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A Survey of Channel Bonding for Wireless Networks and Guidelines of Channel Bonding for Futuristic Cognitive Radio Sensor Networks

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***Abstract*—Channel bonding (CB) is a proven technique to increase bandwidth and reduce delays in wireless networks. It has been applied in traditional wireless networks such as cellular networks and wireless local area networks along with the emerging cognitive radio networks. This paper first focuses on providing a survey of CB schemes for traditional wireless networks such as cellular networks, wireless local area networks and wireless sensor networks, and then provides a detailed discussion on the CB schemes proposed for cognitive radio networks. Finally, we highlight a number of issues and challenges regarding CB in cognitive radio sensor networks and also provide some guidelines on using CB schemes in these futuristic networks.**

***Index Terms*—Channel bonding; cognitive radio; dynamic spectrum access; wireless sensor networks; ad hoc networks; channel aggregation.**

I. Introduction

Channel bonding (CB) is a technique to combine a set of contiguous non-overlapping wireless channels in order to create a single channel of higher bandwidth, and when no more required, this bond can be broken to free up the constituent narrow-band channels. CB offers significantly larger bandwidth for data transfer than what is available through multiple individual channels [1]. CB is a promising solution to transmit large chunks of data (or burst of packets) within a small duration.

A. Motivation: Need of Channel Bonding in Wireless Networks

CB has been used in many types of wireless networks such as wireless local area networks (WLANs), cellular networks, wireless sensor networks (WSNs) and cognitive radio networks (CRNs). Although these wireless networks have been widely researched, it is important to use effective spectrum assignment techniques to support channel bonding, and thereby, improving spectrum utilization. For instance, the cellular networks, which are now implementing Long Term Evolution-Advanced (LTE-A) and femto cells, are providing high bandwidth to their users by combining both contiguous and non-contiguous channels [2]–[4]. Wireless computer networks are also introducing new standards like IEEE802.11ac which is capable to provide flexible channel assignments for both adjacent and non-adjacent channels [5].

In the context of cognitive radio (CR) based networks, dynamic spectrum access (DSA) has turned out to be a promising approach for communication in those bands where radio spectrum is already overcrowded [6]. This approach has already shown a positive impact on the power consumption levels, network life time and the interference faced by its member nodes. DSA can be implemented easily in CRNs as CR nodes can change their operating parameters in order to dynamically tune into a free channel [7]. The benefits of CB in CRNs include larger bandwidth, less complexity and higher channel capacity for the equal amount of transmission power [8]. However, CB-aware CRNs also face certain challenges like security threat from malicious users [9], optimizing the number of CR nodes in a given network for efficient DSA [10], cooperation within a group of CR nodes [11] and co-existence with other networks [12].

WSNs have attracted a lot of attention in industrial automation [13], defense applications [14], utility metering and home automation [15], just to name a few. A WSN has event-driven communication patterns and generally yields a ‘bursty’ type of traffic when deployed in a multi-hop topology i.e. where information is relayed through multiple intermediate nodes [16]. Therefore, the transmission medium is generally under-utilized after the burst has been transmitted. The worldwide frequency utilization measurements [17] also show that wireless nodes generally face contention in a limited range whilst other portions of the spectrum remain vacant. This generates a need to allocate the available resources more efficiently. Experimental measurements show that spectrum sharing (under defined power restrictions) can offer significant frequency reuse opportunities [18] and go smoothly without creating any harmful interference or congestion problems hence contiguous channels can be combined using CB to improve spectrum utilization. However, though effective, implementing CB in WSNs has a number of challenges that need to be addressed. Some of the important challenges are to reduce energy consumption, to minimize interference, to avoid contention and to maximize the use of limited bandwidth assigned to the given network [19].

WSNs enriched with the additional capabilities of cognitive radio has led to the evolution of cognitive radio sensor networks (CRSNs) [20], [21]. Wireless Sensor Nodes are now equipped with DSA that can efficiently utilize both the

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Acronym	Definition	Acronym	Definition
ACI	Adjacent Channel Interference	LB	Load Balancing
APD	Average Packet Delay	LTE	Long term evolution
BFC	Best fit Channel Selection	LTE-A	Long Term Evolution Advanced
BP	Blocking Probability	MAC	Medium Access Control
CB	Channel Bonding	MIMO	Multiple Input Multiple Output
CR	Cognitive Radio	MPDU	MAC Protocol Data Unit
CRAHN	Cognitive Radio Ad hoc Network	MRP	Markov Renewal Process
CRN	Cognitive Radio Network	NC	Network Capacity
CRSN	Cognitive Radio Sensor Network	OFDMA	Orthogonal Frequency Division Multiple Access
CT	Convergence Time	PR	Primary Radio
CWA	Channel Width Adaptation	QoS	Quality of Service
DSA	Dynamic Spectrum Access	RSSI	Received Signal Strength Indication
DR	Delivery Ratio	TL	Traffic Load
GSM	Global System for Mobile Communications	WBAN	Wireless Body Area Network
GC	Guard Channels	W-CDMA	Wideband Code Division Multiple Access
HSPA	High Speed Packet Access	WiFi	Wireless Fidelity
IC	Independent Carrier	WLAN	Wireless Local Area Network
ISM	Industrial, Scientific and Medical band	WMN	Wireless Mesh Network
JC	Joint Carrier	WSN	Wireless Sensor Network

TABLE I
LIST OF ACRONYMS AND CORRESPONDING DEFINITIONS

licensed and the unlicensed bands. Due to potential advantages of CRSNs, it can be deployed in many applications [16]. CRSNs having high bandwidth requirements, for instance, wireless multimedia sensor networks (WMSNs) can get benefit of CB approach to satisfy network requirements. Wireless Body area networks (WBANs), emerging as promising approach for ubiquitous health monitoring systems [22]–[24], are also an application area of CRSNs and CB plays an important role for providing high bandwidth to these systems. CB in CRSNs also face certain challenges which are needed to be optimized for its wide applicability in future applications. The major challenges are adjacent channel interference (ACI) between neighboring channels [25] or bonds, energy [26] and transmit power [27], to name a few.

All the acronyms along with their definitions have been provided in Table. I.

B. Contribution of this survey article

In this survey, we provide a comprehensive discussion on channel bonding schemes for wireless networks and make the following contributions:

- We provide an in-depth discussion of basics, benefits, challenges, limitations and related concepts of channel bonding.
- We provide a survey of existing channel bonding approaches for cellular networks, WLANs, WSNs and CRNs.
- We discuss in detail the channel bonding schemes for cognitive radio sensor networks.
- We provide some guidelines on the channel bonding for cognitive radio sensor networks.

C. Article structure

The next section i.e Section II discusses the related work; Section III provides background on wireless networks and major requirements in their applications; CB is introduced in Section IV; CB schemes in the cellular networks, WLANs, WSNs, CRNs, and CRSNs are discussed in Sections V, VI, VII, VIII and IX respectively; Section X provides the guidelines on using CB for CRSNs, and Section XI concludes the paper.

II. RELATED WORK

CB schemes have been widely studied in the literature for various wireless networks. However, the literature on CB schemes is relatively scarce in a sense that it lacks a thorough survey of CB techniques. A list of the existing surveys on CB schemes is summarized in Table. II for various types of wireless networks. The table shows that while a number of surveys focused on channel aggregation (a concept to be introduced later), the discussion on channel bonding remains scarce.

Survey on bandwidth aggregation approaches is presented in [29]. Bandwidth aggregation in heterogeneous wireless networks provides performance enhancement such as increased throughput, improved packet delivery and load balancing etc. It, at the same time, introduces additional complexity such as packet re-ordering and increased battery power consumption.

References	Considered Network	Publication Year	CB	Channel Aggregation
[28]	WSNs	2007	✗	✓
[19]	WSNs	2011	✗	✓
[29]	Wireless Networks	2012	✗	✓
[4]	LTE-A	2014	✓	✓
[3]	LTE-A	2014	✗	✓

TABLE II
COMPARISON OF SURVEYS ON CHANNEL BONDING AND CHANNEL AGGREGATION

The paper highlights the need to develop bandwidth aggregation solutions to get maximum benefit of aggregation strategy. Bandwidth aggregation is different from CB that in bandwidth aggregation, a node having multiple interface terminals can transmit data parallel on all available channels, hence providing load balancing, whereas CB physically bonds the contiguous available channels to make a broadband channel. An in-network aggregation survey is presented in [28]. The in-network aggregation scheme tries to reduce the traffic over the network by merging the data into lesser number of packets or by using compressing techniques. It not only reduces the overall traffic flow but also increases the network life time. Routing protocols and data representation techniques play major role in in-network aggregation and as more sophisticated routing protocols are being proposed, in-network aggregation is also growing to become more effective and mature.

A comprehensive survey on multi-channel based channel aggregation is discussed in [19]. Channel aggregation is a scheme of utilizing multiple non-contiguous available channels hence providing higher throughput and load balancing. Multi-channel approach using channel aggregation is an efficient approach of minimizing interference and contention caused by large number of sensors deployed within a specified area. The taxonomy of channel aggregation schemes has been presented and it is concluded that most of the schemes do not consider the switching channel overhead and channel overlaps. More work is required in this area to consider all the fundamental requirements of channel aggregation.

Two of the relevant works in this context are [3] and [4], where both have focused on channel aggregation techniques. In [3], authors classified various spectrum aggregation schemes and revealed that channel aggregation is a powerful mechanism of improving throughput, however, the rate of throughput increase does not follow the same pattern in case of high traffic flow. One more important aspect to maximize throughput while minimizing the control overhead is to assign as few channels as possible to conserve signal processing complexity and the node's battery power. [30] has investigated the impact of CB on IEEE802.11n, where two 20MHz channels can be combined to form a 40MHz channels. By contrast, [17] has discussed the issue of guard band awareness while implementing CB in CRNs. In [4], authors have provided a survey of challenges which are raised by application of carrier aggregations and CB on shared access and unlicensed bands. Carrier aggregation schemes can be used to aggregate multiple non-contiguous carriers in licensed and unlicensed bands where as CB scheme is used to combine multiple non-overlapping contiguous channels to make a single broadband channel. Moreover, the carrier aggregation approach is at MAC level while CB is applied on the physical layer [31]. Lin. et. al. have elaborated that channel aggregation and bonding are promising trends in the next generation of cellular networks that will satisfy high QoS requirements in future. It is also highlighted that due to the dynamic nature of shared spectrum and the presence of cognitive nodes, new channel aggregation and CB schemes should be developed.

This paper is an attempt to provide a comprehensive survey on CB schemes for cellular networks, WLANs, WSNs, and CRNs.

III. BACKGROUND: WIRELESS NETWORKS AND MAJOR REQUIREMENTS IN THEIR APPLICATIONS

A. *Wireless Networks*

Wireless networks have basically emerged from two different communities - telecommunication networks and computer data networks. The telecommunication networks, standardized by International Telecommunication Union (ITU), have been evolved over time from first generation networks to the fourth generation (4G) networks, and already planning towards the fifth generation (5G) of networks. The examples of telecommunication-based wireless networks include GSM (second generation network), WCDMA (from 3rd generation), and the LTE networks (amongst the fourth generation). In the computer-based wireless data networks, WiFi (the IEEE-802.11 family) and Bluetooth (the IEEE-802.15 family) have experienced enormous expansion in the last decade [32]. Most of the handheld personal devices are nowadays equipped with both types of networks, for example, various smart phones and personal tablet devices have in-built support for the GSM, WCDMA, Bluetooth and WiFi networks. This has resulted in generation of huge data traffic over the whole radio frequency spectrum that was primarily dedicated for these wireless networks. However, it is interesting to note that most of the data traffic is generated in bursts, and usually do not require a dedicated frequency spectrum for a very large duration. Therefore, cognitive radio networks (CRNs) have been developed to utilize these spectrum bands opportunistically.

