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Transparent Metrology of Signal to Noise Ratios of Noisy Band-Limited Digital Signals

Donald Halford

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I propose the use of a *template method* for quantitative, correct, and transparent measurement of signal power to additive noise power ratios (SNR) of digital signals and systems under full operating conditions. Outer guard chips of digital templates hold intersymbol interference fixed on inner target chips in realizations of the respective template patterns in traffic. The proposed template method needs to be developed and proven as a potentially valuable metrology capability; it can be especially important for real time online performance assessment and monitoring of digital communication systems.

A *correct measurement procedure* by definition actually measures a specified parameter of a specified signal, channel, device, or system. A *transparent measurement procedure* by definition measures the specified parameter without degradation of the usable channel capacity and without modification to or interference with the functioning of the measured system.

I discuss the significance of transparent metrology, the measurement of various SNR's by the template method, and the general applicability of the template method for measurements on any noisy digital signal. The template method can provide transparent metrology procedures for other basic measurands, e.g., intersymbol interference, multiplicative noises, and synchronization.

Key words: communications; correct measurement procedure; digital signals; energy per bit to noise density; monitoring; noise; online measurements; performance assessment; real time; signal to noise ratio measurement; template method; transparent metrology.

1. Introduction

Noise and distortion affect the quality of performance of advanced digital communication systems and place upper limits on the information carrying capacity of digital channels. Some relevant basic quality parameters [1]-[7] for noise and distortion of digital signals are signal

*A talk on this topic was presented at the XXth General Assembly of the International Union of Radio Science (URSI), Washington, D. C., 10-19 August 1981 [8].

power to additive noise power ratios (SNR), intersymbol interference (ISI), dispersion, multiplicative noises, and synchronization. See table 1.

Table 1. Some basic noise and distortion measurands for digital signals, channels, devices, and systems

1. ADDITIVE EFFECTS (RANDOM AND DETERMINISTIC):

    1.1. Digital signal power to additive noise power ratios (SNR, CNR, C/N_0, C/kT, E_b/N_0, E_{chip}/N_0)

    Note: Additive noise power, as operationally defined here, includes power from any additive interference which is uncorrelated with the signal.

2. DISPERSION:

    2.1. Intersymbol interference (ISI)
    2.2. Group delay dispersion (GDD)
    2.3. Amplitude response dispersion (ARD)

    Note: Dispersion, as defined from a measurements point of view, includes effects which arise from the presence of any time invariant, additive interference which is correlated with the signal.

3. MULTIPLICATIVE EFFECTS (RANDOM AND DETERMINISTIC):

    3.1. Incidental amplitude modulation (IAM)
    3.2. Incidental phase modulation (IPM)
    3.3. Synchronization offset and jitter

    Note: Incidental modulation, as defined from a measurements point of view, includes effects which arise from the presence of any time varying, additive interference which is correlated with the signal.

Definitive measurements of these quality parameters are needed for design and redesign of digital communication systems, operational monitoring of performance, impairment detection, technical control of systems (e.g., channel power allocation, impairment isolation), and for proof of performance for contractual purposes. Standards of performance for specifying quality of digital equipment and signals should be based in part upon measurements of these quality parameters.

It is important that it be possible to measure such parameters by practical procedures which are quantitative, *correct*, and *transparent*. For discussion, see section 5.

In this paper I propose the use of a *template method* for explicit measurement of digital signal power to additive noise power ratios of noisy, dispersed (e.g., band-limited) digital signals. For a concise description of the template method, see section 6.1. The measurements can be quantitative, correct, and transparent. They can be made in real time on working systems in full operation and carrying any digital traffic. I propose these concepts as an advance in the state of the art of the science of metrology [8].

In related work, Grabowski and Davis have described the use of digital patterns (templates) at baseband for a novel adaptive equalization technique [9]. Jankauskas and co-workers have developed the Adaptive Channel Equalizer which estimates signal to noise ratio and other parameters of an in-service digital communication system [10]-[12]. Milstein has discussed the importance of correct measurement procedures [13].

The concepts of transparent metrology and correct measurement procedures are presented, defined, and discussed in section 2. The existence of and relationships among various measurands for digital signal power to additive noise power ratio are presented in section 3. The template method as applied to the transparent measurement of digital signal power to additive noise power ratios is introduced and described in detail in section 4. The significance of these concepts is discussed in section 5, together with indicated applications of the template method for transparent and correct metrology of SNR. I also comment on further work to be done on these metrology concepts and methods. Section 6 summarizes the proposed template method and gives a summary review of the paper.

2. Transparent Metrology and Correct Measurement Procedures

A correct measurement procedure by definition actually measures a specified parameter (rather than a proxy for the parameter) of a specified signal, channel, device, or system (rather than of a proxy for the signal, channel, device, or system).

A transparent measurement procedure by definition measures the specified parameter without alteration of its value; without modification to or interference with the functioning of the measured signal, channel, device, or system; and without degradation of the usable channel capacity.

The availability of metrology methods which are transparent and correct would mean that one could measure the desired quantities in the specified system under full operating conditions.

Proxies for parameters, signals, channels, or devices are not required[1]. The system can be carrying any digital traffic. Such non-disruptive in-service measurements can be online and yield results in real time. All channels are fully in service; the measurements do not require any down time. Such measurement results are especially valuable because they are valid for the actual signal in the actual system under the actual operating conditions at the actual time of interest.

Generally speaking, many existing and proposed measurement and estimation methods for digital signals are transparent. Some examples include signal to noise ratio [4]-[5], [11]-[12], [16], out-of-band noise [3], [6], [14], received signal level, eye pattern [3], [6]-[7], [17], pseudo-error [3], [6], [11], [18]-[21], channel tap gains [10], [12], timing jitter [1]-[3], [6]-[7], and partial response format violation [3], [6], [21]-[22].

The concept of correct measurement procedures, defined at the beginning of this section, is useful in discussions of transparent metrology procedures [8], [13]. The terminology is adapted from computer science, which uses the concept of a *correct algorithm* [23]-[26]. For illustration, the eye pattern measurement procedure [3], [6]-[7], [17], properly implemented, is a correct procedure for measuring eye pattern. Furthermore, eye pattern measurement is a transparent metrology procedure. Although it is practical and very useful, and it is affected by many basic parameters, eye pattern does not separate SNR, ISI, and other basic parameters from each other. Eye pattern is not a correct procedure for measuring SNR, nor for ISI, nor for incidental amplitude modulation, nor for any of the other definitive basic measurands shown in table 1.

