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Shortest Propagation Delay-Based Relay Selection for Underwater Acoustic Sensor Networks

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ABSTRACT Underwater acoustic sensor networks (UASNs) have recently attracted considerable attention because of the numerous underwater applications. The propagation delay, however, is the most challenging factor for successful communication in UASNs. This article presents a cooperative communication scheme for reliable transmission in UASNs. To cope with packet collision caused due to propagation delay, we propose an adaptive control packet collision avoidance (ACP-CA) scheme to avoid collision of control packets during the communication channel reservation phase (CCRP). Moreover, to reduce a collision between data packets, we propose a relay selection scheme, called the shortest propagation delay-based relay selection (SPD-RS), to select the best relay node (R) for re-transmission in the data transmission phase (DTP). We evaluate the proposed scheme performance in terms of network throughput, average packet success rate, average packet drop rate, and latency. Compared to opportunistic cooperative diversity (OCD) and conventional medium access protocol (CMAP), the proposed scheme performs remarkably well by improving the network throughput and packet success rate, reducing the packet drop rate, and minimizing the latency.

INDEX TERMS Automatic repeat request, acoustic communication, cooperative networks, collision avoidance, relay nodes, reliable transmission, underwater wireless sensor network.

I. INTRODUCTION

Underwater acoustic sensor networks (UASNs) have recently attracted the attention because of the numerous underwater applications such as environmental monitoring, ocean sampling, undersea exploration, assisted navigation, and pollution monitoring [1], [2]. In UASNs, sensor nodes are deployed randomly over a designated geographic area. Sensor nodes can sense, gather, and convey data to the surface stations. Both academia and industry have been working towards the error-free transmission of the collected useful information transmitted by the sensor nodes to their corresponding surface station. A signal suffered from a bit error rate (BER) and long propagation delay in an underwater communication channel. Therefore, automatic repeat request (ARQ) [3] was adapted at the link layer to achieve reliable communication by re-transmitting the erroneous packet. In the ARQ, like stop and wait (S&W) protocol, the transmitter has to wait for the acknowledgment (ACK) after sending data packets to the receiver. In UASNs, the sink node collects data packets from the surrounding sensor nodes. The sink node transfers the gathered data to a buoy, which transmits the collected data to an onshore sink. The communication between the buoy and the sink node is through high-speed cable [4].

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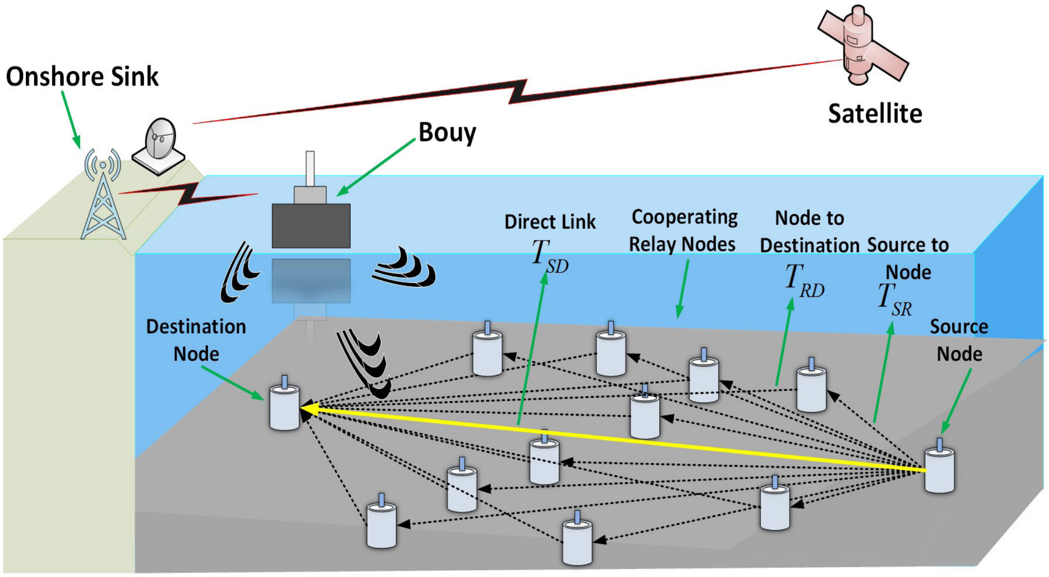

FIGURE 1. System layout of underwater sensor networks.

Wireless sensor networks over the terrestrial environment are also energy-limited scenarios as in UASNs [5]. The main difference between terrestrial and underwater communication is the transmission media [6]. Underwater, a signal travels with a sound speed, which is the dominant cause of long propagation delays [7]. In an underwater cooperative communication, a source node (S) collects surrounding data and transfer it to a destination node (D). Relay nodes (Rs) located between S and D can overhear the transmission of neighboring nodes [8]. Cooperative communication gives reliability and spatial diversity as it supports the transfer of independent copies of the original signal [9], [10]. The system model of the cooperative communication model shown in Fig. 1. In [11], the authors adopted the k-means algorithm for cluster sensor nodes and probability with specific conditions used to pick the cluster head. During the data packet transmission, each R increased the power (strength) of the signal. Additionally, R buffered the data packets for retransmission. The authors didn't consider any proper mechanism for the selection of cooperators (R). A cooperative routing algorithm has been proposed in [12], [13], in which the S wanted to transfer data packets. Different Rs (i.e., both routing relay and cooperating relay) are selected independently from their neighboring nodes based on time of arrival (ToA), signal-to-noise ratio (SNR), and their distances from the D. Moreover, no technique has been adopted to avoid collisions among control packets. Due to this, control packets from compatible relay nodes were discarded and unable to participate in the process of cooperation. In UASNs, cooperative communications can significantly increase spectrum efficiency and performance [12], as it enables efficient utilization of communication resources by allowing nodes to cooperate. Generally, cooperative communication is classified into the following categories: Proactive, Reactive, and Hybrid [14], [15]. If the cooperation process starts before a D receives a data packet, it indicates a proactive. When the D asks for retransmission from the Rs, it is named as a reactive. If both proactive and reactive are combined, it is called a hybrid. Based on the signaling method performed at R, cooperative communication is usually categorized into the following types of protocols: Decode-and-Forward (DF), Amplify-and-Forward (AF), and Compress-and-Forward (CF) [16].

