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RESEARCH ARTICLE

A Supermartingale Theory-Based Random Compensation Algorithm for Visible Light Communication/Radio Frequency Hybrid Networks

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ABSTRACT Visible light communication (VLC)/radio frequency (RF) hybrid networks exhibit large system capacity, high reliability, and low access latency. To simplify the resource allocation process of such hybrid networks, we devise a random compensation algorithm based on supermartingale theory. Firstly, a network queuing model with random arrival traffic and random compensation service mechanism are established. Then, the delay performance is evaluated based on supermartingale theory, and a tighter delay violation probability bound is derived. A search algorithm is designed to obtain the compensation bandwidth and compensation probability based on the RF. Finally, the devised algorithm is compared with that based on large deviation theory. The results of simulations demonstrate that the proposed algorithm is authentic and could save bandwidth.

INDEX TERMS VLC/RF networks, compensation bandwidth, compensation probability, supermartingale, delay performance.

I. INTRODUCTION

Visible light communication (VLC) has emerged as a promising communication technology due to its rich spectrum resources and energy-saving capability [1], [2], [3]. However, the transmission range and transmission path are limited for VLC. With the aid of radio frequency (RF), the heterogeneous networks composed of VLC and RF can formulate a complementary solution of high-speed transmission and wide coverage. In hybrid VLC/RF networks, the access processes of different networks must be well coordinated for efficient resource management. The existing scheduling methods require frequently decision making [4], [5], which increases energy and bandwidth consumption. The decision process based on prevailing machine learning needs the support of effective training information in resource distribution [6], [7]. To improve the service efficiency of VLC/RF networks, it is more practical to study a more suitable scheme for resource allocation.

In recent years, the terminals and applications of communication networks are growing rapidly, which puts forward more and higher requirements on quality of service (QoS). The contradiction between service efficiency and QoS guarantee is becoming increasingly apparent. Reasonable evaluation for network performance is the key to allocate resource efficiently. The effective capacity (EC) is a typical methodology used to analyze and guarantee QoS performance [8]. However, because the effective capacity originates from large deviation theory, it is conservative in performance bound analysis, which may result in a loose estimation of delay QoS. Based on supermartingale theory, the authors of [9] innovatively introduce the concepts of arrival-martingales and service-martingales, and thereby derive a tighter QoS performance bound. Supermartingale is a special stochastic process with decreasing expectation in time series. By leveraging the powerful supermartingale methodology, the rigorous results of performance have been demonstrated in [10], [11], [12],

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[13], and [14]. Therefore, we believe the supermartingale approach could also increase the efficiency of resource distribution in hybrid networks.

Considering these aspects, we establish a random non-scheduling mechanism for VLC/RF systems and extend supermartingale theory to the hybrid communication scenario. To the best of our knowledge, this study represents the first effort to apply supermartingale theory to the analysis of VLC/RF networks. The contributions of this work can be summarized as follows:

- By coupling the randomness of the service and arrival processes, we develop a random compensation model for the mixed service of VLC/RF systems. By mapping the queuing system to the supermartingale domain, we obtain a tighter bound for the delay violation probability.
- Based on supermartingale analysis, we design a search programme to calculate the compensation bandwidth and compensation probability associated with the RF, and a random compensation scheme for VLC/RF networks is developed. The scheme could improve the efficiency of network services.

