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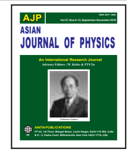

Optimal digitization of one-dimensional dynamic speckle signals for object identification

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This article is dedicated to Prof T Asakura

We investigate a method of object identification using dynamic laser speckles to identify scattering objects such as paper or plastic cards. The effects of sampling interval and quantization level of the speckle signals on authentication performance are examined by using the equal error rate (EER) as a measure of the accuracy of object identification. It is observed that a sampling interval of more than the correlation length of speckle fluctuations and a quantization of two or three bits offers the lowest EER for data sizes ranging from 100 to 500 bytes. The optimal quantization bit number is verified by experiments using plastic cards.

Keywords: Dynamic speckle, Speckle pattern, Artifact-metrics, Authentication, Object identification, Sampling and quantizationn, Equal error rate.

1 Introduction

The study of object identification is important to prevent bank notes, credit cards, ID documents, among others, from being counterfeited. In particular, artifact metrics has been studied in the field of security systems because it uses the intrinsic features of an object and it is difficult to produce a physical copy with the same features as those of the object [1,2]. In several cases, microscopic random structures present in an object are utilized for key generation. If an object has a random distribution of the refractive index inside or microscopic randomness on the surface, a speckle pattern arises when it is illuminated with coherent light. Many artifacts have such random structures; hence, laser speckles can be used in optical authentication systems [3-9]. Speckles as an authentication key have an advantage in that the relationship between the three-dimensional microscopic structure of an object and the speckle pattern that it produces is difficult to model mathematically.

In addition to two-dimensional speckle images, one-dimensional intensity signals of dynamic speckles are used in laser surface authentication [4,7]. In this study, we investigate the identification performance of dynamic speckles under the condition of limited data sizes. Speckle signals are digitized and stored in a computer. The size of the speckle data should be as small as possible in terms of storage space, whereas the accuracy of identification is expected to increase for larger data sizes. We perform simulations to examine the conditions of sampling and quantization for maximizing the accuracy of a speckle authentication system. Experiments are conducted to verify the simulation results.

2 Simulation Method

Simulations were performed using computer-generated speckles. In the simulations, time-varying speckle signals detected at a point are produced by generating a series of independent random complex num-

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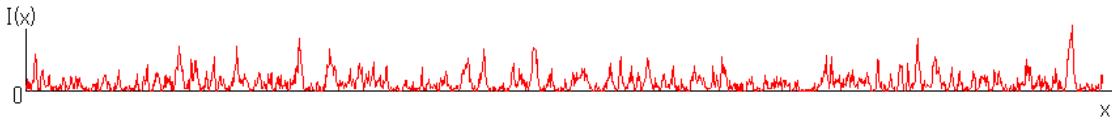
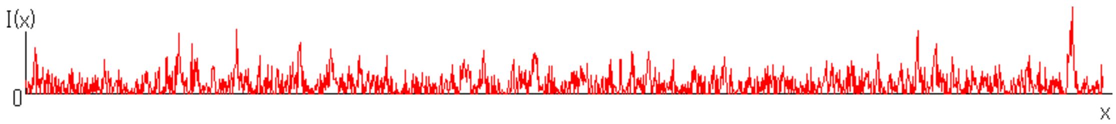
bers exp($i\ \phi_k$) (k = 1, 2, ...). The phases ϕ_k are uniformly distributed in probability between – π and π. By taking a moving average with a window size of 10 numbers and by taking a square modulus of each average, we have intensity variations of dynamic speckles such as those shown in Fig 1(a). A total of 10,000 intensity variations were prepared as original signals before quantization, each of which was a set of 32,000 double-precision numbers.



(a) Original



(b) With Gaussian noise of level $\bar{I}$

Fig 1. Examples of speckle signals generated in simulation (a) without and (b) with Gaussian white noise.

