

Feasibility Analysis of Sewer Pipe Inspection Systems Using Optical Wireless Communication

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Abstract—We propose a novel sewer pipe inspection system utilizing optical wireless communication (OWC). To verify its feasibility, we construct an optical propagation model that simulates the in-pipe environment and conduct a quantitative performance evaluation of the signal-to-noise ratio (SNR) and root-mean-square (RMS) delay spread. Simulation results show that the SNR at a propagation distance of 40 m reaches approximately 20 dB, which, according to Shannon's theorem and assuming a bandwidth of 10 MHz, implies a theoretical data transmission rate of approximately 66 Mbps. Furthermore, the RMS delay spread caused by reflections within the pipe remains at a maximum of approximately 2.3 ns, indicating that inter-symbol interference (ISI) may not adversely affect the communication. Moreover, even when the LED directivity is enhanced by reducing the semi-angle at half-power, high and stable SNR can still be achieved despite random transmitter fluctuations. These results demonstrate that OWC is a highly effective and practical alternative communication method for sewer pipe inspection systems.

Index Terms—Optical wireless communication, sewer pipe inspection, optical propagation model, multipath propagation.

I. INTRODUCTION

In Japan, the aging of sewer pipes has become a critical issue, necessitating urgent inspection and repair. Annually, approximately 2,600 cases of road cave-ins caused by pipeline facilities occur due to sewer pipe deterioration [1]. To prevent such accidents, regular inspections of sewer pipes are essential. Current sewer pipe inspection methods include visual inspection [2], manhole cameras [3], fiber scopes [4], self-propelled wired robots [5], and boat-type robots [6]. Although these methods excel in inspection reliability, they suffer from long operating times, hazardous working conditions, difficult cable management, and high costs.

As a solution to these issues, several systems have been proposed that capture video inside sewer pipes using inspection robots or floating cameras and transmit the video data via wireless LAN [7], [8]. These systems enable faster, cheaper, and safer inspections of sewer pipes. However, in confined spaces such as inside sewer pipes, radio wave propagation characteristics differ significantly from those in free space. According to the theoretical analysis by Nagashima *et al.* [9], in a sewer pipe with a diameter of 200 mm, the theoretical

maximum communication distance for maintaining quasi-free-space propagation quality is limited to less than 2 m for both the 2.4 GHz and 5 GHz bands of wireless LAN. In other words, a major challenge in small-diameter pipes is the limited communication range caused by radio-wave attenuation, primarily due to obstruction of the Fresnel zone. Because common wireless LAN frequencies such as the 2.4 GHz and 5 GHz bands have relatively long wavelengths, their Fresnel zone radii become excessively large compared to the pipe radius, leading to severe signal obstruction and a shortened communication distance.

To resolve these issues, we propose a novel sewer pipe inspection system using optical wireless communication (OWC). Since optical wavelengths are short, the radius of the Fresnel zone is negligibly small compared to the pipe radius, allowing optical signals to propagate without suffering from the obstruction issues that severely restrict radio frequency (RF) signals in narrow pipes. Furthermore, in-pipe environments are generally free from background light, thereby reducing ambient optical noise and interference. To evaluate the communication quality of the proposed system, we construct an optical propagation model that simulates the in-pipe environment to clarify the optical propagation characteristics within sewer pipes. Using this model, we analyze the signal-to-noise ratio (SNR) and the root-mean-square (RMS) delay spread under various conditions of pipe diameter, inner-wall reflectivity, LED half-power angle, and transmitter misalignment. Simulation results show that an SNR of approximately 20 dB is achieved at the propagation distance of 40 m, ensuring sufficient signal quality for video transmission. In addition, the RMS delay spread is on the order of nanoseconds, resulting in negligible inter-symbol interference (ISI). It is also verified that a high, stable SNR can be achieved by increasing LED directivity, with only a marginal SNR fluctuation due to transmitter tilt and positional variations.

The remainder of this paper is organized as follows. In Section II, we present an overview of the proposed system, describe the physical factors that restrict the communication distance of wireless LANs in sewer pipes, and mathematically demonstrate the superiority of OWC using the concept of the Fresnel zone. Section III describes the system model used for the simulations. Section IV presents and discusses the simulation results. Finally, Section V concludes the paper.

