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Cooperative Routing Protocol Design with Congestion Control on Sink for Underwater Wireless Sensor Networks

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Abstract: **Underwater wireless sensor networks experience performance degradation because they endure high latency combined with limited network bandwidth and congestion problems. Existing protocols fail to address congestion control properly so they produce inefficient performance. The research introduces CCCUSN (Congestion Control with Cooperation for UWSNs) as an innovative protocol that integrates optimized congestion control with cooperative communication. CCCUSN leverages the foundation from RACE and ARCUN through its dynamic data-flow control methods which involve priority queues and relay-based cooperation and adaptive rate control. The model underwent 8000 rounds of simulation within a 500m × 500m network space which contained 225 nodes and 10 surface sinks. Multiple performance tests show that CCCUSN delivers better outcomes than ARCUN and CONG-AWARE-ARCUN throughout the testing period. The throughput rate of CCCUSN reaches 30% at 7000 rounds whereas ARCUN only reaches 15% throughput. The data shows that CCCUSN operates with transmission loss reduced to 80 dB which is better than the 135 dB measurement of ARCUN for improved communication reliability. The end-to-end delay of CCCUSN drops to 3 seconds whereas the ARCUN delay remains at 28 seconds. The optimized energy usage in CCCUSN reaches 17 Joules because its energy tax decreases below the 30 Joules level of ARCUN. CCCUSN maintains extended network operational duration through its ability to support 125 alive nodes at 7000 rounds whereas ARCUN survives only 118 nodes. These findings highlight CCCUSN as a promising solution for improving the reliability and scalability of UWSNs.**

Keywords: **Underwater Wireless Sensor Networks, Acoustic Communication, Congestion Control, Cooperative Communication, Routing Protocols, Network Stability, Energy Efficiency.**

1. Introduction

Underwater Wireless Sensor Networks (UWSNs) establish themselves as fundamental technology which serves marine ecosystem monitoring and saves lives during disasters and defends military operations with offshore exploration. Acoustic communication becomes the principal technology in UWSNs since radio waves experience extensive signal loss in underwater environments. UWSNs encounter multiple obstacles because of their excessive propagation delays and restricted bandwidth as well as energy restrictions and critical network congestion. UWSNs experience congestion because both bandwidth restrictions and poor data processing confront the network which results in higher packet failure rates and performance reductions along with diminished energy distribution effectiveness. The current communication protocols prove deficient in managing congestion effectively which leads to insufficient network performance output. In order to overcome these limitations, this study introduces a novel Congestion Control with Cooperation for UWSNs (CCCUSN), an advanced routing protocol that unifies congestion aware mechanisms and cooperative communication strategies to improve the reliability and efficiency of the network. This research investigates the inefficient behavior of existing congestion control mechanisms in UWSNs because they produce high communication losses and energy waste and slow down end-to-end delay times.

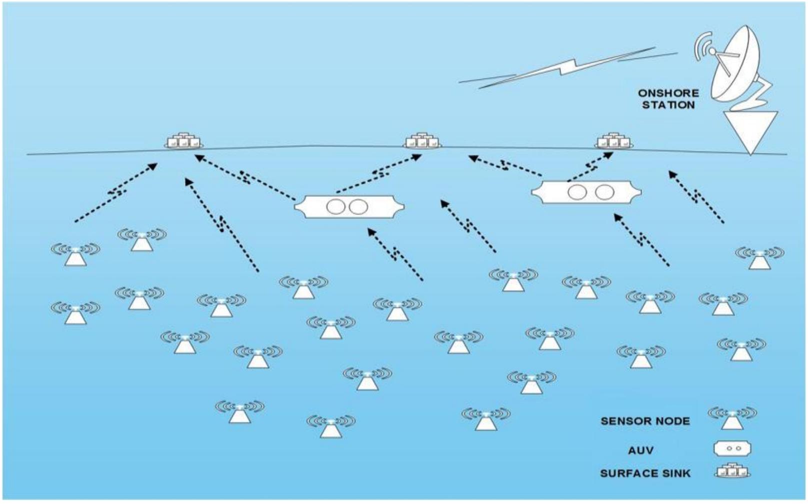

Figure 1: A scenario of UWSN Architecture

UWSNs follow the structure illustrated in **Figure 1**. The sensors within this structure operate through acoustic channels that connect multiple sensors mounted beneath the sea. The sensor nodes transmit their data toward Autonomous Underwater Vehicles (AUVs) through acoustic channels that perform underwater operations and surface sinks that operate above water with radio and acoustic capabilities. The sensor nodes use multiple hops signals to relay observations of native underwater events. The surface sinks utilize acoustic communication sensors together with sea stations to aggregate data through their management function for UWSNs. The primary problem addressed in this research is the inefficiency of current congestion control mechanisms in UWSNs, which lead to high transmission loss, excessive energy consumption, and prolonged end-to-end delays. Traditional routing protocols, ARCUN and CONG-AWARE-ARCUN cannot adjust their behavior when traffic conditions change and they do not evenly spread network traffic. The underwater environment requires nodes to handle multiple signal path problems along with Doppler effects and restricted movement which enhance congestion control complexity. UWSNs can only perform poorly when they lack proper congestion management procedures. The best data flow approach needs to be developed to handle information priority and improve networking performance in UWSNs. The research goal consists of designing a congestion control protocol which delivers optimal load distribution and low data transmission instability while boosting network capabilities. The proposed CCCUSN protocol enhances network speed at the same time it decreases data transmission delays together with optimizing power usage and extending node operational periods. CCCUSN achieves efficient data packet transmission with its combination of cooperative communication and congestion-aware mechanisms that prevents network congestion. The study addresses the implementation of adaptive rate control together with priority queueing along with relay-based cooperation methods to achieve better network stability. The performance evaluation of CCCUSN under different network settings is supported through a mathematical model which ensures its practical application to UWSN field implementations.