B. *Cognitive Radio Networks*

CRNs consist of two type of nodes: primary radio (PR) and cognitive radio (CR) nodes. The PR nodes have the first

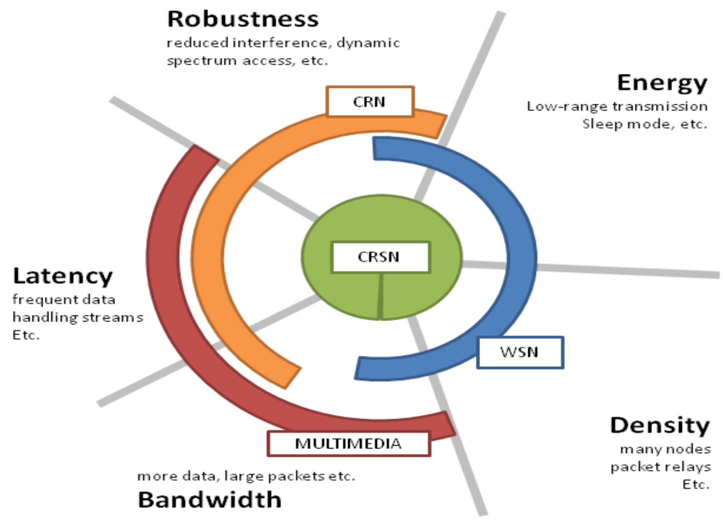


Fig. 1. Types of wireless networks and major requirements in their applications

right to use the given frequency band (usually a device with the paid license) while, unlike the PR nodes, a CR node can only use the licensed spectrum when it is not in use by the PR nodes (a.k.a. opportunistic access). The CR nodes are designed with the cognitive abilities to sense spectrum availability and to dynamically tune their operating frequency to utilize the available spectrum [33]–[38].

A number of methods for spectrum sensing has been discussed in [39] which evaluates the concepts of spectrum opportunity and spectrum sensing whilst considering different dimensions of spectrum space. The performance of wireless transmitter can be improved by performing selection of strongest channel as proposed in [40] where the strongest channel can be identified without probing and avoiding any overhead. Optimal spectrum sensing can be performed using energy detection in coordination with cooperative sensing [41]. Liang et al. suggested that the energy detection with cooperative sensing can achieve 90% of accuracy in spectrum sensing, provided the signal-to-noise ratio (SNR) of PR nodes is known at the CR nodes. The accuracy of spectrum sensing algorithm in TVWS is measured in [42] and collected signal traces from a large area to be added in the database. The optimal size of CR-generated frames can be determined by approximating the optimal tradeoff between throughput and number of packet collisions [43]. Ref [44] suggested that available spectrum can be efficiently utilized by reducing the time taken by the first step in CR communication i.e. detecting spectrum holes. A trade-off between the time duration for both steps needs to be investigated.

In 802.22-based CRNs, channel sensing is performed periodically by using two interfaces to support simultaneous data transmission and spectrum sensing. One interface can use a bidirectional antenna for communication and the other interface can use an omnidirectional antenna to perform spectrum sensing [45]. This standard also supports fast sensing and fine sensing to improve the performance and reducing the signaling overhead for spectrum sensing. In this regard, [46] proposed a scheme, called "KNOWS", that has been implemented to effectively utilize the available bandwidth according to user's preference. If there are few users in the system, KNOWS implements CB and provides each user with a larger chunk of bandwidth. It dynamically provides smaller chunks to all users if there are more contending nodes. [47] suggested a more efficient scheme named as fine-grained spectrum adaptation (FSA) in which per-frame basis spectrum assignment has been performed. This technique optimizes frequency diversity and interference by using fine grained spectrum sensing.

The major challenge in CRNs is to avoid potential interference caused by the CR nodes i.e. sometimes the CR nodes access a channel that is already occupied by another node (usually the PR node).

C. Wireless Sensor Networks

A wireless sensor network (WSN) is a combination of many autonomous small computing nodes (called motes) deployed over an area or a region [48]–[56]. These small motes can be deployed for large number of applications, for example, indoor sensing, industrial automation, forest fire detection, remote surveillance, and collecting weather information [57]–[64]. Although the requirements for each of these applications vary to great extent, majority of these applications require high bandwidth, low latency, network robustness, energy conservation, and simultaneous access from several nodes with in a small geographical area (i.e. high density or mesh networking). Before discussing these requirements, we briefly describe some important terms below in the context of WSNs.

Bandwidth: Bandwidth is the capacity of a link to transceive data between (or among) nodes. The large bandwidth requirement in WSNs is increasing day by day as more networks are being deployed for multiple purposes. Each network has to utilize its assigned spectrum band and node density in the network is defined in such a way that the number of transmitting node should not exceed the available bandwidth.

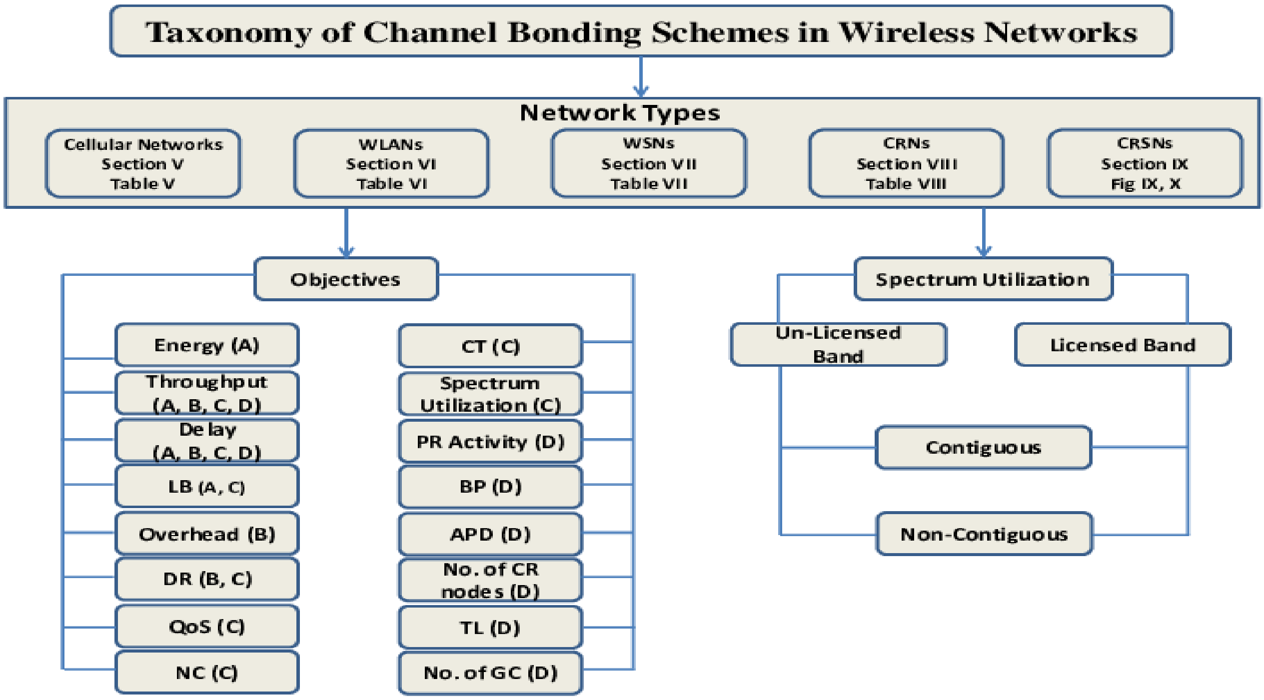


Fig. 2. Taxonomy of Channel Bonding schemes in wireless networks (and their coverage in this paper) Objectives of channel bonding schemes may vary from network to network. Thus, to highlight this, we use different terminology. We use 'A' to highlight the objectives considered in Cellular Networks, 'B' to highlight the objectives considered in WLANs, 'C' represents the major objectives of WSNs, 'D' is used for the objectives of CRNs and 'E' highlights the objectives considered in CRSNs.

Latency: Latency is the amount of end-to-end delay between sender and receiver which is a well-known measure in the field of digital networks. In the context of WSNs, several protocols have been developed to allow fast data transfer between the nodes, and hence, reducing latency in these networks.

Robustness: Robustness is the ability of a network to continuously perform its operations without degradation. The robustness itself has two aspects of reliability and resilience. Reliability of a network is the ability to operate continuously without errors and the resilience aspect deals with its ability to operate under constrained environment e.g. any failures or catastrophe. WSNs are usually designed to be more resilient as compared to their wired counterparts, and also other wireless networks, as they are usually deployed in harsh environments and are required to transmit their sensed data for a long period of time in any kind of climate conditions.

Energy consumption: Energy consumption is another important objective to be optimized as most of the wireless sensor nodes are battery-powered devices and therefore need to be either recharged or replaced after a defined life span. Whilst consuming energy for the purpose of sensing, WSNs cannot afford to dissipate too much for the purpose of communication. Therefore, energy constraints have been much investigated at all the layers of these networks [14], [65], [66].

Congestion: As discussed earlier, WSNs have a specific density constraint where the number of nodes in a given region is usually much higher than the number of nodes in a conventional wireless network. This introduces the problem of congestion where too many nodes have too few bands to share amongst each other. Therefore, a new concept has recently emerged wherein the sensor nodes are proposed to have CR capabilities so that available radio spectrum can be efficiently utilized.

Although developing a cognitive radio sensor network (CRSN) has a benefit of efficient spectrum utilization, there exists a number of challenges to be addressed before making best use of this concept. For example, energy consumption is an important consideration as the nodes cannot use their limited battery power to continuously sense the spectrum for opportunistic access. There exists a need to propose novel techniques to reduce both the computational and spectrum sensing overheads.

D. Main Requirements of Wireless Applications

Fig. 1 shows the five main requirements of wireless applications and also attempts to map different networks on these requirements. For example, a real-time video surveillance system would require high bandwidth and low latency due to audio and video streams that must be transmitted in real-time (see MULTIMEDIA on bottom-left). By contrast, a network of sensors (see WSN on right side of the figure) to monitor climatic conditions may have totally different requirements. They may not require high bandwidth due to handful of readings that are usually transmitted at regular intervals (for example, on hourly basis). Also, these readings

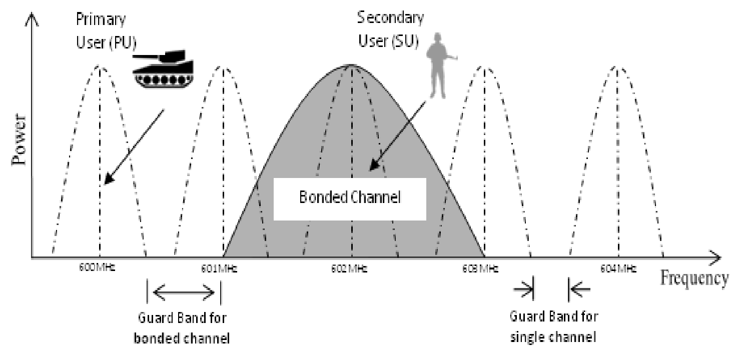


Fig. 3. Channel Bonding in a Battlefield Scenario

do not have strict latency requirements as weather monitoring and forecasting do not have urgent deadlines (in milliseconds). However, unlike multimedia devices, these WSN devices may have strict energy constraints and may be deployed in a dense configuration. These two requirements suggest low-range transmission antennas for these devices and a support for packets relay. An important thing to note is that CRSNs lie at the center of these requirements as all these requirements are equally important for their successful implementation.

IV. Channel Bonding: Basics, Benefits, Challenges, Limitations & Related Concepts

In Fig. 2, we have provided taxonomy of CB schemes. The objectives of CB have been listed which can be achieved when applied to range of networks as shown in figure. By implementing CB in cellular networks, WLANs, WSNs, CRNs and CRSNs, one can satisfy the requirements of bandwidth-hungry nodes. CB is arguably the only solution for problems where there is a big chunk of data to be sent, and contiguous small channels are available to be bonded together. Once the data have been transmitted, the bond can be broken and individual channels can be used again by different users. The CB schemes can be classified on the basis of different network types. The objectives of implementing CB vary according to different network types and their requirements, and therefore, there are usually multiple objectives to achieve which can be prioritized according to the network type. For example, energy consumption may be the most important objective in one scenario while some other scenario may consider energy to be the least important criterion. The spectrum selected for CB can be either licensed or unlicensed or both, which can be used to make a bond of available contiguous free channels.

