

User-Oriented Energy- and Spectral- Efficiency Tradeoff for Wireless Networks

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Abstract

Conventional optimization designs of wireless networks mainly focus on spectral efficiency (SE) as a performance metric. However, as diverse media services are emerging, a green wireless network, which not only meets the quality of experience (QoE) requirements for users and also improves energy efficiency (EE), is the most appropriate solution. In this paper, we firstly propose the unit QoE per Watt, which is termed QoE efficiency (QEE), as a user-oriented metric to evaluate EE for wireless networks. We then analyze which is the kind of wireless resource given priority to use under different scenarios to obtain an acceptable QEE. Particularly, power, delay and data-rate related to QoE are separately addressed for several typical services, such as file download, video stream and web browsing services. Next, the fundamental tradeoffs are investigated between QEE and SE for wireless networks. Our analytical results are helpful for network design and optimization to strike a good balance between the users perceived QoE and energy consumption.

Keywords: Energy efficiency, spectral efficiency, quality of experience, tradeoff

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1. Introduction

The recent development of *ubiquitous services* represents the direction of the next generation wireless networks and draws the grand blueprint for Information and Communications Technology (ICT) infrastructure. However, constant emerging of new services and smart applications rapidly booms energy consumptions, creating ever-increasing carbon footprints. It is reported that energy consumed by ICT industry is rising at 15-20% per year, doubling every five years. The radio access part alone takes up more than 70% of the total energy consumption for many mobile operators [1]. Therefore, there are growing concerns over the energy consumption caused by drastically increasing mobile devices and the base stations. Furthermore, the problem of energy inefficiency in ICT industry shows up and becomes serious. The recent surge in the popularity of cloud computing for providing rich multimedia services has further necessitated the need to consider energy saving and improve energy efficiency.

The escalation of power consumption in wireless networks directly results in great increase of greenhouse gas emission, which is becoming a major threat for sustainable development. European Union has acted as a leading flagship in energy saving over the world and targeted to have a 20% greenhouse gas reduction. China government has also promised to reduce the energy per unit GDP by 20% and the major pollution by 10% by the year of 2020 [2]. Hence, energy saving and environmental protection are becoming urgent demands and global trends, and limit the electricity bill at the same time.

With increasingly high datarates supported by wireless networks, rather diverse multimedia services, such as video streaming, conferencing and file download are becoming ever popular. The emerging services changed the subjects of marketing from developers to users. That is, “consumers” as “users” have come to emerge as principal actors to create changes in today’s societies along with their great influences. Consequently, the interactions between ubiquitous services and users take an important position in ubiquitous industry [3].

For these reasons, the concept of quality of experience (QoE) has the potential to become the guiding paradigm for managing quality in the next generation network [3]. QoE combines user perception, experience and expectations with non-technical and technical parameters, such as network-level quality of service (QoS). It is likely to be the main factor of multimedia service quality metrics for customers [3] and has attracted many interest from academia and industrial areas [4][5]. Hence, how to maintain excellent QoE perceived by users and reduce energy consumption from the perspective of future network design makes more sense.

Recent efforts have been made to tackle energy consumption at all layers of communication systems, from algorithms [6][7] to cooperation communication [8][9][10]. Additionally, energy efficiency (EE) and spectral efficiency (SE), which are conflicting, can be linked through their trade-off. The tradeoff in single cell downlink orthogonal frequency division multiple access networks is investigated in [11]. The EE-SE relation is proved to be a quasiconcave function, and the impact of channel power gain and circuit power is analyzed. The trade-off for the multi-input multi-output (MIMO) Rayleigh fading channel has been accurately approximated for a much wider SE regime in [12], which indicates that MIMO is a promising EE enabler. Onireti et al. derive a generic closed-form approximation of the EE-SE trade-off for the uplink of coordinated multi-point CoMP system in [13]. More fundamental

tradeoffs are analyzed and extended to green wireless networks in [2]. However, the relationships among QoE, power and SE for wireless networks is not clear yet.

In this paper, we first introduce QoE per Watt, termed QEE as a user-oriented metric to evaluate EE in QoE perspective, which is simply defined as the ratio of the QoE perceived by users and the signal power expenditure. The difference between the two metrics lies in that QEE characterizes real acceptability of users with unit power for versatile multimedia services, combining user satisfaction and operator satisfaction (energy consumption) together. SE is a network-level metric emphasizing the network performance to the contrary. We then address the QEE-SE tradeoff issue for wireless services, such as datarate-sensitive services and delay-sensitive services. Moreover, we also analyze which kind of wireless resource should be given priority to use under different scenarios.

The remainder of this paper is organized as follows. In Section 2, we describe the notion of user-oriented QEE in green networks. In Section 3, we explore QoE mapping functions for several typical multi-media services. We then investigate the fundamental tradeoffs and analyze the resource set in network optimization process in Section 4. Finally, we conclude the paper and point out future works in Section 5.

2. QoE-based Energy Efficiency

In this section, we introduce QEE for ubiquitous services. We first investigate main results from information theory and then explore the energy-efficient metric from QoE, energy and spectral perspective.