The main contributions of this research is to developed CCCUSN as a congestion control protocol made specifically for UWSNs through the implementation of cooperative communication which enhances data transmission efficiency. The protocol makes use of priority queueing technology to ensure efficient high-priority packet transmission while achieving balanced network traffic operations. The use of intermediate nodes through relay-based cooperation enhances delivery reliability because it distributes communication loads by assisting in transferring data to the sink node. The system supports adaptive data rate adjustment via network congestion monitoring, preventing packet collisions and reducing useless retransmissions. The research team performed complete simulation evaluations between CCCUSN and ARCUN and CONG-AWARE-ARCUN protocols which showed enhanced performance results in essential metrics. The implementation of CCCUSN results in higher system throughput and reduced transmission loss with shorter delays and enhanced power efficiency which supports its deployment in practical underwater sensor networks

Organization of the Study

The research begins with an overview of UWSNs and their distinctive aspects followed by a description of underwater communication challenges. An in-depth description follows which explains CCCUSN protocol through its main characteristics alongside its congestion control system and cooperative communication capabilities. The study presents a mathematical model to evaluate how CCCUSN handles congestion and optimizes data transfer efficiency.

2. Related Work

A concise overview of current research was presented regarding UWSNs and its classification.
ACSRO in WSN for control and congestion avoidance [1]. It empowers the sensor network for identification of incipient congestion and precludes its events. The ACSRO process is assessed utilizing the evaluation measurements such as Packet loss, Congestion level, Queue size and throughput. Results show that ACSRO scheme is more effective for congestion managing and better performance of the WSN.

There are various network protocols for different types of WSNs but Underwater WSNs have unique characteristics that require new efficient and reliable data communication protocols [2]. Some of the characteristics of different types of WSNs are shown below in **Table 1**.

Table 1: Types of WSNs

Characteristics	Terrestrial	Underground	Multimedia	Underwater
Signal nature	Radio	Radio	Radio	Acoustic
Signal speed	3×108 m/sec	Variable	250 Mbps max	1500 m/sec
Signal bandwidth	High	Low	High	Low
Propagation delay	Low	Elevated	low down	High
inaccuracy rate	Stumpy	Higher	low	High
Mobility	Movable	Immobile & Portable	Static & mobile	Static & mobile
Power source	Battery, Solar	Battery	Battery, solar	Battery

Architecture of UWSNs

UWSNs consists of small-sized sensors fixed to the bottom of the sea which are connected by a wireless acoustic channel. Data is transmitted from sensor nodes to Autonomous Underwater Vehicles (AUVs) which dive inside the water and a surface sink, available at the water surface assembled with radio and acoustic channels. These sensor nodes inspect native underwater events and send their reports using multiple hops signals. Surface sinks are equipped with acoustic communication sensors and seashore stations, thus assembling data and finally handling UWSNs [3], [4].

Underwater sensor nodes are designed to perform consistently over long periods without repairing, servicing, or recharging in the tough isolated environment of the deep sea. These nodes must be deployed in a spatial arrangement due to their inability to autonomous lateral movement in underwater networks [5]. UWSNs need to reconfigure a communication path through a continuous route that is separate from the previous path by which communication was made [6]. The system below water has a lot of complications than global communications like electromagnetic, scattering, and absorption effects, and salty water so, cannot further relocate due to high attenuation [7].

Underwater Sensor Nodes

Submerged sensors are self-governing hubs. However, nodes are essential for the development of UWSNs and for achieving the goals of any underwater application. These sensor nodes have the ability for storage, detection, and also processing. The major difficulty of UWSNs is the sensor node development, including its high cost when compared to terrestrial sensor nodes. Many sensor nodes are application-specific, and lacking in generality. In long-range deployments, sensor nodes can communicate with the sink node which can be overcome by multibounce designs and with the best communication skills among different hubs [8]. Recent UWSN research mainly aims to design smaller size and more efficient energy consumption sensor nodes to improve performance while considering diverse parameters. These nodes should consume minimum power to extend the lifetime and to use minimum hardware due to which luminous conventions are performed to detect any fault and corrections. Hubs are well developed in remote regions like deep sea etc, but openness is a significant question and for maintenance, a proper latest system is required to sense errors [9].

Underwater Sensor Node Architecture

Through, sensor interface hardware these are linked with the main administrator as illustrated in Figure 2. Helpful in an assortment of data, storage space and also sending to other nodes via acoustic modem. These are ensured by outstanding devices that allow an omnidirectional connection, and shielded technologies e.g. modems from any unsafe activities. Underwater sensor nodes can easily determine marine life activities like acidity, turbidity, chemicals, conductivity, warmth, oxygen, hydrogen, saltiness, and density [10].

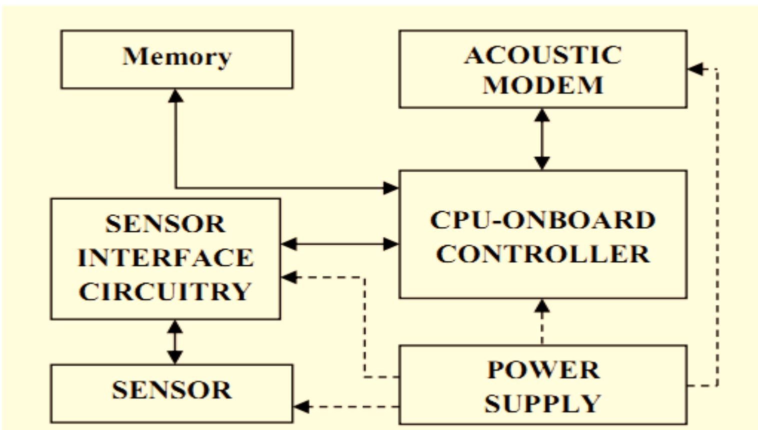

Figure 2: Interior Design of USN [16]

Current Models

Sensor node technologies are beneficial to detect water. According to application necessities, the sensor hubs are structured as needed. For example, nowadays ARGO is used for ocean measurements and also purposeful for vitality, power supply, and profundity management. A well-known technique Hydro Node is widely utilized in waterways. Self-sufficient submerged wayfarer worked to screen aquatic maintenance, which includes a potent component of sensor node [8].