Consider a battlefield scenario, imagine that a set of multimedia sensors has been attached to infantry which transmit the audio-visual data to other nodes in the network. These multimedia sensors will only transmit when infantry gets some data to be sent; thereby generating bursty traffic in a multi hop manner. Suppose the armor units have been configured as the PR nodes and the infantry units as CR nodes in this particular scenario. Since the amount of data containing multimedia information is expected to be large in size, these sensors need a wider frequency band unlike the other sensors. Therefore, CB will be a good option to meet the frequency demand of CR nodes (infantry) as shown in Fig. 3. Here it can be noticed that a wider guard band is required at the edges of bond as compared to when channel is single. This is due to the reason that spectrum spill-over occurs during signal filtering, and to protect the neighboring PR/CR communication, a wider separation is required [17]. As the channel width increases (larger bond size), the chances of frequency leaks also increase monotonically, and so a wider guard band is required for larger bonds [67]. The issue of guard band size selection is of a dynamic nature which is monitored by channel bonding scheme. The size of guard band is adjusted in such a way to protect adjacent communications from ACI [68].

The concept of CB is not just restricted to the battlefield scenario; it can be used at numerous places; for example, in hospitals [1], for habitat monitoring [69], and health monitoring of civil infrastructures [70], etc.

CB helps to enhance the throughput as channel width increases. According to Shannon's capacity formula, the increase in channel width proportionally increases throughput but practically throughput increases slightly less than the increase in channel width due to overheads generated by medium access control (MAC) protocol. MAC is responsible for transmission of data without any collision over the channel in cognitive networks [71]. Various channel sensing and decision making schemes are available for this purpose. In these schemes, each node negotiates with other nodes to utilize a channel for data transmission. This negotiation generates control overheads over the network particularly when user wants to do multi-hop communication. Nonetheless, CB can still provide larger bandwidths and reduce power consumption in wireless networks [67]. However, in the context of CRSNs, we need to investigate whether the same relationship between throughput and channel width exists considering the specific set of constraints faced by CRSNs.

A. Benefits of Channel Bonding

CB can be used to improve the bandwidth, to minimize delay, and to increase overall throughput. The algorithm for CB should also have low complexity in order to reduce overall power consumption of nodes. Therefore, a combination of robust channel sensing and a low complexity CB algorithm is necessary to get these benefits.

1) Bandwidth Improvement: CB is used to change the channel width which in turn effects different network parameters such as capacity, power consumption, transmission range etc. A wider channel can bear a large chunk of data to be transmitted [67]. In a sensor network environment, generally sensors are densely deployed in random topology, so the same transmission power can be maintained if a low transmission range is required. Fig. 4 shows bandwidth improvement which can be utilized by multimedia sensors having large burst to be transmitted. Suppose that frequency channels CH2 and CH3 are free from any PR activity (Fig. 4(a)) and be utilized by any CR node, they can be combined to make a bond as shown in Fig. 4(b).

2) Delay Minimization: By implementing intelligent CB, the transmission delay can be minimized as large bandwidth becomes available so data is transmitted at higher rate [72]. Consider a hospital environment where several types of medical equipment send their data to the central control, and possibly the data center. Assume that there are four frequency channels in the network and packet transmission time for each channel is T, and the channels CH1 and CH4 are occupied as shown in Fig. 5(a) while CH2 and CH3 are free. Now if a sensor gets some data (for example, an MRI image) to transmit, it can sense the two channels CH2 and CH3 as free and contiguous, and therefore, can be combined to get a larger bandwidth. The CH2 and CH3 bond is now providing almost double bandwidth so the data transmission time will be reduced to T/2 (ignoring the overheads for simplicity) and the same data gets transmitted with almost half the normal time of delivery (Fig. 5(b)).

3) Throughput Maximization: A bonded channel as shown in Fig. 5 is providing larger bandwidth and less transmission delay. As larger bandwidth implies higher number of bits being transmitted per unit time, the use of CB provides higher bandwidth and more data can be transmitted with in the same time. By increasing the bandwidth, the overall transmission delay gets reduced, and therefore it is less probable to cause contention to other nodes.

One can use CB if an increased bandwidth is required to send a large chunk of data over the channel, following which the system will deliver higher transmission rates and improved performance [30]. By incorporating an increased bandwidth upon user requirement, the advantage of adaptive bandwidth and adaptive data rate [73] is achieved and user can dynamically select the bond size. In this way, the throughput of the communication system can be maximized [70] and end to end delay can be minimized [72] keeping in view the system limitations.

B. Challenges of Channel Bonding

For efficient CB, it is required that the channel sensing scheme should be intelligent enough to provide reliable information of channel condition [74]. In an efficient CB scheme, nodes are well aware of their neighborhood and the corresponding channels that help them in utilizing the resources in an effective way [75]. This effective utilization can benefit all the applications which require large bandwidth to transmit their data, specifically for multimedia applications.

1) Is RSSI an effective performance indicator?: Received signal strength indicator (RSSI) provides information of signal quality and usually it corresponds to the distance between transmitter and receiver. In IEEE 802.11n networks, the node throughput does not always monotonic with RSSI and it can deviate as per RSSI foot prints. It is possible that a node showing low RSSI can transmit at higher throughput than a node having good RSSI. As RSSI alone is not an effective indicator of network performance so other parameters are also required [76].

2) Effect of MIMO technology in IEEE 802.11n for CB: Using MIMO technology in IEEE 802.11n, multi-path diversity plays a positive role in enhancing throughput of nodes by overcoming fading effects. It can also be adopted in other networks to mitigate fading effects. Moreover the problem of hidden terminal in shared channels should be investigated to realize the advantages of CB [76].

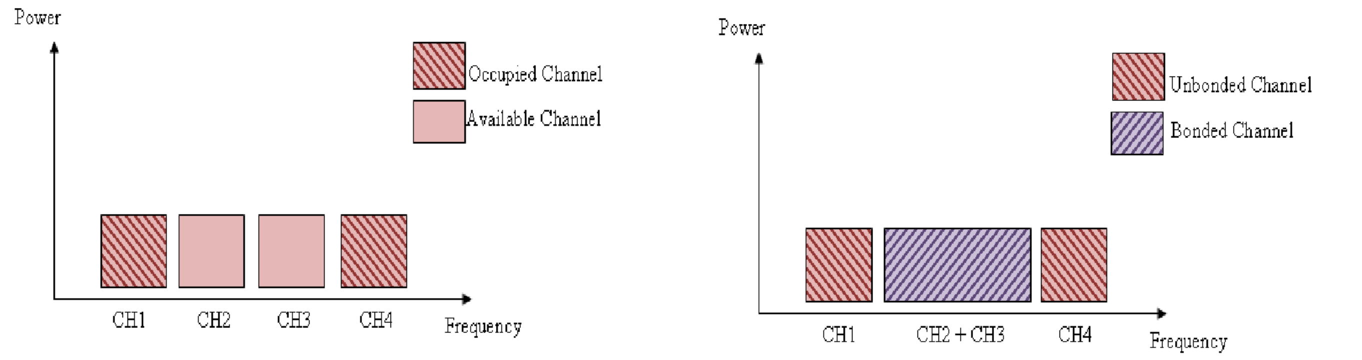
3) Choosing correct size of bond: The correct size of bond must be analyzed and chosen to achieve optimum throughput. It is quite possible that increasing the bond size may reduce the overall throughput of network. It is due to the fact that the bond may be causing harmful interference to adjacent channels or bonds. It is required that CB scheme should satisfy the node's demand choosing the maximum possible size of bond keeping the interference level below the certain threshold.

4) Mobility effects: It is expected that nodes in the network can be stationary as well as mobile. The CB scheme should be capable of providing seamless wide band connectivity with mobility. The issues of mobile nodes such as RSSI, fading and hidden terminal should be closely observed and addressed [67].

5) Power consumption: Any increase in the channel bandwidth implies that more power will be required by those sensor nodes to transmit their messages on wider channels. Also, in the case of frequent bond establishment and termination, some power is wasted due to the fact that nodes exchange control messages for channel sensing and utilization. Therefore, the main concern of any CB scheme is to reduce the overheads that are introduced when nodes coordinate about the condition of each channel in the available set of channels. The scheme should also be power efficient as it is main concern of wireless nodes to operate for a longer time period. Intelligent schemes are required to address these limitations of CB.

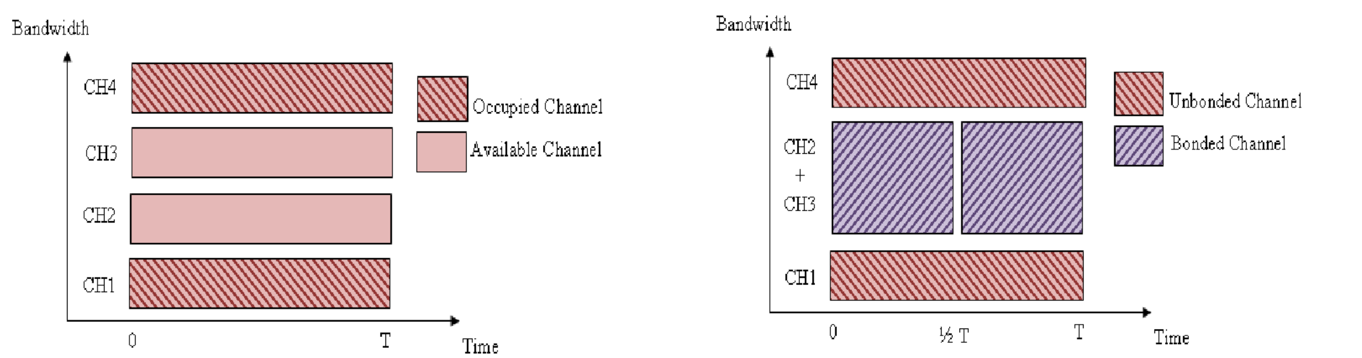
6) Dynamic network requirements: As the network requirements change, the requirements for CB also change accordingly. For instance, the requirement of better energy efficiency while performing CB in WSNs is crucial whereas it may not be an important factor in WLANs. Therefore, this dynamic nature of requirements introduce another challenge in CB i.e. the scheme should also react to the changes in network requirements and not only to the changes in the network itself.

These benefits and challenges are summarized in Fig. 6 for better understanding.



(a) (b)

Fig. 4. Bandwidth Improvement using Channel Bonding



(a) (b)

Fig. 5. Delay minimization using Channel Bonding

C. Limitations of Channel Bonding

Along with providing the benefits of high bandwidth, CB schemes introduce certain limitations and challenges. These limitations incur due to hardware and software changes required at transmitter and receiver. As CB is applied at physical layer so single MPDU is transmitted to multiple channels but separate modulators are required for each channel to be bonded together. Since it has a single bit-interleaver for all the channels, it has a larger combined bandwidth than a single channel however the throughput may severely degrade in the case when there is a significant difference of signal interference plus noise ratio (SINR) present among the channels [31].

While applying CB on multiple contiguous channels, guard bands are required to mitigate adjacent channel interference (ACI) and to protect neighboring PR/CR communications. Guard band is such a separation which keeps two bonded (or un-bonded) blocks at a safe distance to each other to avoid ACI. The addition of guard bands adds the constraint of effective spectrum assignment and utilization. It is required that channel bonding schemes consider the guard band issue while assigning the channels to CR users. Guard band reuse can be a good approach to avoid resource wastage. In this regard, a single guard band can be assigned between two adjacent bonds [17].

Security is a vital issue for any network stability. [77] has shown that CB schemes can cause the loss of orthogonality between the bonded channels which can be exploited by attackers to cause service disruption. The experiments have been performed for LTE-A and HSPA+ networks and loss of throughput due to security vulnerability has been presented.

It is required that CB schemes should be well-aware of these limitations and provide solutions to achieve maximum benefits of CB approach.

