Energy-Efficient, Turbulence-Regime based Adaptive FSO Broadcast Systems

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***Abstract*—The need for digital multimedia has surged with advanced and affordable mobile devices. Offering multimedia via free space optical (FSO) systems is possible but doing so requires a lot of energy. Also, for optical wireless communication systems, signal strength degradation brought on by atmospheric turbulence is an unavoidable drawback. In this paper we present an energy-efficient turbulence-regime based adaptive FSO broadcast scheme, that optimally combines the turbulence-regime information at the receiver with a particular multimedia service (e.g., video quality profile) for adaptive scalable multimedia encoding of the broadcast content. The strength of turbulence at the receiver is obtained a priori based on rytov parameter at that location. Based on this information, in order to optimally use the base station power reserve the transmitter may decide to send turbulence adapted multimedia content quality namely, a fair signal strength instead of good/excellent for weak turbulence, good signal strength instead of excellent for moderate turbulence and excellent signal strength for strong turbulence . By incorporating the turbulence information in the multimedia encoding, the proposed scheme helps to achieve a better quality of experience and higher energy saving both in terms of base station power reserve and user equipment energy saving as compared to the pure quality maximizing scheme or fixed power allocation scheme. The simulation results also show that the churn rate is minimum in the proposed scheme.**

***Index Terms*—Adaptive multimedia broadcast; scalable video coding; heterogeneous users; energy consumption; turbulence regime**

I. INTRODUCTION

Optical signals are susceptible to atmospheric turbulence conditions which can scatter or absorb the signal and degrade the quality of the communication. In order to transmit data through turbulent air, free space optical (FSO) systems require line-of-sight (LoS) path and a power source to generate and amplify the optical signal. However, the amount of power available at the transmitter may be limited, which can affect the quality and range of the communication.

Fig. 1 depicts a scenario in which multimedia content is being broadcasted to different receivers via LoS FSO channel which is impaired by atmospheric turbulence. The receivers range from stationary high-resolution devices such as LCD TVs, PCs and terminals to mobile devices that have limited battery power, as well as low-resolution devices. In short, the base station (BS) is serving a diverse customer base, and due to the heterogeneity of mobile devices and usage patterns such as location, frequency, and duration, there are various constraints on the user side in such a broadcast environment. Also, the base station itself can be stationary or moving (terrestrial BS or aerial BS such as LAP/HAP).

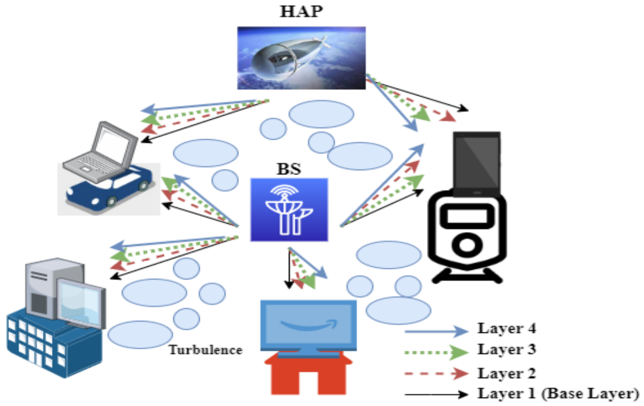

Fig. 1. Heterogeneous free space optical communication broadcast scenario

A. Motivation

The processing of high-resolution and high-frame-rate multimedia content on portable devices consumes significant amounts of battery energy. This sometimes leads to poor user experiences characterized by rapid battery drain and unexpected device shutdowns, especially during multimedia streaming. To tackle this issue, researchers are actively working on developing technologies that can prolong the battery life of low-battery active users [1], [2]. Among these approaches, scalable video coding (SVC) and time-sliced transmission techniques have shown promise in addressing these challenges and enhancing the overall multimedia experience which is the primary focus of this paper.

Moreover, in the era of green communication, it is crucial not only to save the battery reserve of user equipment (UE) but also to prioritize power-saving strategies for base stations. Free space optical communication experiences varying levels of signal degradation across different atmospheric turbulence regimes, including weak, moderate, and strong turbulence. Weak turbulence regimes exhibit minor fluctuations in the signal, resulting in minimal distortion. In moderate turbulence regimes, larger amplitude fluctuations cause increased signal fading and power loss. Strong turbulence regimes feature intense and rapid fluctuations, leading to deep signal fades and significant power loss. Hence, it is not advisable to use a fixed signal strength across all turbulence regimes because this approach would either waste power in mild conditions or result in inadequate signal strength during severe turbulence. By adapting the signal strength to match the turbulence regime, adaptive power control techniques can optimize performance and ensure reliable communication.

