Abstract—In conventional molecular communication (MC) systems, the signaling molecules used for information transmission are stored, released, and then replenished by a transmitter (TX). However, the replenishment of signaling molecules at the TX is challenging in practice. Furthermore, in most envisioned MC applications, e.g., in the medical field, it is not desirable to insert the TX into the MC system, as this might impair natural biological processes. In this paper, we propose the concept of media modulation based MC where the TX is placed outside the channel and utilizes signaling molecules already existing inside the system. We consider signaling molecules that can be in different states which can be switched by external stimuli. Hence, in media modulation based MC, for information transmission, the TX stimulates the signaling molecules to encode information into their state. In particular, we elaborate media modulation for the group of photochromic molecules, which undergo light-induced reversible transformations, and study the usage of these molecules for information transmission in a three-dimensional duct system. We develop a statistical model for the received signal which depends on the distribution of the signaling molecules in the system, the reliability of the state control mechanism, and the randomness of molecule propagation. Furthermore, we analyze the performance of media modulation based MC in terms of the bit error rate (BER). We show that media modulation enables reliable information transmission, which renders a TX inside the channel unnecessary.

I. INTRODUCTION

To facilitate synthetic molecular communication (MC), several concepts and modulation schemes for embedding information into molecular signals have been proposed over the last few years [1]. In [2], concentration shift keying (CSK) and molecular shift keying (MoSK), where information is encoded into the molecule concentration and the molecule type, respectively, have been proposed. Moreover, the authors in [3] proposed molecular type permutation shift keying (MTPSK) where information is encoded into permutations of different molecule types.

For the implementation of these modulation schemes, the signaling molecules are stored, released, and then replenished by the transmitter (TX). However, from a practical point of view, the replenishment of signaling molecules at the TX is difficult to realize, especially at microscale and in medical applications. Therefore, it is desirable to develop alternative concepts that decouple the modulation process from the release of signaling molecules.

In this context, the concept of media modulation has already been proposed for conventional wireless communication systems. Here, information is embedded into the properties of the communication medium, i.e., the carrier signal is not directly modulated [4], [5]. Extending the concept of media modulation to MC, the authors of [6] propose to alter the properties of the channel to embed information. In particular, they advocate the use of chemotaxis or changing the flow velocity of the medium for modulation [7]. In contrast to this channel-based form of media modulation, in this paper, we propose a new form of media modulation, where the properties of signaling molecules already present in the channel are modulated for information transmission via an external stimulus.

In the simplest case, the molecules can be in two different states which can be switched by an external stimulus to encode the information to be conveyed. Such molecules may be naturally present in the environment or they may be injected and remain in the channel. Media modulation based MC can overcome several shortcomings of existing MC systems by (i) avoiding repeated injections of signaling molecules, making the replenishment of the TX unnecessary, (ii) reducing the soiling of the channel due to the deposition of signaling molecules after repeated injection. Furthermore, the TX, i.e., the source of the external stimulus, is not placed inside the channel and does not influence molecule propagation. The practical feasibility of media modulation hinges on the availability of suitable switchable signaling molecules, of course. The general concept of media modulation based MC is new and has not been reported in the literature, yet. Nevertheless, redox-based MC [8] can be interpreted as an instance of media modulation where signaling particles are switched between two states, the reduced state and the oxidized state. However, the focus of [8] was on the biological and experimental aspects of redox-based MC, while a thorough communication theoretical analysis was not conducted. Furthermore, in biological systems, a natural form of media modulation can be observed during phosphorylation, where a phosphoryl group is added to a protein affecting the properties of the protein. The phosphorylation is mediated by a kinase, a specific type of enzyme, which in turn can be controlled by an external stimulus [9], [10].

