3

Energy-Efficiency Metrics and Performance Trade-Offs of GREEN Wireless Networks

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3.1 Introduction

3.1.1 Ubiquitous Mobility and Connectivity: The Societal Change

Since the turn of the century, there has been a tremendous growth in the mobile data market. The number of subscribers and the demand for wireless services has escalated. Indeed, the penetration of mobile services has exceeded that of the power grid. There are 48 million people in the world who have mobile phones, even though they do not have electricity at home [1]. In this context, mobile communications may be allowed to be an indispensable commodity by most, and mobile data, video, as well as television services are also becoming an essential part of everyday life. With the introduction of the Android operating system and the iPhone, the use of ebook readers such as the iPad, and the success of social networking using Facebook, the demand for (cellular) data traffic has grown significantly in recent years. Thus, communication on the move has proven to be transformational, and mobile operators struggle to satisfy the data traffic demands in wireless (cellular) networks, while keeping their costs at minimum to maintain profitability.

3.1.2 Mobile Data Traffic: The Forecast

A further explosion of mobile data traffic is predicted. According to CISCO's estimates predicted in February 2011 [1], the 2010 mobile data traffic growth rate was higher than

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anticipated. The global mobile data traffic grew 2.6-fold in 2010, nearly tripling for the third year in a row. Furthermore, according to CISCO's estimates published in February 2013 [2], the global mobile data traffic grew 70% in 2012, and it reached 885 petabytes per month at the end of 2012, up from 520 petabytes per month at the end of 2011. These growth rates of mobile data traffic resemble those of the fixed network observed during 1997–2001, when the average yearly growth was 150%. The overall mobile data traffic is expected to grow to 11.2 exabytes per month by 2017, a 13-fold increase over 2012, which corresponds to a compound annual growth rate (CAGR) of 66% from 2012 to 2017. More particularly, the Asia Pacific and North America regions will account for almost two-thirds of the global mobile traffic by 2017. Middle East and Africa will experience the highest CAGR of 77%, increasing 17.3-fold over the forecast period. The Asia Pacific region will have the second highest CAGR of 76%, increasing 16.9-fold over the forecast period. The emerging regions of Latin America as well as Central and Eastern Europe will have CAGRs of 67% and 66%, respectively. When combined with the Middle East and Africa, the above-mentioned emerging market will represent an increasing share of the total mobile data traffic, which is expected to be up from 19% at the end of 2012 to 22% by 2017 [2].

3.1.3 Mobile Data Traffic: The In-Home Scenario

Furthermore, a survey conducted by the CISCO Internet Business Solutions Group (IBSG) indicates that much of the mobile data activity takes place in the home [1, 2]. In particular, it has been estimated that the percentage of time spent using the mobile Internet at home is approximately 40%. The amount of mobile data traffic on the move is approximately 35%, whereas the remaining 25% of mobile Internet use occurs at work. The relatively high percentage of home-based mobile data use suggests that next-generation cellular networks require specific data access points installed by home users to satisfy the huge demand for data traffic, and, at the same time, to get improved indoor voice and data coverage. By using these home access points, the telecommunications operators may be able to offload, in a cost- and energy-effective manner, the data traffic onto a fixed network, either by offering their subscribers dual-mode mobile phones or through the employment of femtocells, which are considered the key enabling technology to handle the growing demands for mobile data traffic in the home [3]. In particular, to meet the demand of massive mobile data growth, IDATE Research & Consulting and Infonetics Research has forecast the employment of 39.4 million femtocell units and a $2.98 billion market by 2015 [4].

3.1.4 Next-Generation Cellular Networks: The Compelling Need to be "Green"

The unprecedented surge of mobile data traffic in the cellular industry has motivated telecommunications operators and researchers to develop new transmission technologies, protocols, and network infrastructure solutions for maximizing both the achievable throughput and the spectral efficiency (SE). On the other hand, little or no attention has been devoted to energy consumption and complexity issues. As a result, the Information and Communication Technology (ICT) sector contributes substantially to the global carbon emissions. In particular, at the time of writing the ICT sector represents around 2% of the global carbon emissions already, of which mobile networks contribute about 0.2%. This is comparable to the worldwide carbon emissions of airplanes, and about a quarter of the worldwide carbon emissions of cars. Furthermore, this amount is expected to increase every year at a rapid pace due to the massive increase of the mobile data traffic. Currently, there are more than 5 million base stations (BSs) serving mobile users, each consuming an average of 25 MW/hour/year [5, 6]. In addition to the environmental aspects, the energy costs represent a significant portion of the network operators operating expenditure (OPEX). While each BS connected to the electrical grid may cost approximately $3000 per year to operate, off-grid BSs operating in remote areas generally run on diesel power generators and may cost ten times more [5]. Furthermore, with the advent of data-intensive cellular standards, such as the long-term evolution advanced (LTE-A) system, the energy consumption of each BS can increase up to 1400 W, and the energy cost of each BS may reach $3200 per annum with a carbon footprint of 11 tons of carbon emissions [7]. The radio network itself adds up to 80% of an operator's entire energy consumption. In this context, the development of revolutionary clean-slate wireless communications technologies that are capable of meeting the forecast mobile data traffic growth while reducing the carbon footprint of next-generation cellular networks is a compelling necessity.