2.1 Fundamental Issues

From Shannon's formula, as bandwidth goes to infinity, the capacity of an ideal additive white Gaussian noise (AWGN) channel approaches

$$R = \lim_{W \rightarrow \infty} W \log_2(1 + P_t / WN_0) = P_t / N_0 \quad (1)$$

where W is the system bandwidth, P_t is the given transmit power, and N_0 denotes the power spectral density of AWGN.

From the Shannon capacity, energy efficiency can only be obtained at the cost of huge bandwidth and results in very low spectral efficiency. The analysis also ignores many practical problems with increasing bandwidth, such as wideband circuit power and non-linearity of the power amplifier. Actually, a device will incur additional circuit power which is relatively independent of the transmission rate. Thus the operation cost of transmission is incurred which should be account for energy use in communications. In the following sections, we will discuss the impact of circuit power on the energy consumption.

2.2 User-oriented Metric: QEE

SE is defined as the system datarate for unit bandwidth, is a widely accepted criterion for wireless network optimization [14]. The peak value of SE is always considered as an important indicator in analyzing network performance. The International Telecommunications Union-Radio communications sector (ITU-R) specified a set of requirements for 4G standards, setting peak speed requirements for 4G service at 100 Mbit/s for high mobility communication and 1 Gbit/s for low mobility communication. However, EE is previously ignored by most of

communication standards and research efforts until very recently green communications has become a vital trend. The SE-EE tradeoff has been studied in many researches [2][11]-[13]. On the contrary, EE with users' particular requirements has rarely studied, let alone QoE related tradeoffs.

The up band datarate of an AWGN channel is given by

$$R = W \log_2 \left(1 + \frac{P_t h}{WN_0} \right) \quad (2)$$

where h is the channel gain. Hence, transmission power can be formulated as $P_t = (2^{R/W} - 1)WN_0 / h$. SE and EE can be expressed by $\eta_{SE} = R/W$, and $\eta_{EE} = R/P_t$, respectively. Determined by (2), SE is given by

$$\eta_{SE} = \log_2 \left(1 + \frac{P_t h}{WN_0} \right) \quad (2)$$

From [15], circuit energy consumption increases with the bandwidth. The circuit power includes all electronic power consumption except transmit power, expressed by

$$P_c = WP_{cir} + P_{sb} \quad (3)$$

where P_{cir} is the part of dynamic circuit power consumption which is related to bandwidth, and P_{sb} is the average static power in the transmit mode. Obviously, when circuit power is taken into account, the overall power turns out to be $P = P_t + P_c$. EE can be defined as

$$\eta_{EE} = \frac{W \log_2 (1 + P_t h / WN_0)}{P_t + WP_{cir} + P_{sb}} \quad (4)$$

Performance per watt is a well-accepted measure of the energy efficiency of communication architecture. Literally, it measures the performance that can be delivered by the network for every watt of power consumed. One of the most commonly used energy metrics is to relate the average power used in the network to the average data transfer rate (often measured in bps/J or bps/J per area unit). But focusing on the baseband energy consumption relates only to the data-rate itself and makes user satisfaction unconsidered.

QEE is defined as the ratio of the perceptual QoE to the signal power expenditure. An important advantage of the present metric is further to indirectly consider also QoE constraints, while gains calculated in terms of energy per bit metric do not directly take a possible user perception into account, and thus do not directly guarantee any service fulfillment in the system. Instead, as a user-centric metric, QEE differentiates specific type of services. Moreover, QEE is not only a quality metric, but also a measure of energy efficiency since it decreases with the increase of energy consumption. The two contributors indicate the reason why QEE is suitable to be utilized in analyzing ubiquitous services. Furthermore, considering that the common task for the components is to provide transmission service the required effort, QEE denoted by η_{QEE} can be expressed as power consumed by the component to provide this service as shown below.

$$\eta_{QEE} = \frac{\Delta Q}{P_t + WP_{cir} + P_{sb}} \quad (5)$$

where $\Delta Q = Q - Q_{\min}$, Q denotes current QoE, and Q_{\min} is the minimum Q , which is relevant to the assessment system. It is noted we adopt relative value Q_{\min} rather than Q itself, because when the consumed power goes to zero, η_{QEE} should tend to zero following from it.

3. Quality of Experience

To characterize the QEE-EE tradeoff for point-to-point communication in ubiquitous computing systems, we should address QoE performance for typical multimedia services. In this section, we will first overview the definition of QoE and the qualification metric. Then the QEE-SE tradeoff for several popular services, such as file download, video streaming and web browsing are investigated, respectively. The purpose behind this is to balance the achievable QoE and the energy consumption of the computing system and also provide a direction towards future network optimization designs.

3.1 Mean Opinion Score (MOS)

Although technical QoS has been one of the most important research topics over several decades, the idea of a notion of QoS extended to both users' perception and network performance parameter is mostly accepted. Therefore, a lot of discussions about QoE have taken place as one of the ultimate metrics influencing the success or failure of new applications. International Telecommunication Union-T has defined QoE as "*the overall acceptability of an application or service, as perceived subjectively by the end users.*" It includes the complete end-to-end system effects (terminal, network, services infrastructure, etc.) and may be influenced by user expectations and mood. Thus, a large number of technical factors influence the quality of ubiquitous services and applications as perceived by the end users. Obviously, these technical factors differ for each individual application. This work will concentrate on the main factor effecting wireless network performance for each service when mapping to the perceptual QoE.