II. RELATED WORK

The heterogeneous networks formed by VLC/RF can improve transmission rate, increase network overage, and support the applications of high reliability in future wireless communication. How to coordinate the access process is the core issue of the resource management in VLC/RF networks. To improve the per-user outage data rate performance of VLC/RF networks, the authors of [4] devise a simple RF deployment, and the users are dynamically assigned to VLC or RF according to the channel conditions. With the objective of maximizing the sum rate for the downlink of hybrid VLC/RF networks, an optimized solution for combined power and slot allocation is provided in [5], and the frequency of optimization is reduced. According to the requirements of different terminals and network conditions, the system performance could be optimized through dynamic selection of access point (AP). However, the process of link selection requires frequent decision making, and less attention has been paid to this consumption of energy and bandwidth. In our previous research [15], the random compensation approach that does not require a decision is established relying on the two-hole leaky bucket mechanism, but the work does not involve hybrid networks. The continuous development of machine learning provides a new space for resource management. The authors of [6] present a solution based on a deep neural network to select RF or VLC for device-to-device pairs, which is of low complexity and reaches a close-to-optimal performance. In [7], for a hybrid LiFi/WiFi networks, a reinforcement learning algorithm is implemented to determine the appropriate AP assignment, which increases the long-term average system throughput and ensures the required QoS. However, the rationality of allocation strategy based on machine learning greatly depends on the training information.

The performance of VLC/RF hybrid networks should be reasonably evaluated to ensure efficient service. As the randomness of network services, the large deviation is an alternative methodology to analyze such stochastic system. Large deviation is one of the mainstream branches of probability theory, and mainly studies small probabilities on an exponential scale [16]. Effective capacity is an significant achievement derived from large deviation, and plays an important role in QoS analysis and guarantee. The authors of [17] devise a suboptimal approach based on the partial effective capacity, and they study the power control policy for non-orthogonal multiple access to meet delay QoS. Simulation results confirm that the given delay QoS could be satisfied. For delay-sensitive traffic of orthogonal frequency-division multiple-access networks, the authors of [18] propose a spectrally efficient design based on the effective capacity to guarantee statistical delay QoS. Unfortunately, the analysis methodology based on effective capacity is conservative, which would lead to the over-guarantee of QoS performance.

The evolution of supermartingale theory provides a new perspective for network performance evaluation. In [9], the analysis framework based on the concepts of arrival-martingales and service-martingales are proposed, and then a series of supermartingale-based achievements are produced inspired by their research. The authors of [12] apply a supermartingale model to the delay analysis of short packet access and then develop the energy-efficient differentiated random access algorithm, which achieves energy conservation and satisfies QoS requirements simultaneously. To fulfil diverse service demands, on the basis of a supermartingale, the delay bounds are derived for multi-hop vehicular ad hoc networks and multimedia heterogeneous high-speed train networks in [13] and [14], and simulation results verify that the supermartingale-based delay bounds are remarkably tight with real data. Based on the derived supermartingale delay bound, the authors of [19] propose an optimal task allocation scheme for heterogeneous vehicular networks. The superiority of supermartingale analysis has been widely recognized. However, the existing supermartingale-based research mainly focuses on a single type of access network. Desiring to acquire more efficient solution, we utilize supermartingale theory to explore the random compensation algorithm for the mixed VLC/RF networks.

III. SYSTEM MODEL

For VLC network, the channel stability is prone to decline due to the occlusion issue. This problem could be settled through by RF assistance. In our scheme, we consider a communication scenario with k VLC APs and a single RF AP in an indoor environment. As shown in Fig. 1, the VLC APs are placed on the ceiling, and the RF AP is fixed on the wall. All of the users are equipped with photodetectors. We assume that there is no interference between the VLC APs. RF network reserves

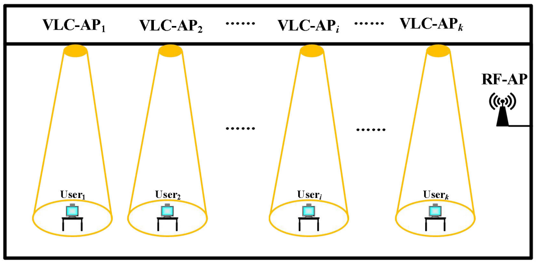


FIGURE 1. VLC/RF scenario.

