Capacity and Power Allocation for Spectrum-Sharing Communications in Fading Channels

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***Abstract*—This paper investigates the fundamental capacity limits of opportunistic spectrum-sharing channels in fading environments. The concept of opportunistic spectrum access is motivated by the frontier technology of cognitive radio which offers a tremendous potential to improve the utilization of the radio spectrum by implementing efficient sharing of the licensed spectrum. In this spectrum-sharing technology, a secondary user may utilize the primary user's licensed band as long as its interference to the primary receiver remains below a tolerable level. Herein, we consider that the secondary user's transmission has to adhere to limitations on the ensuing received power at the primary's receiver, and investigate the capacity gains offered by this spectrum-sharing approach in a Rayleigh fading environment. Specifically, we derive the fading channel capacity of a secondary user subject to both average and peak received-power constraints at the primary's receiver. In particular, considering flat Rayleigh fading, we derive the capacity and optimum power allocation scheme for three different capacity notions, namely, ergodic, outage, and minimum-rate, and provide closed-form expressions for these capacity metrics. Numerical simulations are conducted to corroborate our theoretical results.**

***Index Terms*—Cognitive radio, spectrum sharing, peak and average received-power constraints, ergodic capacity, outage capacity, minimum-rate capacity, fading channels.**

I. Introduction and Related Works

TRADITIONALLY, spectrum regulatory bodies have granted license for spectrum utilization with compulsory and detailed transmission guidelines, and allocated proper guard-bands between neighboring frequency bands to avoid mutual interference. Under this policy, a frequency band license holder has exclusive access to the allocated band while being protected from any interference. However, the growth of wireless applications and demands have caused the frequency allocation table for wireless services to become saturated. In fact, the chart of the allocated frequency bands shows that we are in danger of running out of spectrum [1]. However, as many measurements showed, most of the allocated spectrum experiences low utilization [2], while heavy spectrum utilization often takes place in unlicensed bands.

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These key observations motivated the concept of opportunistic spectrum access, or the so-called cognitive radio technology. The latter, first introduced by J. Mitola in [3], is a radio technology that has a tremendous potential to improve the utilization of the radio spectrum. It consists of an intelligent wireless communication technique which enables secondary users to use spectral bands that are licensed to primary users, as long as they do not cause harmful interference to the primary licensee. The corresponding radio equipments need to be designed in a way to be aware of the radio frequency environment so as to dynamically adapt their transmission parameters, such as carrier frequency, bandwidth and transmission power. With no doubt, cognitive radio has become a timely research topic and is attracting increasing interest on proposing protocols that exploit the capabilities of cognitive radio as well as on defining the fundamental limits on the rates that this technology can achieve. Comprehensive overviews of the fundamental limits, policy issues and challenges of cognitive radio can be found in [4]–[8].

In this context, Horne in [9] proposed a protocol in which the device listens to the wireless channel to determine which part of the spectrum is unused so as to adapt its signal to fill the unused spectrum domain. Later in [7], this approach has been generalized to allow the primary and secondary users to simultaneously transmit over the same time or frequency. In particular, an additive white Gaussian noise (AWGN) channel has been considered in [7] and capacity bounds have therein been derived. In parallel to these studies, Gastpar has introduced a different approach for defining the capacity of spectrum-sharing channels [10]. The latter work used the fact that when different users share the same spectrum band, a constraint on the received-power at a third user's receiver, e.g., primary receiver, may be a more relevant constraint than a maximum on the transmit power. Considering AWGN channels, [10] investigated the capacity under received-power constraint for various configurations, e.g., point-to-point and multiple access channels, and showed that in a point-to-point channel, the transmit and receive-power constraints result in similar capacity formulae as for AWGN channels; a consequence of the interference at the receiver being a deterministically scaled version of the transmit power. This seminal work also showed that transmit and received-power constraints lead to different conclusions in configurations with multiple users. Later, the ergodic capacity of a point-to-point system considering either peak or average received-power constraint at a third party's receiver was studied in [11], which showed that significant capacity gains may be achieved if the channels are time-varying due to fading. This is in contrast to systems with transmit power constraints, where capacity is known to degrade because of fading [12].

In this paper, we consider a point-to-point fading channel under joint peak and average received-power constraints at a third party's receiver. The peak received-power is imposed as the primary user does not tolerate an interference higher than a certain threshold. At the same time, operation of the primary receiver requires that the average interference be limited by a given level that is lower than the peak threshold. Considering both constraints, we derive the capacity of a Rayleigh flat-fading channel under different notions, namely, ergodic, outage and minimum-rate. Ergodic capacity is the long-term average rate that can be achieved by averaging over all states of an ergodic fading channel; a capacity metric that is suitable for delay-insensitive applications [13]. Outage capacity is, on the other hand, a metric suitable for systems that carry delay-sensitive applications, and is defined as the maximum constant-rate that can be achieved for a certain percentage of time. Finally, a metric that can be seen as a combination of the ergodic and outage capacities [14], and which is appropriate for systems that carry out both delay-sensitive and delay-insensitive applications, is the minimum-rate capacity, defined as the maximum long-term achievable rate subject to guaranteeing a minimum constant-rate for a certain percentage of time. More details about each capacity definition will be provided in related passages through the paper. In addition, for comprehensive surveys on various information-theoretic notions pertaining to fading channels, the reader is referred to [13] and [15].

In the following, the system and channel models are introduced in Section II. The ergodic capacity of a Rayleigh fading channel, under joint peak and average received-power constraints at a third party's receiver, is derived in closed-form in Section III. In Section IV, the outage capacity of the channel under consideration is derived. Section V considers the minimum-rate capacity case, followed by numerical results and discussions provided in Section VI. Finally, summarizing conclusions are given in Section VII.

II. System and Channel Models

We consider a spectrum-sharing system in which a secondary user is allowed to use the spectrum licensed to a primary user, as long as the amount of interference power inflicted at the receiver of the primary user is within predefined constraints on average and peak values. We consider a discrete-time fading channel with perfect channel side information (CSI) at the receiver and transmitter of the secondary user. The time-varying channel is assumed to be Rayleigh flat-fading, and the received signal $y_{\rm s}[n]$ at the receiver of the secondary user depends on the transmitted signal $x_{\rm s}[n]$ according to

$$y_{\rm s}[n] = \sqrt{h_{\rm s}[n]}x_{\rm s}[n] + z_{\rm s}[n], \qquad (1)$$

where n indicates the time index, $h_{\rm s}[n]$ is the channel power gain between the transmitter and the receiver of the secondary user, and $z_{\rm s}[n]$ represents the AWGN. We define the channel power gain between the transmitter of the secondary user and the receiver of the primary user by $h_{\rm p}[n]$. We also assume that the channel power gains $h_{\rm s}[n]$ and $h_{\rm p}[n]$ are independent and identically distributed (i.i.d.) exponentially distributed with unit mean. Furthermore, the channel gains are assumed to be independent from the noise. The noise power spectral density and the signal bandwidth are denoted by N_0 and B, respectively.

