The Interplay Between Data Transmission Power and Transmission Link Utilization

Sami Akin

***Abstract*—We consider a single-input single-output communications link in which a transmitter and a receiver, both having data buffers with their own unique quality-of-service (QoS) constraints, perform data transmission over a time-selective flat fading wireless channel. Regarding the stochastic nature of the wireless channel in the physical layer, we first provide the effective capacity at the transmitter buffer. Then, we assume a data arrival process with a constant rate to the transmitter buffer and identify the departure process from the transmitter to the receiver. Noting that the departure process is the arrival process at the receiver buffer, we find the effective bandwidth at the receiver buffer. Establishing the maximum transmission link utilization as the ratio between the effective capacity at the transmitter and the effective bandwidth at the receiver, we investigate the relationship between the transmission power in the channel and the maximum transmission link utilization under QoS requirements by employing different symbol modulation techniques in a Rayleigh fading environment.**

***Index Terms*—Transmission link utilization, effective capacity, effective bandwidth, input modulation, resource allocation.**

I. Introduction

DUE TO THE reserve-limited nature of communications networks, an efficient use of available resources is very important from a cross-layer design perspective. Especially in networks with wireless links, the system design becomes more acute and requires the understanding of the stochastic nature of wireless fading channels. Following this motivation, the authors investigated the spectrum, energy and transport efficiencies in [1] and [2]. In another line of research [3]–[7], the resource allocation efficiency has been studied in delay-constrained channel scenarios as well.

Concurrently, the notions of the effective capacity and the effective bandwidth took a considerable interest in the literature since they provide a bridge between the physical and data-link layers. The effective capacity and the effective bandwidth are duals of each other. Having a stochastic data service process from a buffer, we can invoke the effective capacity that provides the maximum constant data arrival rate that can be supported by the given service process, while satisfying the statistical quality-of-service (QoS) needs [8]. Similarly, having a stochastic data arrival process to a buffer, the effective bandwidth identifies the minimum constant data service rate from the buffer that can sustain the given arrival process under given QoS constraints [9, Remark 9.1.2]. Henceforth, considering both the effective capacity and the effective bandwidth, energy efficiency has been investigated in [10]. Furthermore, effective energy efficiency with an objective of the effective capacity maximization has been studied in [11].

Another aspect in communications networks is the cascaded transmission links. If a data routing algorithm sends too much data over one of these links, the link, which has a certain capacity, becomes congested. Hence, we can associate the delay experienced in a link with its capacity. The higher the capacity is, the bigger the data flow with a minimal delay will be. Therefore, the link utilization, which is the ratio of the data flow rate to the link capacity, has been a metric to characterize the network performance [12, Ch. 5], [13, Ch. 16].

In this letter, we consider a wireless system that is composed of one transmitter, one wireless channel and one receiver. The transmitter takes data into its buffer from a source and then forwards it to the receiver over the wireless fading channel. Subsequently, the receiver, storing the data initially in its own buffer, serves it to a sink. Obtaining the maximum sustainable arrival rate to the transmitter and the minimum required service rate from the receiver by invoking the effective capacity and the effective bandwidth, respectively, we characterize the maximum transmission link utilization. It is the ratio between the maximum acceptable data flow rate to the wireless system under QoS constraints at the transmitter buffer and the minimum required service rate from that wireless system under QoS constraints at the receiver buffer. This can be regarded as the link utilization in the service channel as well. Then, we investigate the impacts of the data transmission power in the channel over the link utilization. We note that the link utilization we describe is different than the one in the aforementioned studies in the sense that ours is the ratio between the arrival rate to a system and the service rate from that system under QoS requirements.

II. System Model

A. Channel Model

In this section, we identify a wireless system that transfers data from a source to a sink as seen in Fig. 1. This can be considered as one point-to-point transmission link in a communications network. The system is composed of one transmitter, one wireless channel and one receiver. The transmitter and the receiver have their own buffers with their unique QoS constraints. The amount of data in the transmitter buffer at time instant t is denoted by $Q_1(t)$, and the amount of data in the receiver buffer is denoted by $Q_2(t)$. The data initially comes to the transmitter buffer from the source with a rate $a(t)$ bits/channel use.[1] Then, it is conveyed to the wireless channel at a rate $r(t)$, which is the

[1]Throughout the letter, we have the arrival, transmission and service rates in *bits/channel use* unless otherwise specified.

