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RESEARCH ARTICLE

MAC Protocol for Two-Tier Underwater Wireless Networks With Distance-Dependent Propagation Delay Variation

PRIYATOSH MANDAL, (Member, IEEE)
Centre for Development of Telematics, New Delhi 110030, India
e-mail: priyotoshtsp@gmail.com

ABSTRACT In this paper, we consider a two-tier communication scenario for the data transmission of underwater sensor network. The underwater sensor nodes form single-hop clusters around the gateway nodes and communicate with them via acoustic wireless links, while the gateway nodes communicate to the remotely located sink node directly via radio frequency (RF) wireless links. Thus, the field data is collected at the sink node via two-hop communication links. The first hop acoustic communication link is characterized by long propagation delay and distance-dependent delay variance, whereas the second hop is considered to be connected by satellite links which is characterized by long propagation delay but negligible propagation delay variance. We use (X, Y) to denote that medium access control (MAC) protocol X is used at first hop and MAC protocol Y is used at second hop. For the first hop communication, we propose and analyze the performance of dynamic reservation protocol (DRP) in presence of transmitter-receiver distance-dependent propagation delay variance. Then, considering TDMA-reservation protocol (TRP) in the second hop, we analyze (DRP, TRP) protocol performance at the sink. Further, we study the optimum cluster size that maximizes the overall network utilization and compare the performance with the (Aloha, Aloha) protocol. We show that, for Exponentially distributed large message the utilization of our protocol set (DRP, TRP) is approximately thrice the utilization of (Aloha, Aloha) protocol. Also, the delay of (DRP, TRP) is significantly less than the delay of (Aloha, Aloha) with long message size as well as with high load scenario. The analytical results are supported by discrete event based random network simulation studies.

INDEX TERMS Underwater network communication, receiver synchronized dynamic reservation protocol, propagation delay uncertainty, many-to-one communication, clustered communication.

I. INTRODUCTION

Underwater network acoustic signal propagation speed is a function of water temperature, salinity of water and underwater depth of the communicating objects. The propagation speed is modelled in [1]. The underwater signal transmission loss due to attenuation with distance is characterized in [1] and is given by equation (1).

$$TL(d,f) = \chi \times 10log(d) + \alpha(f) \times d + A. \tag{1}$$

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Here d is the transmitter-receiver distance, f is the operating frequency, χ is the geometrical spreading factor, $\alpha(f)$ is the absorption coefficient and A is the transmission anamoly. For shallow water, $A = 10$ and $\chi = 1$. For deep water, $A = 20$ and $\chi = 2$. The equation of $TL(d,f)$ implies that, short range communication in underwater networks may be helpful to enhance network utilization.

In remote underwater sensing scenarios, underwater sensor nodes collect data and eventually send them to the monitoring and control center. In such cases, typically, the first hop, i.e., the sensor nodes to gateway node communication would be via underwater wireless (acoustic) channel, whereas the second hop, i.e., the gateway node(s) to the satellite (sink)

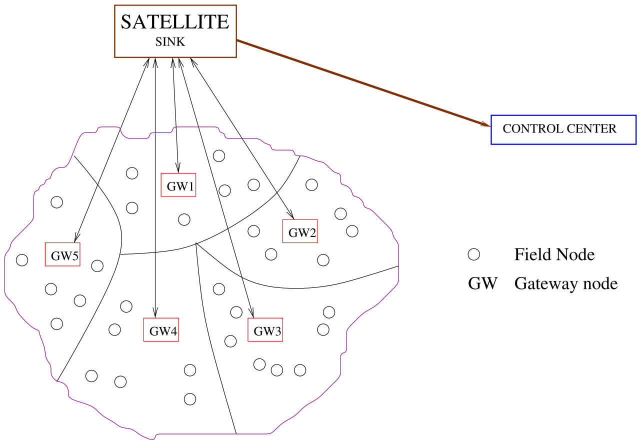

FIGURE 1. A simplified system model for data collection from sensor nodes to sink.

communication would be over long range radio frequency (RF) wireless channel. Different techniques of data gathering from underwater sensor nodes to an underwater gateway node are studied in the recent literature [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. However, underwater network data aggregation at a geographically remotely located sink node (satellite) has not drawn sufficient attention.

In this paper, we look into an underwater sensing and data gathering scenario where the underwater sensor nodes' data have to be collected at a remotely located control center. We propose a two-tier network architecture, as shown in Figure 1, where the satellite will communicate to control center using the downlink, which is collision free. As a result the delay for communication from satellite to control center is negligible with respect to the communication delay from sensor node to satellite. Therefore, we concentrate on the communication from underwater sensor nodes to the satellite via gateway nodes.

The underwater sensor nodes deployed for sensing and communication purposes form clusters around the gateway nodes, which are capable of underwater communication with the sensor nodes as well as RF communication with the satellite. The sensed data at the sensor nodes are sent to their respective gateway nodes, which further forward them to the sink node. Communication in both hops are in the form of many-to-one access mechanism. This many-to-one connectivity, long and unpredictable propagation delay, and normally-sporadic sensed data at the sensor nodes suggest that some kind of reservation protocol would be suitable for the sensor nodes to gateway communication. However, pertaining to the distinctly different signal propagation characteristics, RF multi-access communication protocols are not directly applicable [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]. To this end, for the sensor nodes to gateway communication we consider a DRP which dynamically updates the number of access slots in the frame, based on the system state, where the transmitter-receiver distance-dependent propagation delay variance for communication from the sensor nodes to gateway is additionally accounted in determining the optimum slot size. From gateway to satellite/sink where communication is RF based, we consider TDMA reservation protocol (TRP) as the MAC protocol.

A. RELATED WORKS

Clustering in sensor networks is useful to decrease the node level energy consumption and thereby increase the network lifetime, network coverage, and utilization. For cluster formation, some of the interesting parameters are remaining energy of a node, intra-and inter-cluster communication cost, considered MAC protocol, and failure probability of a node.

In this work, first-hop (sensor node to gateway) communication is based on an underwater wireless acoustic channel. The second hop (gateway to satellite) is based on the RF channel, and clustering in the first hop is also studied, so this section is divided into three subsections: (1) Underwater clustering mechanisms with MAC protocols, (2) Reservation protocols for satellite communications, and (3) Underwater MAC protocols.

1) UNDERWATER CLUSTERING MECHANISMS WITH MAC PROTOCOLS

In distributed minimum cost clustering protocol (MCCP) [20], cost metric is defined as a function of total energy consumption of cluster members for sending data to the cluster-head, residual energy of the cluster-head and its cluster members, and relative location of the cluster-head and the underwater sink. Using this scheme, a node with minimum cost is selected as cluster-head. For intra cluster communication TDMA is used. Clustering protocol for survivable underwater sensor network [21], selects a primary cluster-head and a backup cluster-head. Cluster members are selected to increase the network lifetime. Within a cluster TDMA is considered, and for inter-cluster communication CDMA is used. In [22], fault prevention clustering protocol for underwater sensor network takes into account the reliability and residual energy status of each sensor node during clustering. For intra-cluster communication TDMA is considered and for inter-cluster communication CDMA is used. In [23], a cluster-head selection scheme for underwater acoustic sensor networks consider residual energy and distance to sink during clustering. TDMA is considered for intra-cluster communication and CDMA is considered for cluster head-to-sink communication. In [24], multiple access techniques in clustered underwater acoustic networks are compared.

Various combinations of protocol are used for communication from sensor node to cluster-head and from cluster-head to sink. The various combinations of protocol considered for performance measurement are (Aloha, Aloha-CDMA), (TDMA, CDMA), (TDMA, FDMA), (TDMA, Optimal FDMA). Among these (TDMA, Optimal FDMA) performs better than any other protocol combinations. Optimal FDMA provides exactly the number of bands needed to accommodate all clusters for a given network topology. Distributed clustering scheme for UWSN [25] uses GPS-free routing protocol and data aggregation to eliminate redundant information. A cluster-head is selected as a fraction of the total number of nodes having a higher remaining energy, where TDMA is used for communication inside-cluster and CDMA is used for communication other than intra cluster communication. Multi-cluster protocol for ad hoc mobile underwater acoustic networks [26], consider TDMA for communication inside a cluster and CDMA is considered for communication between clusters. Then it finds an optimum number of cluster to cover the target area. Secure MAC protocol for cluster based communication [27] considers TDMA for intra-cluster communication. The cluster-head schedules the slot to a sensor node based on the link quality and residual energy. This protocol allows direct communication between two sensor nodes of different clusters, provided the nodes are in the communication range of each other.

We describe in Table 1, the MAC protocols used in the first hop and in the second hop of the clustering protocols in underwater networks. Here though these are two hop protocols, all the hops use underwater acoustic wireless link.

