EFFICIENCY CLOSED-FORM EXPRESSIONS FOR ANY IR-HARQ SCHEME AT THE IP LEVEL

A. Le Duc, C. J. Le Martret

Thales Communications, Colombes, France
aude.leduc@fr.thalesgroup.com
christophe.le_martret@fr.thalesgroup.com

P. Ciblat

TELECOM ParisTech, Paris, France
philippe.ciblat@enst.fr

ABSTRACT

Hybrid ARQ with Incremental Redundancy (IR-HARQ) is one of the most popular coding technique for having a reliable transmission link. The efficiency which is the ratio between the number of correctly received bits and the number of transmitted bits is a crucial metric for analyzing the performance of an HARQ scheme. In the literature, closed-form expressions for the efficiency of the IR-HARQ scheme are available at the MAC and IP levels when the information and redundant packets have all the same length. In this paper, we establish the closed-form expressions of the efficiency for any IR-HARQ scheme at the MAC and IP level in a more realistic context, *i.e.*, when the information and redundant packets may have different lengths. The new expressions apply, for example, whatever the puncturing scheme of the error correcting code rate used.

1. INTRODUCTION

In a communication system, it is worthy and now well-spread to combine packet retransmission and forward error coding in order to obtain reliable link. This leads to the so-called Hybrid ARQ (HARQ) technique. One of the most popular HARQ technique is the Incremental Redundancy (IR) HARQ for which the packets transmitted after receiving a NACK at the transceiver side correspond to redundant bits coming from the puncturing of an error correcting code [1, 2].

In general, an information packet of an IR-HARQ scheme is first encoded using a forward error correcting code of rate $1/r_0$ (known as the mother code) where r_0 is an integer. The encoded packet is then split into t_0 subblocks thanks to a puncturing technique of the mother code. The i-th subblocks is transmitted if a NACK is received after the transmission of the $(i-1)$-th subblock. If all the subblocks have the same length, we get r_0 subblocks and the rate of the equivalent code after the transmission of the i-th subblock is $1/i$. In many practical systems, the granularity of such a set of rates is too weak. In order to obtain a more dense set of rates (for example, if $r_0 = 2$, {1,7/8,3/4,5/8,1/2} instead of {1, 1/2}), the subblocks must have different lengths.

Theoretical analysis of HARQ schemes is a crucial task since it enables us to provide fastly practical insights about HARQ schemes behavior and design. For analyzing theoretically an HARQ scheme, one can inspect various metrics such as packet error rate, efficiency, delay, and jitter [1, 3, 4, 5]. The closed-form expressions of the packet error rate (which only depends on the error probability of each puncturing code) takes the same form whatever the subblocks length. Since the delay and jitter are usually defined as a ratio of packets and not as a duration in seconds [5, 6], the subblocks length once again does not affect the closed-form expressions of these metrics. In contrast, the efficiency expresses differently according to the subblocks length property. The HARQ mechanism is usually carried out at the MAC level, but, in order to understand more deeply the whole system using this mechanism, it is worthy to analyze the influence of the HARQ scheme at the upper levels, such as, the IP level.

In the literature, the closed-form expressions found for the efficiency only hold when the subblocks have the same length: one can mention [1] for ARQ scheme at the MAC level, [3] for HARQ scheme at the MAC level, and [4] for any HARQ scheme at the IP level. Therefore, we propose to evaluate theoretically the efficiency (defined as the ratio between received information bits with no error and transmitted bits) of any IR-HARQ scheme at the IP level when the subblocks have different lengths.

The paper is organized as follows: in Section 2, we describe the system model. In Section 3, we propose the new closed-form expressions of the efficiency obtained in the general context. Section 4 is devoted to numerical validation and illustration. Concluding remarks are drawn in Section 5.

2. SYSTEM MODEL

For our communication system based on IP protocol, we consider the three first ISO layers : the PHY layer, the MAC layer, and the IP layer. In order to focus on retransmission performance only, we assume a single user context. As the assumption concerning the different lengths of subblocks only makes sense for IR-HARQ, we focus hereafter on IR-HARQ scheme.

At the transmitter side, the MAC layer has to transmit several IP packets of length L_{IP}. Each IP packet is split into N MAC packets of length $L_{\mathrm{MAC}} = L_{\mathrm{IP}}/N$. From each MAC packet, some subblocks are generated in order to be transmitted by the PHY layer.

