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Collaborative Channel Sensing Under S-Aloha for IoT Based CRSN

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Abstract — To reinforce the expected technological advancement of the Internet of Things (IoT) systems, a highly available, robust, and accessible communication technology will be required. Narrowband-IoT (NB-IoT) is one such radio-based technology developed to connect and control low-power autonomous devices. It is anticipated to concur with the presently used legacy Long-Term Evolution (LTE) standards as well as the imminent fifth-generation communication technologies. The key objective of NB-IoT is to enable immense machine-to-machine (M2M) communication among IoT devices that require low-power, low-throughput, and extended battery life. However, the bandwidth allocation for this technology is restricted between 180 kHz and 200 kHz and is not adequate to handle the explosive growth and development of the number of deployed devices in the NB-IoT systems. Besides, in an attempt to increase the coverage in the NB-IoT network, recent research studies have introduced the notion of retransmission. Since repeated transmissions guarantee coverage improvement but lead to radio resource wastage, the conventional bandwidth distribution techniques are not appropriate for the NB-IoT-based communication systems. Motivated by this research gap we integrate cognitive radio technology and NB-IoT to form Narrowband Cognitive IoT (NBC-IoT) network and we develop an Enhanced Random Access Protocol (ERAP) for this network. Our proposed ERAP exploits (i) a collaborative channel sensing technique to enhance the system throughput; and (ii) a collision-free reporting with dynamic admission control strategy to enable robust communication against packet collisions. The proposed protocol is implemented and its achievable performance is evaluated using the NS2 simulator. Numerical simulation results demonstrate that our proposed protocol considerably outdoes two existing protocols such as normal routing of IoT and slotted-ALOHA in terms of performance measures including throughput, packet delivery ratio, communication cost, transmission latency, and energy consumption.

Keywords *— collaborative channel sensing, collision-free reporting, S-ALOHA; NBC-IoT, random access*

Introduction

The continuous penetration of IoT is changing the fabric of our world more responsive and smarter by integrating the physical and digital universes. In the future IoT systems, billions of physical objects will be employed to enable assisted living, better-quality learning, intelligent transportation of materials/people, industrial automation, real-time environmental monitoring, process management, logistics, telemedicine facilities, etc. [1, 2]. In the last few years, several new terms related to IoT has popped up, for example, but not limited to, smart homes, smart cities, smart industry, smart agriculture, smart healthcare, and smart transportation. IoT is a vision for the forthcoming system to enable direct communication between devices. Without any human involvement, the device-to-device communication needs robust communication with limited radio resources including bandwidth, power, and computational overhead. To meet such a demand, the 3rd Generation Partnership Project (3GPP) projected the standardization of narrowband-IoT systems to enable a wide range of services [3].

NB-IoT is an evolving technology and expected to enable communication among IoT devices over a wide geographical area and difficult-to-reach places such as basements and deep indoors using constrained resources. According to the Grand View Research Inc. report, the international market size of NB-IoT https://www.grandviewresearch.com/industry-analysis/narrowband-nb-iot-marketis projected to touch US$ 6,020.2 million by the end of the year 2025,

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cataloging compounded annual growth rate of 55.4% from 2020 to 2025 [4]. The increasing demands for utilization of advanced technologies to track and monitor assets, vehicles, people, and smart energy meters precisely consistent with the smart city mission being undertaken worldwide is anticipated to bring aggressive growth of the NB-IoT market size. Other aspects, including ultra-low device costs, lower energy consumption, and lower latency sensitivity of applications are also anticipated to contribute toward the swift market's growth [5]. NB-IoT networks have attracted a renewed interest from leading manufacturing industries such as Nokia, Ericsson, and Huawei in developing and implementing technical standards [6]. NB-IoT has been widely considered as a core concept for future communication systems.

NB-IoT devices use licensed cellular spectrum and guarantee reliable and protected communication to end-users. However, the terrific growth of IoT devices and heterogeneous data flow pose significant challenges to the existing communication system since a lot of devices strive to access the shared medium simultaneously [7]. Furthermore, the network traffic in IoT systems comprises data and control packets that are vulnerable to extreme collisions. Obviously, it is very hard to allocate radio resources for every single transmission of the NB-IoT network to handle the explosive growth and development of the number of deployed devices of the NB-IoT system. Besides, in an attempt to increase the coverage of such a network, recent research studies have developed the notion of retransmission. Since retransmissions guarantee coverage improvement but lead to radio resource wastage, the conventional bandwidth allocation techniques are not apt for the NB-IoT systems.

The Cognitive Radio (CR) is the best candidate technology widely used to alleviate the potential frequency spectrum scarcity by improving the utilization of channel [8]. The CR attains the objective by sensing the radio environment efficiently, finding the white spaces or spectrum holes (i.e. idle licensed channel) dynamically, and exploiting this idle portion of spectrum proficiently [9]. Subsequently, the data can be transferred on this selected channel while guaranteeing an interference with licensed users is lower than a presumed threshold constraint. For this reason, we integrate the concept of CR technology with NB-IoT to develop a narrowband cognitive IoT network.

This work investigates the reimbursements of merging NB-IoT with CR technology and a random access medium access control protocol. More precisely, we consider a slotted ALOHA (S-ALOHA) protocol where smart objects can access the unused spectrum dynamically using the sensing process [10]. As opposed to focusing on evaluating the effectiveness of various detecting methods from a single user's point of view as in [11], we evaluate the performance of the NBC-IoT system under the system level interference limitations to the licensed subscribers of the channel. In this work, we implement Collaborative Channel Sensing (CCS) with simple energy detectors to sense the unused spectrum. Additionally, we investigate the correlation between the status of the communication channel and the strategy used to sense. We demonstrate that CCS is used under stringent detecting scenarios with a lower signal-to-noise ratio. As far as we know, we perform the first complete study on the effectiveness of a random channel access-based NBC-IoT system with various spectrum detecting strategies. The contributions made in this work are three-fold:

- We integrate the concepts of NBC-IoT system and S-ALOHA protocol where dynamic spectrum allocation is achieved;
- We devise an enhanced random access protocol that exploits a collaborative channel sensing technique and a collision-free reporting strategy to enhance the system throughput and to enable robust communication against packet collisions.
- We assess our proposed ERAP extensively against two existing protocols.

The article is structured as follows: The following section provides basic concept of collaborative channel sensing in the NBC-IoT network. In Section 3, we explain our proposed model. In Section 4, we discuss different operating phases related to the collaborative channel sensing process. We discuss our simulation results in Section 5. In Section 6, we conclude our article.

Revisiting Collaborative Channel Sensing

In the NBC-IoT sensor network, there are the paid subscribers for the network services and coined as Licensed Users (LUs). They are having access privileges to the radio resources. Conversely, CR users (CRUs), have cognitive radio capabilities. They have the aptitude to detect the radio environment for accessibility of idle frequency spectrums. They request the LUs to utilize these idle bands for data transmission. LUs have more priority than CRUs. The CR users utilize the channel in such a way that they do not lead interference to licensed users. Channel detection is a vital process in cognitive radio technology, which provides the CRUs to sense the existence of licensed users and to detect whether the assigned spectrum is utilized currently or not [12]. To further increase the performance of the sensing process and cope with the well-known hidden terminal problem, collaborative channel sensing is introduced.

