On the Underwater Wireless Network Clustering

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***Abstract*—In this paper, we consider a two-tier communication scenario in an underwater sensor network. The field nodes form single-hop clusters around the gateway nodes and communicate with them via acoustic wireless links, while the gateway nodes communicate directly via radio frequency (RF) wireless links to the sink node. Thus, the field data is collected at the sink node via two-hop communication links. The field data being sporadic, the multi-access communications in the two hops are considered slotted random access (S-Aloha) based. We first analyze the performance of the receiver synchronized S-Aloha in underwater network which is used for data communication from the sensor nodes to their respective gateway nodes. The multi-access throughput performance over the RF links at the sink node is also characterized. We then study the optimum cluster size that maximizes the overall network throughput. Our numerical results are supported by discrete event based random network simulation studies.**

I. Introduction

Short-range underwater wireless ad hoc networks (UWN) are aimed at remotely monitoring various aquatic activities, such as marine biological and zoological lives, geological changes, and underwater human activities. There are many differences between underwater and radio frequency(RF) network; propagation delay is the major among them. Underwater signal propagation speed $v(z, \xi, \theta)$ (in m/s) is modeled as [1]:

$$v(z, \xi, \theta) = 1449.05 + 45.7\theta - 5.21\theta^2 + 0.23\theta^3 + \big(1.333 - 0.126\theta + 0.009\theta^2\big)(\xi - 35) + 16.3z + 0.18z^2,$$

where $\theta = \frac{\Theta}{10}$, Θ is the temperature in ^{o}C, ξ is the salinity in ppt, and z is the depth in km. From this expression it can be noted that the signal propagation speed or propagation delay varies with temperature, depth, and salinity of water, which are functions of the operating conditions. Also attenuation depends on the transmission range (R) and channel frequency (f) as [1]:

$$A(R, f) = R^{\kappa} \cdot a(f)^R$$

where κ is the signal spreading factor and $a(f)$ is the absorption coefficient. Thus, with the increase of transmission range attenuation increases, which suggests that some kind of short range communication can be helpful to enhance throughput.

In remote underwater sensing applications, it is important to find optimal solution to underwater field data collection and eventually sending them to the monitoring and control center, which we call *the sink node*. In such cases, typically, the first hop, i.e., the field nodes to gateway node communication would be via underwater wireless (acoustic) channel, whereas the second hop, i.e., the gateway node(s) to the sink communication would be via radio frequency (RF) wireless channel. While data gathering from the underwater field nodes to an underwater gateway has been addressed in the recent literature [2]–[6], overall network data aggregation at a sink node, which may be located at a remote location from the sensing field, has not been addressed.

In this paper, we look into a underwater sensing scenario where the underwater field nodes' data have to be collected at a remotely located sink node. We propose a two-tier network architecture, as shown in Fig. 1. The underwater field

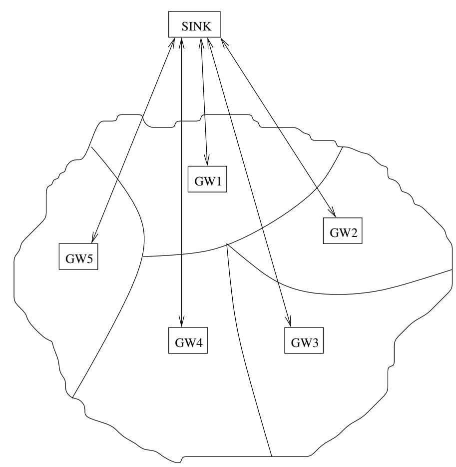

Fig. 1. System model for two hop network

nodes deployed for sensing and communication purposes form clusters around the gateway nodes. The gateway nodes are capable of underwater communication with the field nodes, as well as RF communication with the sink node at a terrestrial location. The field sensors collect and send the data to their respective gateway nodes, which further forward them to the sink node via RF wireless links. Communication in both hops are in the form of many-to-one access mechanism. This many-to-one connectivity and normally-sporadic sensed data at the field nodes suggest that some kind of short range random access protocol would be suitable for the field nodes to gateway communication. However, pertaining to the distinctly different signal propagation characteristics, RF multi-access communication protocols are not directly applicable [2], [3], [7]–[9]. So, for the field nodes to gateway communication we consider receiver-synchronized slotted Aloha (S-Aloha-uw) [6], where the transmitter-receiver distance dependent propagation delay variance for communication from sensor nodes to gateway is accounted in determining the optimum slot size. Also for simplicity we consider S-Aloha-rf for communication from gateways to the sink node.