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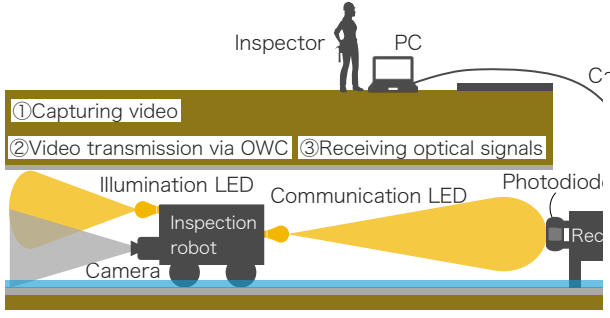


Fig. 1: Overview of the proposed sewer pipe inspection system using OWC.

II. PROPOSED SYSTEM AND SUPERIORITY OF OWC IN SEWER PIPES

A. Overview of the Proposed System

Fig. 1 illustrates an overview of the proposed sewer pipe inspection system using OWC. In this system, video data acquired by an inspection robot traveling through the pipe is wirelessly transmitted as optical signals. The robot is equipped with a camera and lighting LEDs, as well as a communication LED that functions as the transmitter. The acquired video signal is emitted from this communication LED and propagates through the internal space of the pipe to a photodiode at the receiver. The receiver converts the incoming optical signal into an electrical signal using a photodiode and recovers the original video data via demodulation. The recovered video is then examined by an inspector on the ground for pipe condition assessment.

B. Fresnel Zone Analysis inside Pipes

The quality of wireless communication links is greatly affected by the physical behavior of electromagnetic waves within Fresnel zones, particularly the first one, whose concept is illustrated in Fig. 2. Assuming a transmitter and receiver separated by a distance d [m], the maximum radius of the first Fresnel zone defined at the midpoint of the communication link (i.e., $d_1 = d_2 = d/2$), denoted as r_1 , is given by

$$r_1 = \frac{1}{2} \sqrt{\lambda d}, \quad (1)$$

where λ [m] denotes the signal wavelength. It is well-known that to ensure line-of-sight (LoS) conditions and maintain reliable communication quality, at least 60% of the first Fresnel zone radius must be clear of any obstructions [9]. The first Fresnel zone within a pipe is depicted in Fig. 3, where we assume the pipe diameter of D (with radius $R = D/2$) and that both the transmitter and the receiver are aligned along the central axis of the pipe. Accordingly, the condition required to maintain sufficient communication quality is given by $0.6r_1 \leq R$. By substituting Eq. (1) into the inequality and solving for d , the maximum communication distance, $d_{\max}$, is derived as follows

$$d_{\max} = \frac{1}{\lambda} \left(\frac{D}{0.6} \right)^2. \quad (2)$$

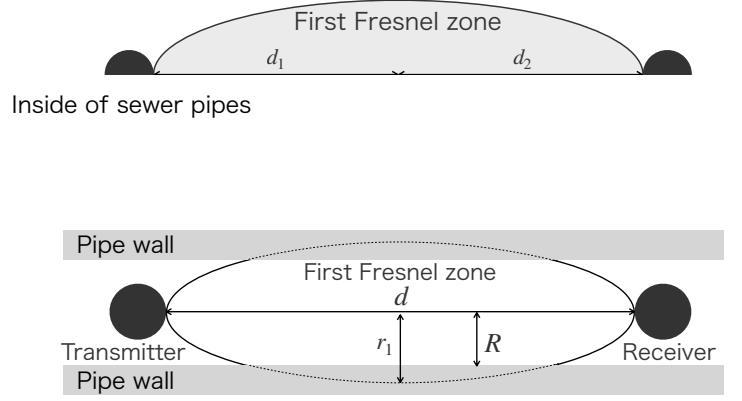


Fig. 3: First Fresnel zone within a pipe.

Assuming a sewer pipe with a diameter of $D = 200$ mm, we compare the theoretical maximum communication distances of wireless LAN and OWC using Eq. (2). Firstly, in the case of wireless LAN operating at typical frequencies of 2.4 GHz band ($\lambda = 0.125$ m) and the 5 GHz band ($\lambda = 0.060$ m), the theoretical distance limits are calculated to be approximately 0.89 m and 1.85 m, respectively. These results indicate that achieving long-range wireless LAN communication in narrow sewer pipes is highly challenging due to the rapid obstruction of the first Fresnel zone. On the other hand, in the case of OWC employing visible light wavelengths ranging from 380 nm to 780 nm, the theoretical maximum distance ranges from approximately 142 km to 292 km. This comparison clearly demonstrates that, whereas the LoS condition for wireless LAN deteriorates within only a few meters in small-pipe environments, OWC links are essentially unaffected by obstruction of the first Fresnel zone under the same conditions.