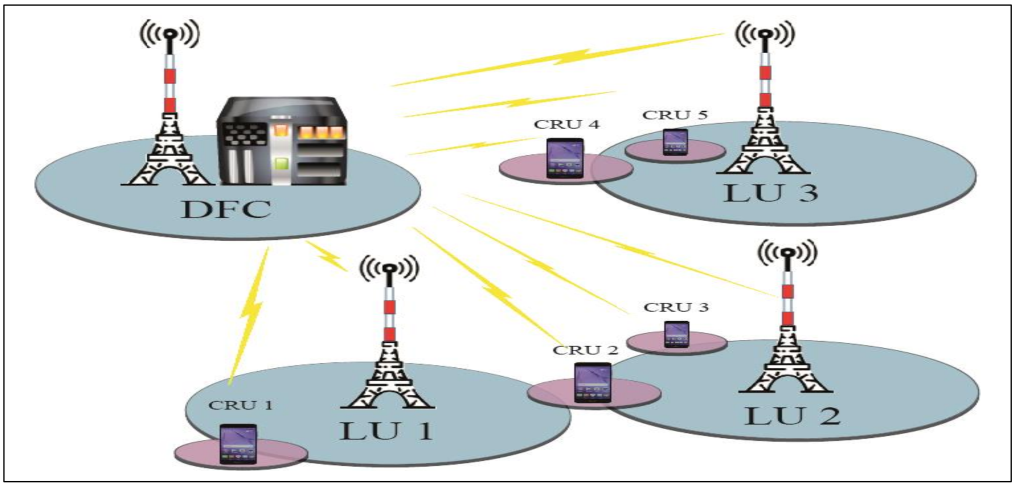

Fig 1: Collaborative channel detection in NBC-IoT network

In collaborative channel sensing, CRUs send their sensed information to the data fusion center (DFC). After that, DFC fuses all gathered information from multiple CRUs and finds out the existence of current transmissions of the licensed user using fusion rules [13, 14]. The tradeoff between reducing interference to LUs and improving the throughput of CRUs is of great significance for collaborative sensing in NBC-IoT. Figure 1 depicts the architecture of collaborative channel sensing in the NBC-IoT network. The basic operations of CCS are organized in three phases: sensing, reporting, and transmission. The CRU has the cognitive function to detect channel, sense the unused frequency band and opportunistic access it. It senses the LUs' spectrum, determines unused band, and transmits its sensing information to DFC. Since the LUs have a more priority to utilize the assigned frequency band, the CRUs need to relinquish the authorized spectrum immediately when LUs reclaim the spectrum and seek new idle band without any interference to LUs. On the other hand, a single CRU usually cannot provide an accurate judgment whether the LUs are absent or present, owing to limited capacity, shadowing and multipath fading. The CCS with collaboration among multiple users can efficiently overcome the limitations of single-user channel detection to increase sensing performance as well as reduce energy consumption.

In recent times, the real-time implementation of collaborative channel sensing has captured much more global attention with a vision of enabling communication among physical devices over the internet at an unprecedented scale [15]. In order to handle this problem, two elementary issues must be taken into account: (i) to form the reporting channel (RCH) between the CRUs and DFC, (ii) to manage the multiple access issues while the CRUs are using the common RCH. In order to address the first issue, the majority of the earlier studies consider that there are dedicated RCH between CRUs and the data fusion center [16, 17]. Few research studies exploit the identified unused bands to send the sensed information [18], which may lead to extra interference to LUs in the reporting phase. In our work, we consider the dedicated RCH-based reporting protocol design.

In order to address the second issue, an efficient medium access control (MAC) protocol is essential to schedule transmissions. The existing MAC protocols used in CR-based sensor networks can be divided into three types: fixed Time-division multiple access (TDMA) [17, 19], random access [16, 20], and hybrid access [21, 22]. In fixed TDMA, where every device connected in the network is provided with an exclusive time slot (which is allocated by system administrators) to send its sensed information, the DFC will always effectively collect those results from the users. However, fixed TDMA scheduling cannot adopt the variation in network size regarding the number of CRUs.

ALOHA is a simple random access MAC protocol extensively employed in CR-based sensor networks. It has many expedient characteristics to create them viable entrants for contention based channel access in NBC-IoT networks. First, it does not exploit the channel bandwidth continuously[31]. Next, it does not need a control spectrum. Moreover, ALOHA is a protocol with minimum overhead and requires sparse communication devices. Finally, it has been demonstrated to perform better to enable a low-power communication which is an important prerequisite for low-cost as well as the low-data rate NBC-IoT communications. S-ALOHA protocol is an enhancement of the classical ALOHA which introduced discrete timeslots and data can be transmitted only at the commencement of every slot [32].

However, using the S-ALOHA will persuade some packet collisions at the DFC since all the devices decide to send their sensing information in the same time slot with a probability. In data communication systems, where the data packet must be delivered effectively, employing the TDMA protocol realizes a greater throughput than that of implementing the S-ALOHA[33]. On the other hand, in distributed sensing when only uncensored decisions will be transmitted to the DFC who can identify the collisions and use them in making a decision, it is thought-provoking to determine when the S-ALOHA-based distributed sensing outdoes the TDMA protocol based distributed sensing [34].

Recently, a collaborative channel sensing with a two-phase reporting mechanism is proposed, namely the dedicated reporting phase and contention-based reporting phase. In this hybrid accessing mechanism, TDMA is used to achieve a dedicated reporting phase and S-ALOHA is used to realize contention-based reporting [22][36]. Conversely, multiple dedicated RCHs are also considered in some research works, which may lead to a higher communication cost. Lee introduced a dynamic random access reporting mechanism in a CR network. In this work, the collection period is determined by resolving a finite-horizon decision problem [15]. Ahmed et al. proposed a decision-based collaborative channel detection method through random medium access in the reporting phase [20][35]. Alhamad et al. proposed two different reporting protocols including reserved-ALOHA (R-ALOHA) and S-ALOHA.

Besides, the impact of detention is also taken into account for evaluating the medium access control techniques [16][37]. Nevertheless, the unavoidable collisions in random access protocols (more than one CRU sends their sensed results at a time slot simultaneously) may reduce the performance of the sensing process. Besides, as the information is transmitted after the sensing phase, the reporting collisions will result in higher energy consumption and reduce the performance of collaborative sensing. Therefore, an efficient reporting method is required to avoid reporting collisions. In this work, we consider the S-ALOHA protocol with a collaborative channel sensing mechanism. We propose an ERAP with collision-free reporting and a dynamic admission control strategy to increase the network throughput while eliminating reporting collisions. Specifically, we analyze the basic trade-off between our proposed channel detection strategy and achievable performance measures in NBC-IoT networks.