2) RESERVATION PROTOCOLS FOR SATELLITE COMMUNICATIONS

Most of the multiple access protocols available for satellite communications are distributed in nature. When any earth station sends any control packet, it is received by all the earth stations via satellite if no packet collision happens at the satellite. Once the control packet is received by all the earth stations, the corresponding data packets are transmitted in FIFO order. A few of the reservation based protocols that are pertinent to our proposed reservation protocols are surveyed below:

Reservation Aloha (R-Aloha) [28] divides a frame into slots of equal length. Length of a slot is the same as data packet transmission interval. Packet access scheme is based on time division multiplexing. Reservations are implicit, and successful transmission in one slot serves as a reservation for the corresponding slot in the next frame. Initial access is random using S-Aloha. Once the transmission is started, the same slot in succeeding frames is reserved for the same station as long as it has data to send.

Aloha Reservation [29] divides the frame into slots. One slot in each frame is further minislotted. The minislots are accessed by reservation packets using S-Aloha. Slots in the data subframe are for reserved data packets. The reservation packets which are successful to access the minislot are received by all the earth stations, and all the stations will keep the reservation packets in its own queue. A FIFO scheduling discipline is used for the service of data packets according to the reservation packets present in the distributed queue.

TDMA Reservation [30] is a contention-less protocol used in satellite communication. Every frame is divided into some large slots. Each large slot is further divided into one data slots and multiple minislots. Minislots are for reservation packets to be used on a fixed assignment TDMA basis. Operational principle is the same as Aloha Reservation. The nodes having data packets transmit reservation packet using its reserved minislot. The reservation packets are received by all the earth stations and again the FIFO scheduling discipline is used for the service of data packets.

Split Reservation Upon Collision (SRUC) [31] uses same frame format as TDMA Reservation. This protocol combines S-Aloha and TDMA Reservation. Data sub-channels can be in two states, such as contention state, and reserved state. The data sub-channel is initially accessed using S-Aloha mode as long as no collision occurs. In addition to packets, users also transmit signalling information in this own reserved minislots. When a collision is detected and a signalling information is received, the data sub channel switches to the reserved state in which the system operates under TDMA Reservation protocol. The data sub-channel remains in the reserved state until the queue of reservation is cleared.

In all these reservation protocols, initial communication is with the use of S-Aloha random access protocol and after reservation the actual data packet are transmitted using some kind of scheduling mechanism. These protocols however do not address the effect of propagation delay uncertainty, as in UWSN.

3) UNDERWATER MAC PROTOCOLS

There are many centralized MAC protocols [10], [11], [12], [13], [14], [15], [16], [17] available in literature, which mainly focus on throughput maximization, and minimization of delay and energy. We briefly describe those here. In [10], medium access control protocol with three modes MACA-EA, MACA-C, DATA-ACK is proposed. Adaptation technique is proposed to switch between the protocol modes based on network requirement, traffic intensity, qos requirements. Optimum value of system parameters to get best performance of MACA-EA and MACA-C are also described. MACA-C is a centralized MAC protocol, where any node interested to receive data sends RTR. Nodes with data to transmit send RTS and wait for CTS. After receipt of CTS, the node transmits data. In [11], delay aware medium access control protocol allows concurrent transmission of packets. The concurrent transmission is possible since the propagation delay map and transmission schedule of neighbor nodes are known to any node. This protocol also works in case of star topology, where multiple nodes communicate to a single node. In [12], load adaptive MAC protocol based on network load uses high load and low load modes of operation. In high load situation, receiver

TABLE 1. Clustering protocol with MAC protocols in underwater networks.

Clustering protocol	First hop MAC protocol	Second hop MAC protocol
MCCP [20]	TDMA	None
Clustering protocol for survivable UWSN [21]	TDMA	CDMA
Fault prevention clustering protocol [22]	TDMA	CDMA
Clustering protocol [23]	TDMA	CDMA
Clustering protocol [24]	Aloha TDMA TDMA TDMA	Aloha-CDMA CDMA FDMA Optimal FDMA
DCCS [25]	TDMA	CDMA
Multicluster protocol [26]	TDMA	CDMA
Secure MAC [27]	TDMA	None

based approach is used and in low load situation, Aloha based protocol is used for communication. Transmit delay allocation MAC protocol [13], is capable to provide time division multiple access to sensor nodes without the need for clock synchronization. This protocol works in a centralized architecture, where many sensor nodes communicate to a single gateway node. Gateway node initiates the communication by broadcasting REQ packet. The request packet mentions the transmission time schedule of sensor nodes. In [14], receiver oriented distributed multichannel MAC protocol is proposed, which works based on the cooperation information of neighbors and load condition of receivers. In [15], delay aware receiver oriented MAC protocol is studied. It schedules the order of transmission based on the information of queue length. Sensor node with data sends a initial request to center node (gateway node). Center node creates a scheduling table and communicates to all sensor nodes. After that sensor node transmits data to the center node. In [16], load based centralized MAC protocol is proposed considering one sink node and multiple sensor nodes. In case of low load this protocol works like CSMA/CA, but in high load the protocol works like TDMA protocol. In [17], receiver initiated MAC protocol for internet of underwater things is proposed. A node with data to transmit and more energy is designated as receiver node. The scheduled receiver node keeps the sleep cycles of other nodes. After receipt of request message from data receiver node, scheduled receiver node transmits data. Once the scheduled receiver node completes transmission of data, the other nodes transmit data to the data receiver node.

None of the protocols specified above are considering distance-dependent propagation delay variation to study the protocol performance. Therefore, there is a need to study the performance of MAC protocol with distance-dependent propagation delay variation.

B. MOTIVATION AND RESEARCH CONTRIBUTIONS

It is observed that the prior works in the literature did not consider the underwater field sensor data collection from a remotely located (e.g., satellite connected) sink node. There is no analytical work which consider the first hop in underwater network and second hop in RF network. Based on the prior studies of MAC protocols, it is well known that the performance of reservation protocol is better than the performance of any MAC protocol when the message size is long. Further, the reservation based MAC protocols available in literature, are not considering distance-dependent propagation delay variation. In this work we study the performance of reservation protocol in presence of distance-dependent propagation delay variance in underwater clustering scenario in the first hop and TRP in the second hop where gateway to sink communication is RF based.

Further, in the absence of any protocol in two hop scenario, where one hop is in underwater network and another hop is in RF network, we select (Aloha, Aloha) for comparison with (DRP, TRP), as the utilization performance of (Aloha, Aloha) is independent of propagation delay and propagation delay variation.

It may also be noted that this study focuses on uplink network communication from the underwater sensor nodes to the satellite connected sink node via a set of gateway nodes.

Our specific contributions in this paper are as follows:

(a) We analyze the proposed DRP [7] in presence of transmitter-receiver distance-dependent propagation delay variance.
(b) Further, we analyze and optimize the performance of the proposed protocol (DRP, TRP) at the sink.
(c) We compare the utilization and delay performance of (DRP, TRP) with (Aloha, Aloha).

C. PAPER ORGANIZATION

The remainder of this paper is organized as follows. In Section II, we analyze our proposed reservation protocol in presence of transmitter-receiver distance-dependent propagation delay variance for underwater ground sensor nodes to gateway communication. Next, considering TRP from the gateway to satellite communication we analyze and optimize the performance in Section III. Numerical and simulation based performance results are discussed in Section IV. The paper is concluded in Section V. A summary of notations used throughout the paper are listed in Table 2.

TABLE 2. Summary of notations.

R	Communication (transmit/receive) range of a node (m)
$r_{\min}$	Minimum transmitter-receiver distance (m)
v	Underwater acoustic signal propagation speed (m/s)
N	Maximum allowed queued-up data transmission requests at the gateway and sink
λ_u	Arrival rate per sensor node per unit time (/s)
λ_g	Effective arrival rate at gateway per unit time (/s)
$\lambda_a(i)$	Successful request arrival rate when the system state is i
X_j	Service time of jth user request, Exponentially distributed with mean $\overline{X} = \frac{1}{\mu}$.
μ	Service rate for sensor node to gateway communication.
μ_g	Service rate for gateway to satellite communication.
n_a	Number of access slots per frame
$n_a(n)$	Number of access slots per frame when system state is n
T_a	Access slot duration at gateway and at sink (s)
$T_a^{(m)}$	Modified access slot duration at gateway only
T_f	Frame duration (for sensor node to gateway communication) (s)
T_f^{rf}	Frame duration (for gateway to sink communication) (s)
T_s^{rf}	Duration of data transmission time in sink frame (for gateway to sink communication) (s)
$T_p^{\max}$	Maximum propagation delay in underwater network (s)
$\sigma(r)$	Propagation delay variance when transmitter-receiver distance is r
$P_a(i, n_a)$	Probability of i successful arrival of new requests in n_a access slots at gateway
$P_c(m, n, T_s^m)$	Probability of service completion of m requests in system state n at gateway
$P_s^m(n_a(n))$	Probability of success to grab an access slot with $n_a(n)$ access slots in frame
P_s^s	Probability of success to successfully grab an access slot at sink
k^{in}	Access slot increment factor for DRP
p_n	Steady state probability that the system state is n
u_n	Numbers of sensor nodes per gateway
n_g	Number of gateways in the given target area
$P_a^{rf}(i, n_a)$	Probability of i successful arrival of new requests in n_a access slots at sink
$P_c^{rf}(m, n, T_s^{rf})$	Probability of service completion of m requests in system state n at sink
T_p^{avg}	Average propagation delay for communication from sensor node to gateway
η_g^{DRP}	Utilization at gateway node
η_s^{TRP}	Utilization at sink node
$T_{p_{rf}}^{\max}$	Maximum propagation delay for communication from gateway to sink

II. RESERVATION PROTOCOL BASED TWO-HOP CLUSTERING

We consider uplink communication from underwater sensor nodes to the sink (satellite) via gateway nodes.

