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Keywords: IEEE 802.11, IEEE 802.11k, radio resource measurements, confidence intervals

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I. Introduction

THE IEEE 802.11 Task Group "k" currently develops an extension to the popular IEEE 802.11™ wireless *Local Area Networks (LAN)* standard [1], referred to as 802.11k [2]. This extension is a specification of new radio resource measurements, i.e., information that needs to be measured to optimize the radio network. For example, with 802.11k, stations will be able to assess how occupied or idle a frequency channel is (by using the 802.11k channel load measurement). The corresponding request and report mechanisms, and the formats of the frames through which the measurement requests and results are communicated among stations, are defined by 802.11k.

In this paper, we discuss the usefulness of such radio resource measurements in general. A measurement result alone may not be sufficient for quality radio resource management: what may be needed in addition is an indicator for the quality of this measurement, to assess what is referred to as confidence in measurement results. A method to estimate the confidence of such measurement results is presented in the following. We propose to apply confidence intervals to 802.11k radio resource measurements, as they are applied to stochastic simulation, where estimating the confidence of simulation results is necessary to obtain meaningful data. A measuring station may not just report a single measurement result, but also the confidence interval that is obtained during the measurement. Our proposed method may allow optimizing measurement durations, and the repetition rate, i.e., the number of required measurements. If different stations would measure the same unknown parameter, then the confidence intervals associated to the different measurement results would help to evaluate those different results. Our method may also enable a radio system to estimate how long after the end of a measurement the results would represent the true reality.

In the following section, we give a brief summary of the 802.11k draft standard. In Section III, the concept of confidence intervals is described, followed by a recapture of the Gilbert model in Section IV. This model will be used to model correlated medium access in the numerical analysis of Section V. Conclusions from our analysis are given in Section VI.

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II. IEEE 802.11k Draft Standard for Radio Resource Measurements

The 802.11k draft standard for radio resource measurements is summarized in this section. More details on the 802.11k standard extension can be found in [2].

The objective of 802.11k is to provide measurements and frame formats by which a radio station can initiate, measure, and assess the radio environment. Note that 802.11k is referring to radio resource *measurements*, and not radio resource *managements*. Therefore, actions that make use of the new information are not defined, only the part of the entire management process is defined by 802.11k that involves the measurement, including requesting and reporting. To fulfill its goal, the current 802.11k draft defines different types of measurements, of which some are briefly described in the following. The following list is not complete, and standardization is still ongoing at the time this paper is written.

802.11k enables a radio network to collect information about other access points (via *beacon report*), and about the link quality to neighbor stations (via *frame report*, *hidden node report* and *station statistic report*). 802.11k also provides methods to measure interference levels (via *noise histogram report*) and medium load statistics (via *channel load report* and *medium sensing time histogram report*).

With the *beacon report*, a measuring station reports the beacons or probe responses it receives during the measurement duration. With the *frame report*, a measuring station reports information about all the frames it receives from other stations during the measurement duration. With the *channel load report*, a measuring station reports the fractional duration over which the carrier sensing process, i.e., *Clear Channel Assessment (CCA)*, indicates that the medium is busy during the measurement duration. This very simple measurement is used as example in the following sections, to discuss the confidence of measurements. In the *noise histogram report*, a measuring station reports non-802.11 energy by sampling the medium only when CCA indicates that no 802.11 signal is present. With the *hidden node report*, a measuring station reports the existence, and frame statistics of hidden nodes detected during the measurement duration. In *station statistic report*, a measuring station reports its statistics related to link quality and network performance during the measurement duration. One interesting measurement is the *medium sensing time histogram report*, which was developed in [3], and discussed in detail in [4], [5]. A measuring station reports the histogram of medium busy and idle time observed during the measurement duration. The states busy and idle are typically defined through the CCA process, but may vary depending on what the requesting station attempts to gain from the measurement. Similar to the noise histogram, non-802.11 energy can be measured, which makes the medium sensing time histogram a powerful measurement for applications like cognitive or agile radio, where 802.11 stations would have to measure the interference patterns from other, non-802.11 radio networks [6].

The optimal measurement durations, the confidence of results, and the relevance of the results for the time following a measurement are important for assessing how meaningful the measurement is. For example, not always improves increasing measurement durations the accuracy of the results. Further, sampling more often with shorter intervals between the samples may not necessarily increase the amount of information.