Next, we discuss a brief comparison of CB and channel aggregation and show how CB can be applied with low complexity and with less power consumption.

D. Channel Bonding and Related Concepts

In this section, the terminologies related to CB are defined explicitly and their comparison with CB has been discussed as follows: These concepts have been summarized in Table. III.

References	Channel Bonding (CB)	Channel Aggregation (CA)	Channel Asssembling (CAs)	Channel Width Adaptation (CWA)	CB as CA
[78]		✓			
[68]	✓	✓			
[79]		✓			
[80]					✓
[81]		✓			
[82]	✓	✓			
[4]	✓	✓			
[83]			✓		
[84]				✓	
[85]				✓	
[3]		✓			
[86]		✓			
[87]		✓			
[88]		✓			
[89]			✓		
[90]					✓
[91]		✓			
[47]				✓	
[76]	✓				
[2]		✓			
[31]	✓	✓			
[91]		✓			
[92]		✓			
[29]		✓			
[93]		✓			
[1]	✓				
[8]					✓
[10]					✓
[94]			✓		
[95]		✓			
[30]	✓				
[77]	✓	✓			
[96]		✓			
[9]	✓				
[97]	✓	✓			
[98]		✓			
[67]				✓	
[72]	✓				
[99]					✓
[100]		✓			
[74]	✓				
[73]				✓	
[101]				✓	
[25]				✓	
[102]		✓			
[103]		✓			
[104]	✓				
[105]				✓	
[106]	✓				
[107]	✓				
[17]	✓	✓			
[108]	✓				
[109]	✓				
[110]		✓			
[111]	✓				
[112]	✓				
[113]		✓			
[114]		✓			

TABLE III
CB = Channel Bonding, CA = Channel Aggregation, CAs = Channel Assembling, CWA = Channel Width Adaptation
Channel Bonding and related concepts: This table overviews the work done for channel bonding and related concepts.

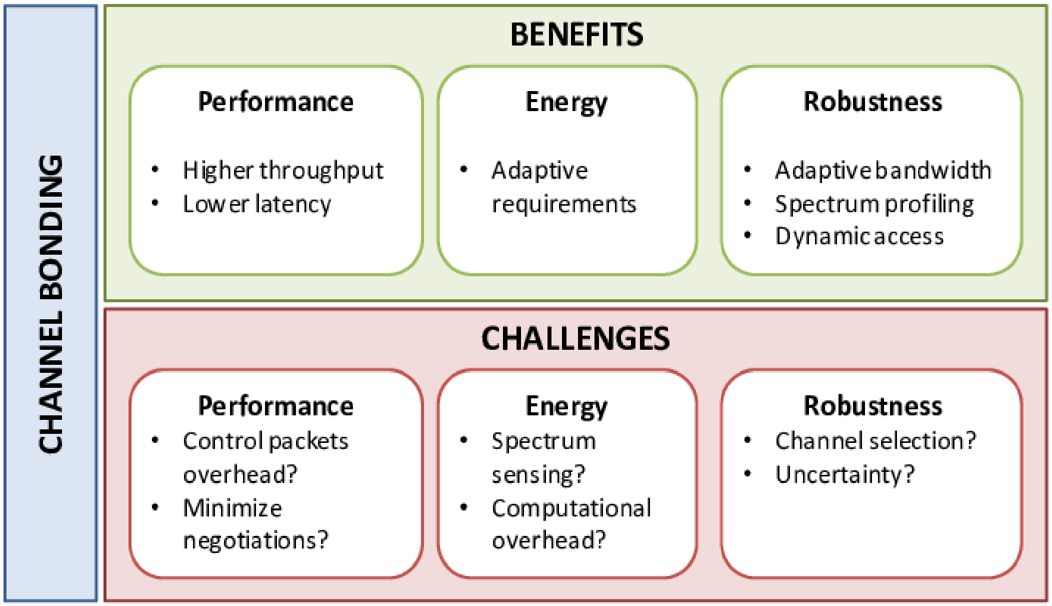


Fig. 6. Benefits and Challenges of Channel Bonding in Wireless Networks

1) Channel Aggregation: Channel Aggregation (CA) is a scheme to combine multiple non-contiguous channels hence differentiating with CB. Channel aggregation is more complex and costly than CB approach [98], primarily due to the requirement of having more intelligent schemes for channel management, scheduling and load balancing. As discussed in [93], a dynamic spectrum management (DSM) engine is required to aggregate television white space (TVWS) spectrum. The non-contiguous channels can be aggregated by DSM and performance of the system can be increased. The availability of white space can be determined over the internet and a database proposed in [95] can be used for its efficient utilization. Complex techniques deployed for channel aggregation introduces delay in the system. A scheme proposed in [92] named MC-MLAS can reduce this latency and decision making can be performed in real time. An optimal channel aggregation system has been given in [91] and it does not require any intermediate hardware or modifications in operating systems. Also in channel aggregation, control messages exchange overhead increases with the increase in number of channels. Strategies for optimum channel selection can help to satisfy QoS requirements for channel aggregation in high speed networks [3]. In this regard, recently channel aggregation has also been adopted for future 5G networks [78].

For an efficient channel aggregation technique, more sophisticated and complex protocols are required to manage all the aggregated channels. It will introduce additional cost and delay in the system. In addition to these, a load balancing technique to manage traffic in all the channels and a scheduler will be required for channel aggregation. An energy efficient dynamic channel aggregation scheme has been proposed in [88] whereas in [31] authors have performed a comparison of MAC layer channel aggregation and PHY layer bonding for WLANs in TVWS and showed that CB has better performance as compared to channel aggregation. MAC layer aggregation transmits multiple MAC protocol data units (MPDU) simultaneously on all parallel aggregated channels however PHY layer bonding requires to transmit a single MPDU for a bond. The partially overlapped channels can be utilized without creating harmful interference using CoCast [115] - a multi-channel multi-cast protocol that effectively avoids ACI and frequency selective fading using parallel data block transmission in OFDM sub-channels. Two joint power-channel allocation schemes (CAD-MAC) have been presented by [87] which perform channel aggregation to increase the data transmission rate along with optimizing energy efficiency of cognitive ad hoc networks. Another channel assignment scheme has been proposed for channel aggregation in multi-channel systems [86] which maximizes the spectrum efficiency by minimizing the size of guard band required to establish a new link. The concept of channel aggregation has been elaborated by [29] in which multiple radio access technologies (RATs) can be combined to form a high speed logical channel. It can result into load balancing and to mininmize the amount of delay introduced by aggregation in the network.

2) Channel Bonding: CB is a technique to combine set of contiguous non-overlapping channels to make a bond of large bandwidth. CB and CA are two different techniques which have different requirements and prerequisites. CB needs to be applied on contiguous channels as shown in Fig. 7 whereas channel aggregation does not need contiguous channels. CB is more beneficent if we want to increase the system capacity. As stated above, Shannon's channel capacity formula gives channel capacity which is directly proportional to bandwidth.

The purpose of CB is to increase the bandwidth by making a bond of contiguous channels, hence the system capacity increases with the number of bonded channels. [4] has provided a survey on CB scheme which enables the opportunistic users to co-exists with the licensed users. To avoid interference with

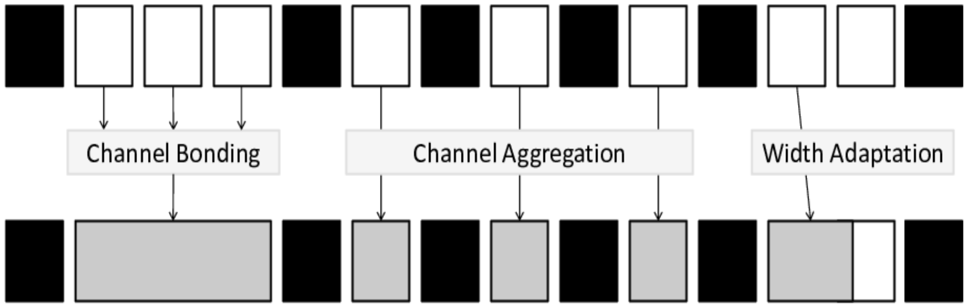


Fig. 7. Difference between Channel Bonding, Channel Aggregation, and Channel Width Adaptation

the adjacent channels, guard bands are required at the edges of bonds whereas the guard band in between the channels can be used and will be assumed to be the part of bond. This will lead to approx. 10% extra capacity as compared to channel aggregation. CB does not introduce any additional overhead as control information is required only at the making and breaking of bond.

The flexibility of changing channel width and creating a bond can be harmful for security as intruders can utilize the band and can attack to disrupt the services. Here attackers can severely damage the service quality by transmitting using low transmit power and will be difficult to get identified [82]. Secure schemes are needed to be developed so that system may get secure from such attacks.

3) Channel Assembling: The two terminologies of CA and CB collectively can be called as channel assembling [83] where the concept of priority based queue has been introduced for PR and CR traffic types and priorities. It has also been demonstrated that with longer queue size, the blocking probability of CR traffic can be reduced in the network but it will add delay in the network so the size of the queues can be adjusted by optimizing delay and blocking probability. Channel assembling along with fragmentation can also improve efficiency of the network given that QoS requirements of the network are satisfied [89].

4) Channel Width Adaptation: Channel width adaptation (CWA) scheme allows to modify the width of channel dynamically according to application's requirement. By using channel width adaptation, throughput can be adjusted hence energy of node can be conserved [67]. A channel width adaptation scheme has been given in [85] which dynamically adapts the channel condition and adjusts the traffic flow in IEEE802.11 based systems. The OFDMA based channel width adaptation can perform even better if the traffic demand for each link is given. It has been performed on WMN traffic and can be extended to other networks too [84]. Table. III shows how these terminologies of CB, channel aggregation, channel assembling and channel width adaptation are adopted in the literature.

Next, we discuss channel bonding schemes in cellular networks, WLANs, WSNs and CRNs. A comprehensive summary of channel bonding schemes has been presented in Table. IV

V. Channel Bonding Schemes in Cellular Networks

Khan et.al. [4] has raised a need to develop new methods for CA and CB to satisfy the spectrum need of next generation cellular networks. These methods can be applied to both licensed and un-licensed bands (as shown in Fig. 2) to achieve maximum benefits of available resources.

The smart devices utilizing new generation facilities are mostly battery-powered and therefore face serious energy conservation issues. In this situation, increasing bandwidth without compromising transmission power can consume significant amount of energy which will affect the on-air time of device. Therefore, novel techniques are required that should not only provide the pervasive data access but should also be energy efficient. A traffic aggregation scheme for smart devices has been presented in [100] where an efficient search algorithm has been tested hence minimizing the energy consumption and delay in the network whereas a clustering based technique is given by [116], which can be used to provide high bandwidth. Hence, CB schemes can be helpful in providing energy efficient solution to the users. The recent shift of research towards high bandwidth applications has highlighted the importance of CB.

