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Service Differentiation in Third Generation Mobile Networks

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Abstract. We present and analyse an approach to service differentiation in third generation mobile networks based on Wideband CDMA, that exposes a new weight parameter designed to reflect allocation of the congestible resource. The approach naturally takes into account the difference in resource scarcity for the uplink and downlink, because it is grounded on fundamental economic models for efficient utilization of resources in WCDMA. Discrete values of the weight parameter can be presented as different service classes. Finally, we present numerical experiments demonstrating the effectiveness of our approach, and investigate its performance and transient behaviour under power control and signal quality estimation errors.

1 Introduction

The percentage of users accessing packet switched networks through wireless access networks is increasing at a very large pace. Hence, the ability to support quality of service (QoS) differentiation in wireless systems is becoming increasingly important. Indeed, the UMTS (Universal Mobile Telecommunication System) third generation mobile telecommunication system allows user negotiation of bearer service characteristics, such as throughput, error rate, and delay [1, 2]. WCDMA (Wideband Code Division Multiple Access) is the main air interface for UMTS. With WCDMA all mobile users can simultaneously transmit, utilizing the whole radio spectrum, and unique digital codes are used to differentiate the signal from different mobiles. Variable bit rates are achieved using variable spreading factors, where the spreading factor determines how much a data bit is spread in time, and multiple codes. The signal quality (error rate) is determined by the signal-to-interference ratio, *SIR*, which is the ratio of the signal's received power over the total interference, the latter given by the sum of the noise and the interference due to signals from other mobiles.

In this paper we propose models and procedures for service differentiation in WCDMA networks, and present numerical investigations that demonstrate the effectiveness of our approach, and show how various characteristics of the wireless system, such as power control and *SIR* estimation errors, and discrete transmission rates, affect service differentiation and the system's transient behaviour. By considering actual resource usage in the uplink and the downlink, our procedures are fair and efficient, and are robust to varying demand for wireless resources. In the uplink, resource usage is radio spectrum limited, being an increasing function of the product of the transmission rate and *SIR*. In the downlink, resource usage is constrained by the base station's total transmission power. Our approach modifies outer loop power control and load control, which runs on the radio network controller (RNC), and does not affect fast closed-loop power control, which operates on a much faster timescale.

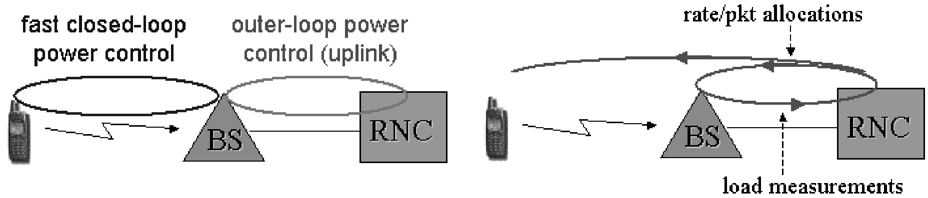
In related work, [3] presents a class-based quality of service framework. The performance for a particular class depends on its elasticity, which specifies how the rate will decrease in periods of congestion. Our approach differs from the above in that allocation of resources is done proportional to weights, thus leading to fair, in terms of weights, allocations. [4] provides an overview of radio resource allocation techniques, focusing on power and rate adaptation in overload periods, and [5] discusses rate adaptation for different wireless technologies.

The rest of the paper is organized as follows. In Sect. 2 we discuss resource management procedures in WCDMA. In Sect. 3 we first discuss resource usage in the uplink and downlink, and then propose procedures for service differentiation in each direction. In Sect. 4 we present and discuss numerical investigations demonstrating the effectiveness of our approach, and in Sect. 5 we conclude the paper identifying related and future research issues.

2 Resource management in WCDMA

Resource management in WCDMA includes fast closed-loop power control, outer loop power control, and load control [2]. In the uplink, with fast closed-loop power control, Fig. 1(a), the base station (BS) continuously measures the received *SIR* for each mobile, and compares it with a target *SIR*. If the measured *SIR* is smaller (larger), then the BS instructs the mobile to increase (decrease) the transmission power. The above cycle has frequency 1500 Hz, which corresponds to one power update every 0.67 msec. In WCDMA, a similar fast closed-loop power control loop exists in the downlink direction, where now the *SIR* is measured by the mobile, which sends power update commands to the BS.

