Distributed Scheduling Schemes for Wireless Mesh Networks: A Survey

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An efficient scheduling scheme is a crucial part of Wireless Mesh Networks (WMNs)—an emerging communication infrastructure solution for autonomy, scalability, higher throughput, lower delay metrics, energy efficiency, and other service-level guarantees. Distributed schedulers are preferred due to better scalability, smaller setup delays, smaller management overheads, no single point of failure, and for avoiding bottlenecks. Based on the sequence in which nodes access the shared medium, repetitiveness, and determinism, distributed schedulers that are supported by wireless mesh standards can be classified as either random, pseudo-random, or cyclic schemes. We performed qualitative and quantitative studies that show the strengths and weaknesses of each category, and how the schemes complement each other. We discuss how wireless standards with mesh definitions have evolved by incorporating and enhancing one or more of these schemes. Emerging trends and research problems remaining for future research also have been identified.

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1. INTRODUCTION

In this era of the Internet, the availability and quality of information communication infrastructure is viewed as a key measure of economic and social development. Wireless solutions are becoming ubiquitous and provide a wide range of communication options: personal area networks, local area networks, campus area networks, metropolitan area networks, wide-area networks, and global area networks, of various coverage limits, capacities, and service qualities [Raisanen and Lehto 2003].

A *Wireless Mesh Network (WMN)* is a special class of infrastructure solution built of high-capacity wireless nodes distributed over a geographical area [Akyildiz and Wang 2005]. In WMNs, each node looks for similar wireless nodes within its radio reachability, learns those neighbours' operational attributes, tunes its settings to match with

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the existing network, initiates and establishes links with neighbours, and effectively handles changes in the radio environment as well as data traffic flow [Akyildiz and Wang 2005; Zhang et al. 2007]. Here, a wireless node (or simply a node) is a router that has one or more wireless interfaces and is operating in infrastructure mode supporting multiple hops of data traversal using one or more wireless technologies.

WMNs are being envisaged as a promising unconventional wireless broadband solution for unfriendly terrain, temporary communication infrastructure, and rapid deployment [Akyildiz and Wang 2005; Zhou et al. 2008]. Typical applications include high-speed community networks for rural and metropolitan areas, backhaul networks over difficult terrain or for places where laying cables is prohibited (e.g., heritage sites), disaster recovery networks, transient networks for short-term events, military networks, and enterprise networking [Akyildiz and Wang 2005; Zhang et al. 2007; He et al. 2007]. The key benefits expected from WMN deployments are low up-front cost, greater service coverage with low "dead zones", adaptability to flow dynamics and radio environment changes, ease of maintenance, high scalability, and faster deployment. While wireless mesh networks resemble ad hoc networks in many aspects, a greater focus on higher-throughput, wider coverage areas and lesser focus on mobility make WMNs distinguishable [Zhang et al. 2007; Zhou et al. 2008]. In other words, a WMN can be visualized as an autonomous infrastructure solution with broadband capabilities whereas an ad hoc network is an autonomous network to provide basic connectivity.

The success of a WMN highly depends on how the limited frequency spectrum is utilized in a coordinated manner to achieve broadband capabilities, scalability, robustness, and service-level guarantees. Distributed scheduling schemes that are deemed to provide such capabilities are the focus of this survey.

Our survey provides a structured and comprehensive overview of distributed scheduling mechanisms in the literature published over a decade that are crucial for WMN deployments. Here, we mainly consider distributed schedulers that are compatible or closely related with wireless standards for mesh operations. We also focus on categorization of distributed schedulers, research directions and goals, emerging trends, open research problems, and developments in standards. Thereby, our survey facilitates a better understanding of the key principles, progress in the research area, effects of standardization in research works and vice versa, and areas that need improvement or remain unresolved.

1.1. Wireless Network Topologies

Wireless nodes capable of peer-to-peer operation can form a complex mesh-like network topology with each node establishing links with multiple nodes within its radio coverage to exchange and relay data packets. Such complex topologies are called mesh topologies and generally involve multiple hops [Chlamtac and Pinter 1987].

As shown in Figure 1(a), when each node in a network has reachability to every other node in the network, the network is called a full mesh network. However, due to limitation in coverage, limited availability of noninterfering channels and the impracticability of handling a high number of links, most practical WMNs are made of partial mesh networks (shown in Figure 1(b)) where multiple hops may exist between two nodes [Zhang et al. 2007]. Throughout this article the term mesh represents such partial mesh topologies with multiple hops unless specifically said otherwise.

Figure 1(c) depicts a scenario where a minimal set of links (shown with strong lines) are utilized for communication purposes, while the rest of the establishable links (shown with dashes) are not utilized, effectively reducing the mesh topology into a tree topology [He et al. 2007; Akyildiz and Wang 2008]. Usage of such tree topologies is common when scheduling decisions are made by a centralized control node which we

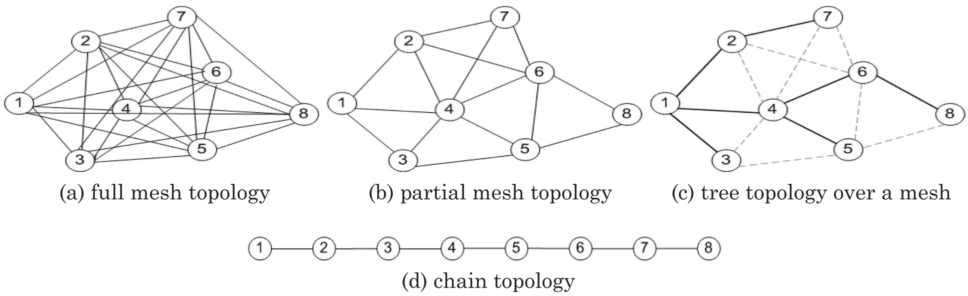


Fig. 1. Possible network formations of wireless solutions that involve multiple access.