The diversity of ubiquitous services makes service differentiation gain more importance. It is necessary to find out a unified method to measure the quality of QoE used for all the types of the services. A subjective approach consists in measuring QoE evaluated by real humans in terms of mean opinion score (MOS) [4][16]. MOS was originally proposed for voice quality assessment and provides a numerical measure of the quality of human speech at the destination. Recently, it is usually extended for many other multimedia services and becomes the most widely used metric. The definition of each score is explained in terms of perceptual quality in [Table 1](#).

Table 1. User perceptual quality rating

MOS	Perceptual quality by users
5	Excellent, I really like the way it works.
4	Good, but I can see a few possible improvements.
3	Acceptable
2	Somewhat annoying, but I can live with it.
1	Terrible, I will not use it any more.

It is common to adopt generalized MOS as the QoE metric in many QoE-oriented techniques [16], where MOS is not composed of discrete ranks but a set of continuous values between 1 and 5. In this work, we adopt generalized MOS as QoE metric. It is worth noting that our analysis can be applied to any other QoE metrics, not only limited to MOS.

In general, QoE functions, which can be constructed for some network performance parameters, such as transmit rate and delay, usually differ for different applications. We will discuss QoE functions and QEE-SE tradeoff for the following services.

3.2 QoE Functions

When discussing QoE assessment for wireless services, the end user perspective has to be taken into account. To quantify and measure the user perceived quality may sometimes be difficult and what metric to use typically depends on the service or application. The QoE requirements and resulting technical requirements from applications differ in many dimensions including transmit rate, delay, packet loss, etc. According to the characteristics of ubiquitous services, they can be mainly categorized into two types: data-sensitive services and delay-sensitive service, such as web service, etc. In specific, two kinds of QoE curves for data-sensitive services are illustrated in Fig. 1.

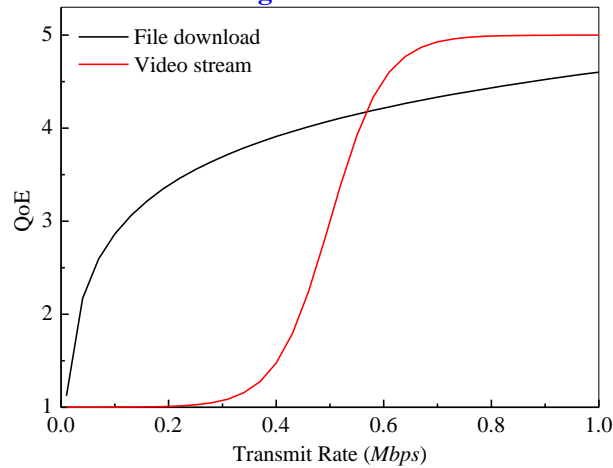


Fig. 1. QoE functions of data-sensitive services.

3.2.1 File Download Service

File share is one of the most popular services, which can be classified by data service. For file download service, user's satisfaction is most related to the effective transmit rate. Moreover, file download service is considered as one kind of elastic applications, whose QoE curve is concave and monotonically increasing of effective transmit rate R . As Fig. 1 shows, QoE improves quickly at the start and approaches 5 as the transmit rate approaches infinite. The logarithmic function introduced in [17] is adopted in this study. When packet loss is ignored, the MOS expressed as a function of datarate is given by

$$Q_{fp}(R) = a_1 + b_1 \log(R) \quad (6)$$

3.2.2 Streaming Video Service

With the introduction of smartphones like the iPhone and Android based platforms, there is an explosion of powerful mobile devices in the market that are capable of displaying high-quality

video content. In addition, these devices are capable of supporting various video streaming applications and interactive video applications like videoconferencing, and they can capture video for video sharing, video blogging, video Twitter, and video broadcasting applications [18]. Cisco predicts that mobile traffic will grow by a factor of 26 until 2015 (almost double every year), and that mobile traffic will be dominated by video; for example, by 2015, various forms of video will exceed 90 percent of global consumer traffic, and almost 66 percent of the world's mobile traffic will be video [19].

From QoE perspective, streaming video service is sensitive to delay and rate, and is less elastic than data services such as file transfer. When the transmission rate decreases below a certain threshold, a significant drop in the QoE will be resulted in. However, when the transmission rate increases above the certain threshold, the QoE will be greatly improved. As a result, the MOS of streaming video service can be modeled as a sigmoidal-like function of the average transmission rate [20] given by

$$Q_{video}(R) = \frac{a_2}{1 + e^{b_2(R-c_2)}} \quad (7)$$

We observe from Fig. 1, a portion of the QoE curve is convex, representing the fact that, once the effective transmit rate is below a certain value, the user satisfaction drops sharply. Similar to data services, as data rate increases, QoE approaches the maximum value.

3.2.3 Web browsing Service

The following work will focus on the web browsing application which is expected to be one of the dominant services in future wireless computing networks. A key challenge in this application is to provide the user less response time in a web application environment.

Unlike file download service, compared with the disinterest in demanded page size, web users pay more attention to response time. An analytic function [16] fitting the MOS results is

$$Q_{web}(\tau) = 5 - \frac{a_3}{1 + (b_3 + c_3 / \tau)^2} \quad (8)$$

The QoE curve which is a monotone decreasing function can be described as Fig. 2. The perceptual quality decrease dramatically when delay increases at the very beginning. Then QoE performance drops quite slowly with longer delay.