In AF, R scales the signal according to its own transmit power and transmits it to the D in the next transmission slot. The S sends data to the D by using a direct path while R overhears the data packet, amplifies, and sends it to the D if re-transmission is required. In DF protocol, R decodes the source message from the received signal, then re-encodes it into a new codeword, and transmits in the upcoming transmission slot [14]. A random backoff timer has been widely used in the past to avoid collision among control and data packets [17]. The contention window (CW) based backoff timer is another useful approach employed in terrestrial networks for the collision avoidance [18].

A. RELATED WORKS

Former studies have introduced many cooperative mechanisms for underwater acoustic communication. In [19], the author proposed Secure Energy Efficient and Cooperative Routing (SEECR) for UASNs. In SEECR, two significant factors are energy efficiency and secrecy. The authors stated that the best R was utilized when the direct link between S and D was either unavailable or infeasible. However, the authors didn't consider collision avoidance techniques for control and data packets. In [20], a cooperative scheme was proposed, which was adjustable for different underwater conditions, to attain improved performance with minimum complexity for computation. Specifically, this technique adaptively changed the transmission power and modulation schemes and selected a proper mechanism for choosing Rs. The authors considered important physical parameters but did not consider the collision reduction technique caused due to the propagation delay of a sound wave. Moreover, the authors adopted an opportunistic R selection scheme that caused data packet collisions at D.

In [21], the authors proposed a relay selection scheme based on double indicators of depth and location of underwater wireless sensor nodes. Besides, the authors proposed a technique to minimize the network's end-to-end latency and improve energy efficiency. The authors selected Rs that lie nearest to D to reduce the packet retransmission time. Rs lie closest to D and far from the S lead to the worst link quality (S-R). Due to this, the data packet from the S couldn't receive successfully by R.

In [22], Liu *et al.* developed a proactive MAC cooperation called CoopMAC. The authors' proposed a rate adaptation technique in which S first determines whether data transfer through a high-capable cooperator (S–R–D) reduced latency compared to direct link transmission (S-D) or not. If the cooperator reduced latency, the S requests the cooperation mode rather than the IEEE 802.11 protocol. Each sensor node overheard the ongoing transmission of packets and occasionally updated a neighboring node table. The table stored the data rate of all the neighboring nodes. To keep up-to-date neighboring node table was challenging in the versatile underwater acoustic channel. CoopMAC applied the S&W ARQ, which indicated that the destination did not demand any participation from the Rs. Cooperative diversity multiple access and collision avoidance (CD-MACA) was proposed in [23], each R overheard the data packet, store it in a buffer and send it to the desired D after listening to CTS. It was reactive cooperation in which the independent copies of data packets lead to a collision at D.

In [24], Bletsas *et al.* proposed a distributed relay selection scheme that did not have any global topology in selecting a single relay. The authors used opportunistic relaying (OR) where each R could overhear RTS/CTS, deduced the channel quality, and derived a timeout time. Time-out was a backoff time used by the R to send the overheard data packet. Using this time, Rs could avoid collision between data packets at the D. In this scheme, D decoded the data packet successfully because it has independent copies of the data packets. In an energy-limited UASNs, it was insufficient to use because this scheme consumed a large amount of energy for sending and receiving multiple copies of a single data packet. In an underwater channel, it is hard to calculate the exact channel quality information. The incorrect time has settled due to improper channel quality information. This timer caused collisions of packets at the D. In [24], the transmission of packet lead to a collision when the timer of two or more Rs expired at the same time.

In [25], R estimated a channel gain between S and R by using the quality of signal received. Each R compared channel gain with a given threshold and checked whether to contribute to the process of cooperation or not. S removed all Rs whose link quality was inadequate. As the underwater channel is varying, so CSI information couldn't be appropriate to select the R. In [26], the R didn't listen to the channel all the time. Only the Rs, whose first link between the S and R was acceptable, remained active for the process of cooperation. If more than one Rs contributed to help, a collision occurred due to the propagation delay. At each R, the SNR of the two links were compared with a specific threshold. The cooperative communication needs to use the 3-way RTS-CTS-DATA handshaking methodology in attaining and distributing R information. Residual energy-based maximum effective communication range (reE-MECR) was proposed in [27], where sensor nodes controlled the consumption of energy adaptively at each hop. The effect of the collision caused due to a long propagation delay wasn't considered. In [28], the authors used the broadcast transmission capabilities of wireless sensor nodes and implemented an incremental routing using cooperation. Here, the authors selected R using the CSI information. The technique in which R selection depends on the CSI information is not appropriate in an underwater environment. In [29], the author proposed the scheme that utilized the information provided by a routing scheme at the system layer for the error-free delivery of the data packet. In [29], any collision avoidance techniques for control packets have not considered.

B. MOTIVATION AND OBJECTIVES

In the previous works, a precise relay selection scheme is not considered. Some techniques selected Rs that could lie either nearer to S or D. R nearest to either S or D is not the best R because one out of two links (S-R or R-D) could be large and erroneous. For the compatible Rs to participate in cooperation, we should adopt a concise packet collision reduction scheme. Moreover, we should use an explicit collision reduction scheme for the data packet.

The main objective of this article is to propose an efficient mechanism that improves the performance of UASNs. The system performance degrades due to collision caused by the propagation delay in an underwater channel. We need to ensure the successful transmission of control packets. Compatible Rs are unable to participate when the collision among the control packet is dominant. After avoiding collision and estimating compatible Rs, S needs to select Rs to reduce collision. As underwater channel states are ever-changing and intrinsic, it is impractical to perform channel variance estimation or achieve exact CSI, so propagation delay is utilized instead. In an underwater channel, the signal travels at the speed of sound and suffers from a long propagation delay. This delay problem causes a collision in both control and data packets. A backoff time is used before transmitting control packets to avoid the collision.

TABLE 1. Literature review.

Article	Collision avoidance (control packets)	Collision avoidance (data packets)	R-Selection	Remarks
[19]			✓	Techniques of collision avoidance for both control and data packets weren't adopted.
[20]			✓	Authors considered important physical parameters but did not consider the collision caused due to propagation delay.
[21]		✓		The authors selected Rs which are nearest to D in order to minimize the packet retransmission time. Actually, Rs lied nearest to D is far from the S which lead to a worst link quality (S-R).
[24]		✓		In an energy limited UASNs, it is insufficient to use because this scheme consumed large amount of energy for sending and receiving multiple copies of a single data packet.
[25]			✓	Collision avoidance methods for both control and data packets weren't considered.
[29]		✓	✓	No technique is adopted to avoid collision among the control packets.
Proposed scheme	✓	✓	✓	Both control and data packet collision is avoided successfully. Best R is selected by considering the severe characteristics of the underwater acoustic channel.

