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Abstract
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Keywords
QoS analysis model, finite state Markov Chain, effective capacity, fading wireless channels

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QoS Analysis Models for Wireless Networks

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Abstract

Guaranteeing of QoS over wireless networks is a very challenging task. The first and critical step in addressing this problem is to build up a QoS analysis model which accurately characterizes the fading channel and time-varying capacity of the link, by quantifying parameters like Bit Error Rate (BER) or delay to protocols of higher layers. This paper presents a study of QoS models from a physical and data link layer point of view, more specifically, we introduce the Finite State Markov Chain (FSMC) model for fading channels at the physical layer and the Effective Capacity (EC) model at the data link layer. The FSMC can provide us with a quick estimate of current channel conditions like BER, while it is very hard using the physical channel model to get parameters like delay which needs an analysis of queueing behaviors; for that reason, a link-layer model – EC which provides a statistical QoS model on the unacceptable delay performance (*i.e.*, the probability of delay exceeds a bound) is then studied. The characteristics, advantages and disadvantages of these two models will be studied and compared in this paper.

Keywords

QoS Analysis Model, Finite State Markov Chain, Effective Capacity, Fading Wireless Channels

1. Introduction

With the proliferation of wireless mobile devices, wireless applications, especially wireless multimedia applications, are becoming increasingly dispensable for low-latency applications such as voice and video transmission of crucial missions on battlefields or rescue missions to time-sensitive interactions of multi-player games in daily entertainment. However, these multimedia applications have stringent quality of service (QoS) requirements on data rates, delays and delay jitter, which pose major challenges to the wireless link whose characteristics are unreliable, time-varying and fading. Therefore it is essential to accurately characterize the fading channel and time-varying capacity of the wireless link to facilitate QoS provisioning over wireless networks. To this end, many example have appeared in the literature, using the physical-layer signal distribution parameters the signal-to-noise ratio (SNR) to construct a discrete Markov analysis model (Wang *et al*., 1995; Zhang *et al*., 1999; Hassan *et al*., 2004; Aráuz *et al*., 2004; Kumwilaisak *et al*., 2008; Sadeghi *et al*., 2008), whereas fewer link-layer examples have been proposed (Wu *et al*., 2003; Liu *et al*., 2004; Zhang *et al*., 2006). These two types of models obviously consider different metrics: besides the SNR, another important metric in the physical layer is the Bit Error Rate (BER), although they are usually mapped to each other; while important metrics at the data link layer typically include: delays, packet loss, and

time varying capacity of the link. A wireless communication system with Finite State Markov Chain (FSMC) and Effective Capacity (EC) models is depicted in Figure 1. The physical-layer model provides a quick estimation of the wireless channel condition, but it is difficult to use the channel model to analyze link-layer QoS metrics like delays. The reason for this will be elaborated later.

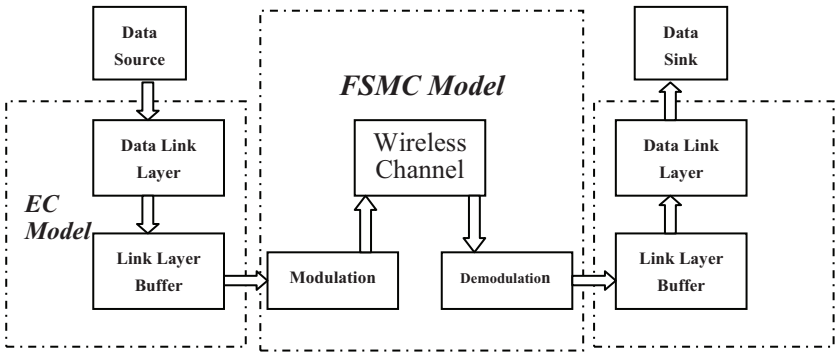

Figure 1: An example of wireless transmission system embedded with the FSMC model and the EC model

In what follows, we describe how the FSMC model represents time-varying wireless channels; we pay special attention to how the channel SNR state is partitioned in Section 2. We introduce the statistical QoS guarantees and the EC model in Section 3. Then we compare these two models and conclude the paper in Section 4.

