IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 19, 2018, accepted January 6, 2019, date of publication January 9, 2019, date of current version January 29, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2891753

Queuing Delay Model for Video Transmission Over Multi-Channel Underwater Wireless Optical Networks

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ABSTRACT In this paper, we analyze a delay-sensitive underwater wireless optical network used for live-video applications. The video streams are generated at the sender and are transmitted through underwater multi-channel paths that span over several meters of length, where the receiver is subject to a maximum end-to-end delay constraint. We model this network with $M/G/1$ Markovian models to quantify the system's performance. Also, we obtain an approximate expression for the probability of blocking at the receiver considering an acceptable QoS. We provide an approximate expression for the minimum number of channels required to satisfy the preset QoS metric. Our model is validated using actual parameters from an existing setup and by comparing the analytical expressions for the end-to-end delay and probability of blocking for different scenarios with the simulation results.

INDEX TERMS Underwater wireless optical networks, video streaming, multi-channel systems, queueing theory, end-to-end delay, loss probability.

I. INTRODUCTION

Underwater Wireless Optical Communications (UWOC) is an emerging technology that has gained a considerable interest from several research communities in the very recent years in pursuit of revolutionizing oceans explorations. Marine organisms are sources for biotechnology-based applications, including natural products, flavors, fragrances, enzymes, and medicines [1]. The brine pools of the Red Sea, for instance, host a wide range of microbial gene communities, which are sources of enzyme for many pharmaceutical products, and some of them can be promising potentials for anti-cancer natural treatment [2]. Environment protection, disaster prediction, accurate weather predictions based on oceanic readings are analyzed to understand the ocean's processes that largely affect on-land processes. Oil and gas fields on the other hand are yet to be discovered massively offshore, operated, inspected and maintained [3], [4].

To facilitate such applications and better understand the ocean's environment, it is imperative to employ new concepts of wireless communications that realize real-time video in good quality underwater. As the Optics and Laser technology is advancing to provide higher bandwidths and transmission speeds at Gigabit per second (Gbps) or beyond, underwater wireless optical communication (UWOC) is considered as an attractive alternative to acoustics and RF systems for their low bandwidth and high delays underwater [5], [6].

However, unlike Free-Space optical links, the ocean's water optical properties pause extreme challenges for UWOC. Scattering and absorption of light are two main causes of degradation of UWOC performance for long range transmissions and high quality imaging systems [7]. Turbulence on the other hand, resulting from varying dissipation rates of temperature and changing salinity, also play a major role in degradation of the optical signal in oceans. Any small changes in salt concentrations can result in salinity variations and subsequently more fluctuations of the refractive index [8]. Moreover, ocean water is blue due to the Rayleigh scattering phenomena, as when the sunlight penetrates into the deep water, the blue and green spectrum region is absorbed the least and therefore can propagate into longer depths up to a kilometer range from the surface. This constitutes to higher levels of ambient interference to the optical communications signal that cannot be avoided during daylight hours [9].

Previous theoretical and experimental work have been carried out extensively for exploring the behavior of optical signals underwater. Although recent projects achieved Gbps speeds, but the aforementioned constrains can confine the

TABLE 1. Summary of technological developments.

Year	2018	2014	2013	2007	2005
Affiliation	KAUST	OUC	MIT	PAS Inc.	NCS
Author	A.Alhalafi	M.Sun	M.Doniec	G.Baiden	M.Chancey
System	Bi-DIR UWON	-	AquaOptical	-	RONJA
Communi.	UWOC	UWOC	UWOC	UWOC	UWOC
Modulation	64-QAM-OFDM	-	Manchester	-	Manchester
Video/Coding	yes/JPEG	yes	yes/RS-LT	yes	yes
Quality	4K UHD	-	1288 HD	-	-
Throughput	30 Mbps	-	4 Mbps	10 Mbps	10 Mbps
Range	4.5 m	4.5 m	25 m	10 m	4.6 m (15 ft)
Wavelength	520nm, 450nm	488nm	480nm LED	450nm	450nm LED
Power	15 mW	50 mW	30 W	-	1 W
Remarks	lab	lab	pool	lake	lab
Water type	harbor II	visibility	clear water	lake	clear water
Reference	[18]	[16]	[15]	[14]	[13]