Our specific contributions in this paper are as follows:

(a) We analyze the modified receiver synchronized S-Aloha-uw, considering transmitter receiver distance dependent propagation delay variance.
(b) We investigate the optimum number of clusters to achieve the maximum network throughput.

The remainder of the paper is organized as follows. Performance analysis of modified receiver synchronized S-Aloha-uw, for field nodes' communication to the gateway in a single cluster, in the presence of transmitter-receiver distance dependent propagation delay variance is presented and its performance is analyzed in Section II. Considering a two hop network, the network throughput is analyzed in Section III. The numerical and simulation results are presented in Section IV. The paper is concluded and a few remarks on future direction is drawn in Section V.

II. Receiver Synchronized S-Aloha

In receiver synchronized S-Aloha, transmitters send data so that the data will be received by the receiver in a receiver's slot. In this section we study the performance of modified receiver synchronized S-Aloha considering propagation delay variance as a function of transmitter receiver distance. The assumption are used throughout the paper are briefly mentioned.

Assumptions: The transmitters are uniformly random distributed around the receiver's communication range R, and each node knows the distance to the receiver. Variability of underwater inter-nodal propagation delay, i.e., propagation delay uncertainty, is Gaussian distributed [10], [11]. No retransmission will be considered at sensor nodes and gateway nodes.

Definition 1: Access performance is measured in terms of *normalized system throughput*, defined as the average number of successful frames in the network per frame transmission time.

A. Modified receiver synchronized S-Aloha for UWN (mRSS-Aloha-uw) with propagation delay variance as function of Tx-Rx distance

In this section we propose to modify the slot size of RSS-Aloha-uw protocol to achieve an improved system performance. Consider, a frame reaches at the receiver at time t_r. The arrival instant is assumed Gaussian distributed as: $t_r \sim \mathcal{N}\left(t_g, \sigma^2(r)\right)$, where t_g is the start time of a time slot at the receiver and $\sigma^2(r)$ is the variance, which is a function of transmitter-receiver distance r.

We propose to increase the slot size of mRSS-Aloha-uw protocol as, $T_s = T_t + 2k\sigma^{max}(r)$, with $k \geq 0$. k is termed as *slot size increment coefficient*. $\sigma^{max}(r)$ is the maximum propagation delay variance among all the transmitters to the concerned receiver.

Considering the minimum transmitter-receiver distance as r_0, the cdf of transmitter-receiver distance is considered as:

$$F_R(r) = \begin{cases} \frac{r^2 - r_0^2}{R^2 - r_0^2}, & r_o \leq r \leq R \\ 1, & r \geq R \end{cases}$$

By Gaussian approximation of arrival time uncertainty distribution, the success probability P_s of a frame designated for slot i, calculated, considering vulnerability caused by up to two-slot neighbors. So P_s can be approximately written as:

$$\begin{aligned} P_s = \int_{r_0}^{R} \int_{(i-2)T_s}^{(i+2)T_s} \Big[\sum_{n_{i_p}=0}^{\infty} \Pr\left(n_{i_p} \text{ arrival in slot } i\right) \\ \prod_{i_p=0}^{n_{i_p}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_i}(\mathbf{r_i}) \leq y + T_t\right)\right\} \Big] \\ \cdot \Big[\sum_{n_{i_{p2}}=0}^{\infty} \Pr\left(n_{i_{p2}} \text{ arrival in slot } i-2\right) \\ \prod_{i_{p2}=0}^{n_{i_{p2}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \leq y + T_t\right)\right\} \Big] \\ \cdot \Big[\sum_{n_{i_{p1}}=0}^{\infty} \Pr\left(n_{i_{p1}} \text{ arrival in slot } i-1\right) \\ \prod_{i_{p1}=0}^{n_{i_{p1}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \leq y + T_t\right)\right\} \Big] \\ \cdot \Big[\sum_{n_{i_{n1}}=0}^{\infty} \Pr\left(n_{i_{n1}} \text{ arrival in slot } i+1\right) \\ \prod_{i_{n1}=0}^{n_{i_{n1}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \leq y + T_t\right)\right\} \Big] \\ \cdot \Big[\sum_{n_{i_{n2}}=0}^{\infty} \Pr\left(n_{i_{n2}} \text{ arrival in slot } i+2\right) \\ \prod_{i_{n2}=0}^{n_{i_{n2}}} \left\{1 - \Pr\left(y - T_t \leq \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \leq y + T_t\right)\right\} \Big] \\ \cdot \Pr(\mathbf{y_i} = y) \Pr(\mathbf{r_i} = r). \end{aligned}$$

By the assumption of Gaussian propagation delay distribution we have: $\mathbf{y_i}(r_i) \sim \mathcal{N}(iT_s, \sigma_i^2)$; $\mathbf{x_i}(r_i) \sim \mathcal{N}(iT_s, \sigma_i^2)$; $\mathbf{x_{i_{p2}}}(r_{i_{p2}}) \sim \mathcal{N}\left((i-2)T_s, \sigma_{i_{p2}}^2\right)$; $\mathbf{x_{i_{p1}}}(r_{i_{p1}}) \sim \mathcal{N}\left((i-1)T_s, \sigma_{i_{p1}}^2\right)$; $\mathbf{x_{i_{n1}}}(r_{i_{n1}}) \sim \mathcal{N}\left((i+1)T_s, \sigma_{i_{n1}}^2\right)$. $\mathbf{x_{i_{n2}}}(r_{i_{n2}}) \sim \mathcal{N}\left((i+2)T_s, \sigma_{i_{n2}}^2\right)$.

In practice, the propagation delay variance is function 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 slot i is Gaussian distributed as: $\mathbf{x_i}(r_i) \sim \mathcal{N}(iT_s, \sigma^2(r_i))$, where the variance is dependent on transmitter-receiver distance r_i. Using the arrival time distribution, the probability expressions of P_s can be simplified as:

$$\begin{aligned}P_1 &= \Pr\left(y - T_t \le \mathbf{x_i}(\mathbf{r_i}) \le y + T_t\right)\\ &= \int_{r_0}^{R} \Pr(y - T_t \le \mathbf{x_i}(\mathbf{r_i} = r) \le y + T_t) \cdot \Pr(\mathbf{r_i} = r)\\ &= \int_{r_0}^{R} \left[\mathrm{erf}\left(\frac{y + T_t - iT_s}{\sigma(r)\sqrt{2}}\right) - \mathrm{erf}\left(\frac{y - T_t - iT_s}{\sigma(r)\sqrt{2}}\right)\right] \frac{rdr}{R^2 - r_0^2}\\ &\triangleq P_{11} - P_{12},\end{aligned}$$

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

$$\begin{aligned}P_{11} &= \int_{r_0}^{R} \mathrm{erf}\left(\frac{y + T_t - iT_s}{\sigma(r)\sqrt{2}}\right) \frac{rdr}{R^2 - r_0^2}\\ &= \int_{r_0}^{R} \mathrm{erf}\left(\frac{y + T_t - iT_s}{\frac{cr^n}{v^n}\sqrt{2}}\right) \frac{rdr}{R^2 - r_0^2}\\ &= -\frac{1}{n}\frac{a_1^{\frac{2}{n}}}{(R^2 - r_0^2)} \int_{\frac{a_1}{r_0^n}}^{\frac{a_1}{R^n}} \frac{\mathrm{erf}(m)}{m^{\frac{n+2}{n}}} dm \end{aligned} \quad (1)$$