Assumption: The transmitters are uniformly random distributed around the communication range R of the nearby gateway node, and each node knows the distance to its gateway node. Variability of underwater inter-node propagation delay, i.e., propagation delay uncertainty, is considered Gaussian distributed [32], [33].

In Section II-A, we briefly describe the working mechanism of DRP. Further, in Section II-B, we present the analysis of the DRP in the presence of transmitter-receiver distance-dependent propagation delay variance.

A. WORKING MECHANISM OF DRP

The fixed frame reservation protocol consists of access slots and time for data transmission. The sensor nodes having data to transfer to the nearby gateway node contend for randomly chosen access slots in a frame. The successful nodes, that are notified through the downlink channel, transmit their data in the subsequent frames accounting for variable propagation delay in underwater network. The frame size, $T_f \geq T_p^{\max}$, so that the transmitter can receive the access response within one frame duration.

DRP is also a frame based protocol where a frame consists of variable number of access slots and variable duration of data transmission time. In DRP, the number of access slots in a frame changes depending on the status of the gateway queue. A pictorial representation of DRP protocol is shown in Fig. 2, where the maximum propagation delay to the gateway node corresponds to the Node 1. Note that, there is a single (combined) access response to all nodes' individual data transmission requests. The access response also contains the number of access slots in the next frame. In this present example of Fig. 2, the number of access slots in the first frame are 3. In the second frame it is 1, and in the third frame it is 3 again. Once the number of access slots vary, the duration of data transmission time changes.

DRP with constant propagation delay variance is analyzed in [7]. In the next section, we consider the analysis of DRP with variable propagation delay variance.

B. DRP WITH VARIABLE PROPAGATION DELAY UNCERTAINTY

In presence of variable propagation delay uncertainty, chances of collision per access slot is expected. To account this collision vulnerability, we use the access slot duration, T_a as $T_a^{(m)} = T_a + 2k^{in}\sigma^{\max}$ [7] and we calculate probability of success, $P_s^m(n_a(n))$, where $\sigma^{\max}$ ($\geq$ 0) is the maximum

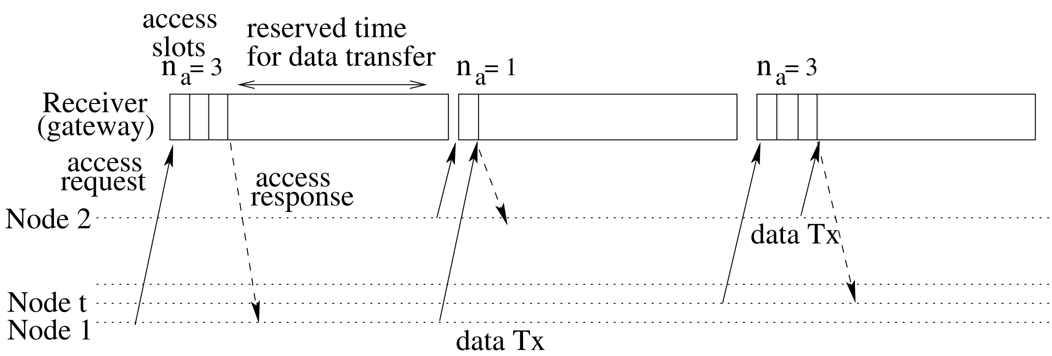

FIGURE 2. Timing diagram of underwater DRP with variable number of access slots in a frame for sensor nodes to the gateway data transfer [7].

propagation delay deviation and k^{in} (≥ 0) is the access slot increment factor, $\sigma^{\max} = cT_p^{\max} = c\frac{R}{v}$, where $0 \leq c \leq 1$.

Further, $n_a(n)$ is the number of access slots in gateway frame when system state is n. $n_a(n)$ is defined in equation (2).

$$n_a(n) = n_a^{\min}\left(\frac{n}{N}\right) + n_a^{\max}\left(1 - \left(\frac{n}{N}\right)\right). \tag{2}$$

where $n_a^{\max}$ is chosen as $n_a^{\max} = \frac{T_f}{T_a^{(m)}} \leq N$, and $0 \leq n_a^{\min} \leq n_a^{\max}$, T_a is the duration of an access slot, and $n_a^{\min}$ and $n_a^{\max}$ are respectively the minimum and maximum number of possible access slots in a frame.

Success probability of receiving a control packet in gateway frame is obtained as in equation (3), as shown at the bottom of the page.

By the assumption of Gaussian delay distribution we have:

$$\mathbf{y_i}(r_i) \sim \mathcal{N}\left(IT_a^{(m)}, \sigma^2(r_i)\right);$$
$$\mathbf{x_i}(r_i) \sim \mathcal{N}\left(IT_a^{(m)}, \sigma^2(r_i)\right);$$
$$\mathbf{x_{i_{p2}}}(r_{i_{p2}}) \sim \mathcal{N}\left((I-2)T_a^{(m)}, \sigma^2(r_{i_{p2}})\right);$$
$$\mathbf{x_{i_{p1}}}(r_{i_{p1}}) \sim \mathcal{N}\left((I-1)T_a^{(m)}, \sigma^2(r_{i_{p1}})\right);$$
$$\mathbf{x_{i_{n1}}}(r_{i_{n1}}) \sim \mathcal{N}\left((I+1)T_a^{(m)}, \sigma^2(r_{i_{n1}})\right);$$
$$\mathbf{x_{i_{n2}}}(r_{i_{n2}}) \sim \mathcal{N}\left((I+2)T_a^{(m)}, \sigma^2(r_{i_{n2}})\right).$$

Also we assume, $R = r_{\min} + \delta \times n_s$, where δ is the difference between the two consecutive values of transmission-receiver distance. We define transmitter-receiver distance as discrete uniform distribution which takes the value from $\{r_{\min}, r_{\min} + \delta, \cdots, R\}$. Thus $\Pr(\mathbf{r_i} = r)$ is defined as [34]:

$$\Pr(\mathbf{r_i} = r) = \frac{1}{n_s + 1}. \tag{4}$$

For a uniformly random node distribution, the expression (3) becomes as in expression (5), as shown at the bottom of the next page.

Note that, $\lambda_s \left(= \frac{\lambda T_f}{n_a(n) T_a^{(m)}}\right)$ in the above equation, is the arrival rate per second to the access portion only, which is different from the actual external arrival rate, λ into the system. In practice, the mean as well as variance of propagation delay

$$\begin{aligned}
P_s^m(n_a(n)) = \sum_{r=r_{\min}}^{R} \int_{(I-2)T_a^{(m)}}^{(I+2)T_a^{(m)}} &\left[\sum_{n_{i_p}=0}^{\infty} \Pr\left((n_{i_p}+1) \text{ arrival in slot } I\right) \prod_{i_p=0}^{n_{i_p}} \{1 - \Pr\left(y - T_a \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_a\right)\}\right] \\
&\cdot \left[\sum_{n_{i_{p2}}=0}^{\infty} \Pr\left(n_{i_{p2}} \text{ arrival in slot } I-2\right) \prod_{i_{p2}=0}^{n_{i_{p2}}} \left\{1 - \Pr\left(y - T_a \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_a\right)\right\}\right] \\
&\cdot \left[\sum_{n_{i_{p1}}=0}^{\infty} \Pr\left(n_{i_{p1}} \text{ arrival in slot } I-1\right) \prod_{i_{p1}=0}^{n_{i_{p1}}} \left\{1 - \Pr\left(y - T_a \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_a\right)\right\}\right] \\
&\cdot \left[\sum_{n_{i_{n1}}=0}^{\infty} \Pr\left(n_{i_{n1}} \text{ arrival in slot } I+1\right) \prod_{i_{n1}=0}^{n_{i_{n1}}} \{1 - \Pr\left(y - T_a \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_a\right)\}\right] \\
&\cdot \left[\sum_{n_{i_{n2}}=0}^{\infty} \Pr\left(n_{i_{n2}} \text{ arrival in slot } I+2\right) \prod_{i_{n2}=0}^{n_{i_{n2}}} \{1 - \Pr\left(y - T_a \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_a\right)\}\right] \\
&\cdot \Pr(\mathbf{y_i} = y) \Pr(\mathbf{r_i} = r).
\end{aligned} \tag{3}$$

are functions of transmitter-receiver distance. Accordingly, the frame arrival time at the receiver is also Gaussian distributed with distance-dependent parameters. The arrival time of a frame destined to the receiver in access slot I is Gaussian distributed as: $\mathbf{x_i}(r_i) \sim \mathcal{N}(IT_a^{(m)}, \sigma^2(r_i))$, where the variance is dependent on transmitter-receiver distance r_i. So, we can write $\Pr(y - T_a \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_a)$ as in equation (6), as shown at the bottom of the page. Denote, $P(I)$ as in equation (7), as shown at the bottom of the page.

