Analysis and Design of Hyperloop Communication Network Based on QoS Requirements

Wafa Hedhly, Osama Amin, Mohamed-Slim Alouini, and Basem Shihada

***Abstract*—Hyperloop is a cutting-edge high-speed rail transportation system. It can achieve aircraft-like speeds thanks to its unique configuration. Nevertheless, this very-high movement speed and the vacuum-tube environment result in multiple challenges to design the communication system. In this work, we propose a hybrid optical-wireless network architecture for Hyperloop communication system where data packets are transmitted from a centralized station through a backhaul optical link to multiple access points (APs) mounted on the tube. Each AP communicates with the moving pod using wireless signals. Then, we model the proposed architecture and analyze the downlink communication performance using queuing theory tools. We propose a design approach for the number of APs and the wireless technology to be implemented at each AP, considering several quality-of-service (QoS) requirements. We show, through multiple simulation examples, the impact of cell coverage and traffic intensity on the proposed design. It was demonstrated that the cost in terms of the required number of APs increases with strict probability of blocking constraints, whereas a wider bandwidth for the wireless link is required when the QoS constraint in terms of packet delay is alleviated.**

***Index Terms*—Hyperloop communications, vacuum tube communications, high-speed flying train, queuing theory, performance analysis.**

I. INTRODUCTION

Current transportation systems are experiencing unprecedented progress, relying more on autonomy and the emergence of smart technologies. It has become possible to monitor sophisticated mechanical and electronic mechanisms through diverse wired and wireless communication technologies, fast and reliable enough to endow distinguished transportation performances. Along this line, Hyperloop emerged as a next-generation flying train, capable of achieving supersonic speeds through the implementation of magnetic levitation and friction-free pressurized tube environment [1]. As expected, this unique integration of technologies requires reliable connectivity and fast communication links, leading to multiple design challenges. The steel-made sealed tube prevents the penetration of external EM waves and creates a waveguide-like, highly scattering environment. Moreover, the speed of the pod hits 1000 km/h resulting in severe Doppler spread and frequent handovers. Subsequently, conventional high-speed rail technologies cannot be applied to Hyperloop unless rigorous experimental justifications are conducted [2]. On this account, the objective is to propose suitable system and network solutions to deliver the performance requirements of Hyperloop and address its unique design features.

Several research works have recently started investigating possible candidate technologies and solutions to implement a reliable communication system for Hyperloop [3]–[9]. Particularly, attempts to provide physical-layer solutions have been proposed, including suitable antennas to be implemented inside the tube [6], [8], [9] and deterministic channel modeling approaches to model the tube EM propagation environment [3], [4]. From a networking perspective, Cloud radio access network (C-RAN) architecture was adopted in [5], [6] to centralize processing tasks at a pool of base-band units and communicate with the pod through a high capacity fronthaul link. However, a quantitative evaluation of the performance (such as enhanced capacity, coverage, communication delay or security) is required to assess the effiency and limitations of the proposed architecture. It is noticeable that the works mentioned above did not provide rigorous analysis and evaluation of the proposed solutions; therefore, we cannot decide on their viability. Hyperloop communication system requires a thorough analysis and design while considering the tremendous speed of the pod, the unique tube configuration and the services requirements in order to achieve decisive conclusions.

Hyperloop tube is a firmly sealed structure spanning long distances where a pod is moving at tremendous speeds, reaching 277 m/s. Therefore, a prompt and rigorous monitoring of this unique configuration is essential to guarantee proper operation and the safety of passengers. Furthermore, Hyperloop system receives high data rates for a variety of operational and passenger-related services. An appropriate approach is to install successive APs, with overlapping wireless coverage to ensure a seamless connection between the core network and the isolated moving pod. Taking into account the expected high upcoming traffic, downlink packets will be competing to be transmitted to the pod through one of the APs, leading to congestion, increased delays and recurrent events of packet dropping. In order to evaluate the impact of the aforementioned phenomena, queuing theory is a powerful tool that has been adopted whenever packets are competing over scarce network resources leading to congestion and losses [10], [11]. It has played a key role in performance analysis and network configurations [12]–[14]. Given the strict requirements of Hyperloop in terms of data rates and transmission delays and its unique configuration, the results of queuing theory can be used to analyze the performance of Hyperloop communication system. Thereby, decisions about the resources needed to

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provide the required communication services with acceptable QoS can be concluded. To the best of our knowledge, queuing theory tools have not been adopted in the literature to model and assess Hyperloop communications performance.