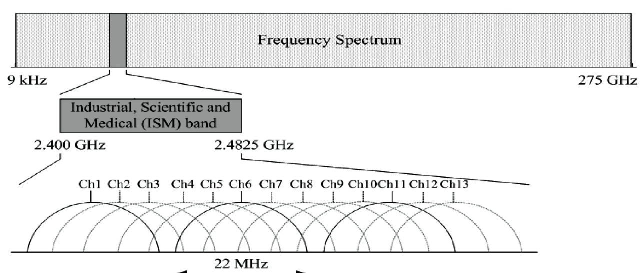


Fig. 2. RF spectrum, band, and channels as allocated for WiFi equipments in North America.

discuss in Section 1.4. A chain topology is a simple form of mesh topology involving multiple hops where each node is connected to two neighbours at most.

1.2. Radio Frequency Spectrum

Wireless equipment uses electro-magnetic signals to transfer information over space without any artificial guide, and the most common form of electro-magnetic signal is radio-wave which has wavelength longer than that of infrared light [Stine 2005]. In another dimension, radio-waves with frequencies from 9 kHz to 275 GHz are proposed as usable by the US Federal communications commission (FCC).

With rapid growth in the number of wireless devices, radio frequency spectrum is fast becoming a scarce resource. To manage the competition, the available frequency spectrum is split into subsets called bands that can be further divided into channels. Each wireless application is allowed to operate within a certain frequency band as governed by the regulatory organizations, and wireless interfaces shall use either the whole band or an individual channel within that band for simultaneous communications in a locality. Figure 2 shows an example of a frequency band and channels that are used by ubiquitous WiFi terminals in North America.

1.3. Media Access in Wireless Mesh Networks

Wireless routers for WMNs are incorporated with multiple access schemes as part of their media access control mechanisms. These mechanisms coordinate wireless interfaces operating in the same geographical area for efficient transfer of data using a limited subset of frequency spectrum [Raniwala and Chiueh 2005; Kyasanur et al. 2006]. Effective multiple access schemes are essential to improve spatial reuse of the frequency spectrum as well as to reduce waste due to collisions and interferences. By doing so, they help to maintain the throughput of the network with a limited number of channels, averting congestions [Kyasanur et al. 2006; Ali et al. 2008]. In addition, they influence the service levels that can be offered by a wireless network as well as the power efficiency.

Adaptability to flow dynamics and topology changes is an essential part of WMNs, which relies on scheduling mechanisms, and the Media Access Control (MAC) layer is considered as the best-suited layer to deploy such functionality [So and Vaidya 2004; Hiertz et al. 2010]. Among the popular multiple access mechanisms, random access, pseudo-random access, and cyclic access schemes are chosen for this survey due to their wide acceptance, and support from standardized wireless technologies with mesh definitions. In these schemes, the terminology "scheduling" indicates timely activation of wireless interfaces and/or maintaining them in transmission or receive mode and conflict management for effective communication.

In general, the nodes in WMNs are equipped with half-duplex transceivers and omni-directional antennas. Hence, scheduling schemes need to avoid primary and secondary conflicts, effectively restricting the simultaneous transmissions to a single transmission within each two-hop neighbourhood at most [Chlamtac and Pinter 1987; Ramanathan 1997; Cidon and Sidi 1989]. Here, sending a signal to a transceiver that is in its transmitting mode is called a primary conflict and two simultaneous transmissions to a common transceiver is called a secondary conflict. Various mechanisms are incorporated within scheduling schemes to mitigate the conflicts, and these provisions for collision avoidance lead to unacceptably low performance with an increase in network size and complexity.

It has been shown that the throughput contribution per node can become unacceptably low with an increase in the number of nodes in a locality, making scheduling schemes of paramount interest in the domain of WMN research and development [Gupta and Kumar 2000; Gastpar and Vetterli 2002]. Furthermore, the majority of the media access schemes incorporated with the wireless equipments are designed for conventional point-to-multipoint architecture and they are either not optimal for WMNs or in the worse case they do not support mesh operation.

1.4. Centralized and Distributed Scheduling Schemes

The task of scheduling the wireless interfaces attached to nodes in a WMN can be either carried out by a single central node or can be shared among individual participating nodes [IEEE 802.16 Working Group 2004; Cao et al. 2005]. When the scheduling is carried out by a single node (or few nodes), similar to that of a Base Station (BS) in a conventional point-to-multipoint wireless network, the scheduling scheme is classified as a centralized scheduling scheme. In this scenario, the central control node has global information and control of all WMN nodes. On the other hand, when each node makes its own decision on the utilization of the channels based on locally available information, the scheme is classified as a distributed scheduling scheme [Chlamtac and Pinter 1987].