3.1.5 Addressing the Energy Efficiency Challenge: Green Heterogeneous Networks

The rising energy cost and carbon footprint of operational cellular networks have motivated both network operators and regulatory bodies, such as the 3rd Generation Partnership Project (3GPP) and the International Telecommunication Union (ITU), to develop innovative solutions for improving the energy efficiency (EE) of cellular systems. This emerging trend has attracted the interest of researchers worldwide to develop "green heterogeneous networks" [8]. In heterogeneous cellular networks, low-power nodes are overlaid within a macrocell hence creating a wireless heterogeneous network. These low-power nodes may be picocells, femtocells, fixed and mobile relays, remote radio heads, distributed antenna elements, and so on. Thanks to the increased heterogeneity, these networks expand the coverage, improve the network capacity, reduce the energy consumption, and enhance the link reliability through a more dense deployment of low-cost and low-power access points. The reason behind all these potential advantages and, in particular, the EE of the heterogeneous network architecture is simple: *the densification of access points inherently reduces the distance between the network elements*. Since, based on electromagnetic laws, the received power falls off with the transmission distance and obeys an inverse power law where the exponent is known as the path loss exponent, this implies that reducing the distance has a beneficial impact on both the capacity and the transmission power. More specifically, the capacity can be increased and the transmission power can be reduced. As a consequence, heterogeneous cellular network architectures are considered as a strong potential enabler for the design of spectral-efficient and energy-efficient cellular networks and for striking a flexible trade-off between these two competing performance indicators.

Numerous collaborative projects have been launched worldwide for addressing the energy efficiency of mobile communications systems. Notable examples are as follows:

- The "Energy Aware Radio and NeTwork TecHnologies" (EARTH) [9] project.
- The "Towards Real Energy-efficient Network Design" (TREND) [10] project.

- The "Cognitive Radio and Cooperative strategies for Power saving in multistandard wireless devices" (C2POWER) [11] project.
- The "GREENET – An early stage training network in enabling technologies for green radio" [12] project.
- The "Green Terminals for next-generation wireless systems" (GREEN–T) [13] project.
- The GreenTouch consortium [14], whose mission is to deliver the architecture, the specifications, and the roadmap to increase, by 2015, the network's energy efficiency by a factor of 1000 compared to the 2010 levels.

Furthermore, in recent press releases (e.g., IP/09/393 [15]), ICT players have been warmly invited to develop innovative technologies in support of a greener world and to make people more aware of how they use energy. In this context, "green heterogeneous networking" constitutes a wide ranging research discipline that intends to cover all layers of the protocol stack and various system architectures, as well as to identify the fundamental trade-offs between spectral efficiency, energy efficiency, system and signal processing complexity, and system-wide performance.

3.1.6 The Emerging Paradigm Shift: From the SE to the SE Versus EE Trade-Off

The conventional response to the surge of mobile data traffic is the proposal of advanced transmission technologies and protocols designed for maximizing the SE. In fact, since the SE is directly linked to the notion of Shannon capacity [16], until recently it has been considered to be the main performance indicator to fueling the design and optimization of wireless communications systems in general and cellular networks in particular. As a result, the vast majority of transmission technologies and protocols used in the operational cellular and mobile networks have been designed by taking into account diverse factors, such as throughput, quality-of-service (QoS), availability, scalability, without paying specific attention to the energy consumption. With this design methodology, the operational cellular systems can only achieve energy savings at the cost of a performance and/or throughput degradation. Explicitly, it is crucial to develop power-efficient, low-complexity solutions that still satisfy the target QoS and throughput requirements.