To examine the noise tolerance of a speckle authentication method, Gaussian white noise is added to the original signals, as shown in Fig 1(b). Standard deviations of the added noise are $\bar{I}$, $2\bar{I}$, and $3\bar{I}$, (with $\bar{I}$ being the average speckle intensity. The signals with noise are then quantized at various bit numbers ranging from 1 to 8. A uniform quantization is used, which simulates a general analog-to-digital converter. We fixed the data size of the quantized signals at a constant value; in this case, the number of data points is inversely proportional to the quantization bit number. For example, if the data size is 500 bytes, a binary (1-bit) signal has 4,000 data points, whereas the number of points decreases to 500 for an 8-bit signal.

As the time interval between adjacent data points in the original signals is arbitrary, the sampling interval can be represented by the number of data points. We changed the sampling interval from 1 to 8 points, which in actual situations corresponds to a change in the total length scanned by a laser beam. The average correlation length of the original speckle signals, or the average speckle width, is approximately 5.2 data points. It follows that the samplings of every 6, 7, and 8 points correspond to sampling a different speckle grain at every time step.

The correlation coefficient, which is employed for the accept/reject decision in an authentication system that we assume, is calculated between samples of different origins (cross-correlation) and between samples of the same origin with different realizations of Gaussian noises (autocorrelation). The number of trials between different samples and between samples of the same origin is 11,175 (150×149/2, cross-correlated among 150 signals) and 10,000, respectively.

3 Simulation Results

Figures 2-4 show the distributions of the correlation coefficient obtained for various values of signal parameters. The data size, quantization bit number, and sampling interval are changed in Figs 2, 3, and 4, respectively, with other parameters being constant. The histograms in red and blue represent the coefficients between different samples and between samples of the same origin, respectively. In Fig 2, the distributions of correlation coefficients become smaller as the data size increases. In contrast, the average correlation coefficients are almost unchanged. As the quantization bit number and the sampling interval are fixed, the result indicates that the number of data points is related to the fluctuations of the correlation coefficient, which decrease as the speckle signal is collected from a wider area of the object.

As can be seen from Fig 3, the correlation coefficients for bit numbers 1 to 3 and for bit numbers 4 to 8 show different behaviors. The average correlation coefficient between samples of the same origin increases as the bit number increases from 1 to 3. This is because a more detailed structure of the speckle signal can be retained for larger bit numbers. When the bit number is increased more, the average coefficient is almost unchanged, but the distributions of the autocorrelation and cross-correlation coefficients become larger. The reason for this is the same as in Fig 2: the number of data points decreases with an increase in the bit number. This is also true for the correlation coefficients between different samples, the distribution width of which increases monotonically as the bit number increases.

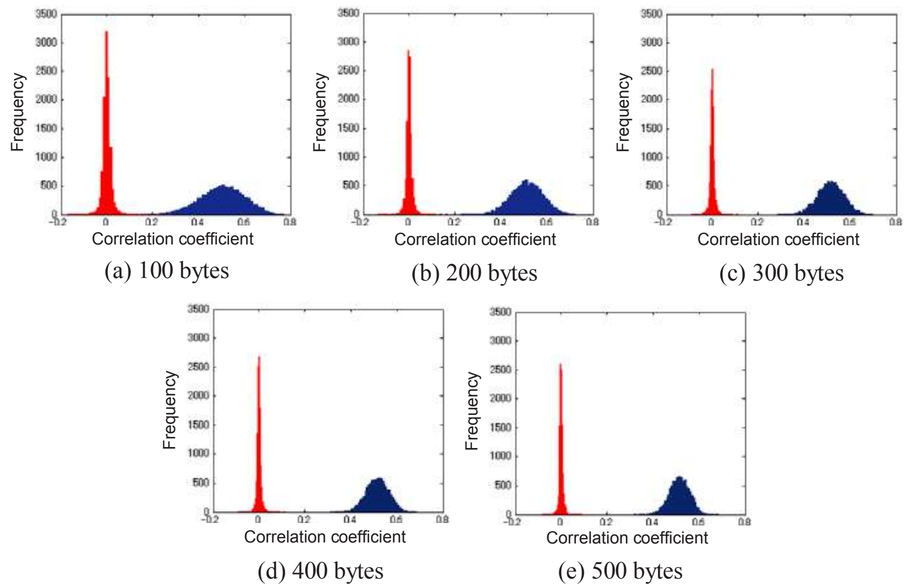


Fig 2. Distributions of correlation coefficient for various data sizes. Histograms in red and blue represent coefficients between different samples and between samples of same origin, respectively. Quantization bit number, sampling interval, and noise level are fixed at 3 bits, 1 data point, and $\bar{I}$, respectively.