ranges to few meters [10]–[12]. Researchers on underwater video transmission utilized the available bandwidth at that time. In 2005, Chancey performed a 10 Mbps video experiment on 4.6 m clear water channel [13]. In 2007, Baiden and Bissiri [14] achieved a 10 Mbps video transmission over 10 meters in a lake. In the 2013 MIT AquaOptical II prototype, Doniec *et al.* [15] used an array of 18-LEDs transmitter for 4 Mbps video. In 2014, Sun *et al.* [16] demonstrated an externally modulated video data in a water tank with different visibility levels. These experiments established the potential of using UWOC for video streaming. However, the received video quality and coverage ranges remain challenging. More recently in 2017, Al-Halafi *et al.* [17], [18] demonstrated good quality of real-time video transmission using 8-PSK and 8-QAM modulations, and further in 2018 designed bidirectional links with implementation of 64-QAM-OFDM to realize 30 Mbps transfer rate of an ultra-high definition (UHD) video using UWOC in different ocean water types. Table 1, summarizes the achieved results in our work [18] against the previous systems or experiments.

In general, performance studies proposed multi-channel and spatial diversity techniques to overcome the range limitations. On the contrary to the single-channel, multi-channel configurations provide higher power efficiencies, higher reliability, resilience to turbulence, and higher capacities [19]. However, adequate designs for transceivers entail additional complexities that may limit experimental implementations. Moreover, the queueing associated delays, the subsequent packet dropping, and setting an acceptable QoS metric for the received video quality were not considered. Nevertheless, while achieving higher transmission ranges increases absorption and loss probability, scattering generates more inter-symbol interference (ISI), and turbulence induces fading, yet we believe using multi-channel spatial diversity can achieve better gains when transmitting multiple copies of the same video packets through different independent and identically distributed fading channels, and thus may increase the probability of receiving a decodable video with an improved quality.

On the other hand, although RF waves experience significant losses as a result of higher conductivity of ocean water, a multi-channel RF scheme was proposed by [20]. It was reported that using QPSK modulation over four transmit antennas achieved 48 Kbps at 23 kHz bandwidth over a 2 km link, but this link is not suitable for video streaming for its very low bandwidth regardless of the achieved long range transmission.

In this work, we provide an analytical study aimed to enable researchers to make better designs of network topologies to meet the optimum QoS for the delay and packet loss. Also, to provide researchers with performance means to design optimal routing policies for contingency planning and to overcome any non-line of sight (NLOS) situations. Moreover, to help engineers design multi-channel systems with optimal capacity assignment to each underwater wireless optical channel. To meet those objectives, we examine the performance of transferring real-time video over an UWOC employing multi-channel diversity gain from a single sender through multiple channels underwater to a single receiver. We examine this network using an $M/G/1$ queuing theory model to quantify the system's performance. We develop an approximate expression for the probability of blocking at the receiver and for the minimum number of channels considering an acceptable QoS and a given end-to-end delay threshold. Finally, we perform measurements to validate our model.

The contributions of this work are summarized in the followings.

- To analyze delay-sensitive UWOC systems intended for live-video streaming applications. The video streams are generated at the sender side and are transmitted through underwater multi-channel paths, where the receiver is subject to a maximum end-to-end delay constraint.
- To design the system model and queue configuration for the multi-channel network based on the outcomes and lessons learned from the previous research on UWOC systems and our previous experimental setup parameters and results.
- To mathematically analyze this network as an M/G/1 stochastic model to quantify the system delay performance and to obtain an approximate expression for the probability of blocking at the receiver side considering an acceptable QoS subject to a given end-to-end delay threshold.
- To derive and present an expression for the minimum number of channels that can support the video transmission given those constrains for a multi-channel system configuration.
- To evaluate and validate our model by using simulation based on previous experimental parameters and to demonstrate that the end-to-end delay and probability of blocking for several scenarios are in agreement with the model hypothesis.

The rest of this paper is organized as follows. In Section II, the proposed system model is presented. In Section III, the analysis is developed. Numerical results are presented in Section IV. Finally, the paper is concluded in Section V.

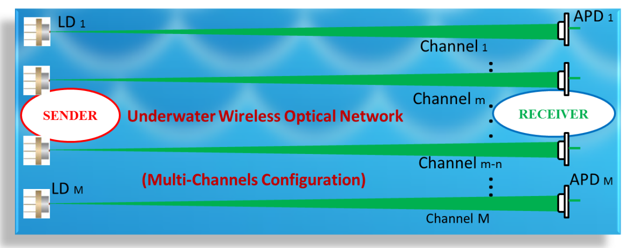

FIGURE 1. An overview of the multi-channel underwater wireless optical system.