Each MAC packet for which an header and an CRC has been added is encoded by a Forward Error Correcting Coding of rate $R_0 = 1/r_0$ (known as *mother code*). The encoded MAC packet is then split into t_0 PHY packets, usually thanks to a puncturing technique of the mother code. The PHY packets (denoted $\mathrm{PPACKET}$) associated with the same MAC packet are then numbered as $\{\mathrm{PPACKET}(i)\}_{i=1}^{t_0}$, and $\mathrm{PPACKET}(i)$ has the length δ_i. The transmitter starts to transmit $\mathrm{PPACKET}(1)$, then $\mathrm{PPACKET}(2)$ (if a NACK is received), then $\mathrm{PPACKET}(3)$ (if a second NACK is received) ans so on up to $\mathrm{PPACKET}(t_0)$. If a NACK is received after the first transmission of $\mathrm{PPACKET}(t_0)$, the first PHY packet $\mathrm{PPACKET}(1)$ is transmitted again and so on. We assume that there are at most $P_{\max}$ PHY packet transmissions per MAC packet. These PHY packets are sent through a propagation channel (that may be Gaussian one, Rayleigh one Frequency-Selective one, etc).

At the receiver side, the incoming PHY packet is demodulated (and decoded if necessary) and sent to the MAC layer which decides to sent back ACKnowledgment (ACK) or a Negative ACKnowledgment (NACK) to the transmitter accordingly. To make a decision on the MAC packet, the receiver has the following sequential process: checking the CRC for $\mathrm{PPACKET}(1)$; if $\mathrm{PPACKET}(1)$ is not correctly received, it sends a NACK and it receives afterwards $\mathrm{PPACKET}(2)$. Then checking the CRC for the concatenation of both previous PHY packets (associated with a FEC of rate $\delta_1/(\delta_1+\delta_2)$), and so on until the reception of $\mathrm{PPACKET}(t_0)$ which is decoded with mother code of rate R_0 followed by the CRC checking. Then, if the MAC packet is not received after $\mathrm{PPACKET}(t_0)$ decoding and the transmission credit is not reached, the received packet memory is flushed (put to zero) and the process starts again.

Then each correctly received MAC packet is sent to IP layer. The IP packet corresponding to N MAC packets is considered to be correctly received if each associated MAC packet is correctly received. For instance, as soon as one MAC packet is not correctly received, the associated IP packet is dropped [7].

3. THEORETICAL DERIVATIONS

The main contribution of this section is to provide a general closed-form expression of the efficiency for IR-HARQ at the IP level valid in the context of different lengths of the PHY packets associated with the same MAC packet.

Let η be the efficiency. By definition, we get

$$\eta = \frac{n_1}{n_2} \tag{1}$$

where n_1 is the average number of received bits (without error) and n_2 is the average number of transmitted bits. Let us inspect the efficiency at the IP level. The transmission error probability for IP packet is denoted by Π_{IP}. The number of received bits without error is equal to the length of the IP packet L_{IP} multiplied by the probability of IP packet success, i.e., $n_1 = L_{\mathrm{IP}}(1-\Pi_{\mathrm{IP}})$. The average number of transmitted bits is equal to the average number of transmitted bits when the IP packet of length L_{IP} is successfully received (noted $\hat{n}_{\mathrm{IP}}$) multiplied by the probability of success, plus, the average number of transmitted bits when the transmission fails (noted $\check{n}_{\mathrm{IP}}$) multiplied by the probability of error, i.e., $n_2 = \check{n}_{\mathrm{IP}}\Pi_{\mathrm{IP}} + \hat{n}_{\mathrm{IP}}(1-\Pi_{\mathrm{IP}})$. This leads to:

$$\eta_{\mathrm{IP}} = \frac{L_{\mathrm{IP}}(1-\Pi_{\mathrm{IP}})}{\check{n}_{\mathrm{IP}}\Pi_{\mathrm{IP}} + \hat{n}_{\mathrm{IP}}(1-\Pi_{\mathrm{IP}})}. \tag{2}$$

This expression can be slightly modified to be applied at the MAC layer (without taking into account that N MAC packets belongs to the same IP packet). Indeed, η_{MAC} can be expressed as in Eq. (2) when replacing subscript IP with subscript MAC and modifying definitions accordingly.