System Model

We consider a NBC-IoT communication network that contains several CRUs within a one-hop area and a DFC. The CRUs and DFC cooperatively sense the existence of LUs. It is also assumed that our network model consists of a Reporting Channel (RCH) and a data Transmission Channel (TCH) [23]. The reporting channel is devoted to the CRUs and DFC, which is free from the interference of LUs. The utilization of a dedicated channel for exchanging control information is a generally recognized technique in cognitive radio networks [15, 16, 22, 23]. Each CRU tries to sense the existence of the LUs on the TCH by individual sensing and then transfers their sensed information to the DFC using the RCH. We assume each CRU has an equal probability of sensing (ρ_s) and false alarm (ρ_f) [24]. It is also considered that the DFC uses hard fusion rules to make the ultimate decision [25]. However, soft decision-based fusion is also appropriate to implement in the proposed ERAP.

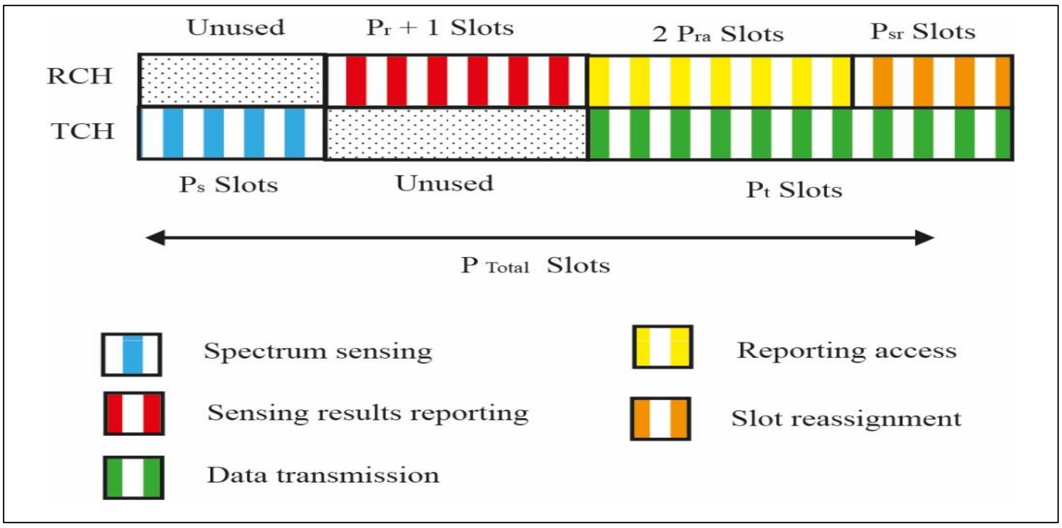

Fig 2: Frame structure of reporting and transmission channels of NBC-IoT system

Figure 2 depicts the frame format of RCH and TCH of the proposed network model. Every frame is composed of three sections: sensing duration with P_s slots, reporting duration with P_r slots, and transmission duration with P_t slots. It is noteworthy that there are P_{Total} slots ($P_{Total} = P_s + P_r + 1 + P_t$) in one frame. There will be a single bit of reporting information used by DFC to inform its decision. In addition, two new phases such as reporting access ($2P_{ra}\ slots$) and slot reassignment ($P_{sr}\ slots$) are included in the reporting channel to avoid collisions in multiple access reporting. The currently arriving CRU attempts to hold the reporting duration in the subsequent frame using the reporting access phase (RAP). Consequently, collision-free reporting is achieved.

The reporting access Request to Send (RTS_{RA}) and a reporting access Clear to Send (CTS_{RA}) control signals are employed in RAP. Therefore, two slots are used as access slots. To capture the dynamic nature of the communication system when the size of the network varies with number of CRUs, the unused reporting slots will be reallocated by implementing reporting slot reassignment (RSR) procedure. To be precise, if any reporting duration remains unused for a certain number of frames, the DFC reassigns those slots to other newly joining CRUs. Hence, the effectiveness of the reporting process is preserved. Also, as we concentrate on the collaborative reporting problem in this work, we consider that P_s is predefined and its length is sufficient enough to obtain better spectrum detecting enactment. Since P_r is varied with the number of reporting CRUs, for our convenience, we assume $M = P_r + 1 + P_t$, $N = P_{Total} - (1 + P_t)$, and $M < N$. Each phase of our ERAP is discussed in the following section.

Enhanced Random Access Protocol

Collaborative channel sensing is extensively explored in CR-based communication systems to enhance the performance of the channel sensing mechanism. In order to address both the deprived scalability issues in conventional TDMA protocols and the reporting collision issues in basic S-ALOHA protocols, we propose an enhanced random access protocol for NBC-IoT sensor networks. The proposed ERAP exploits a collaborative spectrum sensing technique to enhance the system throughput and a two-phase hybrid reporting access phase with a dynamic admission control technique to provide collision-free reporting and dynamic slot reallocation.

In ERAP, initially the CRUs join to S-ALOHA process before entering into the channel sensing phase. Then, the DFC assigns the dedicated reporting durations to the winners. Later, the winners will transmit the sensed information without any collision in the subsequent frames. If any allocated reporting slot is unused, it will be automatically reallocated by the DFC. The benefit of the suggested ERAP comprises (i) Collision-free reporting is achieved, which may increase the performance of the sensing process as well as throughput, and reduce the energy consumption of the sensing process. (ii) It can capture the fluctuations in network size using hybrid RAP and RSR strategies. (iii) It supports the DFC to implement an admission control technique for CRUs based on various performance measures, which further improves the performance of accessing protocol.

4.1 Sensing phase

During the initial MAC frame of the communication, as no CRU reserves any reporting duration, the entire frame will be assigned as an opening RAP with $\left\lfloor \frac{P_{Total}}{2} \right\rfloor$ slots. Any CRU who desires to connect the network and collaborative spectrum sensing can randomly select a slot and send an RTS_{RA} control signal using that slot. If a slot is selected by only one CRU, the RTS_{RA} will be effectively transmitted to DFC and the DFC will send a CTS_{RA} control signal to the corresponding CRU. The CTS_{RA} contains the reporting slot index that can be employed by the CRU in the subsequent frames. If CTS_{RA} is received by a CRU effectively, the CRU will participate in collaborative sensing in the subsequent frame. We name the CRUs who will participate in the collaborative sensing process as sensing CR users (SCRUs).

