Price the QoE, Not the Data: SMP-Economic Resource Allocation in Wireless Multimedia Internet of Things

Wei Wang and Qin Wang

As multimedia services gaining considerable popularity in Internet of Things, providing QoE in smart mmIoT becomes a challenging issue. The authors conceptualize a new framework named SMP, to price the QoE rather than the binary data traffic in IoT multimedia services. By introducing PaaR in QoE-driven network scheduling in mmIoTs, a new dimension of price-distortion is available in multimedia resource allocation, complementing traditional rate-distortion and power-distortion resource allocation approaches.

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Abstract

As multimedia services are gaining considerable popularity in the Internet of Things, providing QoE in smart mmIoT becomes a challenging issue. This article conceptualizes a new framework named SMP, to price the QoE rather than the binary data traffic in IoT multimedia services. By introducing PaaR in QoE-driven network scheduling in mmIoTs, a new dimension of price distortion is available in multimedia resource allocation, complementing traditional rate distortion and power distortion resource allocation approaches. This article also discusses open research challenges in SMP resource allocation, including the difficulty of numerical presentation of QoE, the unavailability of packet-level distortion information, and the non-concavity of the utility functions. A case study is presented to illustrate the PaaR potentials of improving QoE through the SMP framework in mmIoTs.

Introduction

As we enter the age of hyper connectivity, the communication pattern of the Internet of Things (IoT) transcends from machine-to-machine communication to human-to-human communications. The human perception of quality of experience (QoE) from various services plays an important role in designing the IoT communication systems. On the other hand, multimedia plays an essential role in modern complex IoT systems, going beyond simple data sampling (temperature, light intensity, soil moisture, pH value, etc.) to media enriched multimedia Internet of Things (mmIoT). As predicted in [1], Internet video surveillance traffic will increase sevenfold, and virtual reality (VR) and augmented reality (AR) traffic will increase 20-fold between 2016 and 2021. As multimedia becomes the largest class of data traffic, and traditional optimization-based resource allocation and protocol scheduling have reached a certain bottleneck to further improving the performance gain, exploring price as a resource could possibly provide a new angle to solve the QoE-driven resource allocation challenge in mmIoT.

In this article, we first provide an introduction of the basics of smart media pricing (SMP), including the concept of *price the QoE, not the data* and the idea of leveraging price as a resource in wireless network protocol scheduling. Then we discuss the evolution from the successful binary data pricing to QoE-sensitive multimedia pricing, and scan the literature for relevant works in these areas. Then we discuss the open research challenges of the SMP in wireless resource allocation of mmIoT, ranging from QoE presentation to the packet-level distortion reduction determination. Next, we discuss the QoE-driven SMP model, carrying the concept of pricing the QoE, not the data. The SMP model is then translated to a game theoretical QoE maximization problem, bridging SMP with the resource allocation methodologies. Price is then treated as a resource to fine tune the QoE in wireless communications.

Figure 1 illustrates the typical use cases of SMP in mmIoT supporting various applications such as telepresence unifying mmIoT and robotics technologies, VR and AR supported by high-resolution headsets and wireless connections, self-driving cars with cameras to identify the pedestrians and surrounding traffic environments, and video surveillance for security and intrusion detection. Different users and applications over mmIoT have very different QoE requirements, and such QoE requirements lead to diverse strategies in designing the lower-layer resource allocation algorithms and network communication protocols.

For example, self-driving cars have extremely high sensitivity of delay and camera image quality if the pedestrian detection tasks are performed at the edge gateway nodes rather than locally. Thus, the users of self-driving cars would possibly be willing to pay a higher price to ensure the QoE for delay-sensitive and quality-sensitive tasks. For VR and AR users, the traffic could be extremely intensive due to 4K or even 8K picture resolutions and high frame rate at 60 fps. The latency and picture quality are fairly important for VR/AR users, but not as critical as in the self-driving car scenarios. VR/AR users may be willing to pay a moderate price to ensure enough spectrum bandwidth and bounded communication latency. For robotics telepresence users, timeliness is quite important, but the bandwidth requirement is slightly lower than that of VR/AR users. Therefore, these telepresence users could pay lower prices due to the reduced bandwidth requirement. Video surveillance users might have the lowest bandwidth and timeliness requirement among these four types of users, and thus might pay the lowest price for mmIoT services.