In this paper, we propose a suitable network architecture that can guarantee reliable downlink connectivity between a centralized transmitter and the moving pod through intermediary APs placed inside the tube. It consists in a hybrid optical-wireless network where packets are constantly being transmitted through a backhaul optical fiber and then converted at each AP to be wirelessly delivered to the moving receiver. We implement queuing theory techniques in modeling and evaluating the performance of the proposed network. Particularly, we investigate the communication throughput, transmission delays and probability of blocking due to the unavailability of APs. Afterwards, we propose an adaptive design approach for the number of deployed APs and the adopted wireless technology that can be adjusted according to the system's needs in terms of traffic and QoS requirements. We assess the performance of the system through several simulation scenarios.

The rest of the paper is organized as follows. A detailed description of the system model is provided in Section II. In section III, we present the performance analysis of the system in terms of throughput, packet delay, and probability of blocking. Section IV provides an appropriate system design approach to handle the QoS requirements. Simulation results are provided in Section IV. Last, the work is concluded in section V.

II. System Model

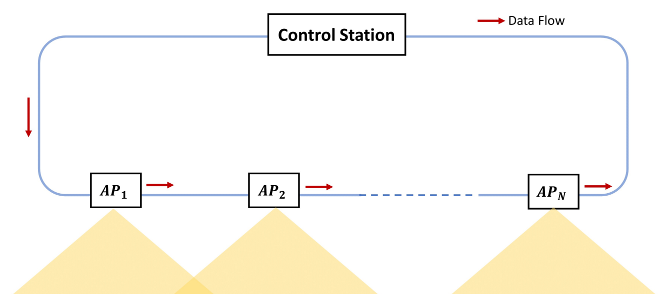

Figure 1: Proposed network architecture.

The architecture of the proposed optical-wireless network for Hyperloop communication system is depicted in Fig. 1. An optical fiber serves as a backhaul link between the CS and the N APs placed inside the tube. The APs are equipped with optical-to-electrical (O/E) converters and radio antennas. They communicate with the moving receiver (Rx) through wireless links and have a cell coverage d. The objective of the centralized operation at the CS is to execute complex signal processing functions and therefore reduce the complexity and costs of the APs. If the pod moves past the coverage area of a specific AP, then this AP is idle. Otherwise, the AP is active and receives data packets from the CS. These packets are temporarily stored in a memory and transmitted to the Rx when the pod crosses the coverage area of the AP. Therefore, the number of active APs decreases as the pod moves along the axis of the tube. The pod communicates with each AP for a time duration $T_{\text{S}} = \frac{d}{v}$. During this time interval, the AP has to transmit the saved data to the pod before it leaves its coverage area. The CS has prior knowledge of the position of the Rx and shares this information with all APs. Data packets are continuously dispatched from the CS to all active APs. If we denote by z_{P} the position of the pod then along the axis of the tube, the number of active APs is expressed as,

$$N_{\text{A}} = \begin{cases} N & \text{if} \quad 0 < z_{\text{P}} \leq d \\ N-1 & \text{if} \quad d < z_{\text{P}} \leq 2d \\ \dots & \\ 1 & \text{if} \quad (N-1)d < z_{\text{P}} \leq Nd \end{cases}$$

This number can be equivalently expressed as,

$$N_{\text{A}} = N - \lfloor \frac{z_{\text{P}}}{d} \rfloor. \tag{1}$$

The system can be modeled as an M/M/K/K queue, where the inter-arrival time of packets is exponentially distributed with mean $\frac{1}{\lambda}$ and the service time of each server is exponentially distributed with mean $\frac{1}{\mu}$. The active APs can be considered as K parallel servers. The optical fiber is modeled as an M/M/1 queue with a service rate μ_{O} equal to its capacity. The queuing model is depicted in Fig. 2.

In this system, we consider the following assumptions:

- We consider an infinite transmission of packets.
- No packet re-sending is allowed. A packet that does not reach its destination is considered permanently lost.
- All APs have the same service rate μ.
- The traffic intensity forwarded to active APs is equal.