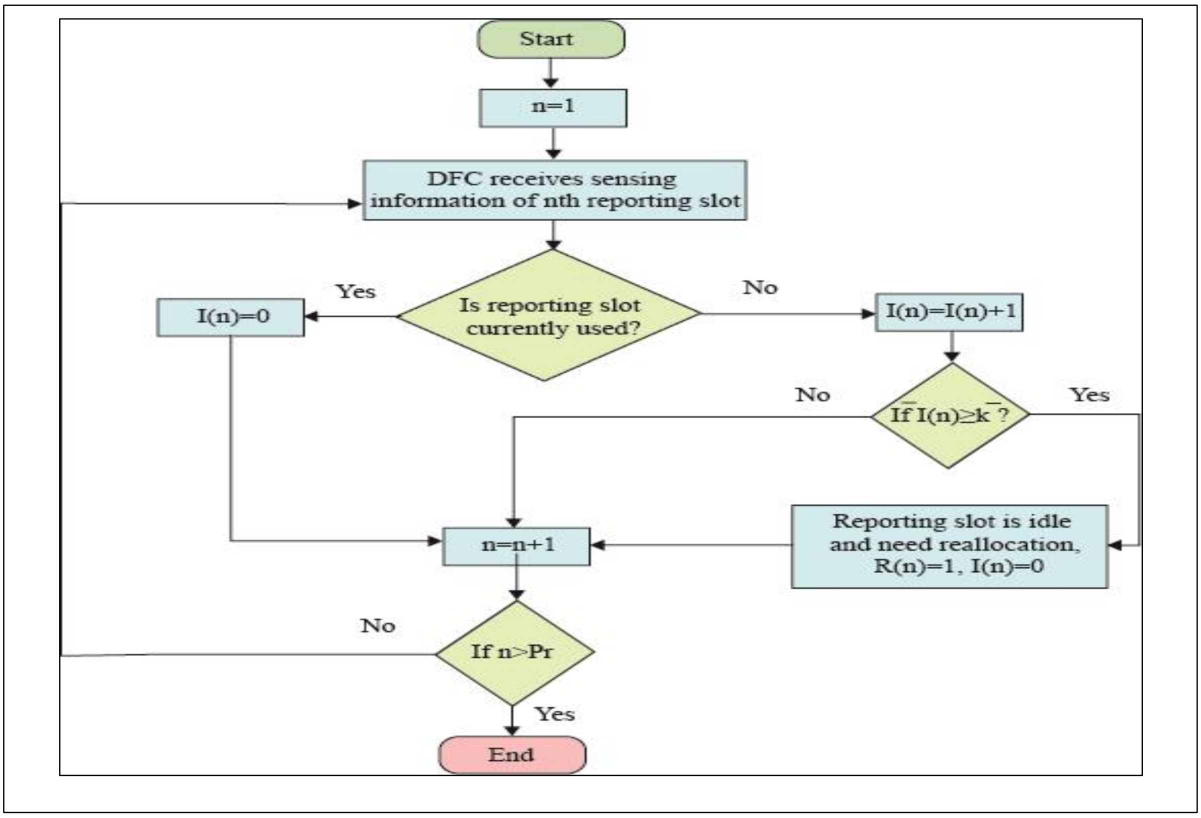

Fig 3: RTS_{RA}/CTS_{RA} handshaking between CRU and DFC

4.2 Reporting phase

After collecting the channel state information in the detection process, each SCRU selects a reporting duration which is allocated in the previous frames and then transmits the sensed results to DFC. After collecting all the channel state information, DFC makes an ultimate decision by implementing an appropriate fusion rule and sends this decision during the completion of the reporting process [24]. Also, if LU is found inactive in the ultimate decision, DFC will send a channel assignment frame to the SCRUs in a sequential fashion. In this manner, collision-free reporting is achieved.

4.3 Data transmission phase

The SCRU, who has gained a channel assignment frame during the completion of the reporting process from DFC, will be assigned to the unused spectrum of the licensed user and send its data packets in this phase.

4.4 Reporting access phase

This phase is intended to manage the recently arriving CRUs. In the commencement of RAP, the DFC broadcasts the number of slots in RAP. Afterward, all the CRUs, who need to participate in the sensing and initiate packet transmission phase in the subsequent frame, will arbitrarily select a RAP slot in

S-ALOHA style and direct an RTS_{RA} signal in the selected RAP slots. As discussed earlier, the CRUs which have effectively gained an RTS_{RA} signal will become SCRU and implement the collaborative sensing process in the next frames. The admission control method can be easily implemented in RAP by assigning the number of slots as zero when no more CRUs are approved to access.

4.5 Reporting slot reassignment phase

To address the scalability issues of the conventional fixed TDMA protocol, the proposed protocol enables the DFC to reallocate the idle slots. The allocated reporting slots are not utilized all time with full capacity due to (i) the SCRU has completed packet transmission and has no newly arriving packet to transmit; (ii) the SCRU has left the communication region of the network; and (iii) the SCRU is switched off. The slot reassignment process comprises two steps:

1. Finding the state of an allotted reporting slot: In this step, the unused reporting slots are identified using a simple rule. If allocated reporting slots continuously unused for successive k frames, then it is identified as an unused slot where k is an application-dependent design factor. The characters I and R are used to denote the index of idle reporting duration and a reporting slot requires reallocation, correspondingly. The flow diagram of this step is given in Figure 4.

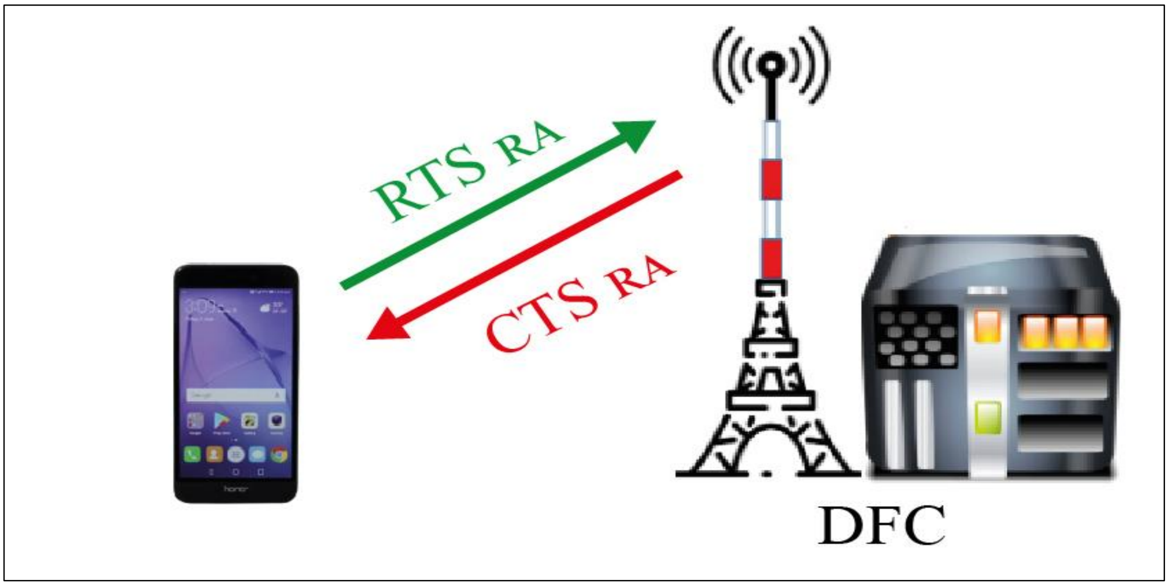

Fig 4: Flow diagram to find the state of allocated reporting slot

2. Reallocating the unused reporting slots: In this step, the unused reporting slots will be reallocated to the currently arriving CRUs. If unused reporting slots enduring with no currently arriving CRUs to allocate, the DFC sequentially reallocates these unused slots to one of the SCRU which has the highest index of reporting slot. Hence, the allocated reporting duration with the highest index is not employed in reporting phase to send the sensed information and the total number of allocated reporting slots is reduced. Therefore, we can allot more slots for the transmission process. Figure 5 illustrates the flow diagram of this process.