where $a_1 = \frac{(y+T_t-iT_s)v^n}{c\sqrt{2}}$, and

$$\begin{aligned}P_{12} &= \int_{r_0}^{R} \mathrm{erf}\left(\frac{y - T_t - iT_s}{\sigma(r)\sqrt{2}}\right) \frac{rdr}{R^2 - r_0^2}\\ &= \int_{r_0}^{R} \mathrm{erf}\left(\frac{y - T_t - iT_s}{\frac{cr^n}{v^n}\sqrt{2}}\right) \frac{rdr}{R^2 - r_0^2}\\ &= -\frac{1}{n}\frac{b_1^{\frac{2}{n}}}{(R^2 - r_0^2)} \int_{\frac{b_1}{r_0^n}}^{\frac{b_1}{R^n}} \frac{\mathrm{erf}(m)}{m^{\frac{n+2}{n}}} dm \end{aligned} \quad (2)$$

where $b_1 = \frac{(y-T_t-iT_s)v^n}{c\sqrt{2}}$. Similarly, P_2, P_3, P_4, and P_5 can be used to denote:

$$\begin{aligned}\Pr\left(y - T_t \le \mathbf{x_{i_{p1}}}(\mathbf{r_{i_{p1}}}) \le y + T_t\right) &= P_2,\\ \Pr\left(y - T_t \le \mathbf{x_{i_{p2}}}(\mathbf{r_{i_{p2}}}) \le y + T_t\right) &= P_3,\\ \Pr\left(y - T_t \le \mathbf{x_{i_{n1}}}(\mathbf{r_{i_{n1}}}) \le y + T_t\right) &= P_4,\\ \Pr\left(y - T_t \le \mathbf{x_{i_{n2}}}(\mathbf{r_{i_{n2}}}) \le y + T_t\right) &= P_5\end{aligned}$$

and there expressions can be derived as in case of P_1.

To find a closed form analytic expression of the system throughput, we need to consider some value of n. We consider $n = 1$. $n = 0$ means constant propagation delay variance, i.e., it is not dependent on the transmitter-receiver distance. $n = 1$ means propagation delay variance is a linear function of transmitter-receiver distance. Denote,

$$\begin{aligned}a_1 &= \frac{(y + T_t - iT_s)v^n}{c\sqrt{2}},\ b_1 = \frac{(y - T_t - iT_s)v^n}{c\sqrt{2}}\\ a_2 &= \frac{(y + T_t - (i-1)T_s)v^n}{c\sqrt{2}},\ b_2 = \frac{(y - T_t - (i-1)T_s)v^n}{c\sqrt{2}}\\ a_3 &= \frac{(y + T_t - (i-2)T_s)v^n}{c\sqrt{2}},\ b_3 = \frac{(y - T_t - (i-2)T_s)v^n}{c\sqrt{2}}\\ a_4 &= \frac{(y + T_t - (i+1)T_s)v^n}{c\sqrt{2}},\ b_4 = \frac{(y - T_t - (i+1)T_s)v^n}{c\sqrt{2}}\\ a_5 &= \frac{(y + T_t - (i+2)T_s)v^n}{c\sqrt{2}},\ b_5 = \frac{(y - T_t - (i+2)T_s)v^n}{c\sqrt{2}}\end{aligned}$$