In second and third generation systems based on CDMA, the main objective of fast closed-loop power control is to tackle the *near-far* problem: If all mobiles



(a) Closed-loop & outer loop power ctrl (b) Load control in uplink & downlink

Fig. 1. Resource management functions in WCDMA

transmitted with the same power, then the signal from the mobile nearer to the base station would overwhelm all other signals. Fast closed-loop power control resolves this problem by maintaining the same *SIR* at the base station, for all mobiles. In third generation system, which will support applications with different quality of service requirements, the target *SIR* need not be the same, since a different target *SIR* yields a different signal quality, in terms of the frame error rate, *FER*. Typically, for non-real-time services the frame error rate is in the range $10 - 20\%$, whereas for real-time services it is close to 1% [2, p. 193].

Because there is no one-to-one correspondence between the target *SIR* and the achieved *FER*, outer loop power control between the base station and the RNC is required, Fig. 1(a); its objective is to adjust the target *SIR* in order to achieve some constant, predefined *FER*. Typically, outer loop power control operates in timescales slower than those of fast closed-loop power control.

In WCDMA data transmission occurs in fixed-size frames, which have minimum duration 10 msec; the rate is allowed to change between frames but remains constant within a single frame. Hence, the timescales of rate control are slower than those of fast closed-loop power control, where one power update occurs every 0.67 msec. Moreover, WCDMA supports discrete bit rates: Specifically, in the uplink the user data rate can obtain the values 7.5, 15, 30, 60, 120, 240, 480 Kbps, which correspond to a spreading factor of 256, 128, 64, 32, 8, 4, respectively [2]. Higher bit rates can be achieved with the use of multiple codes. In addition to code-division scheduling, WCDMA supports time-division scheduling that controls which mobiles can transmit in each frame.

Finally, load control decreases the target *SIR* that is used in fast closed-loop power control, or decreases the transmission rate and/or adjusts the time scheduling of data, for both the uplink and the downlink, during periods of overload, Fig. 1(b); such periods are detected by the RNC based on measurements it receives from the base station.

3 Models for service differentiation

In this section we first discuss resource usage in the CDMA uplink and downlink. Then we present our approach for service differentiation, which involves allocating resources according to weights. An important property of CDMA networks is that there are two control parameters that affect the quality of service: the transmission rate and the signal-to-interference ratio. However, resource usage in the two directions is different, leading to different models for service differentiation.

3.1 Resource usage in CDMA

Resource usage in the uplink. Consider a single CDMA cell. In the uplink, the signal-to-interference ratio at the base station for the transmission from mobile i is given by [6, 7]

$$SIR_i = \frac{W}{r_i} \frac{g_i p_i}{\sum_{j \neq i} g_j p_j + \eta}, \qquad (1)$$

where W is the chip rate, which is equal to 3.84 Mcps for WCDMA, r_i is the transmission rate, p_i is the transmission power, g_i is the path gain between the base station and mobile i, and η is the power of the background noise at the base station. The ratio W/r_i is the spreading factor or processing gain for mobile i.

The value of *SIR* corresponds to the signal quality, since it determines the bit error rate, *BER* [6, 7], and hence the frame error rate, *FER*. If we assume perfect power control, then the value of *SIR* in (1) will be equal to the target signal-to-interference ratio that is used in fast closed-loop power control.

Solving the set of equations given by (1) for each mobile i, we get [7, 8]

$$g_i p_i = \frac{\eta \alpha_i^{\text{UL}}}{1 - \sum_j \alpha_j^{\text{UL}}}\,, \quad \text{where} \quad \alpha_i^{\text{UL}} = \frac{1}{\left(\frac{W}{r_i SIR_i} + 1\right)}\,. \tag{2}$$

Since the power p_i can take only positive values, from (2) we get

$$\sum_i \alpha_i^{\text{UL}} < 1\,. \tag{3}$$

The last equation illustrates that the uplink is *interference-limited*: Even when they have no power constraints, mobile hosts cannot increase their power with no bound, due to the increased interference they would cause to the other mobiles. If (3) is violated, then the target *SIR* values cannot be met for all mobiles.