I note that while many useful measurement procedures in common use in digital communication systems are indeed transparent and practical, their object measurands often are not basic ones. They often are not correct procedures for specific definitive basic measurands of primary interest such as those of table 1.

3. Measurands for Digital Signal Power to Additive Noise Power Ratio

3.1. Varieties of Digital SNR

There are several varieties of signal to noise ratio (SNR) measurands which are relevant to digital signals [1]-[2], [4], [6], [12], [16]. Some appropriate and useful examples are described in this section.

The choice of the most appropriate varieties of SNR measurands for any particular digital signal or system depends upon how the signal is used and what aspects of the digital signal are to be characterized. For example, in some receivers the decision device samples only the center of a

[1]Proxies are often used in measurements when it is difficult or impossible to measure the desired entity directly. One common method [14] used for determination of ratio of carrier power to noise power density (C/N_0) of a specified channel is to measure directly two quantities: (a) the level in the specified channel of the carrier together with the noise and (b) some other noise level in a frequency band adjacent to the specified channel. The latter then is used as a proxy for the noise level in the channel in the algorithm for determining C/N_0 for the specified channel. In a correct measurement procedure for C/N_0 of a specified channel, the noise in the channel *per se* is what would be determined. For other methods using proxies, see [5] and [15].

chip[2]. See figure 1(a). In such a case, an appropriately defined point SNR at the center of the chip is a useful quantity to measure and specify. For an integrate and dump (I/D) decision device [1], an SNR of the integrated chip signal developed by the I/D decision device is appropriate. See figure 1(b). For general use, e.g., in charts of bit error rate (BER) versus ratio of energy per bit to noise power density (E_b/N_0), an appropriate E_b/N_0 [1], [5], [16] is one defined over the entire composite signal. Additional varieties of SNR can be defined and used as needed.

In the following discussion of possible measurands for digital signal power to additive noise power ratio, I assume the composite signal to be measured is a dispersed digital signal corrupted with additive random white noise. For simplicity, I assume that the undispersed digital signal contains sequences of chips which are binary and bipolar and that there are no other corruptions of the composite signal.

3.1.1. SNR of a Point in an Environment (POINT SNR LOCAL)

Consider the specified chip state sequence, <A B C T X Y Z >, for any specified chip states, A,B,C,T,X,Y,Z. Consider the SNR at a specified point in the target chip T. POINT SNR LOCAL is a local measurand; that is, it depends upon the target chip T and upon the chip environment, < A B C - X Y Z >, of the target chip.

$$\text{POINT SNR LOCAL} \equiv \frac{\left[\begin{array}{l}\text{square of:}\\ \quad\text{digital signal amplitude}\\ \quad\text{at specified point}\end{array}\right]}{\left[\begin{array}{l}\text{mean square fluctuations of:}\\ \quad\text{composite signal amplitude}\\ \quad\text{at specified point}\end{array}\right]}. \qquad (1)$$

The target point is any specified point in the target chip T. The target chip T has any specified chip state. The chip environment of the target chip is any specified sequence of chip states.

3.1.2. SNR of a Chip in an Environment (CHIP SNR LOCAL)

Consider the specified chip state sequence, < A B C T X Y Z >, for any specified chip states, A,B,C,T,X,Y,Z. Consider the SNR of the specified target chip T. CHIP SNR LOCAL is a local measurand, that is, it depends upon the chip environment, < A B C - X Y Z >, of the target chip T.

$$\text{CHIP SNR LOCAL} \equiv \frac{\left[\begin{array}{l}\text{square of:}\\ \quad\text{digital signal amplitude}\\ \quad\text{averaged over target chip}\end{array}\right]}{\left[\begin{array}{l}\text{mean square fluctuations of:}\\ \quad\text{composite signal amplitude}\\ \quad\text{averaged over target chip}\end{array}\right]}. \qquad (2)$$

All, or a specified portion, e.g., the middle 70 per cent, of the specified target chip T is used for defining the amplitude of the composite signal for that chip. The target chip T has any

[2] A chip [1], [27]-[28] is the smallest signaling segment, or time interval, in a digital signal. Chip is defined such that baud is a unit of measure for chip rate.