We use the identities $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$, and $\int_a^b \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} = \frac{1}{2}\left[\mathrm{erf}\left(\frac{b-\mu}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{a-\mu}{\sigma\sqrt{2}}\right)\right]$. For $n = 1$, i.e., $\sigma(r) = cT_p(r) = \frac{cr}{v}$
We can write from (1) and (2)

$$\begin{aligned}P_{j1} =& \frac{a_j^2}{(R^2 - r_0^2)}\left[\mathrm{erf}\left(\frac{a_j}{R}\right) + \frac{\mathrm{erf}\left(\frac{a_j}{R}\right)}{2\left(\frac{a_j}{R}\right)^2} + \frac{e^{-\left(\frac{a_j}{R}\right)^2}}{\left(\frac{a_j}{R}\right)\sqrt{\pi}}\right.\\ &\left. -\mathrm{erf}\left(\frac{a_j}{r_0}\right) - \frac{\mathrm{erf}\left(\frac{a_j}{r_0}\right)}{2\left(\frac{a_j}{r_0}\right)^2} - \frac{e^{-\left(\frac{a_j}{r_0}\right)^2}}{\left(\frac{a_j}{r_0}\right)\sqrt{\pi}}\right]\end{aligned}$$

$$\begin{aligned}P_{j2} =& \frac{b_j^2}{(R^2 - r_0^2)}\left[\mathrm{erf}\left(\frac{b_j}{R}\right) + \frac{\mathrm{erf}\left(\frac{b_j}{R}\right)}{2\left(\frac{b_j}{R}\right)^2} + \frac{e^{-\left(\frac{b_j}{R}\right)^2}}{\left(\frac{b_j}{R}\right)\sqrt{\pi}}\right.\\ &\left. -\mathrm{erf}\left(\frac{b_j}{r_0}\right) - \frac{\mathrm{erf}\left(\frac{b_j}{r_0}\right)}{2\left(\frac{b_j}{r_0}\right)^2} - \frac{e^{-\left(\frac{b_j}{r_0}\right)^2}}{\left(\frac{b_j}{r_0}\right)\sqrt{\pi}}\right]\end{aligned}$$

and $P_j = P_{j1} - P_{j2}$, for $j = 1, 2, 3, 4, 5$.

Assuming packet arrival process as Poisson distributed and simplifying the expression of P_s we have:

$$\begin{aligned}P_s =& \int_{r=r_0}^{R}\int_{(i-2)T_s}^{(i+2)T_s} e^{-\lambda T_s(P_1+P_2+P_3+P_4+P_5)}\\ &\cdot \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-iT_s}{\sigma}\right)^2} dy \frac{2rdr}{R^2 - r_0^2}\\ =& \frac{2v}{c(R^2 - r_0^2)\sqrt{2\pi}} \int_{r=r_0}^{R}\int_{(i-2)T_s}^{(i+2)T_s}\\ & e^{-\lambda T_s(P_1+P_2+P_3+P_4+P_5)} \cdot e^{-\frac{1}{2}\left(\frac{v(y-iT_s)}{cr}\right)^2} dy\ dr\end{aligned}$$

Hence, the normalized throughput at gateway is:

$$\eta_g = \lambda T_t P_s. \quad (3)$$

Since propagation delay variability increases with the increase of transmitter-receiver distance, from (3), we can say that the normalized system throughput at gateway will decrease with the increase in transmission range or transmitter-receiver distance. This we have further verified via simulation as demonstrated in Fig. 2.

III. Throughput of two-hop network

Consider there are many clusters in a network for underwater data collection. Each cluster has a gateway node. One target area corresponds to one gateway or cluster as shown in Fig. 1. For simplicity of analysis, a region covered by a gateway is considered circular. All the gateway nodes transmit data of constant packet size to the sink using a common RF communication channel. With S-Aloha random access protocol, the overall network throughput at the sink can be written as:

$$\eta_s = n_g \lambda_g T_{gs} e^{-n_g \lambda_g T_{gs}} \tag{4}$$

where T_{gs} is the frame transmission time from gateway to sink node. n_g is the number of underwater gateway nodes in the network. $\lambda_g = \lambda P_s$. λ is the total arrival rate at each gateway. So λP_s is the successful arrival rate at each gateway. And finally the throughput as in (4), where P_s can be derived as in previous section.

