilience metrics**<br>• node connectivity:algebraic connectivity, natural connectivity, average neighbor connectivity, assortativity coefficient, network criticality, network similarity, graphlets, fragments, motifs, network heterogeneity, network spectrum, symmetry ratio, reciprocity coefficient, rich-club coefficient, matching index<br>• network transitivity: clustering coefficient<br>• network community and clustering: modularity index, single, complete and average linkage, cosine similarity, number of intra/inter-community links<br>• node centrality: average degree, Freeman's degree centrality, information centrality, eigenvector centrality, Katz centrality, PageRank centrality, node closeness, node betweenness<br>• path metrics: average hop-count, network radius,network diameter, average shortest path length, path diversity, effective resistance |
| **Security metrics**<br>• standardized or frequently used metrics: common vulnerability scoring system (CVSS), VEA-bility metric, weakest link security<br>• user defined: mean time-to-compromise (MTTC), relative cumulative risk (RCR), hazard metric, security of intelligent electronic devices (IED), critical Vulnerability Analysis Scale Ratings (CVASR), mean-time-to-problem-report (MTTPR), mean-time-to-problem-correction (MTTPC) |