Centralized scheduling schemes offer collision-free channel allocations and render more optimal channel utilization for directed traffic streams (e.g., Internet traffic flowing through a gateway) that persist for durations greater than the time taken to establish such scheduling [IEEE 802.16 Working Group 2004; He et al. 2007]. It is common that knowledge gained through routing is used in centralised scheduling to achieve near-optimal throughput, and other required network Quality of Services (QoS) [Wei et al. 2005; Patra et al. 2007; Gabale et al. 2010; Chebrolu and Raman 2007]. Without centralised control in scheduling, such flow-level controls are difficult to implement in distributed schedulers [Chebrolu and Raman 2007].

Nevertheless, distributed scheduling schemes outperform centralized scheduling schemes with better scalability, smaller connection setup delays, smaller management overheads, no single point of failure, use of all the possible links to avoid bottlenecks, and are better suited for networks with distributed and occasional traffic [Chlamtac and Pinter 1987; Ali et al. 2008]. To cater for the ever-increasing requirement of network expansion, network throughput, and robustness, distributed scheduling is the most suitable solution for futuristic WMNs [Wu et al. 2007]. Moreover, the increase in network traffic of peer-to-peer nature also justifies the selection of distributed schedulers for WMNs.

1.5. Literature on Distributed Schedulers for WMNs

Motivated by the advantages of distributed scheduling, the leading research institutions, standardization organizations, and wireless equipment vendors are relentlessly working on distributed media access schemes for WMNs. Note that though the term "Wireless Mesh Network" is a relatively new term, distributed media access schemes that are applicable to WMNs do exist under different network terminologies such as packet radio networks [Bruno et al. 2005], multihop radio networks [Chlamtac and Pinter 1987; Ramanathan and Lloyd 1993], ad hoc networks [Stine 2005; So and Vaidya 2004; Marina et al. 2001; Kumar et al. 2006], and multihop relay networks [Erwu et al. 2007; Peters and Heath 2009], where numerous protocols, algorithms, frameworks, and enhancements have been proposed over the last four decades.

The majority of these proposals are centered around a few fundamental ideas and then fine-tuned to improve the performance on certain niche attributes/requirements. These ideas have been incorporated and supported by the prominent wireless standards such as IEEE 802.11 and IEEE 802.16 for mesh operations. Our survey includes a *snapshot* of literature, selected largely from ACM Digital Library and IEEE Xplore, using keyword-based searches sorted by citation count. We selected at least 20 papers per scheduling type considering also the originality of research contribution and recent developments. Due to the myriad nature of distributed scheduling for WMNs, we limit the scope of this survey to three major schemes that are supported by wireless standards for mesh operations.

1.6. Our Contributions

This survey brings a structured overview of distributed scheduling mechanisms that can be used for WMNs. We cover extensive research taken over the last three decades under various names and we categorize predominant schemes into three major groups that are supported by one or more wireless standards with distributed schedulers for WMNs. We build our survey upon the principles of WMNs stipulated by the seminal and widely referenced preliminary survey by Akyildiz and Wang [2005]. The other existing surveys we find either confine themselves to a particular standard [Ali et al. 2008; Ghosh et al. 2008; Kas et al. 2010] or a single fundamental principle [Ramanathan and Lloyd 1993; Kumar et al. 2006; Cheng et al. 2008]. Since the technologies and standards continue to evolve by adapting salient features found in other standards and research proposals, understanding the key principles is certainly helpful for researchers to venture into the research area. At the same time, we believe that the standards play a key role in the development of wireless technologies. Hence, our survey is structured in a way to understand the scheduling principles, progress in research works, developments in standardizations, and open issues that remain to be explored.

In this article, we classify proposals on distributed channel access schemes into three major categories, and provide a summary of fundamental ideas behind each scheme. Then we evaluate enhancements that have been proposed on top of those schemes. Third, we compare the major schemes for their strengths and weaknesses. Then, we discuss the advancements in the wireless standards that have implications on WMN research works and deployments. We also discuss the key issues that remain unresolved in each of these schemes and are open for further research. Finally we conclude the

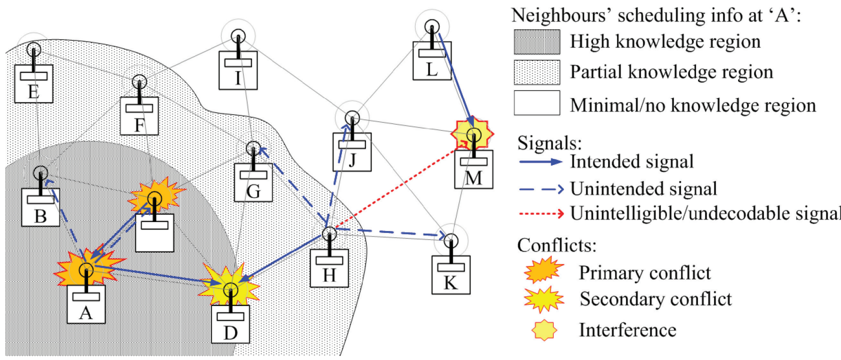


Fig. 3. Knowledge availability of neighbours' future transmissions (with respect to a node A), primary and secondary conflicts, and interference in WMN distributed scheduling.

article with the brief summary of our findings that are of interest to the research community.