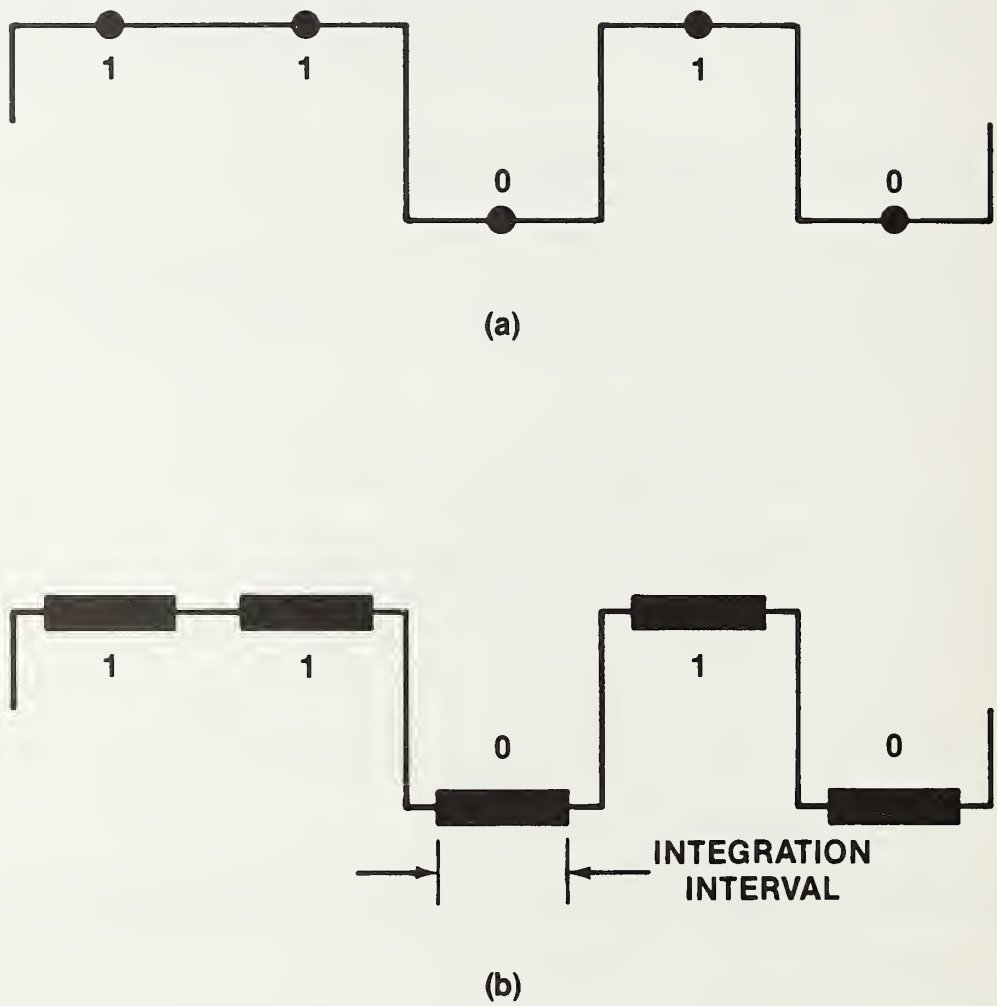

Figure 1. Two commonly used modes of sampling a chip. In curve (a) the sample is taken at a point in the center of each chip. In curve (b) the sample is an average over a significant fraction of each chip. These modes use only a portion of the entire digital signal waveform.

specified chip state. The chip environment of the target chip is any specified sequence of chip states.

3.1.3. SNR of a Chip State (CHIP STATE SNR GLOBAL)

For the composite digital signal being measured, consider the set of all chip sequences < a b c T x y z > in the digital signal, for any specified chip state T and all occurring chip states a,b,c,x,y,z. CHIP STATE SNR GLOBAL is a global measurand; that is, it does not depend upon chip environment.

For a specified target chip state, for example, "0" or "1", this measurand is the ratio of (1) the weighted average, over all possible chip environments of the target chip, of the signal power in the target chip, to (2) the weighted average, over all possible chip environments of the target chip, of the noise power in the target chip. The weighting is proportional to the probability of occurrence of each chip environment in the entire composite signal.

$$\text{CHIP STATE SNR GLOBAL} \equiv \frac{\left[\begin{array}{l}\text{weighted average of:}\\ \quad\left[\begin{array}{l}\text{square of:}\\ \quad\left(\begin{array}{l}\text{digital signal amplitude}\\ \text{averaged over target chip}\end{array}\right)\end{array}\right]\end{array}\right]}{\left[\begin{array}{l}\text{weighted average of:}\\ \quad\left[\begin{array}{l}\text{mean square fluctuations of:}\\ \quad\left(\begin{array}{l}\text{composite signal amplitude}\\ \text{averaged over target chip}\end{array}\right)\end{array}\right]\end{array}\right]} . \qquad (3)$$

All, or a specified portion, e.g., the middle 70 per cent, of the specified target chip T is used for defining the average amplitude of the digital signal and of the additive noise. The target chip T has a specified chip state, for example, "0" or "1".

3.1.4. SNR of a Symbol State (SYMBOL STATE SNR GLOBAL)

SYMBOL STATE SNR GLOBAL is a global measurand for a specified target symbol state. It is similar to CHIP STATE SNR GLOBAL, except it is defined for a symbol rather than for a chip. A symbol is a specified sequence of one or more chips.

3.1.5. SNR of a Word (WORD SNR GLOBAL)

WORD SNR GLOBAL is a global measurand for a specified target word. It is similar to SYMBOL STATE SNR GLOBAL and to CHIP STATE SNR GLOBAL, except it is defined for a word rather than for a symbol or a chip. A word is a specified sequence of one or more symbols.

3.1.6. SNR of the Entire Composite Signal (SIGNAL SNR)

SIGNAL SNR is a global measurand. It is similar to CHIP STATE SNR GLOBAL, except the weighted averaging also is carried out over all target chip states. SIGNAL SNR corresponds closely to the usual concept of SNR of an analog signal in an analog channel.

3.2. SNR and Its Generic Relatives

3.2.1. SNR

As usually defined, SNR refers to the *ratio of signal power of the entire channel and entire signal waveform to additive noise power coincident with the entire channel and entire signal waveform.* The previous subsection discussed several related varieties of digital SNR measurands. The differences have to do with including specified portions of the channel and digital signal waveform while excluding other portions.

$$\mathrm{SNR} \equiv \mathrm{CNR} \equiv \frac{\text{[total signal power in channel]}}{\text{[coincident additive noise power in channel]}}. \qquad (4)$$

SNR also usefully can be defined to be a point function of Fourier frequency, such that it is the ratio of spectral density of signal power to spectral density of additive noise power. CNR is an abbreviation for carrier power to noise power ratio.

In addition to SNR *per se*, there are closely related types of measurands which generically also are ratios of signal power to additive noise power.

3.2.2. C/N_0 and C/kT

One such related type is called *ratio of carrier power to noise power density* [1], [5], [14]. It often is denoted by C/N_0, or equivalently by C/kT, where by definition T (temperature) is such that kT is equal to N_0, where k is Boltzmann's constant. Conceptually, N_0 is the additive noise power per unit bandwidth (e.g., one hertz). Often, N_0 is used as the total additive noise power in the channel normalized by the bandwidth of the channel. The carrier power, C, is the signal power in the entire channel.

$$C/N_0 \equiv C/kT, \qquad (5)$$

$$C/N_0 \equiv \frac{\text{[signal power in channel]}}{\left[\begin{array}{c}\text{additive noise power}\\ \text{in channel}\end{array}\right] \Big/ \left[\text{channel bandwidth}\right]}, \qquad (6)$$

$$C/N_0 \equiv \text{[channel bandwidth]} \times \text{[SNR]}. \qquad (7)$$

Sometimes N_0 is used in its purer sense as a point function of frequency, i.e., as spectral density of additive noise power.