[82] has performed an analysis of security vulnerability while implementing channel aggregation/bonding. It has been observed that algorithms are needed to be developed to secure the spectrum from attacks of malicious users while implementing CB in order to get maximum benefit in terms of throughput. Carrier aggregation has been very promising in providing high data rate applications in LTE-A networks . [2] has performed an up-link performance evaluation while implementing carrier aggregation and observed the behavior of LTE-A with high mobility. Another channel aggregation scheme providing energy optimization has been provided by [88] which proposes two energy efficient schemes joint carrier (JC) and independent carrier (IC). Such schemes for CB are needed to be developed so that CB can be applied in energy efficient way and utilize spectrum effectively. In this scenario, [67] has presented a scheme for channel width adaptation for wireless networks. Chandra et. al. also discusses the unique feature of adapting channel width in which taking energy into consideration, throughput can be adjusted according to system

Work	Network	Year	L/UL	Description
[78]	Cellular	2015	L/UL	This paper discusses spectrum aggregation methods for future 5G cognitive cellular networks
[81]		2015	L	This paper discusses energy-efficient carrier aggregation scheme for uplink and downlink
[4]		2014	L/UL	This paper surveys CA/CB techniques for next generation cellular networks
[100]		2014	L	The authors in this paper discuss scheme to optimize energy for traffic aggregation in cellular networks
[116]		2014	L	This paper discusses promising channel segmentation using data clustering in cellular networks
[88]		2014	L	In this paper, authors present dynamic carrier aggregation scheme to improve energy efficiency of cellular networks
[82]		2014	L	This paper highlights security vulnerabilities in CA/CB methods
[2]		2013	L	This paper discusses carrier aggregation for LTE-A for future cellular networks
[67]		2008	L	This paper takes CB as case study to improve throughput in WLANs
[117]		2009	L	This paper discusses CB as application aware technique in WLANs
[77]		2011	L	This paper discusses the issue of security vulnerability due to CB in LTE networks
[118]		2006	L	This paper takes CB approach for achieving improved transmission rates in cellular networks
[72]	WLANs	2007	UL	Authors in this paper present a comparison of CB and multi-channel CSMA for WLANs
[73]		2013	UL	This paper discusses CB method for channel width adaptaion for 802.11 networks with MIMO technology
[76]		2013	UL	This paper focuses on a case study for intelligent channel bonding in 802.11 WLANs
[84]		2014	UL	This paper discusses OFDMA based CB scheme for Wireless Mesh Networks
[10]		2012	UL	This paper provides an analysis of CB scheme for opportunistic spectrum access networks
[8]		2012	UL	This paper discusses CB scheme for TV white spaces in 802.11af networks
[101]		2011	UL	This paper studies throughput maximization problem to optimize for efficient CB
[90]		2013	UL	In this paper a partial spectrum correlation method is proposed to implement dynamic CB
[31]		2013	UL	This paper provides a comparison of MAC aggegation and physical bonding for WLANs
[25]	WSNs	2009	UL	This paper is focussed on providing QoS for multi-channel Ad-Hoc networks using CB
[119]		2005	UL	This paper presents CB as a bandwidth sharing approach for improved utilization of licensed spectrum
[99]		2007	UL	This paper discusses CB to maximize throughput for multi-radio mesh networks
[104]		2008	UL	This paper discusses CB as load aware technique for WLANs
[120]		2009	UL	This paper is based on joint channel assignment scheme and routing protocol for IEEE 802.11 networks
[105]		2009	UL	This paper discusses QoS aware CB scheme for multi-radio Ad-Hoc networks
[106]		2010	UL	This paper characterizes the link quality of 802.11n network when CB is applied for high data rates
[107]		2008	UL	This paper discusses the objective of interference avoidance and control for CB based methods
[30]		2011	UL	This paper discusses the impact of CB schemes on IEEE 802.11n network management
[68]	CRNs	2015	L/UL	This paper focuses on the size of guard band with CB for DSA networks
[79]		2015	L/UL	This paper discusses spectrum aggregation based cooperative routing protocol for CRAHNs
[80]		2015	UL	This paper discusses a case study for non-contiguous CB for TV white space with NC-OFDM transmission
[108]		2006	L/UL	This paper discusses IEEE802.22 as first wireless standard on CR which supports CB
[121]		2007	L/UL	This paper focuses on interference aware medium access with CB for dynamic spectrum sharing
[109]		2007	UL	This paper discusses CR based multi-channel MAC protocols to enhance throughput in wireless Ad-Hoc networks
[110]		2008	UL	This paper presents a scheme HC-MAC for efficient spectrum management
[111]		2007	UL	This paper proposes a segment-based channel assignment scheme for CB in CRAHNs
[122]		2008	L/UL	This paper discusses the issue of adaptive link maintenance for CR based networks
[17]		2013	UL	This paper discusses the guard band awareness problem for spectrum bonding in CR networks
[112]		2006	UL	This paper discusses cognitive behaviour of Phy and MAC layer for DSA in TV bands
[123]		2009	UL	This paper provides an insight to cognitive frequency hopping based on interference prediction
[113]		2008	L/UL	This paper discusses CB approach for narrowband friendly wideband networks
[97]		2010	UL	This paper provides an analysis on CB/CA schemes for multi-channel CRNs
[114]		2010	L/UL	This paper discusses the overlay structure for DSA in cognitive femtocell networks
[124]		2009	UL	This paper presents conceptual design and issues of CR based WSNs to implement CB
[96]		2011	UL	This paper discusses dynamic channel aggregation schemes with spectrum adaptation in CRNs
[125]		2009	UL	This paper discusses the issue of admission and eviction control problem of CR nodes to optimize CB

TABLE IV

SUMMARY OF CHANNEL BONDING SCHEMES FOR DIFFERENT WIRELESS NETWORKS. WE CLASSIFY CHANNEL BONDING SCHEMES AS LICENSED AND UN-LICENSED BANDS AS SHOWN IN FIG. 2. IN THIS TABLE WE USED 'L' FOR LICENSED AND 'UL' FOR UN-LICENSED FOR CHANNEL BONDING SCHEMES IN WIRELESS NETWORKS.

References	Energy	Throughput	Delay	Load balancing	Security
[78]	✓	✓			
[81]		✓			
[4]		✓			
[100]	✓		✓		
[116]	✓				
[88]	✓	✓			
[82]		✓			
[2]		✓			
[67]				✓	
[117]	✓	✓			
[77]					✓
[118]		✓			

TABLE V
PERFORMANCE METRICS FOR CHANNEL BONDING IN CELLULAR NETWORKS

requirements and hence dynamic channel width can conserve significant amount of energy. A more suitable approach to provide short-term dynamic channel access is provided by [117]. It can be used on multiple channels when there is intermittent PR traffic (to be discussed later) over the spectrum and channels became free for a small amount of time. It is evident from Table. V that throughput and energy consumption are the two major issues which have been under consideration of researchers while implementing CB for cellular networks.

A. Summary

CB and channel aggregation in cellular networks are the requirements of present applications. Users want to achieve high throughput for all applications they are running on smart phones along with low power consumption. The latest standards have given the provision of integrating these schemes, now it is required that promising CB and channel aggregation schemes should be developed. The future of cellular networks lies in providing high speed applications which will revolutionize the whole cellular network industry.

VI. CHANNEL BONDING SCHEMES IN WIRELESS LOCAL AREA NETWORKS

CA and CB schemes can be seen as two effective solutions to handle the ever-increasing demand of high-bandwidth networks. IEEE 802.11 specification for WLANs suggests two approaches to combine multiple available channels for increased data rate. One is the multi-channel technique, which enables a single node to simultaneously use multiple channels for communication, as seen in IEEE 802.11s which defines how devices can connect making a wireless mesh network (WMN) and can be utilized by static or ad hoc networks [126]. The multiple channels need not be contiguous in the multi-channel technique. The other one is to use CB technique, in which a number of contiguous frequency channels can be combined together, as shown in Fig. 7, to make single broadband channel, as seen in IEEE 802.11n [127]. Both approaches have their benefits and limitations, for example, the multi-channel approach attempts to minimize traffic congestion whereas the CB approach attempts to increase the throughput [72]. CB can utilize both licensed and unlicensed bands [4] where contiguous channels can be found and assigned to CR nodes opportunistically. In wireless mesh networks, the use of multi-channel multi-interface [128] can also be a good approach for increasing the throughput. In this scenario, neighboring nodes should not share the same channel in order to allow parallel packet transmission. When two neighboring nodes try to occupy the same channel, only one of them should transmit.

In traditional wireless standards IEEE802.11a/b/g having Single Input Single Output (SISO) systems, CB results in reduced transmission range. While in IEEE802.11n, the Multiple Input Multiple Output (MIMO) smart devices reduce the sacrifice of transmission range providing the true benefits of CB [30]. Using IEEE802.11n standard, CB may become intelligent if neighboring nodes information is provided to transmitter. The essential neighboring information can be listed as signal strength of links, interference patterns and channel utilization. Thus intelligent CB will eventually result in effective utilization of bonded channels and reduced power consumption [76]. Another intelligent scheme ARAMIS is presented by [73] which impressively gets performance gains while adapting the data rate and bandwidth and dynamically optimizing the performance over changing channel characteristics of wireless networks. A spectrum adaptation scheme for IEEE802.11 devices has been given in [85] which dynamically adapts to prevailing traffic and channel conditions as compared to conventional IEEE802.11 systems. If the traffic demand for each link in a WMN is given then an OFDMA based channel width adaptation technique [84] outperforms the MAC protocols based on traditional channel-width adaptation. The implementation of CB in wireless networking standards i.e IEEE802.11n, IEEE802.11ac and IEEE802.22 has been discussed in [10] and it has provided with a conclusion that CB can be beneficial to enhance throughput where there is low PR activity while in case of dense presence of PR nodes, CB may result into throughput loss in the network. [8] has discussed the opportunity of CB provided by IEEE802.11af for TV white spaces can also improve throughput and it is proposed that two OFDM based techniques namely fixed carrier spacing (FCS) and fixed carrier numbers (FCN) can be used for this purpose. Increasing throughput directly impacts the transmission range of communication channels and [101] has proposed to optimize this tradeoff. It is evident from Table. VI that throughput is the most widely investigated indicator by researchers to improve performance of WLANs whereas delay, transmission overhead and delivery ratio (DR) are less used parameters.

A. Summary

To summarize the discussion, when high throughput is required in WLANs, CB is a good solution. Throughput is most widely used parameter which is under consideration when CB is used in WLANs. The tradeoff between high throughput and transmission range is needed to be optimized so that a user can get highest possible throughput using CB while consuming least transmission power.

VII. Channel Bonding Schemes in Wireless Sensor Networks

As conventional WSNs do not consider the presence of any PR activity; all the nodes are considered to have same priority when accessing the available channels. In this scenario, if the traffic is low, CB may be preferred in order to increase the bandwidth [129], [130]. However, in the case of high traffic, CB may lead towards high number of collisions due to lesser number of channels being shared by multiple nodes. The multi-channel technique, on the other hand, is able to handle high traffic demands from multiple nodes. All such network systems, having fixed number of channel widths, face a tough choice between transmitter range and power consumption. In case of WSNs, power consumption becomes a serious issue due to the batteries of limited capacity, installed at each node. Increasing the transmitter power may increase the communication range but at the expense of higher power consumption, eventually reducing the service life of the node. A possible answer to satisfy these constraints is to use CB that can dynamically adjust the channel width, when and as required. We can make a bond of contiguous channels when high throughput is required, and the bond can be broken after data transmission is completed. [67] has shown the method of adaptive channel width allocation in IEEE802.11b/g which can be adapted for WSNs keeping in view the constraints specific to the WSNs. Another dynamic CB scheme has been proposed by [90] that focuses on multicarrier wireless networks. The proposed scheme can perform well in WSNs and play an important role in reducing contention in wideband spectrum sharing and achieving fast spectrum agreement. However, to quantify the performance of any protocol, specific metrics need to be chosen depending upon the type and requirement of that particular protocol.

Channel selection and bonding in WSNs can be gauged using various metrics that have been defined in the literature. As shown in Table. VII, we can choose throughput as most widely used metric to evaluate the performance of CB. It is due to the reason that definition of CB is to increase the throughput of the network so it becomes the basic check whether increasing the bandwidth of a channel is allowing user to send more data or not. Throughput can be seen as a performance indicator as it has been used by more than half of the authors; however spectrum utilization has also attracted the attention of some researchers. In addition to throughput, other metrics have also been used in the literature. Another commonly used metric is spectrum utilization whereas end to end delivery ratio (DR), delay, load balancing (LB), network capacity (NC) and convergence time (CT) are less commonly used parameters. The purpose of all these metrics is to collectively evaluate the performance of network while increasing the bandwidth dynamically. Next we discuss these metrics in detail:

Throughput is indeed the most widely used performance matric by researchers. It reveals the purpose of CB to enhance achieved data rate in WSNs. [67] has done a comparison on the impact of CB and proves that throughput over a channel increases with channel width but number of users and distance between the nodes play an important role to estimate throughput. The combination of throughput, number of nodes and the distance between the nodes has collectively called as load balancing. Other works such as [30], [99], [103], [106], [107], [117], [119], [120], [131] also have focussed throughput while studying CB.