Definition 1. *The channel preference (C_p) refers to the suitability of a channel for broadcasting a specific video quality level, aiming to prevent significant signal degradation/buffering. It is determined based on the chosen video quality levels using the Mean Objective Score (MOS) scale as given in [3]. For each device, the channel preference (C_p) is a measure that considers the selected video quality levels preferred by the user and the corresponding signal strength at the device's location.*

Definition 2. *The Preference Score (PS) scale utilized in this study has been designed following a structure similar to the MOS scale. It signifies how much the channel is preferable for a given video quality transmission as shown in Table I.*

TABLE I

PREFERENCE SCORE (PS) SCALE FOR C_p

PS	Preference level
5	Most preferred
4	Preferred
3	Somewhat preferred
2	Less preferred
1	Not at all preferred

B. Contributions and Significance

This paper suggests a new mechanism for FSO broadcast systems in a heterogeneous environment as shown in Fig. 1. The proposed approach adapts the multimedia broadcast content transmission power at the transmitter based on the atmospheric turbulence strength known at the receiver end. This technique not only enhances energy efficiency at the BS but also ensures that the quality of experience (QoE) is improved for devices facing moderate/strong turbulence regimes. The key contributions of the work are:

- Adaptive power control is used to adjust the transmission power of the FSO system based on the knowledge of atmospheric turbulence strength. The power control mechanism continuously monitors the channel conditions, including the level of turbulence, and adapts the transmission power accordingly. This helps to compensate for the varying atmospheric conditions and maintain a reliable communication link.
- SVC is employed to encode the multimedia content into multiple layers or streams. Each layer represents a different level of quality or resolution. This enables the transmission of scalable video bitstreams that can be adjusted based on the available channel conditions and the receiver's capabilities. In the presence of atmospheric turbulence, SVC allows the system to dynamically adapt the video quality by selecting and transmitting the appropriate layer that can be reliably received.
- Time-sliced transmission optimizes resource efficiency by dividing the transmission time into smaller intervals and dynamically allocating resources based on receiver's needs.

II. SYSTEM ARCHITECTURE

As depicted in Fig. 2, the user equipment side encompasses of: (1) a device location module based on which the turbulence regime present at that location can be inferred; (2) a user video quality profile module that allows users to select the quality of video profile (good/fair) they want to receive; (3) a power manager responsible for monitoring the mobile device's battery level and utilizing time-slicing techniques to conserve energy in accordance with the remaining power.

On the server side, there is an adaptive SVC module responsible for encoding multimedia content into scalable video layers using optimal SVC parameters. The encoding process takes into account information received from the client, such as the channel state at its location, the user's video quality profile choice, energy consumption considerations.

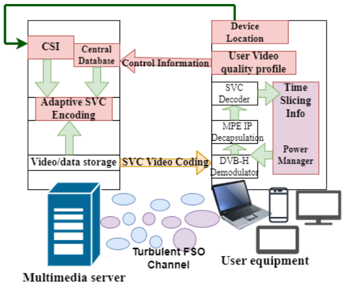

Fig. 2. System Architecture

III. PROBLEM FORMULATION AND ALGORITHM

The proposed scheme has two parts: modeling channel state information and adaptive SVC with time-slicing for energy-efficient multimedia broadcast. This section focuses on the channel state modeling, used for adaptive SVC encoding to achieve efficient broadcasting.