Nowadays, well-accepted sensor hubs are Mica2, MicaZ, and Telosb [11]. In short, hubs change broadly as shown below in **Table 2.**

Table 2: List of Different Sensor Nodes

Sensor Node	CPU	RAM	External Memory	Freq. MHz	Data Rate (Kbps)	OS
WeC	ATMEL	512 K	32 K	916	10	Tiny
Rene1	ATMEL AT90LS85354	512 K	32 K	916	10	TinyOS
ECO[11]	nRF24E1 (8051)	4 K	32 K	2400	1000	-
Fleck[11]	ATMEL ATMEGA 128L	4 K	512 K	925	77	TinyOS
ProSpeckz II[11]	Cypress CY8C2764	256 K	16 K	2400	250	Speckle net
Ant[11]	TI MSP430F1232	256 K	8 K	2400	1000	Ant
XYZ hubs[11]	OKI ML67Q500x	4 K	512 K	2400	250	SOS
RF Module	ATMEL 128L	4K	128 K	2400	250	EmberNet
uPart0140 ilmt[11]	rfPIC 16F675	64 K	1 K	860	19	Smart-its
iMote2[11]	Intel PXA 271	256 K	32 M	2400	250	TinyOS
EnOcean TCM120[11]	PIC 18F452	1.5 K	256 K	868	120	TinyOS
Pluto[11]	TI MSP430F149	4 K	512 K	2400	250	TinyOS
Mica2[11]	ATMEL ATMEGA 128L	4 K	512K	900	38	OS
Mica2Dot[11]	ATMEL ATMEGA 128L	4 K	512K	900	38	OS
IRIS[12]	ATMEL ATMEGA 1281	8K	128 K	2400	250	TinyOS
TelosB[12]	TI MSP430F1611	10 K	48 K	2400	250	TinyOS
TinyNode[12]	TI MSP430	8 K	512 K	870	152	TinyOS
Cricket[12]	ATMEL128L	4 K	512 K	433	250	TinyOS
LOTUS[12]	NXPLPC1758	64 K	512 K	2400	250	TinyOS
EZ-RF2480[13]	TI MSP430F2274	1 K	None	2400	721	-
EZ-RF2500[13]	TI MSP430F2274	1 K	None	2400	721	-
SHIMMER[13]	TI MSP430F1611	10 K	48 K	2400	250	TinyOS
SUN SPOT[13]	ATMEL AT91FR40162S	256 K	4 MB	2400	250	Squawk VM

Current communication protocols for terrestrial networks do not work underwater due to low bandwidth and large latency. These technologies are still more expensive than terrestrial networks. Hubs are sparser in these networks and on the other hand, terrestrial networks are densely deployed. Node mobility can be projected easily in terrestrial but the prediction of node mobility is difficult in underwater networks. Due to large gaps between sensors nodes, readings taken from underwater networks are not correlated compared to terrestrial WSNs [14].

Acoustic networks can do better work in submerged conditions, while electromagnetic and optical waves can also be used at the standard level. At higher frequencies, the magnetic effect has a restricted correspondence run. Many protocols are recommended for terrestrial networks but they cannot be used for UWSNs e.g. less transmission capacity, and propagation delay (i.e. <100 kHz) so, all the sensor nodes are outfitted with a low data transfer capacity. Sensor nodes can propagate very easily and they are generally considered static [15].

Current technology for conventional underwater exploration is not suitable for applications covering a large area so localized exploration is more suitable than remote exploration as it only depends on a single expensive underwater unmanned device or a limited underwater network. UWSNs acquire high costs for node deployment, maintenance, and recovery due to unpredictable undersea conditions, and utilizing compelling systems is very difficult [16].

3. Mathematical Modeling for Cong-Aware-Arcun

In UWSNs, the sensor nodes are considered the primary essentials for the data collection and its transmission to the surface sink. These nodes play a very important role in data communication. These underwater wireless sensor nodes are assembled into ward nodes and parent nodes. At first, the ward node delivered the packet to the parent node regarding the serving rate. The receiving data packet is then transported by the parent node towards the surface sink to the receiving rate.

In UWSNs, an *S* series of nodes contributes during data transmission. The data received from the high-priority ward node is forwarded by the parent node to the surface sink, giving optimized performance in UWSNs. Thus, the congestion in UWSNs is represented by the descriptions which are listed thereafter.

The standing priority of the parent node consists of the impression of data transported by the node towards the surface sink. The standing priority concerning ward node *c* is specified below given expression,

$$Sp_c = \boldsymbol{Id_c} \sum_{i=1}^{n} (\boldsymbol{DP_i})_c \qquad (3.1)$$

Here Id_c is the impression degree of the data stream of the ward node. The parameter $(DP_i)_c$ denotes the n[th] supply data priority concerning ward node *c*. Supply data priority is affected by the kind of sensors that are used by the ward node c.

The globular priority concerning the ward node depends on standing priority in addition to the transferred data stream. Globular priority concerning ward node c is provided by the formula given below,

$$Gp = Sp_c + Tp_c \qquad (3.2)$$

Here Sp_c represents the standing priority and Tp_c is the transferred data priority which describes the priority of the transferred data stream sent with the help of ward node *c*. During the transportation of data involving the parent node and the ward node, the data stream from the ward nodes is accepted by a veritable queue at the parent node. The veritable queue is aimed at holding the identical size of the parent node. Globular priority ratio concerning all veritable queues *v* is distinguished as,

$$(\boldsymbol{GpR_v})_c = \frac{Sp_c}{Gp} \text{ where } v=1, 2, 3\ldots \boldsymbol{Sp_c}+1 \qquad (3.3)$$

The ward node priority in UWSNs depends on the interval in each veritable queue and the capacity of the data stream. The ward priority *H* in the ward node *c* is presented thereafter.

$$(\boldsymbol{H_v})_c = \frac{(GpR_v)_c\,(1-(Z_v)_c).\overline{(Tw_v)_c}.\ \overline{(Dq_v)_c}}{\sum_{v=1}^{Sp_c+1}(GpR_v)_c\,(1-(Z_v)_c).\overline{(Tw_v)_c}.\ \overline{(Dq_v)_c}} \qquad (3.4)$$

Here Z indicates the congestion level, $\overline{(Tw_v)_c}$ indicates the average traffic capacity and $\overline{(Dq_v)_c}$ indicates the interval of each veritable queue *v* in the ward node *c*.

The below mathematical statements show the value of the median traffic capacity and the interval of each veritable queue *v* in the ward node *c*.