II. PROPOSED SYSTEM MODEL

In our system, we consider an underwater wireless optical network, such as Fig. 1, in which a sender transmits video using an equally spaced laser diode (LD) sources through M underwater optical channels to an equivalent number of avalanche photodiode (APD) detectors. We assume that all of the channels are located in line-of-sight (LOS) to the receiver and with an equal separation distance. We also assume that the multi-channel transmission is based on an equal power allocation for transmitters, i.e., $P_i = P/M$. Here, we assume that the fading of each link is independent from the others, in order to make an independent and identically distributed (i.i.d) channels model. The queue model for the multi-channel setup of the underwater wireless optical network is shown in a simplified form as in Fig. 2, where the arrivals to the network are made into multiple copies and sent through the available channels to the receiver. The parameters used in this figure are the arrival rates, denoted as λ, the exponential inter-arrival times γ, the service times rates μ, and the channels propagation delays τ, which are explained in details below.

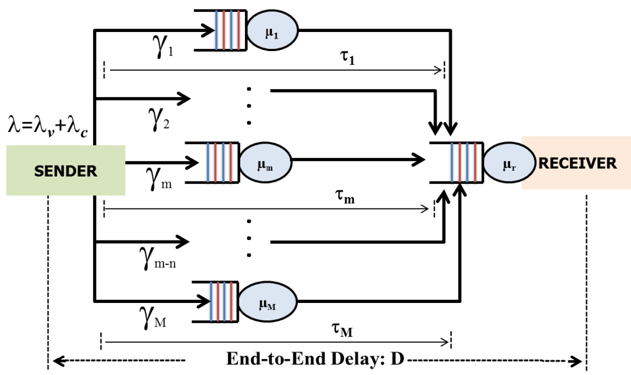

FIGURE 2. Multi-channel system model and queue overview.

The incoming video packets are modeled with an exponential inter-arrival times having rates $\gamma_{i(v)}$, where $i = 1, 2, \ldots M$, and M is the maximum number of available channels. When the video signal arrives from external sources, it is wrapped into packets that include guard bits, synchronization bits, and pad bits which we will call from now on as control packets. These control packets are exchanged with the receiver from the sender's internal sources to manage video packets transmission and to provide statistics about errors and packets loss. The channels are modeled as independent single server facilities with two class queues where video packets are transmitted to the receiver node.

Each path that these packets traverse from the sender to the receiver is characterized in our model by an ordered set of channels π_k, and each channel has a capacity C_i. The service time at each channel is assumed to be exponential with parameter μC_i. We assume that the arrival of class k packets to the network is to be Poisson distributed with rates λ_v for the video packets, and λ_c for the control packets. The arrival to the network in general is:

$$\lambda = \sum_{i=1}^{\infty} [\lambda_{i(v)} + \lambda_{i(c)}] = \sum_{\substack{i=1, \\ k\in\{v,c\}}}^{\infty} \gamma_{i(k)} \tag{1}$$

Hence, we consider an infinitely continuous transmission for the live streams of video packets. Video packets are assumed to originate only from the source, while control packets can arrive from external sources. In general, there are two different flows into the network (i.e. video, and control) if control packets are meant for commanding an underwater robot, for instance, but in our case we assume the control packets are for managing the video transmission signal and is wrapped together with the video payload into one single transmission packet. Going forward we will drop the control packet notion and consider a flow all together to be a video packet. To formulate this concept (i.e., multiple copies of the same packet through the different M channels), the arrival rate to each channel is equally distributed with the same arrival rate:

$$\lambda_{i(k)} = \sum_{i=1}^{M} \gamma_{i(k)} = \begin{cases} \gamma_k, & i \in \pi_k \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where $k \in \{v, c\}$ is the packet class index in the system, and π_k is the set of channels traversed by class k packets.

In our system, we are looking at each channel as a queue in isolation with an exponentially distributed service time that has a mean of $\overline{X_i}$, for each channel where $i \in \{1, 2, \ldots, M\}$. Our objective in this framework is to identify a minimum QoS requirement that defines the latency experienced by the received video packets. We therefore set a minimum acceptable time delay from the moment each video packet is transmitted till it is delivered correctly at the receiver, and we call this threshold as T_{QoS}. Any video packet with an over all delay resulting from waiting due to other packets are already being in the queue or in service either at the channels or at the receiver, or due to an excessive propagation delays at the channels, resulting in the delays exceeding T_{QoS} upon arriving the receiver node will be dropped. This constrain is implemented before the receiver, but we also implement the quality check QoS constraint at the receiver queue. Thus, if we let D be a random variable that stands for a video packet time delay, then the probability of dropping a video packet at the receiver node is:

$$P_{blocking(v)} = Pr\left\{D_{(v)} > T_{QoS(v)}\right\} \tag{3}$$

We also realize our system to be based on a multi-channel configuration, and in order to improve the reliability of the system and fully utilize the diversity of all available channels, we assume the use of simple repetition coding that generates multiple copies of the same packet to be transmitted through each path with the same probability p_m. At the receiver, a maximum of M packets will arrive and we are considering one technique that is often used in such systems. We assume that the arriving video packets are queued based on the precedence of their arriving time, and then wait for a quality check to be performed based on a preset QoS metric. The waiting time at the receiver buffer is based on the probability that a video packet is successfully decoded using packet i of the M transmitted packets, and is denoted by P_{S_i}. It is equal to the conditional probability that we use i versions of the packet to successfully decode the video, given that at least one packet is decoded in order to satisfy the queue stability condition.

$$P_{S_i} = \frac{(1-p)^{(i-1)} \cdot p}{\sum_{m=1}^{M} (1-p)^{m-1} \cdot p} = \frac{(1-p)^{(i-1)} \cdot p}{1-(1-p)^M} \tag{4}$$

III. ANALYSIS

In this section, we present our analytical expressions for the video transmission time Delay D experienced by any K classes of packets, in addition to finding the video packet dropping probability. Our derivations are based on the standard methods for $M/G/1$ queues as in [21]. We start with providing a summary of notations as in Table 2.

TABLE 2. Notations.

Symbol	Definition
M	Number of multi-channels in the system
K	Packet classes
i	Channel index
$\lambda_{i(v)}$	Poisson arrival rate of video packet to Channel i
$\lambda_{i(c)}$	Poisson arrival rate of control packet to Channel i
$\lambda_{i(k)}$	Aggregate Poisson arrival rate of classes k going to Channel i, $k \in \{v, c\}$
X_j	Service time random variable for packet j
χ_i	Service time random variable for Channel i
$p_{i(k)}$	probability of scheduling a packet flow of class k, $k \in \{v, c\}$ into Channel i
$\rho_{i(k)}$	Utilization of packet class k, $k \in \{v, c\}$ at Channel i
R	Residual service time
$W_{i(k)}$	Waiting time in the queue for packet class k, $k \in \{v, c\}$ at Channel i
$\omega_{i(k)}$	Waiting time at receiver for packet i of class k, $k \in \{v, c\}$
T_i	Average response time at Channel i
τ_i	Propagation delay at Channel i from Green Laser Diode source to Avalanche Photo-Detector receiver
$N_{i(k)}$	Number of packets scheduled in the queue with class k, and Channel i, $k \in \{v, c\}$

Because we are considering M channels in our proposed model for the multi-channel configuration of the UWOC network, although we assumed video packets can have an exponentially distributed inter-arrival time, their service time however can be different and does not necessarily have an exponential distribution, it can be considered arbitrary. Therefore, we will model each channel as a queue in isolation and an $M/G/1$ queue and the receiver as an $M/G/1$ queue as well. To simplify derivations, we assume that each packet has a separate queue in logical sense, and when each channel represents a single server, which when becomes free, packets from the head of the non-empty queue enters that channel with free server for transmission. Also, when packets exit the transmission channels and arrive at the receiver queue, they wait in sequence ordered by their arrival time to further undergo a quality check. At least one packet is successfully decoded in our assumption which satisfy the quality check and arrived before any other decodable packet. Packets that do not satisfy the quality check will be dropped. When a decodable packet is found the queue buffer will be flushed and the remaining packets will be dropped.

The probability of successfully finding a decodable packet is provided above in (4). There are no priority over any packet, the arrival rates $\lambda_1, \ldots, \lambda_i$ (Poissonian), and the expectation and second moment of the service time are $\overline{X}$ and $\overline{X^2}$. The stability condition of the queue: $\rho_1 + \ldots + \rho_i < 1$ is viable.