To this end, transmission technologies and protocols should be designed and optimized for next-generation cellular networks by using more appropriate performance indicators, which explicitly take the energy consumption and the system's complexity into account. This implies that new performance metrics quantifying the EE of mobile networks have to be introduced, in addition to the SE, for the design of emerging green heterogeneous networks. Furthermore, it is clear that these new performance metrics will introduce new fundamental trade-offs that have to be accurately investigated in order to appropriately quantify the performance of emerging green heterogeneous networks. The objective of this chapter is to summarize the main efforts of the research community in the definition of these energy-efficiency metrics as well as to describe the most important and fundamental trade-offs that emerge with these new performance metrics at hand. Energy-efficiency metrics and performance trade-offs are described in the next two sections, respectively.

In order to better understand the importance of these new EE metrics and the new trade-offs that emerge from their adoption, let us provide two simple examples from a physical layer point of view (1) the point-to-point single-input-single-output (SISO) additive white Gaussian noise (AWGN) channel and (2) the point-to-point multiple-input-multiple-output (MIMO) Rayleigh fading channel.

SE versus EE Trade-Off of the SISO-AWGN Channel. A widespread definition of EE metric is the throughput per unit energy [16, 17]. By considering the SISO-AWGN channel, the ratio between the SE (η_{SE}), defined as the throughput per unit bandwidth, and the EE, defined as the throughput per unit energy (η_{EE}), can be formulated as follows [16, 18]:

$$\eta_{EE} = \frac{\eta_{SE}}{N_0(2^{\eta_{SE}} - 1)}$$

where N_0 is the noise power. This simple formula highlights that the EE is monotonically decreasing when increasing the SE.

SE versus EE of MIMO-Rayleigh Fading Channel. MIMO communications constitute promising techniques for the design of future wireless communications systems, including the fifth-generation cellular networks. In simple terms, the capacity of MIMO systems is proportional to $\min\{N_t,\ N_r\}$, where N_t and N_r represent the number of transmit and receive antennas, respectively [19]. This implies that the throughput may be increased linearly with the number of antennas. As a consequence, MIMO techniques provide high data rates (SE) without increasing the spectrum utilization and the transmit power. However, in practice, MIMO systems need a multiplicity of associated circuits, such as power amplifiers, RF chains, mixers, synthesizers, filters, which substantially increase the circuit power dissipation of the BSs [5, 20–22]. Recent studies have clearly shown that the EE gain of MIMO communications increases with the number of antennas, provided that only the transmit power of the BSs is taken into account and their circuit power dissipation is neglected. On the other hand, the EE gain of MIMO communications remains modest and decreases with the number of active transmit antennas, if realistic power consumption models are considered for the BSs [23]. As a result, while the SE advantages of MIMO communications are widely recognized, the EE potential of MIMO communications for cellular networks is not well understood.

Thus, the important consideration from these two toy examples is that current solutions that are spectral efficient may turn out to be suboptimal in terms of EE. This leads to the conclusion that energy-efficient solutions may operate relatively far from the Shannon capacity. However, improving the EE at the cost of the QoS (SE/throughput) for the end user may be unacceptable in commercial networks. Therefore, an important message emerge: the development of beneficial wireless communications techniques striking an attractive SE versus EE trade-off for next-generation cellular networks is a compelling necessity [18].

3.2 Energy-Efficiency Metrics

The very broad term “green communications” lacks clear scientifically based definitions and quantifiable metrics. Currently, it is more of a marketing term than a standard to strive for. To truly address this problem on a transformational level, high-risk and high-reward research is required that integrates all aspects of communications stack and peripheral interactions. Most importantly, metrics and their associated measurement science that define green communications from combined energy efficiency and network optimization perspectives must be developed. Metrics are essential to providing guidance to manufacturers and service providers to help them make better decisions regarding infrastructure development and purchases. This is where energy-efficiency metrics play an important role. These metrics provide information in order to directly compare and assess the energy consumption of various components and the overall network. In addition, they also help us to set long-term research goals of reducing energy consumption. With the increase in research activities pertaining to green communications and hence in number of diverse energy-efficiency metrics, standards organizations such as the European Technical Standards Institute (ETSI) and the Alliance for Telecommunications Industry Solutions (ATIS) are currently making efforts to define energy-efficiency metrics for wireless networks [24, 25].

