Scrambled and Unscrambled Optical Speckle with Multiple Scattering Layers: Applications to Optical Wireless Communication

Alfredo Rates*, Joris Vrehen‡, Bert L. Mulder*, Wilbert L. IJzerman‡, Willem L. Vos*

*Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
‡Signify NV, High Tech Campus 7, 5656 AE Eindhoven, The Netherlands
‡Department of Mathematics and Computer Science, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

Abstract—When a beam of incident light waves is sent onto a scattering material, the waves are scattered within the material and the output is a scrambled speckle pattern. By placing a slab near a receiver, relevant properties arise for applications in encryption or as physically unclonable functions and keys, that take advantage of the randomness and complexity of the speckle pattern. Here, we extend this light-scattering system to a situation with two scattering slabs, one near a sending device and the second near a receiving device, and address the question: does the intermediate speckle pattern observed in between the slabs have correlations with the pattern observed at the receiver, after two slabs? To this end, we send spatially shaped wavefronts from the sender that are designed to arrive at the receiver in one of two spatial regions of interest, considered to be states 0 or 1. We then collect the intermediate speckle patterns corresponding to either of the two states and study their properties. We characterize the correlation distribution between speckles using the Kolmogorov-Smirnov (K-S) test, and unsupervised classification algorithms. We found no correlation between the intermediate speckle and the message. Thus, if data are sent as binary 0s and 1s into the system, an observer is not able to infer it from the intermediate speckle pattern. Consequently, we propose a communication link for optical wireless communication (OWC) with a new encoding scheme based on our findings.

Index Terms—optical wireless communication, speckle, light scattering, physical unclonable keys, visible light communication

I. INTRODUCTION

SCATTERING of light occurs in any complex material such as paint, foam, or tissue, independent of its shape - slab or free-form - and possible absorption of light - white, grey, or black [1]–[3]. When light travels through a complex material, it takes many different paths, or channels, inside the medium, whereby the light takes a random walk with a typical step size called mean free path [3]. The light waves pick up a random distribution of phase changes along these paths. Therefore, it is intuitively reasonable that a random interference pattern appears in a target plane, called a speckle pattern.

Historically, light speckle has been considered noise or aberration, and it is therefore typically minimized [4], [5]. Recently, however, speckle has gained relevance as an effective way to study and control light inside scattering media [6], [7]. Well-known characterization methods include measuring the enhanced back-scattering cone to characterize the mean free path [8]–[11], the measurement of the transmission matrix [12]–[14], or the analysis of speckle statistics [15], [16]. In parallel, techniques to control the scattering of light have been developed, such as wavefront shaping [17]–[19] with applications in high-resolution imaging inside and behind opaque materials, and mutual extinction and transparency to control the transparency of an opaque material [20], [21]. Beyond fundamental research, modulation of light waves is used in applications such as optical wireless communication (OWC) as an alternative to radio waves, including long-distance links such as non-line-of-sight communication [22], [23], or for shorter-distance indoor communication such as light fidelity (Li-Fi) [24]–[26] using amplitude modulation.

In practice, studying correlations between different speckle patterns is a widely used technique to study light scattering. While speckle from volume scattering is random, it appears that there are distinct correlations, called memory effects, whereby non-trivial position displacements or wavelength detunings result in correlations in speckle patterns [3], [27], [28]. Such speckle correlations are applied in imaging or to send images through a scattering media [29]–[31]. In addition, many studies have recently focused on training a photonic-based neural network (NN) for image recognition [32]–[34], based on speckle correlations. To use this class of speckle correlation for both studying and controlling light scattering, we need a feedback loop, that is, we need to know beforehand what is the input and output of the system. This is especially pronounced in NN and wavefront shaping implementations.

