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ORIGINAL RESEARCH

Enhancing spectrum sensing efficiency in multi-channel cognitive device-to-device networks: Medium Access Control layer strategies and analysis

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Abstract

The detection and characterisation of electromagnetic signals within a specific frequency range, known as spectrum sensing, plays a crucial role in Cognitive Radio Networks (CRNs). The CRNs aim to adapt their communication parameters to the surrounding radio environment, thereby improving the efficiency and utilisation of the available radio spectrum. Spectrum sensing is particularly important in device-to-device (D2D) communication when operating independently of the cellular network infrastructure. The Medium Access Control (MAC) protocol coordinates device communication and ensures interference-free operation of the CRN coexisting with the primary cellular network. A spectrum sensing strategy at the MAC layer for cognitive D2D communication. The strategy focuses on reducing the overall sensing period allocated at the MAC layer by having each Cognitive D2D User (cD2DU) sense a smaller subset of available channels while maintaining the same sensing time for cellular user detection at the physical layer. To achieve this, the concept of concurrent groups of D2D devices is introduced in proximity, which are formed by using unique IDs of cD2DUs during the device discovery stage. Each concurrent group senses a specific portion of the cellular user band in a shorter time, resulting in a reduced overall sensing period. In addition to mitigating traffic congestion through data diversion from the cellular network, the proposed strategy facilitates the concurrent sensing of multiple channels by cD2DUs within the underutilised cellular user band. This leads to extended data transmission periods, increased network throughput, and effective offloading of the cellular network. The effectiveness of the proposed work is evaluated by considering factors, such as network throughput and transmission time. Simulation results confirm the effectiveness of the approach in improving spectrum utilisation and communication efficiency in multi-channel Cognitive D2D Networks (cD2DNs).

KEYWORDS

5G mobile communication, smart phones

1 | INTRODUCTION

The global transition to fifth-generation (5G) cellular networks, initiated in 2019, is expected to replace existing 4G LTE networks. Anticipating the demands of emerging technologies, efforts are underway in academia and industry to develop solutions for sixth-generation (6G) networks. The forthcoming 6G networks are expected to face significant challenges due to applications, such as the Internet of Everything, Virtual Reality, Augmented Reality, Mixed Reality, holographic communication, high-precision manufacturing, intelligent buildings, smart cities, and smart environments [1]. To integrate new technologies and fulfil the demands of such applications, a novel network architecture for 6G is necessary. While it is premature to define the 6G standard, it is expected to achieve data rates 100–1000 times faster than 5G and latency below 1 millisecond [2]. Achieving these goals will necessitate a network architecture with enhanced intelligence and efficiency, involving technologies like Cognitive Radio (CR) and Device-to-Device (D2D) communication [3].

The concept of CR, initially proposed by Joseph Mitola [4], focuses on enhancing spectrum utilisation by employing cognitive users. These intelligent radio transceivers opportunistically utilise spectrum gaps left by primary or cellular users by ensuring interference avoidance to primary users. D2D communication has recently gained significant attention from both academia and industry [5], mainly due to its ability to improve energy efficiency through proximity communication. Additionally, D2D communication can offload cellular base stations, enhance spectral efficiency, and increase hop gain, consequently improving network coverage and mitigating blind spots within cellular areas [6–9].

The combination of CR and D2D communication forms a cD2DN communication system, which holds great potential for enhancing the energy efficiency, spectrum efficiency, throughput, and coverage of 6G networks. Consequently, the research community has recently shown significant interest in cD2DN communication [10, 11]. By operating beneath cellular networks, D2D communication networks, when integrated with CR, offer increased flexibility to achieve higher spectrum efficiency [12].

In cD2DN, a Cognitive D2D User must dynamically operate on multiple available channels of cellular users or coexist with cellular users on the same channel while controlling interference. Designing an efficient Medium Access Control (MAC) protocol that can accurately sense and utilise spectrum opportunities is one of the greatest challenges in such networks. The goal is to achieve optimal network performance [13–15]. The cD2DU is required to execute a sequence of operations for medium access as illustrated in Figure 1. First, it uses spectrum sensing to identify the available channels. Second, it gives these channels precedence using spectrum sequencing. Thirdly, it uses control information to transmit these findings to the nearby intended cD2DU. Fourthly, by allocating spectrum resources and using the selected channel for data transmission, it engages in spectrum sharing. Finally, it might be necessary to change its position or channel to protect cellular users from interference, which can happen as a result of congestion or the return of a cellular user. Additionally, the cD2DU MAC protocol requires a signalling mechanism to disseminate control data among its entities. In a cD2DN, a control channel serves as the channel accessible to all cD2DUs for sharing information and facilitating coordination among them.

Various spectrum sensing policies have been classified in previous works [16, 17] and their detailed classification is shown in Figure 1. The choice of these policies may influence the throughput and delay performance of CR. The single-channel sensing policy entails scanning one channel from a multi-band. Based on the result of the scan, which determines whether the channel is available or occupied, the CR user decides whether to utilise the channel if its available or continue to scan another channel if its occupied. In contrast, the sequential channel sensing policy involves scanning a specific number of channels before making a channel selection. The effectiveness of this policy is contingent upon the number of channels scanned in each round. However, it should be noted that this approach may not be energy-efficient due to the necessity of scanning a considerable number of channels, which can consume substantial power resources.

The random sensing policy, described in refs. [18, 19], enables CRs to randomly sense a certain number of channels from the pool of cellular user channels without any coordination. On the other hand, the negotiation-based sensing policy, presented in ref. [19], necessitates coordination and negotiation among CRs to distribute the cellular user channels for sensing purposes. This policy enhances efficiency by reducing interference and collisions among CRs, although it comes at the cost of increased control overhead.

The learning-based sensing policies [20] leverage historical data and feedback from past spectrum-sharing activities to make informed sensing decisions. These policies utilise the accumulated knowledge to adapt and optimise the sensing process over time. In contrast, policy-based channel sensing [16] focuses on enhancing the efficiency of cooperative spectrum sensing. It aims to ensure collision-free access to the spectrum among competing CRs by employing predefined spectrum sensing policies. These policies provide guidelines and rules for spectrum sensing, enabling coordinated and efficient utilisation of the available spectrum resources.

The effectiveness of spectrum sharing in the cD2DN MAC protocol relies heavily on the accuracy of the spectrum sensing functionality and the proper management of the control channel. Successful spectrum access is contingent upon reliable spectrum decision-making, efficient channel allocation, and a robust spectrum sensing process. Once the spectrum decision and sensing process are completed, channel allocation can occur via a reliable common control channel for MAC information.