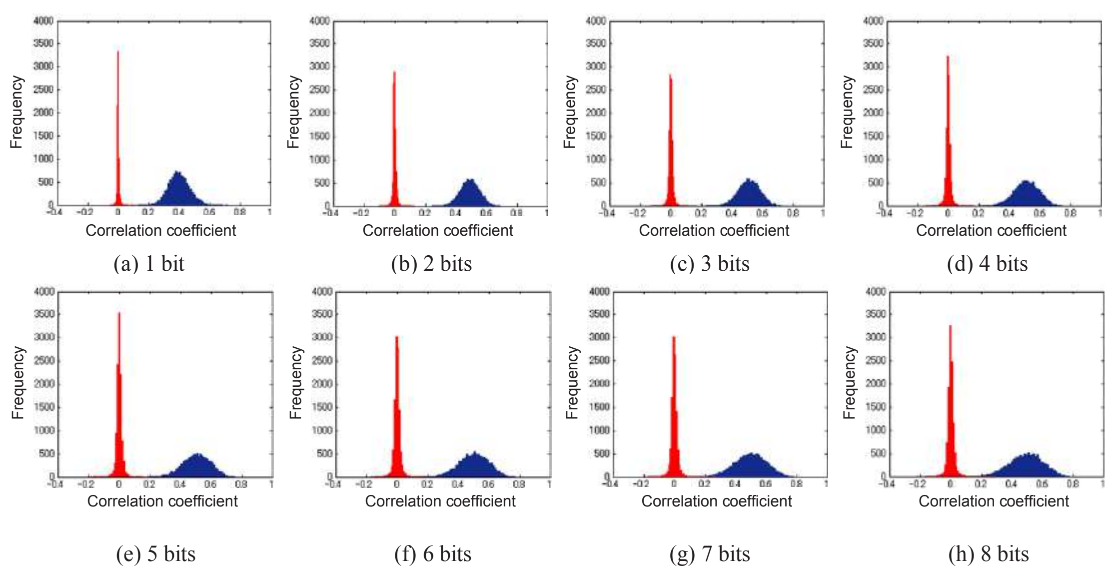


Fig 3. Distributions of correlation coefficient for various quantization bit numbers. Data size, sampling interval, and noise level are fixed at 200 bytes, 1 data point, and $\bar{I}$, respectively.

Figure 4 reveals that the variance of the coefficient distributions for samples of the same origin decreases with an increase in the sampling interval, even though the number of data points remains unchanged. An increase in the sampling interval corresponds to an increase in the number of sampled speckle grains. This result suggests that a larger area should be scanned for more accurate identification. The average correlation coefficient seems to remain constant, except for signals of 1- and 2-point sampling intervals, which show lower values.