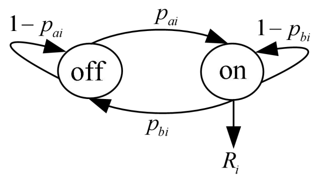


FIGURE 2. The markov chain of MMOO arrival.

the bandwidth to compensate VLC network, which is defined as compensation bandwidth. The compensation bandwidth is provided according to a certain probability, which is defined as compensation probability. The random compensation service is formulated by coordinating compensation bandwidth and compensation probability. The users can receive both the fixed service supplied by the VLC network and the random compensation service supplied by the RF network. Each communication link can be modeled as a queuing system with random compensation service and random arrival traffic. Without loss of generality, we analyse link i in the following investigations.

The random compensation process could be described as a Bernoulli distribution, with the probability mass function $f\left(s_{\mathrm{RF}\_i}(n)\right)$ of:

$$f\left(s_{\mathrm{RF}\_i}(n)\right)=\begin{cases}P_i, & \textit{if } s_{\mathrm{RF}\_i}(n)=R_{\mathrm{RF}}\\ 1-P_i, & \textit{if } s_{\mathrm{RF}\_i}(n)=0,\end{cases} \tag{1}$$

where $s_{\mathrm{RF}\_i}(n)$ expresses the instantaneous service of RF. R_{RF} represents the compensation bandwidth, and P_i represents the compensation probability.

The users are served by the corresponding VLC and aided by the RF with a certain probability. VLC depends on line-of-sight (LOS) transmission, and communication is interrupted when LOS transmission is blocked. Considering these service features of the VLC/RF networks, the instantaneous service process can be expressed as

$$s_i(n)=\begin{cases}R_{\mathrm{VLC}\_i}+R_{\mathrm{RF}}, & P_i\beta_i\\ R_{\mathrm{VLC}\_i}, & (1-P_i)\,\beta_i\\ R_{\mathrm{RF}}, & P_i\,(1-\beta_i)\\ 0, & (1-P_i)\,(1-\beta_i)\,,\end{cases} \tag{2}$$

where R_{VLC_i} indicates the service rate provided from VLC, and β_i is the unblocked probability.

We select the Markov modulated On–off (MMOO) process to carve the arrival traffic. This scheme is not limited to a specific arrival process. The Markov chain of the MMOO process is shown in Fig. 2. The packets arrive at rate R_i in the on state, and no packets arrive in the off state. p_{ai} and p_{bi} represent transition probabilities from the off state to the on state and from the on state to the off state, respectively. $a_i(n)$ defines the instantaneous arrival of the MMOO process.

To quantify the required bandwidth used to compensate VLC from RF, we define the effective compensation bandwidth E_{CB_i}, which could be calculated as the mathematical expectation of the bandwidth provided by the RF. We have:

$$E_{CB\_i}=R_{\mathrm{RF}}P_i\,. \tag{3}$$

IV. RANDOM COMPENSATION ALGORITHM

This section describes the evaluation of the delay performance using supermartingale theory, and the random compensation algorithm is designed.

Using the concepts of arrival-martingales and service-martingales [11], we construct supermartingales for the arrival and service processes based on the exponential transform. For the random arrival process, there exist a parameter $K_{a\_i}\geq 0$ and function h_{a_i}: rng$(a)\to R^+$, then the supermartingale relative to arrival $M_{a\_i}(n)$ can be expressed as:

$$M_{a\_i}(n)=h_{a\_i}(a_i(n))\,e^{\theta_i\left(A_i(n)-nK_{a\_i}\right)}, \tag{4}$$

$A_i(n)$ represents the cumulative arrival process. K_{a_i} is the supermartingale correction function for the arrival process. Both $h_{a\_i}(\cdot)$ and K_{a_i} depend on θ_i, which is an attenuation index.

For the random compensation service process, there exist a parameter $K_{s\_i}\geq 0$ and function h_{s_i}: rng$(s)\to R^+$, then the supermartingale relative to service $M_{s\_i}(n)$ can be defined as:

$$M_{s\_i}(n)=h_{s\_i}(s_i(n))\,e^{\theta_i\left(nK_{s\_i}-S_i(n)\right)}, \tag{5}$$

$S_i(n)$ represents the cumulative service process. $h_{s\_i}(\cdot)$ denotes the relevant characteristic function for the service process. K_{s_i} is the supermartingale correction function for the service process. Both $h_{s\_i}(\cdot)$ and K_{s_i} depend on θ_i.