Several factors must be considered when designing cD2DN MAC protocols. Firstly, the requirement for continuous sensing can lead to an increase in the number of transceivers, as one is needed for sensing and another for data transmission. This can result in higher costs. Continuous sensing may provide more reliable results but at the expense of increased power consumption. Secondly, non-continuous sensing can be achieved using a single transceiver, which is more energy efficient but may impact throughput and delay. Additionally, determining the optimal duration of sensing time is a crucial design consideration to ensure effective and reliable results [21].

The overall sensing phase is critical in CR as it determines the ability of cognitive D2D users (cD2DUs) to detect the presence of cellular users and determine the availability of unused spectrum, called the "spectrum holes". The results of

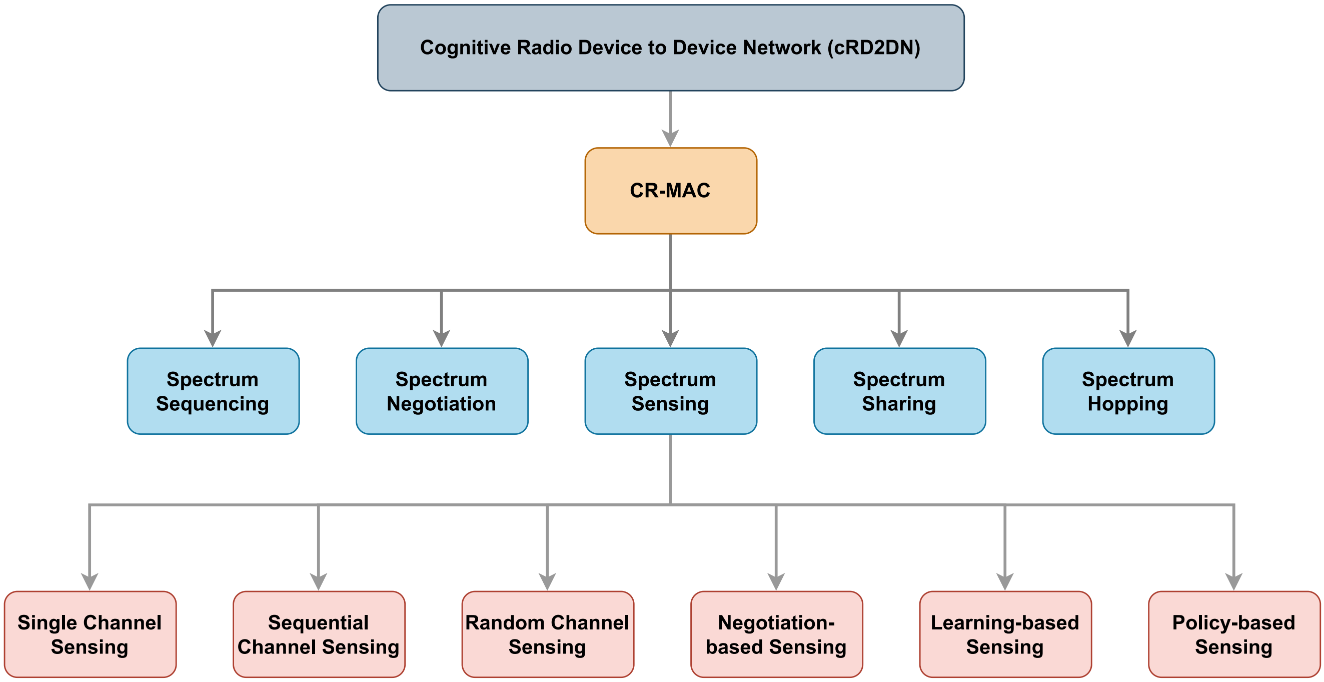

FIGURE 1 Classifications of cRD2DN MAC. MAC, Medium Access Control.

the sensing phase determine the subsequent actions taken by the cD2DUs, such as accessing the spectrum or avoiding it to prevent interference with cellular users. Reliable and efficient use of the sensing phase enables cD2DUs to make informed decisions about spectrum utilisation, improving the overall spectrum utilisation and avoiding harmful interference to cellular users. Also, a reduction in the overall sensing phase can potentially increase the throughput of CR. By reducing the time spent in the sensing phase, the Secondary User (SU) can quickly determine the availability of unused spectrum and access it for data transmission, leading to increased spectrum utilisation, reduced idle time, and an overall increase in the throughput of the Cognitive Radio Network (CRN). However, the reduction of the sensing phase must be done while ensuring that it remains reliable and accurate in detecting cellular users and avoiding harmful interference. Hence, the design of the sensing phase plays a crucial role in the overall performance of CRNs.

In ref. [22], the issues about static spectrum allocation leading to underutilisation and scarcity in wireless networks have been addressed. The proposed solution involves CR technology, enabling dynamic spectrum access by SUs through adjustments in MAC layer functions. It introduces the Extended Generalised Predictive Channel Selection Algorithm, which orders and groups channels based on idling probabilities, significantly reducing delays and maximising throughput for SU. The author in [23] addresses the challenges in CR systems regarding spectrum sensing and proposes a solution with a Modified Cuckoo Search and Hill Climbing (MCSH) algorithm. The primary focus is on mitigating the trade-off between longer sensing periods and reduced data communication, leading to throughput failure. The MCSH algorithm employs asynchronous cooperative spectrum sensing of SU groups to enhance spectrum sensing in the CRN, accurately identifying spectrum holes and optimising energy efficiency, throughput, and detection accuracy. The author in ref. [14] proposed a parallel sensing scheme with sequential channel selection order integrated into the MAC protocol, where it can swiftly discover all available channels in the primary user band in less time. Additionally, a novel approach to organising SUs into groups based on their IDs has been introduced. Each SU group is allocated an equal portion of the spectrum for sensing, resulting in a reduction in the total time for the sensing phase. This leads to increased overall throughput by providing more time for data transmission and enhancing energy efficiency. Our proposed scheme in the Cognitive Device-to-Device (cD2DN) scenario adopts the concept of forming SU groups as previously introduced in refs. [14, 22, 23].

This paper introduces a novel spectrum sensing method for a cD2DN MAC that effectively reduces the overall sensing phase time. As a result, cD2DUs experience increased data transmission time within a specific transmission cycle. Our approach involves forming cD2DU groups based on unique IDs and allocating equal portions of the spectrum for sensing. By enabling simultaneous sensing and sharing of results among SUs, the total sensing time is reduced, leading to enhanced overall throughput. This paper presents several notable contributions, which are outlined as follows:

- A MAC-layer spectrum sensing strategy specifically tailored for cognitive D2D communication. The primary goal is to minimise the overall sensing period while ensuring the same sensing time for cellular user detection at the physical layer.