In practise, due to the limited transmission power of the mobile hosts, imperfect power control, shadowing, etc, the total load must be well below 1. Indeed, in radio network planning [2], all the above factors are used to determine an interference margin (or noise rise) I_{margin}, based on which (3) becomes

$$\sum_i \alpha_i^{\text{UL}} \leq \frac{I_{margin} - 1}{I_{margin}}\,. \tag{4}$$

When each mobile user uses a small portion of the available resources, we have $\frac{W}{r_i SIR_i} \gg 1$, hence $\alpha_i^{\text{UL}} \approx \frac{r_i SIR_i}{W}$ and the constraint (4) can be approximated by

$$\sum_i r_i SIR_i \leq \rho^{\text{UL}} W\,, \quad \text{where} \quad \rho^{\text{UL}} = \frac{I_{margin} - 1}{I_{margin}}\,. \tag{5}$$

The above results can be generalized for multiple cells by considering the intercell interference coefficient $f =$(other cell interference)/(intracell interference) [6, 2], in which case ρ^{UL} is multiplied by $1/(1 + f)$.

Resource usage in the downlink. In the downlink, for the case of a single cell the signal-to-interference ratio at mobile i is

$$SIR_i = \frac{W}{r_i} \frac{g_i p_i}{\theta_i g_i \sum_{j \neq i} p_j + \eta_i}\,, \tag{6}$$

where r_i is the transmission rate, p_i is the transmission power, g_i is the path gain between the base station and mobile i, θ_i is the orthogonality factor for the codes used in the downlink, and η_i is the power of the background noise at mobile i. The orthogonality factor θ_i depends on multipath effects, hence can be different for different mobiles. In the case of multiple cells, (6) can be generalized by multiplying the term $\theta_i g_i \sum_{j \neq i} p_j$ with $(1 + f_i)$, where f_i is the intercell interference coefficient, which in the downlink can be different for different mobiles.

The total transmission power at the base station has an upper bound, say P. Hence, the downlink is *power-limited* and resource usage is determined by the transmission power. As with the uplink, in the downlink the utilization in practise cannot reach 100%. Hence, the resource constraint in the downlink is

$$\sum_i p_i \leq \rho^{\mathrm{DL}} P \,. \tag{7}$$

3.2 Service differentiation in the uplink

In this section we discuss service differentiation in the uplink. Assume that each mobile user has an associated weight; this weight can correspond to a service class selected by the mobile user. To achieve fair resource allocation, wireless resources should be allocated in proportion weights. Due to such proportional allocation, and since resource usage in the uplink is given by the product of the transmission rate and signal-to-interference ratio, from (5) we have

$$r_i SIR_i = \frac{w_i}{\sum_j w_j} \rho^{\mathrm{UL}} W \,. \tag{8}$$

Recall that users can potentially control both the transmission rate and the signal-to-interference ratio. How this selection is done depends on what the user values. Indeed, for users that value only the average throughput, i.e., the product of the transmission rate and frame success rate, one can prove that the optimal signal-to-interference ratio depends solely on the frame error rate as a function of the signal-to-interference ratio, and is independent of the transmission rate [9]. In this case, (8) can be used to compute the transmission rate as follows

$$r_i = \frac{1}{SIR_i} \frac{w_i}{\sum_j w_j} \rho^{\mathrm{UL}} W \,. \tag{9}$$

The application of the above equation would be part of load control. Equation (9) can also be applied for traffic that is rate adaptive, but has fixed quality of service requirements in terms of the frame error rate, *FER*. In this case, outer loop power control would be responsible for adjusting the target *SIR* in order to achieve the predetermined *FER*. Note that for traffic with fixed quality of service requirements, there is no requirement that *FER* is a function of only *SIR*; *FER* can also depend on the transmission rate r, which is the case in practise.

The application of (9) allows two alternatives regarding the value for the signal-to-interference ratio that appears in the right-hand side: SIR_i can be either the target *SIR* for mobile i, or it can be the actual *SIR* for mobile i, which is estimated from (1). We investigate these two alternatives in Sect. 4.

In the case of traffic with fixed-rate requirements that is adaptive to the signal quality, based on (8), *SIR* values can be allocated according to

$$SIR_i = \frac{1}{r_i} \frac{w_i}{\sum_j w_j} \rho W \, .$$

Application of this equation would involve outer loop power control.