To analyse the queuing behaviour with random traffic and random service, we construct a supermartingale relative to the queue length:

$$M_{Q\_i}(n)=\left(h_{a\_i}(a_i(n))\,h_{s\_i}(s_i(n))\right)\times e^{\theta_i\left(A_i(n)-nK_{a\_i}+nK_{s\_i}-S_i(n)\right)}. \tag{6}$$

Based on stopping time theory, we can obtain the delay violation probability bound for this system, as indicated in Theorem 1.

Theorem 1: For any $D_i>0$, the delay violation probability bound holds:

$$P_i\left\{d_i(n)\geq D_i\right\}\leq\frac{E\left[h_{a\_i}(a_i(0))\right]E\left[h_{s\_i}(s_i(0))\right]}{H_i}e^{-\theta_i^*\mu_iD_i}, \tag{7}$$

where D_i is the given target delay, and μ_i is the average arrival intensity. θ_i^* is determined as:

$$\theta_i^* := \sup\{\theta_i > 0 : K_{a\_i} = K_{s\_i}\}, \tag{8}$$

H_i is determined as:

$$H_i := \min\left\{\left(h_{a\_i}\left(a_i\left(n\right)\right)\right) h_{s\_i}\left(s_i\left(n\right)\right) : a_i\left(n\right) - s_i\left(n\right) > 0\right\}. \tag{9}$$

Proof: When $A_i(n)$ - $S_i(n)$ first exceeds the threshold σ_i, we define the stop time N as:

$$N := \min\{n : A_i(n) - S_i(n) \geq \sigma_i\}. \tag{10}$$

$N = \infty$ is possible, and

$$P_i(Q_i(n) \geq \sigma_i) = P_i(N < \infty), \tag{11}$$

where $Q_i(n)$ is the queue length.

Applying the stopping time theory, we obtain:

$$\begin{aligned} &E_i\left[h_{a\_i}\left(a_i\left(0\right)\right)\right] E\left[\left(h_{s\_i}(s_i\left(0\right)\right)\right] \\ &= E[M_{Q\_i}(0)] \\ &\geq E\left[M_{Q\_i}\left(N \wedge n\right) 1_{\{N \leq n\}}\right] \ (N \wedge n := \min\left\{N, n\right\} \left(n \geq 0\right)) \\ &= E\left[h_{a\_i}\left(a_i\left(n\right)\right)\left(h_{s\_i}(s_i\left(n\right)\right) e^{\theta_i^*(A_i(N)-S_i(N))} 1_{\{N \leq n\}}\right] \\ &\geq H_i e^{\theta_i^* \sigma_i} P_i\left(N \leq n\right). \end{aligned} \tag{12}$$

When $n \rightarrow \infty$, we can obtain the bound of the queue overflow probability as:

$$P_i\left\{d_i(n) \geq D_i\right\} \leq \frac{E\left[h_{a\_i}\left(a_i\left(0\right)\right)\right] E\left[h_{s\_i}\left(s_i\left(0\right)\right)\right]}{H_i} e^{-\theta_i^* \sigma_i}. \tag{13}$$

According to Little's law, the delay violation probability bound is derived as follows:

$$P_i\left\{d_i(n) \geq D_i\right\} \leq \frac{E\left[h_{a\_i}\left(a_i\left(0\right)\right)\right] E\left[h_{s\_i}\left(s_i\left(0\right)\right)\right]}{H_i} e^{-\theta_i^* \mu D}. \tag{14}$$

Hence, Theorem 1 holds.

The delay QoS requirements can be determined by the following inequality:

$$P_i\{d_i\left(n\right) \geq D_i\} \leq \varepsilon_i, \tag{15}$$

where ε_i is the threshold of the delay violation probability.

