Impact of Dispersion on OFDM Signals in Hyperloop Tubes

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***Abstract*—This paper examines the influence of EM dispersion on the propagation of OFDM-modulated signals inside the metallic Hyperloop tube, which is caused by the waveguide-like nature of the tube. Intra-tube EM dispersion results in varying propagation speeds among different frequency components, inducing non-uniform propagation delays across OFDM subcarriers. By modeling the Hyperloop channel experiencing such frequency-dependent propagation delays, we show that significant and varying phase rotations are imposed on the OFDM symbols, despite subcarrier orthogonality being still preserved. This suggests OFDM-based intra-tube wireless propagation should consider a method to compensate the aforementioned effect, to avoid any communication performance degradation. Specifically, our analysis emphasizes the necessity of a phase compensation mechanism for reliable OFDM-based Hyperloop communications, and provides a foundation for future work on the performance assessment and compensation strategies.**

***Index Terms*—Rail transportation, circular waveguides, electromagnetic waveguides, dispersion, OFDM**

I. Introduction

The Hyperloop is next-generation ground transportation consisting of a near-vacuum tube and magnetically levitated pods that achieve near-sonic speeds up to 1200km/h. Alongside other core technologies such as magnetic levitation, propulsion, and pod attitude control, its communications system is an essential part for ensuring safe and efficient Hyperloop operations. More specifically, wireless communications can not only enable real-time monitoring and control of pods (e.g., position and attitude control) by the Hyperloop control center, but also enhance passenger convenience like mobile Internet access.

Unlike conventional open-space wireless communications, signal propagation within the waveguide-like Hyperloop tube undergoes EM dispersion, i.e., frequency-dependent variation in the propagation speed of electromagnetic (EM) wave. As a result, higher-frequency components of a signal propagate faster than its lower-frequency components, leading to temporal spreading at the receiver and eventually waveform distortion. Furthermore, the phenomenon varies with EM modes, where a mode refers to a particular E-field solution of the Maxwell's equations fulfilling the waveguide's boundary conditions.

In this regard, our previous work [1] investigated the effect of EM dispersion and derived the maximal bandwidth for each waveguide mode that can limit the temporal spreading within a reasonable range. For multi-carrier communications such as orthogonal frequency-division multiplexing (OFDM), however, EM dispersion introduces more challenges due to the non-uniform delays among the subcarriers, further distorting the composite OFDM signal and potentially degrading the performance. Therefore, this paper aims at analyzing the impact of dispersion on OFDM signals and suggests potential future approaches to mitigate it.

II. System Model

Fig. 1 illustrates our Hyperloop communication system model, adopted from our previous work [2] (which is a follow-up study of [1]). The system comprises a 500km long, 3.3m in diameter metallic tube connecting stations A and B, within which a series of static base stations (BSs) are deployed at regular intervals and multiple pods are travelling. Each pod measures 8.7m in length and 2.4m in diameter, and is aligned concentrically with the tube as depicted in the lower-left corner of Fig. 1. BS antennas are installed every 10km along the tube, granting each BS two 5km half-coverage zones, one to the right and another to the left.

Among the pods, we designate one as the 'target pod' (tPod), which travels within the left-half coverage of its corresponding 'associated BS' (aBS) located at 250km. On the other hand, the pods other than tPod are referred to as 'neighboring pods' (nPods) while the BSs other than aBS are considered as 'interfering BSs' (iBSs) of tPod. Each pod has two antennas installed at its head and tail, and it is associated with the nearest BS by only activating the one closer to its aBS, as shown in the lower-right corner of Fig. 1. Pods are assumed to depart from station A every 30 seconds, and follow the same mobility profile: accelerating at $0.5g$,[1] cruising at the maximum speed of V, decelerating at $0.5g$, and arriving at station B. Note that we have chosen the minimum departure

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[1] g denotes the gravitational acceleration.

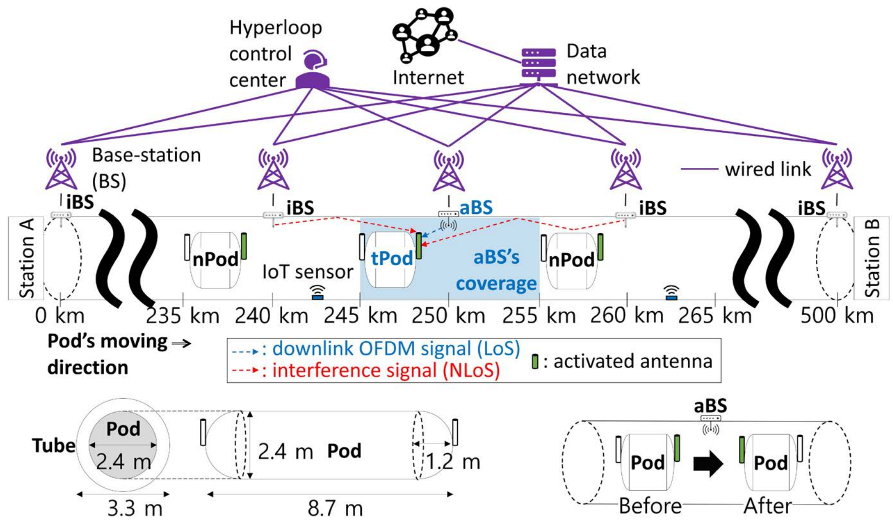

Fig. 1. Hyperloop communication system model [2]

interval proposed by SpaceX, assuming each pod is equipped with an emergency braking system [3].