Although the models and procedures discussed above lead to simple (proportional) allocation of resources, they can be theoretically justified in terms of economically efficient resource usage [9]. Indeed, in the case of rate adaptive traffic with fixed quality of service requirements, mobile users having a fixed weight correspond to users with a logarithmic utility function of the form $w_i \log(r_i)$, where a user's utility function represents his value for a particular level of service. If each user is charged in proportion to his weight, equivalently in proportion to the amount of resources he is receiving, then the resulting allocations in the equilibrium maximize the aggregate utility of all users (social welfare). If the utility of a user i has a more general form $U_i(r_i)$, then the user's weight can be modified slowly in order to satisfy $w_i(t) = U_i'(r_i(t))r_i(t)$.

3.3 Service differentiation in the downlink

In the downlink the resource constraint is related to the total transmission power, (7). Based on this equation we can allocate instantaneous power levels in proportion to weights. However, due to multipath fading, this approach has the disadvantage that the received signal quality at a mobile host would fluctuate. Moreover, it requires modification of the fast closed-loop power control procedure, which is implemented in the physical layer of CDMA systems. Another alternative is to determine *average* power levels, which are then used to compute the transmission rate. According to this approach the average power for user i would be

$$\bar{p}_i = \frac{w_i}{\sum_j w_j} \rho^{\mathrm{DL}} P \, .$$

As was the case in the uplink, if users value only the average throughput of data transmission, then the optimal signal-to-interference ratio is independent of the transmission rate. Hence, from (6), the transmission rate for user i will be

$$r_i = \frac{W}{SIR_i} \frac{1}{l_i I_i} \frac{w_i}{\sum_j w_j} \rho^{\mathrm{DL}} P \, , \tag{10}$$

where $l_i = 1/g_i$ and $I_i = \theta_i g_i \sum_{j \neq i} p_j + \eta_i$ is the path loss and interference, respectively, for user i. If a mobile is moving, it is appropriate to take average values for its path loss and interference. In the last equation observe that, as was the case for the power, the transmission rate is proportional to the weight.

Equation (10) requires estimation of the path loss from the base station to the mobile, which can be done using the pilot bits in the downlink control channel. There are two alternatives as to where the selection of r_i using (10) is performed: the mobile host or the radio network controller (RNC). The first alternative results in more complexity at mobile hosts. Moreover, it requires communicating the ratio $\rho^{\rm DL} P/\sum_j w_j$ from the RNC to the mobiles. On the other hand, if the RNC performs the selection, then there would be increased signalling overhead between the mobile and the RNC, since the values of the path loss and the interference would need to be communicated to the RNC; how often these parameters change depends on the mobile's movement.

It is interesting to observe from (10) that, for the same weight, a higher path loss gives a smaller transmission rate. To avoid such differentiation due to a mobile's position, the parameters in (10) can be replaced with their corresponding averages *over all mobile hosts*. Hence, if $\bar{l}$ is the average path loss and $\bar{I}$ is the average interference over all mobiles, rates can be allocated using

$$r_i = \frac{W}{SIR_i} \frac{1}{\bar{l}\bar{I}} \frac{w_i}{\sum_j w_j} \rho^{\rm DL} P \,.$$

Whether to allocate resources in the downlink with or without dependence on the mobile's position will be determined by a wireless operator's policy.

4 Numerical investigations

In this section we present simulation investigations that demonstrate the effectiveness of our approach for supporting service differentiation, and investigate how various characteristics of the wireless system, such as power control and SIR estimation errors, and discrete transmission rates, affect service differentiation and the system's transient behaviour. Due to space limitations, we present results only for the uplink, where rates are allocated using (9).

The accuracy of approximation (5), on which (9) is based, depends on the number of mobile users and the utilization. Indeed, for the parameters considered in our experiments, the ratio of throughput for mobile users with different weights using (4) differs from the ratio of throughput using the approximation (5) by less than 5%. Moreover, observe from (9) that the rate is inversely proportional to the signal-to-interference ratio, and proportional to the utilization; recall that such an allocation corresponds to a logarithmic utility function. Results for general forms of user utilities, including comparison of resource sharing in the uplink and downlink, and how it is affected by a mobile's distance from the base station and the wireless network's load appear in [9].