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The key contribution of this article is two-fold. First, this article conceptualizes a new framework, SMP, to price the QoE rather than the binary data traffic in IoT multimedia services. By introducing the SMP framework, the gap between end-user QoE and the network economic resource has been bridged. Second, this article introduces a new concept of price as a resource (PaaR) in QoE-driven network scheduling in mmIoTs to bring a new dimension of price-distortion available to multimedia resource allocation. This new dimension will complement traditional rate distortion and power distortion resource allocation approaches in mmIoTs. This article is organized as follows. We discuss the evolution from smart data pricing to smart media pricing, and then we present the open research challenges of SMP and PaaR. In later sections we discuss the SMP model to bridge the QoE and network economics. Following the discussion of PaaR in detail, we introduce relay into the SMP framework. We also present a case study of SMP economics resource allocation, and finally we draw our conclusion.

From Smart Data Pricing to Smart Media Pricing

Smart data pricing (SDP) has been identified as a desirable candidate to lower congestion, enhance user experience, and improve revenue of content providers and wireless carriers [2, 3]. In addition to providing a network economics solution to congestion, it has been applied to many aspects of network research such as studying user behaviors, trading for cognitive radio spectrums, and pricing sponsored contents. It has also been applied to many other fields such as smart grid energy usage management systems, vehicular transportation systems, and smart city systems.

Building on the success of past SDP, QoE, and communication network research, SMP is designed to bridge the gap between price and QoE through resource allocation. Despite the vast potential of SDP in controlling network congestion, there are few research works reported in the literature investigating multimedia pricing policies to improve QoE. For example, Wu *et al.* presented the case that maximum packet delivery rate did not necessarily lead to optimal video quality [4], and proposed an incentive mechanism for video packet offloading [5]. Ji *et al.* established a three-party price model considering video quality layers and rate distortion in utility functions [6], and proposed a joint optimization framework for source coding rate and advertisement durations in video broadcasting [7]. In our preliminary work [8], a nonuniform packet pricing game was studied to enhance wireless multimedia QoE, and the SMP concept of pricing the QoE, not the data was introduced. In [9], the SMP concept was extended to wireless multimedia relay networks, to bring incentives to mobile devices participating in media content forwarding.

Open Research Challenges

Determination of QoE Quantitatively

The quantitative determination of QoE has been a long-term challenge not only for mmIoT but also for generic wireless multimedia communications.

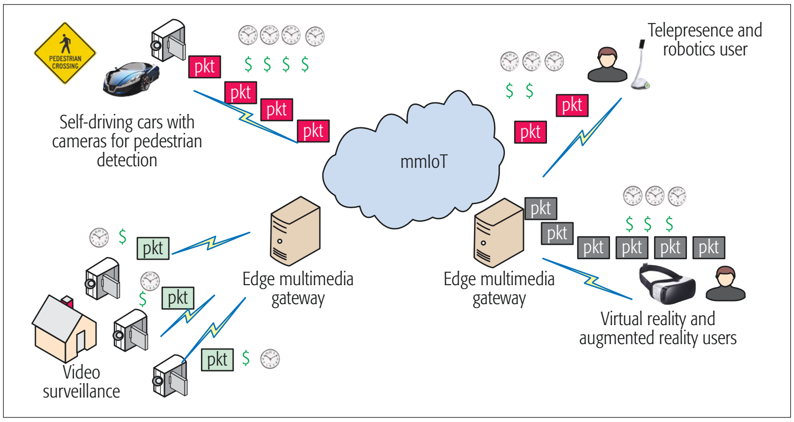

Figure 1. Typical use cases of SMP in mmIoT. The clock symbols denote the delay sensitivity of the packets, and the dollar sign symbols denote the willingness to pay a higher price to ensure higher QoE.