To start with, we are interested in obtaining the mean waiting time $\overline{W}$ and second moment $\overline{W^2}$ that will be experienced by video packets at each underwater optical channel. As we are looking into each channel as a queue in isolation we will remove the channel index i to simplify the notations but we will use i as a packet index in the receiver queue whenever required. The average waiting time in the system is based on the summation of waiting times in the channels $\overline{W_{ch}}$ as well as at the receiver $\overline{W_{rx}}$:

$$E[W] = E[W_{ch}] + E[W_{rx}] \tag{5}$$

To find the average waiting time at the channels, we will start in the same way as in the derivation of the *Pollaczek − Khinchinin* for our proposed type of queueing system. The (P-K) formula states the following:

$$E[W_{ch}] = \frac{E[R]}{1-\rho} = \frac{\lambda \cdot E[X^2]}{2(1-\rho)} \tag{6}$$

Using the following notations: $\overline{N}_q^{(k)}$, which is the mean number of waiting class-k packets in the queue, $\overline{W}_q$, the mean waiting time of class-k packets, ρ_k, the load of class-k, or $\rho_k = \lambda_k \cdot \overline{X}_k$, and $\overline{R}$, the mean residual service time in the underwater optical channel (upon arrival), then video packets average waiting time in channels is:

$$\overline{W_{ch}} = \overline{R} + \overline{X} \cdot \overline{N}_q \tag{7}$$

The latter term represents the average time needed to serve the video packets ahead in the channel queue. By *Little's* result we have $\overline{N}_q = \lambda \cdot \overline{W_{ch}}$. Substituting in (7) above, we get: $\overline{W}_{ch} = \overline{R} + \rho_v \cdot \overline{W}_{ch}$. Rearranging the terms we get the waiting time for the video packets as:

$$\overline{W}_{ch} = \frac{\overline{R}}{1-\rho_v} \tag{8}$$

In general, the total time spend in channels for class-k packets on the average can be found as:

$$\overline{T}_k = \overline{W}_k + \overline{X}_k + \overline{\tau}_k \tag{9}$$

where $\overline{\tau}$ is the propagation delay of the optical signal in the underwater channel, which we will elaborate with more details in the evaluation section later on in this paper. The mean residual service time $\overline{R}$ appearing in $\overline{W}_k$ can be derived by the same kind of graphical *triangle trick* as in the case of the (P-K) mean value formula as:

$$\overline{R} = \frac{1}{2}\sum_{n=1}^{N} \lambda_n \cdot \overline{X_n^2} \tag{10}$$

The first moment of this residual time can then be written as

$$\overline{R} = \frac{1}{2}\left[(\rho_v + \rho_c) \cdot \frac{\overline{X_v^2}}{\overline{X_v}}\right] \tag{11}$$

where $\rho_v = \lambda_v \cdot \bar{X}$ is the fraction of time the channel is serving the video packets. Making additional algebraic manipulations after raising both sides of (7) to the 2nd power and taking expectation, we get the second moment of waiting time:

$$\overline{W^2} = \overline{N}_v \cdot Var(X) + \left[\left(1 + \frac{\rho_v}{1-\rho_v}\right)\overline{R}\right]^2 + Var(R) \tag{12}$$

where $Var(R) = \overline{R^2} - \overline{R}^2$. Finally, we need to evaluate $\overline{R^2}$ by using the law of total expectation, E[Y] = E[E[Y|X]]:

$$\overline{R^2} = \rho_v \overline{R_v^2} + \rho_c \overline{R_c^2} = \frac{1}{3}\left((\lambda_v + \lambda_c)\overline{X^3}\right) \tag{13}$$

At the receiver, the average waiting time is based on the probability of success defined in (4), and is given by:

$$E[W_{rx}] = \sum_{i=1}^{M} \omega_i \cdot P_{S_i} = \sum_{i=1}^{M} \omega_i \cdot \frac{(1-p)^{(i-1)} \cdot p}{1-(1-p)^M} \tag{14}$$

where ω_i is the service time taken by one packet i in the receiver server and is assumed to be exponential with parameter μ_{rx}.

The above equations complete the derivations of the waiting times and blocking probabilities for the video packet traffic both in channels and in receiver queues. We are now ready to proceed next to the derivations of the associated delays and minimum channels count.

A. VIDEO TRANSMISSION TIME DELAY

The average time a class-k packet spends in the system is:

$$\begin{aligned}\overline{T}_k &= \left[\overline{W}_k + \overline{X}_k + \overline{\tau}_k\right]_{(ch)} + \left[\overline{W}_k\right]_{(rx)} \\ &= \left[\overline{W}_k + \frac{1}{\mu_k} + \overline{\tau}_k\right]_{(ch)} + \left[\overline{W}_k\right]_{(rx)}\end{aligned} \tag{15}$$

Using *Little's* formula, and the arrival rate of packets in the system for each class, while considering all packets, the average time delay per packet becomes:

$$\overline{T} = \left[\frac{\lambda_1 \cdot \overline{T_1} + \ldots + \lambda_K \cdot \overline{T_K}}{\lambda_1 + \ldots + \lambda_K}\right]_{(ch)} + \left[\overline{W}_k\right]_{(rx)} \tag{16}$$