We consider a single cell. The simulation parameters are shown in Table 1. Both the power control and *SIR* estimation errors are assumed to be lognormally distributed. We assume that the start time for each mobile is randomly distributed in the interval $[0, \lceil N/2 \rceil]$, where N is the total number of mobiles. The simulation experiments were performed in MATLAB, and utilized some functionality of the RUNE library [10].

There are two alternatives for applying (9), which refer to the value of the signal-to-interference ratio that appears on the right-hand side: SIR_i can be either the target *SIR* for mobile i, or it can be the actual *SIR* for mobile i,

Table 1. Simulation parameters. d is distance in Km

parameter	values
mobile power, $\bar{p}$	250 mW
interference margin, I_{margin}	3 dB
noise, η	10^{-13} Watt
path gain, $g(d) = kd^{-u}$	$u = 3.52, k = 1.82 \cdot 10^{-14}$
target SIR	5
power control error, PCE	0 or 1 dB
SIR estimation error, SIR_{err}	0 or 1 dB
# of mobiles, N	11

which is estimated from (1). The latter leads to more robust behaviour in cases when the mobile does not obey power control commands from the base station.

Figs. 2(a) and 2(b) show the transmission rate as a function of frame number, for continuous and discrete rate values, when the target *SIR* is used in (9). Each graph displays the rate for two mobiles with weights 1 and 2. Figs. 3(a) and 3(b) show the same results when the actual *SIR* is used. Observe that when the target *SIR* is used, Figs. 2(a) and 2(b), convergence is reached very fast, as soon as the last mobile has entered the system. On the other hand, when the actual *SIR* is used, Figs. 3(a) and 3(b), convergence takes longer.

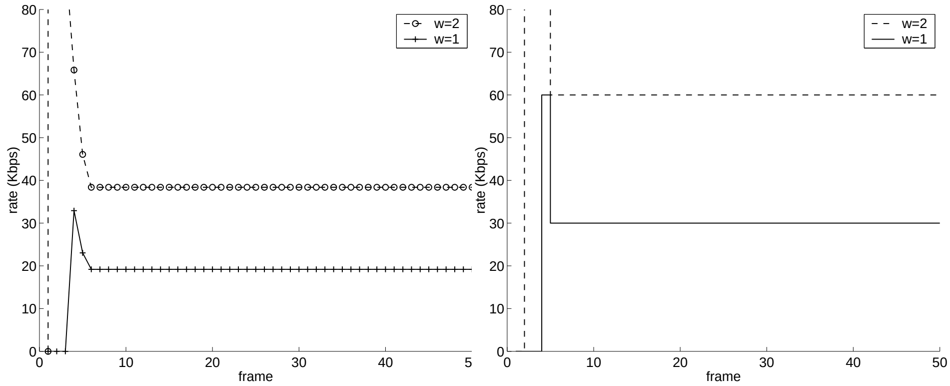
Figs. 4(a) and 4(b) show the rate as a function of frame number, in the case of imperfect power control. Observe in Fig. 4(a) that imperfect power control has no effect when the target *SIR* is used in the rate allocation. On the other hand, Fig. 4(b) shows that imperfect power control has an effect when the actual *SIR* is used in the rate allocation. This occurs because the transmission powers appear in (1). Despite the rate variations in Fig. 4(b), observe that average service differentiation is still achieved.

Figs. 5(a) and 5(b) show the rate as a function of frame number, when *SIR* estimation errors occur. These errors affect the estimation of the target *SIR*, hence they affect rate allocations when the target *SIR* is used, Fig. 5(a). Moreover, errors in the target *SIR* result in fluctuation of the transmitting powers, hence they also affect rate allocations when the actual *SIR* is used, Fig. 5(b).