However, since the nature of distance-dependence on $\sigma(r)$ is not known yet, we consider $\sigma(r) = cT_p^q(r) = c(\frac{r}{v})^q$, where c is constant and $q \geq 0$.

We can write $P(I)$ as in equation (8), as shown at the bottom of the next page. Here, $P_1(I)$, and $P_2(I)$ can be defined as in equation (9), as shown at the bottom of the next page, and (10), as shown at the bottom of the next page, respectively.

Denoting,

$$\Pr\left(y - T_a \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_a\right) = P(I-1)$$
$$\Pr\left(y - T_a \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_a\right) = P(I-2)$$
$$\Pr\left(y - T_a \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_a\right) = P(I+1)$$
$$\Pr\left(y - T_a \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_a\right) = P(I+2)$$

From (9) and (10), in general we can write for j=I, I-1, I-2, I+1, I+2,

$$P(j) = \frac{1}{2}\Big[P_1(j) - P_2(j)\Big]. \tag{11}$$

The success probability expression in (3) now becomes as in equation (12), as shown at the bottom of the next page.

To analyse this system, we define the system state as the number of access requests at the gateway queue at the start of every frame. Accordingly, we calculate the number of access slots. DTMC representation of DRP, where number of access slot changes with the system state is shown in Figure 3. Here, the number of access slots in first frame is considered as 3, so there are three transitions from state 0. In second frame, there is one access slots, so there can be only one transition from state 1. Further, in third frame, there are three access slots, so there can be three transition from this state 2, and so on. This is only an example transition rate diagram.

$$\begin{aligned} P_s^m(n_a(n)) = \sum_{r=r_{\min}}^{R} \int_{(I-2)T_a^{(m)}}^{(I+2)T_a^{(m)}} & \left[\sum_{n_{i_p}=0}^{\infty} e^{-\lambda_s T_a^{(m)}} \frac{(\lambda_s T_a^{(m)})^{(n_{i_p}+1)}}{(n_{i_p}+1)!} \prod_{k=0}^{n_{i_p}} \{1 - \Pr(y - T_a \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_a)\}\right] \\ & \cdot \left[\sum_{n_{i_{p2}}=0}^{\infty} e^{-\lambda_s T_a^{(m)}} \frac{(\lambda_s T_a^{(m)})^{n_{i_{p2}}}}{n_{i_{p2}}!} \prod_{i_{p2}=0}^{n_{i_{p2}}} \Big\{1 - \Pr(y - T_a \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_a)\Big\}\right] \\ & \cdot \left[\sum_{n_{i_{p1}}=0}^{\infty} e^{-\lambda_s T_a^{(m)}} \frac{(\lambda_s T_a^{(m)})^{n_{i_{p1}}}}{n_{i_{p1}}!} \prod_{i_{p1}=0}^{n_{i_{p1}}} \Big\{1 - \Pr(y - T_a \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_a)\Big\}\right] \\ & \cdot \left[\sum_{n_{i_{n1}}=0}^{\infty} e^{-\lambda_s T_a^{(m)}} \frac{(\lambda_s T_a^{(m)})^{n_{i_{n1}}}}{n_{i_{n1}}!} \prod_{i_{n1}=0}^{n_{i_{n1}}} \{1 - \Pr(y - T_a \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_a)\}\right] \\ & \cdot \left[\sum_{n_{i_{n2}}=0}^{\infty} e^{-\lambda_s T_a^{(m)}} \frac{(\lambda_s T_a^{(m)})^{n_{i_{n2}}}}{n_{i_{n2}}!} \prod_{i_{n2}=0}^{n_{i_{n2}}} \{1 - \Pr(y - T_a \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_a)\}\right] \\ & \cdot \frac{1}{\sigma(r_i)\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y - I.T_a^{(m)}}{\sigma(r_i)}\right)^2} \mathrm{d}y \frac{1}{n_s+1}. \end{aligned} \tag{5}$$

$$\begin{aligned} \Pr(y - T_a \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_a) &= \sum_{r=r_{\min}}^{R} \Pr(y - T_a \leq \mathbf{x_i}(\mathbf{r_i} = r) \leq y + T_a) \cdot \Pr(\mathbf{r_i} = r) \\ &= \sum_{r=r_{\min}}^{R} \frac{1}{2}\left[\mathrm{erf}\left(\frac{y + T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \mathrm{erf}\left(\frac{y - T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{1}{n_s+1}. \end{aligned} \tag{6}$$

$$P(I) = \sum_{r=r_{\min}}^{R} \frac{1}{2}\left[\mathrm{erf}\left(\frac{y + T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \mathrm{erf}\left(\frac{y - T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right] \frac{1}{n_s+1}. \tag{7}$$

Now, we denote $P_c(m, n, T_s^m)$ as the probability of m service completion when the system state is n and total time for data transmission is T_s^m. So we define $P_c(m, n, T_s^m)$ as in (13) [7], as shown at the bottom of the next page, where $T_s^m = T_s - 6m\sigma^{\max}$, and $6\sigma^{\max}$ is the padding corresponding to a single data message for transmitter-receiver distance-dependent propagation delay variation. with $\sum_{m=0}^{n} P_c(m, n, T_s^m) = 1$.

Further, we define $P_a(n, n_a(n))$ as in equation (14) [7], as shown at the bottom of the next page.

With the knowledge of $P_s^m(n_a(n))$ and $P_c(m, n, T_s^m)$, we define state transition probability matrix $\underline{P} = \{P(i, j) : i, j = 0, 1, \cdots, N\}$ similarly as in equation (15), (16), as shown at the bottom of the next page, [7].

Then we solve $\underline{p}\,\underline{\mathbf{P}} = \underline{p}$, and $\sum_{i=0}^{N} p_i = 1$ to get the steady state probabilities $\underline{p} = \{p_0\, p_1\, \cdots p_N\}$.

Once we have steady state probabilities, p_n, we define the utilization at gateway as

$$\eta_g^{DRP} = \frac{\sum_{n=0}^{N} p_n \min\{T_s, n.\bar{X}\}}{T_f}. \tag{17}$$

$$\begin{aligned} P(I) &= \sum_{r=r_{\min}}^{R} \frac{1}{2}\left[\operatorname{erf}\left(\frac{y + T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right) - \operatorname{erf}\left(\frac{y - T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\right]\frac{1}{n_s+1} \\ &= \frac{1}{2}\left[P_1(I) - P_2(I)\right]. \end{aligned} \tag{8}$$

$$\begin{aligned} P_1(I) &= \sum_{r=r_{\min}}^{R} \operatorname{erf}\left(\frac{y + T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\frac{1}{n_s+1} \\ &= \sum_{r=r_{\min}}^{R} \operatorname{erf}\left(\frac{y + T_a - IT_a^{(m)}}{\frac{cr^q}{v^q}\sqrt{2}}\right)\frac{1}{n_s+1} \\ &= \sum_{r=r_{\min}}^{R} \operatorname{erf}\left(\frac{c(I)}{r^q}\right)\frac{1}{n_s+1} \end{aligned} \tag{9}$$

where $c(I) = \frac{(y+T_a-IT_a^{(m)})v^q}{c\sqrt{2}}$.

$$\begin{aligned} P_2(I) &= \sum_{r=r_{\min}}^{R} \operatorname{erf}\left(\frac{y - T_a - IT_a^{(m)}}{\sigma(r)\sqrt{2}}\right)\frac{1}{n_s+1} \\ &= \sum_{r=r_{\min}}^{R} \operatorname{erf}\left(\frac{y - T_a - IT_a^{(m)}}{\frac{cr^q}{v^q}\sqrt{2}}\right)\frac{1}{n_s+1} \\ &= \sum_{r=r_{\min}}^{R} \operatorname{erf}\left(\frac{d(I)}{r^q}\right)\frac{1}{n_s+1} \end{aligned} \tag{10}$$

where, $d(I) = \frac{(y-T_a-IT_a^{(m)})v^q}{c\sqrt{2}}$.