Another promising candidate for signaling molecules for media modulation are photochromic molecules. These molecules can be reversibly interconverted between two states, where the transition between the states is induced by light [11]. Photochromic molecules are well established in molecular devices for information processing [11, Chap. 10], but their exploitation for media modulation in synthetic MC systems is new. Photochromic systems facilitate different functionalities including writing, reading, and erasing of information by an external light stimulus. In this paper, we develop a novel modulation scheme for synthetic MC systems employing photochromic signaling molecules. Hereby, the information is embedded into the state of a photochromic molecule. As photochromic signaling molecule, we exemplarily consider the reversibly photo-switchable green fluorescent protein variant “Dreiklang” (GFPD), whose fluorescence can be reversibly switched by light stimuli of mutually different wavelengths [12]. Fluorescence denotes the ability of a molecule to first absorb light and then radiate light back at a higher wavelength, i.e., with a lower energy, which makes it possible to read out the current state of a GFPD. In the proposed system, fluorescent and non-fluorescent GFPD correspond to state A and state B of the signaling molecule, respectively. The fluorescence...
of GFPD can be switched on (B→A) and off (A→B) by light stimuli at different wavelengths. Consequently, assuming the GFPD molecules are suspended in a liquid medium as elements of the envisioned synthetic MC system, optical sources emitting light at mutually different wavelengths can be used as TX (B→A) and eraser (EX, A→B) units, respectively, and an optical sensor can be employed as receiver (RX).

As the proposed form of media modulation is studied for the first time in this paper, we focus on the communication theoretical modeling of the TX, while an in-depth study of the RX and the EX is left for future work. The main contributions of this paper can be summarized as follows:

- We propose a new form of media modulation for synthetic MC and employ switchable photochromic molecules for information transmission. This novel concept does not require a TX that stores and releases molecules, and therefore overcomes several drawbacks of existing modulation schemes, e.g., the need for TX replenishment.
- Since for media modulation, the state of photochromic molecules is switched by external light stimuli, we provide an in-depth investigation of the subjacent photochemical process. The analysis is exemplarily done for GFPD.
- We derive an analytical channel model for the proposed system including the channel impulse response and a statistical model for the received signal. Moreover, we analyze the bit error rate (BER) of the resulting MC system.

The remainder of this paper is organized as follows. In Section II, we introduce the considered MC system and describe the proposed media modulation scheme. In Section III, we derive an analytical end-to-end model for the proposed MC system, and an expression for the BER is provided in Section IV. In Section V, we evaluate the proposed models numerically. Section VI concludes the paper and outlines topics for future work.

II. SYSTEM MODEL

In this section, we describe the proposed media modulation-based MC system, including the modulation, propagation, and reception mechanisms. The system model presented in this section is generic and applicable to different types of photoswitchable fluorescent molecules. Later on, in Section V, the model is specialized to GFPD.

A. Topology, Modulation, Propagation, and Reception

We consider a 3-D straight rectangular duct with height $H$, width $W$, and infinite axial extent, which is oriented along the $z$-axis, cf. Fig. 1. The duct is filled with a fluid, which flows in $z$-direction with constant velocity $v > 0$, i.e., we assume uniform flow, as is widely done in the MC literature [1]. Moreover, we assume that molecules are reflected at the boundaries of the duct, i.e., the duct surface is impermeable to molecules. Additionally, at the duct sections where the TX and the RX are located, we assume the duct surface to be transparent to light. The communication process of interest takes place in a subvolume $S$ of the duct of length $L_{sys}$ and volume size $V_{sys} = WHL_{sys}$.

At time $t = 0$, the fluid is well-mixed and $N_{sys}$ signaling molecules are uniformly distributed in subvolume $S$. These signaling molecules are photochromic, i.e., they can assume two distinguishable states, A and B, and depending on their state, we will refer to them as state A molecules and state B molecules in the following, respectively. The state of a photochromic molecule can be changed by irradiation with light. We assume that the molecules are initially in state B, which might be the equilibrium state or can be enforced by a EX upstream, which forces the molecules into state B.