The 802.11k draft standard does not specify default measurement durations. A station that requests a measurement can however specify its duration. Of course, if a measurement is performed without a previous request, the measuring station itself determines the duration. Similar to the decision about the actual time when the measurement request is issued, and eventually similar to the decision about the interval after which requests may be repeated, it is a local decision of the requesting station to determine how long to measure, and whether or not to repeat it after a certain time.

The local time-correlation of the medium usage (for example the pattern of busy and idle times) is important information to optimize such parameters, as discussed in [5]. It generally depends on the scenario and types of radio system that operate in the medium, as well as on the offered traffic (e.g., packet sizes, arrival rates), what the optimal measurement parameters are, and how long reported results are valid and relevant for future events.

In the following, we provide a method that is established in stochastic simulation, to calculate what is referred to as confidence interval – a range of values that can be reported to a requesting station, together with the actual measurement result. This would indicate the precision and usefulness of the obtained measurement result.

III. Confidence Intervals

A standard method to gain confidence in measurement results is based on a *confidence interval*. The reader is referred to the excellent introductions in [7]-[10] for a detailed discussion of confidence intervals. A confidence interval that is associated to a measurement result represents a range of plausible values which is likely to include the unknown *population* parameter. This population parameter is the parameter to be measured – a measurement result for this parameter is reported after the measurement was performed. The term "population" is used in stochastic mathematics, and refers to the entire set of samples – of which some are collected during the measurement duration.

The estimated range of values, i.e., the confidence interval, is calculated only from the measured data, without any further knowledge about the reality, other than what was measured. This fact is relevant for the understanding of our method: the parameter to be measured is unknown, and will remain unknown during and after the measurement. However, given some a priori assumptions about this parameter's stochastic distribution, the confidence interval will provide certainty ("confidence") in the results.

During the measurement, *independent samples* – samples that are taken for example at sufficiently different times – are taken repeatedly from the same population, and a confidence interval is then calculated for each sample. A so-called *confidence level*, usually expressed as a percentage, determines the range of the confidence interval. Confidence intervals are often calculated for a 95% confidence level, but other levels such as *90*% or *99*% are possible. The confidence level is a probability value $1-\alpha$, with α as level of remaining uncertainty. For example, say $\alpha = 0.05 = 5\%$, then the confidence level is given as $1-0.05 = 0.95 = 95\%$, that is, a 95% confidence level. The size of the resulting confidence interval indicates the uncertainty about the unknown parameter. A wider interval may indicate that more data should be collected before a measurement result precisely represents the true reality. An interval calculated at a 95% confidence level means that the system can be *95*% confident that the resulting confidence interval actually contains the true (but unknown) population parameter. It can also be stated that *95*% of all confidence intervals formed the same way from different samples of the population will include the true population parameter. The wider the confidence interval, the more confident the system can be that the interval contains the unknown parameter. Therefore, for example a 99% confidence interval is always wider than a 95% confidence interval.

The notion of a confidence interval is helpful only if the underlying statistics are unbiased, which is usually the case in radio resource measurements.

A. Calculation of Confidence Intervals for Radio Resource Measurements

The channel load measurement is used as example in the following. A channel may be busy or idle, which is determined by the 802.11 carrier sensing, CCA. Interferences from other radio systems, and noise in general determine the stochastic process that creates the busy/idle pattern over the time. The 802.11k channel load measurement provides a value that hypothetically represents the fraction of time the channel was busy during the measurement. If a channel was busy all the time during a measurement, the result is *1*, if CCA indicates that the channel is busy only for some time during the measurement, the result will be a value between *0* and *1*.

It should be clear that in the real life measurement frames that are exchanged between 802.11 stations, such values are coded by some bits in a specific format. The 802.11k defines this format for all measurement frames. In our paper however, we ignore the real life frame formats, and continue to use real numbers.

During a measurement, a station obtains a number of N samples for the channel load. Typically, the mean of the samples, M, is used as the final measurement result and reported back to the requesting station. This sample mean *M* represents the entire population of the stochastic process that determines the busy/idle pattern: it is interpreted to represent the channel load for the time during, and after the measurement. This may not be the case, and thus the interpretation may be invalid. A confidence interval however would allow assessing if the interpretation of the measurement result was valid.