As the closed-form expression for Π_{IP} is given in [4] regardless of the different sizes of the transmitted subblocks, it only remains to derive closed-form expressions for $\check{n}_{\mathrm{IP}}$ and $\hat{n}_{\mathrm{IP}}$. Nevertheless, before going further, we have to obtain some preliminary results at the MAC layer. Therefore we firstly calculate $\check{n}_{\mathrm{MAC}}$ and $\hat{n}_{\mathrm{MAC}}$.

Derivations of $\check{n}_{\mathrm{MAC}}$ and $\hat{n}_{\mathrm{MAC}}$: The average number of transmitted bits when the MAC packet fails to be received is equal to

$$\check{n}_{\mathrm{MAC}} = \sum_{k=1}^{P_{\max}} \delta_k = w_{P_{\max}}. \tag{3}$$

where $w_k = \sum_{i=1}^{k} \delta_i$ is the total number of bits transmitted at the k-th transmission (including transmissions from $\mathrm{PPACKET}(1)$ up to $\mathrm{PPACKET}(k)$).

The average number of transmitted bits per successful transmitted MAC packet is given by

$$\hat{n}_{\mathrm{MAC}} = \sum_{k=1}^{P_{\max}} w_k \Pr\{\text{MAC packet correctly received in } k \text{ PHY packet transmissions} | \text{MAC packet OK}\}$$

By noting $p_1(k) = \Pr\{\text{MAC packet correctly received in } k \text{ PHY packet transmissions}\}$ and using the Bayes rule, we obtain the following result

$$\hat{n}_{\text{MAC}} = \frac{1}{1-\Pi_{\text{MAC}}} \sum_{k=1}^{P_{\max}} w_k p_1(k). \quad (4)$$

The term $p_1(k)$ will play a great role in the rest of the paper since the efficiency will be only written with respect to this term and the lengths of the PHY packets. We recall that $p_1(k)$ can be expressed in terms of the elementary probability π_j which corresponds to the probability that the $(j+1)$-th PHY packet transmission associated with the same MAC packet fails given the j previous PHY packet transmissions associated with the same MAC packet failed too [4]. Hence

$$p_1(k) = \begin{array}{ll} 1-\pi_0 & \text{for } k=1 \\ (1-\pi_{k-1})\prod_{j=0}^{k-2}\pi_j, & \text{otherwise} \end{array}.$$

The terms π_j have to be estimated via Monte-Carlo simulations and depends on the chosen Error Correcting code and the nature and quality of the propagation channel. In contrast, since all the other terms introduced in this paper only depend on the lengths of the PHY packets and the terms π_j through the terms $p_1(k)$, these other terms can be calculated without additional Monte-Carlo simulations and, especially, without simulating the IR-HARQ mechanism. Let us move now on the derivations of $\check{n}_{\text{IP}}$.

Derivations of $\check{n}_{\text{IP}}$: first of all, let us introduce some useful notations:

- The event $G_{\underline{i}}(j) = \{\bar{F}_1 \text{ and } \bar{F}_2 \text{ and } \ldots \text{ and } \bar{F}_j \text{ and } F_{j+1}(i_1) \text{ and } \ldots \text{ and } F_N(i_{N-j})\ \}$, where $\bar{F}_k$ is the event "MAC packet #k is not received" and where $F_k(i)$ is the event "MAC packet #k is received through the transmission of i PHY packets". The event $G_{\underline{i}}(j)$, $1 \leq j \leq N$, corresponds to the case where j MAC packets associated with one IP packet are not received and the $(N-j)$ remaining ones associated with the same IP packet are successfully transmitted.

- For a given j, we define the following set of indices

  $$\mathcal{S}_j = \{\underline{i} = [i_1, i_2, \cdots, i_{N-j}] \in \mathbb{N}_*^{N-j} | \forall k, i_k \leq P_{\max}\}.$$

The events associated with $\check{n}_{\text{IP}}$ are events where at least one MAC packet (belonging to the considered IP packet) is not received. Noticing that the number of possible events corresponding to the failure of transmitting j MAC packets (belonging to the same IP packet) is $\binom{N}{j}$. As a consequence, we can write

$$\begin{aligned} \check{n}_{\text{IP}} &= \sum_{j=1}^{N} \binom{N}{j} \sum_{\underline{i}\in\mathcal{S}_j} g_{\underline{i}}(j) \Pr\{G_{\underline{i}}(j) | \text{ IP packet KO}\} \\ &= (\Pi_{\text{IP}})^{-1} \sum_{j=1}^{N} \binom{N}{j} \sum_{\underline{i}\in\mathcal{S}_j} g_{\underline{i}}(j) \Pr\{G_{\underline{i}}(j)\}, \end{aligned} \quad (5)$$

where $g_{\underline{i}}(j)$ is the number of transmitted bits associated with the event $G_{\underline{i}}(j)$.