We further assume that perfect knowledge of $h_{\rm p}$[1] is available at the receiver and transmitter of the secondary user. The information about $h_{\rm p}$ can be carried out by a band manager that mediates between the primary and secondary users [5], [11], or can be directly fed back from the primary's receiver to the secondary user as introduced in [16], which proposes an algorithm that allows the primary and secondary users to collaborate and exchange the CSI. It is worth noting that in practice it is hard to obtain perfect information of $h_{\rm p}$ at the secondary user's transmitter. Accordingly, our results serve as upper bounds for the achievable rate in practical systems.

Given that transmissions pertaining to the secondary user should not harm the signal quality at the receiver of the primary user, we impose constraints on the received-power at the primary's receiver. Hence, denoting the average and peak received-power values by $Q_{\rm avg}$ and $Q_{\rm peak}$, respectively, we define the corresponding constraints as:

$$\mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{P(h_{\rm s},h_{\rm p})h_{\rm p}\right\} \le Q_{\rm avg}, \qquad (2)$$

$$P(h_{\rm s},h_{\rm p})h_{\rm p} \le Q_{\rm peak}, \quad \forall\ h_{\rm s},h_{\rm p}, \qquad (3)$$

where $P(h_{\rm s},h_{\rm p})$ denotes the transmit power, and $\mathcal{E}_{h_{\rm s},h_{\rm p}}$ defines the expectation over the joint probability density function (PDF) of $h_{\rm s}$ and $h_{\rm p}$. Hereafter, we derive the ergodic, outage and minimum-rate capacities of the secondary user's fading channel taking into account the above-presented constraints.

III. Ergodic Capacity

Ergodic capacity is defined as the maximum of the long-term average achievable rate with arbitrary small probability of error, subject to constraints on the power. Hence, in systems with no constraints on the delay, the ergodic capacity represents the relevant performance limit indicator [13].

Considering average transmit power constraint, [12] presents the capacity of a point-to-point fading channel under the assumption of perfect CSI at both the receiver and the transmitter. The paper shows that variable-rate multiplexed Gaussian coding scheme with optimally utilized power in time can achieve the fading channel capacity. Closed-form expressions for the channel capacity of the above system in Rayleigh fading have also been derived in [17]. Imposing both peak and average constraints on the transmit power was first considered in [18], wherein the capacity of the Gaussian channel is shown to be achieved by a discrete random variable with finite number of values. These results have been extended to quadrature Gaussian channels in [19]. Later, the capacity of fading channels subject to peak and average transmit power constraints was derived in [20], which

[1]Hereafter, we omit the time index n as it is clear from the context.

shows that a multiplexed Gaussian codebook with optimally allocated power in time, such that both constraints are met, can achieve the ergodic capacity.

On the other hand, the constraint on the received-power was considered in [10] wherein the capacity of AWGN channels for single and multi-user systems have been derived. In particular, it was shown that the capacity of a point-to-point AWGN channel with received-power constraint is equal to the capacity of the channel under appropriately scaled transmit power constraint. This result, however, does not hold for fading channels. The ergodic capacity of a fading channel with either average or peak received-power constraint was provided in [11]. Therein, the optimal power allocation scheme that achieves the ergodic capacity was presented.

In this section, we consider a fading environment with received-power constraints at a third party's receiver, on both peak and average values as given in (2) and (3). Adopting an approach similar to that used in [20], the channel capacity can be shown to be achieved through optimal utilization of the input power over time such that the received-power constraints are met. Therefore, the ergodic channel capacity in this case represents the solution to the following problem:

$$\begin{aligned}\frac{C_{\text{er}}}{B} = \max_{P(h_{\text{s}},h_{\text{p}})>0} \; & \mathcal{E}_{h_{\text{s}},h_{\text{p}}}\left\{\log\left(1+\frac{P(h_{\text{s}},h_{\text{p}})h_{\text{s}}}{N_0B}\right)\right\} \\ \text{s.t.} \quad & \mathcal{E}_{h_{\text{s}},h_{\text{p}}}\left\{P(h_{\text{s}},h_{\text{p}})h_{\text{p}}\right\} \le Q_{\text{avg}}, \\ & P(h_{\text{s}},h_{\text{p}})h_{\text{p}} \le Q_{\text{peak}}, \; \forall\; h_{\text{s}},h_{\text{p}}. \end{aligned} \tag{4}$$

The optimization problem in (4), but with no constraint on the peak received-power, was considered in [11] which presented a solution based on Lagrangian optimization. Considering the problem with both constraints and adopting a similar approach, the optimum power allocation can be found as:

$$P(h_{\text{s}},h_{\text{p}}) = \begin{cases} \dfrac{Q_{\text{peak}}}{h_{\text{p}}} & \dfrac{h_{\text{p}}}{h_{\text{s}}} < \dfrac{\gamma_1}{N_0B}, \\ \dfrac{\gamma_0}{h_{\text{p}}} - \dfrac{N_0B}{h_{\text{s}}} & \dfrac{\gamma_1}{N_0B} \le \dfrac{h_{\text{p}}}{h_{\text{s}}} \le \dfrac{\gamma_0}{N_0B}, \\ 0 & \dfrac{\gamma_0}{N_0B} < \dfrac{h_{\text{p}}}{h_{\text{s}}}, \end{cases} \tag{5}$$

where the cutoff values γ_0 and γ_1 are obtained such that the peak and average received-power limitations are satisfied, with (2) being satisfied at equality. As can be seen from (5), this power allocation policy implies that the transmission is suspended when the link between the transmitter and the receiver of the secondary user is weak compared to h_{p}. As the ratio $\frac{h_{\text{p}}}{h_{\text{s}}}$ decreases, the secondary user benefits from the weak link between its transmitter and the receiver of the primary user to start sending at higher transmission power. The latter, however, is limited to $\frac{Q_{\text{peak}}}{h_{\text{p}}}$ so as to satisfy the peak received-power constraint. It can also be seen from (5) that $P(h_{\text{s}},h_{\text{p}})h_{\text{p}} \le \gamma_0$, for all values of h_{p} and h_{s}. Note that when $Q_{\text{peak}} \ge \gamma_0$, the peak received-power constraint does not affect the ergodic capacity of the channel. In this case, the ergodic capacity can be found directly from [11]. Here we consider the case when $Q_{\text{peak}} < \gamma_0$, and derive the ergodic capacity of the channel. For this purpose, we first obtain an expression for γ_1 as follows:

$$\begin{aligned} Q_{\text{peak}} &= \left(P\left(h_{\text{s}},h_{\text{p}}\right)h_{\text{p}}\right)\Big|_{\frac{h_{\text{p}}}{h_{\text{s}}}=\frac{\gamma_1}{N_0B}} \\ &= \left(\left(\frac{\gamma_0}{h_{\text{p}}}-\frac{N_0B}{h_{\text{s}}}\right)h_{\text{p}}\right)\Big|_{\frac{h_{\text{p}}}{h_{\text{s}}}=\frac{\gamma_1}{N_0B}} \\ &= \gamma_0 - \gamma_1. \end{aligned} \tag{6}$$