- The proposed strategy allows cD2DUs to perform concurrent channel sensing in multiple channels from the underutilised cellular user band. These channels are sensed simultaneously in distinct groups, which are formed based on unique IDs assigned to the cD2DUs.
- By dividing the sensing workload among these groups, each group focuses on sensing a specific portion of the cellular user band, resulting in a reduced sensing time for each group. This reduction in sensing time effectively decreases the overall sensing period required for spectrum sensing.
- The advantage of this strategy is that it increases the data transmission time available for cognitive D2D communication. With a shorter sensing period, more time is allocated for data transmission, leading to improved network throughput and enhanced utilisation of available resources.

The organisation of the paper is structured as follows: In Section 2, we develop spectrum sensing strategies within the multi-channel cD2DN MAC framework. Moreover, it provides a comprehensive discussion of state-of-the-art spectrum sensing techniques. Later on, we focus on the proposed cooperative concurrent spectrum sensing approach, presenting its system model detail in Section 3. The simulation setup and results detailed discussion are presented in Section 4. Finally, Section 5 offers the conclusion of our research work.

2 | SENSING STRATEGIES IN MULTI-CHANNEL CD2D MEDIUM ACCESS CONTROL

The Institute of Electrical and Electronic Engineering (IEEE) 802.11 physical layer supports multiple channels, but the above MAC protocols do not. In a multichannel configuration, single-channel MAC protocols are incapable of dealing with the hidden terminal problem. This can result in interference and collisions when the devices simultaneously transmit data to the receiver. The receiver may not be able to detect the transmissions from all the devices, leading to degraded performance and reduced network efficiency. The hidden terminal problem commonly occurs in scenarios where devices are located in different parts of the network and cannot directly sense or communicate with each other. Effective MAC protocols need to address the hidden terminal problem to ensure proper coordination and collision avoidance among devices in a wireless network.

To overcome the challenges of hidden nodes in multichannel environments while conforming to the IEEE 802.11 standards, the adoption of multichannel protocols is necessary for cD2DN. These multichannel MAC protocols are inspired by CR MAC protocols but tailored specifically for cD2DN. Cognitive Radio Network MAC protocols effectively operate in multichannel scenarios and address similar issues, including hidden terminals across multiple channels [24]. Figure 2 illustrates the evolutionary progression from a single-channel MAC protocol to a cD2DN MAC protocol, while Table 1 provides a comprehensive comparison of sensing and access strategies among various cD2DN MAC protocols.

Cognitive Radio is a technology that allows radios to sense multiple channels and adapt to changes in the wireless environment. Because of this capability, a single-channel MAC protocol cannot handle the dynamic channels used simultaneously. Therefore, a multiple-channel MAC protocol is required to handle these dynamic channels. The cD2DN MAC protocol must incorporate capabilities for anticipating upcoming spectrum utilisation, mitigating interference with authorised cellular users, and ensuring collision-free operation among cD2DUs. In this paper, we will review some CR multichannel MAC protocols and their aspects concerning multichannel cD2DNs in the following sections.

2.1 | Decentralised cognitive Medium Access Control

This distributed or spontaneous network protocol is a multichannel MAC protocol designed explicitly for situations lacking a central authority, where each SU assumes the responsibility of local spectrum sensing and access. To determine spectrum availability, the protocol utilises a Partially Observable Markov Decision Process that considers the limited knowledge of the licenced spectrum [13]. The protocol follows a fundamental structure based on CSMA protocols, employing time slots where channel sensing takes place at the beginning of each slot. With the aid of past decisions and observations, the DC-MAC protocol is designed to achieve optimal channel sensing and access, while also accounting for sensing errors. However, an implementation challenge of this protocol lies in its assumption of known transition probabilities within the Markov model.

2.2 | Hardware-constrained cognitive Medium Access Control

The Ad-hoc CRN protocol presented in [25] aims to achieve optimal channel sensing and access. This contention-based protocol utilises out-of-band signalling and incorporates a sensing-stopping process. The key concept behind this protocol is to consider transmission constraints before initiating spectrum sensing, avoiding unnecessary sensing of a spectrum that is not required by the cognitive user. The protocol operates using a single half-duplex radio without global synchronisation, which means that data transmission and channel sensing cannot occur simultaneously. The HC-MAC protocol comprises three primary operations: Contention, Sensing, and Transmission. These operations involve message exchanges over the common control channel, such as Contention-Ready to Send/Contention-Clear to Send for channel reservation during the contention period and Sensing-Ready to Send/Clear to Send for detecting channel information among cognitive users. However, the presence of hidden terminals across

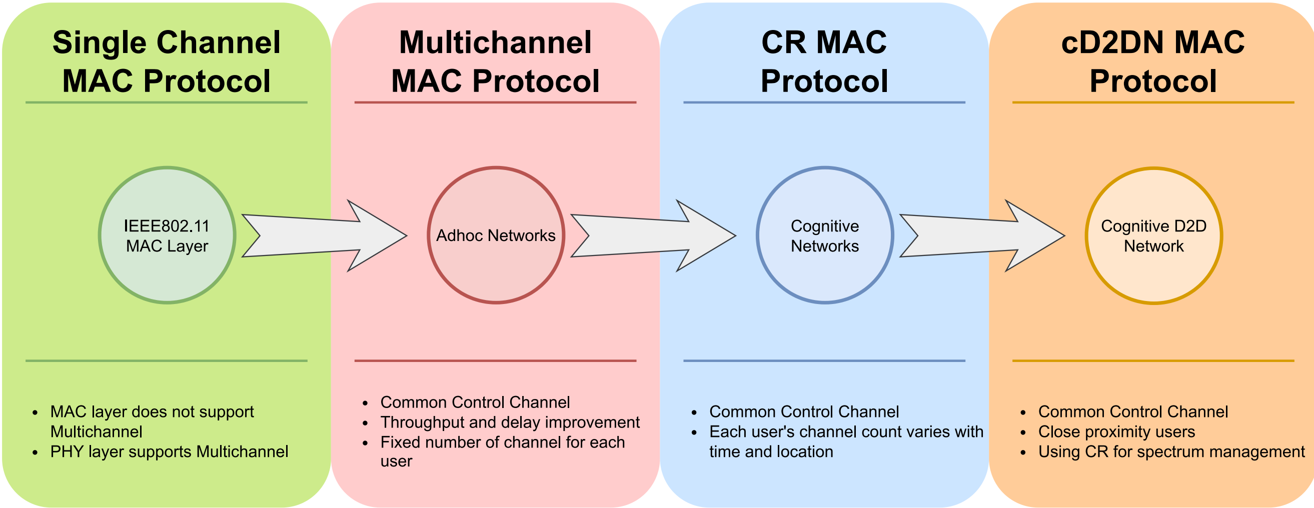

FIGURE 2 The evolutionary path of cD2DN MAC Protocol. MAC, Medium Access Control.