2. BACKGROUND

In this section, we first describe the challenges of devising a distributed scheduling mechanism for WMNs. Then we describe the key attributes expected from such schemes and the indicators of those attributes within the literature. The last subsection discusses our classification of distributed scheduling mechanisms used for WMNs.

2.1. Challenges of Distributed Scheduling

Multiple access schemes for wireless devices face a number of challenges that do not exist in wired communication solutions, namely: (i) limitation of available spectrum, (ii) dynamic nature of environmental conditions affecting radio-wave propagations, and (iii) effects of interferences and noise sources.

Compared with scheduling schemes of conventional wireless networks and/or centralized scheduling schemes for WMNs, developing a distributed scheduling scheme for WMNs is a highly challenging task. The additional challenges that have to be addressed in the design of a distributed scheduling scheme for WMNs are: (i) lack of network-wide information, (ii) lack of network-wide control, (iii) aging of decision support information in relaying, (iv) limitations on overheads that can be used for network control or management purposes in scheduling, (v) complex network topologies, (vi) handling topology changes (e.g., addition of new nodes, node or link failures) with the least interruptions, and (vii) overcoming issues caused by asymmetric transmission distances.

Figure 3 shows technical challenges faced in distributed scheduling, such as conflicts and interferences due to limited network information. Within the first hop, the number of primary conflicts is kept low by using carrier sensing or prediction based on past receptions. Within the second hop, handshakes or schedule information forwarding is used to keep the secondary conflicts low. However, limited or no control exists beyond the second hop to handle possible interferences.

2.2. Crucial Attributes of WMN Scheduling Schemes

While addressing the challenges of distributed scheduling for WMNs, researchers focus on meeting the following key attributes.

(1) *Autonomous operation*. The essential feature that supports fast and easy deployment and ease of maintenance of WMNs is the ability of the nodes to self-organize,

self-configure, and self-heal [Akyildiz and Wang 2005]. In other words, nodes should be able to learn operational aspects of the existing network, join the network, adapt themselves quickly with the network, and have to keep track of the changes to make use of the resources efficiently with the least possible manual intervention. In this regard, a scheduling mechanism should be intelligent enough to quickly adapt and to efficiently coordinate with neighbouring nodes, to share available channels without disrupting the ongoing communications.

(2) *Scalability*. In the context of WMNs, *scalability* is defined as the ease of adding additional nodes to enhance the capacity and/or coverage of a WMN [Raniwala and Chiueh 2005; Aziz et al. 2011]. In this regard, a scalable scheduling scheme is one that can effectively handle the channel assignment problem of WMN nodes over a range of neighbourhood sizes and complex network topology formations with minimal degradation of service qualities.

(3) *Throughput*. To cater for the ever-increasing demand of network throughput, scheduling schemes have to be designed and optimized for WMN-specific network scenarios. For example, since the nodes in a WMN are spread apart over large geographical areas beyond individual nodes' radio coverage, network *throughput* can be improved through an optimal spatial reuse of the frequency spectrum. A scheduling scheme must be capable of coordinating the nodes on the channel usage to improve the network-wide reuse of the frequency spectrum while maintaining collision freeness [Chlamtac and Pinter 1987; Ramanathan and Lloyd 1993]. Minimizing problems such as hidden terminal and exposed nodes also helps to achieve this goal [Karn 1990; Bharghavan et al. 1994]. In addition, multichannel scheduling [So and Vaidya 2004], multiradio scheduling [Raniwala and Chiueh 2005; Kyasanur et al. 2006; Hong et al. 2010], usage of all possible links to avoid bottlenecks (e.g., exploiting a mesh topology instead of a tree), and minimizing the ratio of management overheads to payload [Hiertz et al. 2010] are studied as means to improve the effective *throughput*.

(4) *Delay*. With the increased use of delay-sensitive real-time applications such as voice/video over Internet protocol, delay measures get prominence in design scheduling schemes [Vijayalayan et al. 2010]. Depending on the requirements, schedulers focus on end-to-end transmission delay and/or delay jitter, to maintain them within limits.

(5) *Other service levels*. With the sophistication of Internet protocol-based applications, the level of service a network can offer is becoming a key concern. In addition to maintaining higher throughput and lower delay measures, ability to provide differentiated priority [Bayer et al. 2007] or equal priority (fairness) [Salonidis and Tassiulas 2005; Cicconetti et al. 2007a] to traffic flows, and maintaining a low packet loss ratio [Raniwala and Chiueh 2005] are of concern. Scheduling schemes play an important role in all of these aspects.

(6) *Interoperability*. When wireless solutions adhere to widely used and standardized products, networks can be easily built and expanded without any dependence on specific vendors and the cost can be brought down [Kyasanur et al. 2006]. Therefore it is important that a proposed WMN scheduling scheme maintains a higher degree of compatibility with standardized frameworks.