In our case there are only two classes, video and control. Therefore, the mean time delay per packet simplifies to:

$$\overline{T} = \frac{\lambda_v \cdot \overline{T_v} + \lambda_c \cdot \overline{T_c}}{\lambda_v + \lambda_c} + \sum_{i=1}^{M} \omega_i \cdot \frac{(1-p)^{(i-1)} \cdot p}{1-(1-p)^M} \tag{17}$$

B. MINIMUM CHANNEL-COUNT

In the last part of our analysis, we will try to find the minimum number of channels that can satisfy the delay QoS value that we set for our underwater wireless optical network, in such a way that we only use just enough channels that will improve the network reliability but not introduce excessive delays that can adversely affect the performance. The backscattering from an adjacent channel when increasing the number of channels in a confined space would increase the ISI in effect which we want to avoid.

The minimum channel-count is given by:

$$\begin{aligned} M^* = arg \min_{s} & \left\{\mathbf{1}^T\mathbf{s}\right\}, \\ s.t.\ c1 &: \mathbf{t} \cdot \mathbf{s} \le \mathbf{t_{QoS}}, \\ c2 &: \sum_{i=1}^{M} S_i \geqslant 1, \\ c3 &: \mathbf{s} \in \{0, 1\} \end{aligned} \tag{18}$$

where

$$\overline{T}_i = (p_{k,i}) \cdot \overline{W}_{v,i} + (p_{k,i}) \cdot \overline{W}_{c,i} + \tau_i + \overline{\omega}_i \cdot P_{S_i}, \quad (19)$$

The vector **s** contains a series of 0 and 1 values that indicate whether a channel has satisfied the QoS constraint or not. The vector **t** contains the values of T_i for all channels, and the vector $\mathbf{t}_{QoS}$ contains the preset T_{QoS} values. Notice that in this optimization we try to find the minimum number of channels M by first building the vector **s** that when multiplied as a dot product multiplication by the vector **t** and cross comparing it element by element to the vector $\mathbf{t}_{QoS}$ we will be able to remove channels that did not satisfy the preset QoS values. When we insert the **s** into the minimization argument it will be multiplied by the vector **1**. This process will sum these products as an increment by 1 each time we find a channel to eventually produce the count M of the minimum channels that satisfied the QoS. Hence, this optimization is an NP-complete problem and can be solved by the readily available ILP solvers, such as MATLAB-CVX software package.

IV. NUMERICAL RESULTS

In this Section, we examine the validity of our model through simulation of different scenarios. We simulate a single $M/G/1$ queue with generally distributed service times in order to verify the expressions we found earlier for $\overline{W}$ and $\overline{W}^2$. Although the service times are assumed to be exponentially distributed, we test the model for arbitrary service time distributions, because the formulas hold for single queue when the video arrivals are assumed to be Poisson distributed. The simulation model is written on MATLAB where a multi-channel configuration is designed. We considered a maximum of 4 channels as this setup is found optimum and fits within the space limits of a practical underwater wireless optical communications channel such as our exiting setup. The number of video packets and their average arrival-rate in our evaluation are $N = 45 \times 10^5$ and $\lambda = 1$; respectively. We based our settings on our findings in [18] that an ultra-high definition (UHD) video for UWOC can be achieved with transfer rates of 30 Mbps. A maximum latency of 100 ms, and jitter of 30 ms can be tolerated for real-time and UHD video transmission in UWOC. The propagation delay at the channels is based on the water refractive index at $20°C$ which is ≈ 1.33, so the speed of light in water is $2.25 \times 10^8\ m/s$. We have also considered as a quality metric what we found in [17] that a Structural Similarity Index (SSIM), when it has a value of 70% it would provide us with an acceptable video quality that can be decoded. Therefore, we consider in our evaluation several scenarios where we set the QoS metric to 70%, 80% and 90%, in order to investigate what implications could this quality constraint have on the system's performance.