$$\begin{aligned} P_s^m(n_a(n)) &= \sum_{r=r_{\min}}^{R} \int_{(I-2)T_a^{(m)}}^{(I+2)T_a^{(m)}} \sum_{n_{i_p}=0}^{\infty} e^{-\lambda_s T_a^{(m)}} \frac{(\lambda_s T_a^{(m)})^{(n_{i_p}+1)}}{(n_{i_p}+1)!}(1-P(I))^{n_{i_p}} \\ &\quad \times e^{-\lambda_s T_a^{(m)}(P(I-1)+P(I-2)+P(I+1)+P(I+2))} \cdot \frac{e^{-\frac{1}{2}\left(\frac{y-IT_a^{(m)}}{\sigma(r)}\right)^2}}{\sigma(r)\sqrt{2\pi}} \mathrm{d}y \frac{1}{n_s+1} \\ &= \frac{v^q}{c\sqrt{2\pi}} \sum_{r=r_{\min}}^{R} \int_{(I-2)T_a^{(m)}}^{(I+2)T_a^{(m)}} \frac{\left(e^{-\lambda_s T_a^{(m)} P(I)} - e^{-\lambda_s T_a^{(m)}}\right)}{1-P(I)} \cdot \\ &\quad \times e^{-\lambda_s T_a^{(m)}(P(I-1)+P(I-2)+P(I+1)+P(I+2))} \cdot \frac{e^{-\frac{1}{2}\left(\frac{v^q(y-IT_a^{(m)})}{cr^q}\right)^2}}{r^q} \mathrm{d}y \, \frac{1}{n_s+1}. \end{aligned} \tag{12}$$

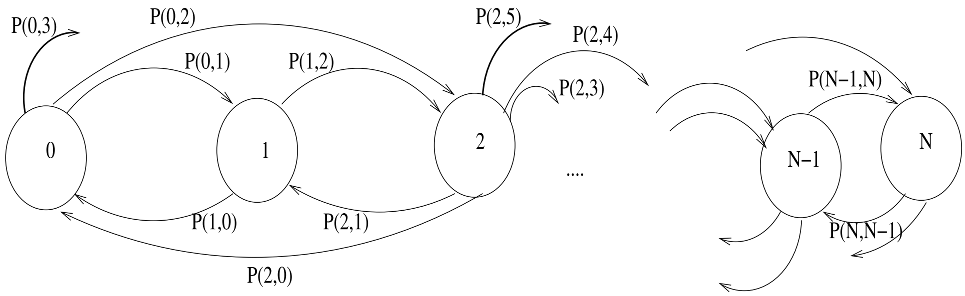

FIGURE 3. System state transition diagram in DRP with variable number of access slots per frame.

So effective arrival rate at gateway can be written as

$$\lambda_g = \frac{\sum_{n=0}^{N} p_n \min\{T_s, n.\overline{X}\}}{T_f} \times \mu. \tag{18}$$

So arrival rate at each gateway will be λ_g, with Exponentially distributed average message transmission time, $\overline{X} = \frac{1}{\mu}$ sec.

Maximization of utilization at gateway: We note that, a right choice of slot increment factor is needed to get the highest success probability to grab an access slot, so that the system utilization η_g^{DRP} can be maximized. Below, we formulate an optimization problem to maximize η_g^{DRP} for the given values of T_f, λ, μ, and N.

$$\underset{k^{in}}{\text{Maximize:}}\ \eta_g^{DRP} = \frac{\sum_{n=0}^{N} p_n \min\{T_s, n.\overline{X}\}}{T_f}$$

$$\text{subject to: } \underline{p}\,\underline{\mathbf{P}} = \underline{p},\ \ \sum_{i=0}^{N} p_i = 1,\ \text{and} \sum_{j=0}^{N} P(i,j) = 1, \tag{19}$$

where $\{P(i,j) :\ i, j = 0,\ 1,\ \cdots,\ N\}$ is obtained as in [7].

To analyze delay we assume $\lambda_u T_f \leq 1$. Also we assume a node will retry till it grabs an access slot corresponding to a generated message. A node will not generate any new message till it grabs an access slot successfully. With these assumption we denote, N_t as the average number of access request attempts for a message to grab an access slot at gateway. N_t is obtained as: $N_t = \frac{1}{P_s^{avg}}$, where P_s^{avg} is the average success probability of a request attempt to grab an access slot, and it is obtained as: $P_s^{avg} = \sum_{n=0}^{N} P_s^m(n_a(n))p_n$. Here $P_s^m(n_a(n))$ is the probability of success to grab an access slot when the system state is n, N is the maximum number of unserved access requests that gateway can queue, and p_n is the probability of n unserved access requests in the gateway queue.

The average access delay D_a^g at gateway is estimated as [7]:

$$D_a^g = (N_t - 1) \cdot \left\lceil \frac{(1/\lambda_u)}{T_f} \right\rceil \cdot T_f + \frac{T_f}{2} + T_p^{avg} + T_f. \tag{20}$$

$$P_c(m, n, T_s^m) = \begin{cases} \int_0^{T_s^m} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx - \int_0^{T_s^m} \frac{\mu(\mu x)^m}{m!} e^{-\mu x} dx, & \text{if } 0 < m < n \\ \int_0^{T_s^m} \frac{\mu(\mu x)^{(m-1)}}{(m-1)!} e^{-\mu x} dx, & \text{if } m = n \neq 0 \\ e^{-\mu T_s^m}, & \text{if } m = 0,\ n > 0 \\ 1, & \text{if } m = n = 0 \\ 0, & \text{if } m > n, \end{cases} \tag{13}$$

$$P_a(n, n_a(n)) = \binom{n_a(n)}{n} \left(P_s^m(n_a(n))\right)^n \left(1 - P_s^m(n_a(n))\right)^{n_a(n)-n}, \quad n_a(n) \geq n, \tag{14}$$

$$\begin{aligned} P(n, n+i) = & \sum_{m \leq N-(n+i)} P_a(i+m, n_a) P_c(m, n) \\ & + P_c(N-(n+i), n) \sum_{m > N-(n+i)} P_a(i+m, n_a), \end{aligned} \tag{15}$$

$$\begin{aligned} P(n, n-i) = & \sum_{m \leq N-n} P_a(m, n_a) P_c(i+m, n) \\ & + P_c(N-(n-i), n) \sum_{m > N-n} P_a(m, n_a). \end{aligned} \tag{16}$$

Out of the four additive terms on the right hand side of the expression of D_a^g in (20), the first term is due to $(N_t - 1)$ times unsuccessful tries, the second and third terms together are due to the last (successful) try, and the last term is due to one frame delay in beginning data transmission after the successful access request.

The system delay D_s^g at gateway is expressed as [7]:

$$D_s^g = D_a^g + \overline{n}\overline{X} + \left\lceil \frac{\overline{n}\overline{X}}{T_s} \right\rceil \cdot \overline{n}_a T_a. \tag{21}$$

which is the time needed for complete service (including access, queueing, and service delay) of average number of unserved user requests $\overline{n}$ $(\sum_{n=0}^{N} np_n)$ in the system. D_a^g is the access delay as defined in (20). In a system where continuous service is possible, the average number of user requests needed is $\overline{n}\overline{X}$ time units. Since the service of a message can be interrupted due to the access slots, the term $\left\lceil \frac{\overline{n}\overline{X}}{T_s} \right\rceil \cdot \overline{n}_a T_a$ accounts for this in the system delay consideration.

III. PERFORMANCE AT SINK

In this section we investigate the performance of a two-hop clustered network. Assume, corresponding to the given target area (TA), there are n_g gateways present. For simplicity of analysis we are considering the region covered by a gateway is circular. So the transmission range corresponding to a gateway can be defined as

$$R = \sqrt{\frac{TA}{\pi n_g}}. \tag{22}$$

Now we define the number of sensor nodes, N_g corresponding to a gateway as

$$N_g = \beta.R, \quad \text{where} \quad \beta > 0. \tag{23}$$

For known value of β and transmission range R, we can get number of sensor nodes N_g. So for given arrival rate per sensor node λ_u, arrival rate in a cluster can be defined as

$$\lambda = N_g \lambda_u. \tag{24}$$

Using this λ, we can find the effective arrival rate at gateway i.e., λ_g as in (18).

Now for given target area and number of gateways n_g in the target area we can find the total arrival rate at gateway according to the equations (22), (23) and (24). Also if we know the total arrival rate at gateway, we can find the effective arrival rate at each gateway as per equation (18). Also the utilization at gateway can be obtained using (17).

A. PERFORMANCE AT SINK WITH TRP

We analyze the TDMA-reservation protocol in this section considering Exponential message size and Poisson arrival process, which is a variant of TDMA reservation protocol explained in [30, Ch. 6]:.

There are n_a^{rf} access slots in a frame. Frame size is fixed and defined as $T_f^{rf} = n_a^{rf} T_a^{rf} + T_s^{rf}$. Here the number of access

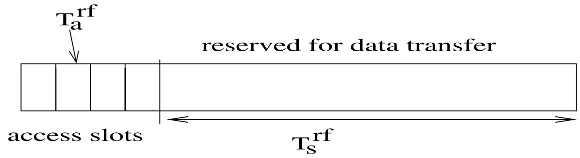

FIGURE 4. Frame structure of TDMA reservation protocol (TRP).

slots are same as the number of gateways (n_g) in the system. When a gateway is ready to transmit data, it sends an access packet in the access slot which is fixed for this node. Each successful access request is put in a queue at Satellite. After the end of access slots, the Satellite allocates the time for data transmission from next frame onwards in a broadcast packet in FIFO order with respect to the queue. So we consider the frame time, $T_f^{rf} \geq 2T_{p_{rf}}^{max}$.