$\overline{(Tw_v)_c} = \frac{\sum_n y_n^k(c) DP_n}{\sum_n DP_n}$, Here $y_n^k(c)$ specify the supply priority *n* of the set of data packets in the veritable queue *v*.

$\overline{(Dq_v)_c} = \frac{\sum_n \bar{D}_n^k(c) DP_n}{\sum_n DP_n}$, concurrently $\bar{D}_n^k(c)$ specify the median packet interval of the *n* class in the veritable queue *v* at the ward node *c*.

During the data transmission, the probability of discarding packets at the parent node relies on the probability of incepted discarding packets and the reformation in the queue span. Hence when the packets are acknowledged by the parent node, it determines the probability of discarding packets at its end. It is represented by the mathematical statement shown below:

$$Pd = \lambda_1 . avl - \lambda_2 (1 - (\sum_{r=1}^{n} q_t / Z)) + Pi \qquad (3.5)$$

Here λ_1, λ_2 are the constant parameters, the mathematical statement $(1 - (\sum_{r=1}^{n} q_t / Z))$ represent the entire available capacity in the active queue. The *avl* shows the reformation in the queue span, q_t is the total span of the veritable queue and *Pi* is the incepted value for the discarding packets probability which is estimated by the given mathematical statement.

$$Pi = \begin{cases} q_v < \epsilon_1 . Z . N_v & 0 \\ \epsilon_1 . Z . N_v < q_v < \epsilon_2 . Z . N_v & \frac{q_v - \epsilon_1 . Z . N_v}{\epsilon_2 . Z . N_v - q_v - \epsilon_1 . Z . N_v} \\ q_v > \epsilon_2 . Z . N_v & 1 \end{cases}$$

With that, the non-metric priority of the ward node is represented by N_v and the lower and upper thresholds are represented by ϵ_1 and ϵ_2 .The formation in the queue span is calculated by the following mathematical statement.

$$avl = \frac{q_v^{rec} - q_v^{pre}}{Z . N_v}$$

Here q_v^{rec} depicts the value of veritable queues on the decline of the closing interval along with the opening of the new interval and q_v^{pre} represent the veritable queue's span value at the beginning of the closing interval. The probability of discarding packets will be reduced if the value of *avl* refers toward negation but if the divergence of the v^{th} veritable queue is affirmative then the value of *avl* will be affirmative.

The data packets at the parent node are either queued or discarded depending upon the incepted value for the probability of the discarding packet. If the packet is in the veritable queue, then the degree of congestion needss to be established to identify the intensity of congestion which will determine the essential circumstances to control the congestion in the network.

Congestion Interception in UWSNs

To identify the presence of congestion in UWSNs some attributes are required which will help in the interception of congestion in UWSNs. The congestion is intercepted according to the queue span which is then used to analyze the intensity of congestion to enhance the data transmission of the ward nodes.

Degree of Congestion

The degree of congestion describes the existence of a congested data stream in the ward node. It depends on the upper ϵ_1 and lower ϵ_2 threshold values. The degree of the congestion is determined according to the span of veritable queue Z. If the entire available capacity of the veritable queue is greater than the active queue span and the upper threshold value and similarly if it is greater than the active queue span and the lower threshold value then in both cases the existence of congestion is confirmed in the network. Similarly, both cases are represented by the mathematical statements below:

$$\sum_{r=1}^{n} q_v > Z . \epsilon_1 \quad ; \quad \sum_{r=1}^{n} q_v > Z . \epsilon_2$$

Intensity of Congestion

The intensity of congestion is to be determined in case the degree related to congestion validates the existence of congestion in UWSNs. The intensity of congestion in the network is calculated by using the intensity of congestion in the ward node in addition to the total number of sensor nodes in the UWSNs. To intercept the intensity of congestion in the ward node, a certain condition needs to be satisfied. The mathematical statement of such a condition is given below:

$$\frac{q_v}{Z . N_v} \geq 1$$

According to the given condition, the congestion in the network will occur if the proportion of the queue span and the increment concerning ward node priority along with the entire available queue's span is in-between the specified range. To determine the intensity of congestion in the ward node, the following mathematical statement is used, which is given below:

$$LC_v = \frac{q_v}{Z . N_v} - 1 \text{ ; else } LC_v = 0 \qquad (3.6)$$

To control the congestion in the network, the consumption of LC_v is mandatory for the rate customization. The intensity of congestion concerning the total number of sensor nodes is determined by the following equation:

$$mLC_v = \sum_{v=1}^{n} N_v . LC_v \quad (3.7)$$

The value of mLC_v allocates the available bandwidth in the node. The congestion occurs when the intensity of congestion concerning the total number of sensor nodes reaches beyond the threshold value for the ward node *c*. This is represented by the following equation.

$$mLC_v > 0$$

The value produced by mLC_v indicates the loss of data packets at ward node *c* due to congestion in the network. The deduction in the intensity of the congestion depends on the values produced by $LC_v$and mLC_v. Hence the available bandwidth of ward node c will decrease if the value of the intensity of congestion increases.

Attenuation in UWSN Channel

In UWSNs the propagation of sound waves is proximately at the rate of *c* =1500m/s. The energy of a sensor node is dissolved and twisted by noise when it accepts the transmission of waves. Here the attenuation function is represented by $A(D, F)$ where D is the distance of a channel that can be covered by a signal and *F* is the frequency of a signal. Both D and *F* have their own influence on the attenuation function. Thus, a received signal has an SNR which relies on the frequency concerning the communication signal. Here the SNR is denoted by $p(D, F)$ [21].