The average packet arrival rate to each active AP is expressed as,

$$\lambda_n = \frac{\lambda}{N_A}. \tag{2}$$

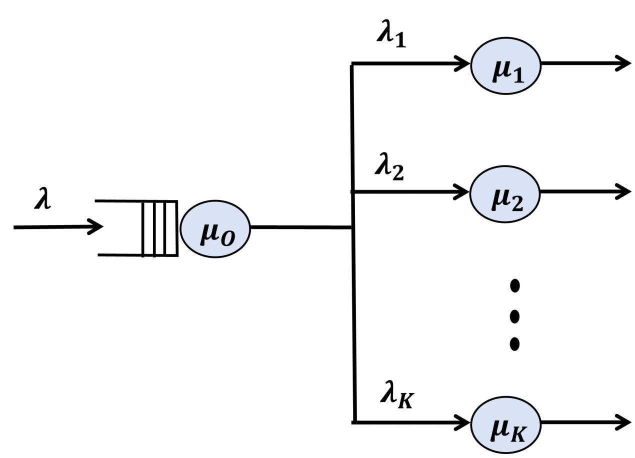

Figure 2: Queuing Model of the proposed system.

III. Performance Analysis

In this section, we evaluate the performance of the proposed queuing system using packet delay, throughput and probability of blocking metrics taking into consideration the impact of the cell coverage of each AP and the speed of the pod [10].

a) Traffic Intensity: The traffic intensity coming to the system is expressed as,

$$\rho = \frac{\lambda}{\mu}. \tag{3}$$

Considering that there are K parallel servers, the traffic intensity flooded to each AP is,

$$a = \frac{\lambda}{K\mu} = \frac{\rho}{K}. \tag{4}$$

b) Packet Delay or Packet Sojourn Time: The total average delay undergone by a packet going through AP_n is expressed as,

$$\overline{T}_n = \overline{T}_{\mathrm{Q}} + T_{\mathrm{P},n} + \tau_n, \tag{5}$$

where $\overline{T}_{\mathrm{Q}}$, $T_{\mathrm{P},n}$ and τ_n are, respectively, the queuing delay, the pod arrival delay and the propagation delay. When a packet is transmitted through the optical fiber towards AP_n, it experiences a propagation delay expressed as,

$$\tau_n = n \times d/c. \tag{6}$$

The pod arrival delay to an active AP depends on the pod and AP positions. If z_{P} is the position of the pod along the z-axis of the tube, then the pod arrival delay can be expressed as,

$$T_{\mathrm{P},n} = \frac{n \times d - z_{\mathrm{P}}}{v}, \tag{7}$$

where $n \times d - z_{\mathrm{P}}$ is the distance separating the pod to AP_n[1].

The average queuing delay $\overline{T}_Q$ is expressed as,

$$\overline{T}_Q = \overline{T}_{\mathrm{O}} + \overline{T}_{\mathrm{AP}}, \tag{8}$$

where $\overline{T}_{\mathrm{O}}$ and $\overline{T}_{\mathrm{AP}}$ are, respectively, the queuing delay of the optical link and the parallel active APs.

The optical link queuing delay is expressed as,

$$\overline{T}_O = \frac{1}{\mu_O - \lambda}. \tag{9}$$

According to Little's theorem, the average queuing time spent by a packet in the system $\overline{T}_{\mathrm{AP}}$ is written as,

$$\overline{T}_{\mathrm{AP}} = \frac{\overline{N}_T}{\lambda(1 - P_K)}, \tag{10}$$

where $\overline{N}_{\mathrm{T}}$ is the average number of packets in the system and P_K is the probability that there are K packets in the system. For an M/M/K/K model, the queue length is expressed as,

$$\overline{N}_{\mathrm{T}} = \rho(1 - P_K) \tag{11}$$

and the probability that there are K packets in the system is [15],

$$P_K = \frac{\rho^K}{K!}\left(\sum_{n=0}^{K} \frac{\rho^n}{n!}\right)^{-1}. \tag{12}$$

[1]Here, $z_{\mathrm{P}} \leq n \times d$, since AP_n is active.