Collision among data packets has been avoided by selecting a single R for the retransmission.

In this article, we propose a reactive cooperative communication for the UASNs. Firstly, collision among control packets is avoided by using adaptive control packet collision avoidance (ACP-CA) in which each R adaptively chooses whether to use a backoff timer or not. After that, the S categorizes Rs and selects the single R by using shortest propagation delay-based relay selection (SPD-RS). S transmits the name of the selected R with the data packet to the D. If the data packet is erroneous, D asks for retransmission to the Rs by broadcasting not acknowledgment (NACK). Only selected R is available to receive NACK. The remaining Rs won't be available to accept NACK. After receiving NACK, the R transmits the buffered data packet to the D. If no Rs available, SPD-RS follows the conventional medium access protocol (CMAP) that uses 3-way RTS–CTS–DATA handshaking and occasionally supplements ACK without cooperation. The main contributions of this article can be summarized as follows:

- ACP-CA technique avoids collision between control packets. In this scheme, by using the distance difference with their neighboring nodes, each R checks whether to use a backoff timer or not. Rs that are expecting to use a backoff timer, calculate the value of CW according to the number of available neighboring nodes, and transmit RTC signal. After receiving RTC from Rs and CTS from D, S estimates the best R contributes to retransmission of data packet to D.
- In SPD-RS, S selects the best R by efficiently combining the propagation delay of two links; S-R and R-D. S transmits the data packet by adding the name of selected R to D. In the meantime, all the eligible Rs overhear and buffer the data packet for retransmission.

A list of acronyms and abbreviations used throughout this article is presented in Table 2. The rest of this article is organized as follows: In Section II, we summarize the system model. We present the proposed collision avoidance best relay node selection scheme (ACP-CA and SPD-RS) in Section III. Section IV evaluates the performance of the proposed work through simulations. Finally, we conclude this article in Section V.

TABLE 2. List of acronyms and abbreviations.

S	Source Node
D	Destination Node
R	Relay Node
RTS	Request To Send
CTS	Clear To Send
RTC	Ready To Cooperate
ACK	Acknowledgment
NACK	Not Acknowledgment
DF	Decode and Forward
CW	Contention Window
ACP-CA	Adaptive Control Packet Collision Avoidance
SPD-RS	Shortest Propagation Delay-based Relay Selection
CMAP	Conventional Medium Access Protocol
OCD	Opportunistic Cooperative Diversity

II. SYSTEM MODEL

The network layout of UASNs consists of an S, a D, and the number of Rs resides between the S and D. We assume that each node is static and fixed on a seabed and sensor nodes are equivalent in terms of physical specification and capability. Due to underwater channel characteristics, sensor nodes can not acquire timing synchronization. Through network initialization, all nodes obtain the propagation delay from/to one-hop distance sensor nodes. Each R uses a reactive type DF signaling strategy. We assume that error occurs in data packets only as control packets are small they are error-free.

Underwater acoustic channel as transmission media is complex and changeable, and the doppler effect arises due to the time-varying propagation of a transmitted signal [30]. The underwater acoustic signal suffers from severe multipath fading, high BER, long propagation delays, and high attenuation. The transmission loss in an underwater acoustic network depends on both the signal frequency and the distance between transmitter and receiver [31]–[34]. In UASNs, the signal travels at the speed of sound causing, collisions due to long propagation delays.

A. CHANNEL MODEL

An ever-changing property of acoustic channels causes path loss that depends on the signal frequency. This dependence is a consequence of absorption loss (i.e., transfer of acoustic energy into heat). In addition to the absorption loss, the loss in a signal which increases with distance is a spreading loss. The overall path loss is given by

$$A(d,f) = A_0 d^m \alpha(f)^t, \tag{1}$$

where m, A_0 and $\alpha(f)$ are the spreading factor, a unit normalizing constant, and the absorption coefficient, respectively. The transmission loss in decibels is calculated as

$$10 \log \frac{A(d,f)}{A_o} = m \cdot 10 \log d + d \cdot 10 \log \alpha(f). \tag{2}$$

In (2), first part denotes the spreading loss with spreading factor $m = 1.5$, and the second part signifies the absorption loss. Absorption coefficient occurs due to frequency of a signal and it can be represented empirically using Thorp's formula which expresses $\alpha(f)$ dB/m as a function of f kHz [35] as

$$\alpha(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{1400+f^2} + 2.75 \times 10^{-4} f^2 + 0.003. \tag{3}$$

For the successful transmission of data packets, it needs to be relayed somewhere between S and D. As path loss increase with distance, the number of a successfully received data packet at the destination becomes very limited. When the data packets are stored somewhere in the middle of two nodes, forward again to the destination if desired, it is the best possible way to transfer the data packet.

B. PROPAGATION DELAY

The time interval between the signal transmitted from the sender to receive at the receiver is known to be propagation delay. It depends on the distance between the sender and receiver and the speed of sound in the underwater environment [36]. The propagation delay that depends on distance d and speed c of sound (1500 m/s) is calculated as $\tau_{PD} = d/c$.

III. PROPOSED COOPERATIVE RELAY NODE SELECTION ALGORITHM

There are two phases in the proposed relay selection scheme; a communication channel reservation phase and a data transmission phase. In the first phase, a channel is reserved by exchanging control packets, and collision among these packets is avoided by using a proposed ACP-CA scheme. In ACP-CA, each R adaptively checks whether it's necessary to use a backoff timer or not. If R is unable to find neighboring nodes that could cause a collision, it transmits a control packet without a backoff timer. Otherwise, CW for backoff timer is calculated by considering the available number of neighboring Rs. Afterward, for data transmission, the best R is selected for the process of retransmission by using the propagation delay of two paths (S-R and R-D). In the second data transmission phase, the name of the chosen R is transmitted along with the data packet by S to D. If there is an error in the reception of the data packet, D asks the selected best R for retransmitting the data packet. When a single R transfers the data packet, D responds by sending ACK/NACK.