Such metrics may be classified as *energy efficiency metrics* or *energy consumption metrics*. An energy-efficiency metric corresponds to the ratio of attained utility (e.g., the transmission distance reached, the area covered, the output power, the bits transmitted) to the consumed power/energy used. On the other hand, an energy consumption metric corresponds to the energy/power consumed per unit of attainable utility. Energy-efficiency metrics of telecommunication systems can be classified into three main categories [26–28]:

- *Facility-level metrics*, which relate to high-level systems where the equipment is deployed, such as data centers and Internet Service Providers (ISP).
- *Equipment-level metrics*, which are defined to evaluate the performance of an individual equipment.
- *Network-level metrics*, which assess the performance of equipments while also considering features and properties related to capacity and coverage of the network.

A comprehensive taxonomy of these metrics is available in [5, 22, 26–32]. In what follows we provide a list of widely used metrics to quantify the energy efficiency of green communications. For simplicity, the analytical formulation of the energy metrics is avoided in the present chapter, but it is available in the references cited provided.

- *Power usage efficiency (PUE)* [28] is used to evaluate the performance of power hogging data centers. The PUE is defined as the ratio of the total facility power consumption to the total equipment power consumption. It is a good metric to quickly assess the performance of data centers at a macro level, but it fails to account for energy efficiency of individual equipments. This is a facility-level metric.
- *Data center efficiency (DCE)* [28] is the reciprocal of the PUE. This is a facility-level metric.
- *Power per user (PPU)* [26], which is measured in W/user, is the ratio of the total facility power to the number of users. This is an equipment-level metric.
- *Energy consumption rating (ECR)* [26], which is measured in W/Gbps, is the ratio of the normalized energy consumption to the effective full-duplex throughput. The ECR provides the manufacturers a better insight into the performance of hardware components. However, it does not account for the network load. This is an equipment-level metric.
- Since even the busiest networks do not always operate at full-load conditions, it would be useful to complement metrics such as the ECR to incorporate the dynamic network conditions, such as energy consumption under different loads. Such metrics are equipment-level metrics and they are as follows [5, 26]:
  - *ECRW* (ECR-weighted), which is the ratio of the energy consumption over the effective system capacity by taking into account full, half, and idle conditions;
  - *ECR-VL* (energy-efficiency metric over a variable-load cycle), which is the average energy rating in a reference network described by an array of utilization weights;

  - *ECR-EX* (energy-efficiency metric over extended-idle load cycle), which is the average energy rating in a reference network, where extended energy savings capabilities are enabled;
  - *Telecommunications energy efficiency ratio (TEER)* introduced by the ATIS and the *Telecommunication equipment energy efficiency rating (TEEER)* introduced by Verizons Networks and Building Systems, which consider the total energy consumption as the weighted sum of the energy consumption of the equipment at different load conditions.
- *Absolute energy efficiency (AEE)* [5], which accounts not only for the consumed power, the bit rate, but also for the temperature aspect of the system since classical thermodynamics is based on the absolute temperature of the system under analysis. This is an equipment-level metric.
- *Performance indicator in rural areas (PIrural)* [5], which is measured in Km^2/W, is the ratio of the total coverage area and the power consumed at the site. This metric is useful since rural areas are characterized by a low load and the main target is the maximization of the coverage area. This is a network-level metric.
- *Performance indicator in urban areas (PIurban)* [5], which is measured in Users/W, is the ratio of the number of users based on average busy hour traffic demand by users and the power consumed at the site. This metric is useful since urban areas have higher traffic demand than rural areas; hence, capacity is more important than the coverage area. This is a network-level metric.
- *Power per Unit Area (PUA)* [22], which is measured in W/m^2, is equal to the network average power usage divided by the coverage area of the network. The metric focuses on the total network power (or, equivalently, the total energy consumption) and is closely related to the CO_2 emissions and the associated carbon footprint. It is further a very relevant quantity at low traffic loads, as in this case the network is coverage limited rather than capacity limited. This is a network-level metric.
- *Energy per bit (EpB)* [22], which is measured in Joule/bit, is defined as the network energy consumption during the observation period divided by the total number of bits that are correctly delivered in the network during the same time period. Since the network energy consumption is simply the (average) power multiplied with the observation period, this metric may, equivalently, be described as the (average) network power in relation to the (average) data rate. This is both an equipment- and network-level metric, depending on how it is measured.
- *Energy consumption gain (ECG)* [6], which defined as the ratio of the energy consumed by the baseline and the one consumed by the system under test. The ECG is useful for comparing two different systems. This is both an equipment- and network-level metric, depending on how it is measured.
- *Energy efficiency*, which is measured in bit/Joule, is defined as the number of bits that can be transmitted per unit energy. This metric is very often used for the analysis of the energy efficiency of wireless communications systems. This is both an equipment- and network-level metric, depending on how it is measured.