(7) *Complexity*. The WMN scheduling solutions should be lightweight such that they can be deployed over less complex hardware and firmware [Hiertz et al. 2010]. For example, a reduced number of wireless interfaces per node and algorithms that require lower processing power and memory can reduce the complexity of the scheduling solution. They help to reduce the hardware cost of WMN nodes, processing delays, and management overheads of data communication and power consumption [Kyasanur et al. 2006].

(8) *Energy efficiency*. WMN applications, such as disaster recovery networks, infrastructure for remote areas, and tactical networks, do have concerns on energy efficiency due to limitations on accessing a stable power supply in those use cases [Calamoneri et al. 2011; Nieminen et al. 2010]. In addition, reducing the carbon footprint has also become a key objective in the telecom industry [Chockalingam and Zorzi 1998]. In WMNs, the major power consumers of wireless equipment are the transmitter and receiver components; and their activation is governed by their scheduling schemes [Nieminen et al. 2010; Sharma et al. 2006]. Hence, scheduling schemes have to be designed in a manner to minimize the wastage of transmitted power due to collisions and interferences as well as to minimize the unnecessary transceiver up times in receive mode.

Table I summarizes the common indicators or measures which suggest the attributes being investigated or considered in a particular scheme.

Quality of Service

In general terms, the Quality of Service (QoS) expected from a network includes one or more performance attributes such as higher throughput, lower end-to-end delay, lower delay jitter, ability to provide differentiated and/or equal priority, and lower packet loss ratio. Due to the complexity of network topologies, multihop packet traversal, and/or distributed decision making, wireless standards use different provisions for QoS of WMNs than that of point-to-multipoint networks.

For example, the IEEE 802.16-2004 standard proposes the use of Dynamic Service Addition (DSA) and Dynamic Service Change (DSC) message dialogs with *Set Type* definitions to offer four service classes of priority: Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), nonreal-time Polling Service (nrtPS), and Best Effort (BE) for point-to-multipoint networks. On the other hand, for mesh distributed scheduling, the same standard stipulates *Xmt Holdoff Exponent* settings for MAC management message exchanges, *Demand_Level* and *Demand_Persistance* parameters, without any service class definitions. Similarly, the IEEE 802.11-2012 standard defines a Mesh Coordination Function (MCF) with MCF-Controlled Channel Access (MCCA) definitions for QoS of mesh distributed scheduling.

Trade-offs between key attributes

It is noteworthy that some of the attributes given before are interdependent and a solution to improve one may impair the other. For example, having multiple interfaces per node can improve *throughput* while affecting the lower *complexity* requirement [Yi et al. 2008]. Similarly, higher *throughput* is generally achieved at the expense of *delay* [Kas et al. 2010] or equal *priority* [Cicconetti et al. 2007a]. Moreover, scheduling scheme implementations for higher *energy efficiency* have an impact on *delay* and *priority* measures [Fallahi et al. 2006]. Furthermore, the more attributes considered, the more complex the solution is to design and implement [Yi et al. 2008].

Therefore careful trade-offs have to be considered in the solution. As a result, proposals tend to investigate only a subset of attributes that are of interest for a given use case.

2.3. Major Types of Distributed Scheduling Schemes for WMNs

Among the numerous distributed scheduling techniques proposed to successfully achieve the preceding goals, three major streams remain predominant:

(1) random access schemes,
(2) pseudo-random access schemes, and
(3) cyclic access schemes (also known as Spatial-reuse Time Division Multiple Access (S-TDMA) schemes).

Table I. Indicators of Performance Attributes

Attribute	Indicator/measure	Description
1. Autonomous operation	1.1 Predictability of next transmission	Ability to predict transmission timing of own and neighbour nodes' wireless interfaces
	1.2 Adaptability to topology or traffic changes	Ability of reactive scheduling to handle node additions, link/node failures and variations on data traffic
	1.3 Support for unicast and/or broadcast	Ability to schedule interfaces targeting a single neighbour and/or all the first hop neighbours
2. Scalability	2.1 Effects of higher network densities	Maintaining the network performance such as *throughput* and *delay* measures at usable level for higher network densities
	2.2 Effects of multiple hops	Maintaining the *delay* measures at usable level over multiple hops
	2.3 Effects of network complexities	Maintaining the network performance such as *throughput* and *delay* measures at usable level over network with loops and a range of number of neighbours
3. Throughput	3.1 Mechanisms to minimize or avoid collisions	Collision avoidance through carrier sensing, schedule information sharing and prediction to minimize the retransmissions
	3.2 Solution for exposed terminal problem	Simultaneous activation of as many links as possible
	3.3 Availability of single-radio multi-channel scheduling schemes	Making use of all the available frequency channels to increase number of simultaneous transmissions with single radio interface per node
	3.4 Availability of multi-radio multi-channel scheduling schemes	Making use of all the available frequency channels to increase number of simultaneous transmissions using two or more radio interfaces per node
	3.5 Control overhead	Ability to have the least ratio of control-packets:data-packets
	3.6 Length of a transmission	The size of user data packet(s) transferred with a single handshake of control messages
4. Delay (lower)	4.1 End-to-end Delay	Maintaining the delay of a packet traversal within a limit
	4.2 Delay jitter	Maintaining the variation of delay within a limit
5. Other service levels	5.1 Fairness	Providing nearly equal opportunity to all the nodes despite position in the network and network traffic
	5.2 Differentiated Priority	Ability to provide priority or increased number of opportunities for certain nodes or types of data traffic
	5.3 Packet loss ratio	Maintaining the ratio of number of packets that are lost during transmission due to collisions or interference to the total number packets that are transmitted within a limit
6. Inter-operability	6.1 Compatibility with wireless standards	Compliance with open standards such as IEEE 802.11 and IEEE 802.16
	6.2 Availability of message templates	Details of control and user data formats
7. Complexity (lower)	7.1 Requirement for time synchronization	Mechanisms of time synchronization or global timers are considered as complex and expensive to incorporate
	7.2 Computational complexity	Algorithms of lower order complexities are considered favourable
8. Energy efficiency	8.1 Expected receiver uptime	Managing sleep and wake-up timing of receivers to save energy
	8.2 Collision avoidance	Minimizing the waste of transmitted power due to collisions

