# Secure HAPS Based FSO Communications Using Metamaterials


1st Seunggi Lee
*School of Electrical Engineering,*
Korea Advanced Institute of Science and Technology
Daejeon, Korea
seunggilee@kaist.ac.kr

2nd Geonho Han
*6G Wireless Access System Research Division,*
Electronics and Telecommunications Research Institute
Daejeon, Korea
ghhan6@etri.re.kr

3rd Miyeon Lee
*School of Electrical Engineering,*
Korea Advanced Institute of Science and Technology
Daejeon, Korea
mylee0031@kaist.ac.kr

4th Junil Choi
*School of Electrical Engineering,*
Korea Advanced Institute of Science and Technology
Daejeon, Korea
junil@kaist.ac.kr



***Abstract*— In this paper, we propose a secure intensity modulation technique that exploits the wavelength-dependent absorption property of a metamaterial in free-space optical communications between high altitude platform stations. The symbol error rate difference between a legitimate receiver and an eavesdropper is adopted as the performance metric, and an optimization problem is formulated to maximize the metric. By optimizing the power ratios of the multiple laser diodes at the transmitter, the proposed method can achieve enhanced physical layer security, outperforming an exhaustive search based on discretized power levels.**



***Index Terms*— Free-space optical communications, high altitude platform stations, physical layer security, metamaterials**


## I. Introduction

As interest in high altitude platform stations (HAPSs) has increased rapidly in recent years, the demand for high-speed and high-capacity communications between HAPSs is growing [1], [2]. Existing radio frequency based communications have various limitations such as frequency congestion, interference, and electronic warfare threats. However, free-space optical (FSO) communications can achieve high data rates with a wide bandwidth by using light and are less affected by electromagnetic interference. Therefore, FSO links are getting attention as a promising candidate for communications between HAPSs [3]. In particular, FSO links can improve security by minimizing signal leakage and reducing unintended interference by using narrow beams.

The directivity of beam, however, may allow receivers located along a line-of-sight path to eavesdrop. Also, the signal may leak in unexpected directions when the propagation path dynamically changes due to the mobility of platforms such as HAPS. In addition, as the propagation distance increases, the footprint of FSO beam becomes larger. If the beam footprint at the receiver exceeds its aperture, the risk of eavesdropping increases [4].

To address these issues, this paper proposes a novel secure intensity modulation technique that exploits a metamaterial with wavelength-dependent absorption. A symbol constellation is designed to maximize the symbol error rate (SER) difference between the legitimate receiver (Bob) and a potential eavesdropper (Eve), thereby enhancing the physical layer security of HAPS-based FSO links.

**Notation:** Scalars, vectors, and matrices are denoted by $a$, $\mathbf{a}$, and $\mathbf{A}$, respectively. The operator $\mathbf{A}^{\mathrm{T}}$ is the transpose of the matrix $\mathbf{A}$. $\mathcal{N}(\mu, \sigma^2)$ represents the normal distribution with mean $\mu$ and variance $\sigma^2$. $\mathcal{LN}(\mu, \sigma^2)$ denotes the lognormal distribution with location parameter $\mu$ and scale parameter $\sigma^2$. $\mathbf{1}_N$, $\mathbf{0}_N$, and $\mathbf{I}_N$ denote the $N \times 1$ all-ones and all-zeros vectors, and the $N \times N$ identity matrix. The operator $\mathrm{diag}(\cdot)$ forms a diagonal matrix from its arguments, and $Q(\cdot)$ denotes the Q function. The expectation operator is denoted as $\mathbb{E}\{\cdot\}$.

## II. System Model

In this paper, we consider an eavesdropping scenario in a HAPS-based FSO system including a Bob HAPS and an Eve HAPS. The transmitter HAPS employs $N_{\mathrm{t}}$ near-infrared (NIR) laser diodes (LDs), each operating at a distinct center wavelength. Both Bob and Eve use a single photodiode (PD), and only Bob is equipped with a metamaterial plate.

### A. Wavelength-dependent absorption of metamaterials

The metamaterial considered in this paper exhibits wavelength-dependent absorption property. Examples of such materials include plasmonic nanoparticles and various 2D materials, whose absorption varies with wavelength across the visible and NIR bands [5]–[8]. Consequently, by employing multiple LDs with different center wavelengths, we can induce different received power at Bob and Eve. The metamaterial used at Bob is the type of plasmonic nanoparticle, and its transmittance $T(\lambda)$ is shown in Fig. 1.