c) Erlang-B Formula: When all APs are occupied, a new incoming packet is blocked. This packet loss can be quantified by computing the probability that there are already K packets in the system. As a result, the probability of blocking is written as,

$$P_{\mathrm{B}} = \frac{\rho^K}{K!}\left(\sum_{n=0}^{K} \frac{\rho^n}{n!}\right)^{-1}. \tag{13}$$

d) Throughput: The communication throughput at every AP is the number of successfully delivered packets per unit of time. Since a number of the transmitted packets is blocked with probability P_{B}, the throughput can be expressed as,

$$R = \frac{\lambda}{K}\left(1 - P_{\mathrm{B}}\right). \tag{14}$$

IV. System Design

In this section, we propose a suitable approach to strategically design of the number of installed APs and the adopted wireless technology while satisfying a minimum QoS. In the unique scenario of Hyperloop network, data is lost because of packet blocking in two different cases:

- All APs are occupied.
- The time spent in the network exceeds a maximum threshold.

The recurrence of these two scenarios can be controlled by maintaining a maximum acceptable probability of blocking and packet sojourn time in the system. Subsequently, we adopt an adaptive system design, where the traffic load, the number of deployed APs and the wireless link communication speed are adjusted in order to satisfy the QoS constraints mentioned above.

A. Number of APs

Blocking events occur more frequently when the number of deployed APs is not sufficient regarding the offered traffic. For this reason, we can increase the number of APs in order to minimize the probability that a packet is blocked due to the unavailability of a server. However, this results in an increase of the deployment cost. Therefore, the objective is to minimize the number of APs while maintaining a particular threshold for the probability of blocking. This design approach can be achieved using the following problem formulation,

$$\begin{aligned} \min_{\rho} \quad & K \\ \text{s.t.} \quad & P_{\mathrm{B}}\left(\rho, K\right) \leq P_{\mathrm{B,max}} \\ & 0 \leq \rho \leq \rho_{\max} \\ & K \in \{1, 2, \ldots, K_{\max}\}. \end{aligned} \tag{15}$$

To solve this problem, we use the Erlang-B traffic table. Then, for a given $P_{\mathrm{B,max}}$, the minimum number of APs K^* is the smallest integer that satisfies $P_{\mathrm{B}}\left(\rho^*, K^*\right) \leq P_{\mathrm{B,max}}$ and $\rho \leq \rho_{\max}$.

AS previously described, the number of active APs K decreases as the pod moves along its trajectory. In this case, the probability of blocking increases if the same traffic is offered to the system. Therefore, the arrival rate is adjusted as the pod is moving to satisfy the probability of blocking constraint in (15) and is expressed as,

$$\lambda^* = \mu\rho^*. \quad (16)$$

B. Wireless Technology

As per the system description, packets transmitted through the optical fiber are stored at each AP until the pod reaches its coverage area and establishes a wireless link. However, unconstrained arrival of packets will overload the APs. Thereby, we define a time delay threshold $\overline{T}_{\max}$ as a QoS constraint. If the overall delay a packet undergoes at a specific AP exceeds $\overline{T}_{\max}$ before the pod reaches the AP, this packet is dropped. Therefore, the packet delay is constrained by the following condition,

$$\overline{T}_n \leq \overline{T}_{\max}. \quad (17)$$

The longer packets are allowed in the network, the more packets will be stored at each AP to be transmitted to the pod. During $\overline{T}_n$, AP_n receives at most $R(\lambda) \times \overline{T}_n$ packets. However, since the communication duration between the pod and each AP is T_{S} and is very short because of the high movement speed, it is necessary to implement the adequate wireless technology that can handle the required transmission rate. During the time interval T_{S}, if the AP transmitter has a communication speed S_{r} (in packets per second), it can deliver $S_{\mathrm{r}} \times T_{\mathrm{S}}$ packets to the pod. Consequently, the required speed S_{r}^* has to be large enough to handle the traffic defined by the QoS threshold $\overline{T}_{\max}$ and is constrained as follows,

$$S_{\mathrm{r}}^* \geq \frac{R(\lambda^*)\overline{T}_{\max}}{T_{\mathrm{S}}} \quad (18)$$

Therefore, according to (18), we can determine the wireless technology capable of handling the service requirements of Hyperloop; λ, P_{B} and $\overline{T}_{\max}$.