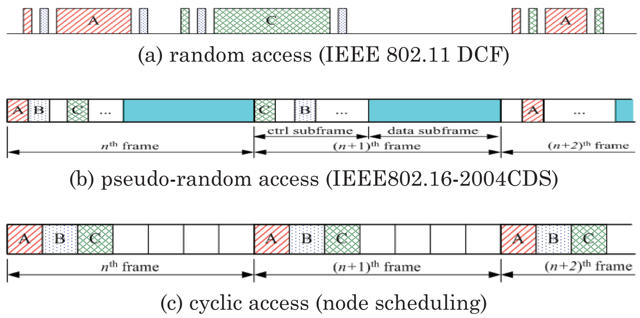


Fig. 4. Implementation examples of major types of scheduling schemes.

This classification of scheduling schemes is made based on the sequence in which nodes access the shared medium, repetitiveness, as well as predictability of next transmission opportunity by a node itself and its neighbours. Among these schemes, pseudo-random access schemes and cyclic access schemes are generally synchronous schemes of a slotted time nature whereas random access schemes can be either asynchronous or synchronous.

Figure 4(a) depicts a contention-based random access scheme used by WiFi terminals, where nodes cannot predict their own nor their neighbours' transmission timings. There is no fixed sequence or repetition of nodes occupying the channel, and the duration of communication may vary from packet to packet.

In a pseudo-random access scheme, while there is no fixed sequence or repetition in channel access, a node can predict its own and its neighbours' transmission timings using a shared algorithm. The position of time slot(s) utilized by a node within a frame changes from one frame to another. Figure 4(b) shows an example of pseudo-random access, where control subframe time slots of IEEE 802.16-2004 terminals are scheduled in a varying sequence over time.

The cyclic access schemes as shown in Figure 4(c) have a repetitive pattern of channel access and the sequence remains the same over a number of frames. Each node or link is allocated with a fixed number of slots within a frame, and their positions within the frame are maintained until a change request arises. More operational details and developments of these schemes are given in the following sections.

2.4. Other Distributed Schedulers for WMNs

In addition to random, pseudo-random, and cyclic access schemes covered in this survey, a number of other schemes have been proposed to handle multiple access in WMNs in a distributed fashion [Ramanathan 1997]. Among them are Code Division Multiple Access (CDMA) schemes that render support for low signal-to-noise ratio operations, longer hops, and security of frequency hoping [Andrews et al. 2007]. With effective multipath interference handling and higher spectral efficiency from Multiple-Input and Multiple-Output (MIMO), Orthogonal Frequency Division Multiple Access (OFDMA) is also emerging as a contender to handle the spectrum reuse in WMNs [Park et al. 2011]. However, these schemes are yet to be included in any wireless standards for mesh operations, and are beyond the scope of this survey.

2.5. Overview of Methodologies for Distributed Scheduling Research

Before diving into the details of the three major schemes, we performed a study to understand the methodologies and tools used in the selected literature. Figure 5 shows trends observed with respect to methodologies used to investigate the research problem of distributed scheduling for WMNs, tools used, and the depth of their

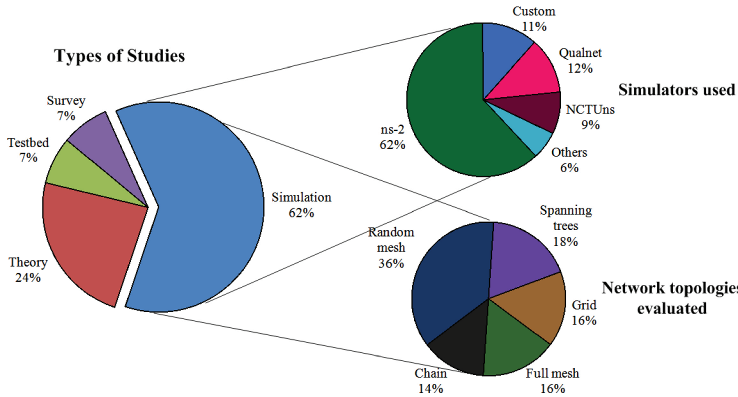


Fig. 5. Demographies of research studies on distributed scheduling schemes for WMNs.

investigation. The main pie chart shows the types of studies observed in the selected literature, namely: simulation studies, theoretical studies, surveys/literature reviews, and testbed-based investigations.