1) Media modulation at the TX and EX: We consider a two-dimensional (2-D) TX with area $A_{TX} = l_{TX}W$, which is attached to the outer boundary of the duct and extends in $z$-direction in the interval $[z_{a,TX}, z_{b,TX}]$, i.e., the TX has an axial extent of $l_{TX} = z_{b,TX} - z_{a,TX}$, cf. Fig. 1. For information transmission, at $t = 0$, the TX radiates light of wavelength $\lambda_{BA}$ and power $P_{in,TX}$ for an illumination duration of $T_{S,TX}$ onto the volume $V_{TX} = \{(x, y, z) \in S | z_{a,TX} \leq z \leq z_{b,TX}\}$ of size $V_{TX} = WHl_{TX}$. The TX uses ON-OFF keying (OOK) modulation [1], i.e., the TX either radiates power $P_{in,TX} = P_{in,TX,\text{on}}$ or is inactive, i.e., $P_{in,TX} = 0$, representing binary symbols $s = 1$ and $s = 0$, respectively. We assume that binary values 0 and 1 are equiprobable. The TX radiation triggers a photochemical reaction that switches the state of a signaling molecule from B to A with probability $P_{\text{switch}}$, see Section II-B. Since the focus of this paper is on the proposed novel modulation technique, we assume single symbol transmission, i.e., inter-symbol interference (ISI) is not considered.

In the context of media modulation, the purpose of the EX is to trigger the photochemical reaction that switches the state of a molecules from A back to B, i.e., the inverse reaction compared to the reaction at the TX. Therefore, the EX radiates light of a different wavelength $\lambda_{AB}$, i.e., $\lambda_{AB} \neq \lambda_{BA}$. The geometry and functionalities of the EX are similar to those of the TX. However, details are omitted here, and the EX is not explicitly modeled in this paper, cf. Fig. 1.

2) RX model: We consider a 2-D RX with area $A_{RX} = l_{RX}W$, which is attached to the outer boundary of the duct and extends in $z$-direction in the interval $[z_{a,RX}, z_{b,RX}]$, i.e., the RX has an axial extent of $l_{RX} = z_{b,RX} - z_{a,RX}$. We assume that TX and RX have the same orientation and therefore the distance between the TX and RX centers is
\[ d = \frac{z_n,_{RX} + z_n,_{TX}}{2}. \]

The RX is capable of emitting light of wavelength \( \lambda_{in} \) and of sensing light of wavelength \( \lambda_{out} \). In particular, the RX constantly radiates light of wavelength \( \lambda_{in} \) and power \( P_{in,RX} \) into the subvolume \( S_{RX} = \{(x, y, z) \in S | z_n,_{RX} \leq z \leq z_n,_{RX}\} \) of size \( V_{RX} = WHL_{RX} \). The radiated light triggers a fluorescence reaction at molecules that are in state A, i.e., the illuminated molecules in state A radiate light with wavelength \( \lambda_{out} \). This results in a received light power \( P_{out,RX} \) at the RX. We note that all considered wavelengths, i.e., \( \lambda_{BA}, \lambda_{AB}, \lambda_{in}, \) and \( \lambda_{out}, \) are mutually distinct. For FPD, the values of these wavelengths are provided in Table I.

As previously mentioned, we focus on the proposed novel modulation process at the TX, and therefore employ a simple RX model. In particular, we approximate the receiver by a transparent receiver RX\(_{simp}\). RX\(_{simp}\) is able to count the number of state A molecules in \( S_{RX} \) at fixed sampling time \( t_s = \frac{d}{v} \), i.e., the time for a molecule to propagate from TX to RX due to the uniform flow.

3) Propagation: In both states A and B, the molecules are subject to 3-D Brownian motion characterized by diffusion coefficients \( D_A \) and \( D_B \), respectively, and uniform flow. While in general a chemical reaction can result in a change of the molecule structure and size, in the absence of experimental data, we assume \( D_A = D_B \) for FPD, i.e., the size of the molecule remains unaltered when the state of the molecule changes.

B. Photochemical Reaction

We employ photochromic molecules as signaling molecules in our system, i.e., molecules that can be reversibly interconverted from state A to state B by external light. This allows reading, writing, and erasing of information embedded in the state of the molecule. In this paper, we focus on the modulation, i.e., the writing of information, by switching molecules in state B to state A.