III. SYSTEM MODEL

This section describes the simulation model developed to analyze the optical propagation characteristics within sewer pipes. In this model, we assume a circular cross-section for the sewer pipe geometry. The total received optical power is calculated as the sum of the LoS component, which travels directly from the transmitter to the receiver, and the non-line-of-sight (NLoS) components, which reach the receiver after reflecting off the inner walls of the pipe. To determine the total power, the inner wall is discretized into segments along both the axial and circumferential directions. We then track the propagation paths via these segments and sum their individual contributions. For the NLoS components, reflections up to second order are considered in the analysis. This is because the computational cost increases significantly with the number of reflections, and the optical power is attenuated by a factor of ρ at each reflection, becoming progressively smaller with each subsequent reflection.

A. Transmitter Model

The transmitter and receiver are assumed to be positioned along the central axis of the pipe, with the transmitter exhibiting a Lambertian radiation pattern. This radiation is widely adopted as a standard approximation for typical emission characteristics, provides the maximum radiant intensity in the normal direction (i.e., along the optical axis) with the intensity decreasing gradually as the radiation angle θ increases. The spatial distribution of the radiant intensity $R(\theta)$ is expressed as [10]

$$R(\theta) = \frac{m+1}{2\pi} \cos^m(\theta),$$

where m represents the mode number that determines the directionality of the source, which is given by

$$m = -\frac{\ln 2}{\ln(\cos \theta_{1/2})},$$

with $\theta_{1/2}$, known as the semi-angle at half power, defined as the angle between the optical axis and the direction where the radiant intensity drops to half of its maximum. As indicated by the equation, decreasing the semi-angle $\theta_{1/2}$ increases the mode number m , thereby concentrating the optical power into a narrower beam. While this improves the quality of the LoS link by increasing the received power along the optical axis, it also makes the system more sensitive to pointing errors.

B. Receiver Model

The receiver is equipped with a photodiode that has a field of view (FoV) denoted by ψ_c . An optical signal can be successfully received if it falls within the receiver's FoV, whereas the received optical power is zero if it falls outside this range. The optical gain of the photodiode, $g(n, \psi_c)$, is expressed as [10]

$$g(n, \psi_c) = \begin{cases} \frac{n^2}{\sin^2 \psi_c} & (0 \leq \psi \leq \psi_c) \\ 0 & (\psi > \psi_c) \end{cases}, \quad (5)$$

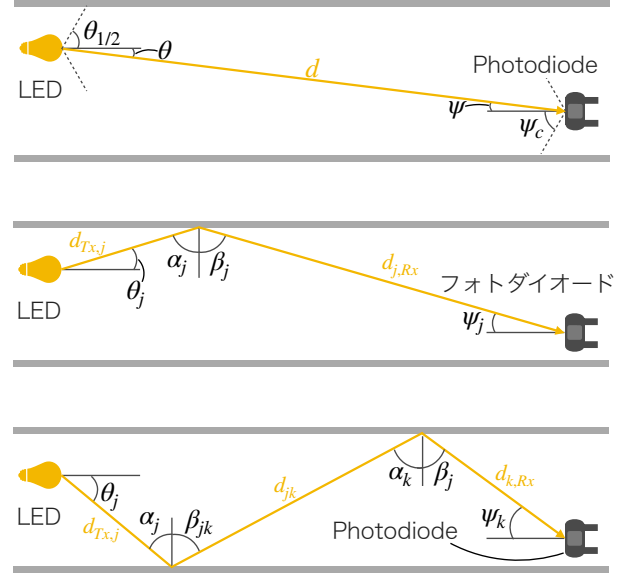
where n represents the refractive index of the optical concentrator and ψ denotes the angle of incidence to the photodiode.