As shown in Figure 5, 62% of the research papers selected for this survey are based on simulation studies. They use simulation tools to quantitatively measure the performance improvements of proposed enhancements or the existing scheduling schemes under specific network criteria or conditions. Constraints such as high cost of using many wireless nodes for large-scale studies, difficulty in deploying and managing nodes over a large geographical area, difficulty in collecting data, and unavailability of modifiable system software, and hardware to implement new algorithms in certain cases, have lead researchers to initiate their studies with the help of computer-based models [Tan et al. 2010].

It is noteworthy that ns-2 is the most widely used simulation environment for these quantitative studies on distributed channel allocations, and is followed by Qualnet, user-developed simulators, and NCTUns. Figure 5 also shows the types of network topologies used for these quantitative studies as a way to quantify the depth of the investigations. Specifically, 52% of the research works include a multitude of complexities such as varying degrees of networking (i.e., number of neighbours), multiple hops, and loop connectivity by using random mesh and/or grid topologies. On the other hand, 48% of the studies lack complete investigations on WMN complexities as stipulated in the Internet Engineering Task Force's RFC 2501 for mobile ad hoc networks (MANETs) [Corson and Macker 1999]. The studies based on chain or tree topologies do not investigate path redundancies (32%) and full mesh topologies miss multiple hops (16%).

Theoretical studies, which include graph-theory-based studies, statistical models, and/or derivations of upper and lower bounds, constitute nearly a quarter of the research works. We observed that early studies under the name of packet radio networks were mostly graph-theory-based theoretical studies.

In recent years, experiments based on testbeds have emerged and provide more realistic results. All of the testbeds included in this survey are built using ubiquitous IEEE 802.11-based WiFi wireless interfaces. Despite continued effort and developments, the research community is not yet satisfied with any scheme to fulfill all their expectations and scope for new research works remains high.

2.6. Common Assumptions in Simulation Studies

A number of assumptions are made when a scheduling problem is modelled and simulated in a computer-based simulation environment. The common assumptions made in many of the simulation studies on distributed scheduling for WMNs are: (i) nodes have distinct identities, (ii) nodes are equipped with isotropic antenna(s), (iii) radio transmission is well received within a defined transmission range and causes no interference beyond that (a scenario also known as "ideal radio environment"), (iv) transceivers are operating in a half-duplex fashion (i.e., a transceiver can either be in transmitting or listening mode at a time), (v) all the nodes have the same transmission range making all the links bidirectional/symmetrical, (vi) links are reciprocal in nature where radio-wave propagational properties between any two nodes are the same in both direction, (vii) only the nonoverlapping channels are used in multichannel scheduling schemes and a transceiver can receive/transmit in only one of those channels at any one time, (viii) upper-layer information is known (e.g., routing, traffic), (ix) WMN nodes are subject to minimal or no mobility, (x) minimal or no topology changes due to environment changes during the simulation period, and (xi) received data is unusable if two separate overlapping transmissions are received at the receiver (both partial and full overlapping) which is known as a collision.

In addition to the previous list of assumptions, slotted time-based scheduling schemes have further assumptions such as: (i) all nodes are equipped with perfect time synchronization or have a global clock, and (ii) a message sent by a node is received correctly within a finite time by all neighbours, and propagation delay is less than the guard band.

3. RANDOM ACCESS SCHEMES

In this section, we first give a brief overview of distributed random access schemes for WMNs, followed by a well-known example, namely distributed coordination function of IEEE 802.11. We then discuss the research progress in random access schemes, both asynchronous and synchronous solutions, as well as common assumptions found in the literature.

3.1. Contention-Based Access

In random access schemes, nodes contend for the earliest possible opportunity to use the channel as soon as they have a packet to transmit and the transmissions by a node cannot be predicted by its neighbours until initiated [Hiertz et al. 2010; Kumar et al. 2006]. Since the packet arrival at each node is considered random in real-world scenarios, the resulting channel access sequence also remains a random sequence. The primary objectives of this solution are maximal channel utilization, minimal waiting time to transmit packets, and the least overheads for coordination between nodes.

The random access schemes can be either synchronous or asynchronous. In synchronous solutions, transmissions can only be started at the start of a predefined time slot and a mechanism for network-wide synchronization is a prerequisite [Rhee et al. 2009]. On the other hand, in asynchronous solutions, which are not synchronous, there is no division of time into time slots, and transmission can be initiated at any point in time given that the conditions for transmission are met. Among these schemes, asynchronous solutions are very popular as they are readily available in commodity WiFi interfaces.