2. Finite State Markov Chain Model of Wireless Fading Channels

The Markov process can be used to model characteristics of dynamics and statistics of the received SNR over fading channels, where each Markov state represents a different signal-to-noise distribution (SNR) or channel condition. In other words, the physical meaning of the channel state partitioning is to discretely categorize fading channel states according to SNR, meaning that each partitioning represents a different probability of bit errors, together with state transition probability, which is used to predict the future condition of the channel. For example, the two-state Gilbert-Elliott model (Gilbert, 1960; Elliott, 1963) which is the earliest work on characterization of the bursty noise channels by the Markov model, partitions the whole range of SNR into two states: one of them representing the good channel state while the other represents the bad channel state. This simple model allowed them to evaluate channel capacity and error rate performance through bursty wireline telephone circuits (Sadeghi *et al*., 2008), but it is inadequate for wireless links because the channel quality varies dramatically (see Figure 2): the reason is that frames falling into a same state would experience quite different SNR distributions (*i.e.*, ΔSNR is too big) if the number were too small; while the number cannot be too large either, because it makes the duration of a state too short to transmit at least one frame (*i.e.*, ΔT is too small). Hence it can be seen that finding a suitable number of

SNR partitions to keep a received packet completely in one state and the following packets in the current state or neighboring states becomes a critical issue of FSMC channel modeling.

2.1. Estimation of BER in the Steady-State n

Suppose we have an N-state Markov chain, the state space is denoted as S={S_1,S_2,S_3,….,S_n}, n=1,2,…,N

Let $p_{n,n+1}$ be the state transition probability from state n to state n+1:

$$p_{n,n+1} = Pr(S_{n+1}|S_n) \qquad (1)$$

If we link the N-state Markov chain to a received signal envelope over a typical multipath flat fading channel with a Rayleigh distribution and the probability density function (PDF) $P(\gamma)$ of SNR γ, then each state of the Markov chain is associated with a channel condition or SNR range $[\gamma_n,\gamma_{n+1}]$.

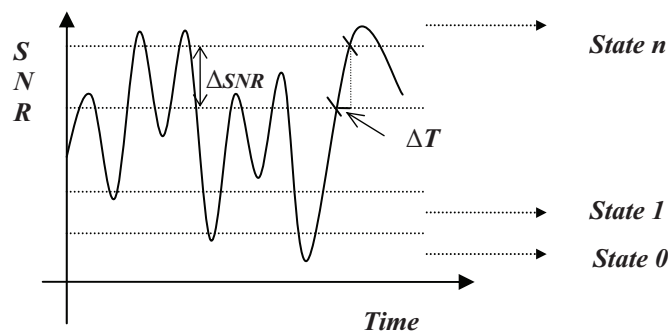

Figure 2: An example of partitioning SNR into n states

To facilitate the QoS analysis of fading channels, one of the most important parameters we want to know is the BER. Having connected the SNR distribution to an N-state model, we can proceed to calculate the probability of symbol errors, which is in other words the BER at state n, denoted as p_e^n and predict the future p_e^{n+1} with the state transition probability $p_{n,n+1}$ and state steady probability π_n:

$$\pi_n = \int_{\gamma_n}^{\gamma_{n+1}} p(\gamma)d\gamma \qquad (2)$$

where γ_n is the SNR threshold at state n, and the average BER at state n can be calculated as:

$$p_e^n = \frac{\int_{\gamma_n}^{\gamma_{n+1}} p_e(\gamma) p(\gamma) d\gamma}{\pi_n} \qquad (3)$$

where $p_e(\gamma)$ is the probability of symbol error function decided by the SNR γ. The average BER at state n given by equation (3) is available to provide the adaptive modulation scheme and protocols of higher layers with an important view of the current channel condition. Therefore corresponding decisions like medium access in the data link layer or choices of video coding schemes in the application layer can then be adapted accordingly at the next channel state. Up to this point, the procedure appears to be clear at the physical channel level, although it is necessary to address how the SNR is partitioned, because an N-state Markov chain was assumed above without mentioning the method of partitioning. In the next subsection, we will describe how to partition the received SNR in the literature.