When a MAC packet is not received, the corresponding number of transmitted bits is equal to $w_{P_{\max}}$ bits. Thus we have

$$g_{\underline{i}}(j) = j w_{P_{\max}} + r_{\underline{i}}(N-j) \quad (6)$$

where $r_{\underline{i}}(N-j) = \sum_{k=1}^{N-j} w_{i_k}$ is the number of transmitted bits for the $(N-j)$ remaining received MAC packets. For $j=N$, all the MAC packets are in error and thus we have $\Pr\{G_{\underline{i}}(j)\} = (\Pi_{\text{MAC}})^N$ with $g_{\underline{i}}(j) = N w_{P_{\max}}$. For $j < N$, the probability that j MAC packets are not received is equal to $(\Pi_{\text{MAC}})^j$ and the probability that the $(N-j)$ remaining FRAGs are received is equal to $\prod_{k=1}^{N-j} p_1(i_k)$, which gives

$$\Pr\{G_{\underline{i}}(j)\} = \begin{cases} (\Pi_{\text{MAC}})^j \prod_{k=1}^{N-j} p_1(i_k) & \text{if } 1 \leq j < N \\ (\Pi_{\text{MAC}})^N & \text{if } j = N. \end{cases} \quad (7)$$

Putting Eqs. (6)-(7) into Eq. (5) leads to

$$\check{n}_{\text{IP}} = \alpha_1 + \alpha_2 + \alpha_3 \quad (8)$$

with

$$\alpha_1 = N w_{P_{\max}} \frac{(\Pi_{\text{MAC}})^N}{\Pi_{\text{IP}}}, \quad (9)$$

$$\alpha_2 = \frac{w_{P_{\max}}}{\Pi_{\text{IP}}} \sum_{j=1}^{N-1} \binom{N}{j} j (\Pi_{\text{MAC}})^j \sum_{\underline{i}\in\mathcal{S}_j} \prod_{k=1}^{N-j} p_1(i_k),$$

$$\alpha_3 = \frac{1}{\Pi_{\text{IP}}} \sum_{j=1}^{N-1} \binom{N}{j} (\Pi_{\text{MAC}})^j \sum_{\underline{i}\in\mathcal{S}_j} \prod_{k=1}^{N-j} p_1(i_k) \sum_{k=1}^{N-j} w_{i_k}.$$

We now show that the terms α_2 and α_3 can be written into a more compact and less complex form in order to make easier its computation. In order to do so, we need to establish the following lemma.

Lemma 1 *The following equalities hold*

$$\sum_{\underline{i}\in\mathcal{S}_j} \prod_{k=1}^{N-j} p_1(i_k) = (1-\Pi_{\text{MAC}})^{N-j}, \quad (10)$$

$$\sum_{\underline{i}\in\mathcal{S}_j} \prod_{k=1}^{N-j} p_1(i_k) \sum_{k=1}^{N-j} w_{i_k} = (1-\Pi_{\text{MAC}})^{N-j-1} \times (N-j) \sum_{k=1}^{P_{\max}} w_k p_1(k). \quad (11)$$

Due to lack of space, the proof has been omitted.

Thanks to Eq. (10), one can write α_2 easily as follows

$$\alpha_2 = N w_{P_{\max}} \frac{\Pi_{\mathrm{MAC}}}{\Pi_{\mathrm{IP}}}(1-(\Pi_{\mathrm{MAC}})^{N-1}). \quad (12)$$

Using Eq. (11) and after some algebraic manipulations leads to the following expression for α_3

$$\alpha_3 = N \frac{\Pi_{\mathrm{IP}} - \Pi_{\mathrm{MAC}}}{\Pi_{\mathrm{IP}}(1-\Pi_{\mathrm{MAC}})} \sum_{k=1}^{P_{\max}} w_k p_1(k). \quad (13)$$

From Eqs. (9)-(12)-(13), we obtain the final expression

$$\check{n}_{\mathrm{IP}} = \frac{N}{\Pi_{\mathrm{IP}}}(w_{P_{\max}} \Pi_{\mathrm{MAC}} + \frac{\Pi_{\mathrm{IP}} - \Pi_{\mathrm{MAC}}}{1-\Pi_{\mathrm{MAC}}} \sum_{k=1}^{P_{\max}} w_k p_1(k)). \quad (14)$$