Therefore, the constraint on the average received-power can be simplified by inserting $P(h_{\text{s}},h_{\text{p}})$, as given in (5), into (2) set at equality, and using the equality $\gamma_1 = \gamma_0 - Q_{\text{peak}}$ (6), thus yielding

$$\begin{aligned} Q_{\text{avg}} = & \iint\limits_{\frac{h_{\text{p}}}{h_{\text{s}}}<\frac{\gamma_0-Q_{\text{peak}}}{N_0B}} Q_{\text{peak}} f_{h_{\text{s}}}(h_{\text{s}}) f_{h_{\text{p}}}(h_{\text{p}}) dh_{\text{s}} dh_{\text{p}} \\ & + \iint\limits_{\frac{\gamma_0-Q_{\text{peak}}}{N_0B}\le\frac{h_{\text{p}}}{h_{\text{s}}}\le\frac{\gamma_0}{N_0B}} \left(\gamma_0 - N_0B\frac{h_{\text{p}}}{h_{\text{s}}}\right) f_{h_{\text{s}}}(h_{\text{s}}) f_{h_{\text{p}}}(h_{\text{p}}) dh_{\text{s}} dh_{\text{p}}, \end{aligned} \tag{7}$$

where $f_x(x)$ represents the PDF of the random variable x. Note that the integration in (7) depends on the random variables h_{p} and h_{s} only through the ratio $\frac{h_{\text{p}}}{h_{\text{s}}}$. Now, define the random variable v as $v = \frac{h_{\text{p}}}{h_{\text{s}}}$. Then, by using the fact that the distribution of the ratio between two Gamma distributed random variables with parameters α_1 and α_2 is a beta prime distribution with parameters α_1 and α_2 [21], we can find the distribution of the random variable v as

$$f_v(v) = \frac{1}{(v+1)^2}, \tag{8}$$

a result which is also presented in [11]. We can now derive the expression for γ_0 by inserting (8) into (7) and evaluating the integration as follows:

$$\begin{aligned} Q_{\text{avg}} &= \int_0^{\frac{\gamma_0-Q_{\text{peak}}}{N_0B}} \frac{Q_{\text{peak}}}{(v+1)^2}dv + \int_{\frac{\gamma_0-Q_{\text{peak}}}{N_0B}}^{\frac{\gamma_0}{N_0B}} \frac{\gamma_0 - N_0Bv}{(v+1)^2}dv \\ &= -\frac{Q_{\text{peak}}}{v+1}\Big|_0^{\frac{\gamma_0-Q_{\text{peak}}}{N_0B}} \\ &\quad - \left(\frac{\gamma_0+N_0B}{v+1} + N_0B\log(v+1)\right)\Big|_{\frac{\gamma_0-Q_{\text{peak}}}{N_0B}}^{\frac{\gamma_0}{N_0B}} \\ &= Q_{\text{peak}} + N_0B\log\left(1-\frac{Q_{\text{peak}}}{N_0B+\gamma_0}\right). \end{aligned} \tag{9}$$

Note that the transmission is cut off for values of $\frac{h_{\text{s}}}{h_{\text{p}}} < \frac{N_0B}{\gamma_0}$. We now define $\lambda_0 = \frac{N_0B}{\gamma_0}$, which represents the optimal threshold for $\frac{h_{\text{s}}}{h_{\text{p}}}$, under which transmission is suspended, and further define the function $f\left(Q_{\text{peak}},\gamma_0\right) = Q_{\text{peak}} + N_0B\log\left(1-\frac{Q_{\text{peak}}}{N_0B+\gamma_0}\right)$. It can be shown that $f\left(Q_{\text{peak}},\gamma_0\right)$ is a strictly increasing function of Q_{peak} and γ_0 by obtaining the first partial derivatives of $f\left(Q_{\text{peak}},\gamma_0\right)$, with respect to

$Q_{\rm peak}$ and γ_0, as follows:

$$\frac{\partial f\left(Q_{\rm peak},\gamma_0\right)}{\partial Q_{\rm peak}} = \frac{\gamma_0 - Q_{\rm peak}}{N_0B + \gamma_0 - Q_{\rm peak}} > 0,$$
$$\frac{\partial f\left(Q_{\rm peak},\gamma_0\right)}{\partial \gamma_0} = \frac{Q_{\rm peak}N_0B}{\left(N_0B + \gamma_0\right)\left(N_0B + \gamma_0 - Q_{\rm peak}\right)} > 0.$$

Therefore, for a constant value of $Q_{\rm avg}$, as $Q_{\rm peak}$ increases γ_0 decreases and, as a result, the optimum cutoff threshold for $\frac{h_{\rm s}}{h_{\rm p}}$, i.e., λ_0, increases.

We now evaluate the integration in the ergodic capacity equation as follows:

$$\begin{aligned}\frac{C_{\rm er}}{B} &= \int_{\frac{N_0B}{\gamma_0}}^{\frac{N_0B}{\gamma_0-Q_{\rm peak}}} \log\left(\frac{\gamma_0 v}{N_0B}\right)\frac{1}{(v+1)^2}dv\\ &\quad + \int_{\frac{N_0B}{\gamma_0-Q_{\rm peak}}}^{\infty} \log\left(1+\frac{Q_{\rm peak}v}{N_0B}\right)\frac{1}{(v+1)^2}dv\\ &= -\log\left(1-\frac{Q_{\rm peak}}{N_0B+\gamma_0}\right)+\frac{Q_{\rm peak}}{Q_{\rm peak}-N_0B}\\ &\quad \times \log\left(\frac{Q_{\rm peak}}{N_0B\gamma_0}\left(N_0B+\gamma_0-Q_{\rm peak}\right)\right), \end{aligned} \tag{10}$$

thus leading to a closed-form expression for the ergodic capacity of the system under consideration.

IV. Outage Capacity

As stated in the previous section, the ergodic capacity determines the maximum achievable long-term rate under no delay constraints. In wireless systems that carry out real-time delay-sensitive applications, such as voice and video, delay-limited capacity (also referred to as zero-outage capacity), which defines the constant-rate that is achievable in all fading states, is a more appropriate notion. In this case, the transmitter uses the CSI to maintain a constant received-power or, equivalently, inverts the channel fading. Using channel inversion, the capacity of fading channels with transmit power constraint has been derived in [12]. This metric corresponds to the capacity that can be achieved in all fading states while meeting the input power constraints. However, in extreme fading cases, e.g., Rayleigh fading, this capacity is zero as the transmitter has to spend a huge amount of power for channel states in deep fades to achieve a constant rate. To alleviate this problem, an adaptive transmission technique, referred to as truncated channel inversion with fixed rate (*tifr*), which can achieve non-zero constant rates, was introduced in [12]. This technique maintains a constant received-power for channel fades above a given cutoff depth. The constant-rate that can be achieved with an outage probability less than a certain threshold is called outage capacity [13]. Our aim in this section is to determine the capacity of a Rayleigh fading channel with *tifr* transmission policy and the outage capacity under joint peak and average received-power constraints at a third party's receiver.