TABLE 1 List of Multi-channel Medium Access Control (MAC) protocols.

MAC	Sensing scheme	Access scheme	Signalling	Radio
DC-MAC [13]	Periodic channel sensing for a subset of channels	CSMA	Dedicated CC	Single
HC-MAC [25]	Sequential channel sensing with stopping rule	Contention based/Random access	Out-of-band	Single
P-MAC [26]	Continuous sensing till found free channel	CSMA/CA	In-band	Single
CREAM-MAC [27]	Cooperative sequential sensing	Contention based/Random access	Out-of-band	Two
OP-MAC [28]	Fixed number of channel sensing as users sense only corresponding channel	CSMA/CA	In-band	Single
MMAC-CR [29]	Periodic sensing, distributed sensing	CSMA/CA	-	Single
CogMesh [30]	Periodic sensing	Hybrid	In-band	Single
CR-i-MAC [31]	Combination of random, fixed/adaptive channel sensing	Contention based/Random access	Dedicated CC	Two
SMC-MAC [32]	Combination of random, fixed/adaptive channel sensing	Contention based/Random access	Dedicated CC	Single

multiple channels can lead to collisions during transmissions due to the single radio and the absence of synchronisation.

2.3 | Predictive Medium Access Control

The protocol described in ref. [26] is an Exponential Smoothing Mode (ESM) based protocol that predicts channel distribution behaviour for both centralised and distributed networks. It employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as a spectrum access strategy and is designed to work with a single transceiver. The protocol offers several advantages, including addressing the hidden terminal problem, achieving higher throughput, reducing sensing overhead time, and being configurable as either slotted or non-slotted. This protocol introduces a parameter called the MAC period, which allows a cognitive user to access the channel during its OFF state, facilitating sensing, negotiation, and data transmission. The MAC period serves as a predictive measure and is active when the channel is in the OFF state. If the MAC period overlaps with an ON state of the channel, it indicates a potential collision during transmission. The duration of the OFF state follows a random distribution. An ESM is employed to estimate the MAC period based on the previous MAC period and the duration of the OFF state. When the predicted MAC period is shorter than the OFF state duration, shorter transmission periods (e.g. 3 ms or 5 ms) are used to enhance throughput, albeit with a higher risk of collisions. However, a comprehensive throughput analysis comparing this protocol to other prominent cognitive MAC protocols is lacking in the paper.

2.4 | CogMeshCognitive radio- enabled multi-channel Medium Access Control

The main objective of this protocol, outlined in ref. [27], is to overcome the challenge of achieving global synchronisation using a single transceiver, which was a limitation in previous protocols. Additionally, it aims to address the issue of multi-channel hidden terminals by incorporating a waiting period for cognitive users. After completing a transmission, a cognitive user continues utilising the same channel group until the waiting period expires. To enable resource reservation among cognitive users, a control channel is employed, and control packets are exchanged for this purpose, assuming the control channel's constant availability. Every cognitive user is equipped with a Software Defined Radio transceiver that can utilise multiple channels for data transmission. Additionally, they are equipped with a variable number of sensors to detect spectrum holes. Channel negotiation is accomplished by exchanging four types of messages over the control channel. However, the influence of the number of sensors on factors like energy consumption, cost, and complexity has not been assessed. Additionally, the introduction of a waiting period to address multichannel hidden terminals may result in increased delays and reduced throughput.

2.5 | Opportunistic periodic MAC

The objective of the protocol, as described in ref. [28], is to enhance the utilisation of channels in CRNs. It comprises four distinct phases: network sensing, reporting, transmission reservation, and data transmission. During the network sensing and reporting phase, cognitive users engage in information exchange to address the challenge of hidden terminals across multiple channels. The protocol is evaluated through analytical modelling to assess its channel utility and capacity. The duration of the first three phases is also analysed concerning the distributed coordination function of the IEEE 802.11 protocol. However, the performance of this protocol in terms of the data transmission phase or throughput has not yet been evaluated.

2.6 | Multichannel Medium Access Control protocol for Cognitive Radio

The purpose of Multichannel MAC protocol for cognitive radio (MMAC-CR) networks, as presented in ref. [29], is to enhance the energy efficiency of multi-hop CRNs by enabling cognitive users to enter a low-power state when no communication is required. The sensing algorithm is divided into two phases: an initial low-power scan for approximate sensing, and a subsequent high-power scan for accurate sensing. Analytical models are constructed for both single-hop and multi-hop networks, and their performance is assessed through simulation using the Network Simulator Version 2 simulator. The protocol's performance is evaluated concerning energy consumption and throughput. The analytical and simulation results are compared, although there is no explicit comparison with other schemes.

2.7 | Cognitive radio intelligent Medium Access Control

The CR-i-MAC protocol is employed to tackle the problem of collisions among multiple cognitive users when accessing unused cellular channels [31]. The protocol is partitioned into three phases: sensing and sharing, contention, and data transmission. A contention-free technique is employed during the contention phase to enable multiple cognitive users to access the same channel. However, it is acknowledged that the protocol's performance may degrade in larger networks.

2.8 | Self-scheduling multi-channel cognitive Medium Access Control

The Self-scheduling multi-channel cognitive MAC (SMC-MAC) protocol, as explored in [32], is a current research focus aimed at enhancing throughput in distributed networks. This protocol incorporates a control channel to enable the exchange of spectrum-sensing outcomes among SUs. It operates across four well-defined intervals: idle, sensing and sharing, contention, and data transmission. Within the sensing and sharing interval, time slots are utilised to identify idle channels. These identified idle channels collectively form the contention interval. If a cognitive user effectively avoids collisions during the contention interval, it gains access to the transmission interval for data transmission. The collision probability in the contention interval relies on the number of employed time slots. A higher number of time slots minimises collisions, while a lower number amplifies them. However, due to the stochastic nature of sensing and collisions within the contention interval, the spectrum resources might not be optimally utilised, potentially resulting in underutilisation.

The above-discussed schemes, such as SMC-MAC, Cog-MeshCognitive radio- enabled multi-channel MAC, Opportunistic periodic MAC, MMAC-CR, and CR-i-MAC have shown promising results in addressing the challenges of CRNs. The comparison of these schemes is shown in Table 1. However, these schemes have their limitations and drawbacks, such as collision during contention interval, spectrum resources not fully utilised, lack of comparison with other schemes, poor performance for larger networks, and inefficient sensing strategies at the MAC level. In light of these limitations, there is a need for further research and development in this field. Although, many of the discussed CRN MAC protocols were initially developed in the early stages of CR, laying a solid foundation. However, the majority of recent advancements and enhancements have evolved from these foundational protocols. For example, the protocols commonly incorporate phases, such as sensing, sharing, and data transmission, with slight variations in the sequence order and duration of each phase. This underscores the enduring influence and adaptability of these foundational protocols in shaping the evolution of CR networks. Our proposed work aims to address the limitations of the random sensing strategy employed in SMC-MAC protocol and enhance the data transmission time by introducing sensing groups of cD2DUs based on device IDs that can sense the given portion of the spectrum simultaneously. This new sensing method improves the overall performance of the system.