To calculate the confidence interval for the channel load measurement, the mean μ and the standard deviation σ_M of the entire population need to be estimated. In the unrealistic case that the standard deviation would be known a priori, the confidence interval is given by [7]

$$M - z \cdot \sigma_M \le \mu \le M + z \cdot \sigma_M .$$

Here, *M* denotes the sample mean and σ_M the true standard deviation. The parameter *z* is derived from the standard normal ("z") distribution. When σ_M is unknown, $s_M = s/\sqrt{N}$ is used as estimate of σ_M, where N is the sample size, and *s* sample variance. Whenever the standard deviation is estimated, the *student's t distribution* instead of the standard normal distribution is used. The values of t are larger than the values of z, which implies that confidence intervals are wider when σ_M is estimated compared to the width of confidence intervals when σ_M is known. Hence, the confidence interval for μ, when σ_M is estimated, is given by [7]

$$M - t \cdot s_M \le \mu \le M + t \cdot s_M ,$$

where M is the sample mean, and s_M is the estimate of σ_M, as defined above. The parameter t depends on the degrees of freedom and the level of confidence. The number of independent information that is used to estimate a parameter is referred to as degree of freedom. The degree of freedom for t is equivalent to the degree of freedom for the estimate of σ_M, which equals $N-1$. The value of t can be determined from a student's t distribution table such as indicated in Table 1, by using the degree of freedom $N-1$.

The following numerical example will help understanding how confidence intervals are calculated for the channel load measurement.

B. *Numerical Example for the Computation of a Confidence Interval for the Channel Load Measurement*

As an example, we assume that a measurement has to report one channel load result, which provides a mean of all busy fraction samples calculated during measurement. Let the channel load samples be

$$X = \begin{bmatrix} 0.52 & 0.21 & 0.03 & 0.95 & 0.99 & 0.51 & 0.82 \end{bmatrix},$$

therefore, $N = 7$. During the measurement duration, a station has collected the channel load samples for seven consecutive intervals, which all contribute to the final measurement result. The sample mean *M* is computed as

$$M = \sum X / N = 0.5757 .$$

This value is typically reported by today's radio stations after a channel load measurement, without taking into account the actual confidence of the results. Whereas the measurement duration (or, the number of samples) may heuristically indicate the usefulness of the reported data, it would be helpful to report an additional indicator for the confidence. For example, multiple different stations may report different channel load values. In this case, it would be helpful for a requesting station that collected all the reports from the different stations to obtain confidence intervals for a predefined confidence level, in order to asses which measurement may be most relevant. To create this confidence interval, the sample variance s is calculated in our example as

Table 1: Student's t distribution [10]

$1-\alpha$ *conf. level.*	*0.1* *90%*	*0.05* *95%*	*0.025* *97.5%*	*0.01* *99%*
⋮	⋮	⋮	⋮	⋮
df=6	*1.4398*	*1.9432*	*2.4469*	*3.1427*
⋮	⋮	⋮	⋮	⋮

$$s^2 = \frac{\sum (X - M)^2}{N-1} = 0.1351 \Rightarrow s = 0.3675 .$$

We compute $s_M = s/\sqrt{N}$ as

$$s_M = \frac{0.3675}{\sqrt{7}} = 0.15 ,$$

and find the degree of freedom $df = N - 1 = 6$. Now, we can find t for this degree of freedom using a student's t distribution such as shown in Table 1. For example, for a confidence level of *90%*, $t = 1.4398$. Now, it remains to calculate the lower limit M_l of the confidence interval,

$$M_l = M - t \cdot s_M \approx 0.36 ,$$

and also the upper limit M_u of the confidence interval,

$$M_u = M + t \cdot s_M \approx 0.79 .$$

The *90%* confidence interval is hence given by the interval $0.36 \le M \le 0.79$. In our example, it can be stated as a result that the radio system can be *90%* confident that the interval $[0.36, 0.79]$ contains the true population mean, i.e., the true channel load value. It could also be stated that *90%* of all confidence intervals formed in this way, will include the true population mean. Note that it cannot be stated that the true population mean lies in the interval $[0.36, 0.79]$ with the probability of *0.975*.