Recalling that in *tifr* technique, the transmitter inverts the channel fading in order to maintain a constant-rate at the receiver, and defining γ_0 as the cutoff value such that the transmission is suspended when $\frac{\gamma_0}{N_0B} < \frac{h_{\rm p}}{h_{\rm s}}$, we can express the power allocation policy according to

$$P(h_{\rm s},h_{\rm p}) = \begin{cases} \frac{\alpha}{h_{\rm s}} & \frac{h_{\rm p}}{h_{\rm s}} \le \frac{\gamma_0}{N_0B},\\ 0 & \frac{\gamma_0}{N_0B} < \frac{h_{\rm p}}{h_{\rm s}}, \end{cases} \tag{11}$$

where γ_0 and α must be found such that the average and peak received-power constraints, (2) and (3), are satisfied. Accordingly, the constraints can be simplified as follows:

$$\iint\limits_{\frac{h_{\rm p}}{h_{\rm s}} \le \frac{\gamma_0}{N_0B}} \alpha\frac{h_{\rm p}}{h_{\rm s}} f_{h_{\rm s}}(h_{\rm s}) f_{h_{\rm p}}(h_{\rm p}) dh_{\rm s} dh_{\rm p} \le Q_{\rm avg}, \tag{12}$$

$$\alpha\frac{h_{\rm p}}{h_{\rm s}} \le Q_{\rm peak}, \ \left\{\forall\ h_{\rm s},h_{\rm p} : \frac{h_{\rm p}}{h_{\rm s}} \le \frac{\gamma_0}{N_0B}\right\}. \tag{13}$$

It is worth noting that (13) implies that under peak received-power constraint, outage is unavoidable for any fading channel. Using the fact that the transmission is cut off when the ratio $\frac{h_{\rm p}}{h_{\rm s}}$ is higher than $\frac{\gamma_0}{N_0B}$, the outage probability can be found as

$$\begin{aligned} P_{\rm out} &= \Pr\left\{\frac{\gamma_0}{N_0B} < \frac{h_{\rm p}}{h_{\rm s}}\right\}\\ &= \int_{\frac{\gamma_0}{N_0B}}^{\infty} \frac{1}{(v+1)^2}\, dv\\ &= \frac{N_0B}{\gamma_0+N_0B}, \end{aligned} \tag{14}$$

where $\Pr\left\{\frac{\gamma_0}{N_0B} < \frac{h_{\rm p}}{h_{\rm s}}\right\}$ indicates the probability that the inequality $\frac{\gamma_0}{N_0B} < \frac{h_{\rm p}}{h_{\rm s}}$ holds true.

Furthermore, a closed-form expression for the average received-power constraint can be obtained using (12) as follows:

$$\begin{aligned} Q_{\rm avg} &= \int_0^{\frac{\gamma_0}{N_0B}} \frac{\alpha v}{(v+1)^2}dv\\ &= \alpha\left(\log\left(1+\frac{\gamma_0}{N_0B}\right) - \frac{\gamma_0}{\gamma_0+N_0B}\right). \end{aligned} \tag{15}$$

Thus, α can be found as a function of γ_0. Let us now define the function $g(\gamma_0)$ as $g(\gamma_0) = \log\left(1+\frac{\gamma_0}{N_0B}\right) - \frac{\gamma_0}{\gamma_0+N_0B}$. It can be shown that $g(\gamma_0)$ is a non-decreasing function of γ_0 by obtaining the first derivative of $g(\gamma_0)$, with respect to γ_0, yielding

$$\frac{\partial g(\gamma_0)}{\partial \gamma_0} = \frac{\gamma_0}{(\gamma_0+N_0B)^2} \ge 0. \tag{16}$$

Hence, for a constant value of average received-power constraint, as γ_0 increases, the value of α decreases. Furthermore, we recall that in order to satisfy the peak received-power constraint, the inequality $\alpha \le N_0B\frac{Q_{\rm peak}}{\gamma_0}$ must hold. Therefore, the channel capacity under *tifr* policy can be found as the solution of the following optimization problem:

$$\begin{aligned}\frac{C_{\rm tifr}}{B} &= \max_{\gamma_0} \log\left(1+\frac{\min\left\{\alpha, N_0B\frac{Q_{\rm peak}}{\gamma_0}\right\}}{N_0B}\right)\\ &\quad \times \Pr\left\{\frac{h_{\rm p}}{h_{\rm s}} \le \frac{\gamma_0}{N_0B}\right\}, \end{aligned} \tag{17}$$

where $\Pr\left\{\frac{h_{\rm p}}{h_{\rm s}} \leq \frac{\gamma_0}{N_0B}\right\} = 1-P_{\rm out} = \frac{\gamma_0}{\gamma_0+N_0B}$. The maximum on the right-hand-side of (17) can be found by searching numerically for the optimal value of γ_0. On the other hand, to find the outage capacity, the cutoff value γ_0 must be selected so as to achieve a specific permitted outage level using $P_{\rm out} = \frac{N_0B}{\gamma_0+N_0B}$. By using (15), one can show that $\alpha = \frac{Q_{\rm avg}}{-\log(P_{\rm out})-1+P_{\rm out}}$, and hence, the channel capacity can be found as

$$\frac{C_{\rm out}}{B} = \log\left(1+\frac{\min\left\{\frac{Q_{\rm avg}}{-\log(P_{\rm out})-1+P_{\rm out}}, \frac{Q_{\rm peak}}{\frac{1}{P_{\rm out}}-1}\right\}}{N_0B}\right) \times (1-P_{\rm out}). \tag{18}$$

Note that the outage capacity is given by $C_{\rm outage} = \frac{C_{\rm out}}{1-P_{\rm out}}$.

V. Minimum-Rate Capacity

As previously stated, in order to achieve the ergodic capacity of the channel, the transmitter must adapt to the channel variations by transmitting at high power levels during strong channel states. This is in sharp contrast with the power allocation policy for achieving the outage capacity, wherein the transmitter scales the power to invert the fading, allocating hence more power to weaker channel states so as to achieve a constant-rate during non-outage states. While the first scheme is not suitable for delay-sensitive applications, e.g., voice transmission, the second approach can also suffer from great losses in the achievable rate since it does not take advantage of the stronger channel states. Therefore, none of these approaches appears optimal for systems that simultaneously transmit delay-sensitive and delay-insensitive applications [14].

Another capacity metric that is more appropriate for this kind of systems has been introduced and studied in [14], [22]–[24]. In the so-called minimum-rate capacity, the idea is to utilize the input power to maximize the long-term average rate, provided that a minimum-rate, $R_{\rm min}$, is guaranteed for a certain percentage of time. It is worth noting that an outage state in the minimum-rate capacity sense is defined as a state where the transmission rate is less than the minimum required-rate and does not necessarily imply that the transmission is cut off during outage.

The minimum-rate capacity can be viewed as a combination of the ergodic and outage capacities [14] and can be defined as

$$\frac{C_{\rm min}}{B} = \max_{P(h_{\rm s},h_{\rm p})>0} \mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{R(h_{\rm s},h_{\rm p})\right\} \tag{19}$$

$$\text{s.t.}\quad \mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{P(h_{\rm s},h_{\rm p})h_{\rm p}\right\} \leq Q_{\rm avg}, \tag{20}$$

$$P(h_{\rm s},h_{\rm p})h_{\rm p} \leq Q_{\rm peak},\ \forall\ h_{\rm s},h_{\rm p}, \tag{21}$$

$$\Pr\left\{R(h_{\rm s},h_{\rm p}) < R_{\rm min}\right\} \leq P_{\rm out}, \tag{22}$$

where $R(h_{\rm s},h_{\rm p}) = \log\left(1+\frac{P(h_{\rm s},h_{\rm p})h_{\rm s}}{N_0B}\right)$ and $R_{\rm min}$ is the minimum required-rate per bandwidth.