C. Calculation of Received Optical Power

First, we describe the calculation method for the received optical power of the LoS component illustrated in Fig. 4a. Given the transmitted optical power P_t , the receiver area A_{rx} , and the distance d between the transmitter and the receiver, the LoS received optical power P_{r-LoS} is calculated as follows

$$P_{r-LoS} = P_t R(\theta) g(n, \psi_c) \frac{A_{rx}}{d^2} \cos(\psi). \quad (6)$$

For the calculation of the NLoS components, the inner wall of the pipe is modeled as a Lambertian reflecting surface with reflectivity ρ and is treated as a collection of infinitesimal surface areas dA . A Lambertian surface is an ideal diffuse reflector that scatters incident light uniformly in all directions, characterized by a radiant intensity proportional to



(c) NLoS propagation model for second-order reflections

Fig. 4: Optical propagation models within the sewer pipe.

the cosine of the angle between the surface normal and the radiation direction, in accordance with Lambert's cosine law. The propagation model for the first-order NLoS component is shown in Fig. 4b. The total received power of the first-order NLoS component, $P_{r-NLoS1}$, is determined by summing the contributions from all propagation paths that travel from the transmitter to each wall element j (distance $d_{Tx,j}$) and then to the receiver (distance $d_{j,Rx}$). Based on [10], this is expressed by

$$P_{r-NLoS1} = \sum_j P_t \frac{R(\theta_j) A_{rx}}{(d_{Tx,j} d_{j,Rx})^2} \rho dA \times \cos(\alpha_j) \cos(\beta_j) g(n, \psi_c) \cos(\psi_j), \quad (7)$$

where α_j is the angle of incidence to the wall element j , and β_j is the angle of radiation from the element.

Furthermore, Fig. 4c illustrates the NLoS propagation model for second-order reflections. The total received optical power of the second-order NLoS component, $P_{r-NLoS2}$, which reaches the receiver after an initial reflection at wall element j followed by a subsequent reflection at another element k , is calculated based on [10] using the inter-element distance d_{jk} as follows

$$P_{r-NLoS2} = \sum_j \sum_k P_t \frac{R(\theta_j) A_{rx}}{(d_{Tx,j} d_{jk} d_{k,Rx})^2} \rho^2 dA_j dA_k \times \cos(\alpha_j) \cos(\beta_{jk}) \cos(\alpha_k) \cos(\beta_k) \times g(n, \psi_c) \cos(\psi_k). \quad (8)$$

Finally, the total received optical power P_{total} is obtained as the sum of the received optical powers from the LoS and all NLoS components:

$$P_{total} = P_{r-LoS} + P_{r-NLoS1} + P_{r-NLoS2}. \quad (9)$$

TABLE I: List of simulation parameters.

Parameter	Value
Number of circumferential divisions (first-order NLoS)	72
Number of circumferential divisions (second-order NLoS)	6
Axial division width	1.0 m
Bandwidth, B	10 MHz
Noise power spectral density, N_0	$10^{-22} \text{ A}^2/\text{Hz}$
Transmitted optical power, P_t	10 W
Semi-angle at half power, $\theta_{1/2}$	60°
Physical receiver area, A_{rx}	10^{-4} m^2
FoV, ψ_c	60°
Photodiode responsivity, γ	0.54 A/W
Refractive index of the optical concentrator, n	1.5

IV. SIMULATION RESULTS AND ANALYSIS

For simulations, we consider two types of circular se pipes: a small-diameter pipe with a diameter of 200 mm and a large-diameter pipe with a diameter of 2,000 mm. Furthermore, simulations are performed for two conditions of the inner wall reflectivity: a low-reflectivity ($\rho = 0.15$), representing a soiled surface with reduced light reflect and a high-reflectivity ($\rho = 0.6$), representing a clean surface. Unless otherwise noted, the parameters used in the simulations are summarized in Table I. Note that the absorption and scattering effects of water inside the pipe are not considered in this model. Since water is typically present only at the bottom of the pipe, its direct impact on the LoS component, which accounts for the majority of the received optical power, is expected to be limited.