The main causes for a considerable attenuation in the UW acoustic channel are spreading loss and absorption loss. Attenuation in UW acoustic channel $A\ (D, F)$ is stated by Urick [17], [18] is depicted as

$$A(D,F) = A_0\ D^j\ a(F)^D\ , \quad (3.8)$$

Here A_o Showed a normalized fixed value and *j* here depicts a spreading aspect. The absorption factor $a(F)$ which is expressed in dB/km is represented by the formula given by Thorps as [19]

$$10 \log a(F) = \frac{0.11\ F^2}{1+F^2} + \frac{44\ F^2}{4400+F^2} + \frac{2.75\ F^2}{10^4} + 0.003 \quad (3.9)$$

Noise in UWSNs Channels

Data transmission in UWSNs is influenced by various factors including turbulence(T_n), shipping(P_n), waves $(W_n)$and thermal noise (M_n) that are presented by Gaussian analysis as depicted in [20],[21]

$$N(F) = T_n(F) + P_n(F) + W_n(F) + M_n(F) \quad (3.10)$$

Where

$$10 \log T_n(F) = 17 - 30 \log F\ ,$$

$$10 \log P_n(F) = 40 + \{\frac{40}{2}\ (s(\frac{1}{2}))\} + 26 \log F - 60 \log (F + 0.003),$$

$$10 \log W_n(F) = 50 + (\frac{15}{2})\sqrt{w} + 20 \log F - 40 \log (F + (\frac{40}{100})),$$

$$10 \log M_n(F) = -\ (\frac{30}{2}) + 20 \log F, \quad (3.11)$$

Where *s* is the shipping transition aspect which is in between 0 and 1 for low and high transition, respectively, and *w* is the wind speed ranging from 0 to 10 m/s.

SNR in UWSNs Channels

In UWSNs a signal of a limited band is perceived at distance *D* with a frequency *F*, bandwidth *b* [Hz], and transmitting power *p* [watts]. SNR feature of such signal at the receiver is represented by

$$\text{SNR}(D, F) = \rho(D, F) = \frac{p}{A(D,F) N(F) b} \quad (3.12)$$

Here the attenuation in the underwater channel is represented by $A(D,F)$ and the power spectrum of noise is denoted by $N(F)$[W/Hz]. There is an assumption that the channel will remain stabilized from noise interference for some coherent time due to Gaussian distribution. The upper bound of an efficiently transmitted signal over a communication link is represented by a channel capacity of an unlimited bandwidth Gaussian channel. It is represented by the Shannon-Hartley theorem [22][23]:

$$C(D,F) = b\log_2(1+\rho(D,F)) \quad (3.13)$$

Here the channel capacity is represented by $C(D,F)$ [bits/sec] which is influenced by both distance and frequency. In UWSNs a successful transmission of a signal over volatile channels is considered if the rate of data transmission *R* at every sensor node is lesser or equal to the channel capacity, then which is represented as

$$C(D,F) \geq R \quad (3.14)$$

The strength of an arriving signal can be evaluated at the receiving end by using the above clause. For different complex measures in wireless systems, the channel stability is estimated without any constraint [22]. Here T_d represents signals in underwater channels. Compared to radio signals, these underwater signals face more complex frequency and channel path loss which is indicated by [23]

$$T_d = 10\log_{10} d + 10^{-3}\,\alpha(F)\,d, \quad (3.15)$$

In wireless communication channels, the power consumed by transmitted signals concerning the source node towards the receiving node is represented by the first term in equation (5.15). Due to the mechanical characteristic of acoustic waves, the absorption of power of passing waves in underwater channels is affected which is represented by the second term in the above given equation [23]. Where as $\alpha(F)$ is related to the equation given in (5.9).

3.5. Cooperation Phase

In the cooperation phase, a non-overlapping communication is allowed by a dual-phase transmission strategy for the source node as well as the relay node. The entire phase of cooperation is completed in dual segments. In the first segment, the source node sends its data concurrently to the relay as well as the destination, while, in the second segment, the relay node *R* send the data to the destination node *D*, which it receives from the source node. Here d_1 represents the distance between a source node and the relay node and d_2 represents the distance between the relay node and the destination node. The data sent from the source node to the relay node as well as the destination node in the first segment can be represented by the following given equations [24]

$$y_{S_iR_i} = \sqrt{P_I}\,h_{S_iR_i}x_{S_i} + N_{S_iR_i}(F), \quad (3.16)$$
$$y_{S_iD_i} = \sqrt{P_I}\,h_{S_iD_i}x_{S_i} + N_{S_iD_i}(F),$$

Here P_I indicates source transmission power, x_{S_i} shows the transmitted stream of data from S_i. The attributes of the wireless channel from S_i to R_i is represented by $h_{S_iR_i}$ and from S_i to D_i is represented by $h_{S_iD_i}$. These coefficients with zero mean and variance σ^2 are formed as a composite Gaussian random variable expressed as G $\mathcal{N}$ $(0, \sigma^2)$. The variance of a link is represented as

$$\sigma = \eta\, d_{ij}^{-\alpha} \quad (3.17)$$

Where d_{ij} represents the nodes' distance from *i* to *j*, α here is the loss factor related to transmission, and η represent a constant value related to the UW environment. $N_{S_iR_i}$ from S_i to R_i and $N_{S_iD_i}$ from S_i to D_i are the noise factors established in the channels [24]. Their values in terms of the factors are represented in (5.10).

$$y_{R_iD_i} = \sqrt{P'_2}\,h_{R_iD_i}x'_{s_i} + N_{R_iD_i}(F) \quad (3.18)$$

Here P'_2=0 but if the transmitted symbol is received by the relay node accurately then P'_2 *is equal to* P_2. The signal which is received by the destination followed by the signal passing from link *S-R* and received at the destination node is x'_{s_i}.The noise components are represented as variance N_0 with zero-mean complex Gaussian random variables. h_{RD} is the link factor from R_i to D_i. The FRC technique is used at the destination D_i which merge the signals acknowledged from S_i and R_i. Here P represented the sum of transmission power represented by the equation below

$$P = P_1 + P_2$$

Relay Strategy

We are using the AF method instead of DF because it only retransmitted the received signal from S_i at relay R_i with amplify component β before passing it to the end node D which is represented by the following equation below

$$y_{RD} = \beta(y_{SR})$$

The component β can be written as [24]

$$\beta = \sqrt{\frac{P_r}{P_s\,|T_{d(SR)}|^2 + N(f)^2}}. \qquad (3.19)$$

Here the transmission powers at S and R are represented by P_s and P_r accordingly.