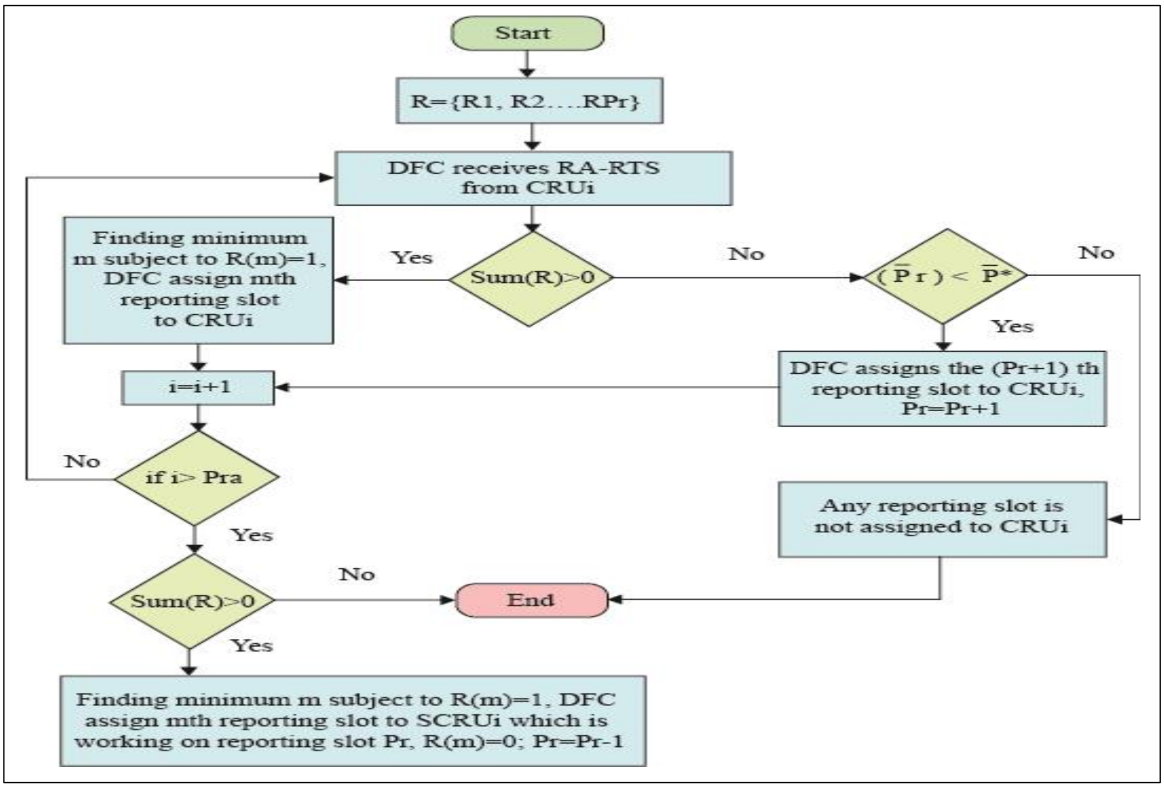

Fig 5: Flow diagram to reallocate the unused slot

Since the RAP can impact both the number of users in the communication system and the performance of channel detection, we study the RAP initially. As discussed earlier, to hold the reporting slot in the subsequent frames, CRUs participate in RAP by selecting one of the P_{ra} slots arbitrarily like the S-ALOHA protocol [19]. Since P_{ra} is affected by the number of reserved reporting access slots, when i reporting slots have been reserved in the present frame, we have

$$P_{ra}(i) = \left\lfloor \frac{N-i}{2} \right\rfloor \quad (1)$$

In contrast to [16], we implement an RSR phase in our protocol; CRUs do not need to relinquish the assigned reporting slot sporadically. Therefore, we can reduce the communication cost by carrying out reporting access process sporadically. For convenience, we consider that the winners of the RAP will continue the collaborative channel detection without exiting the NBC-IoT network. Consequently, we employ a discrete Markov chain function to investigate the RAP with a lot of frames in a long time scale. In accordance with [16], the possibility that only one CRU chooses one particular slot among the $P_{ra}(i)$ slots is

$$\rho_{s\,i} = \frac{\lambda_i^n (P_{ra}(i)-1)^{\lambda_i^n - 1}}{{P_{ra}}^{\lambda_i^n}} \quad (2)$$

In Equation (2), the term λ_i^n denotes the number of CRUs participating in RAP, where i and n represent the index of reporting slot and reserved MAC frame respectively. Then, the number of CRUs participating in RAP is measured as

$$\lambda_i^n = C - n \qquad (3)$$

Here, C is the number of CRUs in the network. Next, the following Equation (4) defines the initial state row vector of the RAP.

$$v^1 = \lambda_0^1, \lambda_1^1, \lambda_2^1, \ldots . \lambda_C^1 \qquad (4)$$

Based on the concept of the Markov chain [27], the transition matrix can be defined as $V \in R^{(C+1)(C+1)}$. Now, the probability of transition $V_{i+1,m+1}$ from state λ_i^n to state λ_m^{n+1} is expressed as follows:

$$V_{i+1,m+1} = \begin{cases} \binom{P_{ra}(i)}{m-i} {\rho_{s\,i}}^{m-i}(1-\rho_{s\,i})^{P_{ra}(i)-(m-i)}, m \geq i \\ 0, \qquad\qquad\qquad\qquad otherwise \end{cases} \quad (5)$$

According to (5), we have

$$V_{C+1,m+1} = \begin{cases} 1, & m = C \\ 0, & otherwise \end{cases} \quad (6)$$

Besides, if $i \neq C$, we have

$$V_{i+1,C+1} = \left\{ \binom{P_{ra}(i)}{C-i} {\rho_{s\,i}}^{C-i}(1-\rho_{s\,i})^{P_{ra}(i)-(C-i)} \geq 0 \right. \quad (7)$$

As stated in [28], the RAP is considered as an absorbing Markov function with an absorbing state $V_{C+1,C+1} = 1$. As the RAP is evaluated on a long time scale, if the absorbing state is obtained after the mth frame, we can calculate the number of CRUs participating in RAP as $\lambda_C^m = C - C = 0$. Now, the number of reporting CRUs is defined as $\overline{P_r} = C$. For implementing our admission control strategy, we set the maximum number of reporting CRUs as $P^* < C$. Now we have

$$V_{P^*+1,m+1} = \begin{cases} 1, & m = P^* \\ 0, & otherwise \end{cases} \quad (8)$$