A. COMMUNICATION CHANNEL RESERVATION PHASE (CCRP)

In this phase, cooperation is enabled among D and S when they are well apart. Assuming the half-duplex constraint, in the first transmission phase, a request-to-send (RTS) control packet is transmitted to S, whereas, all neighboring nodes overhear RTS. Only sensor nodes that satisfy an index of merit-based on end-to-end propagation delay participate in cooperation. Specifically, relay nodes take part in cooperation if eligible for the process of retransmission. At the initialization time, each sensor node obtained the propagation delay to/from one hop distance neighboring nodes. After receiving RTS, i-th R ensures that the propagation delays i.e. S to R_i and R_i to D should be less than S to D propagation delay. Eligibility of each R is defined as whether the sensor nodes can take part in the process of cooperation or not, and it is calculated as

$$T_{SR_i} < T_{SD} \text{ and } T_{R_iD} < T_{SD}, \tag{4}$$

where T_{SD} shows the propagation delay of a direct path between S and D, T_{SR_i} and T_{R_iD} donate the propagation delay of an alternative path, i.e., S to R_i and R_i to D, where R_i is the i-th R between S and D. Sensor nodes are located around S and D but every node cannot play the role of R. Hence, each sensor node will check whether it is eligible to take part in the process of cooperation or not. Moreover, Eq. (4) shows that i-th R takes part in the cooperation only if it satisfy the condition, i.e., T_{SR_i} and T_{R_iD} should be less than the T_{SD}.

1) CONTROL PACKETS COLLISION AVOIDANCE

After validating eligibility, Rs transmit ready-to-cooperate (RTC) control packet to S. After checking the availability, D also transmits clear-to-send (CTS). At this moment, S is going to accept a large number of control packets both from Rs and D. As the number of control packets increases, the collision among them also increases. To cope with the collision aforementioned, we propose an ACP-CA mechanism in which each R performs adaptively, based on inequality measurement of (5). At first, each R calculates the propagation delay difference Δ_d with its neighboring Rs as

$$\begin{aligned}\Delta_d &= |D_{R_x} - D_{R_y}| \\ &= |(T_{SR_x} - T_{SR_y}) \times c| \geq \frac{N_{pkt}}{DR} \times c, \end{aligned} \tag{5}$$

where D_{R_x} and D_{R_y}, T_{SR_x} and T_{SR_y} are the distances and propagation delays of two Rs, respectively. N_{pkt} is the length of packet, and DR is the data rate in bps. If the distances of two Rs assure the inequality of (5), the two packets transmit by R_x and R_y at the same time reach at S without collision. In such case, R transmits control packet immediately without using any backoff timer.

Second, if R does not satisfy (5), it avoids collision by using a backoff time by waiting before the transmission of the control packet. A contention-based backoff timer technique is utilized in which each R calculates the backoff time for R to limit its access to the channel for a specific period. The main objective of this article is to develop an algorithm for the adaptive adjustment of CW according to the network condition. Fixed-CW algorithm ignores the network conditions while calculating the value of CW. However, the underwater channel does not guarantee success/failure, as the network load is unpredictable, and this extreme deviation in CW affects overall system performance. The proposed mechanism adaptively selects CW according to the network situation that dynamically reduces collisions between the control packets. For the calculation of CW, channel-state probabilities are calculated as important performance metrics such as, success probability $Pr_{\text{suc.}}$, collision probability $Pr_{\text{coll.}}$ and transmission probability Pr_{tran}. In order to calculate $Pr_{\text{coll.}}$, we assume that the total k neighboring nodes or at least one from the remaining $(k-1)$ Rs transmit at the same time. Collision probability is calculated as

$$Pr_{\text{coll.}} = 1 - (1 - P_{\text{CP}})^{k-1}, \tag{6}$$

where P_{CP} is a probability that R tries to transmit a control packet which can be calculated as

$$P_{\text{CP}} = \frac{2}{(c_{\text{win}} + 1)}. \tag{7}$$

where c_{win} is the contention window when R tries to transmit control packet. Pr_{tran} is calculated by considering at least one R attempting to transmit a control packet, and is given as

$$Pr_{\text{tran}} = 1 - (1 - P_{\text{CP}})^{k}. \tag{8}$$

If there is no transmission and channel is idle, Pr_{idle} can be calculated as

$$Pr_{\text{idle}} = 1 - Pr_{\text{tran}}, \tag{9}$$

The $Pr_{\text{suc.}}$ can be calculated when there is only one R transmitting with the similar distance in a given time. It can be calculated as

$$Pr_{\text{suc.}} = \frac{k \cdot P_{\text{CP}}(1 - P_{\text{CP}})^{k-1}}{1 - (1 - P_{\text{CP}})^{k}}. \tag{10}$$

Due to long propagation delays, S does not send ACK for control packets. Thus, time for collision and success depends only on time of control packet and propagation delay. These constant parameters of the network are calculated as

$$T_{\text{suc.}} = T_{CP} + T_{SR}, \tag{11}$$

$$T_{\text{coll.}} = T^{*}_{CP} + T_{SR}, \tag{12}$$

where T_{CP} and T^{*}_{CP} is the length of control packet and the length of longest control packet (in terms of time), respectively. In this article, it is assumed that all control packets are of same length $T^{*}_{CP} = T_{CP}$. The throughput for the control packet reception is the function of $Pr_{\text{suc.}}$, Pr_{idle}, and $Pr_{\text{coll.}}$ and are calculated in (13). For a given k, there is a specific CW which accomplishes the maximum throughput and avoid collision between the control packets. By using CW, we can initiate a backoff timer and limit transmission to avoid collision at the S. Now, we follow the similar procedure as in [37] to calculate the throughput (R) as

$$R = \frac{Pr_{\text{suc.}}.T_{CP}}{(1 - Pr_{\text{tran}})T_{\text{idle}} + Pr_{\text{suc.}}.T_{\text{suc.}} + Pr_{\text{coll.}}.T_{\text{coll.}}}, \tag{13}$$

where $Pr_{\text{suc.}}$ is the probability of success, $Pr_{\text{coll.}}$ is the collision probability, Pr_{tran} is the transmission probability and T_{idle}, $T_{\text{suc.}}$ and $T_{\text{coll.}}$ are the duration of idle, successful, and collision transmissions, respectively. Our target is to maximize the achievable throughput by increasing the success probability $Pr_{suc.}$ while reducing the collision probability $Pr_{coll.}$ and idle back of time T_{idle}.