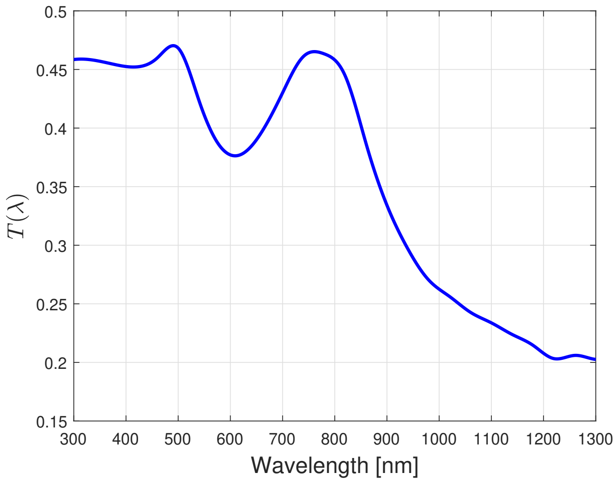


Fig. 1: Transmittance spectrum example of metamaterial.

### B. Channel model

The statistical FSO channel for a HAPS-based link $h$ can be modeled as the product of atmospheric turbulence $h_{\mathrm{t}}$, path attenuation $h_{\mathrm{a}}$, and pointing error $h_{\mathrm{p}}$ [9]. Atmospheric turbulence conditions are characterized by the Rytov variance, $\sigma_{\mathrm{R}}^2$. When $\sigma_{\mathrm{R}}^2 < 0.3$, the atmospheric turbulence is considered weak and can be modeled as a lognormal distribution. Combining the turbulence term with the deterministic path attenuation and pointing error factors, the probability density function of the composite FSO channel can be represented as

$$f_h(h) = \frac{1}{2h\sqrt{2\pi\sigma_{\mathrm{F}}^2}} \exp\left(-\frac{\left(\ln h - (\ln(h_{\mathrm{a}}h_{\mathrm{p}}) - 2\sigma_{\mathrm{F}}^2)\right)^2}{8\sigma_{\mathrm{F}}^2}\right), \tag{1}$$

where $\sigma_{\mathrm{F}}^2 \approx \frac{\sigma_{\mathrm{R}}^2}{4}$. Consequently, the channel $h$ follows a lognormal distribution, i.e., $h \sim \mathcal{LN}(\mu, \sigma^2)$, with the parameters $\mu = \ln(h_{\mathrm{a}}h_{\mathrm{p}}) - 2\sigma_{\mathrm{F}}^2$ and $\sigma^2 = 4\sigma_{\mathrm{F}}^2$.

### C. Received signal model

The NIR spectrum that can be detected by the PDs lies within the wavelength range $[\lambda_{\mathrm{L}}, \lambda_{\mathrm{H}}]$. The PD can only measure the intensity of signal, and the received signal can be expressed as an integral over wavelengths where the integral involves the responsivity of PD and the spectral power distribution (SPD) of the LD [10]. Therefore, after the $k$-th symbol from the transmitter passes through the statistical channel and the metamaterial at Bob, the received signal at Bob can be expressed as

$$\begin{aligned} y_{\mathrm{B},k} &= \sum_{w=1}^{N_{\mathrm{t}}} h_{\mathrm{B},w} p_{w,k} \underbrace{\int_{\lambda_{\mathrm{L}}}^{\lambda_{\mathrm{H}}} P_{\mathrm{T}} R(\lambda) S_w(\lambda) T(\lambda) d\lambda}_{b_{w,k}} + n_{\mathrm{B}} \\ &= \mathbf{h}_{\mathrm{B}}^{\mathrm{T}} \mathbf{B}_k \mathbf{p}_k + n_{\mathrm{B}}, \end{aligned} \tag{2}$$

where $\mathbf{h}_{\mathrm{B}} = [h_{\mathrm{B},1}, \cdots, h_{\mathrm{B},N_{\mathrm{t}}}]^{\mathrm{T}}$ is the channel vector of Bob, $\mathbf{B}_k = \mathrm{diag}(b_{1,k}, \cdots, b_{N_{\mathrm{t}},k})$ denotes the coefficient matrix that incorporates the effect of the metamaterial, and $\mathbf{p}_k = [p_{1,k}, \cdots, p_{N_{\mathrm{t}},k}]^{\mathrm{T}}$ denotes the power ratio vector of the $k$-th symbol. In (2), $R(\lambda)$ denotes the responsivity of the PD, and $S_w(\lambda)$ denotes the SPD of the $w$-th LD. The transmit power is denoted as $P_{\mathrm{T}}$, and the thermal noise is modeled as $n_{\mathrm{B}} \sim \mathcal{N}(0, \sigma_{\mathrm{n}}^2)$ with the noise power $\sigma_{\mathrm{n}}^2$.