In this work, we study the intermediate speckle in scattering media. In light scattering theory, and in general in mesoscopic physics, having a single thick slab of scattering material with thickness $L$ is equivalent to considering $N$ thin slabs with the same total thickness $L$ (in this case, $N = 2$, illustrated in Fig. 1). In coherent light transmission, a scattering material is represented as a random transmission matrix that couples the modes of the incident light to the ones of the outgoing light, and the random components of the transmission matrix represent the scattering events inside the material [3], [35]. Having $N = 2$ scattering slabs is represented as the multiplication of two of these random matrices, which results in yet
a) Modulated Wavefront

CCD 1

b) Channel Wavefront

L1

Receiver

Modulated

Fig. 1. Schematic of the light scattering systems studied here. (a) A single incident light beam is sent through \(N = 1\) scattering slab, yielding a complex speckle pattern as output. The speckle pattern transmitted through the slab is described by a transmission matrix \(Z\). (b) A single incident light beam is sent through \(N = 2\) scattering slabs. The speckle pattern emanating from the first slab is the intermediate pattern (described by transmission matrix \(X\)) that is sent onto the second slab (with transmission matrix \(Y\)). The final output is a new speckle pattern described by a transmission matrix \(Z' = X \times Y\).

II. EXPERIMENTAL METHODS

To study the speckle correlation, we used the experimental setup shown in Fig. 2. The initial light source is a frequency-doubled continuous wave green (\(\lambda = 532\) nm) Nd:YAG\(^3+\) laser (Coherent Compass, 100mW). The signal is encoded as a phase-modulated wavefront using a digital mirror device (DMD, Vialux VX4100), in the same way as usually done in Wavefront Shaping experiments \(^{36}\). The modulated wavefront is focused into a diffuser (Ground Glass Diffuser 220 Grit, Thorlabs), and collimated using a microscope objective (NA=0.3, Nedoptifia Zeist). To measure the light speckle between the diffusers, a beamsplitter is used to pick up half of the signal, which is collected by a charge-coupled device (CCD) camera (Guppy F-146B), to detect the intermediate speckle pattern. The other half is focused on a second diffuser similar to the first one, and collected by a second CCD camera (Stingray F-125), which we call the receiver.

Light coherence is a key factor in our experiment. We need spatial coherence in order to obtain and measure the speckle pattern. In our experiment, we use a well-defined laser beam as a source, meaning we have a high temporal and spatial coherence. The coherent length of our laser source is on the order of hundreds of meters, while the coherence length of our experiment is on the order of meters, thus ensuring the wavefront is spatially coherent. This coherent is not achievable using a white source such as a light-emitting diode (LED).

The goal of this experiment is to send a signal through the two diffusing slabs, and study if there is any correlation between the intermediate speckle pattern and the resulting pattern. As a starting point, we aim to obtain a binary signal, \(i.e.,\) only two levels: state 0 and state 1. Still, the modulated incident wavefront has many more degrees of freedom than these two states. For this reason, there exist multiple incident wavefronts, and thus multiple intermediate speckle patterns, that can result in the same signal. We use this to see if different intermediate speckle patterns need to have some correlation in order to result in the same final state.

To be robust against environmental noise and to have a large dynamic range, we consider at the receiver plane only two Regions Of Interest (ROI), called spot A and spot B, as shown in Fig. 3. Only when the local intensity of spot A is high and the local intensity of spot B is low, a state 0 is received. Conversely, if the local intensity of spot A is low and the local intensity of spot B is high, state 1 is received, see Fig. 3b). To select the speckle patterns corresponding to state 0 or state 1, we sent a total of \(N_W = 50000\) randomized wavefronts. For each wavefront, the speckle pattern at CCD2 was collected along with the intensities at spot A and spot B. From the definition of each state, we defined arbitrary intensity thresholds based on the joint intensity distribution of spot A and spot B, shown in Fig. 4, where the thresholds are marked with dashed lines. For both spot A and spot B, we set the thresholds at 20% and 80%. This means that a speckle pattern is classified as state 0 only if the intensity at spot A is
higher than 80% of the distribution, and the intensity at spot B is lower than 20% of the distribution. The classification of wavefronts as state 1 follows the same principle.

The red and blue regions in Fig. 4 highlight which speckle patterns are accepted as state 0 or state 1, respectively. With the given thresholds, there is a total of \(N_{W,0} = 1839\) available wavefronts (3.7% of total) to get a state 0, and \(N_{W,1} = 1774\) (3.5%) to get a state 1. We modulated the wavefront using a grid of 15 × 15 segments, controlling the phase of each segment. In our current realization, we modulate the phase from 0 to 2\(\pi\) in 16 steps. That means that the maximum number of different wavefronts we generate is \(N_W = 16^{225}\), which is on the order of \(O(10^{307})\). The complexity of the scattering material is such, that small changes in the phase of a single segment at the modulator produce large changes in the intensity distribution at the receiver. This means that the number of available wavefronts can be made arbitrarily large, at the expense of longer measurements and digital memory.