Various numerical QoE models have been reported in the literature to address the different emphasis of multimedia communications. For example, a parametric packet video QoE model considering packet loss ratio and cumulative data rate was adopted in [10]. A comprehensive personalized QoE model considering a user's personal preference of multimedia content was proposed in [11]. The QoE model adopted in [12] was enumerated as the average video quality subtracted by the negative factors including quality variation, re-buffering, and initial startup delay of video stream. In fact, different users of the multimedia communication systems could put different weights on different components in the QoE model, and the adopted QoE model could be very different from user to user. Even for the same user, the QoE model could be different from time to time, impacted by both network side and human side factors. Since QoE is the essential component (and also the positive part) of the utility function, and the numerical presentation of QoE is still challenging, the SMP framework has to be designed to be generic and independent of QoE models. Thus, various widely adopted QoE models could possibly be integrated into the SMP framework.

Knowledge of Packet-Level Distortion Reduction

Unlike binary data communications, the packets in multimedia communication streams have diverse impact on the QoE at the user side. The distortion reduction of a multimedia packet is defined as the amount of quality gain when this packet is transmitted and decoded successfully. Some packets may have higher distortion reduction (i.e., quality contribution) to the decoded multimedia than other packets. Typically, the intrinsic packet distortion reduction is determined by factors such as the quantization and resolution settings in the compression algorithms. Thus, when receiving and decoding these packets with high-quality contribution, the QoE could be improved considerably over receiving other packets. On the other hand, the user side QoE is also primarily impacted by those packets with high influence; that is, if some of these packets are lost in the wireless channel, there will be severe QoE degradation at the user side [13]. Typically, the QoE influence of a packet is determined by the encoding dependency graph generated during the compression process. The

In the SMP interplay, the profit of a SU is defined as the income generated from user satisfaction such as multimedia QoE minus the payment for the SP's service. The optimization problem for the SU is to set the proper amount of buying power that maximizes its profit, subject to transmit power constraints.

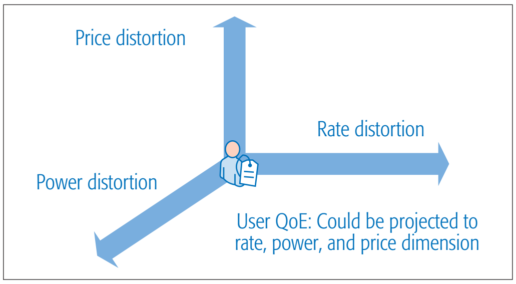

Figure 2. Adding a new dimension to resource allocation: price as a resource, in conjunction with rate distortion and power distortion approaches.

packets with high QoE influence and distortion reduction certainly deserve more resource and price allocation in communication [14]. However, tracking per-packet distortion reduction and QoE influence is not practical, especially when there are a large number of multimedia packets transmitted in a short period of time. Therefore, appropriate grouping of packets and reasonable approximation are necessary to price the multimedia data in the wireless environment.

Non-Concavity of the Utility Functions

The utility function of the user side is typically formulated as QoE expectation of the multimedia service subtracted by the financial cost of getting such service at the expected QoE. Depending on the specific QoE model adopted in the mmIoT system, there is no guarantee as to whether the utility function is concave or not. For example, if we choose the Shannon capacity data rate as the primary factor impacting QoE, and assume a linear relationship between the cost and price, the utility function is concave, and the maximum point could be attained by getting the first order derivative. On the other hand, both the parametric QoE model and the personalized QoE model have several parameters calibrating the presentation of QoE, and thus, depending on the choices of parameters, the utility function may not be concave at all. Thus, we have to determine appropriate methods such as the best-response algorithm to attain the maximum point of the utility function. In this best-response algorithm, each player searches for the best response assuming the other player has determined his/her choices of strategy. Therefore, as long as the choices are finite, this algorithm can attain the Nash equilibrium no matter whether the utility function is concave or not.

The QoE-Driven SMP Model

Suppose that there is a client device in mmIoT that needs to download a sequence of multimedia packets from the base station. In the QoE-driven SMP model, the mmIoT client device is the service user (SU), and the base station is the service provider (SP). The SP helps transmit multimedia data and provides communication service QoE by charging the SU appropriately. Most of the traditional pricing methods determine prices according to the throughput or flow data rate, regardless of the multimedia content characteristics such as the quality contribution or distortion impact of certain groups of packets. Different from binary data pricing models, the multimedia content should be prioritized in the transform domain (e.g., wavelet or cosine transform coefficients), spatial domain (e.g., the quadtree pixel clustering, flat areas and edges), or temporal domain (e.g., video frame coding mode) in the QoE-driven SMP model. Thus, the SP could possibly request a higher price to transmit premium content and a lower price for regular content. PaaR can be diversely allocated among prioritized multimedia content, in a way similar to other communication resources.