The under utilized spectrum by cellular networks can be effectively used by wireless sensor nodes [119] using DSA approach and CB scheme enhance throughput of nodes. [104] has discussed the problem with fixed channel assignment that it does not effectively utilizes the spectrum. In contrast, using dynamic spectrum allocation can assign the vacant slot to CR nodes which can effectively utilize the channel by using CB. In the same fashion, [132] has proposed a spectrum auction scheme (VERITAS) which assures that spectrum is efficiently utilized and assigned to those users only who qualify to access the channels.

Delay is a fundamental parameter while considering the performance of any network. Embedding CB scheme in a network may have a significant impact over propagation delay. A user can experience more delay if there is large PR traffic over the network [119], however in case of low PR traffic the propagation delay can be minimized by using CB scheme. [120] has revealed in his work that non-overlapping channels can be used simultaneously which will not only enhance throughput but will also reduce end-to-end delay.

Other performance metrics which have been used by researchers include load balancing (LB), network capacity (NC), quality of service (QoS), delivery ratio and convergence time (CT). Many authors such as [25], [102], [105] and [106] have considered these parameters for network performance optimization.

References	Delay	Throughput	Overhead	Delivery Ratio
[72]	✓	✓		
[128]	✓		✓	✓
[73]		✓	✓	
[76]		✓		
[84]		✓		
[10]		✓		
[8]		✓		
[101]		✓		
[90]		✓		
[31]		✓		

TABLE VI
PERFORMANCE METRICS FOR CHANNEL BONDING IN WIRELESS LOCAL AREA NETWORKS

A. Summary

All the performance metrics mentioned above (cf. Section VII and Table VII) have the same objective i.e to provide better services by meeting user requirements. Indeed, throughput is the most widely used performance indicator which is the main reason that research is focusing towards increasing throughput by applying CB schemes in WSNs. The dynamic channel width property of CB can also be significantly used to optimize the relation of throughput and power consumption.

VIII. CHANNEL BONDING SCHEMES IN COGNITIVE RADIO NETWORKS

CRNs are generally composed of two types of nodes: primary radio (PR) nodes and the CR nodes. Those users having a valid license to use the band are usually termed as the primary users [7]. They have a priority to access the channel over those users which do not have the license – generally called the CR users or secondary users. CR capable nodes can be made to operate in licensed bands, as well as in the unlicensed bands.

In literature, various models have been used to imitate the activity of PR nodes, like Bernoulli Process [133], Markov Renewal Process (MRP) [134], Deterministic Process [135], M/M/1 [136], M/G/1 [137] etc (as shown in Fig. 2). Out of these models, the model of MRP has been widely used (See [46], [138] for details). The ON/OFF PR activity model approximates the spectrum usage for CRNs. MRP has also been used for IEEE802.11b/g (WiFi) [139], voice networks [140], [141] and the patterns of communication in public safety band [142], [143]. Consider a frequency channel that remains occupied for 3 minutes on average and then remains unoccupied for next 2 minutes on average. In such a scenario, when a CR node wants to communicate, the probability of finding the channel vacant is highly dependent on the current state (i.e. whether vacant or occupied) and the total duration of renewal (i.e. going back to the vacant state). MRP assumes an exponential distribution for both the vacant and occupied states of the channel. MRP is applied where most applications involve processes in which a transition from a state to itself is possible and these states should be finite [134].

The PR activity patterns are generally categorized into four major types: long-term, high, low and intermittent activities. The four types are also shown in Fig. 8 for better visualization. The long-term activity is generated by those nodes that has long ON and long OFF periods. This type of activity can be seen in the cellular networks scenarios where users are subscribed to special packages e.g. free call packages. In high PR activity, the channel has long active time but much shorter OFF periods. This can be seen in a highly congested urban area where all the channels are mostly occupied. In low PR activity, the channel has short ON and long OFF periods. This type of PR activity can be observed in remote areas or during less peak hours. In the intermittent activity, the channel has short ON and short OFF periods. This type of PR activity can be observed where users use the channels for very short period of time e.g. at bus stations or railway stations [144].

These days most of the wireless equipments are using Industrial, Scientific and Medical (ISM) radio band for communication. Due to humungous increase in the Wi-Fi and Bluetooth enabled devices, the ISM band of 2.4 GHz have started becoming overly saturated. This is the reason that, nowadays, unlicensed traffic has been allowed to operate in the TV broadcast range. The spectrum dedicated for TV broadcasts can be used for data communication in a cognitive way [46]. However, it has introduced certain new challenges: first, the CR nodes should be aware of TV broadcast traffic (through spectrum sensing); second, the CR nodes should be able to use the available bandwidth in an intelligent and efficient manner.

When dealing with multiple channels in CR network, channel assembling technique can get better performance as compared to unassembled channels [94]. The effectiveness of dynamic spectrum aggregation has been studied in [96] and results prove that dynamic schemes can achieve higher throughput than randomly combining the idle frequency slots and assigning them to contending CR nodes. One main concern, while enjoying the higher throughput, is the increased complexity. The dynamic schemes are more complex as re-

References	LB	NC	QoS	Throughput	CT	Spectrum Utilization	Delay	DR
[67]	✓	✓						
[25]			✓					
[102]					✓			
[119]				✓		✓	✓	
[103]				✓				
[99]				✓				
[131]				✓				
[104]						✓		
[120]				✓			✓	
[105]								✓
[117]				✓				
[132]						✓		
[106]				✓				✓
[107]				✓				
[30]				✓				

TABLE VII
PERFORMANCE METRICS FOR CHANNEL BONDING IN WIRELESS SENSOR NETWORKS

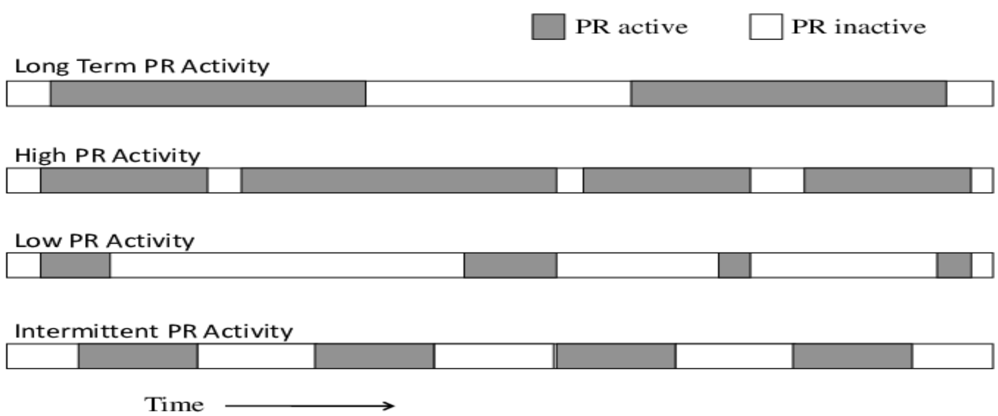


Fig. 8. Activity Pattern for Primary Radio nodes

quired number of handshakes are increased in dynamic CR schemes [145].

The concept of PR and CR nodes in a network make CB difficult to implement. Channel sensing and selection schemes (as discussed earlier) play vital role to provide opportunistic access to CR nodes. To access the spectrum while minimizing the interference caused by secondary users, two approaches have been discussed in [12] i.e. spectrum underlay and spectrum overlay. In spectrum underlay, the CR nodes can communicate with in a certain threshold to avoid interference but it limits the role of CB as maximum benefits of wideband cannot be achieved. Spectrum overlay limits the transmit power of secondary users so as to minimize the interference. However, the worst case is assumed for this technique that primary users will be communicating constantly. Spectrum overlay uses the concept of spectrum pooling in which cognitive radios seek spectrum holes for communication. Within such a hole, no restriction of transmission on secondary user is imposed. As discussed earlier, performance evaluation is necessary to check the effectiveness of CB. As in CRNs, the concept of PR and CR node activity exists so one cannot ignore these parameters while analyzing CRNs. The higher the number of active PR nodes at any given time, the lower the probability of contention. Therefore, the networks having low PR activity are considered to be suitable for CR nodes as higher throughput is achievable in such networks. If we assume that there is no PR activity, only the CR nodes will be contending for a channel, and will determine the throughput and bond size.

In CRNs, the CR nodes have to first sense the channel and in case of presence of PR activity, it identifies the type of PR activity present on the channel. The type of PR activity (please refer to sub-section 6.3 for detailed discussion of PR activities) is important for CR nodes to apply CB. Let us assume when a CR node senses a particular channel and long-term PR activity is identified. This type of PR activity is suitable to apply CB as there will long ON and long OFF periods on the channels. These long OFF periods can be utilized by CR node for CB. In a scenario where CR node detects short-term PR activity, it will be having short ON and short OFF periods. This type of PR activity is not suitable for CB as there will be very short periods available for CR nodes and very frequent bond establishment and termination will be required.

Table. VIII shows a summary of performance metrics while implementing CB in CRNs. It shows that various parameters affect the network performance in CR based network and throughput can be chosen as one of the most widely used performance metric. This is also visible in Table. VIII, however PR node activity and blocking probability can also be considered along with throughput for performance evaluation. Other commonly used metrics are blocking probability (BP) and PR user activity whereas average packet delay (APD), number of CR nodes present in the network, traffic load (TL), number of guard channels (GC) and delay are less widely used metrics. This trend also shows that while implementing CB, researchers are more interested in factors such as enhancing throughput , considering PR activity and blocking probability, as compared to various other performance indicating factors. All these metrics help to investigate the performance of CB, and to check the capacity of network to accommodate CB. These metrics have been discussed in detail as follows:

For CB in CR based networks, throughput has a tradeoff with number of contending CR nodes at any given time [109]. This is the reason why most of researchers have selected this parameter for performance optimization. [108] has discussed about IEEE802.22 the standard based on cognitive radios support DSA which can futuristically used for CB. [121] has reviewed DSA based approach as throughput-delay relationship in which maximizing one reduces the other. For efficiently utilizing the benefits of CB in cognitive networks, a throughput efficient scheme is presented by [74] which divides the spectrum in slots so that traffic over these slots can be sensed correctly and when slots found idle can be bonded for increasing bandwidth. Throughput has also been used as key factor for indicating performance by other researchers in the literature [17], [96], [110]–[113], [122]–[124].

As discussed in section 5.3, PR user activity has a large impact over the spectrum utilization by CR nodes as well as other CR related performance parameters also rely on activity pattern of PR nodes [146]. The CR nodes has to wait unless PR nodes vacate the spectrum [122]. This time duration impacts the performance of CR nodes which are continuously sensing the spectrum for utilization. Hence a low PR activity is desirable for CR nodes to maximize the opportunistic spectrum utilization [10]. The concept of cognitive femtocells has been proposed by [114] so that spectrum efficiency can be achieved in a smaller region and chances of opportunistic access increases as PR traffic is spread over a large region as compared to smaller cognitive femtocells.

Blocking Probability has also been considered an important candidate while considering for CB in CR based networks. When a CR node tries to access a channel it sets a probability known as blocking probability which depends on the type of PR traffic present on the channel. If there is high PR traffic over the channel, the value of blocking probability may be high. Blocking probability may also occur due to number of guard channels to avoid adjacent channel interference (ACI) [17]. Blocking probability is also concerned with number of available channels which are shared between PR and CR nodes [97]. If there are fewer parallel channel, blocking probability will be high. If blocking becomes too high it will result into dropping of packets. This situation needs to be avoided and should be optimized [125].

Some less widely used parameters are average packet delay (APD), number of CR nodes contending for the channel, traffic load (TL) and number of guard channels (GC) to avoid adjacent channel interference (ACI). Some researchers which have used these parameters are [121], [109], [114], [123], [108], [17], [111] and [112].