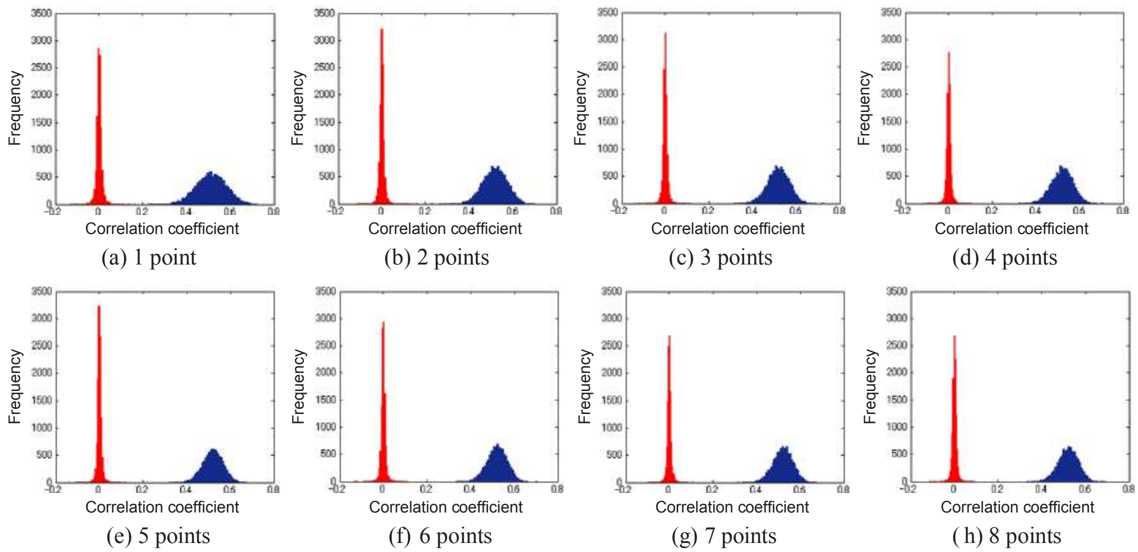


Fig 4. Distributions of correlation coefficient for various sampling intervals. Data size, quantization bit number, and noise level are fixed at 200 bytes, 3 bits, and $\bar{I}$, respectively.

Next, we evaluate the equal error rate (EER) to examine the performance of an authentication method using speckle signals. The EER is the error rate when the accept/reject threshold is chosen such that the false acceptance rate (FAR) and the false rejection rate (FRR) become equal. The lower is the EER value, the higher is the accuracy of identification. To evaluate the EER, the distributions of the correlation coefficient were fitted to Gaussian functions, which are the most appropriate functions for approximating the data. The FAR and FRR for various values of the correlation coefficient threshold were then calculated using the fitted curves. The EER is obtained by finding the threshold at which the FAR and FRR are equal.

Figures 5 and 6 show the EERs for various combinations of the data size, quantization bit number, and sampling interval. The data with a size of 100 bytes and a noise level of $2\bar{I}$, and the data with a noise level of $3\bar{I}$, are not presented here because their EER values are higher than 10^{-4} for all combinations of the quantization bit number and the sampling interval. Low EER values can be obtained for bit numbers of 2 or 3 and sampling intervals of 7 or 8. It is also demonstrated that increasing the data size dramatically reduces the EER. When the data size is small or the noise level is high, 2-bit quantization is optimal. On the contrary, a speckle signal of 3 bits demonstrates the best performance if the data size is larger than 300 bytes or the noise level is low. These results indicate that 1) even though the number of data points becomes maximum for 1-bit quantization, binarized speckle codes do not demonstrate good performance; 2) the number of data points should be as large as possible for small (100 and 200 bytes) data sizes under the condition of multilevel quantization; and 3) if more than 300 bytes can be used for speckle codes, the surplus data capacity should be used for an increase in the bit rate as well as in the number of data points. We further increased the data size to 1,000 bytes and evaluated the EER, but the optimal bit number still remained at 3 bits. Therefore, a quantization of 3 bits seems to be suitable for speckle codes when the noise level is almost the same as the average speckle intensity.