5 Conclusions

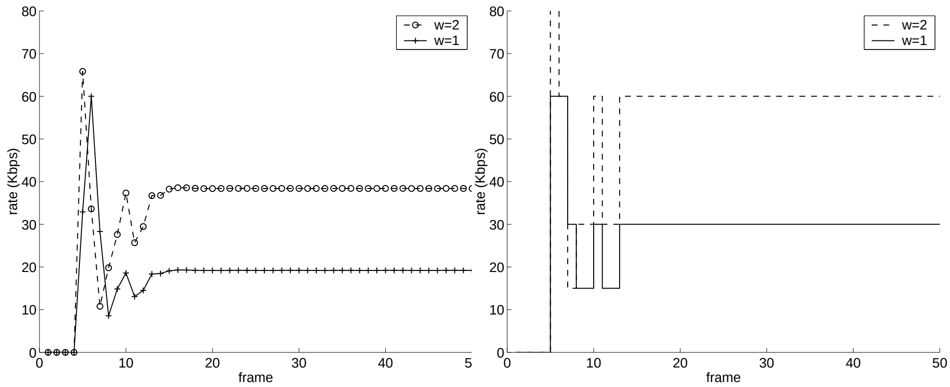
We have presented models and procedures for fair and efficient service differentiation in third generation mobile networks based on WCDMA. With simulation experiments, we demonstrated the effectiveness of our approach, and investigated the effects of power control and *SIR* estimation errors, and discrete transmission rates on service differentiation and the system's transient behaviour.

Ongoing work includes extensions for traffic that is adaptive to both the transmission rate and the signal quality and, unlike best-effort traffic, has a utility that depends on the loss rate in addition to the average throughput. Related work involves the investigation of models and procedures for service differentiation and seamless congestion control in wireless and wired networks.



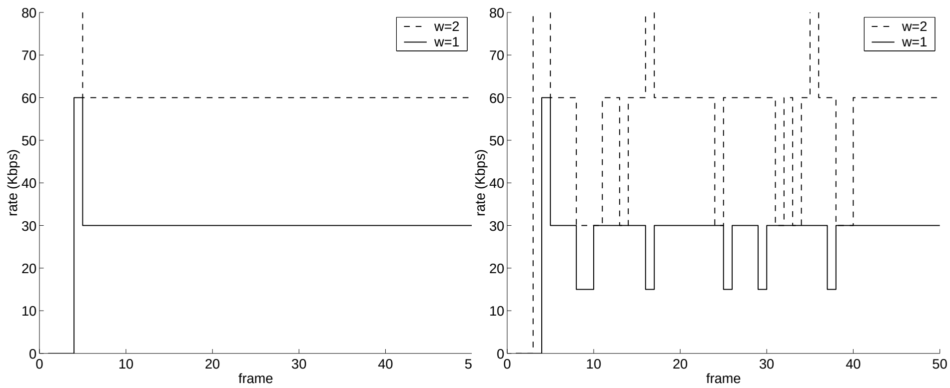
(a) Continuous rate values (b) Discrete rate values

Fig. 2. Rate as function of frame number, when rate allocation is based on the target *SIR*. $PCE = 0, SIR_{err} = 0$



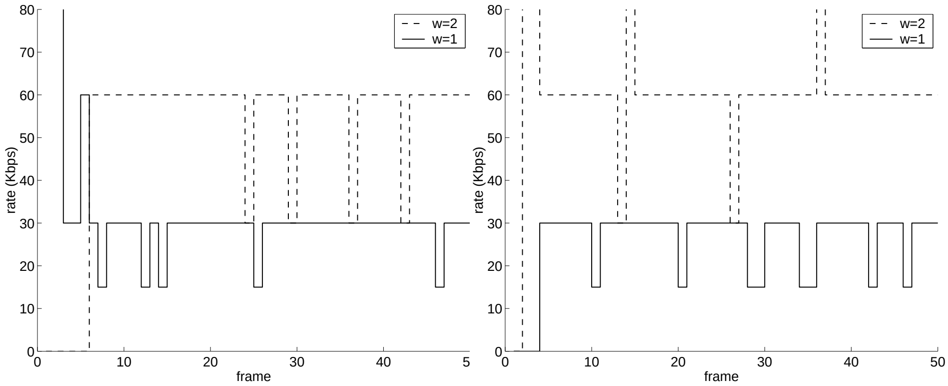
(a) Continuous rate values (b) Discrete rate values

Fig. 3. Rate as function of frame number, when rate allocation is based on the actual *SIR*. $PCE = 0, SIR_{err} = 0$



(a) Target *SIR* (b) Actual *SIR*

Fig. 4. Rate (discrete values) as function of frame number. $PCE = 1$ dB$, SIR_{err} = 0$



(a) Target *SIR* (b) Actual *SIR*

Fig. 5. Rate (discrete values) as function of frame number. $PCE = 0, SIR_{err} = 1$ dB

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