3 | COOPERATIVE CONCURRENT SPECTRUM SENSING

Cooperative concurrent spectrum sensing refers to a technique in wireless communication networks where multiple nodes collaborate to sense the spectrum simultaneously and cooperatively. This approach aims to improve spectrum sensing accuracy, reduce sensing time, and enhance overall network performance. In cooperative concurrent spectrum sensing, nodes within the network, such as cognitive devices or SUs, work together to detect the presence or absence of primary users in the shared spectrum. By coordinating their sensing activities, these nodes can achieve better-sensing results compared to individual sensing. The process involves dividing the available frequency bands into sub-bands or channels, and each node is responsible for sensing a specific sub-band. The nodes then exchange their sensing information and combine the results to make a collective decision regarding the occupancy status of each sub-band. By leveraging the collective intelligence of multiple nodes, cooperative concurrent spectrum sensing can mitigate the effects of fading, shadowing, and other wireless propagation impairments. It helps in improving detection accuracy, reducing false alarm rates, and enhancing the overall reliability of spectrum sensing. This technique finds applications in various wireless communication scenarios, including CRNs, dynamic spectrum access, and next-generation wireless systems. It plays a crucial role in efficient spectrum utilisation, enabling opportunistic spectrum access while minimising interference with the primary users.

3.1 | System model

We consider a cD2DN containing cellular users and cD2DUs as shown in Figure 3. The cD2DUs are cellular users with proximity and they are working autonomously under a 5G cellular network. The clustering approach is used to divide the cD2DUs in the proximity of a cellular network into four groups $G = \{G1, G2, G3, G4\}$, forming a cD2DN. The preference of cD2DUs in proximity to establish a direct connection and offload cellular base station (gNodeB) depends upon the formation of groups during the device discovery process. To organise into groups, the CD2DUs discover candidate D2D devices (cDUs) by scanning their surroundings and with base station or network assistance [33]. Network-assisted device discovery significantly enhances cDU performance and offloads the gNodeB, providing advantages such as robustness, security, improved discovery, and low battery consumption, as the gNodeB handles most signalling [33]. After the formation of groups, communication between cDUs can be established. Direct sessions can be established using widely available interfaces like WiFi, Bluetooth, or cellular channels, without requiring hardware upgrades [34]. However, for efficient communication between cDUs, a millimetre wave or Terahertz communication link is most suitable due to the high performance of these state-of-the-art technologies at short distances [35].

The cellular users' band consists of N_c number of channels or time slots and the cD2DN consists of N_{cD2DU} users in 4 groups 4 Each cD2DU is equipped with a single transceiver,

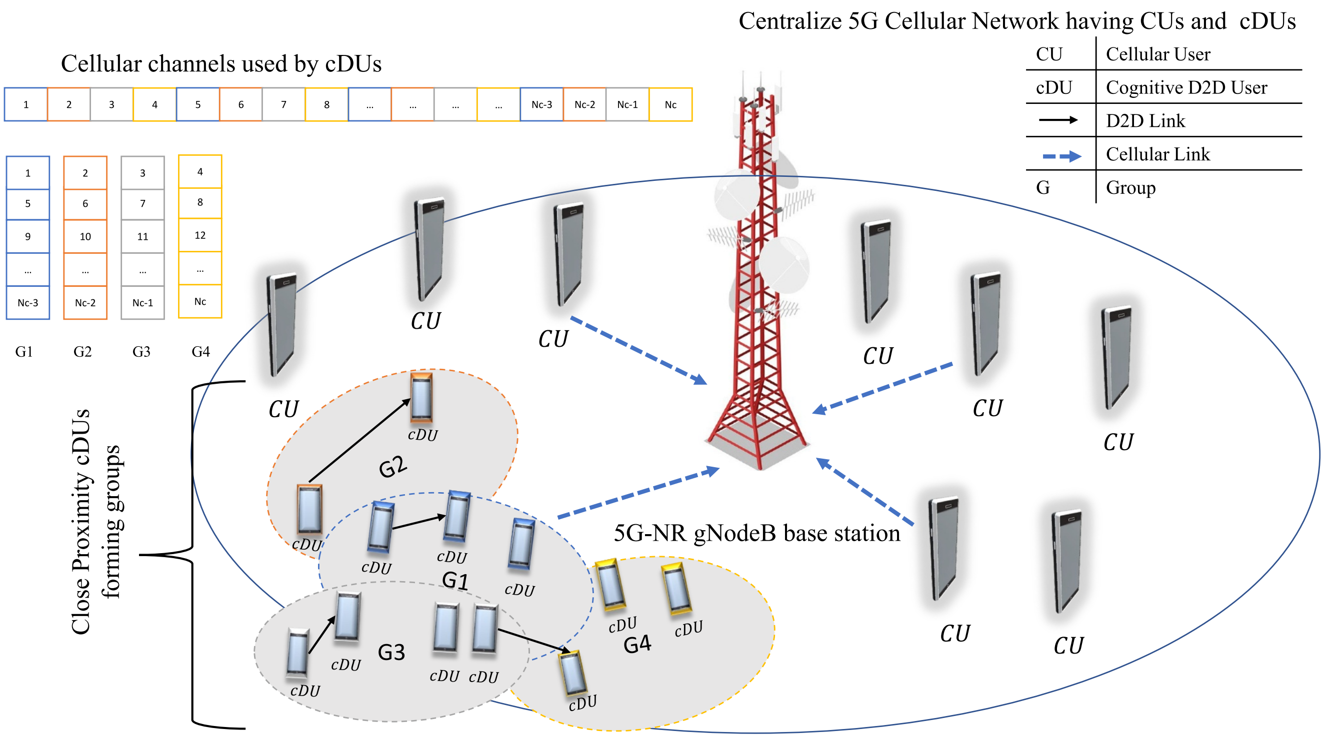

FIGURE 3 Network model showing four concurrent groups.

and it is assumed that they are organised into clustering groups, each with a unique ID. This unique ID could be a MAC address of a cD2DU. These IDs are utilised to form multiple concurrent groups with the help of network assistance. For example, *ID* 1, 5, 9, 13, 17, … belongs to group 1 (G1) and *ID* 2, 6, 10, 14, 18, … belongs to group 2 (G2) and so on. For instance, as shown in Figure 3, four groups of cD2DUs are established based on the clustering number. Additionally, the cellular user band is divided into four segments. Each group simultaneously senses a specific segment of the cellular user band, allowing all cD2DUs within the same group to sequentially scan the channels corresponding to their respective groups. Without loss of generality, the channels are divided among groups sequentially. To elaborate the technique we keep the system simple by dividing the cD2DUs into four groups, that is, $G = 4$, however, the idea can be extended to any arbitrary number of groups, $G = N$. The sensing information acquired by the sensing nodes, that is, cD2DUs, is shared among all the stakeholders through a common control channel, which is accessible to all the cD2DUs of cD2DN.