To find the steady state probabilities at sink node, we follow the same approach as in [7]. We denote, $P_a^{rf}(i, n_a^{rf})$ to indicate the probability of i successful arrival of new requests in n_a access slots, and $P_c^{rf}(m, n)$ to indicate the probability of service completion of m requests when the state of system is n.

$P_a^{rf}(i, n_a^{rf})$ can be expressed as in equation (25),

$$P_a^{rf}(i, n_a^{rf}) = \begin{cases} \binom{n_a^{rf}}{i}(P_s^{rf})^i(1-P_s^{rf})^{n_a^{rf}-i}, & n_a^{rf} \geq i \\ 0 & n_a^{rf} < i \end{cases} \tag{25}$$

where $P_s^{rf} = 1 - e^{-\lambda_g T_f^{rf}}$, λ_g is the data arrival rate per unit time corresponding to a single user (node), and T_f^{rf} is the fixed frame duration at sink.

Hence, $P_c^{rf}(m, n, T_s^{rf})$ can be expressed as in equation (26), as shown at the bottom of the next page, with $\sum_{m=0}^{n} P_c^{rf}(m, n, T_s^{rf}) = 1$.

With the knowledge of $P_a^{rf}(i, n_a^{rf})$ and $P_c^{rf}(m, n, T_s^{rf})$, we define state transition probability matrix $\underline{P} = \{P(i,j) : i,j = 0, 1, \cdots, N\}$ similarly as in previous Section II-B. Then we solve $\underline{p}\,\underline{\mathbf{P}} = \underline{p}$, and $\sum_{i=0}^{N} p_i = 1$ to get the steady state probabilities $\underline{p} = \{p_0\, p_1 \cdots p_N\}$.

The utilization at the sink can be defined as in equation (27).

$$\eta_s^{\text{TRP}} = \frac{\sum_{n=0}^{N} p_n \min\{T_s^{rf}, n.\overline{X^{rf}}\}}{T_f^{rf}}. \tag{27}$$

With the same logic as in equation (21), assuming $\lambda_g T_f^{rf} \leq 1$, the system delay D_s^s for communication from gateway to sink, is expressed as:

$$D_s^s = D_a^s + \overline{n}\overline{X^{rf}} + \left\lceil \frac{\overline{n}\overline{X^{rf}}}{T_s^{rf}} \right\rceil \cdot n_a^{rf} T_a^{rf}, \tag{28}$$

which is the time needed for complete service (including access, queueing, and service delay) of average number of unserved user requests $\overline{n}$ in the system. D_a^s is the access delay as defined in (29). In a system where continuous service is possible, the average number of user requests needed is $\overline{n}\overline{X^{rf}}$ time units. Since the service of a message can be interrupted due to the access slots, the term $\left\lceil \frac{\overline{n}\overline{X^{rf}}}{T_s^{rf}} \right\rceil \cdot n_a^{rf} T_a^{rf}$ accounts for this in the system delay consideration.

Here D_a^s is defined as:

$$D_a^s = \frac{T_f^{rf}}{2} + T_{p_{rf}}^{\max} + T_f^{rf}. \tag{29}$$

Now we define total delay for communication from sensor node to sink as $T_d = D_s^g + D_s^s$, where D_s^g is defined in (21) and D_s^s is defined as in (28).

IV. RESULTS AND DISCUSSIONS

We have considered the common parameters as in Table 3. Exponentially distributed data packets are generated by any sensor node. For satellite communication i.e., for the second hop communication we consider transmission speed as 100 Kbps, which is in the order of Kbps as considered in [28], [29], [30], and [31]. In all cases of result generation of DRP, the number of access slots are generated according to the state of the gateway queue of DRP protocol as specified in equation (2).

In the present two hop MAC protocol study, we only concerned about MAC layer without considering other protocol layers, so we choose our developed C based discrete event simulation model for creation of random network and for verification of analytical results. To study the performance of the reservation protocol for sensor node to gateway node via simulation, sensor nodes were uniformly random distributed around a gateway node. Sensor nodes generated data according to Poisson process. After data generation, node transmits access request in access slot of frame at gateway. The nodes with successful access request are added in the queue at gateway as long as the queue is not full. Sensor nodes are scheduled to transmit data as per the FIFO order. With this we find the utilization (η_g) as well as the arrival rate of messages at gateway node (λ_g). Once we know the arrival rate (λ_g) at a single gateway, we study the performance of TRP in the second hop, i.e., from gateway to sink, where gateway nodes generate data message according to Poisson process with arrival rate found at the gateway node (λ_g). The length of the data message generated by gateway node is considered as Exponentially distributed with same parameter value as sensor node, i.e., $\frac{1}{\mu} = \frac{1}{\mu_g}$. Gateway node after generation of data, sends an access request on the reserved access slot of sink frame. After successful grab of access slot, the access request is added in the sink queue and scheduled according to FIFO order. Simulations were repeated for 10000 consecutive frames and 5 times to get the average value. For the numerical results we use the difference between two consecutive values of transmitter-receiver distance (δ) as 1 in the first hop. In this present work we analyze delay for $\lambda_u T_f \leq 1$ and $\lambda_g T_f^{rf} \leq 1$, so during generation of results we consider the value of parameters accordingly. In the present work, during generation of results, we consider the distance between any gateway node and satellite is 20000 Kilo and minimum frame size at sink (T_f^{rf}) as 0.2 second.

TABLE 3. System parameters.

Underwater signal propagation speed, v	1500 m/sec
Mean of Exponentially distributed data packet size	500 Bytes
Access packet size	40 Bytes
Transmission speed in UW network	16 Kbps
Minimum communication range, $r_{\min}$	1 m
Propagation delay exponent, q	1
Number of gateway, n_g	9
Number of users per gateway, u_n	8

A. PERFORMANCE WITH RESPECT TO ARRIVAL RATE

In this section, we study the performance of (DRP, TRP) with respect to the arrival rate per sensor node. We increase the arrival rate per sensor node from 0.1 message/second to 1 message/second and maximize the utilization of DRP ($\eta_g^{\max}$) with respect to slot increment factor (k^{in}). Corresponding to $\eta_g^{\max}$ we find the delay for communication from sensor node to gateway and arrival rate at gateway (λ_g). Once we find the arrival rate at gateway, we maximize the utilization at sink using TRP protocol with respect to frame duration. We plot the maximum utilization of (DRP, TRP) and total delay in Figure 5. We also plot the utilization and delay of (Aloha, Aloha) with Exponentially distributed message size in the same figure. Here we can see the utilization of (DRP, TRP) is always higher than (Aloha, Aloha), but the delay of (Aloha, Aloha) is lower than (DRP, TRP) for low value of arrival rate per sensor node. With low arrival rate the probability of success in case of (Aloha, Aloha) is higher than (DRP, TRP). In case of (DRP, TRP) there is a fixed waiting time of frame time duration after the successful grab of access slot and with low arrival rate due to failure to grab access slot, forces the node to retry after a long interarrival time ($\frac{1}{\lambda_u}$). For high arrival rate the delay of (Aloha, Aloha) decreases due to the increase of collision. So (DRP, TRP) performs better than (Aloha, Aloha).

$$P_c^{rf}(m, n, T_s^{rf}) = \begin{cases} \int_0^{T_s^{rf}} \frac{\mu_g(\mu_g x)^{(m-1)}}{(m-1)!} e^{-\mu_g x} dx - \int_0^{T_s^{rf}} \frac{\mu_g(\mu_g x)^{m}}{m!} e^{-\mu_g x} dx, & \text{if } 0 < m < n \\ \int_0^{T_s^{rf}} \frac{\mu_g(\mu_g x)^{(m-1)}}{(m-1)!} e^{-\mu_g x} dx, & \text{if } m = n \neq 0 \\ e^{-\mu_g T_s^{rf}}, & \text{if } m = 0,\ n > 0 \\ 1, & \text{if } m = n = 0 \\ 0, & \text{if } m > n, \end{cases} \tag{26}$$