Since the throughput at gateway increases with the decrease of transmission range while it decreases in the second hop multi-access communication, this motivates us to find an optimal number of clusters in the underwater so as to achieve a maximum network throughput with the chosen multi-access protocols in the two stages. With this intention, if each such target area (TA) corresponding to a gateway is further divided into n_c sub-clusters, then the new transmission range,R can be defined as

$$R = \sqrt{\frac{TA}{\pi n_c}} \tag{5}$$

After this sub-division of original clusters into sub-clusters, the network throughput at sink can be written as:

$$\eta_s = n_g n_c \lambda_g T_{gs} e^{-n_g n_c \lambda_g T_{gs}} \tag{6}$$

λ_g is calculated with the decreased transmission range as in (5). For known transmission range R, the node density ρ can be defined as:

$$\rho = \beta R^2, \quad \text{where} \quad \beta > 0$$

Lastly, for a known node density ρ and arrival rate per sensor node λ_u, the total arrival rate in a cluster can be defined as:

$$\lambda = \rho \lambda_u$$

IV. Results and Discussion

We have considered the common parameters as packet size 40 Bytes, transmission speed 16 kbps, acoustic signal propagation speed 1500 m/sec.

Considering a single cluster first we verify the simulation and analysis result as shown in Fig. 2, which also shows that, with the increase in transmission range throughput at the gateway decreases. This is because, the propagation delay variability increases with the increase of transmission range. Here, the throughput is calculated based on the total arrival rate at the gateway irrespective of the number of sensor nodes present in a cluster.

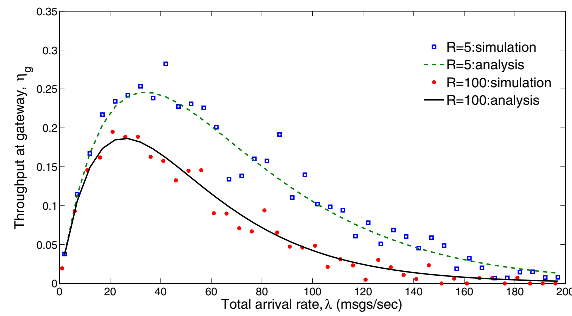

Fig. 2. Normalized system throughput at gateway: simulation and analysis verification assuming $c = 1, n = 1, k = 0.5$.

In Fig. 3 shows the variation of network throughput with the number of clusters for a given arrival rate per sensor node λ_u and by changing the value of β, i.e., explicitly changing the arrival rate at each gateway. Corresponding to the number

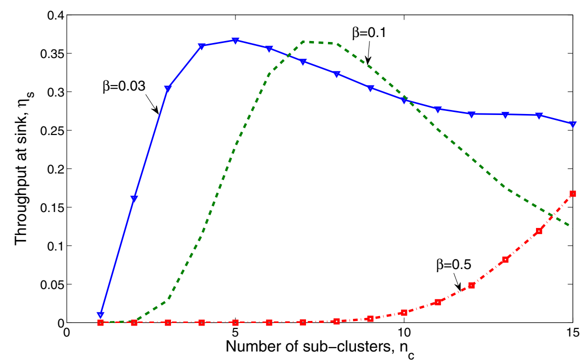

Fig. 3. Network throughput at sink corresponding to number of clusters, n_c for given arrival rate at each gateway. $c = 0.1$, $\lambda_u = 2$, $k = 0.5$, $n_g = 50$, target area= 10000 sqm.

of clusters, the transmission range R and node density ρ can be easily obtained. For a given β, throughput at the gateway is derived. Once the throughput at the gateway is known and n_c is given, the throughput at the sink η_s can be derived as in (6). The plots indicate that the throughput increases with the increase of number of clusters. But further increase of clusters causes a degradation of network throughput at the sink, due to high number of gateway nodes accessing the sink.