2.2. SNR State Partitions

Several studies have addressed the concern of appropriate partitions of the received SNR (Hassan *et al*., 2004; Wang *et al*., 1995; Zhang *et al*., 1999; Zorzi *et al*., 1998; Tan *et al*., 2000). Hassan *et al*. proposed a novel partitioning approach for the received SNR utilizing Jake's level crossing rate. The author partitioned the wireless channel in a manner that matches the service rates at transmitter buffer to the total consumption rate in the model. This requires partitioning thresholds corresponding to a given number N of active consumers, while N also satisfies the ratio between the nominal service rate when the channel is in the best state n, where $\gamma \in [\gamma_n, \gamma_{n+1}]$, and the corresponding service rate when the channel is in the second worst state 1, where $\gamma \in [\gamma_1, \gamma_2]$. Wang *et al*. used a fixed 8-SNR-state model with equal steady state probability which is $\pi_0=\pi_1=\ldots=\pi_n=1/n$, which is a common way for the SNR partitioning in the literature, but the equal steady state probability partitioning simply does not take the non-linearity distribution of SNR into account. An optimization suggested by the author is to make $\pi_n=2\pi_{n-1}$ and $\pi_0=1/2^n-1$, then the probability of being in a higher level doubles that of a lower level, which presumes that the SNR has a higher probability of staying at good states; the validity of the assumption is, however, not clearly specified.

Zhang *et al*. gave a different approach to partitioning SNR and calculating the number of states, assigning an equal average duration to each state with a guideline that the SNR range should be large enough so that a received packet falls completely in the corresponding state; on the other hand, it should not be too large because packets received in the same state are expected to experience a similar BER. Based on this, the authors set the average duration of each state to be equal to a duration of multiple-packet transmission. By solving a series of equations developed in (Zhang *et al*., 1999), one can obtain a vector of SNR thresholds $\{\gamma_2,\ldots\gamma_n\}$ with $\gamma_1=0$ and $\gamma_{n+1}=\infty$.

For some other partitioning methods, those of Zorzi *et al*. (1998), using a 2-state model, and Tan *et al*. (2000) using a 50 to 100-state model, are noteworthy. There is no simple and clear solution on how to partition the received SNR in the FSMC

model. This may depend on many factors including application, model complexity, required accuracy and modulation/demodulation format, and the coding scheme, which is always a trade-off between model accuracy and its complexity (Sadeghi *et al*., 2008). Exploring how the received SNR can be partitioned is still an open research area; current literature focuses on either equal-state steady probability or equal duration of n states without considering non-linearity distribution of the SNR. Obviously, it is very challenging to partition SNR with that concern; one solution could be partitioning SNR into n states but with a different weight for each state, which is to say that some states in a good channel condition would have longer residences.

This study of a Finite State Markov Chain model to characterize wireless fading channels has highlighted how to estimate average BER at state n to facilitate QoS analysis, and has paid the special attention to ways of partitioning SNR. In the next section, we move to the higher layer to present a QoS analysis model at the link-layer level.

3. Effective Capacity Model of the Data Link Layer

In section 2, we have seen that a FSMC channel model can provide us with BER to facilitate the QoS analysis; however, the physical layer channel model does not explicitly characterize the channel in terms of delay, which is a more direct QoS concern in multimedia applications. For this reason, a data link layer QoS analysis model is required, in the following two subsections the effective capacity model proposed by Wu *et al*. (2003) is studied, and some observations are made.

3.1. The Concept of Statistical QoS Guarantees

Multimedia applications have stringent QoS requirements: once a received real-time packet exceeds its delay bound, it is considered useless and has to be discarded. Thus we would like to add a delay bound to multimedia data transmission. An arising problem is that the capacity of the wireless channel is randomly changing, hence an attempt to provide a hard delay guarantee is therefore practically impossible. For example, over a Rayleigh fading channel, the only lower bound of the system bandwidth that can be deterministically guaranteed is a bandwidth of zero (Zhang *et al*., 2006). Therefore, Wu *et al*. (2003) extended the concept of deterministic service curve $\Psi(t)$ of wired networks to a statistical version for wireless networks, specified as the pair $\{\Psi(t),\varepsilon\}$, where ε is the probability of violating the QoS requirement. This statistical service curve pair satisfies:

$$\sup_t Pr\{S(t) < \Psi(t)\} \leq \varepsilon \qquad (4)$$

where $S(t)$ is the actual service provided by a channel, and sup is the short term for supremum that is also referred to the least upper bound, $\sup_t\{*\}$ means the least element in a subset that is greater than or equal to each element of $\{*\}$ with the variable t. For a practical value of ε, a non-zero service curve $\Psi(t)$ can be guaranteed, which is to say we guarantee an arriving process to be served by at least the channel service -- $\Psi(t)$ with a small violation probability ε.