A. Scintillation study and turbulence mathematical modeling

Rytov variance is a parameter which is commonly used to characterize the strength of optical turbulence. It is related to the index of refraction structure parameter (C_n^2), the horizontal distance (L), travelled by the optical field/radiation by the following equations:

$$\sigma_I^2 = 1.23 C_n^2 k^{7/6} L^{11/6}. \tag{1}$$

Remark: *We have assumed a plane wave propagating through a homogenous turbulent field, which can be assumed for near-ground horizontal-path propagation and hence, the refractive-index structure parameter is treated as constant in our study.*

Based on the Rytov variance which changes with receiver's location, the scintillation levels are usually divided into three regimes [4]: a weak fluctuations regime $(\sigma_I^2 < 0.3)$, a moderate-fluctuations regime (focusing regime) $(0.3 \leq \sigma_I^2 < 5)$, and a strong fluctuations regime (saturation regime) $(\sigma_I^2 \geq 5)$. Based on type of turbulence regime at the UE, the average PS versus signal strength (PS-SS) trends are shown in Fig.

3(a) for the 'good' and 'fair' video quality profiles. The signal strength values were determined using the phase screen simulation method [5]. This method generates realistic atmospheric turbulence and produces optical scintillation. By simulating the phase screens, we were able to obtain accurate signal strength measurements that reflect the actual atmospheric conditions and the resulting optical scintillation effects. Subsequently, the average Preference Score (PS) scale was computed based on the definitions provided earlier (Definition 1 and Definition 2). It is an indication of how much the present channel conditions are preferable (PS is more than '3') for satisfactory delivery of particular video quality selected by user. Phase screen simulation data suggest that for satisfactory (avoiding deep fades) streaming of 'fair' video quality profile, the signal strength needed at receiver should be more that 30%. For 'good' video profile streaming the signal strength needed at receiver is more than 45%. The Preference Score for channel increases with increase in received signal strength for 'good' and 'fair' video quality profile streaming.

An inverse exponential function is used to model the PS-SS variation trends. The average PS to the signal strength at the user equipment (UE) for the 'good' and 'fair' video quality profiles is given by: $f(s) = \frac{1-\exp^{-\zeta.s}}{1-\exp^{-\zeta}}$, where ζ is a parameter, that closely approximates the variation of PS with signal strength as shown in Fig. 3(b) and 3(c).

A channel's preference C_p is determined by the chosen video quality profile and the suitability of the channel state for transmitting the desired video quality as given below :

$$C_p(S) = \Omega_{exc}.C_{p_{exc}}(S)+\Omega_{good}.C_{p_{good}}(S)+\Omega_{fair}.C_{p_{fair}}(S) \tag{2}$$

where, Ω is an indicator of the chosen video quality profile by the user. For example, if a user request an 'excellent' video profile then, $\Omega_{exc} = 1$, $\Omega_{good} = \Omega_{fair} = 0$, $C_{p_{exc}} = 5$. As can be seen from Fig. 3(a), the signal strength required at such setting will be more than 80% at the UE. Similarly for 'good'/'fair' video quality profile $C_{p_{good/fair}}(S)$ can be calculated by putting $\Omega_{exc} = 0$, $\Omega_{good/fair} = 1$. Accordingly, the inverse exponential function that best fits is given by:

$$C_{p_{good/fair}}(S) = C^{max}_{p_{good/fair}}.\left(\frac{1-\exp^{-\zeta_{good/fair}.S/S_{max}}}{1-\exp^{-\zeta_{good/fair}}}\right). \tag{3}$$

The modeling of channel preference, represented by the function $C_p(S)$ in equations (2) and (3), is depicted in Fig. 3(b) and 3(c) for the 'fair' and 'good' video quality profile respectively. The parameters used in the inverse exponential function, $\zeta_{fair} = 2.49$ for the 'fair' profile and $\zeta_{good} = 0.88$ for the 'good' profile. The absolute errors between the mathematical model and simulation data is less than 1% for both profiles, indicating a high degree of accuracy.

B. Adaptive Power Allocation at BS

Once the level of atmospheric turbulence experienced by the receiver is known, adaptive power control techniques can be employed at the base station (BS) to optimize the utilization of its power reserves. Simulation results indicate that, for streaming a 'good' video profile, signal strength exceeding 45% is required at the receiver. This requirement can typically be met in weak turbulence regions and, in some cases, even in moderate turbulence. However, it may not be sustainable in strong turbulence. Consequently, instead of transmitting equal power to all receivers, the BS can categorize its heterogeneous users based on their turbulence levels and employ adaptive power coding accordingly. This approach involves using high signal power for users experiencing strong turbulence, good signal power for those in moderate turbulence, and marginal signal power for users in weak turbulence regions.