The modulation process is described by the following chemical reaction \[ B + \varphi BP_{BA} \rightarrow A, \]

where \( P_{BA} \) denotes a photon with energy \[ E_{P_{BA}} = hf_{BA} = \frac{c}{\lambda_{BA}}. \]

In the following, we assume the molecules are approximately static during illumination, which is a valid assumption if the propagation distance of a molecule within the illumination duration, \( T_{S,_{TX}} \), is much shorter than the TX length \( L_{TX} \), i.e.,

\[ \sqrt{2D_BT_{S,_{TX}}} << L_{TX}, \]

where the propagation distance due to diffusion is characterized by its standard deviation \( \sqrt{2D_BT_{S,_{TX}}} \). Inequality (4) holds for typical system parameters, see Table I. Therefore, in the following, the reaction process is modeled for a closed volume, i.e., we assume that during modulation molecules do not move into or out of the volume.

Photons generated by light of wavelength \( \lambda_{BA} \) can only be absorbed by molecules in state B. Hence, the absorption of photons emitted by the TX is governed by the Beer-Lambert law [11, Eqs. (12.21), (12.22)]

\[ \frac{dN_B(t)}{dt} = q_{in,_{TX}} 1 - \exp\left( -\frac{\log(10)e HN_B(t)}{V_{TX}NA}\right) \]

where \( q_{in,_{TX}}, e, \) and \( NA \) denote the photon flux into \( V_{TX} \), the molar absorption coefficient in \( \text{m}^2\text{mol}^{-1} \), and the Avogadro constant, respectively. Note that the duct height, \( H \), determines the maximum distance a photon can propagate through the volume. The photon flux, \( q_{in,_{TX}} \), is constant within \( T_{S,_{TX}} \) and is given by

\[ q_{in,_{TX}} = \frac{P_{in,_{TX}}A_{TX}}{E_{P_{BA}}}, \]

where all photons have the same energy \( E_{P_{BA}} \), as defined in (2), due to the use of light with fixed wavelength \( \lambda_{BA} \). We assume an initial number of molecules in state B of \( N_B(t=0) = N_{TX} \) in \( S_{TX} \), cf. Section III-B1. We note that \( N_{TX} \) is random, hence, \( N_{TX} \) can be different for every modulation process. Finally, the number of molecules in state B in \( S_{TX} \) as a function of time follows from (5) and (6) as follows

\[ N_B(t) = \frac{1}{a} \exp\left( -\frac{\varphi_B a q_{in,_{TX}} t}{V_{TX}NA} \left( 1 - \exp\left( N_{TX}a \right) \right) \right), \]

where \( a = \frac{\log(10)e H}{V_{TX}NA} \). Finally, the probability of any molecule in \( S_{TX} \) to be switched from state B to state A within the irradiation time \( T_{S,_{TX}} \) is given by

\[ p_{switch} = 1 - \frac{N_B(T_{S,_{TX}})}{N_{TX}}. \]

Note the impact of other possible chemical reactions, e.g., spontaneous switching, i.e., \( B \xrightarrow{k_s} A \) with rate \( k_s \), is neglected in this paper and will be studied in future work.

III. ANALYTICAL END-TO-END CHANNEL MODEL

A. Channel Impulse Response

The system introduced in Section II-A can be modeled as a 1D channel with infinite extent, i.e., \(-\infty < z < \infty\), due to the assumptions of uniform flow and reflective boundaries, and the transparent RX model. We derive the probability of molecules to be observed at RX\(_{simp}\) after being switched to state A at position \( z_{TX} \) at time instant \( t_{BA} \) as a function of time. We refer to this probability as \( h(t) \). Here, \( t_{BA} \) is within the illumination duration \( T_{S,_{TX}} \) for illumination start time \( t = 0 \), i.e., \( t_{BA} \in [0, T_{S,_{TX}}] \). In the following, we approximate \( t_{BA} \) by \( t_{BA} = 0 \), which is a valid assumption for small \( T_{S,_{TX}} \), i.e., if the end of the modulation time length is still approximately at \( t = 0 \). The position \( z_{TX} \) where the molecule is switched to state A is random and uniformly distributed in \( \{z_{a,_{TX}}, z_{b,_{TX}}\} \).