A. Relationship between Propagation Distance and SNR

Let γ [A/W] be the responsivity of the photodiode, which represents the conversion efficiency of the photodiode in converting the received optical power into electrical current. Furthermore, let B [Hz] be the signal bandwidth and N_0 [A²/Hz] denote the noise power spectral density. The SNR is then given by

$$\text{SNR [dB]} = 10 \log_{10} \left(\frac{(\gamma P_{\text{total}})^2}{N_0 B} \right). \quad (10)$$

Fig. 5 illustrates the calculated SNR as the propagation distance varies from 3 m to 100 m. The results indicate that the SNR remains almost unchanged regardless of the pipe diameter or the reflectivity of the inner walls. This is because the LoS component accounts for the vast majority of the total received optical power. These results suggest that ensuring the LoS is crucial for achieving stable communication performance.

Simulation results further demonstrate that a sufficient SNR can be maintained over relatively long propagation distances. For instance, the SNR at a propagation distance of 40 m is approximately 20 dB. According to Shannon's theorem [11], this corresponds to a maximum theoretical data rate of approximately 66 Mbps, which is sufficient to support real-time video streaming applications.

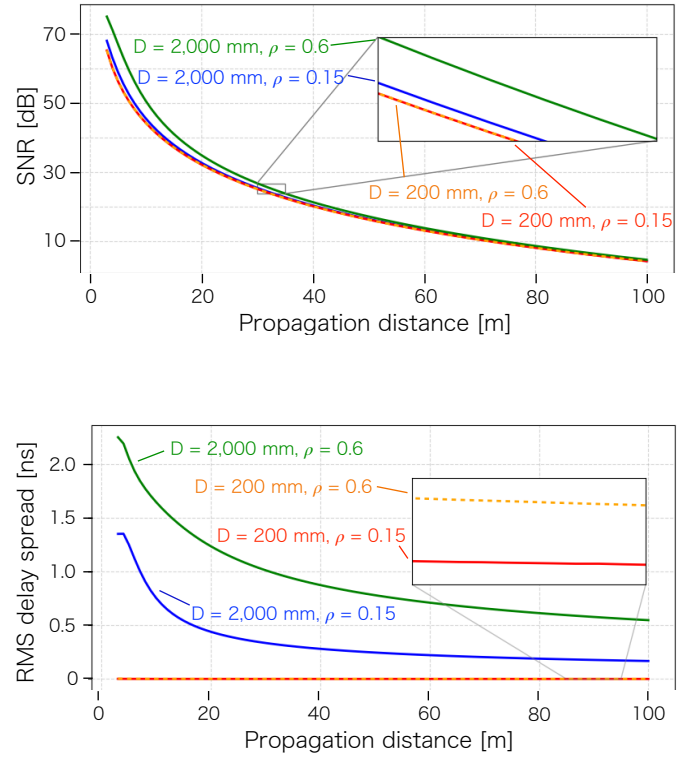


Fig. 6: Relationship between propagation distance and RMS delay spread.

B. Relationship between Propagation Distance and RMS Delay Spread

In the proposed system, multipath propagation occurs due to reflections from the inner walls of the pipe. Since each propagation path has a different length, the received signals arrive at different times, causing adjacent signal pulses to overlap. This effect, known as ISI, degrades communication quality. To quantitatively evaluate the impact of multipath propagation, the RMS delay spread is employed. The RMS delay spread is defined as the standard deviation of the delay distribution of the received optical power and represents the degree of temporal dispersion of the signal energy. Specifically, let P_i and τ_i be the received optical power and time delay of the i -th propagation path. The RMS delay spread τ_{rms} is then given by [12]

$$\tau_{\text{rms}} = \sqrt{\left\{ \frac{\sum P_i \tau_i^2}{\sum P_i} \right\} - \left\{ \frac{\sum P_i \tau_i}{\sum P_i} \right\}^2}. \quad (11)$$

Fig. 6 shows the RMS delay spread as the propagation distance varies from 3 m to 100 m. Simulation results showed that the RMS delay spread was almost negligible in the 200 mm-diameter pipes. This is due to the fact that the received optical power of the NLoS components is extremely small in such environments. In contrast, in the larger 2,000 mm-diameter pipe, a maximum RMS delay spread of approximately 2.3 ns was observed. Generally, to mitigate the impact of ISI, the RMS delay spread should be less than 10% of the symbol duration [13]. Based on this criterion, the theoretical