A. Summary

In CR based networks, the pattern of PR activity determines how effectively spectrum can be used by CR nodes. To this end, spectrum decision schemes are important to consider for efficient channel utilization. However, number of contending CR nodes for the spectrum will determine the size of bond. The future CB schemes for CRNs must ensure that the activities of PR nodes will not be affected along with providing required QoS for CR networks. To avoid any harmful interference to PR nodes, efficient and less complex spectrum sensing schemes are required. In the presence of many spectrum sensing schemes, it is required that a complete CB model should be proposed for CRNs which should be less complex meanwhile capable of optimizing the performance metrics as shown in Table. VIII.

IX. Channel Bonding Schemes for Futuristic Cognitive Radio Sensor Networks

CB in CRSNs has to cope with twofold issues [147]; firstly, it has to use low transmit power due to life time of the power-constrained sensor nodes; and secondly, it has to provide maximum capacity gain to CR nodes. Hence, we can say that we have to take all the issues of CRNs and WSNs while implementing an efficient CRSN. The efficient radio resource allocation in CRSNs is important due to the dynamic channel selection of CR nodes. A comprehensive survey on radio resource allocation in CRSNs has been presented recently in [148]. The survey covers the existing resource allocation schemes along with probing un-explored research directions such as inter-network interference and cross-layer resource optimization.

In the need for larger bandwidth, CB in traditional wireless networks is performed at data-link layer [112]. The data-link layer protocols, like media access control (MAC), usually establish a central node for decisions regarding channel selection and bonding. Although these schemes work quite well in traditional networks, the concept of self-organizing and self-healing nodes makes them inappropriate for CRSNs [14]. These protocols do not address the issues raised by topological

References	PR activity	APD	Throughput	BP	No. of CR nodes	TL	No. of GC	Delay
[78]			✓					
[68]			✓					
[79]			✓					✓
[80]								
[10]	✓		✓					
[72]		✓	✓					
[108]			✓			✓		
[121]		✓	✓					
[109]			✓		✓			
[110]			✓					
[111]			✓					✓
[122]	✓		✓					
[17]			✓	✓				
[112]			✓					✓
[123]			✓			✓		
[113]			✓					
[97]				✓				
[114]	✓				✓			
[124]			✓					
[96]			✓					
[125]				✓				
[74]			✓					

TABLE VIII
PERFORMANCE METRICS FOR CHANNEL BONDING IN COGNITIVE RADIO NETWORKS

changes and scalability, which can be addressed if channel selection and bonding are done at network layer.

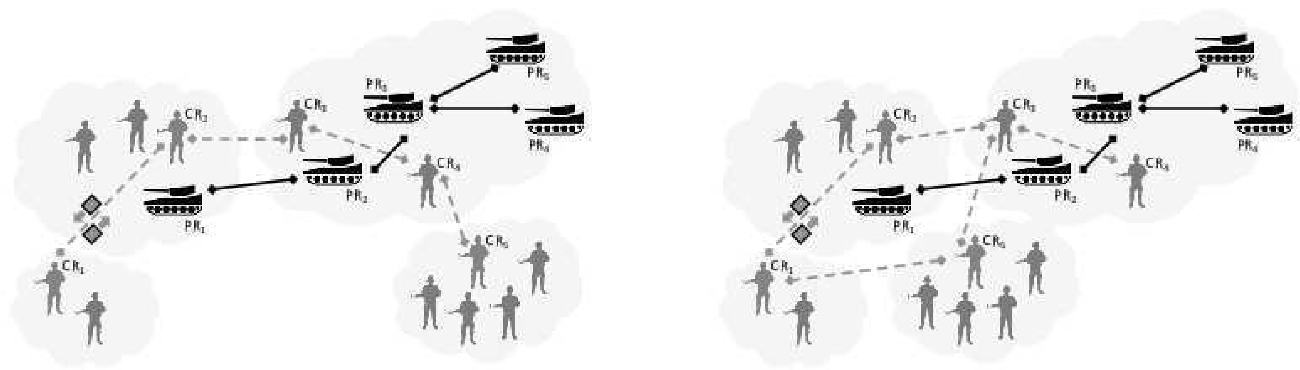
To our knowledge, there exists no protocol for CB in CRSNs. Hence, it is interesting to investigate whether and how CB can help CRSNs. To make this investigation more meaningful, we discuss it through the following example scenarios where sensor nodes have been replaced with CRSNs.

A. *CRSNs in a Battlefield Scenario*

Consider the battlefield scenarios in Fig. 9 where numerous sensor nodes have been attached with armor and infantry units in order to monitor various parameters like unit health, battlefield conditions, movements etc. Suppose the armor units have been configured as the PR nodes and the infantry units as CR nodes in this particular scenario. The connections between CR nodes have been mentioned by dotted lines whereas the communication between PR nodes has shown by plain lines. The infantry units are spread in the field for surveillance (or other military operations) and share their information with the other CR nodes in a multi-hop manner. For example, the soldier (labelled as CR1) on the bottom left of Fig. 9(a) is sending information to another soldier, labelled as CR5. CR nodes may also act as relay agents to forward information from distant nodes to a destination node. In this situation, CR nodes are sharing same set of available channels f_i for communication.

To effectively utilize the channel in opportunistic manner, a simplistic MAC protocol can be implemented to avoid collisions between contending CR nodes [149]. Due to the dynamics of battlefield, it is possible that the formation of nodes changes significantly. Consider the example of Fig. 9 where the formation of units changes from Scenario 1 (shown in Fig. 9(a)) to Scenario 2 (shown in Fig. 9(b)). Here, the group of soldiers on bottom-right has moved towards the center of the battlefield. Due to this movement, they may disconnect from CR4, and create a new connection with another node (CR3 in this case). CR1 is now in transmission range of CR5 so the two can also communicate now. CR5 can also relay data between CR1 and CR3. Hence, such networks may follow the concepts of self organization.

As discussed earlier, the multimedia sensors attached to infantry will only transmit when required; thereby generating bursty traffic. Considering the multimedia nature, the amount of information may be large enough so that a wider frequency band is required for these sensors, unlike the other sensors transceiving textual or other smaller messages. Therefore, CB will be a good option to meet the frequency demand of CR nodes (infantry) as shown in Fig. 3. CB is arguably the only solution for problems where there is a big chunk of data to be sent and contiguous small channels are available to be bonded together. Once the data has been transmitted, the bond can be broken and channels can be re-used individually by different



(a) (b)

Fig. 9. Wireless Sensor Network in a Battlefield Scenario

sensors.

When infantry units move in a battlefield, they may connect to new nodes and disconnect from the old ones, hence the dynamics of topology may change. In this scenario, the channel selection and CB should be performed at the network layer in order to grab the picture of the dynamically changing network.

B. CRSNs in Food Security

Transport of food items across the globe has remained a normal practice throughout the history of mankind. Due to their perishable nature, the freshness and quality of food items become a crucial issue as they directly impact the supplier's reputation and consumer's health. Perishable food items (for example, vegetables, meat, and fish) need a specific temperature and must be kept in a refrigerated container during transportation. WSNs have recently been introduced in this process where the temperature of each container, along with its location, is regularly sensed and monitored from a remote location [150]. Food can be monitored all the time and its quality can be maintained, hence improving the customer satisfaction and business growth [151]. WSNs can also be applied inside silage stacks to monitor any decomposition, oxygen level and temperature. It can ensure the freshness of food not only during transportation but in storage stacks too [152].

As shown in Fig. 10, a large number of containers are mounted on the ship for transportation. Each container is equipped with a CR node that collects the data from several other locally connected sensors within the container, and relays the information outside to the ship gateway. The ship gateway is then responsible to further transmit the information to remote locations. In this setting, it is quite possible that a CR node receives plenty of information from local sensors that cannot be transmitted on a single channel due to their limited bandwidths. In this case, the CR node can utilize the concept of CB to transmit the big chunk of data to the gateway. The gateway node may also perform CB to forward this data to a remote place (a control room or a data logging centre). Apart from data of containers, the ships gateways also play as relay agent and forward the important parameters of other nearby ships in the ocean, hence behaving like a true CRSN, an ad hoc network is constituted in the oceans in an opportunistic manner.

C. CRSNs in Railway Track Selection

Railway system plays an important role in transportation of goods in many countries. A train on its way has to change several tracks to reach its destination. This is a normal process and is executed several times on each junction everyday. The junction first senses the arrival of train, takes parameters from train to have a decision about the changing of track in the right direction, and then actuate the motors accordingly.

A practical implementation of CRSN can be done in the process of railway track selection. Normally this process is done by taking help of traditional wireless networks, or by using WSNs [153]. In both technologies, there is spectrum wastage in the absence of train. The efficient spectrum utilization can be made possible by implementing CRSN in trains as well as at railway junctions. When there is a train approaching a junction, the sensors deployed at the junction sense the train direction, speed and other related parameters. At this point, the sensors first perform the channel sensing process that whether the junction is allocated to some other train or not. If not, the channel is allocated to the arriving train. On getting a channel, sensors deployed in the train send request for the track selection on the junction, and the junction activate the appropriate motors to fulfil the request. Once the train has crossed the junction, the wireless connection is terminated and channel becomes free again. If the channel sensing process returns a busy signal it means that junction is busy and there is already a train on the track, the train can be parked at the backup track available at the junctions to avoid collision, waiting the other train to pass and then to utilize the junction when its available.

A junction is also collecting the important parameters from the tracks, as well as trains passing the junction. These parameters can track health monitoring, instantaneous speed of train while passing the junction, direction, weight loaded on train (to make relation between the train's weight, speed and track condition). All the junctions are collecting the information in the same manner and sending this information to other junctions (data sharing) and control centre (data logging). This information sharing requires a bond to transmit the large chunk

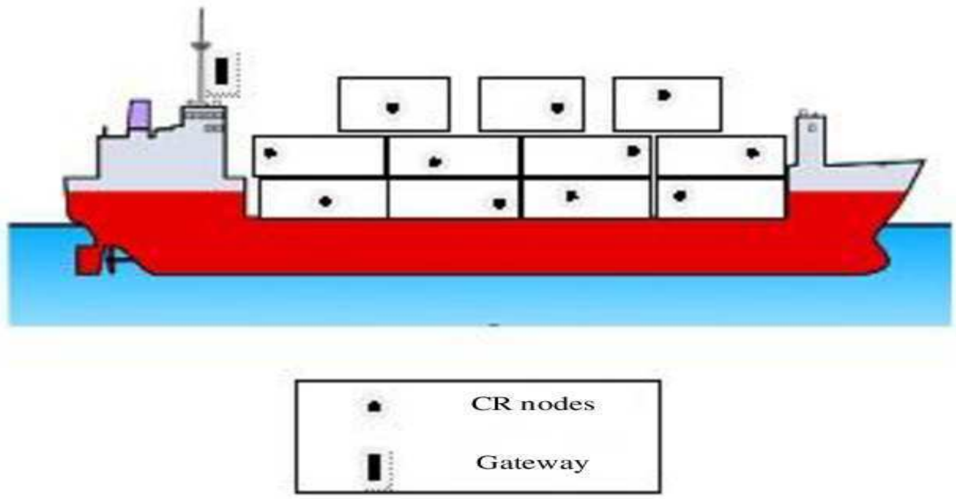


Fig. 10. Sensing Food Quality during Transportation

instantaneously so that every other node (junction) get its database updated. Also this bond can be setup when junction is idle and no train is present on it.

In this manner we can opportunistically utilize the spectrum only when the train is present. Also the number of accidents which happen due to mistakes of track selection at junctions can be avoided effectively.

D. CRSNs in Health care Monitoring

WSNs have been widely used in healthcare monitoring. The small-sized sensors and their wearable nature make them quite comfortable for the patients. The physicians also get the benefit of continuously monitoring the activities of human organs with the help of these sensors [154]. Presently, the sensors deployed for this purpose are meant to take the readings and store it in a data storing device (Holter Monitor) and patient need to visit the physician periodically to transfer that data into the hospital database. The other practise normally done is the use of GSM/GPRS modules to transmit this data wirelessly. If the patient is supported by GSM/GPRS module, any anomaly in the data can be taken as emergency and patient can be provided emergency treatment by the physician.