Taking the derivative of (13) with respect to P_{CP} that results in (14), which is a function of CW [37].

$$\begin{aligned}&\frac{dR}{dP} \\ &= \frac{kP_{\text{CP}}(1 - P_{\text{CP}})^{k-1}T_{\text{suc.}}}{\begin{matrix}(1-P_{\text{CP}})^{k} \times (1-(1-P_{\text{CP}})^{k})T_{idle} + (kP_{\text{CP}}(1-P_{\text{CP}})^{k-1}) \\ T_{\text{suc.}} + (1 - (1 - P_{\text{CP}})^{k-1}) \times (1 - (1 - P_{\text{CP}})^{k})T_{coll.}\end{matrix}}.\end{aligned} \tag{14}$$

To obtain the optimal CW from (14), for the sake of brevity we omitted the detailed steps since there were in [37]. Thus, the optimal CW^{*} relation with the number of neighboring R is

$$CW^{*} = \left(\frac{CW_{\text{i}}}{2}\right) \times k - 1, \tag{15}$$

Here, CW^{*} is the optimal contention window for k number of neighboring Rs and CW_{i} is the minimum contention window. In this algorithm, each R has already acquired the neighbor Rs that have similar propagation delay (neighboring sensor nodes) and calculate $Pr_{\text{coll.}}$ using (6). Next, when each R receives an RTS signal, it determines CW^{*} using (15) and selects a backoff timer from the interval $[0, CW^{*} - 1]$. After waiting for a backoff time, each R transmits an RTC signal to S which determines the eligibility of a particular R. The collision among control packets from D and Rs perhaps occurs at the S if the R is nearest to D and enables retransmission. To avoid RTC-CTS collision, D first checks colliding

Algorithm 1 Communication Channel Reservation Phase

```
Function performed at relay nodes;
Eligibility check using: $T_{SR}$, $T_{RD}$ and $T_{SD}$;
for ( $j = 1$ : all relay nodes ) do
    if $T_{SR_jD} < T_{SD}$ then
        $R_j$ is eligible;
        if colliding neighbors then
            $R_j$ calculates $CW$ for backoff time;
            $R_j$ waits for timer;
            $R_j$ transmits $RTC$;
        else
            $R_j$ transmits $RTC$ without backoff timer;
        end
    else
        $R_j$ discarded $RTS$;
    end
end
Function performed at source nodes;
S Broadcasts $RTS$;
$T_{SR}$ and $T_{RD}$ Summation;
Select $R_i$ with $minimum(T_{SR} + T_{RD})$;
transmit $Data + R_i$ ;
Function performed at destination nodes;
if colliding neighbors then
    Calculates $CW$ for backoff time;
    Waits for timer;
    Transmits $CTS$;
else
    Transmits $CTS$ without backoff timer;
end
```

neighbors using (5). When a collision occurs, D estimates CW^* for the backoff timer before the transmission of the CTS control packet. Otherwise, D transmits CTS without any backoff time.

Generally, the propagation delay between R to D is unknown to the S at the time of initialization. When any R overhears the RTS signal, it transmits the RTC signal to the S. The RTC signal additionally contains the corresponding R to D propagation delay. Fig. 2 shows the overall procedure of the communication channel reservation phase. In the figure, R1 and R2 are far from each other and will not cause a collision. Thus, R1 and R2 transmit RTC packet without a backoff time, R3 and R4 can cause a collision at S, so RTC signal is transmitted after a backoff time.

2) BEST RELAY NODE SELECTION SCHEME

In the proposed scheme (SPD-RS), S selects the best single R to obtain the reliable transmission of the data packet. S already received RTC signals from all the eligible Rs. Thus, S generates a list of Rs and chooses the best R (single). R is selected by considering additional information of propagation delay transmitted with RTC by each R. R shared R-D propagation delay while S already knows S-R propagation delay. By combining these propagation delays, S estimates the alternative minimum propagation delay routing path for the data packet transmission as

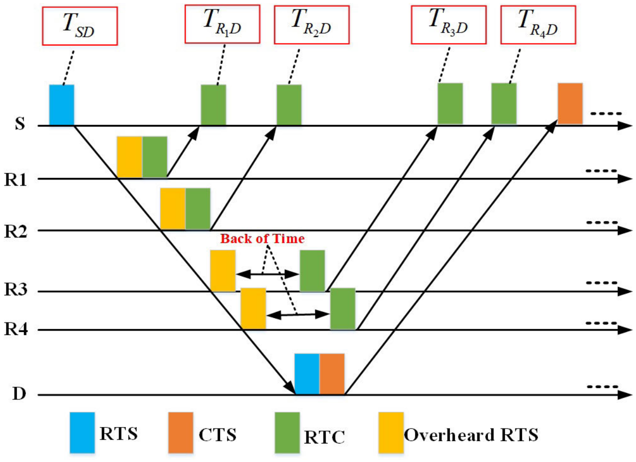

FIGURE 2. Communication channel reservation phase.

$$P(R_i) = \sum_{g=1}^{n} \tau_i, \tag{16}$$

where R_i indicates the eligible $i-th$ R available for cooperation, P is the summation of two paths for a particular R, and n is the number of routing paths. Here, (16) sums up the propagation delay of two links (S-R and R-D) that is why n is equal to 2. Some Rs are located nearest to either S or D. Special conditions are applied in (17) which eliminates all Rs that are nearest to either S or D.

$$L(R_i) = \begin{cases} \text{Discarded, if } T_{SR_i} < \frac{1}{4}T_{SD} \& \ T_{SR_i} > \frac{3}{4}T_{SD} \\ \text{Discarded, if } T_{R_iD} < \frac{1}{4}T_{SD} \& \ T_{R_iD} > \frac{3}{4}T_{SD} \\ P(R_i), \text{otherwise} \end{cases} \tag{17}$$

Here, the sum of propagation delays of those Rs nearest to either S or D is discarded. The sum of propagation delays of remaining Rs is added in $L(R_i)$. The Rs located at the exact midpoint of S and D is reasonable in fixed deployment only [38]. However, due to the random deployment of sensor nodes, the placement concluded in [38] cannot be the optimal solution for the proposed scenario. When we try to find R with minimum propagation delay, R could lie nearest to either S or D. In both cases, when R is close to S or D, it has the large T_{SR} or T_{RD}. Any lengthy path results in erroneous reception of data packets. Hence, the propagation delay is used for estimating the region where the best R could lie. Using (17), it is ensured that selected R must not lie nearest to S or D. All Rs that lies either nearest to S or D are discarded. Among the remaining available Rs, the shortest path is calculated as

$$RN^* = \min[L(R_i)], \tag{18}$$

where, RN^* is the selected R acts as an assistant to S for the reliable data packet transmission. The function performed by each node in CCRP is explained using Algorithm II. The total time interval for the communication channel reservation phase is computed as

$$T_{CCRP} = \begin{cases} 2\,T_{RTS} + 2\,T_{CTS} + T_{\text{backoff}} \\ +2\,T_{SD}, \text{ if backoff time is utilized} \\ 2\,T_{RTS} + 2\,T_{CTS} + 2\,T_{SD}, \text{ otherwise} \end{cases} \tag{19}$$

where, T_{CCRP} is total time period of communication channel reservation phase, T_{RTS} is the time interval of RTS control packet, T_{backoff} is backoff time, T_{CTS} is the time period of CTS control packet, and T_{SD} is the propagation delay between S and D.