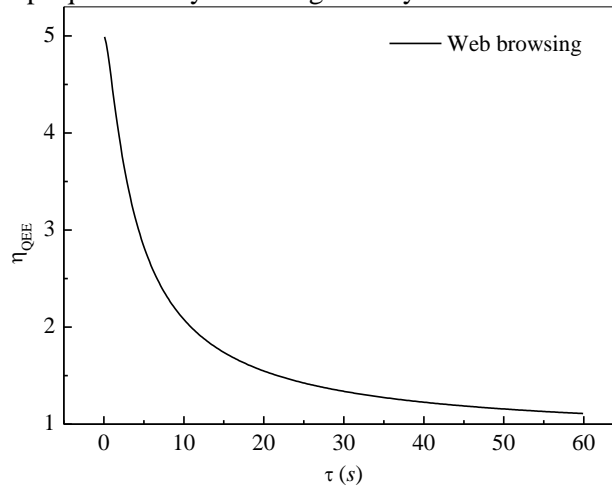


Fig. 2. QoE functions of data-sensitive services.

4. QEE-SE Tradeoff

The aim of optimization in wireless network is to deliver the applications to the end user at high quality, while minimizing the costs of the energy consumptions. In network optimization process, the throughput-oriented resource allocation should shift into EE-oriented designs. Moreover, given the diverse QoE requirement for the users, unnecessary energy consumption should be reduced in any possible way. But how to stand a good balance between the two metrics is a question. Which kind of resource is preferred to be used to achieve a satisfying QEE.

For green wireless networks, the goal of resource trading is to consume the minimum energy for the demanded QoE performance. Fig. 3 shows that the resource trading relationship for green wireless networks. As indicated in Fig. 3, the resources such as power, time, spectrum and datarate are tightly associated with perceived QoE for users. And some interesting tradeoffs exist between the five essential factors. We can see in Fig. 3 that in some scenarios, bandwidth are trading more than other three factors for energy resource saving. In some other scenarios, the case is different. The relationships changes with different kinds of services. For example, it's beneficial to trade longer service time for QoE gain with the delay-tolerant services. In this paper, we mainly consider three types of resources, i.e. bandwidth, delay and power.

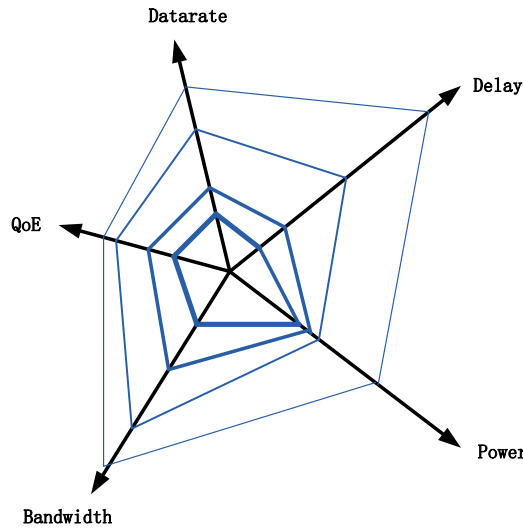


Fig. 3. Resources and QoE tradeoffs in green networks (Example).

4.1 Data-Rate Sensitive Service

4.1.1 File Download Service

We start with file download services whose QoE is the function of R . Plugging (6) into (5), we obtain

$$\eta_{QEE} = \frac{a_1 + b_1 \log(R + c_1) - Q_{\min}}{P_t + WP_{cir} + P_{sb}} \quad (9)$$

where $Q_{\min} = 1$. According (2), transmit power can be given by

$$P_t = \frac{(2^{R/W} - 1)WN_0}{h} \quad (10)$$

From (10), we observe that transmit power monotonically decreases with W . However, the operating power cannot be ignored in ubiquitous networks. Therefore, the relationship among consumed power, bandwidth and datarate will be changed when including all system power. In this case, we derive the overall power consumption as follows:

$$P = P_t + P_c = \frac{(2^{R/W} - 1)WN_0}{h} + WP_{cir} + P_{sb} \quad (11)$$

Obviously, there are three parameters affecting power consumption in (11): the channel bandwidth W , datarate R and h . Under the free space propagation model, the channel gain, denoted by $h(d)$, is the function of transmission distance d , which is given by

$$h(d) = \frac{G_t G_r \lambda^2}{(4\pi)^2 d^\alpha L} \quad (12)$$

where G_t and G_r are the transmit and receive antenna gains, respectively, λ denotes wavelength and L is the system loss unrelated to propagation.

For fixed transmit distance $d = 1000$ m, **Fig. 4** shows the relationship by trading bandwidth and datarate for power. From **Fig. 4**, we can see the minimum power consumption exists when both datarate and allocated bandwidth is extremely small. In the scenario with a narrow bandwidth, adequate power provision is necessary to enhance the datarate and improve QoE at the same time. That is why power scales with the datarate in **Fig. 4**, when given a fixed bandwidth. While a certain transmission rate is required, the power decreases as bandwidth increasing in that lower SNR is acceptable. However, when a quite wide bandwidth is available, the circuit power consumption dominates the budget of energy costs, and consequently leads to overall power increase. Therefore, when a certain datarate required, i.e., a QoE level for datarate- sensitive service, there is an optimal bandwidth for the minimal transmit power.