The calculation of the interval is only meaningful if samples are independent and statistics are unbiased. This is discussed in more detail in Section V.

IV. Discrete Gilbert Model to Simulate a Correlated Spectrum Access Pattern

The discrete Gilbert model is used in our analysis to simulate a correlated spectrum access pattern *s(t)* of busy/idle intervals. Figure 1 illustrates the model. The model precision is given in slot duration t_{slot}. The expected duration for the system *s(t)* in state *busy* is $E[t_b]$, with t_b being the duration the system stays in state *busy*, with n_b being the number of slots in which the system is in the state *busy* and $t_b = t_{slot} \cdot n_b$. The Markov chain solution is obtained as

$$E[n_b] = \frac{E[t_b]}{t_{slot}}, \text{ and } p_i + p_b = 1 \Rightarrow \underline{\underline{p_i = 1 - p_b}} , \qquad (1)$$

where p_i and p_b denote the stationary distributions of the system *s(t)* in state *idle* or *busy*, as indicated in Figure 1:

$$\lim_{t \to \infty} P\{s(t) = x\} = p_x , \quad x \in [busy, idle] .$$

The state transition probabilities

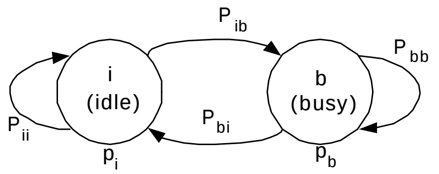


Figure 1: Discrete Gilbert model used for correlated spectrum utilization.

$$P\{s(t+1)=x \mid s(t)=y\}=P_{x\,y}, \quad x\in[busy, idle],$$

are given as

$$P_{b\,i}+P_{b\,b}=1 \text{ and } P_{i\,b}+P_{i\,i}=1. \quad (2)$$

We obtain for the simple Gilbert model

$$p_i\cdot P_{i\,b}-p_b\cdot P_{b\,i}=0, \quad (3)$$

and with

$$E[n_b]=\sum_{n=1}^{\infty}(n-1)\cdot P_{b\,i}\cdot P_{b\,b}^{(n-1)}$$

$$=P_{b\,i}\cdot\sum_{k=0}^{\infty}k\cdot P_{b\,b}^{\;k}=P_{b\,i}\cdot\frac{P_{b\,b}}{\left(1-P_{b\,b}\right)^2}$$

and (2) it follows

$$\Rightarrow E[n_b]=\left(1-P_{b\,b}\right)\cdot\frac{P_{b\,b}}{\left(1-P_{b\,b}\right)^2}=\frac{P_{b\,b}}{1-P_{b\,b}}.$$

Finally, we find

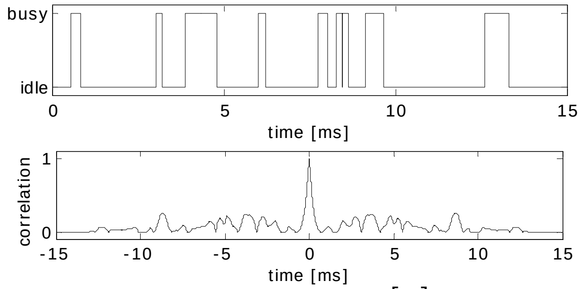
$$\Rightarrow \underline{\underline{P_{b\,b}=\frac{E[n_b]}{1+E[n_b]}}} \text{ and (2) } \Rightarrow \underline{\underline{P_{b\,i}=1-P_{b\,b}}},$$

$$(3)\Rightarrow \underline{\underline{P_{i\,b}=\frac{1}{p_i}\,p_b\cdot P_{b\,i}}} \text{ and } \underline{\underline{P_{i\,i}=1-P_{i\,b}}}.$$