In conclusion, the proper evaluation of the energy efficiency of green communications is a serious matter that the green networking community shall face soon. In that regard, the adoption of effective energy efficiency metrics is instrumental to assess the potential gains. In this section, we have summarized the most common energy-efficiency metrics that can be found in the literature. In general, due to their intrinsic difference and relevance, no single metric can represent the whole state of the system. Nevertheless, choosing a metric rather than another may yield significantly different evaluation results. As a consequence, a large consensus needs to be reached as soon as possible on a reduced set of well-defined performance indicators to promote fair and accurate cross-comparisons among different solutions.

3.3 Performance Trade-Offs

Generally speaking, energy efficiency means using less energy to accomplish the same task. In case of communications systems, the task to be accomplished could be a file transfer, a phone call, and so on. It is clear that improving the energy efficiency of a communication system is expected to have some "costs" in terms of other aspects of their overall performance. In Section 3.1.6, we have provided two simple examples that support this intuition by considering the SISO-AWGN channel and the MIMO-Rayleigh fading channel. We have shown that improving the EE inevitably implies reducing the SE, which for MIMO systems may lead to switching off some antenna elements in order to decrease the overall power dissipation. This section is aimed at summarizing some fundamental trade-offs to be considered when designing an energy-efficient communication system.

The SE versus EE trade-off is one of the main trade-offs that arise in the design of green wireless networks. In Ref. [18], the authors have recently identified four main fundamental trade-offs that are now widely accepted by the research community. These four trade-offs are as follows:

- *SE versus EE trade-off*, which, for a given available bandwidth, provides the balance between the achievable rate and the energy consumption of the system.
- *Deployment efficiency (DE) versus EE trade-off*, which provides the balance between the deployment cost, throughput, and energy consumption in the network as a whole.
- *Bandwidth (BW) versus power (PW) trade-off,* which, for a given transmission rate, provides the balance between the utilized bandwidth and the power needed for transmission.
- *Delay (DL) versus PW trade-off*, which provides the balance between the average end-to-end service delay and the average power consumed for transmission.

3.3.1 The SE Versus EE Trade-Off

As mentioned in Section 3.1.6, the SE is defined as the capacity per unit bandwidth and the EE is defined as the capacity per unit energy. The SE is a widely accepted criterion for wireless network optimization. The peak value of SE is always among the key performance indicators by standardization bodies. On the other hand, the EE has raised the attention of standardization bodies only recently [33]. For example, reducing the number of active RF chains (i.e., active antenna elements in MIMO-aided BSs) for the sake of reducing the power consumption of BSs has been actively discussed within 3GPP standardization bodies [34]. The main idea is to enable the BSs to use only a subset of the available antenna elements in order to reduce the power consumption during low traffic periods. The reason of this choice is that in practical systems the SE versus EE trade-off has a mathematical formulation that is more difficult than that provided in Section 3.1.6, and that the circuit power consumption significantly affects the overall power efficiency of communications networks. The SE versus EE trade-off is also a function of the hardware impairments. For example, the power amplifiers (PAs) play an important role in the power efficiency of wireless communications systems [5]. Their role is to increase the power level of the transmit signal so that the corresponding received signal can be demodulated by the receiver meeting a given error probability requirement. Two important metrics quantifying the performance of PAs are linearity and efficiency. The linearity of the response of a PA is an important factor for wireless communications since the distortion of the signal causes an increase in the required transmit power to meet the same error rate requirement and an irreducible error floor. The drain efficiency is the ratio between the output RF power and the input DC power; therefore, this is a measure of how much DC power is converted to RF power. High efficiencies are required to minimize the needs for thermal dispersion and to decrease the energy consumption. However, high efficiency and high linearity are conflicting requirements in PAs. If PA linearity is required, there must be a direct relationship between the output power and the power supplied to the PA. On the other hand, in order to be power efficient the electronic device/system should use a limited amount of power even when a high output power is needed. This conflicting behavior leads, for example, to find the right modulation scheme in order to balance the SE (amplitude modulations) and the EE (constant-envelope modulations).