Fig. 3 presents the blocking probability for a system of 4 channels, when the different values of quality metrics constraints are implemented. We observe that the more stringent our quality check is (i.e. at 90%), then the lower the success rate of delivering a decodable video packet with

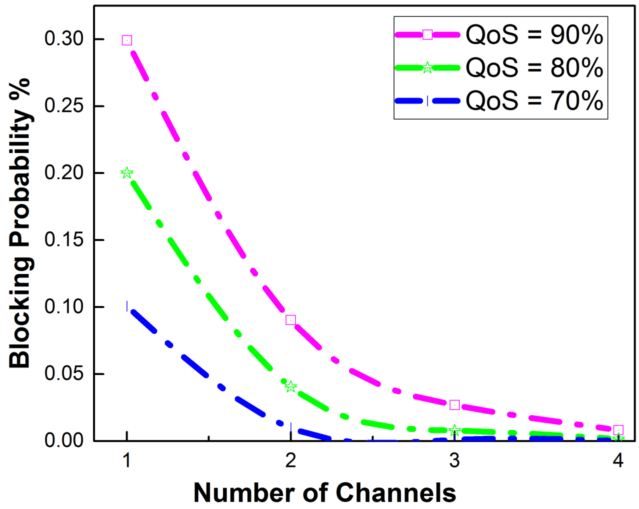

FIGURE 3. Blocking probability vs. preset QoS constraint for 4 channels.

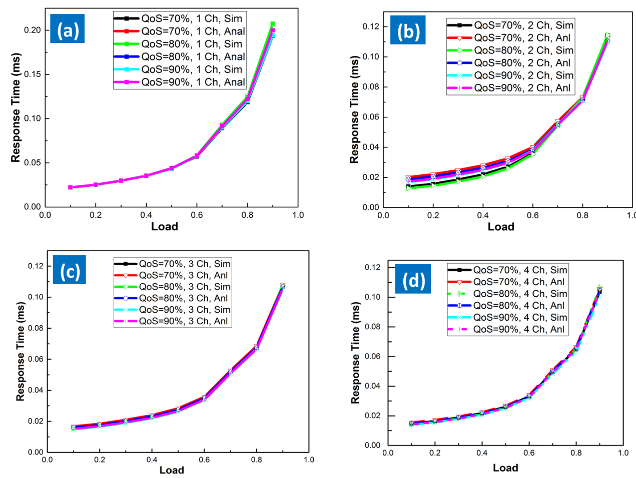

FIGURE 4. Response time (simulation and analytical) vs. preset QoS constraint for (a) 1 channel, (b) 2, (c) 3, and (d) 4 channels.

only one channel. However, by increasing the number of channels up to 4 channels, we observe that the failure rate is greatly minimized to negligible levels, and this supports our hypothesis.

Next, in Fig. 4, we show the strong agreement between the analytical and simulation results for the response time when 1, 2, 3, and 4 channels are available as in (a), (b), (c) and (d) respectively, and under the various QoS constraints that we implemented.

In Fig. 5, we present the response time versus the number of available channels while the QoS metric is set to 90%. It is apparent that while increasing the number of channels can help reduce the probability of failure it can also decrease the delay by about 15% at full load. We implemented a feedback channel in our simulation to guarantee fairness and stability of the queue. Nevertheless, we notice that the delay is still within the acceptable bounds of real-time video without having latency or jitter. The results for the response time reveal the benefits of using more channels, as we are within the bounds

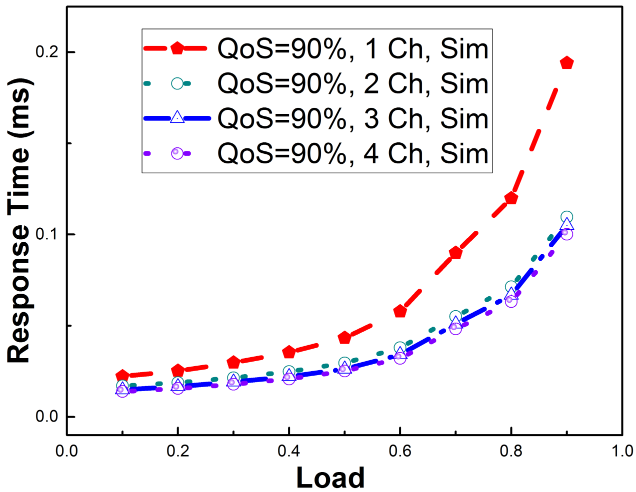

FIGURE 5. Response time for QoS = 90% versus number of channels (simulation).