When we are considering energy then the transmission powers of S and R (5.19) can be denoted as

$$\beta = \sqrt{\frac{E_r}{P_s\,|T_{d(SR)}|^2 + N(f)^2 \cdot \Delta t}}. \qquad (3.20)$$

In the second phase when the signal is acknowledged at destination D then it is represented by the equation.

$$y_{RD} = \sqrt{P_2'}\, h_{RD} \beta x_S\, N_{RD}, \qquad (3.21)$$

Here P_2' is the transmission power from the relay to the destination. The characteristics of the communication link from source to destination are different from the link from relay to destination.

Congestion Strategy

In UWSNs the occurrence of congestion during data transmission among sensor nodes and surface sink is a great concern. Here the congestion strategy is based on Relay. Let us consider a network where S represents the sum of surface sink and sensor nodes which are categorized into parent nodes and ward nodes. Let c_x be the ward node, N_y be the parent node, and P_z represents data signals that are transferred from the ward node to the parent node. These sensor nodes are presented by mathematical statements below:

$$c_x = \{c_1, c_1 \dots c_j\}, \quad 1 \ll x \ll j$$

$$N_y = \{N_1, N_2 \dots P_k\}, \quad 1 \ll y \ll k$$

$$P_z = \{P_1, P_2 \dots P_i\}, \quad 1 \ll z \ll i$$

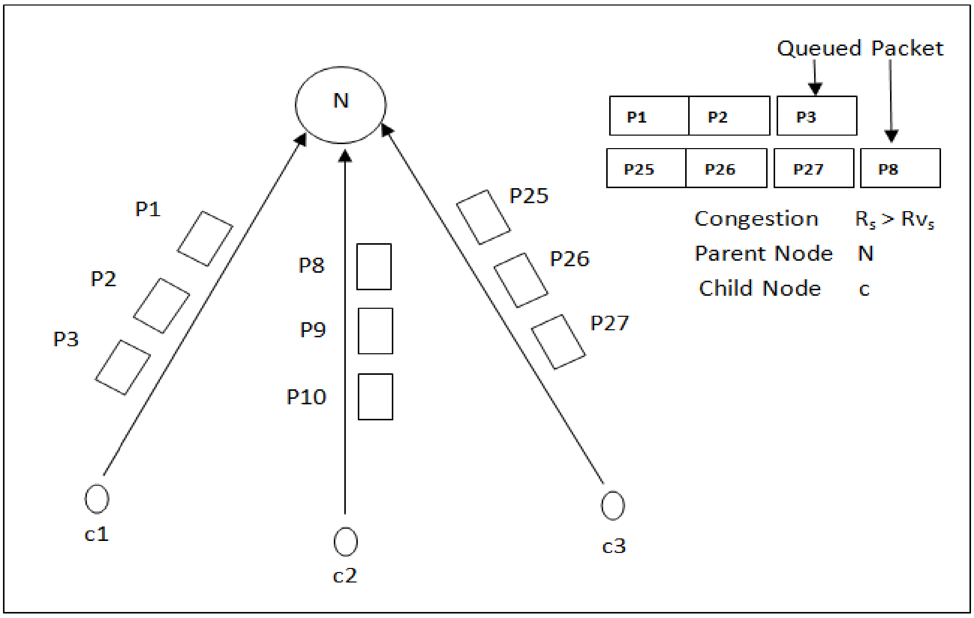

Figure 3: Congestion in UWSNs

Consider Rv_s represent the receiving rate concerning the parent node and R_s represent the sending rate concerning the ward node. Figure 4.1 shows the congestion as a result of variation between the sending rate concerning the ward node as well as the receiving rate concerning the parent node. If the receiving rate concerning the parent node is lower than the sending rate concerning the ward node subsequently the parent node will queue the data packets sent by the ward node which will lead to congestion in the network [25][26]. The major reason behind the occurrence of congestion is the reduction in the receiving rate of the parent node to the sending rate of packets from the ward node which is represented by $R_s > Rv_s$. The optimized rate customization minimizes the serving rate of the ward node due to which congestion is controlled in the network [27]. The presence of congestion in UWSNs is shown in **Figure 3** which is caused by the serving rate of the ward node which is much higher than the receiving rate of the parent node.

Signals Combination Strategy

During the cooperation technique destination node receives signals from both the source node and the relay node and they are combined at the destination with the help of a diversity combining technique. The FRC technique is functional at the destination and the arriving signals are adjusted with a fixed proportion along with adding the signals. FRC is indicated by the subsequent mathematical statement below in terms of a single relay node.

$$y_{d} = + g_1 y_{SD} + g_2 y_{RD}, \quad (3.22)$$

Where y_d indicates the output at end node D in the form of a combined signal. g_1 and g_2 are the taxes of both communication channels from source to relay and to destination. These taxes represent factors including transmission power and communication links. Their proportions are represented as [20]

$$\frac{g_1}{g_2} = \frac{\sqrt{P_1 h_{SD}}}{\sqrt{P_2' h_{RD}}} \quad (3.23)$$

The best possible estimation of the fixed proportions is two ratio one when using the AF technique [23], where

$$g_1 = \frac{\sqrt{P_1 h_{SD}}}{N_0}, \quad g_2 = \frac{\sqrt{P_2' h_{RD}}}{N_0} \quad (3.24)$$

4. Results and Discussions

In the present chapter, results based on different simulations of ARCUN and CONG-AWARE-ARCUN are obtained. Both protocols are measured using different parameters. Every plot in these simulations is evaluated in seconds in terms of time. During data transmission, the time acquired by the data packet to reach from the source node to the destination node is considered as a time slot. To evaluate the development of CONG-AWARE-ARCUN, it is differentiated from the extant scheme of ARCUN. In the simulation of 8000 rounds, up to 225 sensor nodes are positioned arbitrarily in the network ranging 500 meters × 500 meters with 10 sinks deployed on the water surface.

Performance Parameters: Definition

The following simulation parameters are considered for performance evaluation

Throughput

During data transmission from the source node to the destination node, the total number of successful data packets is termed throughput. It is measured as the number of successful packets in a given period.

Transmission loss

During data transmission from the source node to the destination node, the average packet loss in one round is called transmission loss. It is represented by decibels.