In the exponential power control policy [6], the transmit power P is related to the received signal power y given by:

$$P = P_{max} * f(y) \tag{4}$$

where P_{max} is the maximum allowable transmit power, and $f(y)$ is the exponential power control function given by:

$$f(y) = \frac{1-e^{-d.y}}{1-e^{-d.y_0}}. \tag{5}$$

The function $f(y)$ maps the received signal power y to a transmit power P in a non-linear manner that depends on the value of d. The function is typically derived based on the channel characteristics and the desired performance (in our case SNR). The value of d determines the rate at which the transmit power has to be increased for maintaining a desired received signal power. A higher value of d leads to a more aggressive power control policy, where the transmit power increases more rapidly with increasing received signal power, while a lower value of d leads to a more conservative power control policy, where the transmit power increases more slowly with increasing received signal power.

C. Energy efficient multimedia content reception for UE

In this subsection, our focus is on maximizing energy efficiency for the user equipment by determining optimal video encoding parameters based on the subscriber's quality profiles, channel preference score, and QoE constraints.

The Quality of Experience (QoE) for the n^{th} user, denoted as QoE_n, is determined using the parametric video quality model described in [7], and is given by equation (6).

$$\begin{aligned} QoE_n = QoE(q,t_n) &= QoE_{max}.QoE_{t_n}.QoE_q(q) \\ &= QoE_{max}.\frac{e^{-g\frac{q}{q_{min}}}}{e^{-g}}.\frac{1-e^{-h\frac{t_n}{t_{max}}}}{1-e^{-h}} \end{aligned} \tag{6}$$

where t_n, q are the frame rate and quantization level. $q = 2^{(Q-4)/6}$ for a specific video parameters (h and g) and quantization parameter Q. QoE_{max} is the max. video quality achievable at min. quantization level (q_{min}) and highest frame rate (t_{max}).

The time-slicing mechanism allows conservation of energy by selectively switching off the receivers if they are not receiving certain SVC layers. The energy-saving E_{save} is given by equation (7) for a particular user, which is influenced by factors such as the overhead duration (H), burst size of the base layer (b), and the rate ($\Re$) of the received SVC video,

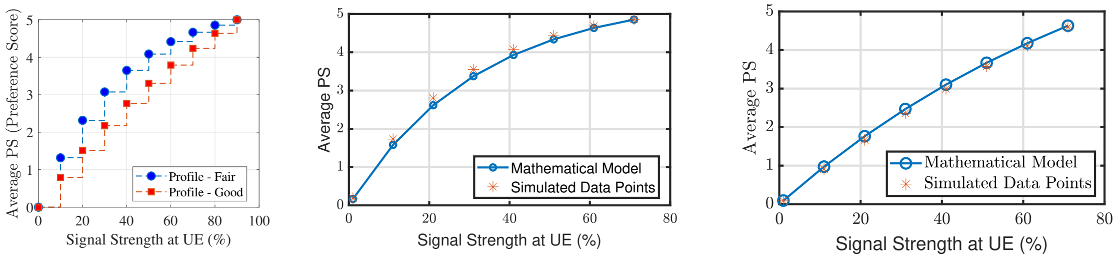

Fig. 3. (a)The average Preference Score (PS) based on the signal strength values obtained from the phase screen simulation (b) Mathematical and simulation result comparison for average PS to signal strength for 'Fair video quality' (c) Mathematical and simulation result comparison for 'Good video quality '

considering the quantization level (q), frame rate (t_n), and spatial resolution (s_n).

$$E_{save} = 1 - \Re^{-1}\Re(q, t_n, s_n) - H.c.b^{-1}\Re(q, t_{min}, s_{min}). \quad (7)$$

By employing a time-sliced approach in the transmission of optimized video encoding using SVC, the energy-saving potential for subscriber User Equipment (UE) is greatly influenced. The concept of time-slicing governs the extent to which energy can be conserved by the UEs. Therefore, by determining the optimal video encoding parameters considering factors such as subscribers' quality profiles, channel preference score, and Quality of Experience (QoE) constraints, we can effectively enhance the energy-saving capabilities of the subscriber UEs.