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The author is with the Institute of Communications Technology, Leibniz Universität Hannover, 30167 Hanover, Germany (e-mail: sami.akin@ikt.uni-hannover.de).

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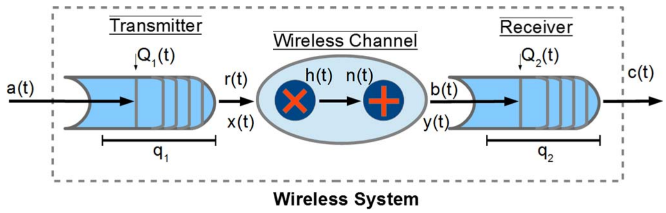

Fig. 1. System model.

instantaneous maximum achievable rate in the channel. Finally, the data, arriving at the receiver buffer with a rate $b(t)$, is sent to the sink with a rate $c(t)$. Note that $b(t)$ is the departure rate from the transmitter buffer, and it is given as follows:

$$b(t) = \begin{cases} r(t), & Q_1(t-1) + a(t) \geq r(t), \\ Q_1(t-1) + a(t), & \text{otherwise.} \end{cases}$$

Above, we assume that at time instant t, the data arrival is followed by the data service at each buffer. As for the input-output relation in the physical layer during the data transmission in the wireless channel, we have

$$y(t) = \sqrt{\gamma} x(t) h(t) + n(t) \quad \text{for } t = 0, 1, \cdots, \tag{1}$$

where x and y are the wireless channel input at the transmitter and the wireless channel output at the receiver, respectively. The average power of the input is normalized, i.e., $\mathbb{E}\{|x|^2\} = 1$. Moreover, n is the independent and identically distributed additive zero-mean, circularly symmetric, complex Gaussian random noise variable with a unit variance. We consider a memoryless time-selective flat fading channel, and h denotes the complex channel fading with an arbitrary marginal distribution and an average $\mathbb{E}\{|h|^2\} = 1$. In the above channel, the average signal-to-noise ratio is denoted by γ. Furthermore, the instantaneous achievable rate in the wireless channel is given by $r(t) = I(x(t); y(t)|h(t))$, where $I(x(t); y(t)|h(t))$ is the mutual information[2,3] between $x(t)$ and $y(t)$, given $h(t)$.

B. Effective Capacity

Recall that the rate of the incoming traffic to the transmitter buffer is $a(t)$, and the rate of the outgoing service from the transmitter queue is equal to the instantaneous achievable rate $r(t)$. Now, we can characterize the transmitter queue, i.e., the number of bits in the buffer at time instant t, with $Q_1(t) = [Q_1(t-1) + a(t) - r(t)]^+$, where $[x]^+ = \max\{0, x\}$. Here, we assume that the buffer size is infinite. Now, considering a work-conserving link and that $a(t)$ and $r(t)$ are independent of each other, we have a unique $\theta_1^\star$ such that $\Lambda_A(\theta_1^\star) + \Lambda_R(-\theta_1^\star) = 0$, and $\theta_1^\star = -\lim_{q_1\to\infty} \frac{\log \Pr\{Q_1(\infty)\geq q_1\}}{q_1}$, where q_1 is the threshold and θ_1 is the decay rate[4] of the tail distribution of the queue length Q_1 [15, Theorem 2.1]. Above, $\Lambda_A(\theta_1) = \lim_{t\to\infty} \frac{1}{t} \log \mathbb{E}\{e^{\theta_1 A(t)}\}$ is the asymptotic log-moment generating function of the total amount of arriving bits at the transmitter in t channel uses, i.e, $A(t) = \sum_{\tau=1}^t a(\tau)$, and $\Lambda_R(\theta_1) = \lim_{t\to\infty} \frac{1}{t} \log \mathbb{E}\{e^{\theta_1 R(t)}\}$ is the asymptotic log-moment generating function of the total service from the transmitter in t channel uses, i.e., $R(t) = \sum_{\tau=1}^t r(\tau)$. In particular, when the arrival rate is constant, i.e., $a(t) = a$ for all t, we have

$$a = -\frac{\Lambda_R(-\theta_1)}{\theta_1} = -\lim_{t\to\infty} \frac{1}{\theta_1 t} \log \mathbb{E}\left\{e^{-\theta_1 R(t)}\right\} \tag{2}$$

for $\theta_1 > 0$, which is the effective capacity and indicates the maximum constant arrival rate that the channel process can support while satisfying the QoS constraints specified by θ_1.