First, we find the minimum values for $Q_{\rm peak}$ and $Q_{\rm avg}$ which are required to achieve the minimum-rate, $R_{\rm min}$, for at least $(1-P_{\rm out})$ percentage of time. By using (18), we can find the minimum average received-power limit, $Q_{\rm avg}^{\rm min}$, and the minimum required peak received-power limit, $Q_{\rm peak}^{\rm min}$, as follows:

$$Q_{\rm avg} \geq Q_{\rm avg}^{\rm min} = N_0B\left(e^{R_{\rm min}}-1\right)\left(-\log(P_{\rm out})-1+P_{\rm out}\right), \tag{23}$$

$$Q_{\rm peak} \geq Q_{\rm peak}^{\rm min} = N_0B\left(e^{R_{\rm min}}-1\right)\left(\frac{1}{P_{\rm out}}-1\right). \tag{24}$$

If either of the above inequalities does not hold, the constraint in (22) can not be satisfied and no feasible power allocation exists. Moreover, it is easy to verify that if condition (23) holds with equality, the minimum-rate capacity is indeed $\frac{C_{\rm min}}{B} = R_{\rm min}(1-P_{\rm out})$. The interesting case arises when this inequality is strict. Now, let us define $P_{\rm min}(h_{\rm s},h_{\rm p})$ as the minimum power required at each fading state to guarantee $R_{\rm min}$ for $(1-P_{\rm out})$ percentage of time, and $P_{\rm exc}(h_{\rm s},h_{\rm p})$ as the excess power allocated optimally to maximize the long-term achievable rate. Then, the minimum-rate capacity can be expressed as

$$\begin{aligned}\frac{C_{\rm min}}{B} &= \mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{\log\left(1+\frac{P_{\rm min}(h_{\rm s},h_{\rm p})h_{\rm s}}{N_0B}+\frac{P_{\rm exc}(h_{\rm s},h_{\rm p})h_{\rm s}}{N_0B}\right)\right\}\\ &= \mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{\log\left(1+\frac{P_{\rm min}(h_{\rm s},h_{\rm p})h_{\rm s}}{N_0B}\right)\right\}\\ &\quad+\mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{\log\left(1+\frac{P_{\rm exc}(h_{\rm s},h_{\rm p})h_{\rm s}}{N_0B+P_{\rm min}(h_{\rm s},h_{\rm p})h_{\rm s}}\right)\right\}\\ &= R_{\rm min}(1-P_{\rm out})+C_{\rm exc},\end{aligned} \tag{25}$$

where $C_{\rm exc}$ can be seen as the ergodic capacity of an effective channel with a channel power gain given by

$$h_{\rm s_{\rm eff}} = \begin{cases}\dfrac{h_{\rm s}}{1+\dfrac{\alpha_{\rm min}}{N_0B}} & \dfrac{h_{\rm p}}{h_{\rm s}} \leq \dfrac{\gamma_{\rm min}}{N_0B},\\ h_{\rm s} & \dfrac{\gamma_{\rm min}}{N_0B} < \dfrac{h_{\rm p}}{h_{\rm s}},\end{cases} \tag{26}$$

with $\alpha_{\rm min} = N_0B\left(e^{R_{\rm min}}-1\right)$ and $\gamma_{\rm min} = N_0B\left(\frac{1}{P_{\rm out}}-1\right)$, under effective received-power constraints given by

$$\mathcal{E}_{h_{\rm s},h_{\rm p}}\left\{P_{\rm exc}(h_{\rm s},h_{\rm p})h_{\rm p}\right\} \leq Q_{\rm avg}-Q_{\rm avg}^{\rm min}, \tag{27}$$

$$P_{\rm exc}(h_{\rm s},h_{\rm p})h_{\rm p} \leq Q_{\rm peak}-P_{\rm min}(h_{\rm s},h_{\rm p})h_{\rm p},\ \forall\ h_{\rm s},h_{\rm p}. \tag{28}$$

By adopting a similar approach as used in [11], the optimal power allocation to achieve $C_{\rm exc}$ can be found as $P_{\rm exc}(h_{\rm s},h_{\rm p}) = \left(\frac{\gamma_0}{h_{\rm p}}-\frac{N_0B}{h_{s_{\rm eff}}}\right)^+$, where $(x)^+$ denotes $\max\{0,x\}$ and γ_0 must be determined such that the effective received-power constraints given in (27) and (28) are satisfied. We can now expand the power allocation $P_{\rm exc}(h_{\rm s},h_{\rm p})$ to

$$P_{\rm exc}(h_{\rm s},h_{\rm p}) = \begin{cases}\dfrac{Q_{\rm peak}}{h_{\rm p}}-\dfrac{\alpha_{\rm min}}{h_{\rm s}} & \dfrac{h_{\rm p}}{h_{\rm s}} < \dfrac{\gamma_0-Q_{\rm peak}}{N_0B},\\ \dfrac{\gamma_0}{h_{\rm p}}-\dfrac{N_0B+\alpha_{\rm min}}{h_{\rm s}} & \dfrac{\gamma_0-Q_{\rm peak}}{N_0B} \leq \dfrac{h_{\rm p}}{h_{\rm s}} \leq \dfrac{\gamma_0}{N_0B+\alpha_{\rm min}},\\ 0 & \dfrac{\gamma_0}{N_0B+\alpha_{\rm min}} < \dfrac{h_{\rm p}}{h_{\rm s}} \leq \dfrac{\gamma_{\rm min}}{N_0B},\\ \dfrac{\gamma_0}{h_{\rm p}}-\dfrac{N_0B}{h_{\rm s}} & \dfrac{\gamma_{\rm min}}{N_0B} < \dfrac{h_{\rm p}}{h_{\rm s}} \leq \dfrac{\gamma_0}{N_0B},\\ 0 & \dfrac{\gamma_0}{N_0B} < \dfrac{h_{\rm p}}{h_{\rm s}}.\end{cases} \tag{29}$$

Here it is worth noting that if $\frac{\gamma_{\min}}{N_0B} \leq \frac{\gamma_0}{N_0B+\alpha_{\min}}$, then $P_{\rm exc}(h_{\rm s},h_{\rm p}) > 0$ for all $\frac{h_{\rm p}}{h_{\rm s}} \leq \frac{\gamma_{\min}}{N_0B}$. This implies that $Q_{\rm avg}$ is large enough for the ergodic capacity to achieve the minimum required-rate, $R_{\min}$, for $(1-P_{\rm out})$ percentage of time. Hence, in this case the minimum-rate capacity is equal to the ergodic capacity of the channel and can be determined from (10). On the other hand, if $\gamma_0 \leq \gamma_{\min}$, then no power is transmitted during outage sates and the transmission is cut off.