B. DATA TRANSMISSION PHASE

In the data transmission phase, S transmits the data packet to the desired D. Before transmitting a data packet, S adds the additional information (name of selected R) for retransmission, when required. After sending the RTC control signal, each R remains active to receive a data packet from the S. R decodes the received data packet and finds the name of selected R (with shortest propagation delay) in the data packet. If the name of particular R is available, it keeps the data packet into a buffer otherwise discards, and goes to sleep mode. The function performed by each node in DTP is explained using Algorithm 2.

Algorithm 2 Data Transmission Phase

```
Function performed at source nodes;
S transmits $Data + R$ ;
Function performed at relay nodes;
$R$ decodes $Data + R$ ;
$R$ buffers $Data$;
Wait for control packet;
if $NACK$ received then
    Transmits $Data$;
end
if $ACK$ received then
    Discard $Data$;
end
Function performed at destination nodes;
Wait for $Data$;
if $Data$ is erroneous then
    Transmit $NACK$;
    if $Data$ is erroneous then
        continue;
    else
        Break;
    end
else
    Transmit $ACK$;
end
```

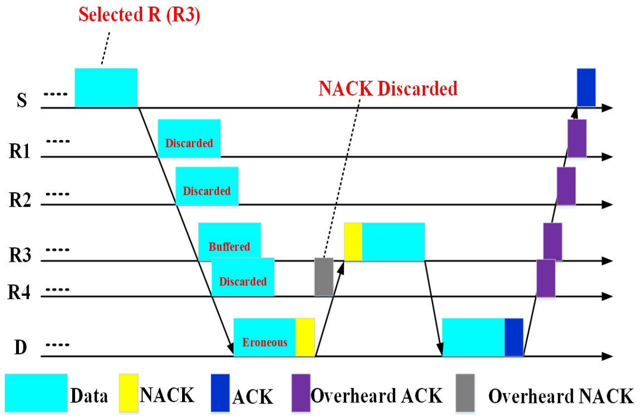

FIGURE 3. Data transmission phase.

If the received data packet at the D is erroneous, D broadcasts NACK. All Rs receive NACK but only selected R is available for accepting it. When the best R receives NACK, it transmits the data packet to D. After the successful reception of the data packet, D transmits ACK to S while R overhears it. The process of DTP is expressed in Fig. 3. The total time interval for the data transmission phase is given by

$$T_{DTP} = \begin{cases} 4T_{DP} + 2T_{NACK} + 2T_{ACK} \\ +2\,T_{DR^*} + 2\,T_{SD}, \text{ if erroneous} \\ 2T_{DP} + 2T_{ACK} + T_{SD}, \text{ otherwise} \end{cases} \tag{20}$$

where T_{DTP} is total time required for the data transmission phase, T_{DP} is the time interval of data packet, T_{ACK} and T_{NACK} are the ACK and NACK times, respectively. T_{DR^*} is the propagation delay between selected best R^* and D. Moreover, for r times retransmissions, the total time for data transmission phase is calculated as

$$T_{DTP\_r} = \begin{aligned} &(2+2r)T_{DP} + 2rT_{NACK} + 2T_{ACK} \\ &+2rT_{DR^*} + 2T_{SD} \end{aligned} \tag{21}$$

where T_{DTP_r} is the total time required for r number of retransmissions during the data transmission phase. The flow chart of communication channel reservation and data transmission phases is shown in Fig. 4.

IV. SIMULATION RESULTS

We randomly deployed 30 static sensor nodes. Each sensor node operates in a half-duplex mode and can result in a busy terminal problem [39]. We simulate the empirical underwater channel model for acoustic communication [33] to generate the underwater acoustic channel characteristics. Moreover, we have one hop cooperative communication that results in two communication links. As no error correction scheme is implemented, the data packet received even with a one-bit error is counted as an error, whereas, we assume that the control packets are error-free. We generated a data bit sequence and transmitted it through the underwater acoustic channel. Transmission/path loss and propagation delay cause errors in the data packet. If the received signal strength of the received signal is less than the pre-defined threshold, then the received packet is erroneous, and retransmission

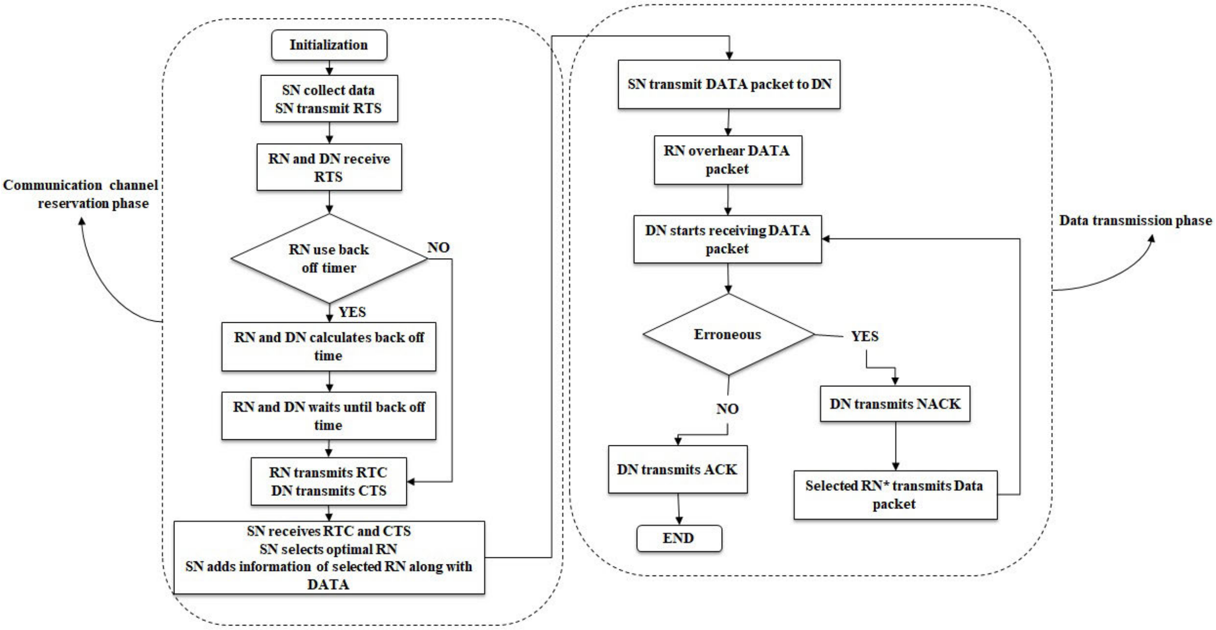

FIGURE 4. Flowchart of the proposed ACP-CA and SPD-RS scheme.