The optimization problem for maximising UE's energy saving for our proposed scheme is defined as follow:

$$\begin{aligned} \max_{q} \quad & \sum_{n=1}^{U_{served}} E_{save} \\ \text{s.t.} \quad & QoE_n \geq 0.25, 1 \geq n \geq U_{served}, and \\ & C_p(S) \geq 3, 1 \geq n \geq U_{served} \end{aligned} \quad (8)$$

where U_{served} represents the count of users whose $QoE_n \geq 0.25$ (given by eq (6)), out of the total U subscribers, $C_p(S)$ represents channel preference score for user U given by eq (2), and E_{save} is the energy saved by user U because of time-slicing based transmission (eq. 7).

Remark: *The constraint on $C_p(S)$ in equation (8) ensures that the delivered video quality and energy saving provided to the receiver are in accordance with the available channel state information.*

IV. RESULTS AND DISCUSSION

A. Simulation scenarios

For simulation study, a Harbor test video sequence is used consisting of 300 frames. The video sequence is broadcast to a group of 300 users, with parameters $h = 7.38$ and $g = 0.06$. We have analyzed the proposed scheme under different scenarios, as listed in Table II, considering varying proportions of users experiencing different turbulence levels and requesting different video quality levels, such as 'good' or 'fair'.

B. Performance Metrics

1) *Churn rate:* In our context it refers to the no. or % of subscribed users who are lost ($\nu_{subscriberslost}$) because of bad signal strength ($C_p(S) < 3$). A user is considered served if they receive at least a 'fair' video quality ($C_p(S) > 3, QoE_n > 0.25$) . However, in some cases, users may not be able to achieve even the 'fair' video quality due to weak signal strength caused by high turbulence, resulting in them churning out of the service provider. A better scheme is one that reduces churn rate, implying fewer users are lost due to signal issues.

TABLE II
SIMULATION SCENARIOS WITH VARYING USER RATIOS (IN %) ENCOUNTERING DIFFERENT TURBULENCE LEVELS AND DESIRING DIFFERENT VIDEO QUALITY PROFILES (GOOD OR FAIR).)

Scenario	Good Video Quality			Fair Video Quality		
	Weak	*Moderate*	*Strong*	*Weak*	*Moderate*	*Strong*
1	40	5	5	40	5	5
2	10	20	20	10	20	20
3	25	12.5	12.5	25	12.5	12.5

2) *BS power saving efficiency, P_{served}:* It refers to the proportion of users who are served according to their demanded video quality profile while utilizing a fixed power reserve at the base station (BS). Mathematically, it can be expressed as:

$$P_{served} = \frac{(N_{served}^{weak} + N_{served}^{moderate} + N_{served}^{strong})}{N}. \quad (9)$$

The numerator represents the total number of served users across all video quality profiles, and the denominator represents the total number of users in the system. The higher the value of P_{served}, the more number of users are served which in turn implies efficient utilisation of the BS fix power reserve to serve users based on their demanded video quality profiles.

3) *Average QoE:* To assess the overall video quality experienced by users in the system under different scenarios outlined in Table II, we calculate the weighted average parametric video quality, denoted as (QoE_{avg}). This metric allows us to evaluate the collective video quality considering the varying types of users in the system. The calculation of QoE_{avg} is determined by dividing the sum of subjective video quality ratings, Q_n, for all users (n) by the total number of subscribed users, N. In other words, QoE_{avg} represents the average video quality experienced by each user in the system.

4) *UE average energy saving:* To assess the overall energy saving achieved by different types of users in the system under the scenarios outlined in Table II, we calculate the weighted average energy saving, denoted as ϵ_{save}. This metric allows us to evaluate the collective energy efficiency considering the

varying types of users in the system. It is defined as $\epsilon_{save} = \frac{\sum_{n=1}^{N} E_{save}}{N}$, where N is the total number of subscribed users.

C. Simulation results

The performance is evaluated by comparing the proposed scheme with three other approaches: P_{fix}, E_{max}, and Q_{max} scheme. The P_{fix} scheme delivers the same power to all users, while the E_{max} scheme focuses on maximizing energy saving (while ensuring at least 'fair' video quality). The Q_{max} scheme aims to maximize the quality of experience (QoE) for served users. The relative performance of these schemes based on the four performance metrics discussed above (Section IV-B) are given in Tables III and IV. It's worth noting that neither the P_{fix}, E_{max}, nor Q_{max} schemes take into account the channel preference score ($C_p(S)$) in their evaluations.