At this point, we set the number of reporting CRUs as $\overline{P_r} = P^*$. In the channel detection process, considering the steady-state is realized, there are $\overline{P_r}$ CRUs participating in the detection process to find the LU signals. Generally, there are two states associated with the licensed users to represent their existence: absent and present. The terms Ψ_{detect} and Ψ_{false} represent the probabilities of global detection and global false alarm, correspondingly. In this study, M-out-of-N fusion rule is used to calculate these probabilities as given below

$$\Psi_{detect}(\overline{P_r},\beta) = \sum_{n=\beta}^{\overline{P_r}} \binom{\overline{P_r}}{n} \rho_{detect}^n \left(1-\rho_{detect}^n\right)^{\overline{P_r}-1} (9)$$

$$\Psi_{false}(\overline{P_r},\beta) = \sum_{n=\beta}^{\overline{P_r}} \binom{\overline{P_r}}{n} \rho_{false}^n \left(1-\rho_{false}^n\right)^{\overline{P_r}-1} (10)$$

where β represents the decision threshold of the fusion rule employed in this work. Based on above Equations (9) and (10), the average throughput (T_{avg}) can be calculated as

$$\mathrm{T}_{avg}(\overline{P_r},\beta) = \frac{r_0(1-\Psi_{false}(\overline{P_r},\beta)(M-\overline{P_r})\rho_0}{M} + \frac{r_1(1-\Psi_{detect}(\overline{P_r},\beta)(M-\overline{P_r})\rho_1}{M} \quad (11)$$

where ρ_0 and ρ_1 are the likelihood for the transmission channel to be idle and busy, correspondingly. The terms r_0 and r_1 represent the average baud rate of a CRU without and with LU interference, respectively. The energy consumed by the nth frame can be measured as follow

$$\mathrm{E}_T(n) = P_r^n E_s + P_r^n E_r + \rho_{free} E_t + (C - P_r^n) E_{ra} + P_{sr} E_{sr} \quad (12)$$

In Equation (12), $E_s = \rho_s t_s$ and $E_r = \rho_r t_r$. The terms E_s and E_r represent the amount of energy consumed by one SCRU in sensing and reporting phases respectively. $E_t = \rho_t t_{tr}$ denotes the energy consumption of the selected SCRU in the transmission period, $E_{ra} = \rho_{ra} t_{ra}$ and $E_{sr} = \rho_{sr} t_{sr}$ are the energy consumption of one CRU in the RAP and RSR phase. As stated earlier, RAP is an absorbing Markov chain function, the average energy consumption in the absorbing state is defined as

$$\overline{E_T} \approx \overline{P}_r E_s + \overline{P}_r E_r + \rho_{free} E_t \quad (13)$$

Now, the average energy performance can be defined as [29].

$$\zeta(\overline{P}_r, \beta) = \frac{\zeta(\overline{P}_r, \beta)}{\overline{E_T}} \; (14)$$

Simulation Results

To develop valuable insights into the usefulness of our projected protocol, a comprehensive simulation was carried out to assess the transmission efficiency with respect to packet delivery ratio, overhead, delay, throughput, and energy consumption for different existing protocols. This section presents simulation results to relate our proposed ERAP with other existing protocols. It is worth mentioning that our proposed protocol is considered collaborative channel sensing with collision-free reporting and dynamic admission control mechanisms. As far as we know, there is no other prevailing protocol that has precisely similar features as ERAP.

Table 1: Simulation parameters and values

Parameter	**Value**
Coverage of sink node	250m
Total number of sensor devices	250
Buffer size	50 Packets
Packet size	1000 to 5000
Total slots in a MAC frame	400
Number of sensing slots	40
Number of slot reassigned	20
Duration of sensing phase	0.01s
Duration of reporting phase	0.01s
Power consumption in the sensing phase	0.01w
Power consumption in the reporting phase	0.1w
Power consumption in the transmission phase	0.1w
The average baud rate of a CRU without interference (r_0)	2Mbps
The average baud rate of a CRU with LU interference (r_0)	0.2Mbps
Simulation Time	200 s

To assess the performance enhancement by implementing our collision-free reporting and dynamic admission control mechanisms, we compare the proposed protocol with two existing protocols as follows: normal IoT routing protocol [XX], and classical S-ALOHA [31]. The normal IoT routing protocol uses traditional data reporting techniques without using any channel sensing mechanisms. The classical S-ALOHA uses a sensing-based reporting mechanism without any admission control. We consider these protocols for evaluation since they are widely used medium access protocols developed for the same system settings as ERAP. As stated in [16], the reporting phase length of normal IoT routing protocol and classical S-ALOHA is assigned as 25 slots. Table 1 summarizes the simulation parameters utilized in our evaluation process. The sensor nodes are uniformly distributed in the coverage region. Besides, we assume all the CRUs participate in collaborative channel sensing in each MAC frame unless stated otherwise.

Figure 6 illustrates the packet delivery ratio comparison among ERAP, S-ALOHA, and normal of IoT routing protocols according to the number of packets. From the simulations, we can conclude that our proposed protocol outdoes the other two protocols regarding throughput. As the number of packets arriving at the slot increases the packet delivery ratio of all the protocols decreases due to the collisions in the random access phase. In order to assess the effectiveness of our proposed protocol ERAP (random access protocol with collaborative channel sensing using collision-free reporting and admission control mechanisms), we compare ERAP with S-ALOHA (a protocol with traditional reporting method without admission control) and normal IoT routing protocol (conventional protocol without spectrum sensing). From Figure 6, it is observed that ERAP delivered more packets successfully (maximum 99.98%) as compared to S-ALOHA (maximum 99.96%) and normal IoT routing protocol (maximum 99.83%). The proposed collision-free reporting mechanism decreases the access failure probability of CRUs and achieves a greater packet delivery ratio.