### III. Results and Discussion

Every wavefront used to send a message also generates an intermediate speckle pattern between the slabs. When sending two messages separately, we generate two intermediate speckles, and we calculate the correlation between these two speckles. We are interested in comparing three cases: the correlation between two speckle patterns from state 0 (0-0 correlation), the correlation between two speckle patterns from state 1 (1-1 correlation), and the correlation between a speckle pattern from state 0 (0-1 correlation), the correlation between two speckle patterns from state 0 (0-0 correlation), the correlation between two speckle patterns from state 1 (1-1 correlation), and the correlation between a speckle pattern from state 0 (0-1 correlation).

We illustrate the combinations of speckles in Table I using the sub-figure indexes of Fig. 3. If any correlation is needed to result in the same state, we expect the correlation between two points from the same group to be larger than between two points from different groups, e.g., the 0-0 and 1-1 correlations to be larger than the 0-1 correlation. To characterize the correlations between speckle patterns, we use the Pearson correlation coefficient \(C_P\) from the Python SciKit library, calculated as follows:

\[
C_P := \frac{\sum_{i,j}(x_{i,j} - \bar{x})(y_{i,j} - \bar{y})}{\sqrt{\sum_{i,j}(x_{i,j} - \bar{x})^2(\bar{y}_{i,j} - \bar{y})^2}}.
\]

with \(x_{i,j}\) the value of pixel \((i,j)\) of the first speckle, \(y_{i,j}\) the value of the pixel \((i,j)\) of the second speckle, and \(\bar{x}, \bar{y}\) the average pixel values of the first and second speckle, respectively. When we calculate \(C_P\) between all \(N_W\) available intermediate speckles, i.e., \(C_P\) between individual pairs of speckles with all the combinations possible, we get a distribution of \(C_P\). In Fig. 5 we show the correlation distribution for the three cases previously described, 0-0, 1-1, and 0-1. We see that, qualitatively, the distributions are very similar, with the same peak position.

To compare these distributions quantitatively, we used the two-sample Kolmogorov–Smirnov (K-S) test. This test compares the empirical distribution of two sets of observations. When the two observations are from the same distribution, the K-S statistic tends to zero. The results of this test are shown in Table II. We see that the K-S statistic is close to zero and that the \(p\)-value is lower than 5% (\(O(10^{-15})\), this

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**Table I**

| Case       | Pairs of speckle patterns |
|------------|---------------------------|
| 0-0 correlation | (a,b), (a,c), (a,d)       |
| 1-1 correlation | (d,e), (d,f), (e,f)       |
| 0-1 correlation | (a,d), (a,e), (b,d), (b,e), (c,d), (c,e), (c,f) |

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**Fig. 3.** Examples of observed speckle patterns. (a-c) Speckle patterns that correspond to state 0. (d-f) Speckle patterns that correspond to state 1. The dashed circles in each panel show the region of interest (ROI) of spot A (purple circles with rounded dashes) and of spot B (green circles with rectangular dashes). (g) Average intensity of spot A and spot B for each speckle pattern normalized by the average intensity of the background.

**Fig. 4.** Joint distribution of intensities at spot A and at spot B at the receiver for different incident wavefronts (green symbols). The horizontal and vertical dashed lines are the intensity thresholds that define the states 0 or 1. Here, the red region indicates the accepted states 0 with high intensity in spot A and low intensity in spot B. The blue region indicates the accepted states 1 with low intensity in spot A and high intensity in spot B.
Fig. 5. Probability density histograms of speckle cross-correlation between different signals: a) between all pairs of speckle patterns belonging to state 0, b) between all pairs of speckle patterns belonging to state 1, and c) between speckle patterns from state 0 and speckle patterns from state 1. The vertical dashed red lines indicate the peaks of the distributions.

tells us that the correlation distributions of the three groups are indistinguishable.