We now find a solution for γ_0 when $\frac{\gamma_0}{N_0B+\alpha_{\min}} < \frac{\gamma_{\min}}{N_0B} < \frac{\gamma_0}{N_0B}$ as follows:

$$\begin{aligned}
Q_{\rm avg} - Q_{\rm avg}^{\min} &= \int_0^{\frac{\gamma_0 - Q_{\rm peak}}{N_0B}} \frac{Q_{\rm peak} - \alpha_{\min} v}{(1+v)^2} dv \\
&\quad + \int_{\frac{\gamma_0 - Q_{\rm peak}}{N_0B}}^{\frac{\gamma_0}{N_0B+\alpha_{\min}}} \frac{\gamma_0 - (N_0B+\alpha_{\min})v}{(1+v)^2} dv \\
&\quad + \int_{\frac{\gamma_{\min}}{N_0B}}^{\frac{\gamma_0}{N_0B}} \frac{\gamma_0 - N_0Bv}{(1+v)^2} dv \\
&= Q_{\rm peak} + N_0B\frac{\gamma_0 - \gamma_{\min}}{N_0B+\gamma_{\min}} + N_0B\log\left(1+\frac{\gamma_{\min}}{N_0B}\right) \\
&\quad + N_0B\log\left(1 - \frac{Q_{\rm peak}}{N_0B+\gamma_0}\right) \\
&\quad - (N_0B+\alpha_{\min})\log\left(1+\frac{\gamma_0}{N_0B+\alpha_{\min}}\right).
\end{aligned} \tag{30}$$

We can also obtain a closed-form expression for $C_{\rm exc}$ when $\frac{\gamma_0}{N_0B+\alpha_{\min}} < \frac{\gamma_{\min}}{N_0B}$ as follows:

$$\begin{aligned}
C_{\rm exc} &= \iint \log\left(1+\frac{P_{\rm exc}(h_{\rm s},h_{\rm p})h_{\rm s_{eff}}}{N_0B}\right) \\
&\qquad \times f_{h_{\rm s}}(h_{\rm s}) f_{h_{\rm p}}(h_{\rm p}) dh_{\rm s} dh_{\rm p} \\
&= C_{\rm exc_1} + C_{\rm exc_2},
\end{aligned} \tag{31}$$

where

$$\begin{aligned}
C_{\rm exc_1} &= \int_{\frac{N_0B}{\gamma_0}}^{\frac{N_0B}{\gamma_{\min}}} \frac{\log\left(\frac{\gamma_0 v}{N_0B}\right)}{(v+1)^2} dv \\
&= \log\left(\frac{\gamma_0 + N_0B}{\gamma_{\min}+N_0B}\right) - \frac{\log\left(\frac{\gamma_0}{\gamma_{\min}}\right)}{1+\frac{N_0B}{\gamma_{\min}}},
\end{aligned} \tag{32}$$

and

$$\begin{aligned}
C_{\rm exc_2} &= \int_{\frac{N_0B+\alpha_{\min}}{\gamma_0}}^{\frac{N_0B}{\gamma_0 - Q_{\rm peak}}} \frac{\log\left(\frac{\gamma_0 v}{N_0B+\alpha_{\min}}\right)}{(v+1)^2} dv \\
&\quad + \int_{\frac{N_0B}{\gamma_0 - Q_{\rm peak}}}^{\infty} \frac{\log\left(\frac{N_0B+Q_{\rm peak}v}{N_0B+\alpha_{\min}}\right)}{(v+1)^2} dv \\
&= \log\left(1+\frac{\gamma_0}{N_0B+\alpha_{\min}}\right) \\
&\quad + \frac{N_0B}{Q_{\rm peak}-N_0B}\log\left(1+\frac{\gamma_0 - Q_{\rm peak}}{N_0B}\right) \\
&\quad + \frac{Q_{\rm peak}}{Q_{\rm peak}-N_0B}\log\left(\frac{Q_{\rm peak}}{\gamma_0}\right).
\end{aligned} \tag{33}$$

Therefore, closed-form expression for the minimum-rate capacity of the Rayleigh fading channel under peak and average received-power constraints can finally be expressed as shown in (34).

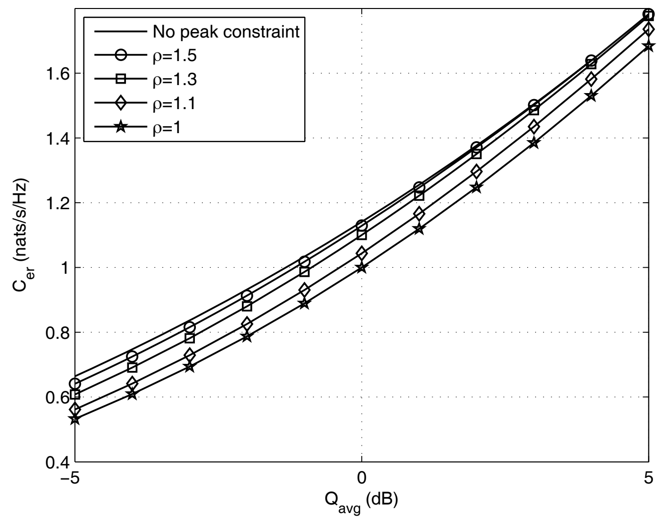

Fig. 1: Ergodic capacity under peak and average received-power constraints for different values of $\rho = \frac{Q_{\rm peak}}{Q_{\rm avg}}$.

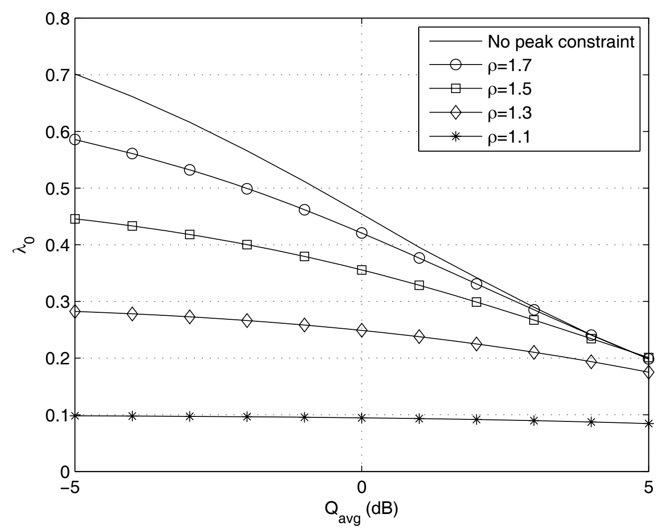

Fig. 2: Optimal cutoff threshold for ergodic capacity for different values of $\rho = \frac{Q_{\rm peak}}{Q_{\rm avg}}$.

VI. Numerical Results and Comparisons

In this section, we numerically illustrate the different capacity metrics studied in this paper, namely, the ergodic capacity, the outage capacity and the minimum-rate capacity, under joint peak and average received-power constraints at a third party's receiver. In the following, we assume $N_0B = 1$.

A. Ergodic Capacity

The ergodic capacity of the fading channel under consideration, and the optimal cutoff threshold associated with this capacity, i.e., λ_0, are studied in Fig. 1 to Fig. 3.