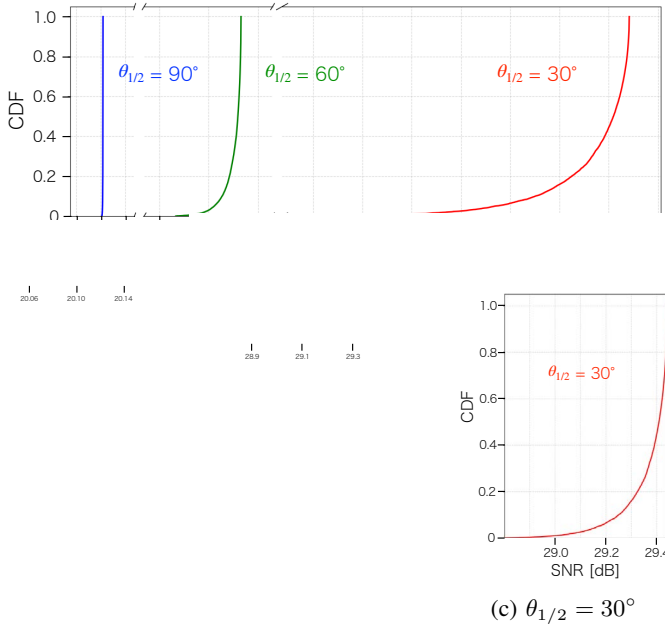


Fig. 7: CDFs of the SNR for different LED half-power angles under transmitter tilt and positional variations.

maximum allowable data transmission rate under a 2.3 ns delay environment is approximately 43 Mbps, which is still sufficient for video streaming applications. These results indicate that ISI caused by multipath propagation does not pose a significant limitation in the proposed system.

C. Impact of LED Half-Power Angle, Transmitter Tilt, and Position on SNR

Increasing the LED directivity is expected to improve the SNR. However, since the position and orientation of the transmitter can vary during the inspection robot's motion, highly directive beams may suffer from pointing errors that degrade the SNR.

In this section, we evaluate the statistical variation of the SNR for three LED half-power angles ($\theta_{1/2} = 30^\circ, 60^\circ, 90^\circ$), taking into account both the position and tilt variations of the transmitter. To emulate the motion of the inspection robot, the transmitter tilt angle θ_{tilt} is modeled as a truncated normal distribution with a mean of 0° and a standard deviation of 3.3° , restricted to the range $0^\circ \leq \theta_{\text{tilt}} \leq 10^\circ$. The tilt direction is uniformly distributed from 0 to 2π . The transmitter position is modeled as a two-dimensional truncated normal distribution with a mean at the pipe center and a standard deviation of 16.7 mm, and the distance from the pipe center is restricted to within 50 mm. The simulation assumes a 200 mm-diameter pipe with $\rho = 0.15$ and a propagation distance of 40 m. Fig. 7 shows the CDFs of the SNR for the three half-power angles, and Figs. 7a–7c provide magnified views of each distribution.

Simulation results show that narrowing the LED half-power angle improves the SNR. The median SNR is approximately 14.3 dB for $\theta_{1/2} = 90^\circ$, 20.1 dB for $\theta_{1/2} = 60^\circ$, and 29.4 dB for $\theta_{1/2} = 30^\circ$. On the other hand, the SNR degradation

caused by the position and tilt variations of the transmitter is small, increasing only from approximately 0.02 dB for $\theta_{1/2} = 90^\circ$ to approximately 0.7 dB for $\theta_{1/2} = 30^\circ$. Although higher directivity makes the SNR more sensitive to position and tilt variations, this degradation is considerably smaller than the SNR gain achieved by enhanced directivity. These results confirm that a stable SNR can be maintained even under position and tilt variations of the transmitter caused by the inspection robot's motion.

V. CONCLUSION

We proposed a sewer pipe inspection system using OWC to overcome the limited communication range of existing systems employing wireless LAN. The performance of the proposed system was evaluated through simulations using a constructed in-pipe optical propagation model. Simulation results indicated that, for a pipe with a diameter of 200 mm and a transmitted optical power of 10 W, the proposed system can achieve an SNR of approximately 20 dB at a propagation distance of 40 m, with a negligible RMS delay spread on the order of nanoseconds and high robustness to transmitter tilt and positional variations, making it suitable for real-time video streaming. We are currently developing a prototype capable of video transmission using OWC and plan to conduct demonstration experiments of video streaming in sewer pipes.

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