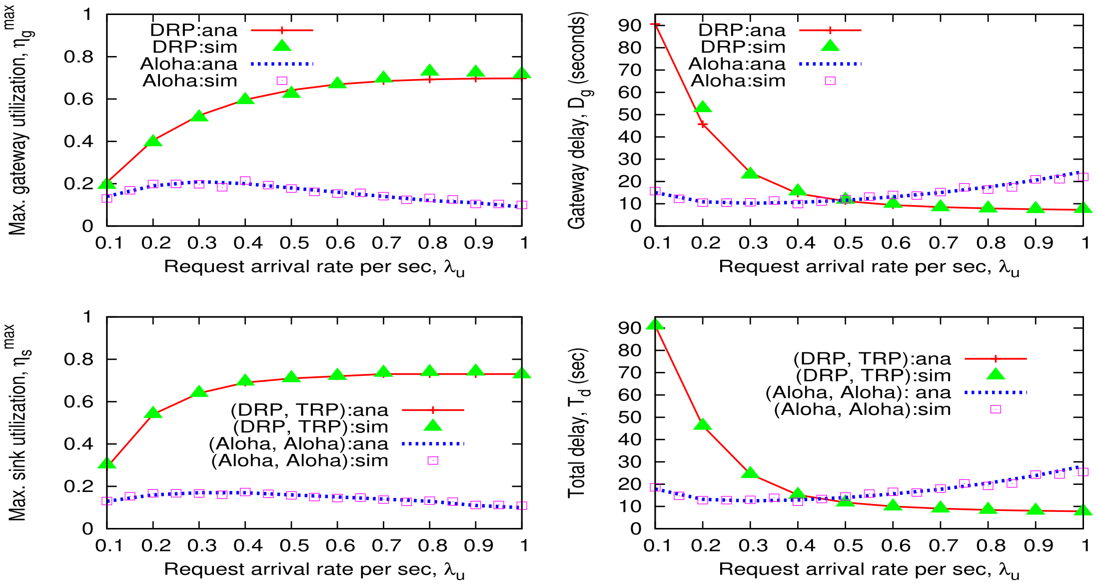

FIGURE 5. **Maximum utilization at gateway using reservation protocol: simulation and analysis verification assuming $c = 0.1$, $q = 1$, $R = 200$ meters, $n_g = 9$, $u_n = 8$, Target area $= \pi 600^2$ sq.m., $T_f = 1$ second.**

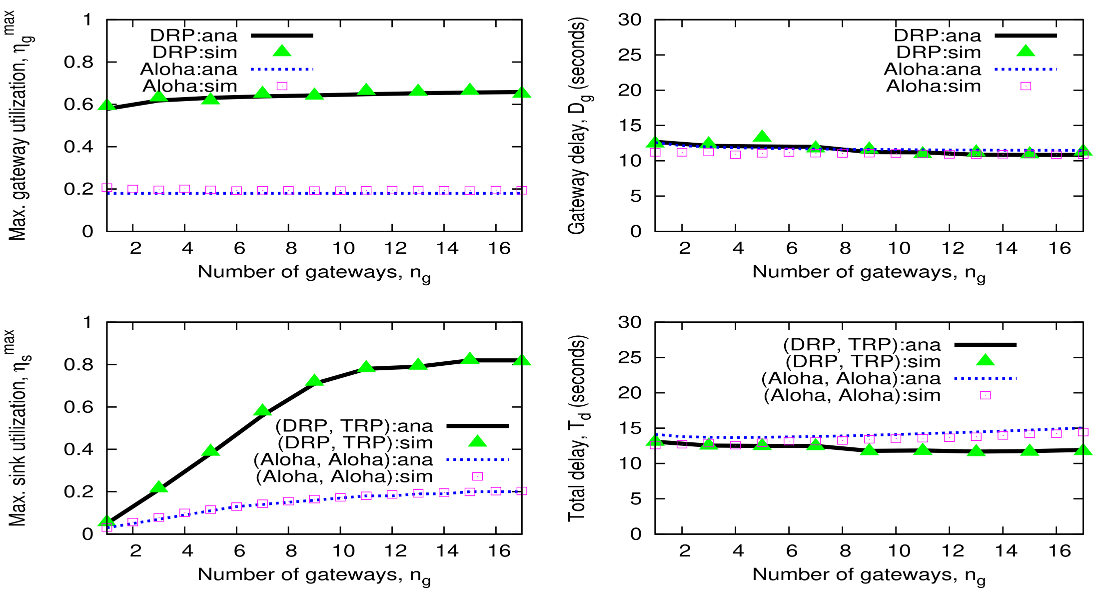

FIGURE 6. **Maximum gateway and sink utilization versus n_g using (DRP, TRP), for given $\lambda_u = 0.5$ messages/second, $n_g = \frac{\pi.600^2}{\pi.R^2}$, $c = 0.1$, target area $= \pi.600^2$ sq.m. Number of sensor nodes per gateway, $u_n = 8$, $T_f = 1$ second.**

B. PERFORMANCE WITH RESPECT TO NUMBER OF GATEWAYS

Assuming the number of sensor nodes per gateway as fixed, i.e., $u_n = 8$. We increase the number of gateways in the given target area $\pi.600^2$ sq.m. With the increase of number of gateways in the given target area, the transmission range, R decreases. With the increase of gateways in the given target area, the propagation delay variability ($c.T_p^{\max}$) decreases, so the collision decreases and the utilization increases at gateway. After finding the utilization and the corresponding arrival rate at gateway (λ_g), we further find the utilization at sink considering TRP, where number of access slots per frame is same as the number of gateways in the system. It can be observed from Figure 6, that sink utilization using (DRP, TRP) is higher than (Aloha, Aloha). Also the total delay using (Aloha, Aloha), is better than the performance of (DRP, TRP). We further capture the performance at sink by changing the bandwidth from gateway to sink in Figure 7. With the increase of bandwidth for gateway to sink communication, the utilization decreases. Increase of bandwidth for communication from gateway to sink causes the under utilization of the frame, so the utilization decreases with the increase of the bandwidth for communication from gateway to sink.

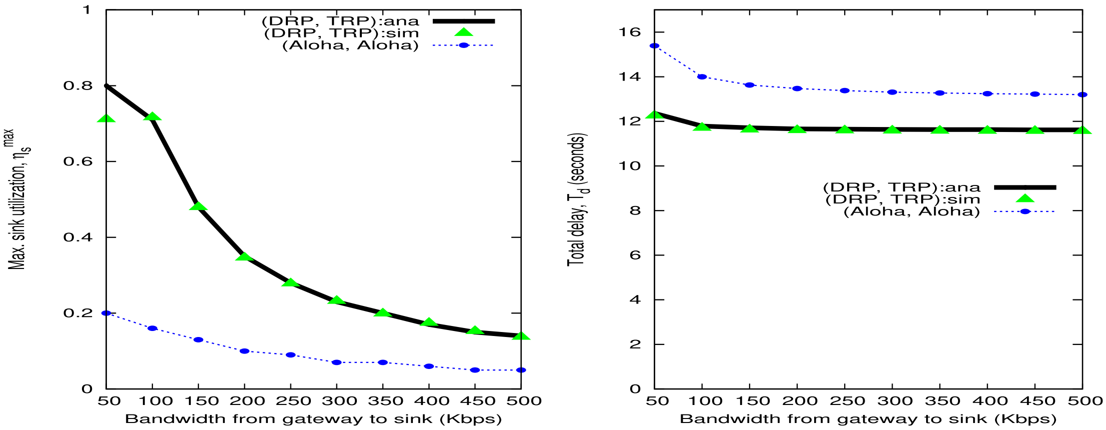

FIGURE 7. Maximum utilization and delay at sink for various values of bandwidth with number of gateways, $n_g = 9$ and number of nodes per gateway, $u_n = 8$.

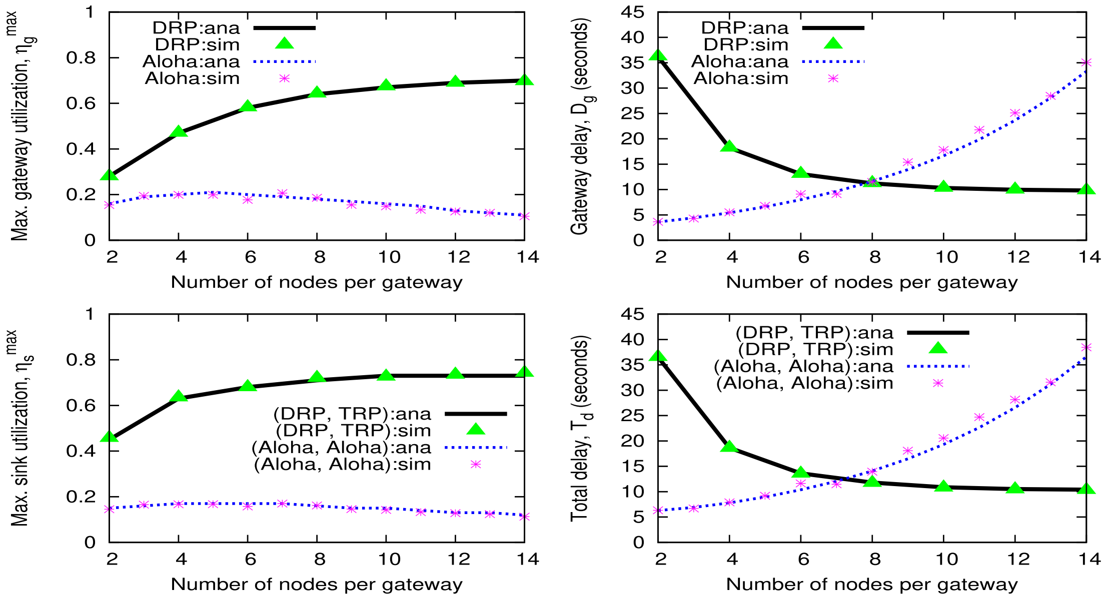

FIGURE 8. Performance with respect to number of sensor nodes u_n per gateway. Number of gateways, $n_g = 9$, $\lambda_u = 0.5$ messages/second, $T_f = 1$ second.