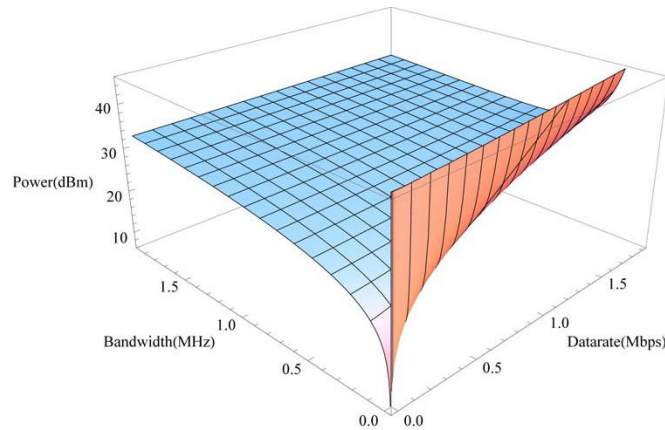


Fig. 4. Power consumption vs bandwidth and datarate.

From (11), (9) can be simplified by

$$\eta_{QEE} = \frac{a_1 + b_1 \log(R) - Q_{\min}}{(2^{R/W} - 1)WN_0 / h + WP_{cir} + P_{sb}} \quad (13)$$

Fig. 5 depicts the relationship by trading bandwidth and datarate for QEE of the FTP service according with (13). It indicates QEE does not scale monotonously with bandwidth and datarate, but keeps a unimodal function of these factors.

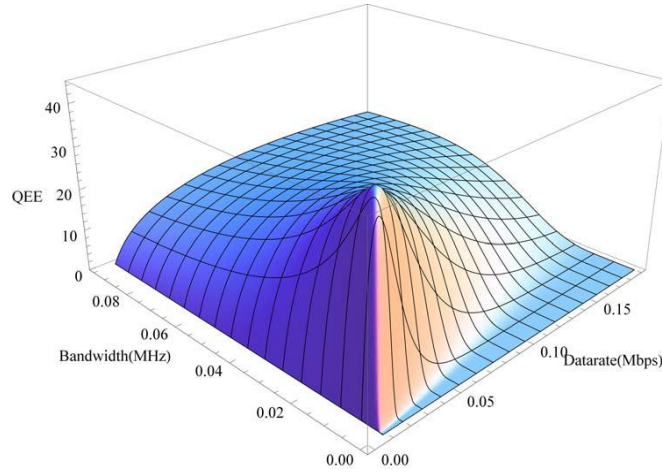


Fig. 5. QEE vs bandwidth and datarate for FTP service.

Intuitive, the optimal QEE can be obtained by allocating proper bandwidth and datarate. The *steepest descend method* can be used to find the optimal resource set. But sometimes it is impossible to get the optimal QEE due to the minimum QoE requirement, such as datarate cannot be lower than a fixed threshold. In this case, a sub-optimal resource set is needed instead. If we look at a cross section of the QEE graph, we may see that the optimal value of the curve exist which indicates the sub-optimal QEE is in the boundary of the minimum datarate. The key idea is that the QEE is modified as allcoted different kinds of resources so that less QEE loss focuses the decent of QEE change is flatest. As a result, as indicated in **Fig. 5**, more power should be given priority to use rather than bandwidth for the seek of less QEE loss.

Beside the resource allocation, we also desire to derive the trading relationship between QEE, bandwidth and datarate, so we will analyze each trading relationship with the fixed value of the other one in the following.

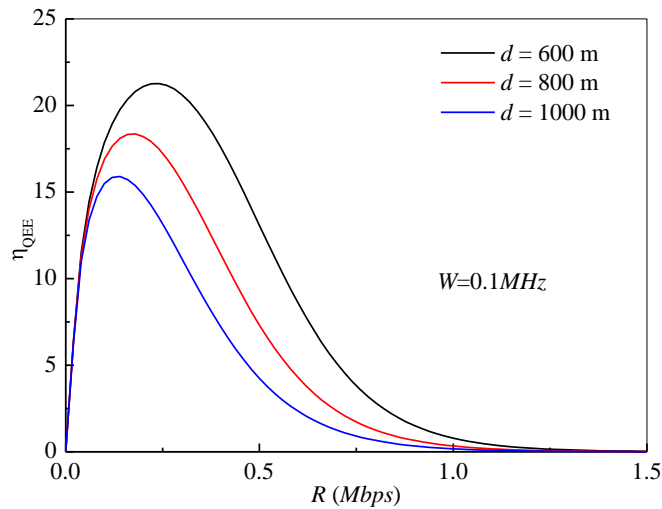
For fixed W , the relationship between η_{QEE} and R is expressed as (setting $W = 1$ MHz for simplicity)

$$\eta_{QEE} = \frac{a_1 + b_1 \log(R) - Q_{\min}}{(2^R - 1)N_0 / h + P_{cir} + P_{sb}} \quad (14)$$