C. Effective Bandwidth

At the receiver, we have $b(t)$ and $c(t)$ as the arrival rate and the service rate, respectively. Hence, we have the accumulated arrival rate at the receiver buffer as $B(t) = \sum_{\tau=1}^t b(\tau)$ and the accumulated service rate as $C(t) = \sum_{\tau=1}^t c(\tau)$ in t channel uses. Now, we can identify the receiver queue at time instant t with $Q_2(t) = [Q_2(t-1) + b(t) - c(t)]^+$. Because $b(t)$ and $c(t)$ are independent of each other, we can find a unique $\theta_2^\star$ such that $\Lambda_B(\theta_2^\star) + \Lambda_C(-\theta_2^\star) = 0$, and $\theta_2^\star = -\lim_{q_2\to\infty} \frac{\log \Pr\{Q_2(\infty)\geq q_2\}}{q_2}$, where q_2 is the threshold and θ_2 is the decay rate[5] of the tail distribution of the queue length Q_2 [15, Theorem 2.1]. Moreover, $\Lambda_B(\theta_2)$ and $\Lambda_C(\theta_2)$ are the corresponding asymptotic log-moment generating functions. If the service rate is constant, i.e., $c(t) = c$ for all t, we have

$$c = \frac{\Lambda_B(\theta_2)}{\theta_2} = \lim_{t\to\infty} \frac{1}{\theta_2 t} \log \mathbb{E}\left\{e^{\theta_2 B(t)}\right\}$$

for $\theta_2 > 0$, which is the effective bandwidth. Above, c denotes the minimum constant service rate that can guarantee the QoS requirements specified by θ_2 given that there is a stochastic data arrival process $b(t)$. Furthermore, considering [15, Example 2.5], for a given constant arrival rate at the transmitter buffer, a, we can show that the log-moment generating function of $B(t)$ is given by

$$\Lambda_B(\theta_2) = \begin{cases} a\theta_2, & \theta_2 \leq \theta_1, \\ a\theta_1 + \Lambda_R(\theta_2 - \theta_1), & \text{otherwise.} \end{cases}$$

III. Transmission Link Efficiency

In the aforementioned system, with a given signal-to-noise ratio and an input distribution, the wireless channel can support a data arrival process with a maximum rate a (i.e., the effective capacity) from the source. At the same time, the arrivals from the same wireless channel to the receiver buffer can be supported by a service process with a minimum rate c (i.e., the effective bandwidth) to the sink. In particular, the data flow rate

[2]If $x(t)$ is zero-mean complex Gaussian-distributed, i.e., $x(t) \sim \mathcal{CN}(0, 1)$, the instantaneous channel capacity is achievable [14, Ch. 9.1], and it is given by $r(t) = \log_2\{1 + \gamma|h(t)|^2\}$.

[3]Given the channel fading coefficient, h, the mutual information as a function of the signal-to-noise ratio, γ, can be expressed as

$$I(x; y|h) = \sum_x p(x) \int_y f(y|x, h) \log_2\left(\frac{f(y|x, h)}{f(y|h)}\right),$$

where $p(x)$ is the marginal probability density function of x, and $f(y|x, h) = \frac{1}{\pi}\exp\{-|y - \sqrt{\gamma}hx|^2\}$ and $f(y|h) = \sum_x p(x)f(y|x, h)$ are the conditional probability density functions of y given x and h, and h, respectively [14].

[4]We can approximate the buffer overflow probability at the transmitter buffer in the steady-state as $\Pr\{Q_1(\infty) \geq q_1\} \approx e^{-\theta_1 q_1}$.