Similarly, by excluding the effect of the metamaterial, the received signal at Eve can be derived as

$$\begin{aligned} y_{\mathrm{E},k} &= \sum_{w=1}^{N_{\mathrm{t}}} h_{\mathrm{E},w} p_{w,k} \underbrace{\int_{\lambda_{\mathrm{L}}}^{\lambda_{\mathrm{H}}} P_{\mathrm{T}} R(\lambda) S_w(\lambda) d\lambda}_{e_{w,k}} + n_{\mathrm{E}} \\ &= \mathbf{h}_{\mathrm{E}}^{\mathrm{T}} \mathbf{E}_k \mathbf{p}_k + n_{\mathrm{E}}, \end{aligned} \tag{3}$$

where $\mathbf{h}_{\mathrm{E}} = [h_{\mathrm{E},1}, \cdots, h_{\mathrm{E},N_{\mathrm{t}}}]^{\mathrm{T}}$ is the channel vector of Eve, $\mathbf{E}_k = \mathrm{diag}(e_{1,k}, \cdots, e_{N_{\mathrm{t}},k})$ is the coefficient matrix without the metamaterial, and $n_{\mathrm{E}} \sim \mathcal{N}(0, \sigma_{\mathrm{n}}^2)$ is the thermal noise.

## III. SER Difference Maximization

In this section, we propose the binary pulse amplitude modulation (PAM) symbol design that exploits the different received signal distributions resulting from the wavelength-dependent absorption property of the metamaterial. Only the second-order statistics of FSO channel are assumed to be known at the transceiver, the receivers try to detect the symbols based on these statistics. To ensure the physical layer security performance, we aim to maximize the SER difference between Bob and Eve. The SER difference maximization problem for obtaining the optimal binary PAM symbols is formulated as

$$\begin{aligned} (\mathrm{P1}): \quad & \max_{\mathbf{p}_1, \mathbf{p}_2} \quad \mathrm{SER}_{\mathrm{E}} - \mathrm{SER}_{\mathrm{B}} \\ & \text{s.t.} \quad \gamma \leq \mathbf{1}_{N_{\mathrm{t}}}^{\mathrm{T}} \mathbf{p}_k \leq 1 \quad \forall k, \qquad \text{(1-a)} \\ & \qquad \mathbf{p}_k \succeq \mathbf{0}_{N_{\mathrm{t}}} \quad \forall k, \qquad \text{(1-b)} \end{aligned}$$

where $\mathrm{SER}_{\mathrm{B}}$ and $\mathrm{SER}_{\mathrm{E}}$ denote the SERs at Bob and Eve, respectively. In the constraint (1-a), the unit power is constrained while setting a lower bound on the sum of power ratios given by $\gamma = \frac{R(\lambda_{\mathrm{L}})}{R(\lambda_{\mathrm{H}})}$. Given that both the absorption of the metamaterial and the responsivity of PD vary with wavelengths, a lower bound needs to be considered to utilize only the metamaterial effect and eliminate the influence by the responsivity of PD.

To derive the SER, we first determine the received signal distributions at Bob and Eve. From (2) and (3), the received signals except noise are the linear combinations of lognormally distributed random variables, but their closed form expressions do not exist. For the weak turbulence, however, the scale parameter of lognormal distribution is small and the distribution of the received signal can be approximated as a normal distribution [11].

It is still challenging to compute the SER because the variance of the received signal distribution changes depending on the power ratios. Considering the pessimistic scenario, the variance of received signal distribution is fixed at its upper bound $\alpha$ for Bob and its lower bound $\beta$ for Eve. Each bound can be easily calculated by the convex optimization. With the fixed variances of the received signal distributions, each SER depends only on the distance between the two symbol distributions. When the two symbols are transmitted with equal probability, the SER difference can be represented as