In Fig. 4, by considering maximum throughput at gateway, we have found the throughput at sink. Corresponding to the number of clusters, n_c transmission range, R can be found. With a given β, node density ρ can also be found. For all possible slot increment factor k, we have maximized the throughput at gateway and with the maximum throughput at gateway, finally we find network throughput at the sink. This figure shows that the throughput at sink is low when the number of clusters are low, and the throughput increases with the increase of n_c per target area till a certain value of n_c and after that throughput decreases both at gateway and at sink. Also the slot increment factor k varies with n_c, since

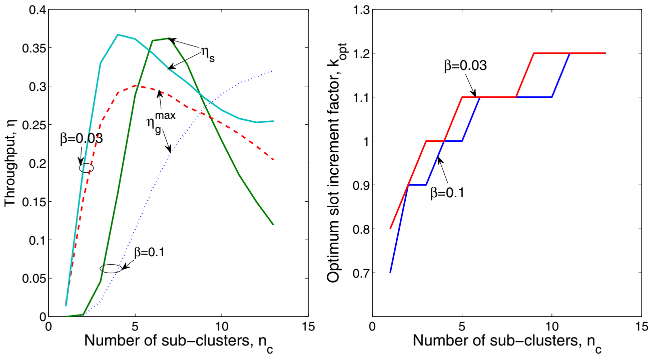

Fig. 4. Maximum throughput at gateway and network throughput at sink corresponding to number of clusters for a given target area 10000 sqm. Also the corresponding optimal value of slot increment factor, k. $c = 0.1, \lambda_u = 2, n_g = 50$.

due to the increase of number of clusters the total arrival rate decreases at each gateway. To get a high throughput at the gateway, we need to increase the slot size by increasing the slot increment factor k, which is also shown in this figure.

In Fig. 5, the network throughput is maximized by optimally choosing the slot size increment factor at different values of n_c. For a given arrival rate per sensor node λ_u, propagation delay variability constant c, β, target area, and the number of clusters n_c, the transmission range R is obtained. Then by changing the value k the network throughput at sink is maximized. Also the gateway throughput and optimum k

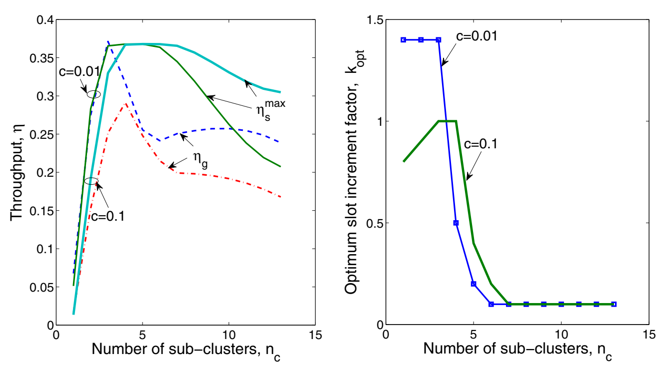

Fig. 5. Optimum k and maximum network throughput versus n_c, for given $\lambda_u = 2$, $\beta = 0.03$, target area $= 10000$ sqm, and $n_g = 50$.

are noted. These figures show, maximum network throughput does not necessarily occur simultaneously when the gateway throughput is maximized. A lesser number of clusters means, the transmission range R of the nodes is large, causing a large propagation delay variance, which leads to a large value of k to get the maximum network throughput.

V. Conclusion

In this paper, we have presented an analysis of modified receiver synchronized S-Aloha-uw in presence of distance dependent propagation delay variability. We have shown through analysis and simulation that, with the increase of transmission range, i.e., with the increased cluster size, the throughput decreases at the gateway, since propagation delay variability increases. Although an increased cluster size, i.e., a reduced number of clusters, increases the second hop (gateway nodes to the sink) throughput, the overall network throughput does not vary monotonically. To this end, we have further investigated the optimum cluster size that maximizes the overall network throughput.

While the proposed two-tier architecture and the study of optimum clustering would be of interest for remote data collection from the underwater field nodes, the considered S-Aloha multi-access protocol, especially for the gateway to the sink communication may not be suitable if the sensed data traffic intensity is high. To this end, our current and future studies include investigation of two-tier network communication scenario with some kind of reservation based protocols from the underwater field nodes to the gateway and the gateway nodes to the sink.

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