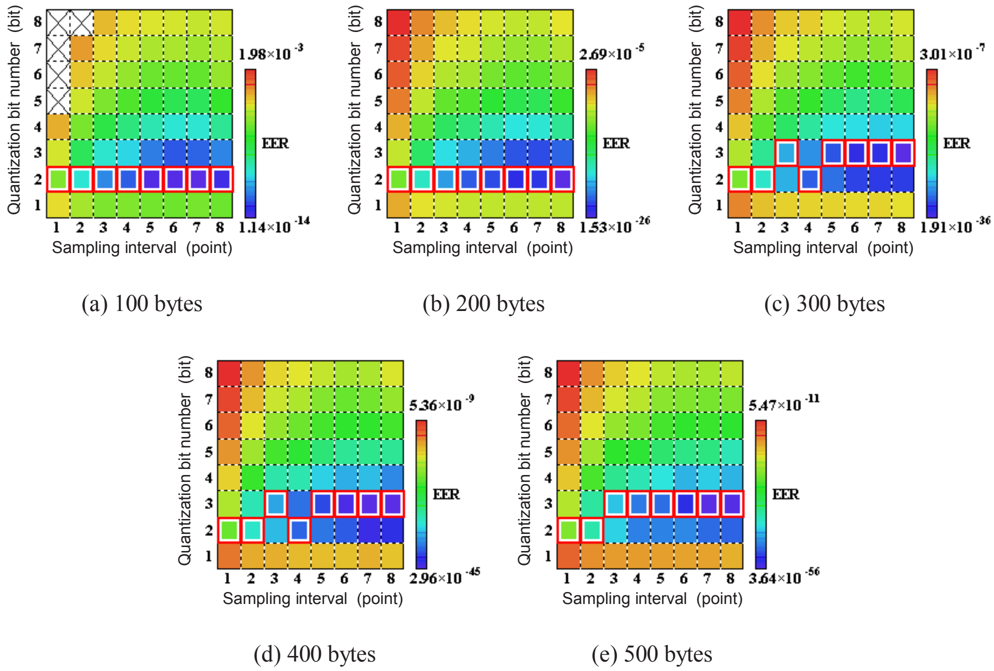


Fig 5. Equal error rates for a noise level of $\bar{I}$. X-marks denote the conditions in which the EER values are larger than 10^{-4}, which are generally unacceptable for authentication systems. The red box represents the least EER for each sampling interval.

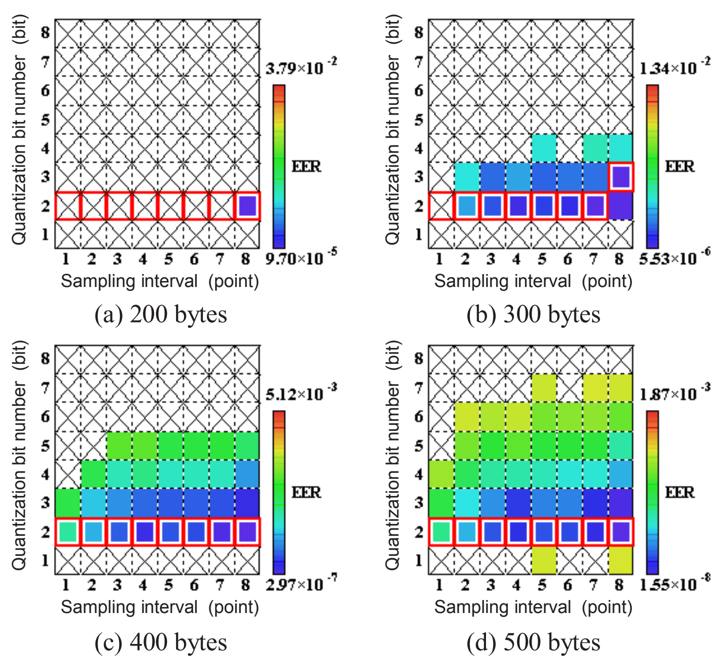


Fig 6. Equal error rates for noise level of $2\bar{I}$. X marks denote conditions in which EER values are higher than 10^{-4}, which are generally unacceptable for authentication systems. The red box represents the lowest EER for each sampling interval.