[5]We can approximate the buffer overflow probability at the receiver buffer in the steady-state as $\Pr\{Q_2(\infty) \geq q_2\} \approx e^{-\theta_2 q_2}$.

to the wireless link system should be at most a, and the data service from the wireless link system should be at least c, so that the desired QoS constraints at both the transmitter and the receiver specified by θ_1 and θ_2, respectively, can be satisfied. Hence, we define the ratio between a and c as the maximum transmission link utilization[6] and denote it by ν, i.e., $\nu = \frac{a}{c}$. As long as the transmission link utilization is lower than ν for given γ and input distribution, both the transmitter and the receiver queues will be stable. On the other hand, if the transmission link utilization is above ν, the queue at either the transmitter or the receiver, or both queues, will not be stable.

Considering the stochastic nature of the wireless channel, we provide the following two propositions that illustrate the maximum transmission link utilization performance in high and low signal-to-noise ratio regimes:

Proposition 1: In the aforementioned wireless system, when the signal-to-noise ratio, γ, goes to 0, we have

$$\nu_0 = \lim_{\gamma\to 0} \nu = \lim_{\gamma\to 0} \frac{a}{c} = 1. \quad (3)$$

Proof: For given θ_1 and θ_2, we can easily show that when $\theta_1 \geq \theta_2$, the maximum link transmission utilization is 1, since $a = c$. On the other hand, when $\theta_1 < \theta_2$, we have a, as given in (2), and c as follows:

$$\begin{aligned} c &= a\frac{\theta_1}{\theta_2} + \frac{1}{\theta_2}\Lambda_R(\theta_2 - \theta_1) \\ &= \lim_{t\to\infty} \frac{1}{\theta_2 t}\left(\log \mathbb{E}\left\{e^{(\theta_2-\theta_1)R(t)}\right\} - \log \mathbb{E}\left\{e^{-\theta_1 R(t)}\right\}\right). \end{aligned}$$

In the rest of the letter, we use the signal-to-noise ratio index, γ, rather than the time index, t, to denote the achievable rates, i.e., $r(\gamma)$ and $R(\gamma)$. Now, the maximum transmission link utilization when γ goes to zero can be obtained by using the L'Hospitale rule, i.e.,

$$\begin{aligned} \nu_0 = \lim_{\gamma\to 0}\frac{a}{c} &= \frac{\lim_{t\to\infty} \frac{-1}{\theta_1 t}\frac{d}{d\gamma}\log \mathbb{E}\left\{e^{-\theta_1 R(\gamma)}\right\}\Big|_{\gamma=0}}{\lim_{t\to\infty}\frac{1}{\theta_2 t}\frac{d}{d\gamma}\log\frac{\mathbb{E}\{e^{(\theta_2-\theta_1)R(\gamma)}\}}{\mathbb{E}\{e^{-\theta_1 R(\gamma)}\}}\Big|_{\gamma=0}} \\ &= \frac{\lim_{t\to\infty}\frac{\mathbb{E}\{R'(0)\}}{t}}{\lim_{t\to\infty}\frac{\frac{\theta_2-\theta_1}{\theta_2}\mathbb{E}\{R'(0)\}+\frac{\theta_1}{\theta_2}\mathbb{E}\{R'(0)\}}{t}} \\ &= \frac{\lim_{t\to\infty}\frac{\mathbb{E}\{R'(0)\}}{t}}{\lim_{t\to\infty}\frac{\mathbb{E}\{R'(0)\}}{t}} = 1. \end{aligned}$$

Proposition 2: In the aforementioned wireless system, when the signal-to-noise ratio, γ, goes to infinity, we have

$$\nu_\infty = \lim_{\gamma\to\infty} \nu = \lim_{\gamma\to\infty}\frac{a}{c} = 1. \quad (4)$$

[6]In the literature, the transmission link utilization is defined as the fraction of the transmission capacity of a communications channel that contains data [13]. The maximum transmission link utilization is achieved when there are no transmission errors, and it is bounded above by one [12]. In this letter, we express the transmission link utilization as the ratio between the arrival rate to a wireless system and the service rate from that system. In particular, it is the transmission link utilization in the service channel from the receiver buffer to the sink.