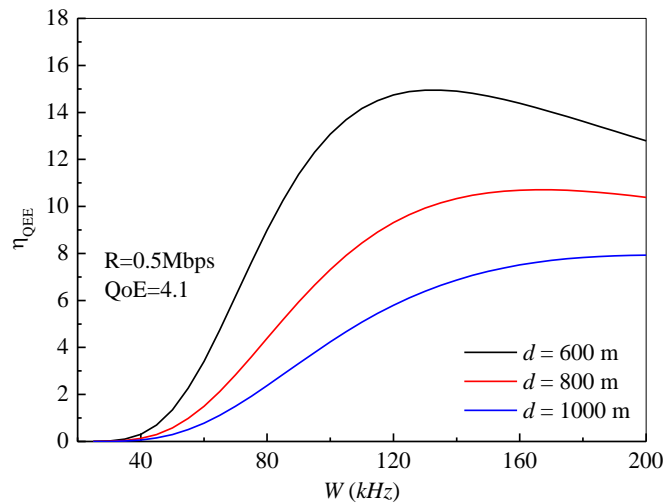
For fixed R , the relationship between η_{QEE} and W is expressed as (setting $R=1$ for simplicity)

$$\eta_{QEE} = \frac{a_1 - Q_{\min}}{(2^{1/W} - 1)WN_0 / h + WP_{cir} + P_{sb}} \quad (15)$$

In **Fig. 6(a)** and **Fig. 6(b)**, the three curves stand for QEE with fixed bandwidth and fixed datarate, respectively. Each type marked with $d = 600m$, $d = 800m$ and $d = 1000m$ denotes different transmit distance. In **Fig. 6(a)**, we set $W = 0.1MHz$ and investigate the relationship between η_{QEE} and R . In **Fig. 6(b)**, we set $B = 0.5Mbps$ and explore the relationship between η_{QEE} and W afterwards.



(a) QEE-Datarate relation



(b) QEE-Bandwidth relation

Fig. 6. Results on influence factor in QEE of FTP service.

Fig. 6 shows that taking operating power into account; there exist the maximum QEE either when given limited datarate or bandwidth. As the distance increases, less datarate is required to obtain the maximum QEE. It is noted the maximum value also drops with further distance, since more energy consumption is required.

Combined with **Fig. 5** and **Fig. 6(a)**, we can see larger power consumption is necessary to enhance datarate by raising SNR. At the saturation region of QoE, the increase of power can enhance transmission performance, but can hardly improve QoE, which results in the QEE drop. Therefore, in a bandwidth limited system, there is a optimal power consumption value providing the highest QEE, i.e., QoE per Watt.

For datarate concerned services, the QoE indicator is related only with the throughput. In order to keep QoE in a satisfying level, the transmission rate should be guaranteed adequate enough. A wider bandwidth can lower the requirement of the transmit power; meanwhile enlarge the energy costs in circuit power. Thus, there is minimal power consumption by a appropriate bandwidth as shown in **Fig. 5** and **Fig. 6(b)**. Given a target QoE, the optimal QEE can be obtained by adjusting the overall power to the minimal value.

According to (2), transmit power can be expressed by

$$P_t = \frac{(2^{\eta_{SE}} - 1)WN_0}{h} \quad (16)$$

As a result, we derive QEE-SE relation using (7) as follows:

$$\eta_{QEE} = f_1(\eta_{SE}, W) = \frac{a_1 + b_1 \log(W\eta_{SE}) - Q_{\min}}{(2^{\eta_{SE}} - 1)WN_0 / h + WP_{cir} + P_{sb}} \quad (17)$$

In this case, it is noted that QEE is not only related to SE, but also related to allocated bandwidth. It is possible to find a way to achieve satisfying QEE by jointly adjusting bandwidth and SE. **Fig. 7** illustrates a visual example of the 3-dimension relation among SE, bandwidth and QEE. From the figure, we have the following observations.

- Full utilization of bandwidth resource may not be the most energy efficient way under fixed SE in the QoE perspective, since circuit power scales with the transmission bandwidth. When SE is low, bandwidth can be trade with certain gains in terms of QEE. However, when SE is above a certain value, QEE achieves a satisfying level given a quite small bandwidth and decrease afterward with more bandwidth used.
- Given a target QEE, the bandwidth-SE relation is non-monotonic. Because QoE does not monotonically rises by increasing SE for fixed bandwidth.
- In a bandwidth limited system, a proper SE obtains highest QEE. Thus, there are at most two corresponding SE to achieve the same QEE. We will choose the larger one with higher datarate in limited bandwidth. Because a higher perceptual QoE can be obtained despite of more energy costs.

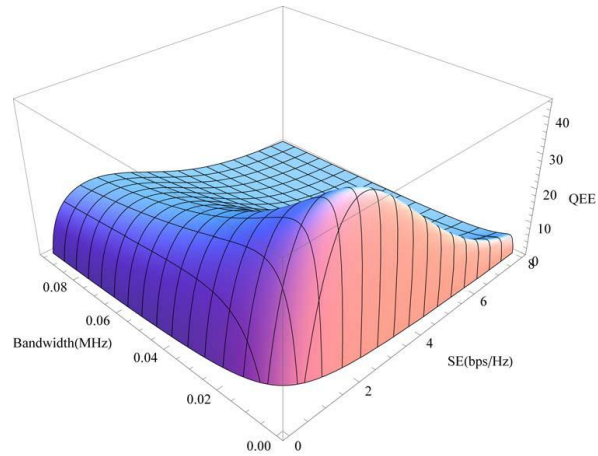


Fig. 7. QEE-SE tradeoff of the FTP service.