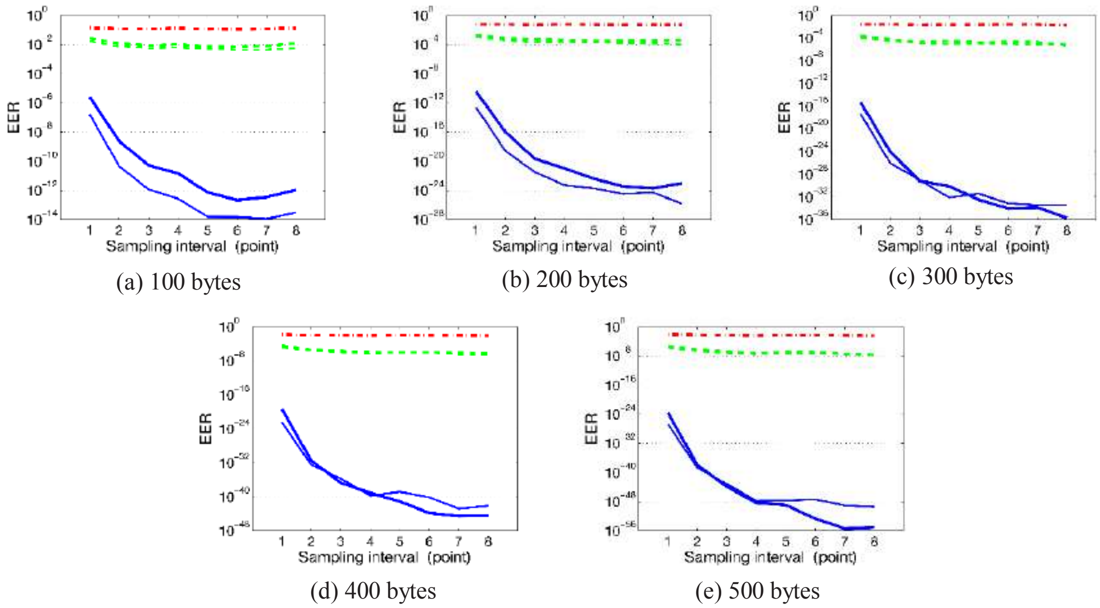


Fig 7. Equal error rates as function of sampling interval for quantization bit numbers of 2 and 3 and noise levels of $\bar{I}$, $2\bar{I}$, and $3\bar{I}$. Solid (blue), dashed (green), and dashed-and-dotted (red) lines denote noise levels of $\bar{I}$, $2\bar{I}$, and $3\bar{I}$, respectively. Thin and bold lines represent 2- and 3-bit quantizations, respectively.

The effect of the sampling interval on the EER is shown in Fig 7 when the quantization bit numbers are 2 and 3. In most cases, the EER decreases monotonically with an increase in the sampling interval. By comparing the curves of 2- and 3-bit signals, one can see that EERs for 3 bits are lower than those for 2 bits only when the data size is relatively large and the sampling interval is larger than or almost equal to the average speckle width. As for the effect of the noise level, the EER values become larger than 10^{-4} in any conditions we tested if the level of Gaussian white noise is three times larger than the average speckle intensity. Therefore, the noise should be suppressed to less than if the data size is limited to less than or equal to 500 bytes.

4 Experiment

Experiments were performed to verify the simulation results. Figure 8 shows the experimental setup for detecting and analyzing dynamic speckle signals. We used 100 sheets of plastic having dimensions of 85.6 mm, 54.0 mm, and 1.0 mm as sample objects to be identified. A He-Ne laser beam with a wavelength of 632.8 nm was incident normally on the sample, which was on a translation stage and moving in the lateral direction. The moving speed of the sample was 3 mm/s. A dynamic speckle pattern 200 mm away from the sample was detected at an angle of 35° by a photomultiplier through a 15-mm-diameter pinhole. The pinhole diameter was chosen such that the effect of the spatial integration of the speckle pattern was negligible.

To improve the contrast of the speckle signals, an analyzer was placed before the photomultiplier, which passed only the scattered light with a polarization direction perpendicular to that of the incident light. The linearly polarized speckles detected through the small aperture resulted in negative exponential statistics of the detected intensity. The dynamic speckle signal was stored in a computer through a 12-bit A/D converter (voltage range: 0.1 V). The sampling interval was varied from 0.4 to 3.2 ms, which corresponds to a scanning length of 4.8 to 38.4 mm on the sample.

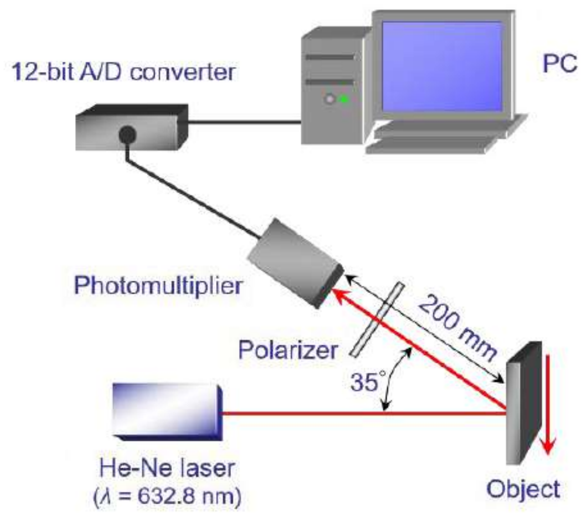


Fig 8. Experimental setup for object identification using dynamic speckle.