Proof: The mutual information between $x(t)$ and $y(t)$ can be expressed as follows:

$$r(\gamma) = I(x; y|h) = H(x|h) - H(x|y, h) = H(x) - H(x|y, h),$$

where $H(\cdot)$ and $H(\cdot|\cdot)$ are the entropy and conditional entropy functions, respectively [14]. Considering the input-output relation given in (1) when γ goes to infinity, we know that $\lim_{\gamma\to\infty} H(x|y, h) = 0$. Hence, we have $\lim_{\gamma\to\infty} r(\gamma) = H(x)$. Now, we can express $R(t) = tH(x)$.

We know that when $\theta_1 \geq \theta_2$, the maximum link transmission utilization is 1. On the other hand, when $\theta_1 < \theta_2$, the maximum transmission link utilization is

$$\begin{aligned} \nu_\infty = \lim_{\gamma\to\infty}\frac{a}{c} &= \frac{\lim_{t\to\infty}\lim_{\gamma\to\infty}\frac{-1}{\theta_1 t}\log\mathbb{E}\left\{e^{-\theta_1 R(\gamma)}\right\}}{\lim_{t\to\infty}\lim_{\gamma\to\infty}\frac{1}{\theta_2 t}\log\frac{\mathbb{E}\{e^{(\theta_2-\theta_1)R(\gamma)}\}}{\mathbb{E}\{e^{-\theta_1 R(\gamma)}\}}} \\ &= \frac{\lim_{t\to\infty}\frac{-1}{\theta_1 t}\log\mathbb{E}\left\{e^{-\theta_1 tH(x)}\right\}}{\lim_{t\to\infty}\frac{1}{\theta_2 t}\log\frac{\mathbb{E}\{e^{(\theta_2-\theta_1)tH(x)}\}}{\mathbb{E}\{e^{-\theta_1 tH(x)}\}}} = \frac{H(x)}{H(x)} = 1. \end{aligned}$$

Note that $H(x)$ is not a function of the channel fading, h. Therefore, we have $\mathbb{E}\{e^{-\theta_1 tH(x)}\} = e^{-\theta_1 tH(x)}$.

Remark 1: Propositions 1 and 2 state that when γ is very high or when it is very low, the wireless system tends to behave deterministically. In particular, the decreasing scattering of the probability distribution of the achievable rate, $r(t)$, as γ goes to zero or infinity makes the channel behave deterministically. We measure the scattering of a probability distribution by the dispersion index, which is a normalized measure of the dispersion of a probability distribution [16]. As t becomes very large, we invoke the Central Limit Theorem and express $R(t)$ as a Gaussian random variable with mean tm_r and variance $t\sigma_r^2$, where $m_r = \mathbb{E}\{r(\tau)\}$ and $\sigma_r^2 = \mathbb{E}\{(r(\tau) - m_r)^2\}$. Hence, the maximum transmission link utilization becomes [17]

$$\nu = \frac{a}{c} = \frac{m_r - \frac{\theta_1}{2}\sigma_r^2}{m_r + \frac{\theta_2-2\theta_1}{2}\sigma_r^2} = \frac{1 - \frac{\theta_1}{2}\frac{\sigma_r^2}{m_r}}{1 + \frac{\theta_2-2\theta_1}{2}\frac{\sigma_r^2}{m_r}}, \quad (5)$$

where $\frac{\sigma_r^2}{m_r}$ is the statistical dispersion index of the achievable rate, $r(t)$. The dispersion index of $r(t)$ goes to zero with γ going to zero or infinity. As a result, the maximum transmission link utilization goes to 1 as seen in (5). The dispersion index of $r(t)$ depends on the channel fading distribution, the input modulation and the signal-to-noise ratio.

Remark 2: In both propositions, the maximum transmission link utilization is independent of QoS constraints specified at each buffer, i.e., it is not a function of either θ_1 or θ_2, or both, when the signal-to-noise ratio goes to zero or infinity.