We recall that the MAC packet error probability (namely Π_{MAC}) and the IP packet error probability (namely Π_{IP}) are provided in [4] and take the following forms respectively

$$\Pi_{\mathrm{MAC}} = 1 - \sum_{k=1}^{P_{\max}} p_1(k)$$

$$\Pi_{\mathrm{IP}} = 1 - \left(\sum_{k=1}^{P_{\max}} p_1(k)\right)^N$$

The expression given in Eq. (14) is much more compact than those of Eq. (8) and it is also less complex to program since we have succeeded to remove the summation over the sets $\mathcal{S}_j$ in (8) to simple summations. Indeed, for a given j, the summation over $\mathcal{S}_j$ requires $P_{\max}^{N-j}$ additions which leads to a total complexity of $(P_{\max}^N - P_{\max})/(P_{\max}-1)$ additions when j goes from 1 to $(N-1)$, whereas the summations in Eq. (14) offer a complexity of $P_{\max}$.

Derivations of $\hat{n}_{\mathrm{IP}}$**:** Since the MAC packets are independent, the average number of transmitted bits is equal to N times the average number of transmitted bits per MAC packet. Therefore we have

$$\hat{n}_{\mathrm{IP}} = N \hat{n}_{\mathrm{MAC}} = N \frac{\sum_{k=1}^{P_{\max}} w_k p_1(k)}{\sum_{k=1}^{P_{\max}} p_1(k)}. \quad (15)$$

We are now able to obtain the final expressions for the efficiency at the IP level when the subblocks have different lengths.

Final result: By combining Eqs. (14)-(15) established for $\check{n}_{\mathrm{IP}}$ and $\hat{n}_{\mathrm{IP}}$ respectively into Eq. (2), we obtain, after some simple algebraic manipulations, the following compact closed-form expression for η_{IP}

$$\eta_{\mathrm{IP}} = \frac{L_{\mathrm{IP}}}{N} \frac{(\sum_{k=1}^{P_{\max}} p_1(k))^N}{w_{P_{\max}}(1-\sum_{k=1}^{P_{\max}} p_1(k)) + \sum_{k=1}^{P_{\max}} w_k p_1(k)}. \quad (16)$$

This expression is the main contribution of this paper and enables us to compute very fastly the efficiency of an IR-HARQ scheme without simulating this HARQ mechanism. Notice that the puncturing codes have however be implemented in order to evaluate the terms π_j. When equal length is assumed for the subblocks, we have $w_k = kL_{\mathrm{MAC}}$ and Eq. (16) simplifies and becomes equal to closed-form expression provided in [4]

For obtaining the efficiency at the MAC layer, we just have to put $N = 1$ and to replace L_{IP} with L_{MAC} in Eq. (16). Then we get

$$\eta_{\mathrm{MAC}} = \frac{L_{\mathrm{MAC}} \sum_{k=1}^{P_{\max}} p_1(k)}{w_{P_{\max}}(1-\sum_{k=1}^{P_{\max}} p_1(k)) + \sum_{k=1}^{P_{\max}} w_k p_1(k)}. \quad (17)$$

This expression is also new. In the literature, only the case when the subblocks have equal length has been treated in [3, 4]. Therefore by considering $w_k = kL_{\mathrm{MAC}}$, Eq. (17) boils down to closed-form expression given in [3, 4].

Moreover as $L_{\mathrm{MAC}} = L_{\mathrm{IP}}/N$ and as $\sum_{k=1}^{P_{\max}} p_1(k)$ is less than 1 (since it corresponds to a detection probability), we have $\eta_{\mathrm{IP}} \leq \eta_{\mathrm{MAC}}$ which sounds natural and traduces the price to pay to transmit N MAC packets simultaneously.

4. NUMERICAL ILLUSTRATIONS

In this simulation part, the theoretical and empirical evaluations of efficiency for IR-HARQ at the IP level are done under the following assumptions:

- The IR-HARQ is implemented with the Rate Compatible Punctured Convolutional (RCPC) codes ([2]) with a mother code rate of $R_0 = 1/4$. The number of MAC packets per IP packet is $N = 3$. The number of bits per MAC packets is $L_{\mathrm{MAC}} = 320$. We use a QPSK modulation.
- We consider an Additive White Gaussian Noise channel.
- As done for the derivations, the ACK/NACK feedback is error-free. The CRC is also assumed to be ideal.