**Proposition 1:** The probability \( h(t) \) that a molecule in state A, which is uniformly distributed inside the TX region, \( z_{a,_{TX}} \leq z_{TX} \leq z_{b,_{TX}}, \) at \( t = 0 \), is observed by RX\(_{simp}\) with dimension \( z_{a,_{RX}} \leq z_{RX} \leq z_{b,_{RX}} \) is given by

\[ h(t) = \frac{1}{2L_{TX}} \sum_{i=0}^{3} (-1)^i \left( \frac{a_i}{\pi} \exp\left( -\frac{a_i^2}{4D_{AT}} \right) + \sqrt{\frac{2D_{AT}L_{TX}}{\pi}} \exp\left( -\frac{a_i^2}{4D_{AT}} \right) \right), \]
where \( \{a_0, a_1, a_2, a_3\} = \{z_{a, RX} - z_{a, TX} - vt, z_{b, RX} - z_{b, TX} - vt, z_{a, RX} - z_{a, TX} - vt, z_{a, RX} - z_{b, TX} - vt\} \). Here, \( \text{erf}(x) \) denotes the Gaussian error function.

**Proof:** The probability \( C_A(t, z_{RX}, z_{TX}) = \frac{1}{\sqrt{4\pi D_A t}} \exp\left(-\frac{(z_{RX} - z_{TX} - vt)^2}{4D_A t}\right) \) that one molecule released at \( z_{TX} \) is observed at \( z_{RX} \) can be derived from [1, Eq. (18)] by integrating over the \( x-y \) plane. The probability of a molecule in state \( A \) to be observed at \( z_{RX} \), initially in state \( B \), observed as state \( A \) follows a Binomial distribution, as the molecules in \( S \mbox{ at } z_{TX} \) are within \( p \mbox{ molecules at } z_{TX} \), and the randomness of the availability of the signaling molecules.

\[
\Pr\{N_{\mbox{sys}} = n_r \} = \binom{N_{\mbox{sys}}}{n_r} p^{n_r} (1-p)^{N_{\mbox{sys}} - n_r},
\]

where \( p = \frac{1}{\sqrt{\pi t}} \int_{z_{RX}}^{z_{TX}} \exp\left(-\frac{(x-z_{TX})^2}{4D_A t}\right) dx \).

Finally, the number \( N_{RX}(t) \) follows the Binomial distribution

\[
N_{RX}(t) \sim \binom{N_{\mbox{sys}}}{p_{\mbox{TX}}p_{\mbox{switch}}},
\]

where \( p_{\mbox{TX}} + p_{\mbox{switch}} = 1 \).

**IV. Symbol Detection and Performance Analysis**

In this section, we provide a threshold based detection scheme and derive the BER for the media modulation based MC.

**A. Detector**

According to the proposed system model, we assume that initially all signaling molecules are in state \( B \) and the state of these molecules can only be switched by illumination at the TX. Hence, for transmit bit \( s = 0 \), probability of \( p_{\mbox{switch}} = 0 \) follows, and according to (13) zero molecules in state \( A \) are observed. On the other hand, once the receiver counts at least one state \( A \) molecule, the receiver should estimate \( \hat{s} = 1 \). Therefore, we employ the following threshold based decision rule

\[
\hat{s} = \begin{cases} 
1, & \text{if } N_{RX}(t) \geq \theta \\
0, & \text{otherwise}
\end{cases}
\]

with threshold \( \theta = 1 \).

**B. Bit Error Rate**

According to (14), the transmission of bit \( s = 0 \) is error free. The transmission error probability for \( s = 1 \) is non-zero due to the probability, that none of the randomly distributed, randomly switched, and randomly propagating molecules is observed at \( z_{TX} \). Therefore, the BER can be expressed as

\[
P_e = \frac{1}{2} \Pr\{\hat{s} = 1 \mid s = 0\} + \frac{1}{2} \Pr\{\hat{s} = 0 \mid s = 1\}
\]

\[
= \frac{1}{2} \left( \binom{N_{\mbox{sys}}}{p_{\mbox{TX}}p_{\mbox{switch}}}(1-p_{\mbox{TX}})^{N_{\mbox{sys}} - 0} \right) + \frac{1}{2} (1-p_{\mbox{TX}})^{N_{\mbox{sys}} - 0}.
\]

(15)
V. PERFORMANCE EVALUATION

In this section, we first specify the properties of GFPD [12], which we investigate as a practically feasible option for photoswitchable fluorescent molecules. Then, we evaluate the statistical model in (13) and compare it to results from particle-based simulation (PBS). Finally, the analytical expression for the BER in (15) is evaluated for different system configurations.