3.2.3. E_b/N_0 and E_{chip}/N_0

Another type of basic digital signal measurand which is a ratio of signal power to additive noise power is called *ratio of energy per bit to noise power density,* usually denoted by E_b/N_0 [1], [3], [16]. The energy per bit is the digital signal power in the channel normalized by the bit rate. For the exactly analogous *ratio of energy per chip to noise power density* (E_{chip}/N_0), the energy per chip is the digital signal power in the channel normalized by the chip rate.

$$E_b/N_0 \equiv \frac{[\text{digital signal energy in channel per bit}]}{[\text{additive noise power in channel per unit bandwidth}]}, \tag{8}$$

$$E_b/N_0 = \frac{[\text{channel bandwidth}] \times [\text{SNR}]}{[\text{bit rate}]}, \tag{9}$$

$$E_b/N_0 = \frac{[C/N_0]}{[\text{bit rate}]}. \tag{10}$$

I have discussed three closely related types of measurands, SNR, C/N_0, and E_b/N_0. Bandwidth, bit rate, chip rate, symbol rate, and word rate are auxiliary parameters of a digital system which usually are well determined, or can be. Insofar as these auxiliary parameters are well determined, in many situations a measurement of one variety of a measurand belonging to any one of the above three types is adequate to determine the corresponding measurands belonging to each of the other two types.

4. The Template Method for SNR

4.1. Statement of the Problem

The template method is presented as a solution to a problem. The problem is to measure, transparently and correctly, for composite digital signals, the ratio of the power of the dispersed digital signal to the power of the additive noise. This is to be accomplished, to better than some specified precision and accuracy (see Appendix A), in the presence of the intersymbol interference (ISI) [1], [17], [27] engendered by the dispersion of the digital signal.

In practice, there are many ways to implement the template method for transparently measuring SNR and other quantities. I present the basic concept here. The essential function of the template is to fix the ISI in the *target chips* of a large set of realizations corresponding to that template and to provide a means of distinguishing additive noise from the dispersed digital signal.

The template method may be used under a wide variety of conditions. In the following example, the assumed constraints are not necessary; they are used only for simplicity and clarity of presentation.

As a specific example, I assume the composite signal to be measured is a dispersed digital signal corrupted with additive random white gaussian noise. I assume the undispersed digital signal is a continuous sequence of chips which are binary and bipolar. The chip state sequence, the relative amount of additive noise, and the amounts and spectral shapes of the amplitude response dispersion and group delay dispersion are unknown *a priori*.

I further assume there are no other corruptions of the composite signal, for example, multiplicative noises (incidental amplitude modulation, IAM, and incidental phase modulation, IPM) and imperfect synchronization. I assume the statistical parameters of interest of the composite signal are stable over the measurement interval.

4.2. Measurements Using a Template

The test set uses a digital template, a specified pattern of N chips. In the following example, I arbitrarily consider a single template of five chips with the pattern "1-1-0-1-0". See figure 2(d). The test set transparently and continually looks for realizations of that particular digital pattern to come along in the native digital traffic of the composite signal. I assume the test set has available to it the following three specific signals[3], shown in figure 2(a-c):

a) Baseband analog signal before input to decision device, representing the composite signal,

b) Digital output of decision device, representing the digital aspect of the composite signal, and

c) Digital clock signal, representing the clock rate of the composite signal.

A measuring device, e.g., an analog to digital converter, in the test set is repetitively measuring the baseband analog signal. For the current example, the measuring device is triggered by the digital clock signal, figure 2(c), to perform three uniformly spaced measurements on every chip as it occurs in the baseband analog signal, figure 2(a). These measurements provide the raw data for the template method. Concurrently, a sequence comparator is comparing the digital pattern of the five-chip template, figure 2(d), to the most recent five digital chip values of the output of the decision device, figure 2(b).

Each raw datum from the measurements of the baseband analog signal is put immediately into a buffer, which, for the example of a template with five chips and three data points per chip, need be only fifteen elements long. This raw data buffer is used as a queue to temporarily and sequentially hold the raw measurements. As each new raw datum is pushed into the front end of the queue, the oldest raw datum is discarded from the other end.

[3]The front end of the test set itself can generate the three specific signals from the composite signal sampled at any desired place of measurement, e.g., at carrier band. It must generate the signals precisely and accurately.