3.2 | Concurrent sensing

The frame format proposed includes four distinct phases: the idle phase, sensing phase, sharing phase, and data transmission phase, as depicted in Figure 4. These phases are defined as follows: idle time (T_i), concurrent sensing time (T_{cs}), sharing time (T_{sr}), contention time (T_{ct}), and data transmission time (T_{tr}). The T_i, T_{ct}, and T_{tr} phases align with those outlined in refs. [31, 32]. In the work by Lim et al., [32], the sensing and sharing time (T_{ss}) is divided into N_{ch} slots, with each slot further divided into three sub-slots. The first sub-slot is designated for random sensing of the corresponding channel in the cellular user band by the cD2DUs, while the second and third sub-slots are utilised for sharing the outcomes of the sensing process.

In the proposed concurrent sensing scheme, the sensing and sharing phase (T_{ss}) has been replaced by the concurrent sensing time (T_{cs}) and sharing time (T_{sr}). In this concurrent sensing scheme, each cD2DU is assigned a unique ID based on its MAC address and geographical location, and these IDs are employed to form cD2DU groups. cD2D users are organised into groups according to their IDs. Within group 1, each member is assigned the task of scanning specific channels within the frequency band. This allocation ensures that group 1 users efficiently sense a reduced number of channels within a shorter timeframe. Subsequently, during the sharing phase, each user in Group 1 communicates their sensing results through the designated time slots on common control channels, utilising two bits for this purpose. Specifically, Bit 10 signifies that the channel is idle, while Bit 11 indicates that the channel is currently occupied. For instance, during the T_{cs} phase, cD2DUs in group 1 with G-ID = 1 sequentially sense channels (1, 5, 9, 13…, $N_c - 3$), while cD2DUs in group 2 with G-ID = 2 sequentially sense channels (2, 6, 10, 14…, $N_c - 2$), cD2DUs in group 3 with G-ID = 3 sequentially sense channels (3, 7, 11, 15…, $N_c - 1$), and cD2DUs in group 4 with G-ID = 4 sequentially sense channels (4, 8, 12, 16…, N_c) from the cellular user band, as illustrated in Figures 3 and 4.

Following the scanning process, these users share their results on common control channels during designated time

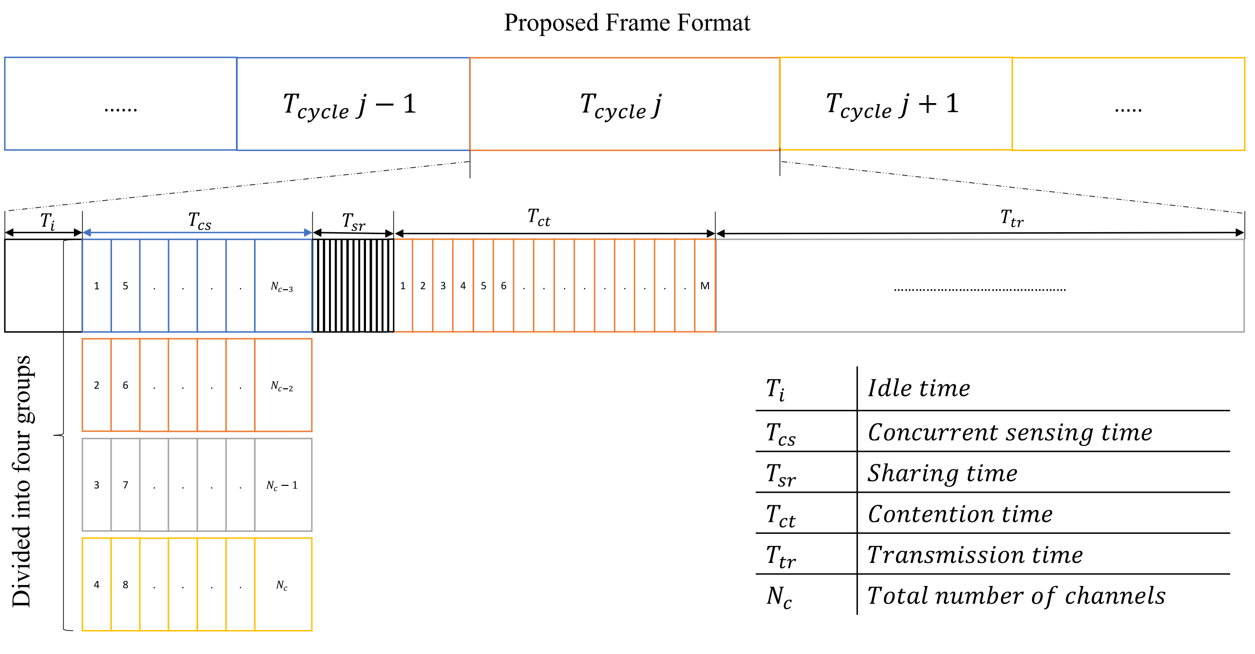

FIGURE 4 Illustration of the proposed frame format for the concurrent sensing scheme, showcasing the different phases and their duration. The diagram provides a visual representation of the frame structure, including the idle phase, sensing phase, sharing phase, contention phase, and data transmission phase. It demonstrates the temporal organisation of these phases within the frame, offering insights into the timing and sequence of operations for efficient concurrent sensing in the scheme.

slots in the subsequent sharing phase. Group 1 participants share their sensing results during the subsequent sharing phase, utilising dedicated slots corresponding to the channels they monitored, such as slots 1, 5, 9, and so forth. Similarly, users within Group 2 share their scan results with the corresponding designated slots during the subsequent sharing phase. As illustrated in Figure 5, the specific channels sensed by Group 1 during the concurrent sensing phase are