is required. The transmission loss (Path loss) and propagation loss is also considered to model a real-time underwater effect. Propagation delay is calculated based on distances between the nodes. Nodes are randomly deployed in a region, and the success and failure of transmission in a hop are determined by using channel characteristics. The data rate (2400 bps) and the transmission/receiving (Tx/Rx) powers (20W) considered here according to the specifications of the commercial Teledyne Benthos ATM-903 underwater modem. Each node generates data traffic that follows the Poisson arrival process with the rate λ. The arrival rate is the number of packet arrivals u per unit of time T that is expressed as

$$\text{Arrival-rate} = \frac{(\lambda T)^u \exp^{-\lambda T}}{u!}. \tag{22}$$

For opportunistic cooperative diversity (OCD), we consider that all the neighboring nodes act opportunistically, remain active, listen, and hold the packet for a particular time. After that period, all the sensor nodes transfer their buffered data to the D. Moreover, we set the R carries data packet time and the memory size to 40 s and 200 packets, respectively. CMAP is no cooperation scheme. It is a three-way mechanism where cooperation is not considered. We summarize the main network parameters in Table 3.

The performance of the jointly proposed ACP-CA and SPD-RS scheme for UASNs is evaluated using the performance matrices such as network throughput, average packet success rate, average packet drop rate, and latency. The metrics considered in this article are elaborated here. Network throughput: total number of bits in a packet successfully received by D over the time (t) in seconds.

TABLE 3. Key network parameters.

Parameters	Values
Network grid	1 km
Transmission power	20 W
Received power	756 mW
Control packet length	120 bits
Speed of sound	1500 m/s
Data rate	2400 bps

$$R_N = \frac{\sum_j \text{pkt}_j}{t}. \tag{23}$$

Average success rate: the average number of data packets successfully received at D out of total transmitted data packets.

$$\text{Succ\_rate} = \text{avg}\frac{\sum_j \text{pkt}_j}{\sum_l \text{pkt}_l}. \tag{24}$$

Average packet drop rate: the average number data packets dropped at the D out of total transmitted data packets, and is calculated as

$$\text{Drop\_rate} = 1 - \text{Succ\_rate}. \tag{25}$$

Latency: it is the time span between the time taken for the data packet generation and its successful reception at D. It can be calculated as

$$\text{Latency} = T_{SD} + T_d + T_{DTP_r}, \tag{26}$$

where T_d is the time required for the transmission of data packet and T_{SD} is the propagation delay between S to D, and

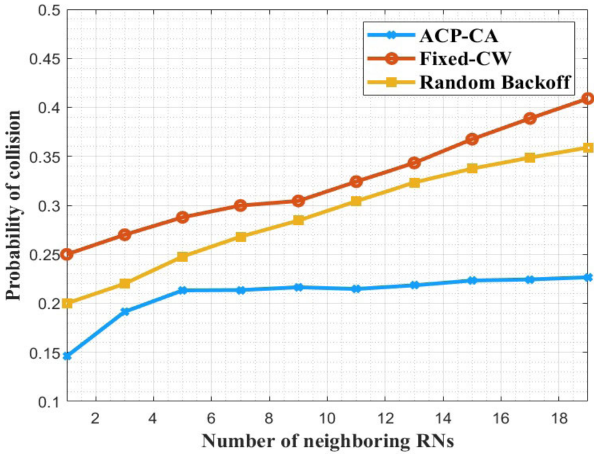

FIGURE 5. Collision probability vs. number of neighboring Rs.

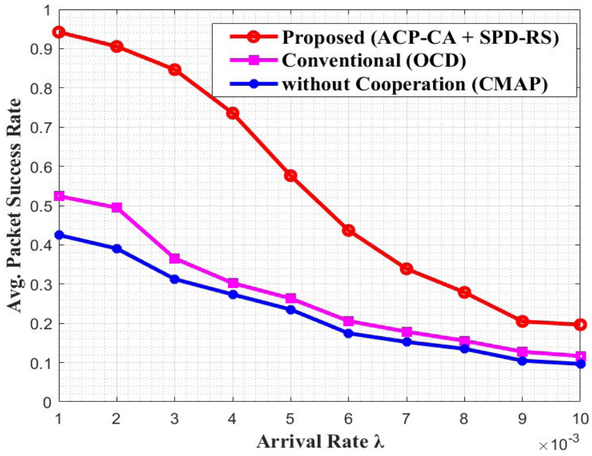

FIGURE 7. Average packet success rate vs. arrival rate.

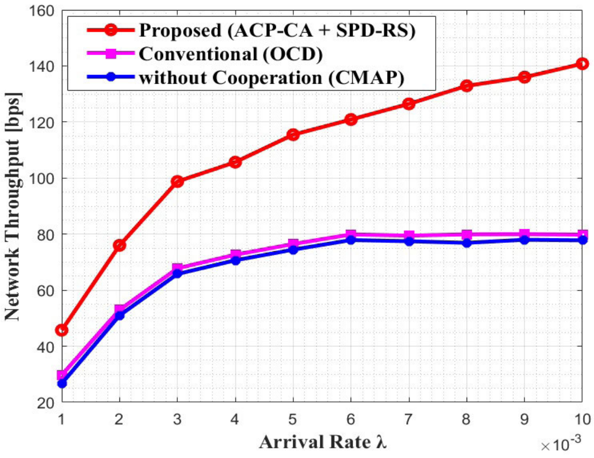

FIGURE 6. Network throughput vs. arrival rate.

T_{DTP_r} is retransmission indicator, and its value is zero when no retransmission is required.