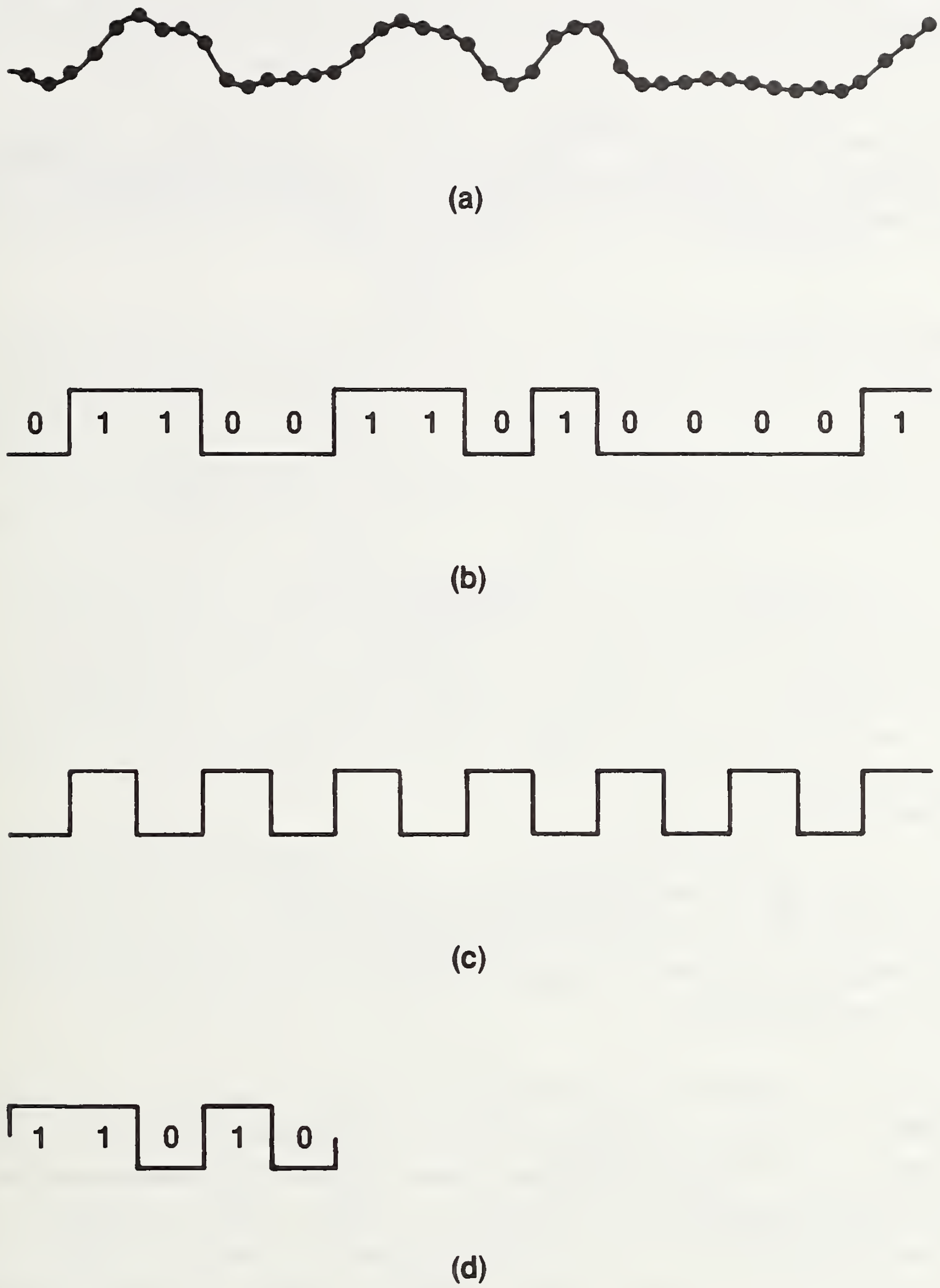

Figure 2. The test set uses three specific signals derived from the composite digital signal under test: (a) noisy dispersed baseband analog signal before input to decision device, representing the composite signal, (b) digital output of decision device, and (c) digital clock signal. Curve (d) shows a digital template with the pattern "1-1-0-1-0". Raw data samples for the example of three points per chip are shown on curve (a).

At any particular moment, the raw data buffer contains the most recent fifteen data points; they represent the baseband analog signal for the most recent five chips. When the sequence comparator decides that the most recent five chips are a realization of the chosen digital template, the contents of the raw data buffer are frozen, and those fifteen data points then are transferred into the first row of an initially empty array in long term memory.

The test set continues looking for another realization. When another realization occurs, its ordered set of fifteen data points (which are different in value from the earlier set of fifteen) is transferred from the raw data buffer into the second row of the array of realizations in memory.

The embedded digital pattern (in effect, a sporadically recurring known digital sequence) is the same for both the first and second realizations. The embedded dispersed digital signal, i.e., the digital signal with its ISI, has the pattern of the template, "1-1-0-1-0" in the example. The additive noise contribution is different for each realization, figure 3(a-d). The ISI in the outermost chips is somewhat different for each realization, figure 3(a-d).

The test set continues to find realizations until there is a statistically useful number of realizations, e.g., one thousand, stored in the array of realizations (see Appendix A). The array has fifteen columns and one thousand rows. For a stream of random chip states, there are about one thousand realizations of a specified five-chip template in a thirty-two thousand chip interval. For a one-megachip per second signal, this occurs within about 32 milliseconds.

4.3. Data Analysis for SNR

The central chip, a "0" in the example, is used as a *target chip*; the two leading chips and the two trailing chips are used as *guard chips*, as in figure 4(b). In general, there can be any number of *target chips* and any number of leading and trailing *guard chips*, depending on the size of the template. See figure 4(a-c).

There is ISI in the target chips engendered by the neighboring chips. To the extent that any ISI from chips which are three or more chips away may be neglected, the ISI in the target chips is an invariant. That is, over those one thousand target chips in the array of realizations, there is negligible variance engendered by ISI, because the adjacent symbol environment for the target chips is the same for each of the realizations. If the ISI from more distant chips were not negligible, then one would use a longer digital template in order to have more guard chips around the target chip(s).

For the target chip points, the average of the measured realizations represents the dispersed digital signal which is embedded in the composite signal, while the variations from each other of the different realizations represent the additive random noise (figure 5). For averages of one thousand realizations with noise, the random noise of the averages is about 30 decibels lower than the random noise of the numbers being averaged.