To properly arrange mmIoT SPs participating in data transmission and network SUs downloading multimedia data, the mmIoT profit maximization problem of an SP and an SU is investigated here. The price resource can be jointly allocated with traditional communication resource such as transmit power, data rate, forward error correction (FEC) channel coding, packet length, and automatic repeat request (ARQ) limit in QoE-driven mmIoT. We take the transmit power as an example. The transmit power requested by the SU affects the selling price that the SP charges for the provided service; on the other hand, the selling price also has impact on the amount of transmit power the SU buys.

SU (Buyer) Side

In the SMP interplay, the profit of an SU is defined as the income generated from user satisfaction such as multimedia QoE minus the payment for the SP's service. The optimization problem for the SU is to set the proper amount of buying power that maximizes its profit, subject to transmit power constraints.

SP (Seller) Side

Being a rational player, the SP knows how much power the SU will request with given prices. Consequently, the SP can set its optimal price according to the power responses of the SU. The profit of the SP can be defined as the income received from the SU's payment minus the transmission cost. The optimization problem for the SP is to set a proper charging price that maximizes its profit, subject to the cost constraints.

The SP and SU both want to maximize their own profit by changing selling price and purchasing transmit power, respectively. The interactions between the SP and the SU can be formulated as a Stackelberg game. As rational players, they aim to find the stable state equilibrium, where they both achieve the best possible profit and will not unilaterally deviate. There are two ways to obtain the game equilibrium, depending on whether the profit function is concave or not [8]. If the profit function is concave, the maximum stable point could be attained by getting the first order derivative of a player's profit function. If the profit function is not concave, one can keep updating reactions in a limited interval according to other participators' responses until arriving at the point where nobody will get more profit by changing his/her own action.

Price as a Resource in Multimedia Communications

In order to better support diverse users with various QoE requirements and resource consumptions, price could be leveraged as a powerful resource transcending traditional rate-distortion or power-distortion resource allocation optimization or game research.

Figure 2 illustrates the concept of PaaR in SMP for mmIoT services. Traditionally, a plethora of research works have been focused on rate-distortion-oriented resource allocation for wireless multimedia communications and mmIoT. In such rate-distortion-optimized resource allocation approaches, the source coding algorithm and compression codecs are jointly designed with the channel coding schemes and lower-level network protocols. The compression ratio of the source multimedia is typically adaptive to the wireless channel conditions or the feedback of network congestion. In more recent power-distortion-oriented resource allocation approaches, energy efficiency was the primary concern rather than network throughput. Power was treated as a new dimension in resource allocation in addition to the rate. In the new PaaR, price is identified as another resource independent of power and rate to fine tune the multimedia communication QoE and resource consumption trade-off. Thus, in addition to the existing rate distortion and power distortion dimensions, price distortion potentially brings a new dimension to resource allocation research.

In PaaR, the QoE is measured in terms of distortion, plus other factors such as bandwidth, rate fluctuation, and startup delay, as well as personalized user profiles. The projection of QoE to the price distortion dimension should have a trend similar to the rate distortion and power distortion dimensions. The monotonicity of these three functions are all increasing: higher price, higher power, and higher rate all lead to higher QoE and thus lower distortion.

Interplay between SMP and Relay

In mmIoT systems, various devices have diverse communication distances and channel loss conditions. Some devices could have very long distances to the IoT base station or the access point, and some others may have short distances and good channel qualities. In order to provide a fair and ubiquitous environment to all the devices in mmIoT systems, bridging the connections between long-distance devices and the access base station becomes an essential issue [15]. The philosophy of this SMP relay interplay is to incentivize mmIoT devices with high residue energy and short or medium distances to the base station participating in multimedia transmissions and relays, as shown in Fig. 3. In this scenario, the base station gives incentives to the relay, and the relay helps the base station forward multimedia data to the end user. Typically, the end users may be far from the base station, and the signal quality could be very low. In order to provide relatively stable multimedia service to end users, the help of an intermediate relay is necessary.