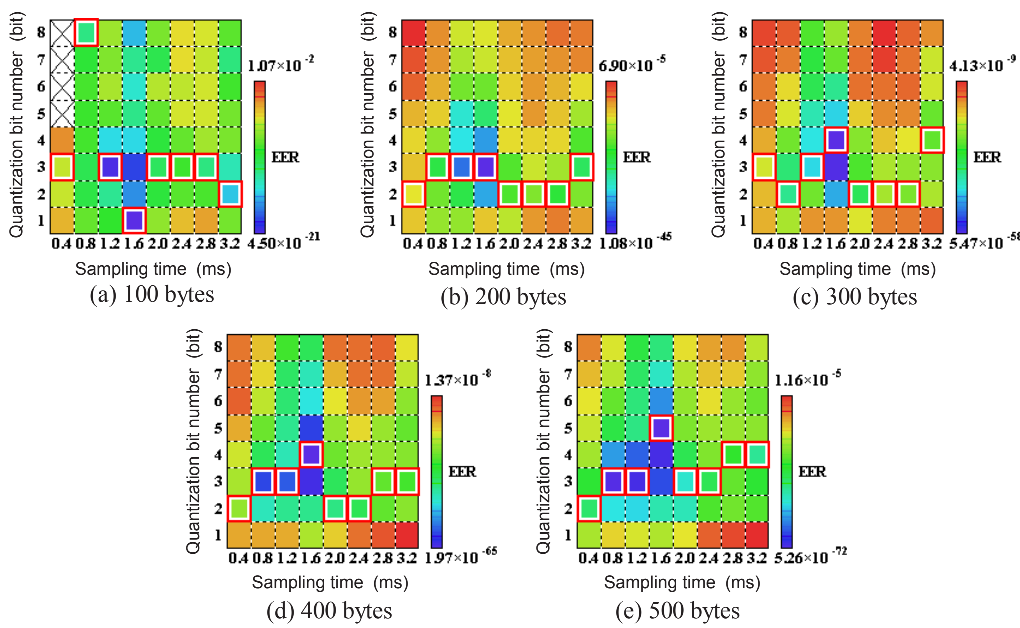


Fig 9. Equal error rates obtained by experiments. X-marks denote conditions in which EER values are higher than 10^{-4}, which are generally unacceptable for authentication systems. The red box represents the lowest EER for each sampling interval.

The distributions of the correlation coefficient were fitted to Gaussian functions as in the simulation. Figure 9 shows the experimental results for the EERs obtained with the same data sizes and quantization bit numbers as those of the simulation. The average correlation length of the detected speckle signal was 33.7 ms, corresponding to 84.2 data points at a maximum sampling rate of 0.4 ms/sample. Therefore, the sampling intervals of 0.4, 0.8,…, 3.2 ms shown in Fig 9 correspond to 0.061, 0.124,…, 0.494 in the unit of the "point" in Figs 5 and 6. Despite this discrepancy in the sampling intervals between the simulation and experiment, low EER values were obtained for bit numbers of 2 or 3 in most sampling intervals, which is in good agreement with the simulation results. For each data size, the experimental values of the EERs for both 2 and 3 bits are observed to be lower than the simulated EER values for a bit number of 2, a sampling interval of one point, and a noise level of $\bar{I}$. Thus, the noise level of our experiments is estimated to be less than the average speckle intensity, although the measurement noise is not necessarily Gaussian.

5 Conclusions

We investigated the performance of an authentication system using intensity variations of dynamic speckles as an identification key. The optimal sampling and quantization of dynamic speckle signals were examined under the condition of limited data sizes. The simulation results suggested that a quantization of 2 or 3 bits results in speckle codes that present low EER values, which was confirmed by the experiments. It was also demonstrated that the optimal bit number is dependent on the data size and the noise level. In addition, we observed that the sampling interval should be as large as possible for accurate identification. Although our simulation and experiment were performed under limited conditions, the results obtained in this study will be of some use in designing a speckle authentication system.

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