A. Choice of Parameter Values

The default values of the channel parameters are given in Table I and are used if not specified otherwise. We consider GFPD as signaling molecules, as GFPD possesses the properties needed according to Section II. The GFPD specific parameter values are taken from [12], [13]. The parameters related to the duct are chosen such that they have the same order of magnitude as those found in a cardiovascular system [14, Chap. 14]. To verify the accuracy of the analytical expression for the statistics of the received molecules in (13), stochastic PBS were carried out. The results from PBS were averaged over 10^4 realizations.

B. Evaluation of the Switching Process

First, we investigate the photochemical reaction, discussed in Section II-B, for GFPD. In Fig. 2, \( p_{\text{switch}} \), as defined in (8), is shown as a function of input light power \( P_{\text{in,TX}} \) with irradiation duration \( T_{S,TX} = 5 \times 10^{-3} \text{s} \). \( T_{S,TX} \) is chosen such that it is in the range of values considered in [12], where an irradiation duration between \( 1 \times 10^{-7} \text{s} \) and \( 5 \text{s} \) was used. Note that condition (4) is satisfied, since \( 5.1 \times 10^{-5} \text{m} \ll 5 \times 10^{-2} \text{m} \). Moreover, the range of values for \( P_{\text{in,TX}} \) considered here is also reasonable according to [12], where power values ranging from \( 1 \times 10^{6} \text{W/m}^2 \) to \( 1.6 \times 10^{8} \text{W/m}^2 \) were used for light sources with wavelength \( \lambda_{BA} \). From Fig. 2, we observe that the likelihood of a molecule to switch within the irradiation time is low for small input power, increases for increasing input power, and converges to 1 for large values of \( P_{\text{in,TX}} \). Moreover, Fig. 2 shows that \( p_{\text{switch}} \) remains unchanged for a large range of \( N_{TX} \).

Only for systems with a very large number of signaling molecules, i.e., if \( N_{TX} \geq 10^{14} \), a larger input power is necessary to achieve a given switching probability due to the competition for photons among the signaling molecules. Thus, approximating \( p_{\text{switch}} \) to be independent of \( N_{TX} \) is possible for the system under investigation if \( N_{TX} \) is sufficiently small, see Section III-B2. Therefore, as \( N_{TX} \) is random and upper bounded by \( N_{\text{sys}} \), \( N_{TX} \leq N_{\text{sys}} \leq 10^{14} \) is sufficient to ensure statistical independence of the signaling molecules.

C. Evaluation of the Statistics of \( N_{RX} \)

In Fig. 3, we show the end-to-end channel impulse response \( N_{RX}(t) \) derived in Section III-B3, and compare it to results obtained from PBS. We observe that the analytical results are in excellent agreement with the PBS results. We further observe that for \( l_{TX} = l_{RX} \), \( N_{RX}(t) \) has a unique peak at sampling time \( t = t_s = 20 \text{s} \) and the peak height scales linearly with \( p_{\text{switch}} \). Moreover, for larger TX lengths, i.e, \( l_{TX} > l_{RX} \) (blue), the extent of the modulated molecules is larger than the axial extent of the transparent RX. Therefore, not all modulated molecules can be detected by the RX\(_{\text{simp}} \) at once, and hence, \( N_{RX}(t) \) is constant around the sampling time. In contrast, for