In the SMP-Relay interplay, it is critical to provide incentives to the devices participating in the relay service in mmIoT. By default, each individual device in the mmIoT is a selfish unit, reluctant to provide relay services to others due to the extra energy, bandwidth, scheduling time, and other associated resource consumption. In order to fight against selfishness of the relay node, the key challenge is to quantitatively determine the amount of incentives, either monetary or in other measurable units such as free service time or virtual accumulated points. This incentive should also be proportional to the service QoE provided by the relay device. Higher QoE typically requires higher communication bandwidth and energy resource consumption from the relay. On the other hand, the relay may opt to choose to receive lower incentives but also consume lower energy or bandwidth resources.

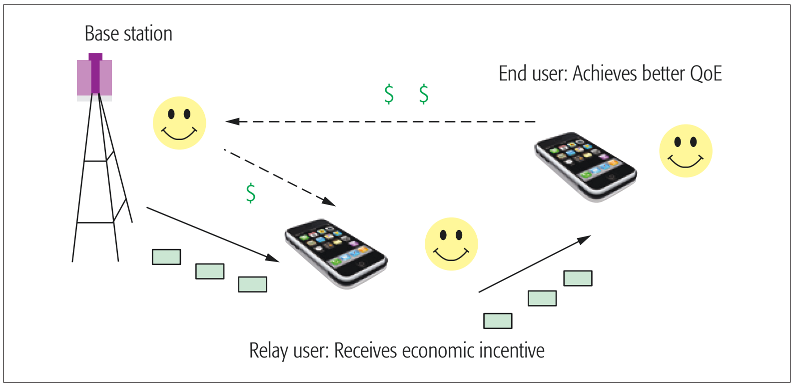

Figure 3. Interplay of SMP and relay for multimedia data forwarding in mmIoT. The device with shorter distance to the base station will provide relay service to the device with longer distance, and will get economic incentives based on service QoE.

In the SMP-Relay interplay framework, the relay device will price its energy and communication resource used on the relay transmission, and the source (could be the base station for downlink traffic or the source device in mmIoT for uplink traffic) will price its incentive to the relay. Providing more incentives from the source to the relay, the relay device will have higher marginal profit, and thus could increase its energy and communication resource usage on the relay transmission, and eventually increase the user-side QoE. The SMP-Relay interplay could be formulated as a QoE-driven multistage Stackelberg game between the source device and the relay device.

Downlink Traffic Relay

In the SMP-Relay interaction for downlink traffic relay, the base station's utility function could be presented as the revenue charged from the end user receiving this service in mmIoT, subtracted by the cost function in a way similar to [9]. The cost function is further decomposed into two parts: the communication cost spent on communication between the base station and the relay, and the economic cost paid to the relay for forwarding the media content to the receiver. The QoE of such relay service should be no less than the QoE provided by the direct transmission from the base station. This is equivalent to the situation when the base station requests the relay to use enough communication resource to provide a relatively low bit error rate, and thus the QoE of the relay service could be ensured. As the base station strives for higher QoE at the receiver side, the relay device asks for higher price to compensate for the resource consumption. The desirable QoE and price could be attained by finding the Nash equilibrium of the Stackelberg game between the base station and the relay device.

Uplink Traffic Relay

In the SMP-Relay interaction for uplink traffic relay, the utility function of the relay could be presented as the revenue charged from the source device, subtracted by the communication cost to deliver media content to the base station at the pledged QoE. The utility function of the source device could be presented as the expected QoE to deliver the uplink traffic content to the base station, subtracted by the economic cost to delegate such uplink transmission to the relay device. The relay delegation price and the pledged QoE could be attained in a way similar to the downlink traffic scenario via approaching the Nash equilibrium of the Stackelberg game.