The above mentioned technologies have provided the life-saving services to the patients but the present technologies are not economically viable in many settings, especially the developing countries. Even in the developed countries, patients have to pay for the spectrum he/she is using, regardless of the fact that the sensors will be transmitting only in an emergency. If these wireless sensors get the cognitive radio capability, they can transmit anytime, anywhere according to the need of patient. The CR nodes will perform spectrum sensing and transmit at any idle channel. Whilst monitoring the activities of human organs, it is likely that some of the information require higher bandwidth than what is available in a single channel, so a more suitable approach will be to use CB by these CR nodes.

E. CRSNs in Smart Grids

Cognitive sensor nodes have evolved the concept of smart grids. These sensor nodes may be wired or wireless and connected with the control station with the help of relays. The problem with the wired sensors is their scalability issue with topological changes in the network. The wireless sensors can be deployed anywhere and new installations can easily get services of power companies. By implementing cognitive radio wireless sensor nodes in smart grid applications, the power companies can get most efficient and reliable information in case of any faults in a network, and hence timely action can be taken [155]–[160]. Cognitive sensor nodes have already solved the issue of detecting various problems during power generation, transmission and distribution [161]. In a typical configuration, each cluster head transmits the information about its cluster to the related power distribution centers. This action can be done in an opportunistic manner using three step process of DSA. Again, CB can help transmitting the large burst generated by processing the information received from multiple nodes simultaneously.

X. Guidelines on using CB for Futuristic Cognitive Radio Sensor Networks

In general, CB is useful when a network has few PR nodes and a large pool of channels is available [10]. But, as the density of PR users increases, CB for two nodes may result in less number of channels available for other contending CR nodes. Also, to fully utilize the channel, a dynamic MAC protocol is required which adaptively changes the bond size depending upon the number of available channels and number of contending CR nodes. Although useful, CB introduces certain issues and challenges which need to be focused in order to gain maximum benefit when deploying CRSNs using this technique. Some of these challenges are discussed below.

A. Separation distance between adjacent channels

As shown in Fig. 3, it is suitable to leave guard bands on both sides of bonded channels to avoid adjacent channel interference (ACI), also called the spectrum leaks. The size of guard band for a bonded channel is generally kept half the bandwidth of an individual channel [1]. In this way, interference can be avoided at the cost of leaving some bandwidth useless. This wastage of bandwidth can be saved by using more efficient approach than the existing ones. There exists a tradeoff between the size of guard band for interference avoidance and the bandwidth utilization. As in the battlefield scenario, it is possible when infantry has got free channels to make a bond, the next neighboring channel was being utilized by armored units. We must avoid any interference between these two communications, so a considerable size guard band is required. This problem of guard band size has not been investigated yet for CRSNs and hence can be taken as optimization problem for CB in CRSNs. ACI has also been reduced in traditional wireless networks by applying various techniques like antenna engineering, filtering and power control [131]. As CRSNs has its own unique requirements, these schemes are required to be investigated to find a solution for ACI in CRSNs. Techniques for providing QoS for fixed width and variable width are also available in ad-hoc networks [25]. These techniques can also be investigated under the needs of CRSNs.

B. Energy conservation problem

CRSN nodes are energy constrained devices. The higher the bandwidth of bonded channel, higher will be the energy consumption by these nodes [1]. Recall the QoS and power constraints; an optimal balance between energy consumption and size of bonded channels needs to be investigated. Here it can be noticed that different nodes in a network may have different energy constraints. Some nodes may be powerful and have more energy as compared to other nodes. These nodes also act as cluster heads (CHs) or gateway nodes. Hence bandwidth of bonded channel relates with energy of these nodes. The network layer protocol which performs CB should be well aware of node(s) energy. It should combine fewer channels to conserve energy. Whereas, when dealing between high energy nodes (CHs), the bond size can be increased to get high data rates. Consider the food security scenario, the CR node in each container is likely to perform CB more frequently as compared to other local sensor nodes within the container, therefore these nodes should be installed with more power than others. The adaptability of channel width can be used keeping in view of node energy. When CR nodes are facing low energy, the bond size can be reduced to conserve energy. This facility was not available in fixed width systems [67]. CR nodes can also co-exist with narrowband devices by using an intelligent scheme split wideband interferer friendly technology (SWIFT) and can save energy of nodes as well as avoiding interference [113].

C. How to use channel for the bursty traffic?

CRSN nodes may generate bursty traffic, so a fixed channel assignment technique will not provide a good solution in this scenario. It is quite possible that a node may get silent just after transmitting a burst or it can continue to transmit for uncertain amount of time. Recall the railway track selection process, each junction node communicates only when a train is approaching. Similarly, in health monitoring modules, the sensors will transmit only when they sense an anomalous activity, which will generate a bursty traffic pattern. To address this problem, an opportunistic channel assignment technique is required to increase reliability and decrease packet losses. SWIFT has been successfully deployed for wideband bursty traffic using TCP in 802.11a wireless network without harming the narrowband users [113]. The same can be extended to wideband bonded channel for CRSNs. [67] proposed a technique for UDP flows which shows that throughput can be increased by increasing either modulation rate or channel width.

D. Impact of PR activity type

The type of PR activity determines the behavior of PR nodes in the network. Due to this reason, PR activity model is considered an important block in any CR based network. If the model appropriately approximates the activity of nodes, effective channel utilization can be made. As in the case of smart grids with CR capabilities, the impact of PR activity will be very high in channel selection process because PR activity will be different in different areas or locations [160]. A channel selection scheme has to make decisions on the basis of results generated by PR activity model. So, a suitable PR activity model should be selected in each area which avoids CR nodes to have a collision with PR nodes. Four types of PR activities have been shown in Fig. 8. [144] states that these four PR activities can be classified as Long term PR activity, High PR activity, Low PR activity and Intermittent PR activity. The details can be seen in section 8. [162] proposed a non-selfish scheme best fit channel selection (BFC) for Cognitive Radio Ad hoc Networks (CRAHNs) which senses the PR activity and selects the channel which is best suitable for CR transmission time. The scheme can be made intelligent by provisioning the WSN capabilities in it.

E. How to check the accuracy?

It is very important to measure the performance of any system that how accurately it is working. The term accuracy stands for how accurate the results were generated about the availability of channels or how accurately the PR activity was analyzed. The accuracy of PR activity model can be measured in many ways including number of collisions occurred between PR and CR nodes. Energy detection is the simplest way to analyze PR activity, however it can also result into a collision. IEEE 802.22 includes two stage spectrum sensing process i.e., fast sensing and fine sensing [39]. The Markov exponential model is memory less and has high degree of imperfect detections. If CR nodes keep track of bad channel selection decisions, it will help them to analyze the network and will improve their performance [149]. In the example of food security, if a CR node sends its data and senses collision with some PR node, it can mark this channel as a bad channel to transmit. This process of channel profiling can help CR nodes to select those channels that are less likely to be occupied by PR nodes.

F. Size of the network

The size of network is important to monitor the activity of PR nodes operating in the network. If more number of PR nodes are present in the network, it will become difficult for the PR nodes to estimate their activity. Research contribution can be made in this direction to investigate the ideal size of network. If the network size is large and difficult to handle, it can be divided into clusters. In such scenario the lifetime of cluster heads (CHs) will reduce due to extra calculations and coordination of data with other CHs. A good clustering scheme will need to be chosen to change the designation of nodes as CHs periodically, so as to keep the node's lifetime almost equal. Alternatively, the energy resources of CHs will need to be increased so that they can perform the assigned tasks for long duration of time. When the number of CR nodes in a network is very dense, CB scheme cannot perform well due to the reason of increase in frequency scarcity by contending CR nodes. As in the battlefield scenario, if too many troops of infantry become deployed in a small area, there may become a state that these CR nodes face difficulty in finding a free channel. However, low number of CR nodes can result into good CB scheme to satisfy the wideband requirements [72].

G. Spectrum profiling for CB

The instances of CB can be logged over time, and time-series analysis can be performed for better understanding of the spectrum availability. For example, a CR node may observe channel activities in the given spectrum and may also learn the most suitable channels to be bonded together when required. We consider this to be an interesting area for further investigation that overlaps with several other fields like machine learning and decision analysis.

Also, due to memory constraints in practice, the history of CB can grow infinitely, and must be truncated in order to save the memory space. This leads to another set of questions like which part of information is less useful that can be compromised. For example, if time stamp is the only consideration, the oldest entries should be removed first. However, if channel utilization is considered, the records with least-utilized channel can be discarded. In the smart grids scenario, when sensor nodes (CRs) need to transmit the data to the control station or grid, they will try to select the channel which will be the most suitable for them. In this way, the older entries will be of no use to nodes as the most recent entries will be providing the updated information about the channels condition.

H. Defining the goal for channel selection

One should be very clear about the specific goal for which channel selection has to be made. It is due to the fact that CRSNs have emerged due to complicated nature of objectives hence there cannot be a single objective which can be ideally optimized. The set of objectives may include reliable data dissemination, efficient spectrum utilization, maximum power conservation, least possible interference, and load balancing [163]. This list is provided as an example and should not be considered exhaustive by any means. These goals may vary depending upon the purpose of network for which it has been implemented and a tradeoff between the critical ones can be found. For example, one network may require higher throughput at the cost of low security while other one may ask for highly reliable and secure communication without emphasis on the higher data rates. A mature scheme should achieve an optimal tradeoff among all the required objectives.

Considering CB in CRSNs, data dissemination and least interference can be suitable goals for optimization because a bond can be successful only when it can disseminate the required data to the node which can be multihop away from the transmitter without introducing any harmful interference to other users in the network. In healthcare monitoring, the patient's data is required to be sent from the patient to the physician in a multihop manner, hence it is expected that this transmitted data should reach the required destination accurately so data dissemination and least interference are the key goals to implement CB in CRSNs.

I. Channel suitability for bonding

Based on the network requirements and the set of required goals, an efficient CB scheme should be able to assign weights to the channels depending upon their suitability level to be used by the CR nodes. The most suitable channel for a given node will receive the highest relative weight. In a CRSN, it is assumed that the nodes will be mobile and can change their locations hence the network dynamics will change, therefore the weights must be recalculated every time the network parameters change.

It is important to investigate the optimum time interval for updating all the weights. Too frequent recalculations will lead towards extra control overhead in the network whereas a long interval between two recalculations can leads towards the expired entries in the database and ultimately a PR-CR collision. For example, recall the battlefield scenario where infantry keeps moving, the channel condition will also change, and hence, there is a requirement of calculating weights calculation at a regular interval of time. The time period for recalculating and updating these weights is an area to be investigated.

J. False alarm and missed detection

In case of any wrong calculation leading towards a collision or underutilization of bandwidth, it should be investigated that either it was due to false alarm or missed detection [142]. These problems are fatal for any type of scenario like battle field, railway track selection, healthcare monitoring, forest fire detection etc. False alarm means that there was no PR node active at any specific instant of time and due to some un-avoidable reasons the channel sensing algorithm detected the PR activity. As a result, no CR node utilized the channel hence causing the wastage of resource. Whereas missed detection means the failure of PR activity detection and causing collision between PR and CR nodes. When a decision mistake has happened due to above mentioned reasons, the remedial measures become important. Either all parameters in the database need to be recalculated or to use some intelligent scheme to identify the causes of wrong decision. False alarm and missed detection problems are related with the issue of assigning priorities to channels according to their availability for CR communication. When there are long intervals between recalculation of priorities, these problems can occur in the network.

XI. Conclusion

In this paper, we presented the survey on CB schemes for cellular networks, WLANs, WSNs and CRNs. The classification of CB schemes has been performed depending upon the type of network and for each network, discussion on CB has been made with respect to performance metrics. From the literature review, we noticed that considerable work has been done on channel bonding schemes for cellular networks, WLANs, WSNs and CRNs. In this regard, few survey papers are available in the literature which highlight certain issues related with channel bonding, however, a comprehensive survey on CB schemes was missing in the literature. This survey provides insight into the issues and challenges related to the existing CB schemes and identifies the potential application areas for CB schemes belonging to cognitive radio sensor networks.

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