| Parameter   | Description                              | Value       | Ref. |
|-------------|------------------------------------------|-------------|------|
| \( L_{sys} \) | Pipe length of S                         | 0.5 m       | [14] |
| \( H \)      | Pipe height                              | 0.001 m     | [14] |
| \( W \)      | Pipe width                               | 0.001 m     | [14] |
| \( l_{TX} \) | TX length                                | 0.05 m      |      |
| \( d \)      | Distance between TX and RX               | 0.2 m       |      |
| \( l_{RX} \) | RX length                                | 0.05 m      |      |
| \( v \)      | Flow velocity                            | 0.01 m s\(^{-1}\) | [14] |
| \( D_A \)    | Diffusion coefficient                    | 1 \times 10\(^{-10}\) m\(^2\) s\(^{-1}\) | [14] |
| \( N_{sys} \) | Number of molecules in S                 | 1000        |      |
| \( \lambda_{BA} \) | Wavelength to switch GFP at TX  | 365 \times 10\(^{-9}\) m | [12] |
| \( \lambda_{AB} \) | Wavelength to switch GFP at EX       | 405 \times 10\(^{-9}\) m | [12] |
| \( N_{in} \) | Wavelength to trigger fluorescence       | 515 \times 10\(^{-9}\) m | [12] |
| \( N_{out} \) | Wavelength of fluorescence               | 529 \times 10\(^{-9}\) m | [12] |
| \( \epsilon \) | Molar absorption coefficient             | 8.3 \times 10\(^{-4}\) m\(^2\)mol\(^{-1}\) | [12] |
| \( \varphi_f \) | Quantum yield                            | 0.41        | [12] |
| \( T_{S,TX} \) | Irradiation time at TX                   | 5 \times 10\(^{-3}\) s | [12] |
| \( \Delta t \) | Time step PBS                            | 1 \times 10\(^{-2}\) s | [12] |

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{The probability of a molecule within the TX to switch from state B to state A within the modulation time length \( T_{S,TX} \) as a function of the input power \( P_{\text{in,TX}} \) for different numbers of molecules \( N_{TX} \) in \( S_{TX} \).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure3.png}
\caption{End-to-end channel impulse response \( N_{RX}(t) \) for \( l_{TX} = l_{RX} \) (black), \( l_{TX} \neq l_{RX} \) (blue and red) with \( l_{TX} = 0.1 \text{m} \) and \( l_{TX} = 0.02 \text{m} \), respectively, and switching probabilities \( p_{\text{switch}} \) obtained for \( P_{\text{in,TX}} = 10^{4} \text{W/m}^2 \), \( P_{\text{in,TX}} = 10^{5} \text{W/m}^2 \) (both dashed), and \( P_{\text{in,TX}} = 10^{6} \text{W/m}^2 \) (solid), see Fig. 2. The results obtained from PBS are depicted by triangle markers.}
\end{figure}
smaller TX lengths, i.e., \( l_{TX} < l_{RX} \) (red), \( N_{RX}(t_s) \) decreases, which is intuitive as, for a smaller TX, \( p_{TX} \) is smaller, i.e., fewer signaling molecules \( N_{TX} \) are within \( S_{TX} \). In Fig. 4, we show the probability mass function of the number of received molecules \( N_{RX}(t_s) \) for \( s = 1 \) according to (13) and compare it to results obtained by PBS. We observe that the results obtained from PBS and (13), respectively, match, which confirms the statistical model proposed in Section III-B.

D. Evaluation of BER

In Fig. 5, the BER is shown as a function of the irradiation power \( P_{in,TX} \) for different numbers of signaling molecules \( N_{sys} \). Here, \( h(t = t_s) = 0.999 \) and \( p_{TX} = 0.1 \). We observe that BER decreases as \( P_{in,TX} \) increases. For \( P_{in,TX} > 6 \times 10^4 \text{W m}^{-2} \), the BER approaches an error floor, which is visible for \( N_{sys} = \{10, 50, 100\} \), but also occurs for larger \( N_{sys} \) at lower BER values. In particular, for large power values, \( p_{\text{switch}} = 1 \) follows, i.e., the switching is deterministic. However, the BER exhibits an error floor due to the TX noise \( n_{TX} \) caused by the randomness of the actual number of signaling molecules, \( N_{TX} \), available at the TX, cf. Section III-B2. Moreover, we note that in agreement with (15), the BER decreases as \( N_{sys} \) increases.