REALIZATIONS

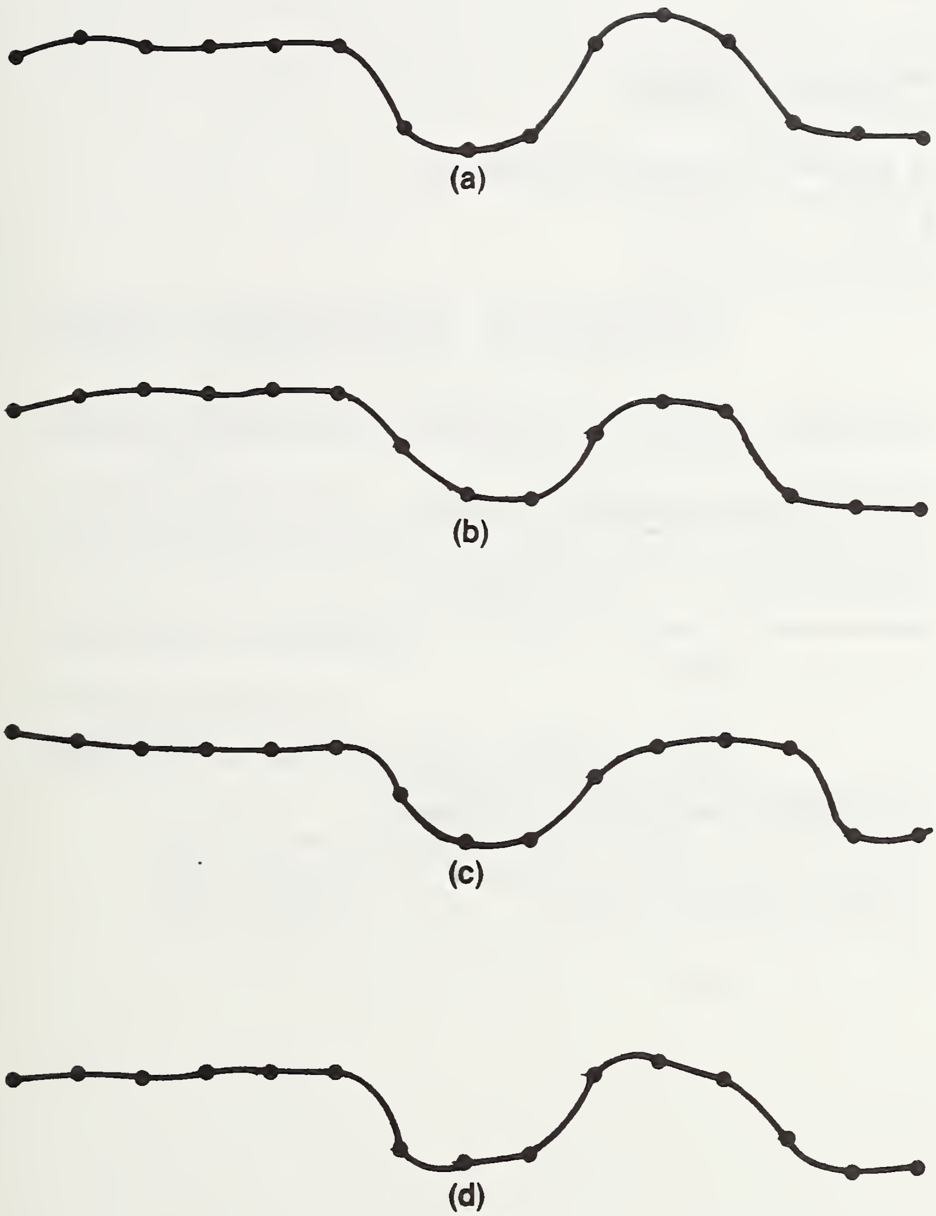

Figure 3. Four different realizations of the five-chip digital template "1-1-0-1-0". They are stored as ordered sets of fifteen points in an array of realizations. Each curve is the amplitude of a composite noisy dispersed baseband analog signal before input to the decision device.

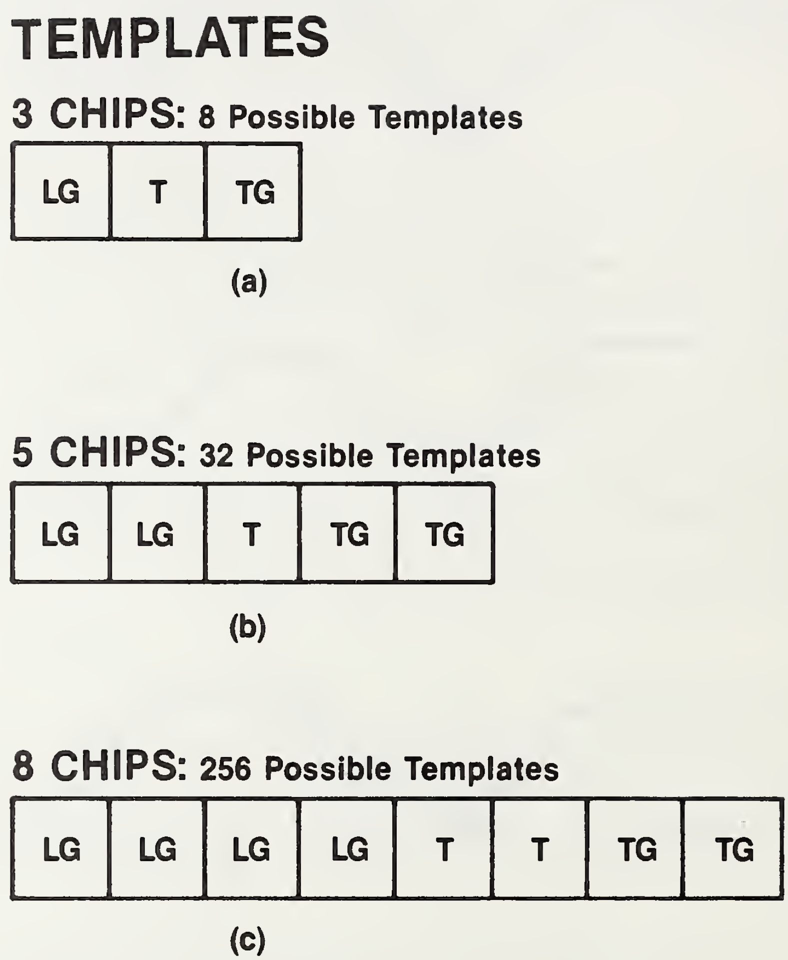

Figure 4. Some practical template structures. LG is leading guard chip. T is target chip. TG is trailing guard chip. Template (b) corresponds to the choice of target versus guard chips in the example discussed in the text.

FOR TARGET CHIPS

EMBEDDED DISPERSED DIGITAL SIGNAL

**Corresponds to
Average Realization**

ADDITIVE NOISE

**Corresponds to
Variation about Average Realization**

Figure 5. The embedded dispersed digital signal, additive noise, and SNR can be obtained for the target chips of a template. The embedded digital signal with its ISI is the same for each realization. The additive noise varies from realization to realization. SNR is the ratio of the square of the average of the realizations to their variance.

The square of the average realization for the target chip points represents the power (subject to a normalizing scalar which need not be determined) of the dispersed digital signal at those points, while the variance of each realization from the average realization represents the power of the additive noise at those points.

Hence, the ratio of the dispersed digital signal power to additive noise power at each point is the ratio of the squared average to the variance at that point (figure 5). This is the POINT SNR LOCAL described in section 3.1.1. In general, the POINT SNR LOCAL is different at each point in the template, and is template dependent as well.