We start by comparing the ergodic capacity for various peak received-power limits in Fig. 1, which plots the ergodic capacity in nats/s/Hz versus $Q_{\rm avg}$ for various values of $\rho = \frac{Q_{\rm peak}}{Q_{\rm avg}}$. For comparison purposes, we also provide results for cases

$$\frac{C_{\min}}{B} = \begin{cases} \text{No feasible power allocation} & \text{if } Q_{\text{avg}} < Q_{\text{avg}}^{\min} \text{ or } Q_{\text{peak}} < Q_{\text{peak}}^{\min}, \\ R_{\min}\left(1 - P_{\text{out}}\right) & \text{otherwise if } Q_{\text{avg}} = Q_{\text{avg}}, \\ R_{\min}\left(1 - P_{\text{out}}\right) + C_{\text{exc}_2} & \text{otherwise if } \dfrac{\gamma_0}{N_0 B} \leq \dfrac{\gamma_{\min}}{N_0 B}, \\ R_{\min}\left(1 - P_{\text{out}}\right) + C_{\text{exc}_2} + C_{\text{exc}_1} & \text{otherwise if } \dfrac{\gamma_{\min}}{N_0 B} < \dfrac{\gamma_0}{N_0 B} \ \& \ \dfrac{\gamma_0}{N_0 B + \alpha_{\min}} < \dfrac{\gamma_{\min}}{N_0 B}, \\ \dfrac{C_{\text{er}}}{B} & \text{otherwise if } \dfrac{\gamma_{\min}}{N_0 B} \leq \dfrac{\gamma_0}{N_0 B + \alpha_{\min}}. \end{cases} \tag{34}$$

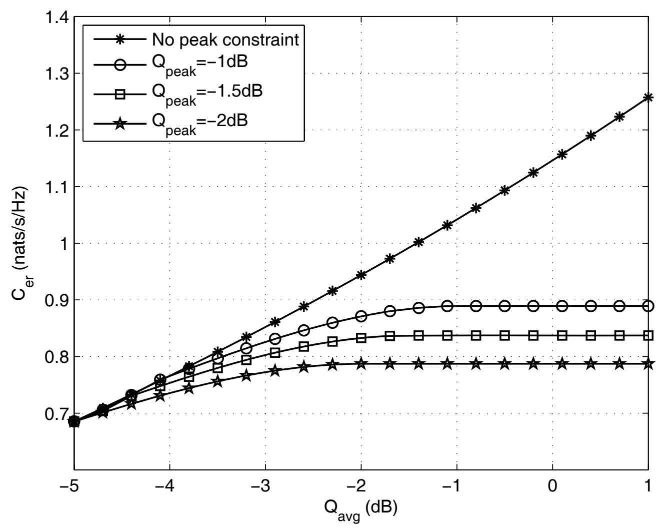

Fig. 3: Ergodic capacity under peak and average received-power constraints for different values of Q_{peak}.

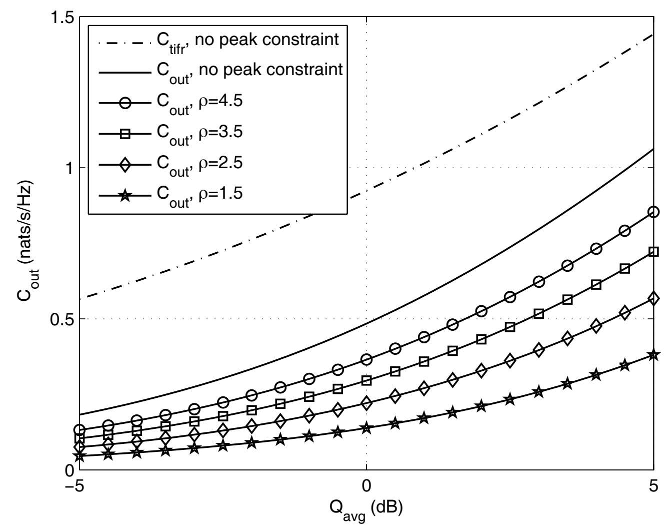

Fig. 5: C_{out} under peak and average received-power constraints with $P_{\text{out}} = 0.1$ for different values of $\rho = \frac{Q_{\text{peak}}}{Q_{\text{avg}}}$. The capacity with *tifr* transmission policy is shown with dashed lines.

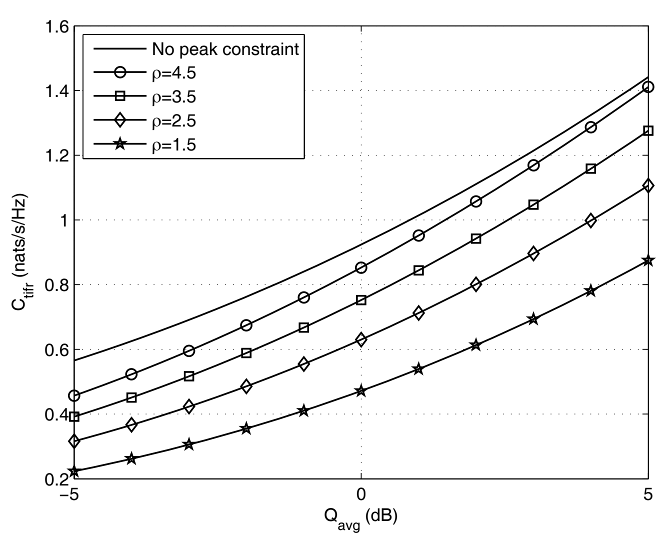

Fig. 4: Capacity with *tifr* transmission policy under peak and average received-power constraints for different values of $\rho = \frac{Q_{\text{peak}}}{Q_{\text{avg}}}$.

where only one constraint on either peak or average received-power is considered. The figure shows that, even under a strict case of $\rho = 1$, the loss in the ergodic capacity is not significant when a constraint on the peak received-power is applied on top of the average received-power constraint. As ρ increases, the capacity plots converge towards the case with no peak constraint.

The behavior of the optimal cutoff threshold for $\frac{h_{\text{s}}}{h_{\text{p}}}$, i.e., λ_0, under which the transmission is suspended is studied in Fig. 2. As can be seen from the figure, this threshold increases as the value of the constraint on the peak received-power increases, confirming hence the analytical results provided in Section III.

We further consider constant values for the peak received-power and plot the ergodic capacity versus Q_{avg} in Fig. 3 which reveals that, for low values of Q_{avg}, the constraint on the peak received-power does not have a big impact onto the ergodic capacity. However, as the value of the average received-power limit approaches the peak received-power limit, the capacity plots become flat and limited by the peak received-power constraint.

B. Outage Capacity

The capacity with *tifr* transmission policy and C_{out} of a Rayleigh fading channel under peak and average received-power constraints are examined for various values of $\rho = \frac{Q_{\text{peak}}}{Q_{\text{avg}}}$ in Fig. 4 and Fig. 5. The former figure, showing the plots for C_{tifr} of a channel with and without constraint on the peak received-power value, reveals that imposing a constraint on the peak received-power can significantly degrade C_{tifr}.