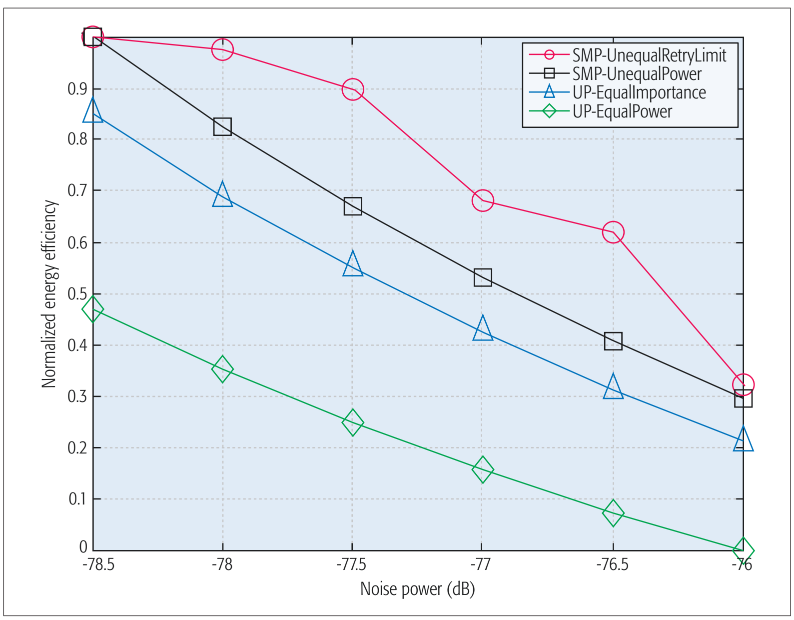

Figure 4. Energy efficiency comparison of SMP and uniform pricing methods under various noise power levels.

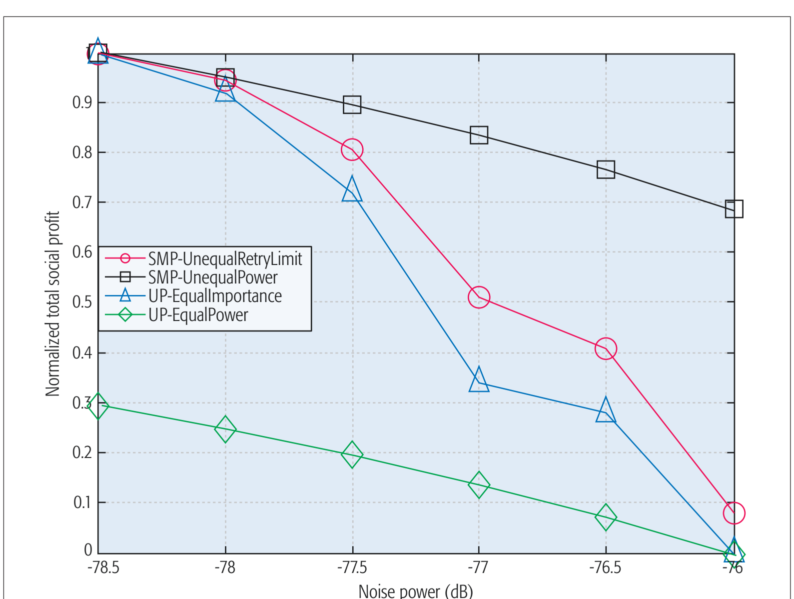

Figure 5. Social profits of SMP and uniform pricing methods under various noise power levels.

A Case Study of QoE-Driven SMP

In this section, we develop a case study in order to demonstrate the effectiveness of the proposed SMP framework. The standard *Foreman* video sequence is used during simulation. To illustrate the performance gain of the unequal SMP resource allocation method, the media packets are encoded diversely. Every other packet is encoded as an important intra reference packet (I frame), with the remaining half being encoded as regular inter reference packets (P frame). I frames are more important than P frames because the transmission errors of I frames will impact the successful transmission of subsequent P frames. With the priority among packets, resource like ARQ retry limit and transmit power can be allocated unequally based on nonuniform media pricing.