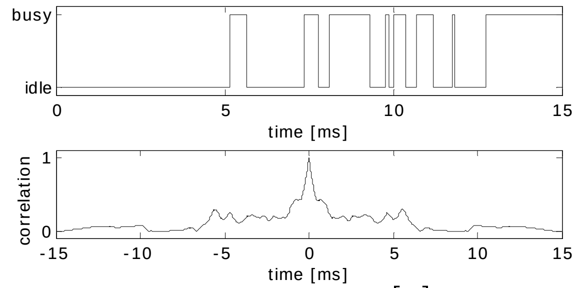
V. Numerical Analysis

Figure 2 illustrates three patterns that are analyzed in the following. The patterns are created with the help of the Gilbert model, and are assumed to represent correlated medium access from 802.11 frame exchanges, i.e., correlated busy/idle times. Figure 3 shows measured channel loads and confidence intervals for PATTERN#2 (mean busy duration *1ms*). As expected, the intervals decrease with increased measurement duration. Figure 4 shows how measurement durations, confidence intervals, and the actual measuring sampling rate are related to each other. A smaller sampling rate is used, which reduces the computational effort of the measurement (less data to process), but the increased confidence intervals associated with the measurements still allow assessing the quality of the measurements. Compared to Figure 3, intervals are larger, hence, the measurement duration may have to be increased, depending on the target confidence.

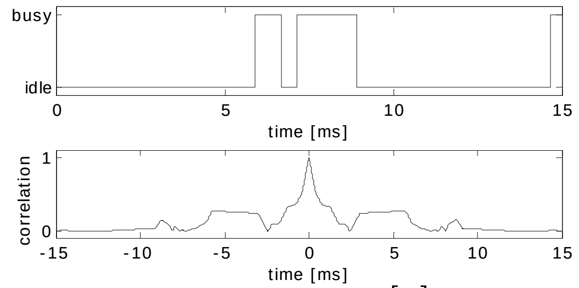
This relation allows classifying radio systems with respect to their confidence. For example, a high quality class radio system, as applied to public access networks, will only report measurements where a confidence interval is smaller than a given size. On the contrary, a low cost/low quality indoor radio system may measure with reduced effort, and report results with less confidence. A quality measure associated to each radio device would allow differentiation of products from different vendors.



(a) PATTERN#1: mean busy duration $E[t_b]=0.5ms$



(b) PATTERN#2: mean busy duration $E[t_b]=1.0ms$



(c) PATTERN#3: mean busy duration $E[t_b]=2.0ms$

Figure 2: Extracts of three typical patterns created with the discrete Gilbert model, and their autocorrelation. Three different mean durations for the busy intervals are shown. The slot size $t_{slot}=0.01ms$.

Figure 5 however illustrates the importance of the correlation of patterns. It is shown that sampling data with slots smaller than the main lobe of the autocorrelation function, does not improve the accuracy of the measurement, but reduces the confidence interval (compared to Figure 3). Care must be taken not to use confidence intervals with oversampled data. Note that we required in Section III independent samples and unbiased statistics.

Finally, Figure 6 and Figure 7 indicate again how optimal measurement durations depend on the correlation in time, which supports our previous statements.

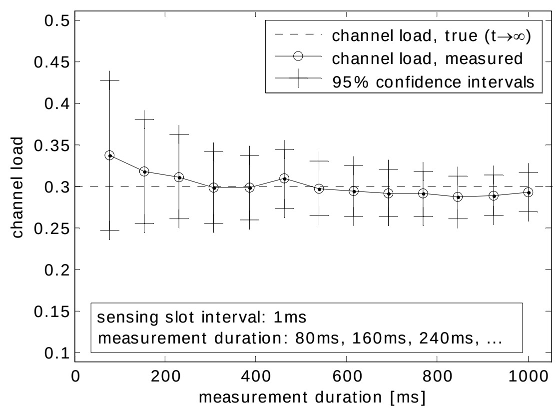


Figure 3: Measured channel loads and confidence intervals for PATTERN#2, for different measurement durations. The intervals decrease with increased measurement duration.

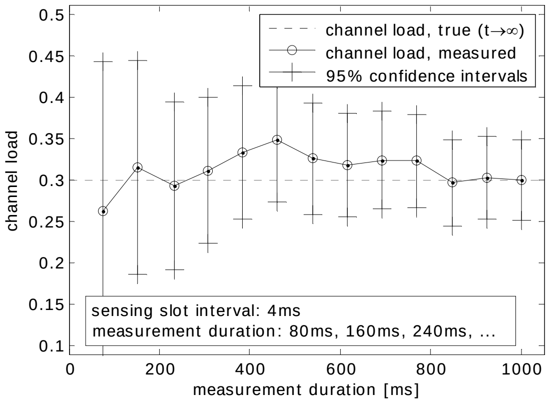


Figure 4: Results for PATTERN#2 with smaller number of samples. The confidence intervals allow reduced effort in measurement (*4ms* samples instead of *1ms*). They can help determining the optimal measurement duration.