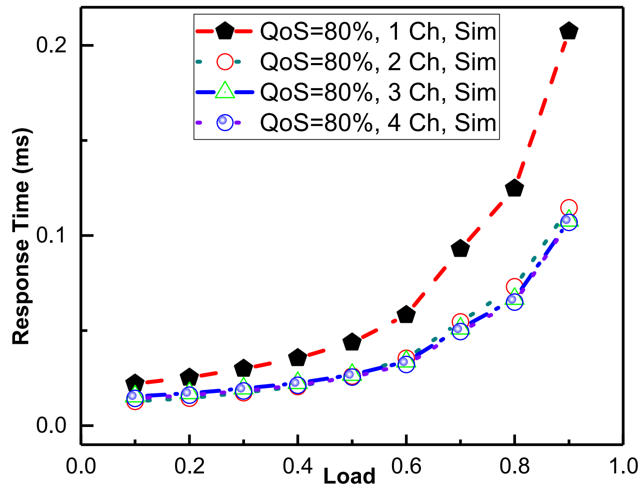

FIGURE 7. Response time for QoS = 80% versus number of channels (simulation).

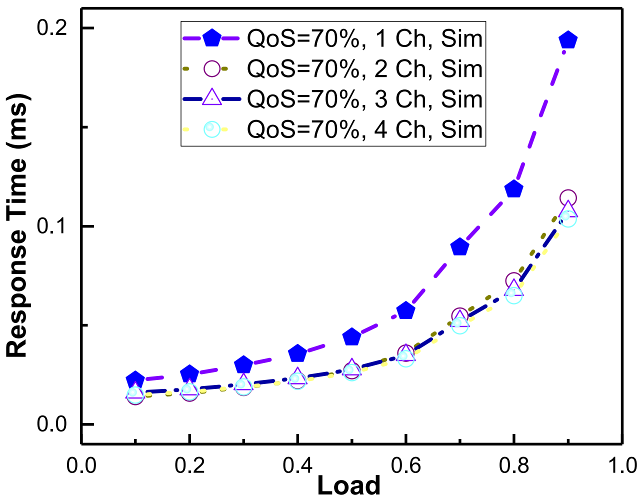

FIGURE 6. Response time for QoS = 70% versus number of channels (simulation).

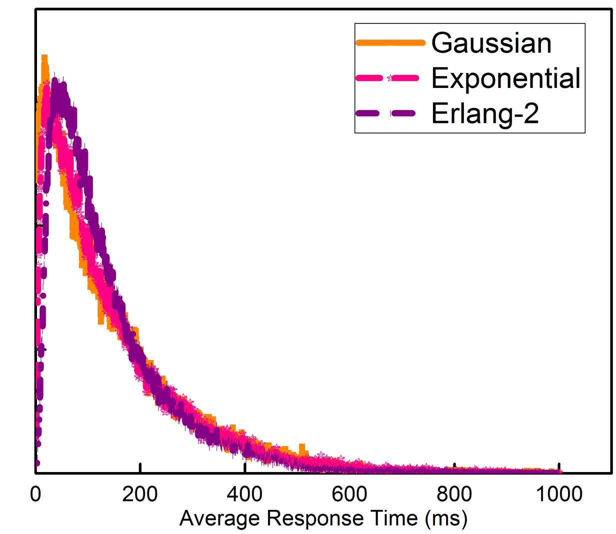

FIGURE 8. PDF of the proposed model with general distributions.

of acceptable QoS metric for decoding a good video packet, we therefore do not notice a big effect of setting the quality metric, opposed to when having only a single channel.

Similarly, in Fig. 6 we present the response time versus the number of available channels while the QoS metric is set to 70%. Also, in Fig. 7 we present the response time versus the number of available channels while the QoS metric is set to 80%. Those two figures show similar findings as in Fig. 5.

Finally, in Fig. 8, we show the close match of the density functions of the proposed model response time using different distributions. We test Exponential, Gaussian, and Erlang-2 distributions as service times for the channels and receiver. A summary of the analysis is that we could improve the reliability of the system by greatly increasing the success rate of decoding the video from multiple copies received through the proposed multi-channel configuration. Even when implementing the most stringent quality metric, we did not exceed or even come close to the limits of the allowable latency for real-time underwater video applications even when using the maximum number of transmission channels.

V. CONCLUSION

Video streaming using underwater wireless optical communications is essential for many underwater applications. Those delay sensitive tasks mandate further investigations on how to design more efficient UWOC networks. We proposed using stochastic models to facilitate analyzing and exploring any tradeoffs between the end-to-end delay, packet dropping probability and the appropriate number of channels when a multi-channel configuration is implemented. The analytical work in this paper introduced the queue models for a delay-sensitive network, investigated the analytical derivations of the proposed queue models, and discussed the verifications of the results against the associated simulation. The analysis show strong agreements between the analytical and simulation. Our proposed model should provide the network designers with the necessary tools to evaluate various system's performances considering the QoS constraints that we implemented.

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