Theoretical expressions of efficiency are obtained by inserting the estimated values of π_j (for $j \in \{0, \cdots, t_0 - 1\}$). Empirical efficiencies are obtained by sending thousand IP packets.

In Fig. 1, we display theoretical and empirical efficiency (for IR-HARQ at the IP level) versus SNR for different values of the transmission credit $P_{\max}$. The number of puncturing schemes is equal to $t_0 = 6$. Moreover the considered puncturing codes have the following set of rates $\{1, 4/5, 2/3, 1/2, 4/11, 1/4\}$ which leads to different lengths for the transmitted subblocks. Theoretical and empirical curves are in perfect agreement. Besides, increasing the number of transmission credit slightly improves the efficiency at low SNR.

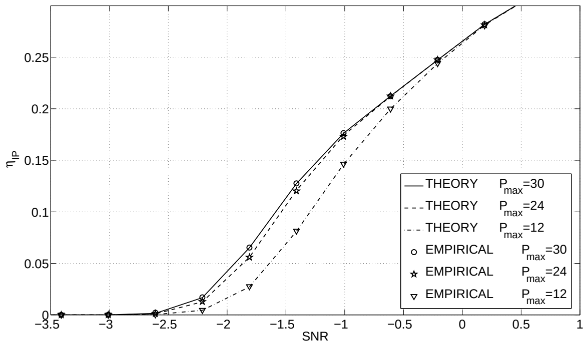

Fig. 1. Theoretical and empirical efficiency vs. SNR.

The data rates viewed as the number of well received bits per channel use can be directly connected to the efficiency. Indeed, denoting the data rate by κ_{IP}, we have $\kappa_{\mathrm{IP}} = 2\eta_{\mathrm{IP}}$ since we use a QPSK modulation. The upper bound for the data rate κ_{IP} is the so-called Shannon capacity for QPSK modulation, denoted by C_{QPSK} which corresponds to the maximum number of well received bits per channel use regardless of the transmission technique used. In Fig. 2, we plot the theoretical data rates (for the IR-HARQ at the IP level) versus SNR for different sets of puncturing code rates. For the configuration 1, we have $P_{\max} = 12$, $t_0 = 4$, and the set of rates equal to $\{1, 1/2, 1/3, 1/4\}$. For the configuration 2, we have $P_{\max} = 21$, $t_0 = 7$, and the set of rates $\{1, 2/3, 1/2, 4/10, 1/3, 2/7, 1/4\}$. For the configuration 3, we have $P_{\max} = 39$, $t_0 = 13$, and the set of rates $\{1, 4/5, 2/3, 4/7, 1/2, 4/9, 4/10, 4/11, 1/3, 2/7, 4/15, 1/4\}$. As expected, we observe that the most granular the puncturing code rates are, the smoother the data rates curve is. Indeed, when a NACK is received at the transmitter side and when the set of puncturing code rates has a lot of possible rates, it is easier to adapt well the number of needed redundant bits. As a consequence, it is possible to improve greatly the efficiency of an IR-HARQ mechanism only by well designing the set of rates. Finally it is important to notice that the curves have been obtained without simulating the IR-HARQ mechanism but with the proposed closed-form expression of the efficiency.

5. CONCLUSION

Closed-form expressions for the efficiency of an IR-HARQ scheme at the MAC and IP levels when the subblocks associated with one MAC packet have different lengths have been proposed in this paper. The expressions hold for different types of propagation channels (Gaussian channel, Rayleigh channel, Binary Symmetric channel). The next step would be to use more realistic assumptions such as imperfect feedback link.

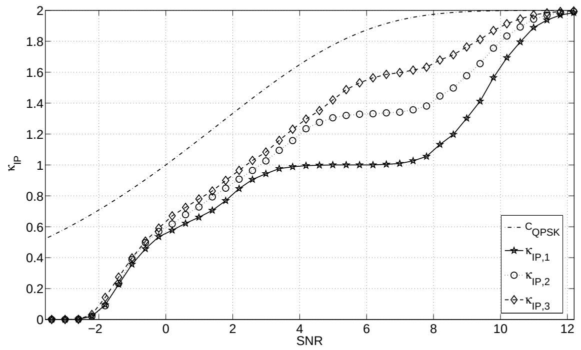

Fig. 2. Theoretical data rates vs. SNR.

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