In Fig. 2, we plot the maximum transmission link utilization, ν, as a function of the signal-to-noise ratio, γ, for different decay parameter pairs (θ_1, θ_2), when the complex Gaussian-distributed input signaling is employed at the transmitter. While the above analysis is valid for any fading distribution with a finite variance, we consider zero-mean, circularly symmetric, complex Gaussian distributed fading coefficients in the numerical analysis. Hence, we consider a Rayleigh fading environment. The maximum transmission link utilization, ν, reaches the minimum when $\gamma = 10$ dB in all curves. Notice that the signal-to-noise ratio at which ν reaches its minimum

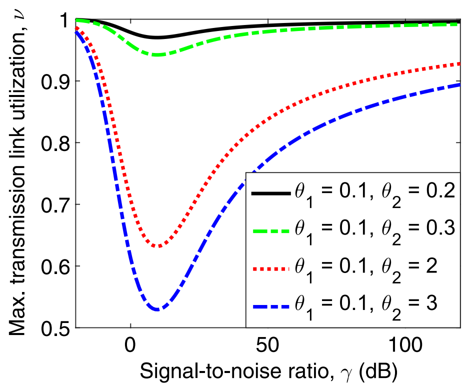

Fig. 2. Gaussian-distributed input is applied with different QoS constraints.

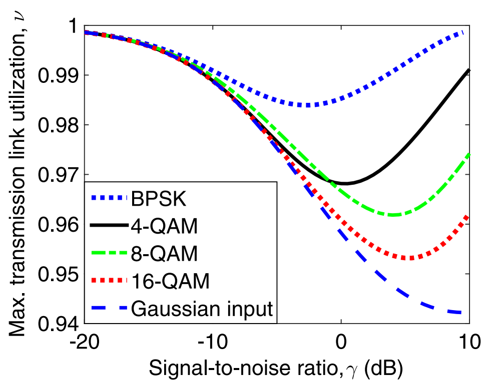

Fig. 3. Different modulations are employed when $\theta_1 = 0.1$ and $\theta_2 = 0.3$.

is independent of the decay rate parameters θ_1 and θ_2 (i.e., QoS constraints). As also seen in (5), ν reaches its minimum as a function of γ when the dispersion index of the achievable rate reaches its maximum as a function of γ, and ν reaches its maximum when the dispersion index goes to its minimum. Since the dispersion index is not a function of θ_1 and θ_2, the minimum and maximum of ν do not depend on the decay rate parameters. This is due to the independent realization of the channel fading parameters. Moreover, ν increases to 1 with increasing γ when γ is over 10 dB and with decreasing γ when γ is below 10 dB. We also see that the maximum transmission link utilization decreases with increasing θ_2. Moreover, we plot the maximum transmission link utilization, ν, as a function of γ with different modulation techniques when $\theta_1 = 0.1$ and $\theta_2 = 0.3$ in Fig. 3. We observe that the maximum transmission link utilization, ν, for any given γ is higher when binary phase-shift keying (BPSK) modulation is employed than when the others are employed. On the other hand, it is the lowest when complex Gaussian-distributed input modulation is applied. This occurs because the dispersion of the probability distribution of $r(t)$ is higher when Gaussian input is employed, and it is lower when BPSK is employed.

Remark 3: The above results indicate that the data transmission power level should be taken into consideration while determining resource allocation policies. The service rate for each bit arriving at the wireless system depends also on the data transmission power. When the maximum transmission link utilization is of interest, lower and higher signal-to-noise ratio regimes can be relied on in wireless links. Moreover, stricter QoS constraints at both buffers (smaller buffer overflow probabilities or shorter delays) result in a decrease in the maximum transmission link utilization because larger θ_1 and θ_2 cause a decrease in a and an increase in c, respectively.

IV. Conclusion

In this letter, we have focused on a one-to-one wireless transmission link. Establishing the maximum transmission link utilization, which is the ratio between the data flow rate to the wireless system and the data service rate from the wireless system, we have investigated the impact of data transmission power on the system performance. We have shown that the wireless system tends to become more deterministic, and the maximum transmission link utilization is 1 when the signal-to-noise ratio goes to zero or infinity. Then, we compared different modulation techniques with respect to their maximum transmission link utilization results. We observed that BPSK modulation is, in general, better than the other modulation techniques, while Gaussian input signaling is worse than the others. We have also noted that the signal-to-noise ratio at which the maximum transmission link utilization reaches its minimum is not a function of QoS decay rate parameters.

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