To guarantee the delay QoS, when D_i is fixed, the delay violation probability must be less than or equal to the given delay violation probability threshold. Comparing (7) and (15), we obtain:

$$\frac{E\left[h_{a\_i}\left(a_i\left(0\right)\right)\right] E\left[h_{s\_i}\left(s_i\left(0\right)\right)\right]}{H_i} e^{-\theta_i^* \mu_i D_i} \leq \varepsilon_i. \tag{16}$$

According to this expression, the delay violation probability bound and R_{RF} are negatively correlated. A smaller R_{RF} corresponds to a larger delay violation probability bound. For efficient utilization of the bandwidth resources, the minimum R_{RF} guaranteeing QoS requirements is derived by setting (16) to be an equality relation. We construct the following equation:

$$\begin{cases} \dfrac{E\left[h_{a\_1}\left(a_1\left(0\right)\right)\right] E\left[h_{s\_1}\left(s_1\left(0\right)\right)\right]}{H_1} e^{-\theta_1^* \mu_1 D_1} = \varepsilon_1, \\ \ldots \\ \dfrac{E\left[h_{a\_i}\left(a_i\left(0\right)\right)\right] E\left[h_{s\_i}\left(s_i\left(0\right)\right)\right]}{H_i} e^{-\theta_i^* \mu_i D_i} = \varepsilon_i, \\ \ldots \\ \dfrac{E\left[h_{a\_k}\left(a_k\left(0\right)\right)\right] E\left[h_{s\_k}\left(s_k\left(0\right)\right)\right]}{H_k} e^{-\theta_k^* \mu_k D_k} = \varepsilon_k. \end{cases} \tag{17}$$

In the supermartingale model, the compensation parameters cannot be obtained directly, because θ_i cannot be determined when the service is uncertain. To address this problem, we design a random compensation algorithm based on the search mechanism. To illustrate the process flow of the algorithm, we consider an example with two links. When the delay QoS requirements of the two links are not satisfied, the devised algorithm is implemented via the following Algorithm 1:

Algorithm 1 Random compensation algorithm

Input: $\varepsilon_1, \varepsilon_2; p_{a1}, p_{b1}; p_{a2}, p_{b2}; D_1, D_2$.
Output: $R_{\text{RF}}; P_1; P_2$.
1: $R_{\text{RF}} = R_{\text{RF}} + \Delta R$ ← *update the values of* R_{RF}
2: *flagT*1 ← *judge whether link* 1 *meets delay* QoS *requirements*
3: If (*flagT*1 = 0)
4: P_1 ← *calculate* P_1 *by Binary − Search algorithm*
5: $P_2 = 1 - P_1$
6: *flagT*2 ← *judge whether link* 2 *meets delay* QoS *requirements*
7: If *flagT*2 = 0)
8: Return $[R_{\text{RF}}, P_1, P_2]$
9: Else
10: Go to line 1
11: End if
12: Else
13: Go to line 1
14: End if

- Update the compensation bandwidth R_{RF} and evaluate whether link 1 meets delay QoS requirements according to (16). If link 1 does not meet QoS requirements, return to line 1 to continue updating the value of R_{RF}. If QoS requirements are satisfied, *flagT*1 = 0; otherwise, *flagT*1 = 1. ΔR represents the increment in R_{RF}.
- If link 1 meets QoS requirements, determine the compensation probability P_1 using the binary-search algorithm. Then, calculate the compensation probability P_2 and evaluate whether link 2 meets delay QoS requirements using (16). When QoS requirements are satisfied, *flagT*2 = 0; otherwise, *flagT*2 = 1.
- If link 2 does not meet QoS requirements, return to line 1 and continue to update R_{RF} until link 2 meets delay QoS

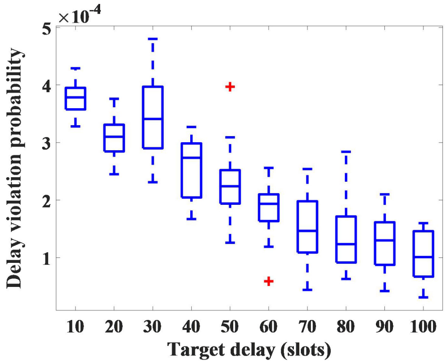


FIGURE 3. Delay violation probabilities in the experiments.