Streaming Video Service

In the similar way, we can get the relationship by trading bandwidth and datarate for QEE of the streaming video service, i.e.,

$$\eta_{QEE} = \frac{a_2(1 + e^{b_2(R-c_2)})^{(-1)} - Q_{\min}}{(2^{R/W} - 1)WN_0 / h + WP_{cir} + P_{sb}} \quad (18)$$

Fig. 8 images QEE of streaming video service according to the (18). It also keeps unimodality of bandwidth and datarate. Compared with **Fig. 5**, QEE approaches to 0 more quickly with decreasing of the datarate, because QoE perceived by end users is totally unacceptable in this case, which is highly dependent with the particular MOS function of video service.

It is most significant for allocation resources in networks providing ubiquitous services. When the channel of the users who is enjoying video service is in a bad condition, datarate is falling dramatically. In this case, more bandwidth provision may not be a wise choice, since power consumption expands much faster than the speed of QoE improvement. So it is a better way to settle down the contradiction by enhancing datarate in the energy and QoE perspective.

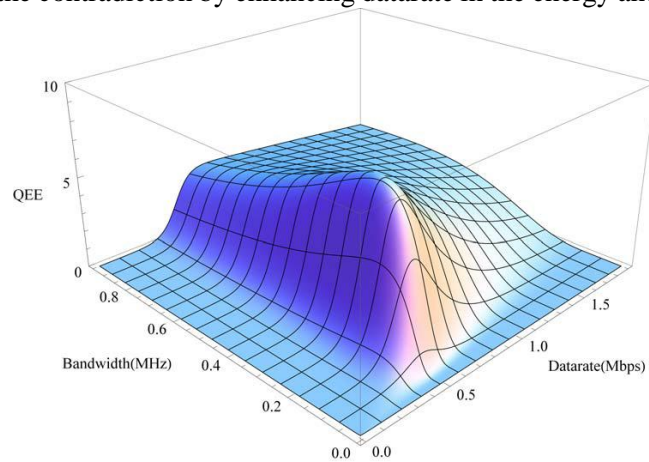


Fig. 8. QEE vs bandwidth and datarate for video service.

The QEE-SE relation for streaming video service is denoted as

$$\eta_{QEE} = f_2(\eta_{SE}, W) = \frac{a_2(1 + e^{b_2(W\eta_{SE} - c_2)})^{(-1)} - Q_{\min}}{(2^{\eta_{SE}} - 1)WN_0 / h + WP_{cir} + P_{sb}} \quad (19)$$

Fig. 9 illustrates the graphical results of (19). It is a belt-like function of bandwidth and SE and has the optimal value with allocated proper resources. In addition, with the same bandwidth, It requires more power consumption to providing higher SE. But it is beneficial to achieve a more satisfying QoE. Thus there is a tradeoff with QEE.

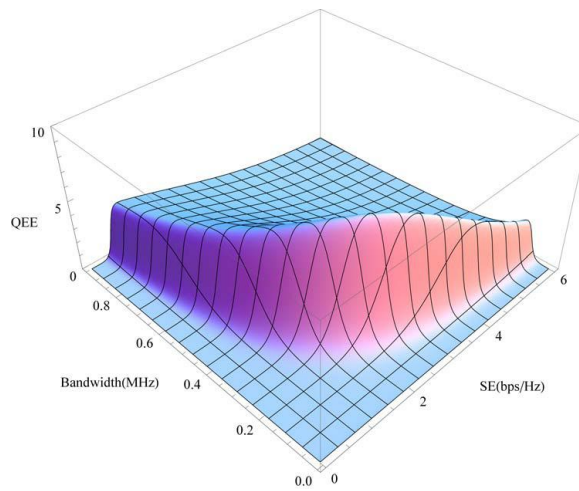


Fig. 9. QEE-SE tradeoff of the video service

4.2 Delay Sensitive Service

Different from the datarate-sensitive services, such as FTP and video, some services concerns less with throughput but delay, like web service. Web browsing users prefer shorter waiting time, i.e. the response delay. This kind of services is delay-sensitive. The average delay is related to the request sizes of the packets. The time to transmit one bit is t and thus the corresponding datarate is $R = 1/t$. Suppose the average packet size is L bit for web browsing service, $\tau = L/R$ is the response time of the requested web page. The transmit power consumption with various delay values can be expressed as

$$P_t = \frac{(2^{L/(\tau W)} - 1)WN_0}{h} \quad (20)$$

We draw the results of power costs in **Fig. 10**. The relationship between the power consumption and bandwidth with regard to web service is similar with that of the datarate-sensitive services. With a narrow bandwidth, higher datarate and transmit power is necessary for demanded delay. While increasing the bandwidth, transmit power decreases but circuit power consumption increases. Therefore, an appropriate bandwidth is desired to minimize the energy costs. With a constant bandwidth, the power consumption is a decreasing function of delay value. Longer response time correspond lower datarate and less energy.