In a metallic circular waveguide like the Hyperloop tube, the EM field forms distinct spatial patterns known as 'EM modes' that satisfy both the Maxwell's equations and the tube's boundary conditions. For a given carrier frequency, there exist only a finite number of EM modes that can propagate through the tube, because each mode has a specific cutoff frequency below which its propagation becomes impossible. Note that this paper assumes single-mode communications (i.e., only one EM mode is utilized for communications), to avoid excessive system design complexity.

III. Analysis of OFDM Signal Reception under EM Dispersion

We model and analyze the downlink OFDM signal from aBS to tPod as follows. For simplicity, we assume that the channel experiences EM dispersion only while its path loss is negligible, which is often true for intra-waveguide signal transmission with a limited traveling distance, like in our system model.

The baseband signal of the kth subcarrier is defined by

$$x_k(t) = \frac{1}{\sqrt{T}} e^{j2\pi k \Delta f t} \quad \text{for} \quad 0 \le t < T, \tag{1}$$

where T is the OFDM symbol duration and $\Delta f = 1/T$ is the subcarrier spacing. The composite baseband OFDM signal $s_b(t)$ is then given by

$$s_b(t) = \sum_{k=0}^{N-1} X_k x_k(t) = \frac{1}{\sqrt{T}} \sum_{k=0}^{N-1} X_k e^{j2\pi f_k t}, \tag{2}$$

where N is the number of subcarriers, X_k is the data symbol on the kth subcarrier, and $f_k = k\Delta f$ is the frequency of the kth subcarrier.

The corresponding passband OFDM signal $s(t)$ can be expressed as

$$s(t) = \text{Re}\left\{s_b(t) e^{j2\pi f_c t}\right\} = \text{Re}\left\{\frac{1}{\sqrt{T}} \sum_{k=0}^{N-1} X_k e^{j2\pi(f_k+f_c)t}\right\}, \tag{3}$$

where f_c denotes the carrier frequency.

Also, the simplified intra-tube wireless channel, denoted by $h(t,t')$, can be expressed as

$$h(t,t') = \sum_{k=0}^{N-1} \delta\left(t - \tau_k(t')\right), \tag{4}$$

where $\delta(\cdot)$ is the Dirac delta function modeling an ideal impulse response delayed by the frequency-dependent propagation delay $\tau_k(t')$. The delay $\tau_k(t')$ is given as

$$\tau_k(t') = \frac{5000 - Vt'}{c\sqrt{1 - \frac{f_{\text{cutoff}}}{f_c + \left(k - \frac{N}{2} + \frac{1}{2}\right)\Delta f}}} \quad \text{for} \quad 0 \le t' < 15 \text{ sec}, \tag{5}$$

where t' denotes the time relative to the mobility of tPod (with $t' = 0$ corresponding to the moment when tPod enters the coverage area of aBS), V is the maximum speed of pods, c is the speed of light, and f_{cutoff} is the cutoff frequency. Eq. (5) is based on the fact that (i) the maximum distance between aBS and tPod is 5000m and the time required to traverse half of the aBS's coverage is 15 seconds, and (ii) the intra-tube propagation speed $v(f)$ of the wave at frequency f is given as [4]

$$v(f) = c\sqrt{1 - \frac{f_{\text{cutoff}}}{f}} \quad \text{for} \quad f_{\text{cutoff}} < f. \tag{6}$$

Then, the received signal $r(t,t')$ can be expressed as

$$\begin{aligned} r(t,t') &= s(t) * h(t,t') \\ &= \frac{1}{\sqrt{T}} \sum_{k=0}^{N-1} X_k \text{Re}\left\{e^{j2\pi(f_k+f_c)\left(t-\tau_k(t')\right)}\right\} + n(t), \end{aligned} \tag{7}$$

and the corresponding baseband received signal $r_b(t,t')$ is given as

$$r_b(t,t') = \frac{1}{\sqrt{T}} \sum_{k=0}^{N-1} X_k \mathrm{Re}\left\{ e^{j2\pi f_k \left(t-\tau_k(t')\right)} \right\} + n_b(t), \quad (8)$$

where $n(t)$ and $n_b(t)$ denote the noise components associated with $r(t,t')$ and $r_b(t,t')$, respectively. After removing the cyclic prefix, the mth received symbol Y_m can be obtained by the following:

$$Y_m = \frac{1}{T} X_k e^{-j2\pi f_k \tau_k(t')} \int_0^T e^{j2\pi(f_k - f_m)t} dt + N_m, \quad (9)$$

where f_m represents the frequency of the mth subcarrier, and N_m denotes the noise component associated with Y_m.

As a result, it is observed that the subcarrier-dependent propagation delay in the tube introduces corresponding subcarrier-dependent phase shifts on the subcarrier symbols, while preserving their mutual orthogonality. This is because the integral term in Eq. (9) becomes zero for all the cases but $f_k = f_m$. Unfortunately, the conventional phase shift compensation method based on channel equalization and common phase error (CPE) [5] may not fully account for such extra and irregular subcarrier-dependent phase shifts caused by the intra-tube EM dispersion. Therefore, a novel subcarrier-aware compensation method is required to mitigate the aforementioned artifact and prevent decoding errors in the received symbols.

IV. Conclusion

This paper analyzed the impact of intra-tube EM dispersion on OFDM signal transmissions. We demonstrated that the orthogonality among subcarriers is preserved even under the dispersive intra-tube channel. However, we showed that each OFDM subcarrier experiences a phase shift corresponding to a distinct subcarrier-dependent propagation delay caused by the dispersive waveguide channel in the Hyperloop tube. In future, we plan to evaluate the performance degradation due to the additional phase shift that vary with subcarriers, and propose a novel compensation method to mitigate the effect.

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