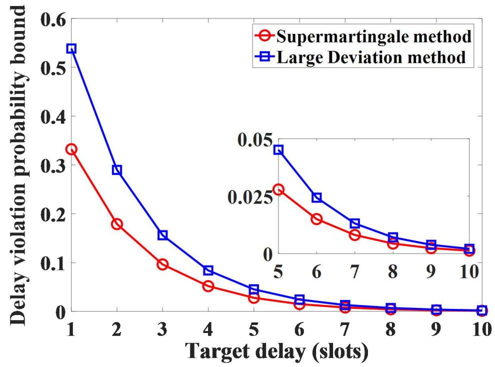


FIGURE 4. Comparison of delay violation probability bound between the supermartingale method and the large deviation method.

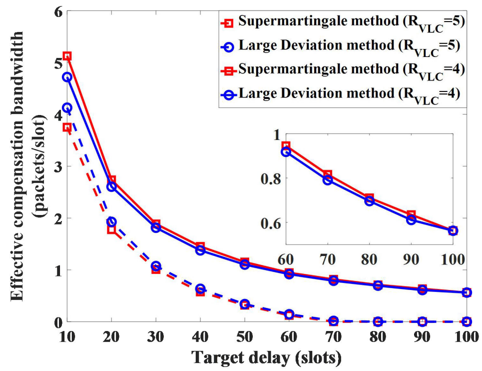


FIGURE 5. Comparison of effective compensation bandwidth between the supermartingale method and the large deviation method.

requirements. If link 2 meets QoS requirements, output the compensation bandwidth and probability associated with RF.

Overall, if delay QoS requirements of only one link are not satisfied, the RF provides compensation service for the link with the compensation probability of 1. The value of R_{RF} is continuously updated until delay QoS requirements are satisfied. If delay QoS requirements of both links are satisfied, the compensation algorithm does not need to be implemented. In the case of multiple links, we can sequentially evaluate whether delay QoS requirements are met, and the value of R_{RF} is updated until delay QoS requirements are satisfied.

This mechanism requires neither decision making nor historical information. RF network merely needs to reserve resource with the compensation bandwidth and provide service to VLC with the compensation probability. In this manner of resource allocation, delay QoS requirements could be satisfied in VLC/RF networks.

V. SIMULATION RESULTS AND ANALYSIS

The performance of the random compensation algorithm is evaluated through simulations. The parameters are set as follows: $p_{a1} = 0.2$, $p_{b1} = 0.3$, $R_1 = 8$ packets/slot, $p_{a2} = 0.4$, $p_{b2} = 0.1$, $R_2 = 5$ packets/slot, $\Delta R = 0.05$, $\varepsilon_i = 10^{-3}$. Firstly, the experiments of the delay violation probability are conducted to evaluate the authenticity of the scheme. The results are shown as box plots in Fig. 3. The lines in top, middle, and bottom of the box represent the values of maximum, median, and minimum respectively. The symbol "+" expresses the outlier. The results manifest that the delay violation probabilities are smaller than delay QoS threshold ε_i, which illustrates that delay QoS requirements are guaranteed.

In Fig. 4, we perform the comparison of delay violation probability based on supermartingale theory and the large deviation theory. It can be seen that the supermartingale-based bound is tighter than the large-deviation-based bound, which highlights the advantage of supermartingale analysis. Under the same target delay, the bandwidth evaluated by the supermartingale method would be smaller, which could increase efficiency of the resource allocation.