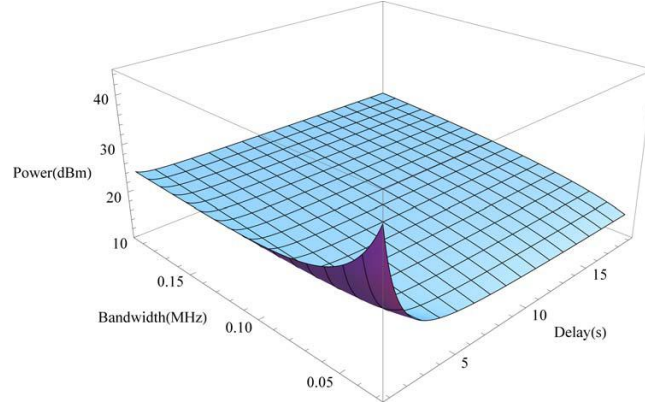


Fig. 10. QEE-SE tradeoff for delay sensitive service.

Then, the relationship by trading bandwidth and datarate for QEE of the web browsing service can be expressed as

$$\eta_{QEE} = \frac{Q_{web}(\tau) - Q_{min}}{(2^{L/(W\tau)} - 1)N_0 / h + P_{cir} + P_{sb}} \quad (21)$$

Fig. 11 indicates the relationship by trading bandwidth and datarate for QEE of the web service in accordance with (21).

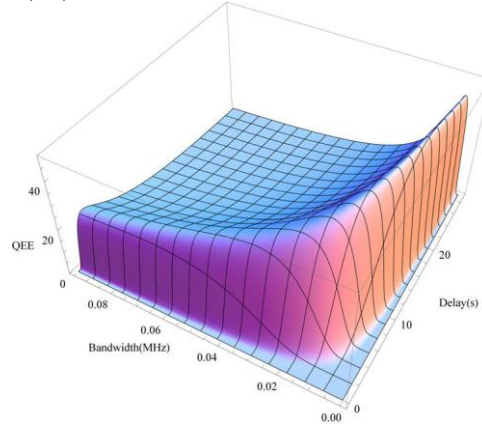


Fig. 11. QEE vs bandwidth and delay for web service.

The bandwidth is given by $W = L / (\tau\eta_{SE})$. In this case, we derive the QEE-SE relation:

$$\eta_{QEE} = g(\eta_{SE}, \tau) = \frac{\tau\eta_{SE}h(5 - Q_{min} - a_3 / (1 + (b_3 + c_3 / \tau)^2))}{(2^{\eta_{SE}} - 1)LN_0 + hLP_{cir} + P_{sb}\tau\eta_{SE}} \quad (22)$$

Fig. 12 gives a description of QEE and SE tradeoff for web browsing service. An optimal value in terms of QEE also exists with proper allocation of bandwidth and SE. With limited bandwidth, improving the SE will shorten the delay time but will lead to higher power consumption. There is also a tradeoff to handle with. Therefore, for bandwidth limited system, an appropriate SE value is desired for the optimal QEE.

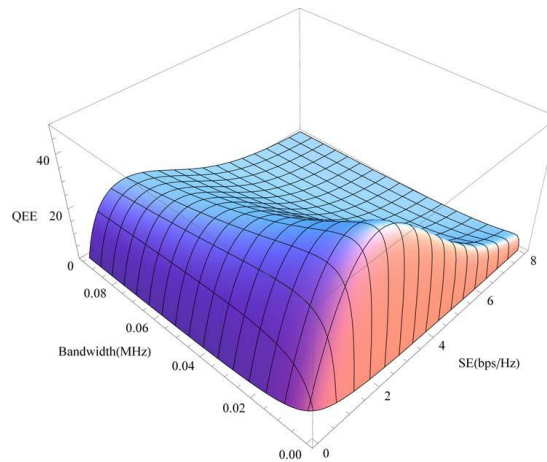


Fig. 12. QEE-SE tradeoff of the Web service.

5. Conclusion

In this paper, we propose QEE, as an user-oriented metric focusing on energy efficiency in wireless networks. As higher QEE can be achieved, the system becomes more energy efficient in that it provides more QoE gains for end users with unit consumed power. For green wireless networks, we propose that data-rate, delay and bandwidth resources can be traded to save energy consumption under certain perceptual quality demands. In addition, the relationships of QEE and SE are thoroughly studied for typical services, including data-rate sensitive services and delay sensitive services. Analytical results indicate QEE and SE do not always coincide and may even conflict sometimes. However, the optimum QEE can always be achieved for diverse multimedia services as long as resources such as power, delay and bandwidth resources are appropriately traded. We also analyze the relationships between the wireless resources and performance. The priority of wireless resources under different scenarios to obtain an acceptable QEE has been further investigated.

This paper gives a deep insight into fundamental tradeoffs for green networks in a comprehensive perspective. However, the analysis of this work addresses the scenario of point to point communications. There are more open issues to be investigated in the view of multi-cell networks, including the tradeoff between the unified QEE and SE considering inter-cell interference, and the tradeoff among deployment cost, pricing and QEE. Correspondingly, more optimization schemes could be designed for achieving a flexible and desirable tradeoff between the perceived performance and energy saving in the future networks.

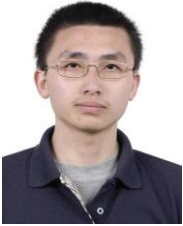
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