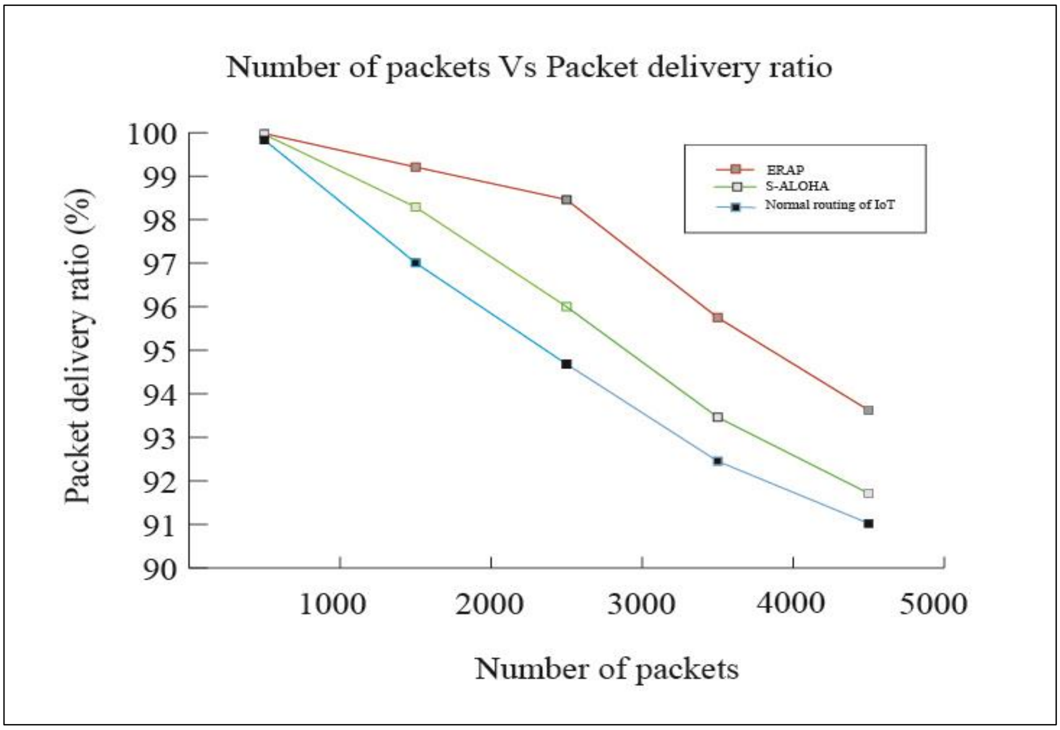

Fig 6: Number of packets Vs Packet delivery ratio

One of the essential performance metrics in a CR networks is the overhead ratio. We consider the sensing and reporting periods as the sensing cycle overhead since they cause delays and consume energy without transferring any data packets. Furthermore, decreasing such periods will lead to an increase in throughput and system efficiency. Figure 7 illustrates the effect of the number of packets on the overhead ratio of the communication due to information exchange under ERAP, S-ALOHA, and normal IoT routing protocols. It can be observed that ERAP always outperforms the other two protocols since it implements collision-free reporting as well as admission control mechanisms. It can decide whether or not to admit the CRUs to participate in channel sensing. Therefore it can achieve minimum overhead (4.95 for the number of packets equal to 5000) as compared to S-ALOHA (5.39) and normal IoT routing protocol (7.32).

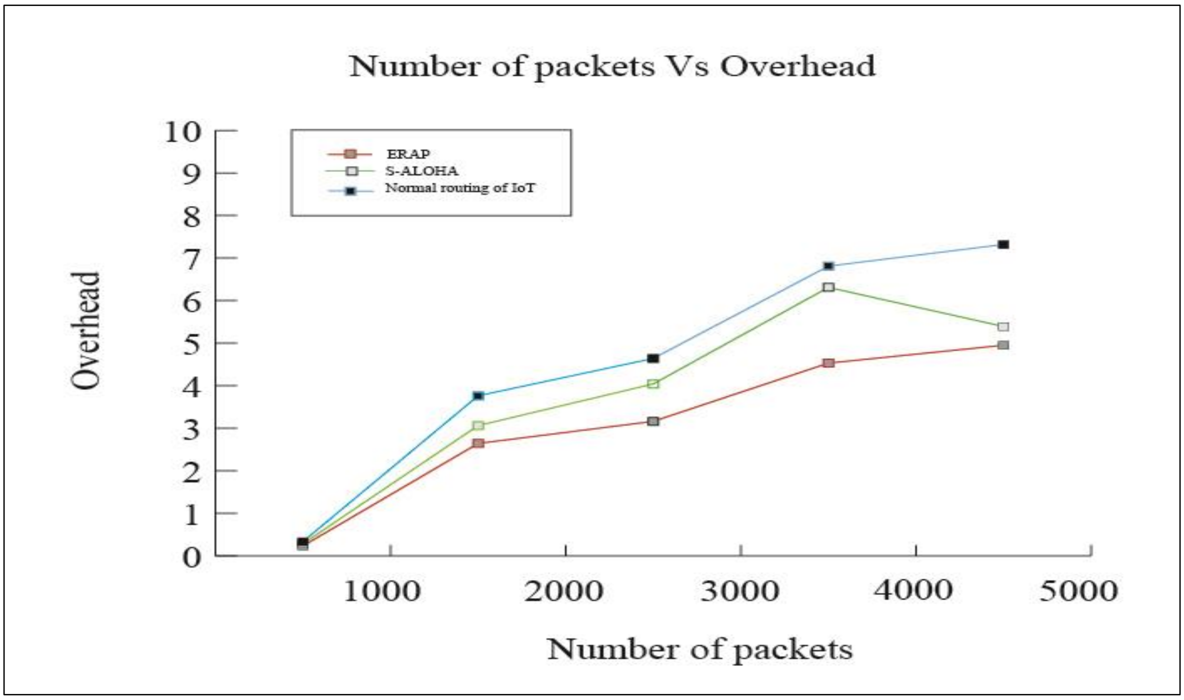

Fig 7: Number of packets Vs Overhead

Figure 8 illustrates end-to-end communication latency according to the number of packets. Decreasing the duration of the slot can decrease this latency. The simulation results have shown that the decrease of total latency leads to an increase in throughput as well as packet delivery ratio. The end-to-end latency is lower in ERAP as compared to the other two protocols; however, it upturns as the number of packet increases, especially the end-to-end latency increases from 3.18 ms for 1000 packets in the network to 5.04 ms for 5000 packets, and from 4.08 ms for 1000 packets to 5.88 ms for 5000 packets in S-ALOHA. The end-to-end communication delay increases from 4.66 ms for 1000 packets in the network to 7.29 ms for 5000 packets. This is because, in ERAP, the proposed reporting mechanism has high processing capability.

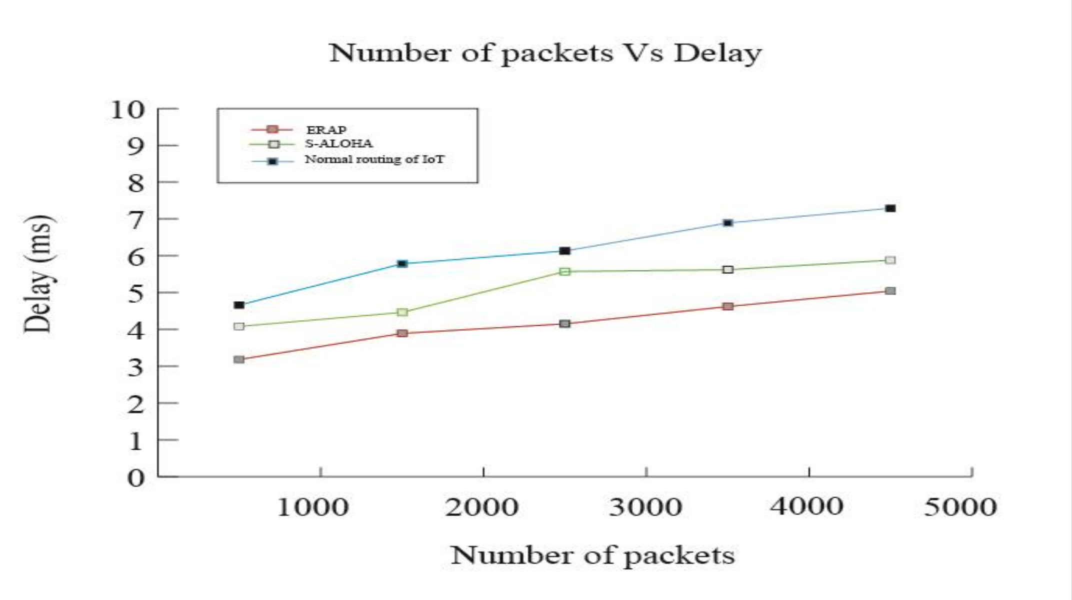

Fig 8: Number of packets Vs Delay

Figure 9 compares the system throughput using collaborative spectrum sensing with collision-free reporting and dynamic admission control mechanisms to two other existing protocols. The throughput of all the protocols studied in our work increases with the number of packets arriving in a slot. Moreover, the normal IoT routing protocol gets a similar throughput as compared to S-ALOHA. However, our proposed ERAP achieves greater throughput related to other protocols which reveal the usefulness of our Algorithm 1 and Algorithm 2. In our simulation, the maximum achievable throughput of normal IoT routing protocol is approximately 68.07 Kbps and S-ALOHA is 69.07 Kbps whereas our proposed protocol achieves approximately 73.1 Kbps when the number of packets arriving at the slot is 5000.