The SNR of the entire composite digital signal (SIGNAL SNR) can be obtained by averaging the target chip SNR values (CHIP SNR LOCAL) for all possible digital templates of the chosen length, with appropriate weighting given to each template based upon its relative probability of occurrence in the entire composite signal. See section 3.1.

Consider an integrate and dump (I/D) type of digital detection [1]. The I/D receiver's decision device samples each chip. It averages the composite baseband analog signal over all or nearly all of the chip, as shown in figure 1(b). Instead of obtaining three raw data points for each chip, the template method measuring device can digitize the I/D chip sample, or an equivalent sample, to yield one raw datum. The SNR's obtained from such raw data are SNR's of the I/D samples; for many applications these are appropriate SNR's to specify and measure for an I/D system. This corresponds to the CHIP SNR's described in sections 3.1.2. and 3.1.3.

4.4. Comments on the Measurements

The measured values are valid at the place of measurement in the system under test. They are not necessarily good estimates for a different place in the system.

Depending upon the nature of the digital channel, the additive noise power may tend to be the same for all points in the template. The dispersed digital signal power depends upon the point where it is sampled inside the digital template, and it may depend slightly upon the choice of structure of the template.

There are advantages in using a set of several, or all, templates of length N, rather than using only a single template. More information can be obtained per unit of measurement time; the signal can be sampled in a more representative manner; and additional statistical information on the validity of the results can be obtained. Note that any and every sequence of five chips is a realization of one member of the set of thirty-two possible five-chip templates. If only one of the set of possible templates of length N is to be used, I expect that most choices will work well, and that a few template structures, e.g., all "1"'s or all "0"'s, will be relatively ineffective.

The effect of statistical sampling scatter on the precision of determination of SNR is discussed in Appendix A.

5. Remarks

5.1. Significance

Practical, economic, and administrative advantages accrue when digital communication systems can be measured transparently. The transparent measurement procedures can measure meaningful quantities of interest on a communication system at the appropriate time under the actual operating conditions with the system totally in service. Users of the communication system are in no way inconvenienced by transparent measurements. System revenues and system availability are not impaired. Instead, they are enhanced by the system improvements which occur with the better knowledge of the technical status of the operating communication system made possible by transparent metrology.

The ability to perform transparent measurements of basic performance parameters, using correct procedures, on digital traffic directly, without taking the system offline, and without using proxies, is expected to lead to more meaningful measurement data and ultimately to reductions in the cost of obtaining information on the true performance of systems.

The template method is expected to be a powerful method for correct and transparent measurements of definitive fundamental parameters of digital signals, channels, devices, and systems. The template method has no adverse impact on the capacity of the channel being measured. All of the channel capacity can be used for other system functions, e.g., traffic and protocols.

The template method can be applied without exception to any and all types of digital data. Any kind of source coding, channel coding, and channel design can be accommodated. From the standpoint of metrology, there is no need for redundancy. The digital symbol stream can represent completely encrypted information; code groups; plain text; framing, stuffing, and idling symbols; or any combination of any type. This is an important aspect of the transparency feature of the template method.

5.2. Applications

Transparent metrology methods, e.g., the proposed template method, can measure directly and correctly most of the definitive basic measurands, including digital signal power to additive noise power ratios (SNR, C/N_0, E_b/N_0), intersymbol interference, multiplicative noises (random noise modulation of amplitude and of phase), and synchronization parameters (jitter and offset). Transparent metrology methods will support efforts to establish definitive performance standards which are technically relevant and valid, highly useful, unquestionably objective, and potentially widely acceptable. Such performance standards are needed to specify quality and acceptability of equipment, systems, and service.

These new methods of correct and transparent measurement of basic performance parameters are relevant to the technical quality of operational systems. They will influence hardware design, system validation, technical performance objectives, performance standards, system monitoring, and technical control. They may lead to more powerful language and terminology for the specification of system design and operation.

Correct and transparent procedures give increased confidence that the measurements being made are indeed appropriate and adequate. They permit less overdesign (e.g., less fixed margin in the design) of digital communication systems, because the measurements are more informative and allow more intelligent control of operating conditions.

The transparency of the template method allows it to be used by a system manager to measure or monitor SNR on customers' leased channels with no knowledge, either *a priori* or *a posteriori*, of the information content of the traffic. There is no need to violate in any way the confidentiality and security of customers' traffic.

The template method can be the basis for test sets for transparent measurements. In the future, if it proves to be sufficiently useful, the template method can be built into communication equipment as part of its original design. Generally speaking, the template method can be applied to any digital system. The details of optimum implementations for each system are expected to be strongly system dependent.

5.3. Comments

I note that bit error rate (BER), *per se*, can not be measured transparently. However, via transparent measurement of SNR, ISI, multiplicative noises, and synchronization parameters, together with knowledge of a reasonable model of the system, one expects to be able transparently and accurately to estimate BER and other related overall performance parameters of in-service digital systems.

The template method concept is similar to techniques used in some automatic adaptive equalizers for digital channels [1]-[2], [9], [27]. In this paper, I am concerned with improved fundamental methods of measurement. Prior art from adaptive equalization will assist greatly the development of the template method for transparent metrology [4], [9]-[12], [16].

5.4. Further Work

The proposed template method is expected to be especially important for digital communication systems, especially for those systems with stringent design constraints on transmitted signal power and system bandwidth, i.e., for systems with critical amounts of additive noise and intersymbol interference. The template method for SNR measurement should be studied, developed, and evaluated, and then further tested and proven by being applied to synthesized channels and to actual traffic on actual channels.

In the development of the template method one should look at various factors involving template design: which templates, how many different templates, length of template, numbers of target chips and guard chips, and points per chip. In the design of analysis algorithms, the factors to be studied include choice of SNR measurands (point, chip, symbol, word, or signal;

local or global), Fourier transform methods versus non-Fourier transform methods, and measurement speed. Accuracy and precision must be studied as functions of the number of realizations, leading and trailing guard chips, and target chips. The effects of ISI from distant chips, incidental AM and PM, and synchronization jitter and offset can be controlled; they must be studied.

Development of the template method should be extended to the transparent metrology of other basic measurands. The raw data (analog values stored in the array of realizations) that are used for SNR analysis also can be used for analyses of ISI, multiplicative noises, and synchronization parameters. Transparent measurements of these additional measurands by the template method need not require any hardware beyond what is used in measurement of SNR. Data processing for these additional measurands will be much more complicated than for SNR and will require much more time for computation.