3.2. Effective Capacity with Statistical QoS Guarantees

The concept of effective capacity proposed by Wu *et al*. comes from so-called effective bandwidth theory, where the effective bandwidth is defined as the minimum service rate required by a given arrival (Wu *et al*., 2003); though the effective capacity is not clearly defined, it can be considered as the maximum arrival rate that a channel can serve. Wu *et al*. suggests that for a long-term arrival and service process, the probability that a queue length $Q(t)$ at time t exceeds a required threshold B decreases exponentially when B increases:

$$\sup_t Pr\{Q(t) \geq B\} \approx \alpha\, e^{-\theta B} \qquad (5)$$

where $\alpha = Pr\{Q(\mathrm{t})>0\}$ is the probability that a queue is not empty and θ is a positive real number called QoS exponent which is an important parameter, we will make some remarks of it later. If the issue of interest in QoS is the delay D(t) experienced by a packet at time t, then the probability that D(t) exceeds a delay bound D_{max} can be written similarly to equation (5):

$$\sup_t \Pr\{D(t) \geq D_{max}\} \approx \alpha\, e^{-\theta D_{\max}} \qquad (6)$$

Thus, a data link layer QoS model is specified by the pair $\{\alpha, \theta\}$ with a delay bound D_{max}, which can tolerate a delay-bound violation probability of about $\alpha\, e^{-\theta D_{\max}}$. Detailed developments of $\{\alpha, \theta\}$ and the concepts of effective bandwidth and effective capacity may be found in the literature (Chang *et al*., 1995; Wu *et al*., 2003).

Through equations (5) and (6), it can be seen that the QoS exponent θ plays an important role in statistical QoS guarantees: this associates the effective capacity with the QoS performance and indicates the decaying rate of the QoS violation probability. A larger θ corresponds to a smaller delay, meaning that stricter QoS guarantees can be provided and vice versa. Specifically, as $\theta \to \infty$, the network cannot tolerate any delay ($D(t)$ will not exceed the delay bound), which corresponds to an extremely stringent delay constraint; as $\theta \to 0$, the network transmission can never satisfy the delay bound, which corresponds to an extremely loose delay constraint. In other words, we account for it from the effective capacity perspective: while the QoS becomes more and more stringent, in order to ensure that the queue will never build up, the channel can serve a lower and lower arriving traffic rate.

I am proposing a framework combining the physical-level and link-level QoS analysis models in a cross-layer manner, which utilizes the FSMC model to dynamically choose a modulation rate according to the physical channel condition and extracts wanted parameters like delay from the EC model based on the dynamic service rate provided by the FSMC model, or maybe involve the network-layer and higher-layer models: this is the subject of ongoing research.

4. Concluding Remarks

In this paper, we have introduced two types of QoS analysis model: the FSMC at physical-layer level and EC at link-layer level. The former one theoretically observes the QoS concern in terms of BER and SNR, providing a quick estimate of the physical-layer performance, which makes the FSMC very useful in modeling wireless channels for data transmissions. However, wireless systems are expected to deal with increasing time-sensitive multimedia traffic, which is affected more by QoS metrics like delay. One problem is the physical-layer channel model cannot easily handle link-layer QoS guarantees such as delay, which needs an analysis of the queueing behavior of the link, and this is hard to do from the physical-layer analysis model. For this reason, we moved to the higher layer to look for an alternative model, the link-layer EC model that can provide us with QoS analysis in terms of delay bound or queue size using a statistical probability model. We see that be different from the physical-layer model, the EC model can more easily extract the link-layer QoS concern like delay through relating the effective capacity to a statistical delay-violation probability indicated by the QoS exponent θ.

As mentioned at the beginning of this paper, it is critical to accurately model the fading channel and time-varying capacity of the link for QoS analysis, so it is appropriate to attempt to combine these two models in a cross-layer way, in which the routing or video coding of higher layers would have a clear and holistic view of the overall set of networks.

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