We define the video quality per unit of transmission power as the energy efficiency. Since various resource allocation methods affect the performance in different orders of magnitudes, we normalize the energy efficiency in period [0, 1] in order to compare the performance. From Fig. 4 we can see that the SMP methods based on unequal retry limit (SMP-UnequalRetryLimit) or unequal power control (SMP-UnequalPower) obtain much higher energy efficiency than the uniform pricing based on equal importance (UP-EqualImportance) or equal power control (UP-EqualPower). This is because the SMP-UnequalRetryLimit and SMP-UnequalPower methods allocate different retry limit and transmission power, respectively, for different packets, which are priced diversely using Stackelberg game. The UP-EqualImportance method does not consider packet importance diversity, that is, resource is sold at the same price regardless of what content is transmitted. The UP-EqualPower method selects the same transmission power for all packets, ignoring smartly differentiated pricing. The traditional uniform pricing methods neglect the multimedia characteristic diversity and the nonuniform pricing among packets.

Figure 5 compares the total social profit of the SMP methods and the uniform pricing methods when changing the noise power. The social profit is the sum of the seller's and buyer's utilities. The smart pricing methods enhance the profit gain of the seller (SP) and the buyer (SU) significantly. The reason is that the transmission resource is distributed among packets intelligently using Stackelberg game with regard to the incentives and distortion impacts. In SMP methods, the regular packets are priced lower with less transmission resource, thus saving communication resource for important multimedia packets.

The utility of a resource buyer is the income minus the economic spending. The income of the buyer is linked to multimedia transmission QoE; thus, better media quality means higher income. When we change the scaling coefficient between the utility gain and the video quality, the social profit comparison of SMP methods and uniform pricing methods is shown in Fig. 6. For all resource allocation methods, the social profit is enhanced when we increase the utility gain per unit of video quality. The SMP methods allocating resource unequally outperform the uniform pricing methods using equal retransmission limit and equal transmission power.

Conclusion

In this article we introduce a new concept of SMP to leverage price as a resource for QoE-driven wireless multimedia communications in mmIoT. The proposed SMP framework priced the QoE rather than the binary data in communication resource allocation. By introducing PaaR to mmIoT, a potential new dimension of price distortion in wireless multimedia resource allocation would be available to further improve QoE gain, in parallel to the rate distortion and power distortion approaches. In this article we also discuss the open research challenges including the difficulty of numerically presenting QoE, the knowledge of packet-level distortion reduction contribution, and the non-concavity of the utility functions. Some QoE-driven resource allocation solutions of the SMP framework are presented, such as the SMP game model, the PaaR concept, and the price enabled relay. We also present a case study of the QoE-driven SMP framework performance gain.

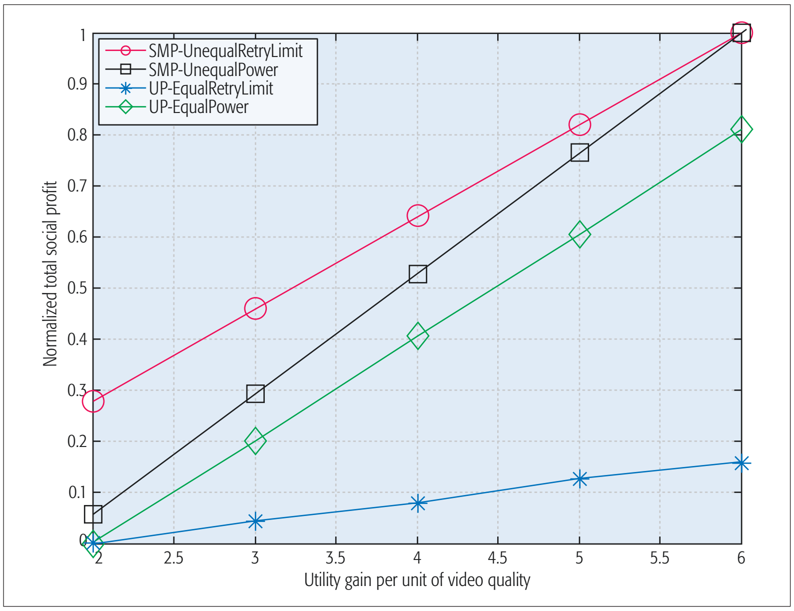

Figure 6. Social profits of SMP and uniform pricing methods under various utility gain per unit of video quality.

Acknowledgment

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