TABLE III

POWER, QUALITY, AND ENERGY SAVING PERFORMANCE FOR THE SCENARIOS IN TABLE II OF QoE_{avg} AND ϵ_{save} FOR P_{same}, Q_{max}, E_{max}, AND THE PROPOSED SCHEME (PR).

Scenario	QoE_{avg}				ϵ_{save}			
Table II	P_{same}	Q_{max}	E_{max}	Pr	P_{same}	Q_{max}	E_{max}	Pr
1	0.773	0.854	0.621	0.796	0.855	0.821	0.955	0.941
2	0.245	0.512	0.404	0.496	0.637	0.776	0.951	0.902
3	0.312	0.629	0.438	0.527	0.656	0.706	0.971	0.931

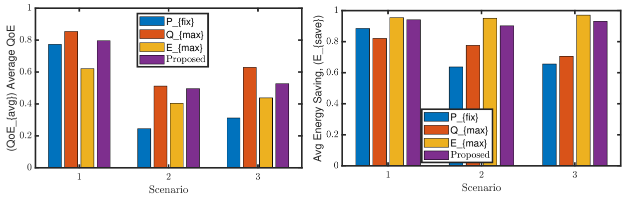

Fig. 4. (a) Avg QoE , (b) Avg Energy Saving, for, scenarios of Table II.

Figure 4(a) presents a bar graph displaying the average quality of experience (QoE), while Figure 4(b) showcases a bar graph illustrating the average energy saving (E_{save}) for the scenarios described in Table II. It is noteworthy that among the four schemes considered, the P_{fix} and E_{max} schemes yield the lowest average QoE. Interestingly, our proposed scheme achieves a nearly identical average QoE compared to the Q_{max} scheme. On the other hand, the Q_{max} scheme yields the lowest average energy saving. Additionally, it is evident that the proposed scheme, performs at an intermediate level between all the four schemes. Fig. 5 illustrates a bar graph depicting the churn rate (%) and BS power efficiency (P_{served}) based on the proportion of users served for the P_{fix}, Q_{max}, E_{max}, and proposed schemes. The results demonstrate that the proposed scheme has a lower churn rate compared to the P_{fix} and Q_{max} schemes, while achieving the highest BS power efficiency. Although the churn rate of the proposed scheme is slightly higher than that of the E_{max} scheme. However, the E_{max} BS power efficiency is lower (only 60.19%, i.e., 10% less than the proposed scheme). Therefore, it can be inferred that the proposed scheme outperforms the P_{fix}, E_{max}, and Q_{max} schemes by serving more users based on their device capabilities and video quality profiles, considering channel preferences, and making better use of the base station power reserve.

TABLE IV

CHURN RATE(%) AND BS POWER SAVING EFFICIENCY,I.E. P_{served} FOR P_{fix},Q_{max},E_{max} AND PROPOSED SCHEME (PR).

	P_{fix}	Q_{max}	E_{max}	Pr
Churn rate (%)	34.67	29.00	17.00	21.00
P_{served}	45.19	52.33	60.19	79.83

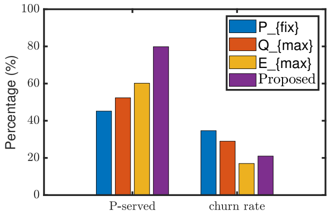

Fig. 5. Churn Rate & BS power efficiency for P_{fix}, Q_{max}, E_{max} and Proposed Scheme

V. CONCLUSION

This paper presents a study on a channel adaptive FSO broadcast system, focusing on the impact of atmospheric turbulence on the reception of multimedia content by mobile devices. A turbulence preference-based adaptive multimedia broadcast method is introduced. It employs analytical adaptive power control to determine the transmit power based on statistical channel preference scores, optimizing parameters for SVC. The goal is energy efficiency through time-sliced SVC transmission. Compared to the Q_{max} based approach, the proposed scheme achieves significantly higher energy savings and a lower churn rate. Additionally, the QoE with the proposed scheme surpasses the purely energy-saving (E_{max}) approach. Two additional advantages include adherence to user preferences for video quality and broader subscriber coverage, along with more efficient utilization of base station power reserves than fixed power allocation scheme.

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