C. PERFORMANCE WITH RESPECT TO NUMBER OF SENSOR NODES

We investigate the effect of number of sensor nodes for a given number of gateways. Considering number of gateways, $n_g = 9$, in the given target area $\pi.600^2$ sq.m., we capture the performance comparison in Figure 8. At gateway with the increase of u_n, load increases, as a result success probability decreases and delay increases for Aloha protocol. But in case of DRP, with low value of u_n, total arrival rate at gateway is low and most of the frame time goes vacant and delay increases, but with the increase of u_n, load at gateway increases and frame time is used properly as a result utilization increases and delay decreases.

D. PERFORMANCE WITH RESPECT TO MESSAGE SIZE

In this section we observe the performance of the protocols for various value of message size in Figure 9. We fix the number of gateways, $n_g = 9$ and number of sensor nodes, $u_n = 8$, then we observe the effect of message size on the performance. With the decrease of message size, the delay performance of (Aloha, Aloha) is lower than (DRP, TRP) protocol. For small message, the success probability to transmit a message increases as a result delay decreases for Aloha protocol. But the DRP performs bad for small messages because every message (small or big) needs to reserve data transmission time in frame by transmission of control packet. So atleast approximately two frames are required, to transmit a small message, which results into higher delay and low utilization for reservation protocols. With the increase of message size, the success probability to receive a message decreases as a result $\frac{1}{P_s}$ increases and delay increases for Aloha protocol. Since for short and long message in both cases, probability of success to receive a packet at gateway is same, only the transmission time of any message is increasing with the increase of

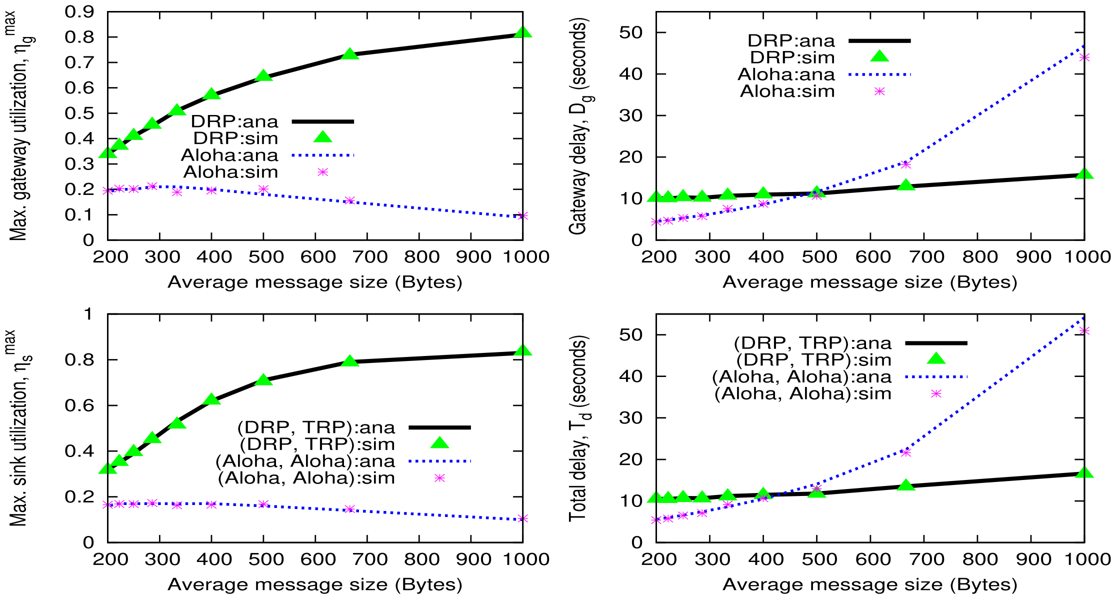

FIGURE 9. Performance with respect to message size, with number of gateways $n_g = 9$ and number of sensor nodes per gateway $u_n = 8$, $T_f = 1$ second, $\lambda_u = 0.5$ messages/second.

message size. As a result delay is increasing for DRP and (DRP, TRP).

V. CONCLUDING REMARKS

In this paper we have proposed and analyzed a novel two-tier network communication protocol (DRP, TRP) where first hop is acoustic link and second hop is RF link. In the analysis, transmitter-receiver distance-dependent propagation delay variance is accounted in the first hop. We have shown through analysis and simulation that, with the increase of transmission range, the utilization decreases at the gateway, since propagation delay variability increases.

In the absence of any performance study for communication from sensor node to satellite via gateway, we compare the performance of (DRP, TRP) with (Aloha, Aloha). Comparison results show that the proposed (DRP, TRP) protocol set outperforms (Aloha, Aloha) in terms of number of gateways, number of sensor nodes per gateway, and message size in a sensing scenario where the sensor nodes generate Exponentially distributed message size.

APPENDIX. ANALYSIS OF (Aloha, Aloha) WITH EXPONENTIALLY DISTRIBUTED MESSAGE SIZE

Utilization at gateway using Aloha with Poisson distributed arrival process and Exponentially distributed packet size can be found as in equation (30), as shown at the bottom of the page, [8], [35, Ch. 3], where T_t is the average packet transmission time in underwater acoustic network and T_t^{rf} is the average packet transmission time in RF network.

$$\begin{aligned}\eta^{g}_{\text{Aloha-uw}} &= \lambda T_t \cdot \Pr[\text{system idle at the message arrival instant}]\\ &\quad \cdot \Pr[\text{next interarrival time } \tau > \text{current message duration } \mathbf{T_t}]\\ &= \lambda T_t e^{-\lambda T_t} \cdot \int_0^\infty \Pr[\tau > t | \mathbf{T_t} = t] \cdot \Pr[\mathbf{T_t} = t]\\ &= \lambda T_t e^{-\lambda T_t} \cdot \int_0^\infty e^{-\lambda t} \frac{1}{T_t} e^{-\frac{t}{T_t}} dt = \frac{\lambda T_t}{1 + \lambda T_t} e^{-\lambda T_t}. \end{aligned} \tag{30}$$

$$\begin{aligned}\eta^{s}_{\text{Aloha-rf}} &= \lambda T_t^{rf} \cdot \Pr[\text{system idle at the message arrival instant}]\\ &\quad \cdot \Pr[\text{next interarrival time } \tau > \text{current message duration } \mathbf{T_t^{rf}}]\\ &= n_g \lambda_g T_t^{rf} e^{-n_g \lambda_g T_t^{rf}} \cdot \int_0^\infty \Pr[\tau > t | \mathbf{T_t^{rf}} = t] \cdot \Pr[\mathbf{T_t^{rf}} = t]\\ &= n_g \lambda_g T_t e^{-n_g \lambda_g T_t} \cdot \int_0^\infty e^{-n_g \lambda_g t} \frac{1}{T_t^{rf}} e^{-\frac{t}{T_t^{rf}}} dt = \frac{n_g \lambda_g T_t^{rf}}{1 + n_g \lambda_g T_t^{rf}} e^{-n_g \lambda_g T_t^{rf}}. \end{aligned} \tag{31}$$

Similarly, we can find the utilization at sink as (31), as shown at the bottom of the previous page.

The system delay D_s^g at gateway can be found as:

$$D_s^g = \left(\frac{1}{\lambda_u} + T_p^{avg}\right) \cdot \left(\frac{1}{P_s}\right) + T_t = \left(\frac{1}{\lambda_u} + T_p^{avg}\right) \cdot \left(\frac{1+\lambda T_t}{e^{-\lambda T_t}}\right) + T_t. \quad (32)$$

The system delay from gateway to sink, D_s^s can be found as:

$$D_s^s = \left(\frac{1}{\lambda_g} + T_p^{\max}\right) \cdot \left(\frac{1}{P_s}\right) + T_t^{rf} = \left(\frac{1}{\lambda_g} + T_p^{\max}\right) \cdot \left(\frac{1+n_g\lambda_g T_t^{rf}}{e^{-n_g\lambda_g T_t^{rf}}}\right) + T_t^{rf}. \quad (33)$$

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PRIYATOSH MANDAL (Member, IEEE) received the B.Sc. degree (Hons.) in mathematics from Jadavpur University, in 1998, the M.C.A. degree from Jawaharlal Nehru University, New Delhi, India, in 2001, the M.Tech. degree in information technology from GGSIPU, New Delhi, in 2004, and the Ph.D. degree in electrical engineering from IIT, New Delhi, in 2013. He has been working with the Signaling Group, Centre for Development of Telematics (C-DOT), New Delhi, where he is currently a Senior Research Engineer. He has more than 20 years of work experience in the field of 4G LTE, 5G, cloud computing, SS7, and sigtran protocols. His research interest includes performance analysis of communication protocols.