$$\begin{aligned}
&\mathrm{SER_E} - \mathrm{SER_B} \\
&= Q\left(\frac{|\mathbb{E}[y_{\mathrm{E},2}] - \mathbb{E}[y_{\mathrm{E},1}]|}{2\sqrt{\beta}}\right) - Q\left(\frac{|\mathbb{E}[y_{\mathrm{B},2}] - \mathbb{E}[y_{\mathrm{B},1}]|}{2\sqrt{\alpha}}\right) \\
&= Q\left(\frac{|\mathbf{m}_{\mathrm{E}}^{\mathrm{T}}(\mathbf{E}_2\mathbf{p}_2 - \mathbf{E}_1\mathbf{p}_1)|}{2\sqrt{\beta}}\right) - Q\left(\frac{|\mathbf{m}_{\mathrm{B}}^{\mathrm{T}}(\mathbf{B}_2\mathbf{p}_2 - \mathbf{B}_1\mathbf{p}_1)|}{2\sqrt{\alpha}}\right) \\
&= Q\left(|\tilde{\mathbf{m}}_{\mathrm{E}}^{\mathrm{T}}(\mathbf{E}_2\mathbf{p}_2 - \mathbf{E}_1\mathbf{p}_1)|\right) - Q\left(|\tilde{\mathbf{m}}_{\mathrm{B}}^{\mathrm{T}}(\mathbf{B}_2\mathbf{p}_2 - \mathbf{B}_1\mathbf{p}_1)|\right),
\end{aligned} \tag{4}$$

where $\mathbb{E}[\mathbf{h}_{\mathrm{B}}] = \mathbf{m}_{\mathrm{B}}$ and $\mathbb{E}[\mathbf{h}_{\mathrm{E}}] = \mathbf{m}_{\mathrm{E}}$.

The objective function (4) is difficult to handle directly since the Q function includes the integral operation. Thus, we approximate the Q function by (5) for minimizing the sum of square errors [12], which can be expressed as

$$Q(x) \approx \exp(-qx^2 - rx - s), \quad x \geq 0, \tag{5}$$

where $q = 0.3842$, $r = 0.7640$, and $s = 0.6964$. The objective function is, however, still intractable since it is not a concave function with respect to $\mathbf{p}_1$ and $\mathbf{p}_2$. To address this issue, we solve (P1) by converting it into a standard convex optimization form using the successive convex approximation (SCA) approach and the alternating optimization (AO) technique.

## IV. Simulation Results

In this section, the performance of proposed method is validated through simulations. The transmitter employs three LDs with center wavelengths of 800 nm, 900 nm, and 1000 nm. The transmitter HAPS is located at $(0, 0, 20)$ km, while the Bob HAPS and Eve HAPS are located 10 km above the transmitter HAPS. The thermal noise variance is $\sigma_{\mathrm{n}}^2 = -140$ dBm.

Fig. 2 shows the SER performances at Bob and Eve and compares the proposed method with the Monte-Carlo (MC) simulation baseline. The baseline computes the received signal distribution via MC simulation and performs the exhaustive search over a discrete symbol set to determine the optimal symbols. The proposed method and the MC baseline both show that increasing transmit power decreases the SER at Bob while keeping the SER at Eve high. However, the proposed method achieves lower SER than the MC baseline for Bob while simultaneously achieving a higher SER at Eve. By optimizing the symbols over the continuous set, the proposed method further increases the SER difference compared with the MC baseline. Although the MC baseline employs the exhaustive search, its performance is degraded due to finding symbols in the discrete set.

## V. Conclusion

This paper proposed a novel secure intensity modulation technique by employing the wavelength-dependent absorption property of a metamaterial in HAPS-based FSO links. Leveraging this property, we formulated an optimization problem that maximizes the SER difference between Bob and Eve with respect to the transmit power ratio. The nonconvex optimization problem was solved by using SCA and AO approach. Simulation results verified that the proposed method achieves better SER difference compared to the exhaustive search in a discrete set.

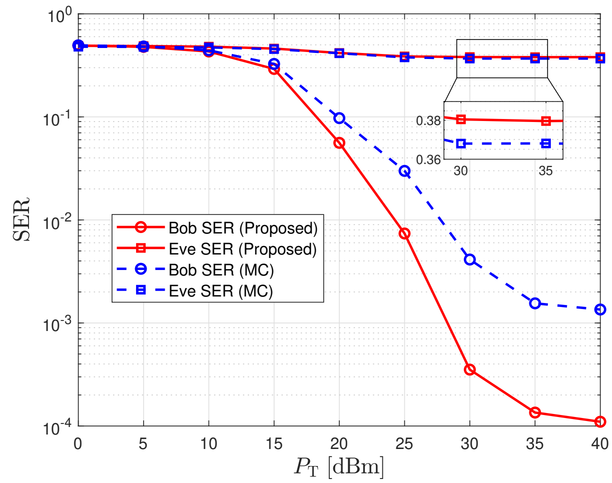


Fig. 2: SERs at Bob and Eve depending on the optimization methods.

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