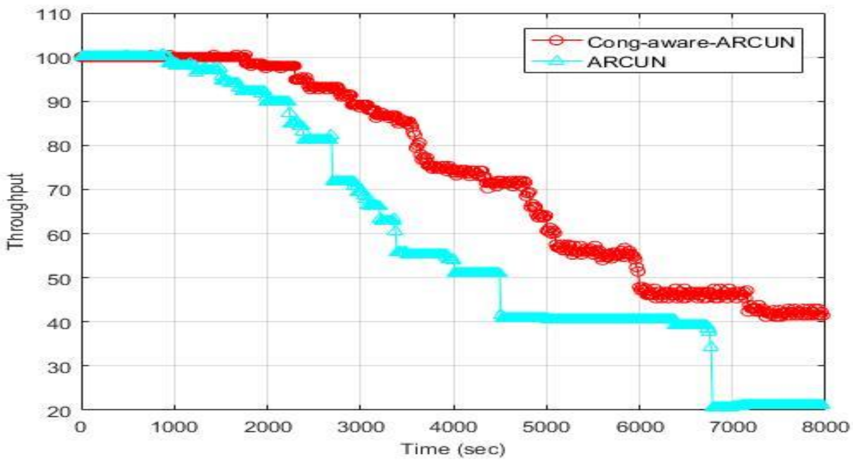

Figure 4: Throughput

End-to-End Delay

It is the time that a packet takes to reach from source node to the destination node with transmission delay factors. It is measured in seconds.

Energy Tax

It is the average energy consumed by sensor nodes during data transmission. It is measured in joule.

Number of Alive Nodes

These are the nodes that are active and capable of performing data transmission. They are measured in seconds.

Performance Parameters: Discussion

Throughput

Figure 5.1 clearly shows the improved performance of CONG-AWARE-ARCUN to its previous version ARCUN scheme is without congestion control. The packet delivery ratio of CONG-AWARE-ARCUN is 100% till round number 1500. **Figure 4.2** also depicts that the throughput decline of ARCUN very rapidly as compared to CONG-AWARE-ARCUN and at round number 7000 the throughput of ARCUN declined near to 15% while at this round CONG-AWARE-ARCUN has throughput about greater than 30%.

Transmission loss

Transmission loss is also called path loss i.e. loss of data during the transmission. **Figure 5** shows the transmission loss of CONG-AWARE-ARCUN as well as ARCUN. The outcome depicts that the transmission loss in CONG-

AWARE-ARCUN is enough smaller than the ARCUN. The Transmission loss of CONG-AWARE-ARCUN is nearly 80 while the transmission loss of ARCUN is almost 135 dB.

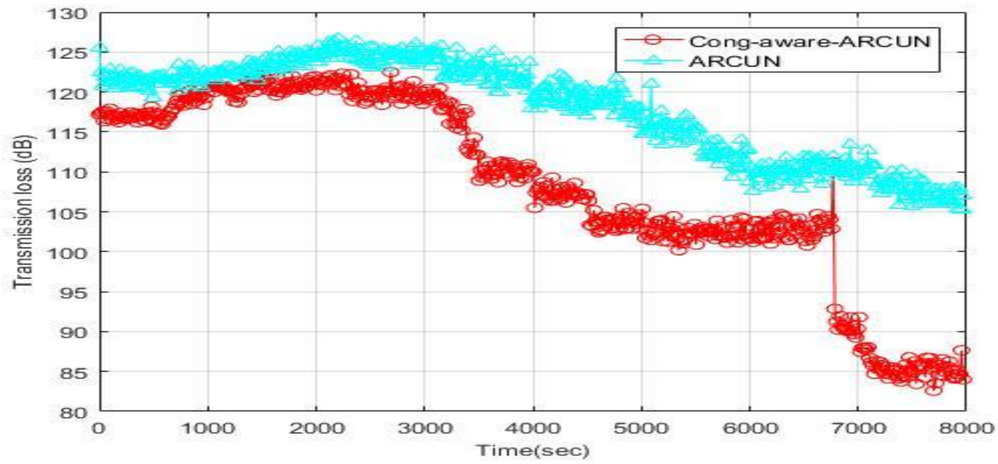

Figure 5: Transmission loss

End-to-End Delay

Reducing transmission delay is a significant feature to be considered in UWSN. **Figure 6** depicts that CONG-AWARE-ARCUN performance is improved than ARCUN. The figure shows that delay of CONG-AWARE-ARCUN is 38 at 1000 seconds and 3 at 7000 seconds while ARCUN is 75 at 1000 seconds and 28 at 7000 seconds. The availability of more than one surface sink in CONG-AWARE-ARCUN attains improved performance as every surface sink collects a limited amount of node data.

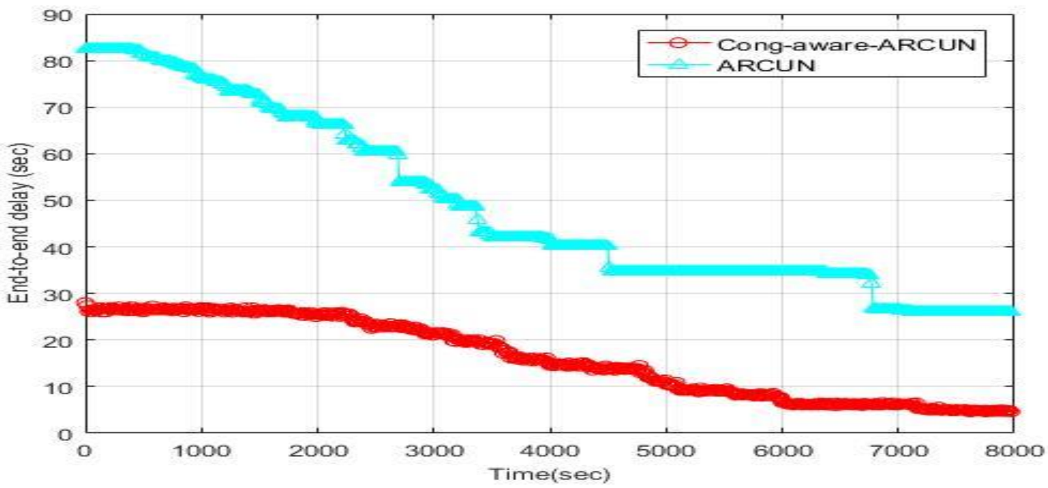

Figure 6: End-to-End Delay

Energy Tax

In **Figure 7** the energy tax is getting lower with the rise in network denseness for CONG-AWARE-ARCUN. The figure shows that the energy tax of CONG-AWARE-ARCUN is 35 at 1000 seconds and decreases to 17 at 7000 seconds while ARCUN is nearly 45 at 1000 seconds and decrease to almost 30 at 7000 seconds. ARCUN shows high energy consumption in a sparse network compared to CCCUWSN, as the mechanism of depth adjustment and continuous beaconing of nodes increase its energy consumption.