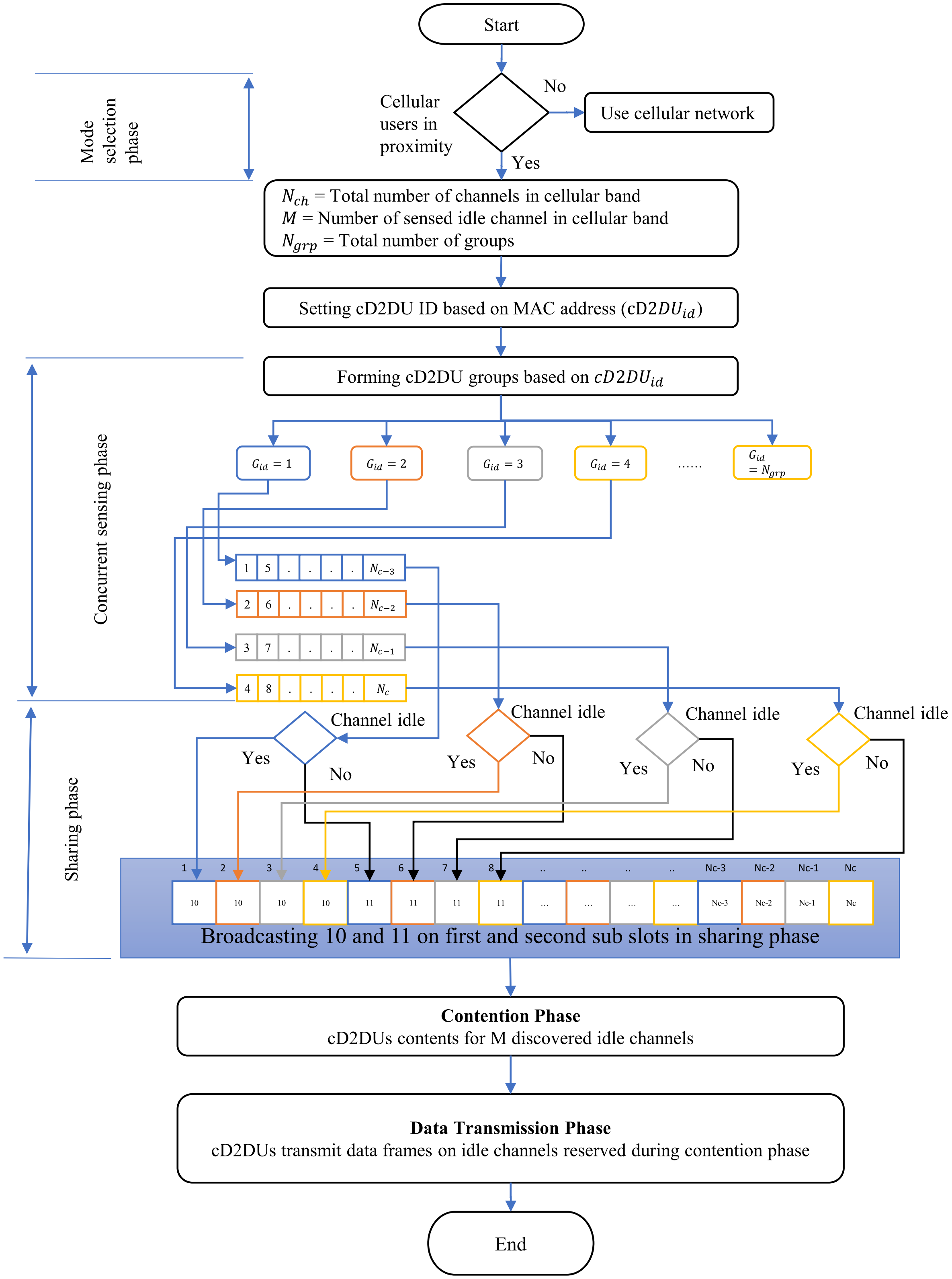

FIGURE 5 Flow diagram illustrating the sequential steps involved in the Mode Selection, Concurrent Sensing, and Sharing phase of the proposed protocol.

sequentially shared in the sensing phase timeframe, following the sequence 1, 5, 9, 13, …, $N_c - 3$. Assuming that channel 1 is idle and channel 5 is busy, the corresponding slots in the sharing frame would be configured as 10 for idle and 11 for busy. Similarly, the channels sensed by group 2 during the concurrent sensing phase are shared in the sensing phase time frame in the following sequence 2, 6, 10, 14…, $N_c - 2$ and are assigned the corresponding slots with channel 2 set as 10 (idle) and channel 6 set as 11 (busy).

In contrast to the sensing strategy utilised in ref. [32], the proposed approach significantly reduces the overall duration of the sensing phase to a quarter by organising the cD2DU units into four concurrent groups. During the sharing phase (T_{sr}), the sensing results from the four concurrent groups are sequentially shared. The number of slots in T_{sr} corresponds to the channels in the cellular user band, and the procedure for sharing the status of channels as busy or idle remains consistent with that in ref. [32]. Subsequently, the idle channels obtained from the sharing process form the contention interval. The contention and data transmission processes align with the description provided in ref. [32]. The formation of cD2DU groups based on the Group ID, concurrent sensing strategy, and sharing process is also depicted in the flow diagram illustrated in Figure 5.

By introducing more groups in the concurrent sensing phase, as depicted in the flow diagram presented in Figure 5, the duration of the sensing phase is reduced, thereby increasing the data transmission time. Mathematically, the data transmission time can be expressed as follows:

$$\mathbf{T}_{tr} = \mathbf{T}_{cycle} - (\mathbf{T}_i + \mathbf{T}_{cs} + \mathbf{T}_{sr} + \mathbf{T}_{ct}), \tag{1}$$

The values of T_{cycle}, T_i, T_{sr}, and T_{ct} remain unchanged, consistent with the values reported in ref. [32]. However, the duration of the concurrent phase is calculated as follows:

$$\mathbf{T}_{cs} = \left(\frac{\mathbf{N}_c}{\mathbf{N}_{grp}}\right), \tag{2}$$

Here, N_c represents the total number of channels in the cellular user band, while N_{grp} denotes the overall number of concurrent groups formed.

4 | SIMULATION RESULTS

The network employs the user channel model described in ref. [36] to determine the duration T_{cycle} for the cD2DUs to detect the presence of cellular users. It assumes that the arrival of cellular users follows an exponential distribution with rate λ. The probability P_i of cD2DU interfering with a cellular user is calculated using the cumulative distribution function when the inter-arrival time (T_{int}) of the cellular user is less than or equal to T_{cycle}.

$$\mathbf{P}_i = \mathbf{P}\left(\mathbf{T}_{int} \le \mathbf{T}_{cycle}\right) = \mathbf{1} - \mathbf{e}^{-\lambda \mathbf{T}_{cycle}} \tag{3}$$

By evaluating Equation (3), we get the value of T_{cycle}:

$$\mathbf{T}_{cycle} = -\ln\left(\frac{\mathbf{1} - \mathbf{P}_i}{\lambda}\right) \tag{4}$$

Table 2 provides a summary of the critical simulation parameters for the assessment of our suggested method.