| Dataset 1    | Dataset 2    | K-S statistic | p-value |
|--------------|--------------|---------------|---------|
| 0-0 correlation | 1-1 correlation | 0.03          | 0.00    |
| 0-1 correlation | 0-0 correlation | 0.03          | 0.00    |
| 1-1 correlation | 0-1 correlation | 0.02          | 0.00    |

Although the correlation between speckle patterns is low, it is never truly zero. When we claim there is no clear correlation between speckles from the same group, it is because this correlation is the same as the correlation between speckles from different groups. However, the fact that the correlation is not zero leads to the question if there is any underlying relation between speckle patterns that the Pearson correlation coefficient does not have access to. To test this further, we used unsupervised classification algorithms.

For our analysis, we used two different classification algorithms: The K-means algorithm and the Hierarchical clustering algorithm. We used the open-access Scikit-learn Python library to implement both algorithms. The procedure for classification, illustrated in Fig. 6, is the following: First, to reduce the computational time we reduce the resolution of the picture by ×5 averaging the adjacent pixels. Then, we transform the representation of the data: we consider each pixel as a different dimension and the intensity of this pixel as the position of the realization in that dimension. This forms a new high-dimensional space, called the feature space. Due to the resolution of our camera (1280 × 960) and the reduced resolution, the feature space has almost 50000 dimensions, where each point is a realization (or speckle).

To reduce even further the dimensionality of the problem and thus make the problem addressable for a personal computer, we used the principal components analysis (PCA) and only consider the first 100 principal components. This new data representation is finally used for the classification algorithm, where each principal component is now a dimension of the feature space, and its value corresponds to the position of that dimension. Now, the feature space has Nd 100 dimensions.

For both algorithms, we used two different classes, intending to separate state 0 and state 1. For the K-Means algorithm, we used 100 initializations and a maximum of 30000 iterations. For the Hierarchical clustering algorithm, the agglomerate strategy was used. For the sake of generality, we also run the classification without reducing dimensionality, i.e., without using the PCA. For these cases, the image was reduced ×10, considering the data memory compared with the previous cases.

We show the results of the classification in Table III. In total, four classification methods were used, with two different algorithms and two different data representations. Each classification was repeated 5 times and averaged.

| Method               | Average (%) | std (%) |
|----------------------|-------------|---------|
| K-Means              | 52.38       | 0.04    |
| Hierarchical         | 51.81       | 0.61    |
| K-means without PCA  | 52.32       | 0.12    |
| Hierarchical without PCA | 51.41     | 0.00    |

We see in Table III that the accuracy of all the methods we used is close to 50%. Although this number seems to be large, it is relevant to realize that only two classes are present. This means that using a random classifier, such as tossing a coin, yields on average an accuracy of 50%.

The accuracy of all methods is slightly higher than a random classifier, with a maximum difference from a random classification of 2.38% using the K-Means classification and the PCA representation. This suggests that the unsupervised algorithm finds a small difference between the distribution of the two classes. Further studies are needed to rule out if it is possible to exploit this difference with a new different
classification algorithm. Still, the increase in percentage using the current classification methods is not enough to clearly separate the two classes, and if the emitter is aware of this they can compensate by excluding the outliers points on the distribution using statistical tools such as the Mahalanobis distance [39].

Here we have shown that there is no trivial correlation between the intermediate speckle patterns and the resulting states 0 or 1. Furthermore, the different unsupervised classification algorithms are not able to find any correlation. With this, we conclude that no clear correlation is needed for different intermediate speckles to result in a specific state, meaning that it is not possible to predict the final state only by knowing the intermediate speckle pattern with the studied methods. We believe that this knowledge is relevant for real-life applications, particularly in the field of optical wireless communication (OWC), to make communication more secure. Therefore, in the following section, we described a possible implementation of a communication link based on these findings.

### IV. Proposed Communication Scheme

In OWC applications, a proposed alternative to digital encoding is using Physical Unclonable Functions (PUFs) [40]. A PUF is a physical object with a complexity so large, that making an exact copy of it becomes unfeasible. A PUF then can be used as a personal key, to encode or decode a message. Many architectures have been proposed to build a PUF, such as memory-base [41], time-delay [42], and light speckle [43]. This last architecture is based on a light-scattering media, exactly like the diffuser used in our experiments.