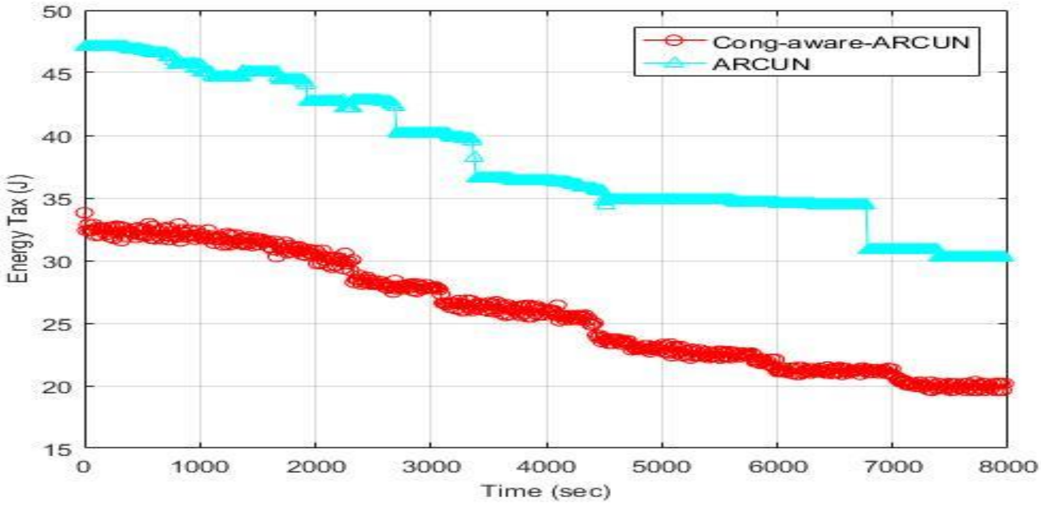

Figure 7: Energy Tax

Number of Alive Nodes

The comparison of the network lifetime of CONG-AWARE-ARCUN with ARCUN is depicted in **Figure 8**. The first node dies at round number 350 in ARCUN and then the nodes start to expire rapidly in every round. On the other hand in CONG-AWARE-ARCUN till 600 rounds all nodes are alive and then this expiration of nodes is increased but very slow. Hence for this reason at around 7000 in CONG-AWARE-ARCUN about 125 nodes are alive while at this round in ARCUN 118 nodes are alive.

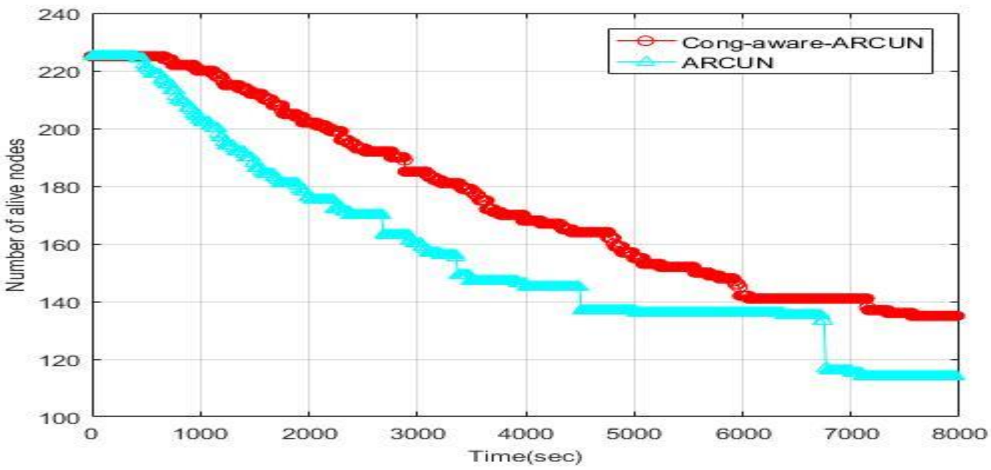

Figure 8: Number of Alive Nodes

5. Conclusion

Wireless Sensor Networks (WSNs) face various challenges based on their environment, particularly in Underwater Wireless Sensor Networks (UWSNs). UWSNs are deployed in challenging environments such as underwater, where data is transmitted from sensor nodes to Autonomous Underwater Vehicles (AUVs) via acoustic channels. The underwater environment, with high electromagnetic attenuation, makes communication via electromagnetic and optical waves impractical, whereas acoustic waves are the most viable option. UWSNs are designed to function autonomously over extended periods, operating without the need for recharging or repairs.

Due to the unique challenges of underwater communication, existing terrestrial communication protocols are not suitable for UWSNs, mainly due to issues like low bandwidth, high transmission delays, and limited node mobility. Acoustic modems, used for communication in UWSNs, operate with low bandwidth, resulting in longer transmission delays compared to terrestrial radio channels.

UWSNs have widespread applications in deep-sea monitoring, oil and gas industries, military surveillance, mine detection, and marine life monitoring. Despite significant progress, congestion remains a major issue in both WSNs and UWSNs, impacting network stability and performance. Several studies have proposed congestion control techniques and cooperative transmission protocols to enhance network efficiency.
This study aims to address congestion control in UWSNs through a cooperative approach, focusing on reducing data transmission loss and improving load balancing. The proposed routing protocol, CCCUSN (Congestion Control with Cooperation for UWSNs), integrates congestion control with cooperative techniques to enhance network stability. This study also includes an analysis of underwater acoustic channel characteristics, such as attenuation, propagation delay, and noise, and provides a mathematical evaluation of relay nodes and combining strategies at the sink.
The findings suggest that a cooperative approach combined with optimized rate customization can effectively address congestion in UWSNs, contributing to better network performance and stability.

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