V. Simulation Results

In this section, we evaluate the results presented in the previous sections through different simulation examples. We particularly investigate the impact of the movement speed and specific network architecture of Hyperloop communication system on the performance. The simulation parameters are the following unless otherwise specified; the packet size is 1 KB, the cell coverage is d = 100 m, μ = 125 K packets, μ_{O} = 100 Gbps = 12.5 M packets[2].

In the first simulation example, we plot the minimum number of APs to be installed inside the tube versus the traffic intensity for different probability of blocking requirements in Fig. 3. When higher values of probability of blocking are permitted, the system can increase the traffic intensity while implementing a smaller number of APs. For traffic intensity $\rho = 82$ Er, the number of installed APs can be reduced by $20\ \%$ at the expense of increasing the probability of a packet being blocked 10 times. As a result, the deployed number of APs depends on the packet rate offered by the CS and the probability of blocking tolerated by the system.

[2]Here, the cell coverage is considered for a Line-of-Sight communication link. Wireless cell coverage inside the tube is constrained by the relatively small radius of the tube, which is around 1.75 m.

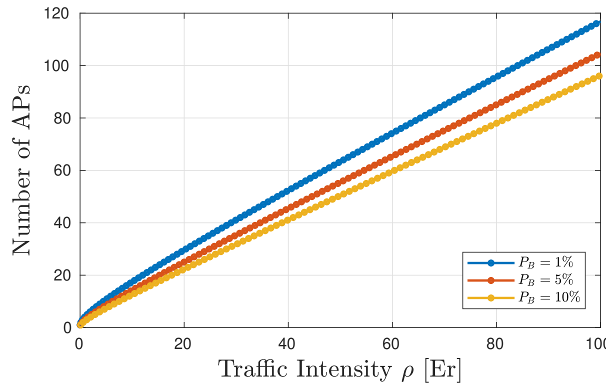

Figure 3: Minimum required number of APs for different blocking probabilities.

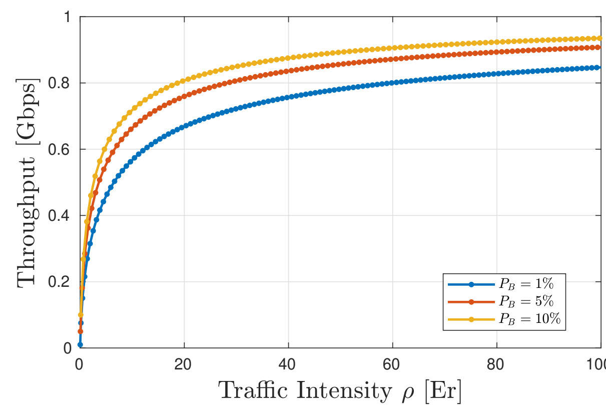

Figure 4: Throughput for different blocking probabilities.

In the second simulation example, we investigate the rate of successively delivered packets at each AP for different probabilities of blocking as function of the traffic intensity circulating through the optical backhaul. Thus, we plot the communication throughput versus the traffic intensity in Fig. 4. When the system tolerates a higher probability of blocking, the throughput at each AP increases despite the higher number of blocked packets. This can be explained by the fact that a smaller number of APs are deployed for higher permissible P_{B}. Consequently, each AP receives higher traffic intensity.

In the third simulation example, we plot the packet sojourn time at the last AP (AP_N) versus the position of the pod along its trajectory for different AP cell coverage in Fig. 5. As the pod gets closer to AP_N, the mean time a packet spends in the network decreases. For shorter cell coverage, the packet spends a shorter amount of time before being transmitted to the pod. Therefore, a smaller number of packets are dropped. Nevertheless, in order to ensure a seamless connectivity along