The extension of the template method from the measurement of SNR to the other measurements represents a sophisticated software challenge, with critical trade-offs anticipated among speed, precision, accuracy, and memory requirements. Optimum algorithm design and efficient code will be important factors in the extension to the additional measurands. The extension to these additional measurands will be the topic of another paper.

6. Summary

6.1. Template Method for SNR

In the template method, measurements of raw data are performed continually on an analog baseband value of the composite noisy, dispersed digital signal under test. Concurrently, the digital signal's chip stream is monitored for occurrences of a digital pattern corresponding to a designated and arbitrary N-chip-long digital template.

The template has leading and trailing guard chip(s), with target chip(s) located between them. The function of the template is both to fix the intersymbol interference in the target chips by using a sufficiently large number of guard chips and to distinguish the digital signal from additive noise. The length of the template is arbitrary and can be chosen to be short, e.g., five chips. The test instrumentation determines *a posteriori* when the pattern of the template has occurred in the signal under test.

Each time the designated N-chip pattern is found, the analog values for these N most recent chips are saved and put aside for analysis; the earlier intervening analog data points need not be retained. That is, an array of sets of analog data points is created in memory; each set corresponds to a realization (occurrence) of the template's pattern. The target chips portion of the array of sets of analog values then is analyzed for a) its average dispersed digital signal component and b) its noise variation about the average signal. Additional computation using a correct algorithm yields the desired SNR measurands.

In a complete measurement protocol, a variety of templates is used, possibly concurrently, to improve the accuracy of the measurement and to obtain confidence measures for the results. For some applications, it is possible to use every template of length N; as an example, for binary signals and N of four chips, there are only sixteen distinct templates to process.

The measurement of SNR by the template method is quantitative, correct, and transparent. A correct measurement procedure actually measures the specified parameter of the specified signal, channel, device, or system. A transparent measurement procedure measures the specified parameter without degradation of the usable channel capacity and without modification to or interference with the functioning of the measured signal, channel, device, or system.

6.2. Review

I presented the concept of the template method for transparent measurement of digital signal power to additive noise power ratios (e.g., SNR, C/N_0, E_b/N_0). The template method needs to be developed; it has widespread applicability to important useful measurements in digital communication systems.

I discussed the existence of various useful measurands for digital SNR, the concept of transparent metrology for digital systems, and the concept of correct measurement procedures. I pointed out that the template method is generally applicable to transparent measurements of several important measurands other than SNR (i.e., intersymbol interference, incidental amplitude and phase modulations, and synchronization jitter and offset) on any noisy, dispersed digital signal.

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Appendix A: Confidence of Measured SNR

I expect the template method to provide measurement precision and accuracy for SNR which is adequate for many if not all practical applications. A complete error budget for SNR measurement accuracy capability would contain several factors. A detailed analysis of all of these factors is dependent upon the specific system implementation and is beyond the scope of this concepts paper.

For many practical situations, the accuracy capability is expected to be limited by sampling scatter. Insofar as sampling scatter is dominant, precision and accuracy can be improved by increasing the number of realizations used in the determination. Another factor is the number of target chips in the template, which, for measurement efficiency, should be only one or two. For POINT SNR LOCAL, in the example with one target chip, for M realizations, the sampling scatter gives rise to a fractional precision [29]

$$\frac{\begin{bmatrix}\text{standard deviation}\\ \text{of POINT SNR LOCAL}\end{bmatrix}}{[\text{measured POINT SNR LOCAL}]} = \sqrt{2/M}\ . \qquad \text{(A1)}$$

For M equal to one thousand realizations, sampling scatter limits the fractional accuracy capability to be not better than ± 4.5 per cent (one sigma). For M of only fifty, sampling scatter amounts to ± 20 per cent (one sigma), which is sufficiently small for many useful system applications.

Appendix B: Glossary

ARD	amplitude response dispersion
BER	bit error rate
C	carrier power (same as signal power)
C/kT	ratio of carrier power to noise power density
C/N_0	ratio of carrier power to noise power density
chip	smallest signaling element, or time interval, in a digital signal
CNR	carrier power to noise power ratio
correct	see definition in section 2
E_b/N_0	ratio of energy per bit to noise power density
E_{chip}/N_0	ratio of energy per chip to noise power density
GDD	group delay dispersion
global measurand	value is averaged over all local environments
guard chips	leading and trailing chips in a template
I/D	integrate and dump
IAM	incidental amplitude modulation
IPM	incidental phase modulation
ISI	intersymbol interference
k	Boltzmann's constant
local measurand	value is averaged only over specified environments
M	number of realizations in a measurement set
N	number of chips in a template
N_0	noise power per unit bandwidth
proxy	surrogate or substitute used in place of a specified parameter or signal
realization	an occurrence of the pattern of the template
SNR	signal power to additive noise power ratio
T	equivalent noise temperature
target chip(s)	central chip(s) in a template
template	a finite length, specified search pattern of chips
transparent	see definition in section 2

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I propose the use of a template method for quantitative, correct, and transparent measurement of signal power to additive noise power ratios (SNR) of digital signals and systems under full operating conditions. Outer guard chips of digital templates hold intersymbol interference fixed on inner target chips in realizations of the respective template patterns in traffic. The proposed template method needs to be developed and proven as a potentially valuable metrology capability; it can be especially important for real time online performance assessment and monitoring of digital communication systems.

A correct measurement procedure by definition actually measures a specified parameter of a specified signal, channel, device, or system. A transparent measurement procedure by definition measures the specified parameter without degradation of the usable channel capacity and without modification to or interference with the functioning of the measured system.

I discuss the significance of transparent metrology, the measurement of various SNR's by the template method, and the general applicability of the template method for measurements on any noisy digital signal. The template method can provide transparent metrology procedures for other basic measurands, e.g., intersymbol interference, multiplicative noises, and synchronization.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

communications; correct measurement procedure; digital signals; energy per bit to noise density; monitoring; noise; online measurements; performance assessment; real time; signal to noise ratio measurement; template method; transparent metrology.

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