It is crucial to keep in mind that the ratio between the sensing phase time and the data transmission time in CR MAC can significantly affect the network's performance. The amount of time available for data transmission will be shortened by a longer sensing phase time, which may result in a reduction in the network's total throughput. There would be more time available for data transmission if the sensing phase time is shorter. Introducing a concurrent sensing group during the sensing phase allows each cD2DU in the group to sense the assigned number of channels simultaneously, thereby reducing the overall duration of the sensing phase. This reduction in the sensing phase duration extends the data transmission time. Thus, this increase in the transmission time can improve throughput as it allows for more data to be transmitted within a given period. This is because the longer the transmission time provides more opportunity for data transmission. Additionally, longer transmission times enable the transmission of more packets, potentially increasing throughput.

Figure 6 shows that data transmission time increases as the number of concurrent groups in the sensing phase increases from 1 to 10. It is assumed that the total transmission time for the transmission of one frame is 1 s, that is, $T_{cycle} = 1$. Whereas the effect of creating concurrent groups can be seen as an enhancement in the data transmission time. Data transmission time is 89.8% seconds for group $N_{grp} = 1$ and data transmission time is increased to 94.8% for $N_{grp} = 2$. Similarly, the data transmission time is 96.5% for $N_{grp} = 3$, and so on. Finally, for $N_{grp} = 10$, the data transmission time is almost 98.8%.

The SMC-MAC protocol [32], which is equivalent to the single concurrent group of the proposed model, is now used to compare the results. Figure 7 depicts the relationship between data transmission time in the proposed concurrent sensing strategy and the sensing strategy employed in the SMC-MAC protocol. The results reveal that the transmission time in the SMC scheme is shorter compared to our proposed work. However, the true advantage of our sensing scheme in terms of communication effectiveness becomes evident when considering the overall system throughput.

TABLE 2 Simulation parameters.

Parameters	Name	Value
Channels in the cellular band	N_c	50
Available contention slots	M	25
Concurrent groups	N_{grp}	{1, 2, …, 10}
Number of users	*cD2DUs*	50

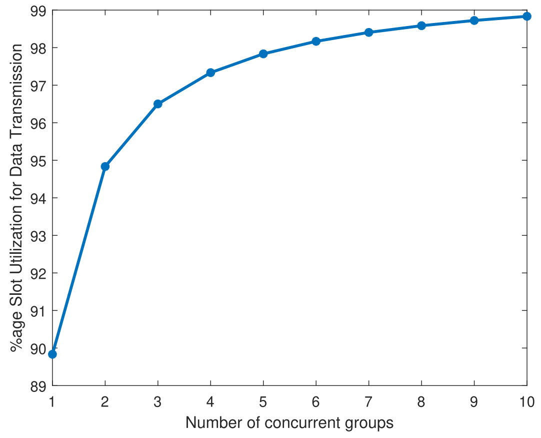

FIGURE 6 Increasing concurrent number of groups improves slot utilization percentage.

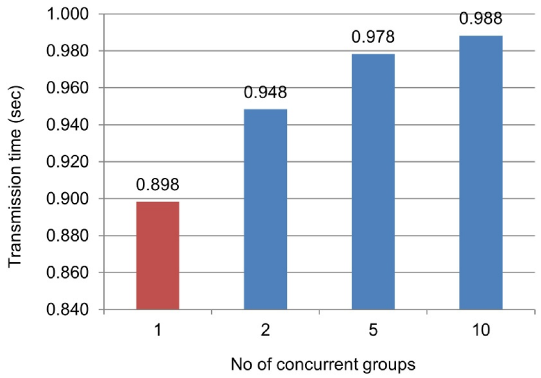

FIGURE 7 Comparison between sensing schemes and transmission time.

Figure 8 shows that the system throughput increases as the number of cD2DUs grows. This is because with more number of cD2DUs in the system greater number of channels are being utilised for communication. The better system throughput with our proposed sensing scheme compared to SMC-MAC is the consequence of an efficient sensing strategy, which leaves more time for data transmission.

5 | CONCLUSION

In conclusion, this research paper presented a novel concurrent sensing strategy for cD2DN at the MAC layer. By forming concurrent groups of cD2DUs, the proposed strategy effectively reduced the overall sensing phase time, leading to increased data transmission time and improved network throughput. Through extensive simulations and performance evaluations, we compared the concurrent sensing strategy with the sensing scheme in the SMC-MAC protocol. The results demonstrated the superiority of our proposed strategy, showing significant enhancements in system throughput compared to the existing scheme. This research contributes to the advancement of spectrum sensing techniques in cD2DNs,

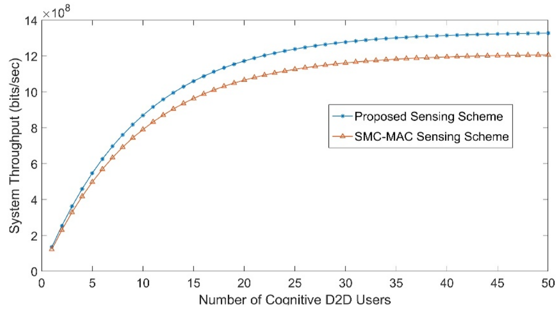

FIGURE 8 Throughput comparison between the proposed sensing scheme and SMC-MAC. SMC-MAC, Self-scheduling multi-channel cognitive MAC.

offering practical implications for improving spectrum utilisation and communication efficiency. Further research can be conducted to explore additional aspects such as energy efficiency, interference management, and the impact of varying network scenarios on the proposed strategy.

AUTHOR CONTRIBUTIONS

Irfan Latif Khan: Conceptualization; Formal analysis; Methodology; Visualization; Writing – original draft; Writing – review & editing. **Adeel Iqbal**: Conceptualization; Formal analysis; Methodology; Software; Writing – original draft; Writing – review & editing. **Ali Nauman**: Conceptualization; Investigation; Methodology; Project administration; Supervision; Writing – original draft; Writing – review & editing. **Muhammad Ali Jamshed**: Data curation; Funding acquisition; Methodology; Project administration; Supervision; Writing – original draft; Writing – review & editing. **Atif Shakeel**: Conceptualization; Formal analysis; Project administration; Visualization; Writing – original draft; Writing – review & editing. **Riaz Hussain**: Conceptualization; Formal analysis; Methodology; Resources; Supervision; Writing – original draft; Writing – review & editing. **Adnan Rashid**: Conceptualization; Data curation; Investigation; Validation; Visualization; Writing – original draft; Writing – review & editing. **Tommaso Pecorella**: Methodology; Writing – original draft; Writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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