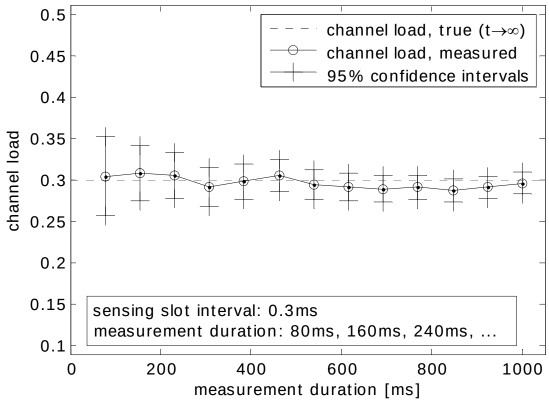


Figure 5: Oversampled (*0.3ms* instead of *1ms*) measurement results for PATTERN#2. Confidence intervals are smaller than in Figure 3, and may therefore imply the misleading conclusion that the results are now more accurate.

VI. CONCLUSION

"Nothing exists until it is measured." [1] This observation bears some interesting truth for the wireless world, and radio resource management. In the increasingly complex world of wireless communication, radio systems will face the specific challenge that they have to measure and learn about their radio environment. Instead of having command-and-control regulation, and instead of standardized air interfaces, future radio systems will operate in dynamically changing environments, where traffic patterns, interference scenarios, and their own requirements and their own capabilities change over time. Improved measurements will enable radio systems to assess the existence of such dynamics to understand their environment with higher confidence.

We have proposed in this paper a method to construct an indicator for the confidence of radio resource measurement results. Using the confidence intervals, the proposed method may allow optimizing measurement durations and determining the optimal rate of measurements. The method also allows estimating how long after the end of a measurement a reported result represents the true reality.

Future work on radio resource measurement may focus on determining optimal measurement parameters such as durations and repetition rate of a measurement. Also, certifying radio devices with respect to their actual quality should be of interest for future radio systems: the exploitation of radio resources, i.e., the scare unlicensed spectrum, may be improved by applying our method.

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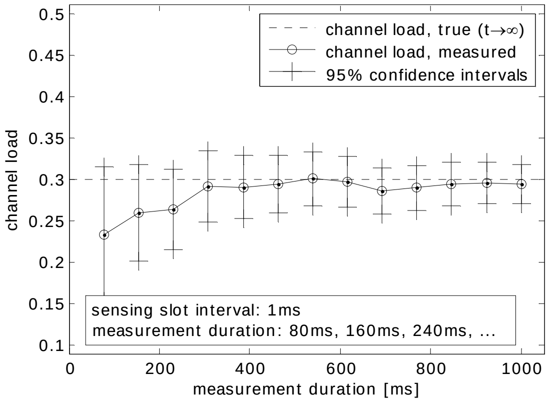

Figure 6: Measured results for PATTERN#1 instead of PATTERN#2. In this case, measurement durations larger than *500ms* may not significantly improve the reliability of the measurement results.

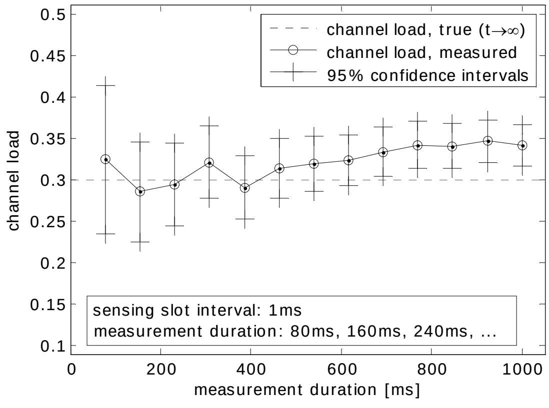

Figure 7: Measured results for PATTERN#3 instead of PATTERN#2. In this case, for reliable results, measurement durations should be larger because of the longer time correlation of the sequence in PATTERN#3.