In our previous research [15], a random compensation scheme based on large deviation theory is proposed. In this work, we focus the more complex hybrid networks, take advantage of supermartingale theory, and a different compensation mechanism is established. We utilize the method of [15] to achieve the compensation scheme for the hybrid networks, and then compare the large-deviation-based results with the supermartingale-based results.

As is shown in Fig. 5, we set parameters as $R_{\mathrm{VLC}} = 4$ packets/slot, $R_{\mathrm{VLC}} = 5$ packets/slot. The variation trends of the effective compensation bandwidth obtained by both methods are similar. However, the values obtained using the supermartingale-based algorithm are smaller than those obtained by using the large deviation method. Thus, the supermartingale-based algorithm could save bandwidth. In Fig.5, we also observe that the effective compensation bandwidth decreases as the target delay increases. This is because the service capability is improved as the VLC service rate increases, and the required bandwidth is small. The effective compensation bandwidth decreases to zero as the target delay increases, which indicates that delay QoS require-

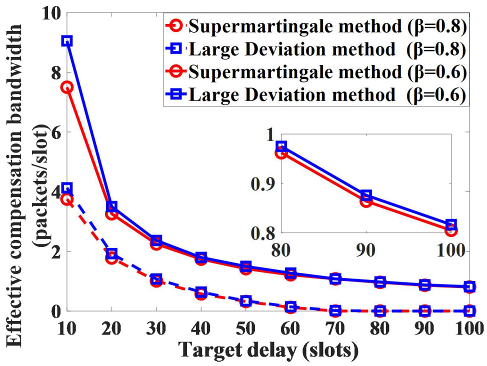
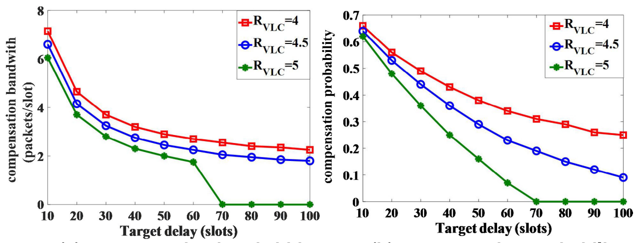


FIGURE 6. The effective compensation bandwidth affected by the unblocked probability.



(a) compensation bandwidth (b) compensation probability

FIGURE 7. Effect of fixed service rate on compensation bandwidth and compensation probability.

ments are met by the fixed VLC service rate. Therefore, the system does not require the RF to provide compensation service.

In the following, we explore the relationship between the effective compensation bandwidth and unblocked probability. We set β to be 0.6, 0.8, respectively. With the same target delay, the supermartingale-based is smaller than the large-deviation-based in effective compensation bandwidth. As is shown in Fig. 6, the effective compensation bandwidth increases as β decreases. Compared with a smaller β, a larger β means that the VLC provides more bandwidth, and thus delay QoS requirements can be satisfied with a smaller required bandwidth from RF.

The effective compensation bandwidth depends on the compensation bandwidth and compensation probability. As shown in Fig. 7, the compensation bandwidth and compensation probability decrease as the fixed VLC service rate increases. As the target delay increases, both the compensation bandwidth and compensation probability decrease. These trends highlight that the compensation algorithm ensures QoS by adjusting the compensation bandwidth and the compensation probability simultaneously.

VI. CONCLUSION

In this paper, a supermartingale-based scheme was devised to simplify resource management for the hybrid VLC/RF networks. By utilizing an RF to aid VLC, we established a compensation mechanism to realize non-scheduling. Supermartingale theory was employed to evaluate QoS performance for hybrid networks, and a stricter delay violation probability bound was derived. By capitalizing on the supermartingale analysis, we designed a random compensation algorithm to obtain the compensation bandwidth and compensation probability. This analytical framework could also be extended to other hybrid communication scenario, and we will continue to investigate this in future work.

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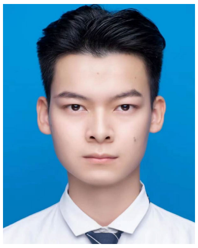

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