The capacity of a fading channel under peak and average received-power constraints with an outage probability $P_{\text{out}} = 0.1$ is plotted in Fig. 5, which also includes the capacity of the channel under *tifr* transmission policy and

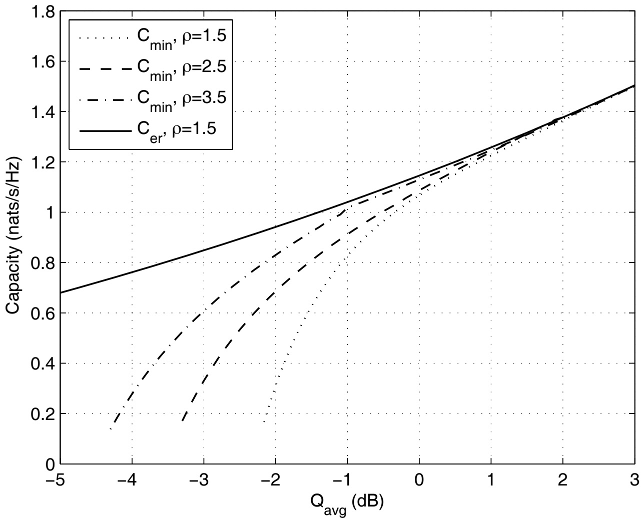

Fig. 6: Ergodic and Minimum-rate capacity with $P_{\text{out}} = 0.2$ and $R_{\min} = 0.2\text{nats/s/Hz}$ under peak and average received-power constraints for different values of $\rho = \frac{Q_{\text{peak}}}{Q_{\text{avg}}}$.

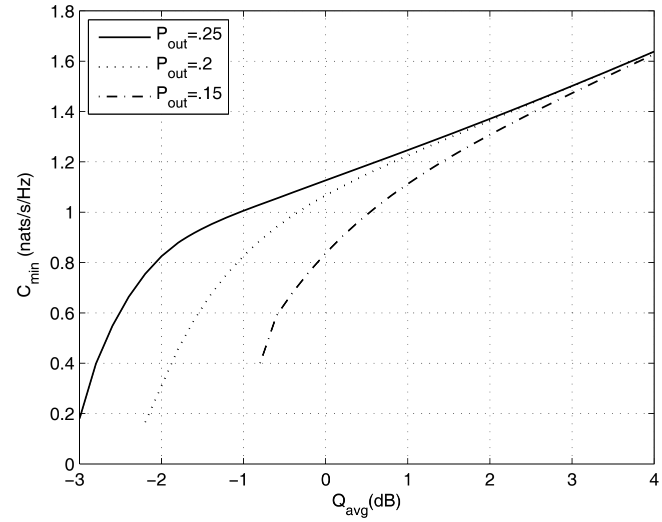

Fig. 7: Minimum-rate capacity under peak and average received-power constraints with $R_{\min} = 0.2\text{nats/s/Hz}$ and $\rho = 1.5$ for different values of the outage probability, P_{out}.

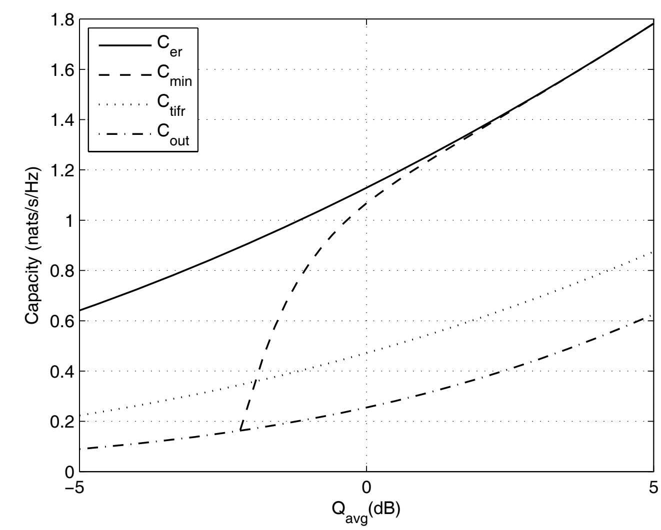

Fig. 8: Ergodic capacity, capacity with *tifr* transmission policy, C_{out} with $P_{\text{out}} = 0.2$, and minimum-rate capacity with $P_{\text{out}} = 0.2$ and $R_{\min} = 0.2\text{nats/s/Hz}$, under peak and average received-power constraints with $\rho = 1.5$.

C_{out} when no constraint is imposed on the peak received-power. We observe that C_{out} is smaller than C_{tifr}, and that it decreases significantly as the limitation on the peak received-power decreases.

C. Minimum-Rate Capacity

We further present the plots for the minimum-rate capacity of a Rayleigh fading channel under peak and average received-power constraints and minimum required-rate $R_{\min} = 0.2\text{nats/s/Hz}$ in Fig. 6 and Fig. 7. In particular, we consider a probability of outage $P_{\text{out}} = 0.2$ and study in Fig. 6 the variation of $C_{\min}$ as a function of Q_{avg} for various values of $\rho = \frac{Q_{\text{peak}}}{Q_{\text{avg}}}$. For comparison purposes, the plot of the ergodic capacity of the channel with $\rho = 1.5$ is also presented. We observe that as the limit on the average received-power increases, the minimum-rate capacity approaches the ergodic capacity of the channel. Also, the effect of the peak received-power constraint on the minimum-rate capacity is higher for lower values of Q_{avg}.

Results of the minimum-rate capacity for various outage probabilities and $\rho = 1.5$ are plotted in Fig. 7 which confirms that the capacity decreases as the outage probability decreases. It can also be observed that the effect of the outage probability on the minimum-rate capacity is higher at lower values of Q_{avg}. In this figure, we considered parameters so that to illustrate $C_{\min}$ does not necessarily start from $R_{\min}(1 - P_{\text{out}})$.

Finally setting the ratio of peak-to-average power limits to $\rho = 1.5$, comparative results are illustrated in Fig. 8, wherein plots for the ergodic capacity, capacity with *tifr* transmission policy, C_{out} with $P_{\text{out}} = 0.2$, and minimum-rate capacity with $P_{\text{out}} = 0.2$ and $R_{\min} = 0.2\text{nats/s/Hz}$, are provided. It can be observed that the minimum-rate capacity converges towards the ergodic capacity as the average received-power limit increases. The results also show that C_{tifr} is higher than $C_{\min}$ for low average received-power limits. However, as Q_{avg} increases, the minimum-rate capacity exceeds C_{tifr}.

VII. Conclusions

We considered a spectrum-sharing system and assessed the capacity of a fading channel under average and peak received-power constraints at a third party's receiver. Imposing such constraints is motivated by the spectrum-sharing configuration, where a spectrum band assumed to be licensed to a primary user may be shared by secondary users, while the interference power, inflicted on the primary's receiver as an effect of the transmission performed by the secondary user, should be within limits set by the primary user in terms of both peak and average received-powers. In this context, we investigated the capacity gains offered by this spectrum-sharing system in Rayleigh fading environments. Specifically, we considered three different capacity notions, namely, ergodic, outage, and minimum-rate, and determined the corresponding capacities under joint peak and average received-power constraints when

CSI is available at the receiver and transmitter of the secondary user. We obtained the optimal power allocation strategies to achieve the channel capacity for the above-mentioned scenarios, and further derived closed-form expressions for the capacity metrics. Numerical results corroborating our theoretical analysis were also provided. In particular, it was shown that imposing a constraint on the peak received-power does not yield a significant impact on the ergodic capacity as long as the average received-power is constrained, and that the capacity under *tifr* transmission policy suffers a great loss due to limitations on the peak received-power.

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