Light speckle PUFs are believed to be the most reliable and secure PUF architecture [44], although currently harder to adapt to silicon-based technology. This is due to the random positions of scatterers in a scattering object (such as a diffuser) and its 3D nature. For this reason, many studies have focused on light speckle PUFs for quantum authentication and Quantum Key Distribution (QKD) with promising results [45]–[49].

Based on the described scenario, we propose a new communication scheme based on two slabs of PUFs. This scheme is depicted in Fig. 7 which is inspired by the experimental setup shown in Fig. 2. Alice sends a message to Bob through free space using visible or infrared coherent light. The initial digital message is encoded as a phase-modulated wavefront. The message is encrypted using a Physical Unclonable Function (PUF), which is a highly scattering random material. When arriving at the destination, the signal passes through a second PUF and the message is recovered as light intensity by Bob. If an attacker, depicted in Fig. 7 as Eve, intercepts the signal, the message will not be recovered as the second PUF is not known. Similarly, if Eve tries to send a false message to Bob, this will not be considered as it does not pass through the first PUF.

![Fig. 6. Schematic diagram of the classification procedure. The green lines represent the path followed when the principal components analysis is used, and the orange lines show when PCA is not used. The speckle image shows only a portion of the full speckle image, to highlight the reduction of resolution. The colors red and blue at the bottom plots represent the two different classes of classification.](image)

![Fig. 7. Scheme of the communication link. Alice sends a message to Bob through the channel (free-space), which is encrypted using two Physical Unclonable Functions (PUF).](image)
cation, Eve can record the speckle of these bits to identify each binary 0 and binary 1. In this case, the number of messages Eve needs to record to obtain all speckles grows as \( O(N_W \log(N_W)) \) [50]. An implementation without this identification is possible by changing the digital codification to avoid any predictable bit. Even more, based on the complexity of the scattering material and the degrees of freedom at the wavefront modulation, the number of available wavefronts can be made arbitrarily large, increasing the number of messages needed. This also limits Eve to send a false message to Bob.

Many alternatives have been studied to break the secrecy of PUFs making use of Machine Learning (ML) techniques, which have proved to be powerful tools for these attacks [44], [51]. In most of these studies, however, they needed to obtain a Challenge-Response Pair (CRP) set for training a supervised algorithm. To do so, they assume Eve can send a challenge to the PUF and read the response. In our case, obtaining a CRP means Eve has a subset of speckle patterns at CCD2 with their respective classification at CCD1. This is not possible without an invasive measurement, meaning Eve is not able to extract a CRP set. Based on that, we disregard the use of supervised classification.

An attacker may still try to classify the speckle patterns using unsupervised algorithms. The results from Section III show that none of the unsupervised methods used are significantly better than a random classification, which suggests that the data are not classifiable given the speckle pattern obtained from the channel. Thus, the communication is secure against an attacker in free-space.

V. CONCLUSION

In this paper, we studied the correlation between speckle patterns when passing through multiple slabs of scattering media. We spatially modulated the phase of the incoming light and we sent a signal through two diffusers, measuring the resulting speckle pattern both between and after the two diffusers. The signal is encoded as changes in light intensity at two regions of interest (ROI) at the receiver, where multiple modulated incoming wavefronts may result in the same message. We have studied the correlation between speckle patterns when sending different messages. Therefore, we used the Pearson correlation coefficient and two unsupervised classification algorithms. In all cases, we observed that there is no correlation between the intermediate speckle pattern and the resulting pattern (or message). This method is attractive for optical wireless communication (OWC) schemes, particularly in line-of-sight communication and wireless indoor communication. Independently of the complexity of the modulated wavefront or the scattering media, the receiver only needs to collect the average intensity at two separate positions, which is easy and cheap to execute with a photodiode.

The need to have a coherent light source hinders us to extend our technique to applications such as light fidelity (Li-Fi). This restriction is present in any technology that wants to take advantage of luminaries already installed. Nevertheless, our technique remains applicable for indoor communication when using infrared or UV sources and for laser-driving lightning [52].

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