VI. CONCLUSION

In this paper, we introduced a new form of media modulation for MC. Media modulation does not require a TX that stores signaling molecules and controls their release. In particular, in media modulation based MC, a TX is utilized which alters the state of signaling molecules already present in the channel. We investigated the properties of media modulation for the group of photochromic molecules, whose states can be controlled by external light stimuli. Furthermore, we studied the usage of these molecules for information transmission in a 3-D duct system with one TX and one RX. We developed a statistical model for the received signal taking into account the randomness of the initial molecule distribution, i.e., their availability at the TX, the randomness of the switching process, and the randomness of molecule propagation. Finally, we analyzed the performance of a transmission link based on media modulation in terms of BER. Our numerical results showed that media modulation enables reliable information transmission. Therefore, media modulation provides a new perspective for designing non-invasive MC systems.

REFERENCES

[1] V. Jamali, A. Ahmadzadeh, W. Wicke, A. Noel, and R. Schober, “Channel modeling for diffusive molecular communication—A tutorial review,” Proc. IEEE, vol. 107, no. 7, pp. 1256–1301, Jul. 2019.
[2] M. S. Kuran, H. B. Yilmaz, T. Tugcu, and I. F. Akyildiz, “Modulation techniques for communication via diffusion in nanonetworks,” in IEEE Int. Conf. Commun. (ICC), Kyoto, Japan, Jun. 2011, pp. 1–5.
[3] Y. Tang et al., “Molecular type permutation shift keying for molecular communication,” IEEE Trans. Mol. Biol. Multi-Scale Commun., vol. 6, no. 2, pp. 160–164, Nov. 2020.
[4] A. K. Khandani, “Media-based modulation: A new approach to wireless transmission,” in 2013 IEEE Int. Symp. Inf. Theory, Jul. 2013, pp. 3050–3054.
[5] E. Basar, “Media-based modulation for future wireless systems: A tutorial,” IEEE Wireless Commun., vol. 26, no. 5, pp. 160–166, Oct. 2019.
[6] A. Gohari, M. Mirmohseni, and M. Nasiri-Kenari, “Information theory of molecular communication: Directions and challenges,” IEEE Trans. Mol. Biol. Multi-Scale Commun., vol. 2, no. 2, pp. 120–142, Dec. 2016.
[7] M. Farahnak-Ghazani, M. Mirmohseni, and M. Nasiri-Kenari, “On molecular flow velocity meters,” Accepted for Publication in IEEE Trans. Mol. Biol. Multi-Scale Commun., Dec. 2020.
[8] E. Kim et al., “Redox is a global biodevice information processing modality,” Proc. IEEE, vol. 107, no. 7, pp. 1402–1424, Apr. 2019.
[9] M. Grusch et al., “Spatio-temporally precise activation of engineered receptor tyrosine kinases by light,” The EMBO Journal, vol. 33, no. 15, pp. 2173–2176, Jul. 2014.
[10] K.-Y. Chang et al., “Light-inducible receptor tyrosine kinases that regulate neurotrophin signalling,” Nature Communications, vol. 6, no. 1, pp. 1–10, Jun. 2014.
[11] V. Balzani, P. Ceroni, and A. Juris, Photochemistry and Photophysics: Concepts, Research, Applications. Weinheim: John Wiley & Sons, 2014.
[12] T. Brakemann et al., “A reversibly photoswitchable GFP-like protein with fluorescence excitation decoupled from switching,” Nature Biotechnology, vol. 29, no. 10, pp. 942–947, Sep. 2011.
[13] C. Junglas, J.-Z. Schmitt, V. Vukojević, and T. Friedrich, “Diffusion behavior of the fluorescent proteins eGFP and dendra2 in solvents of different viscosity monitored by fluorescence correlation spectroscopy,” Optofluidics, Microfluidics and Nanofluidics, vol. 3, Jan. 2016.
[14] J. E. Hall and M. E. Hall, Gayton and Hall Textbook of Medical Physiology e-Book. Elsevier Health Sciences, 2020, vol. 12th ed.