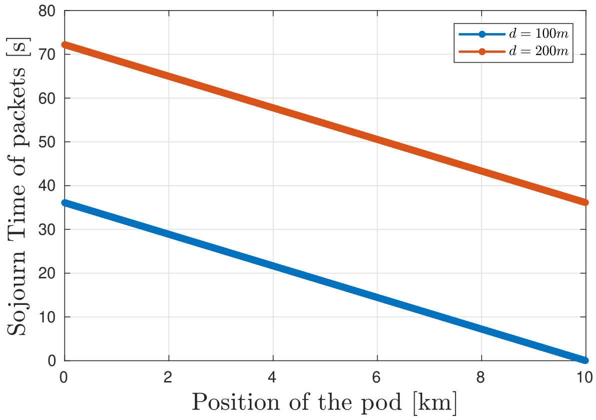

Figure 5: Mean sojourn time of packets at AP_{N}.

the tube, a larger number of APs is required when the coverage of each AP decreases. As a result, the system needs to maintain a tradeoff between the implementation cost and achievable communication performance.

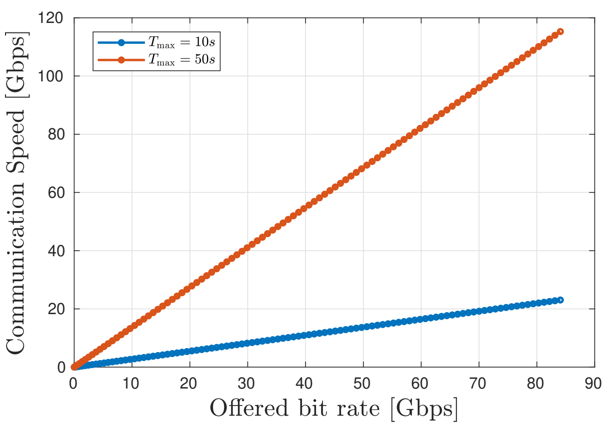

Figure 6: Required wireless communication speed to satisfy QoS requirements.

The objective of the last simulation example is to provide guidelines to determine the appropriate wireless technology used at the AP, given the QoS requirements and the system parameters. For this reason, we plot in Fig. 6, the minimum required wireless communication speed versus the offered data rate for different packet delay QoS constraints. The communication throughput increases with the offered traffic intensity as depicted in Fig. 4. Hence, the minimum required wireless communication speed increases with the offered data rate since a higher number of packets are stored at the AP, waiting to be transmitted to the pod. Moreover, setting stricter QoS constraints in terms of packet sojourn time results in a decrease in the number of packets successfully reaching the AP, leading to a lower required communication speed of the wireless transmitter. The cell coverage of each AP d and the movement speed of the pod are two critical factors contributing to the communication system design. In particular, increasing d gives a longer time interval for the stored packets to be transmitted to the pod. Therefore, we can relieve communication speed restrictions on the implemented wireless technology at each AP. However, it is important to mention that extending wireless coverage leads to more challenges in terms of channel fading and achievable rates at the pod's receiver. As a result, the wireless technology depends on the offered traffic load, the QoS requirements in terms of probability of blocking and maximum sojourn time, and the inner-tube network architecture. For instance, for $\overline{T}_{\max} = 50\,s$ and $d = 100\,m$, a speed of tens of gigabits per second is required at the wireless transmitter of the AP. In this case, Terahertz signals can be implemented because they are capable of achieving hundreds of gigabits per second [16]. On the other hand, when $T_{\max} = 10\,s$, millimeter wave can be used because it can reach a peak data rate of 20 Gbps [17].

VI. Conclusion

In this paper, we proposed a suitable hybrid optical-wireless network architecture suitable for the unique sealed tube environment of Hyperloop. We adopted the M/M/K/K queuing model to analyze the performance of the proposed architecture. Due to the considered architecture, the packets are transmitted from the CS to each AP and are stored at each AP until the pod reaches its coverage area, leading to high packet delays. For this reason, a sojourn time constraint is used to maintain a minimum QoS and to determine the required wireless technology at the AP. A strict time constraint alleviates the requirements of the wireless transmitter in terms of bandwidth and communication speeds. On the contrary, tolerating longer packet delays reduces the number of lost packets while imposing a larger bandwidth constraint on the wireless transmitter at the AP. Similarly, when higher probabilities of blocking are permitted, a smaller number of APs is required given a certain traffic load. To summarize, the configuration parameters of the network in terms of the number of APs, wireless technology and cell coverage depend on the offered traffic load and the predefined QoS requirements.

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