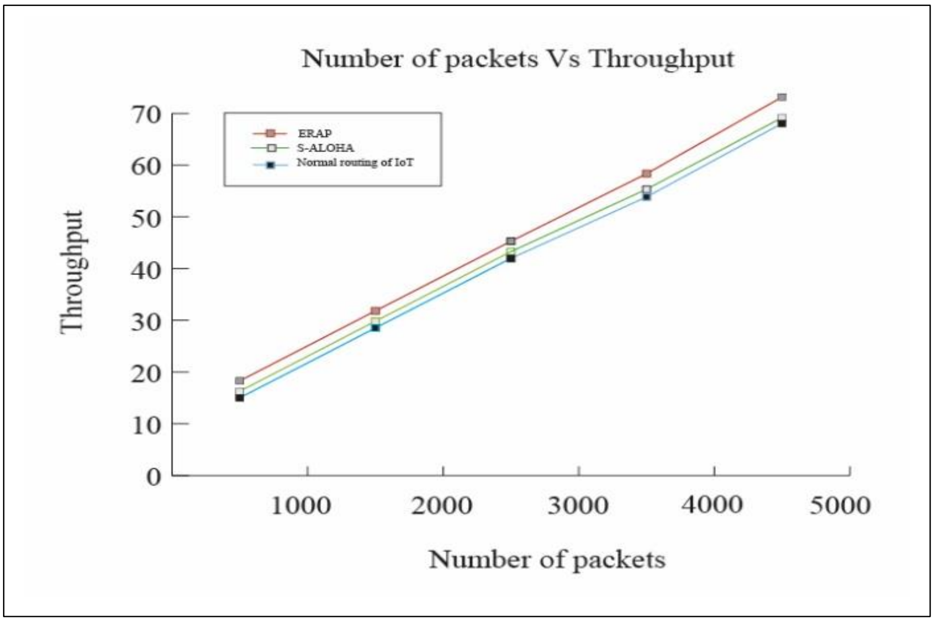

Fig 9: Number of packets Vs Throughput

We also analyze the energy consumption performance for varying number of packets. Figure 10 illustrates the simulation results on energy consumption according to number of data packets arriving in a slot. As the number of packets initially less (i.e., 1000), a complete collaboration is stimulated and consumes less energy for sensing, reporting, and data transmission. For example, normal IoT routing consumes 2.62 mw, S-ALOHA consumes 1.32 mw and ERAP takes only 0.64 mw to manage 1000 packets.

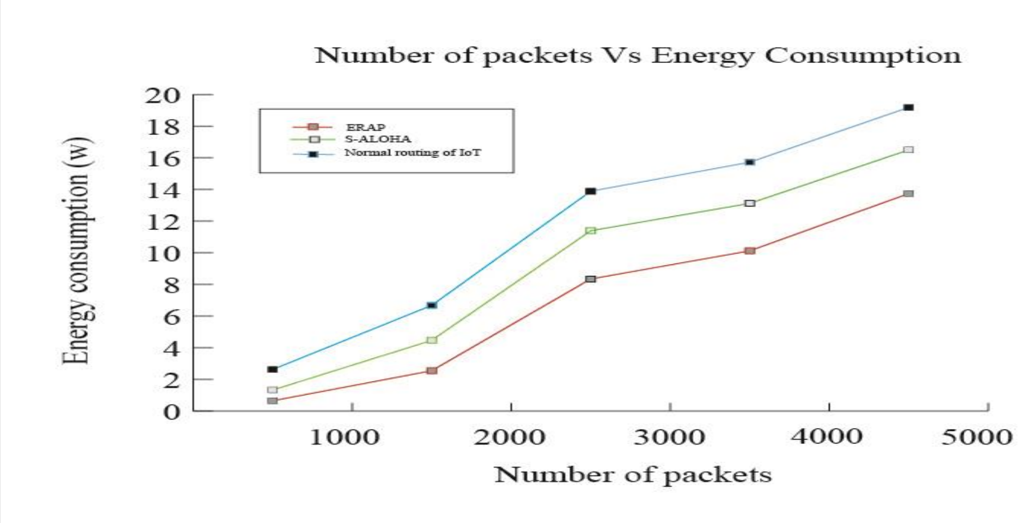

Fig 10: Number of packets Vs Energy consumption

The transmission overhead increases with the number of packets, resulting in an increase in energy consumption. In our simulation, the maximum energy consumption of normal IoT routing protocol is approximately 19.19 mw and S-ALOHA is 16.50 mw whereas our proposed protocol consumes approximately 13.74 mw when the number of packets arriving at the slot is 5000. As expected, ERAP consumes less energy among all three protocols by exploiting collision-free reporting and admission control mechanisms. These results demonstrate that admission control is crucial for energy-efficient collision-free reporting protocols.

Conclusion

The narrowband IoT is an evolving technology and expected to enable communication among IoT devices over a wide geographical area using constrained resources. However, the bandwidth allocation for the NB-IoT network is restricted and is not adequate to handle the explosive growth and development of the number of deployed devices of the NB-IoT network. For this reason, we integrate the concept of CR technology with NB-IoT to develop a Narrowband Cognitive IoT network. This work proposes an enhanced random access protocol that exploits a collaborative channel sensing technique to enhance the system throughput with a collision-free reporting strategy to enable robust communication against reporting collisions in NBC-IoT sensor networks. We have developed a new RCH design for collaborative channel detection. To further enhance the performance of the reporting process, a dynamic admission control mechanism has been developed, which can be embedded in our presented ERAP easily. The enhanced random access protocol is implemented and its achievable performance is evaluated using the NS2 simulator. Numerical simulation results demonstrate that our proposed protocol considerably outdoes two existing protocols such as normal routing of IoT, random access slotted-ALOHA in terms of performance measures such as packet delivery ratio, overhead, delay, throughput, and energy consumption.

Future Scope

In future, for sensing the spectrum and allocation of bandwidth it can be implemented by machine learning algorithms, neural networks which speeds up the sensing process. With addition to this, energy can be saved effectively and enhance the performance parameters of the cognitive radio sensor networks.

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