Fig. 5 depicts the collision probability with a different number of neighboring Rs. Results indicate that the collision probability increases linearly with increasing the number of neighboring Rs. In ACP-CA, an adaptive backoff timer is utilized to decrease the collision of control packets at S. Results show that ACP-CA collision probability is not affected by increasing the neighboring Rs. For conventional fixed-CW backoff timer, the increase in the number of neighboring nodes increases the chances of a collision that results in the exponential flow of collision probability. Besides, the maximum collision probability is around 35% for the conventional fixed-CW, whereas, almost 30% for the random backoff. The graph of the proposed ACP-CA remains constant at around 20%. Fig. 6 demonstrates the network throughput performance of the proposed scheme by comparing it with the conventional OCD and CMAP schemes. The throughput performance of the proposed method is better than the conventional OCD and CMAP schemes. The maximum throughput of the proposed scheme is around 140 bps, whereas, for the OCD and CMAP schemes, the maximum throughput is around 80 bps and 78 bps, respectively. Hence, the proposed scheme achieves around 60% throughput improvement as compared to conventional schemes. The reason for this improvement is the best R selection using cooperative communication that ensures the reliable transmission of a data packet. CMAP is a non-cooperative scheme, if D receives an erroneous data packet, D transmits NACK directly to S, and in return, S retransmits the data packet. Unexpectedly network throughput of OCD is lower than the proposed scheme and almost similar to CMAP. The reason behind this drop is the collision at D when all the opportunistic Rs transfer the stored data packet and receive it at D simultaneously. Due to varying propagation delays, data packets collision in OCD occurred more often. Fig. 7 shows the average packet success rate for the proposed, conventional OCD, and non-cooperation CMAP schemes. The maximum packet success rate of the proposed scheme is 95%, whereas, for the conventional OCD and CMAP schemes, the maximum success rate is around 52% and 42%, respectively. The reason for the improvement in the proposed scheme is due to the efficient usage of backoff time for control packets that ensured the successful data reception at D via single R participation in data retransmission. However, in CMAP average success rate is declined because of no cooperation among the nodes shown in Fig 7. From Fig. 8, we can notice that the long source to destination distance causes unsuccessful reception of the data packet, and the average packet drop ratio is also increased in CMAP. In OCD, all Rs transmit at the same time causing more collisions of data packets. Due to this reason, OCD shows the maximum packet drop rate and increase exponentially as the arrival rate increase. In the proposed scheme, the average packet success rate shows the maximum outcome by comparing with OCD and CMAP. Moreover, the minimum packets are dropped in the proposed scheme due to fewer retransmissions, as shown in Fig. 8.

In CMAP, data retransmission is performed by S. Here, S transmits a data packet after some backoff time, to avoid

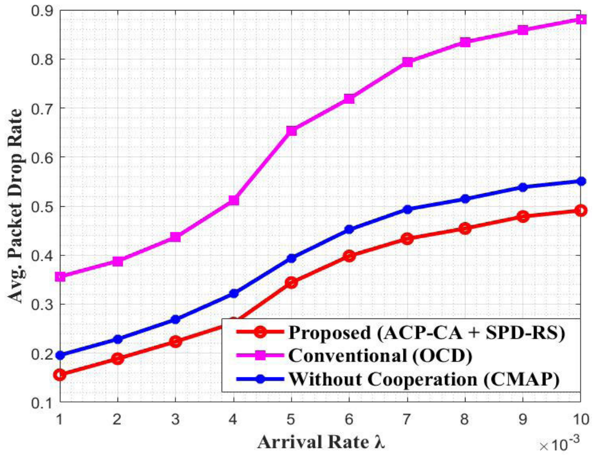

FIGURE 8. Average packet drop rate vs. arrival rate.

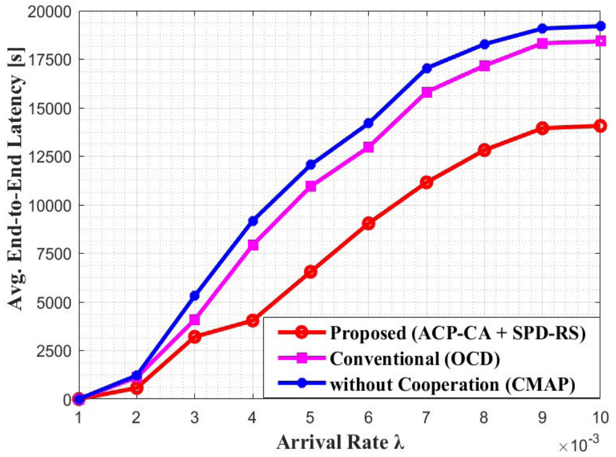

FIGURE 9. End-to-end latency vs. arrival rate.

the collision. This results in a large delay to successfully receive data packet at the D, which in turn increases the average end-to-end latency of a system as shown in Fig. 9. For OCD, as collision increases, *CW* for backoff timer used by the source, also increases resulting in an increase in latency. In the proposed scheme, to avoid control packet collision between neighboring Rs, an adaptive backoff timer is efficiently utilized. Moreover, D communicates with a single R for data retransmission, which mainly decreases data packet collision and latency, and increases system throughput.

V. CONCLUSION

This article proposes a cooperative relay selection scheme for reliable communication in UASNs. In an underwater environment, the cooperation between nodes is appeared to be beneficial. Each sensor node selects its cooperator for the process of retransmission. In UASNs, propagation delay results in a collision among the packets. When there is a need for cooperation, all the Rs try to contact S by sending control packets that cause a collision at S. To avoid collision of control packets send by Rs, the ACP-CA scheme performed remarkably well. In ACP-CA, Rs adaptively chose whether to use backoff time or not by comparing the distance between each neighboring node with the minimum threshold. If the distance is long, each R transmits the packet without backoff time. Otherwise, the *CW* based time is used in which the backoff time is selected wisely by using the information of available neighboring nodes. The collision of control packets is removed up to 20% by using ACP-CA. To avoid the collision of data packets, SPD-RS schemes are proposed in this article. This scheme has the capability to efficiently selects a single R by combining the propagation delay of two links (S-R and R-D), for the retransmission. This results in a significant improvement in network throughput, gain in the average packet success rate, a reduction in the average packet drop rate, and minimizing the latency compared to conventional OCD and CMAP schemes. Hence, both the ACP-CA and SPD-RS schemes act wisely by avoiding the collision of control packets and data packets effectively.

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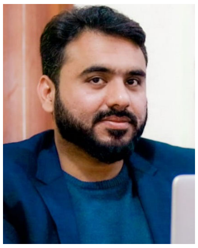

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