3.3.2 The DE Versus EE Trade-Off

The DE is a measure of the system throughput per unit of deployment cost, which is an important network performance indicator for mobile operators. The deployment cost consists of both capital expenditure (CAPEX) and OPEX. For radio access networks, the CAPEX comprises the infrastructure costs and the OPEX includes operational and maintenance costs. The main issue behind this trade-off is that the DE is estimated during the network planning phase, whereas the EE is estimated when the network is operational. A typical example where this trade-off arises is the choice of the cell coverage. Usually, the DE is reduced by increasing the cell coverage as much as possible, since this reduces the expenditure costs. On the other hand, increasing the cell coverage by having bigger cells results in the need of increasing the transmission power of the BSs to reach the users in the cell edges, which in turn reduces the EE averaged over the cell of interest. The heterogeneous cellular network infrastructure described in Section 3.1.5 is considered to be a promising solution for addressing this trade-off. In particular, with the combination of macrocells and micro/pico/femtocells, coverage and capacity provision can be decoupled into different tiers of the network, where the macrocells handle coverage and mobility issues whereas the femtocells focus on local throughput. In addition, relay stations and remote radio heads may further help in improving the DE versus EE trade-off, since they are of much lower cost and smaller coverage compared to macro BSs, hence bringing mobile users closer to the network and making the system deployment more flexible.

3.3.3 The BW Versus PW Trade-Off

Both BW and PW are limited resources in wireless communications. From Shannon's capacity formula for a simple SISO-AWGN channel, the relation between transmit power and signal bandwidth for a given transmission rate, R, can be formulated as follows:

$$\mathrm{PW} = WN_0(2^{R/W} - 1)$$

which shows that the transmit power increases by decreasing the signal bandwidth. Furthermore, it shows that as the bandwidth increases without limit, there is a minimum power limit that cannot be overcome. This formulas also highlight that, for a given data transmission rate, the expansion of the signal bandwidth is preferred in order to reduce the transmit power and thus to achieve a better energy efficiency. This trend for bandwidth demand is indeed the core tenet of the different generations of cellular systems. In particular, the second and third generations of wireless communications systems use a fixed BW transmission. On the other hand, future deployments of LTE and LTE-A standards provide a higher flexibility in spectrum usage so that the transmission BW can be tuned for different applications (i.e., by using carrier aggregation). Furthermore, new transmission concepts, such as the cognitive radio (CR) [5], are capable of adjusting the modulation order according to the available BW as function of time, hence supporting a more flexible use of the BW. However, both carrier aggregation and CR incur in some practical overhead, such as multiple RF chains and spectrum sensing, both of them increasing the energy consumption. Thus, it is important to pay attention to how these technologies will be integrated in next-generation green wireless networks.

3.3.4 The DL Versus PW Trade-Off

DE, SE, and BW are physical layer-oriented metrics, which account for either the system efficiency or network resources. The DL (or service latency) is, on the other hand, a measure of the QoS experienced by the user, and it is closely related to the upper layers of the protocol stack and to the traffic statistics. In the second generation of mobile systems, the DL was mostly associated with the signal processing time and with the propagation delay. On the other hand, emerging wireless communications standards, such as the LTE-A, provide a wide plethora of wireless services and applications with heterogeneous DL requirements. Therefore, in this emerging application scenarios, it is important to understand the trade-off between transmit power and delay. By still using the Shannon's capacity formula for a simple SISO-AWGN channel, PW can be formulated as:

$$\mathrm{PW} = WN_0T_b(2^{1/T_bW} - 1)$$

where W is the signal bandwidth and $DL = T_b = 1/R$ is the delay for transmitting one bit, given the rate R. This formula shows that the transmission power increases by decreasing DL. In practical systems, however, the DL versus PW trade-off is more complicated and its mathematical analysis needs advanced information and queuing theories. From queuing theory, it is known that the average DL of a packet queue is determined by the statistics of the traffic arrivals and departures. In general, there is no closed form expression available to show the direct relation between DL and PW. Therefore, the investigation of simplified but approximate models is desirable for providing insights for practical system design.

In summary, in this section we have outlined some fundamental trade-offs that originate in green wireless networks. Although the trade-offs have been illustrated by considering idealized toy examples showing monotonic behaviors among the different metrics of interest, it is worth emphasizing that in practical systems the trade-off relations usually deviate from simple monotonic curves, thus making the design and optimization of green communications networks a challenge.

3.4 Conclusion

Future mobile communications networks will not only be optimized for capacity, but also their design will implicitly take energy efficiency into account. This implies that new performance metrics quantifying the energy efficiency of mobile networks are necessary, which inevitably introduce fundamental performance trade-offs. In this chapter, we have outlined the most common and widely used energy efficiency metrics and have summarized the main performance trade-offs arising from their utilization.

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