The early research into asynchronous random access solutions for WMNs was initiated with the Multiple Access with Collision Avoidance (MACA) [Karn 1990] scheme incorporating *Request-To-Send* (*RTS*) and *Clear-To-Send* (*CTS*) control messages for virtual carrier sensing. The exchange of short control messages kept the collisions among control messages to a lower level and minimized the chances of data packet corruption. MACA was further developed into MACA for Wireless (MACAW) [Bharghavan et al. 1994] by introducing *Data-Sending* (*DS*) and *Acknowledgement* (*ACK*) messages. Since these schemes sense the carrier before transmission and use control

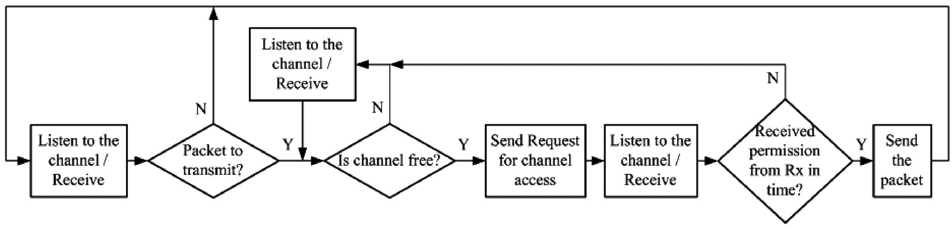


Fig. 6. Basic operational principle of a CSMA/CA-based random access scheme.

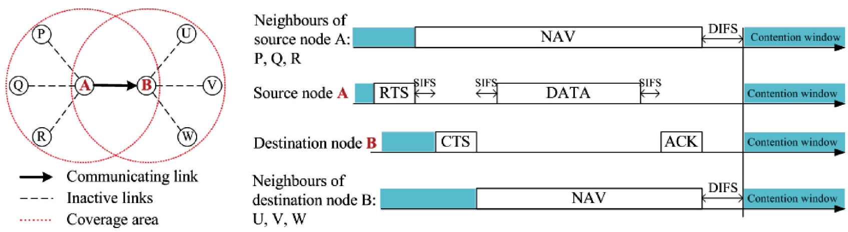


Fig. 7. Handshakes of messages in a DCF-based random access scheme.

message handshakes for dynamic reservation and/or collision resolutions, they are named Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) schemes. Figure 6 shows the basic operation principle of a CSMA/CA-based random access scheme [Kumar et al. 2006].

These schemes primarily depend on protocols that determine which packet has to be transmitted next and when it can be transmitted based on the events observed. Algorithms are used in the secondary areas such as contention window size adaptations [Kim et al. 2009; Lee et al. 2010] and preferable channel selections [Kyasanur et al. 2006; Wu et al. 2000].

3.2. The Distributed Coordination Function

The well-known Distributed Coordination Function (DCF) of the IEEE 802.11 family adapted MACAW and introduced a backoff mechanism on top of it to handle contentions and collisions. DCF, with its availability on ubiquitous WiFi terminals and readiness to support basic WMN operations, has become the foundation for many variants of random access schemes that are widely studied for WMN solutions [Hiertz et al. 2010].

Under these schemes, the transceiver on each node is maintained in its receiving mode except during its transmitting durations, and each node maintains a Network Allocation Vector (NAV) to keep track of any ongoing transmissions in the neighbourhood [IEEE 802.11 Working Group 2012]. A node can start transmission only when the NAV is reset and such a period is called a contention period. As shown in Figure 7, a sender node "*A*" may initiate a new communication with an *RTS* message during a contention window. If this *RTS* message has been received by the intended receiver node "*B*" and no other ongoing transmissions were observed at *B*'s neighbourhood, *B* will send a *CTS* message to *A*. Upon reception of *CTS*, *A* will send the data frame (DATA) and the successful reception is positively acknowledged (*ACK*) by *B*. The next contention window starts after the *ACK* where any node can attempt to initiate a communication using an *RTS* message with a further random *backoff* period. Note that *Short InterFrame Spaces* (*SIFS*) and *DCF InterFrame Spaces* (*DIFS*) are there to accommodate the switching delays of transceivers between transmitting and receiving modes, and to make sure that the channel is free for a new transmission, respectively.

The *backoff* period is calculated in a way to minimize the collisions through an adaptive contention window calculation scheme and the equation used is

$$BackoffTime = Random[0, CW] \times aSlotTime, \tag{1}$$

where $Random[0, CW]$ is a random integer number generated from a uniform distribution of 0 to CW, with Contention Window - CW adapting itself with the number of previous attempts failed, and $aSlotTime$ based on the physical-layer properties. Collisions are understood with no replies and they also increase the value of CW.

3.3. Progress in the Research of Random Access Schemes

Asynchronous random access schemes

Due to the wide availability, affordability, maturity, and *interoperability* of IEEE 802.11-based equipments, numerous studies have been carried out on the use of random access schemes for WMNs based on both computer-based simulations and testbed implementations [Raniwala and Chiueh 2005; Xu et al. 2002]. These studies are focused on enhancing the basic DCF function such as multichannel scheduling schemes, fine-tuning of backoff mechanisms [Kim et al. 2009], advanced usage of cross-layer knowledge on scheduling decisions, and introducing QoS features [Lee et al. 2010].

MACA [Karn 1990], MACAW [Bharghavan et al. 1994], DCF [IEEE 802.11 Working Group 2012], and other variants depend neither on any network hierarchy nor on network topology information, and readily support distributed scheduling for WMNs. In addition, they are open to any number of neighbours and readily adapt to network topology changes, fulfilling the requirement of *autonomous operation*.

Since the 2.4 GHz Industrial, Scientific, and Medical (ISM) frequency band used by WiFi terminals comprises a number of nonoverlapping channels, multichannel solutions were explored to improve the network *throughput*. The authors in So and Vaidya [2004] propose a scheduling scheme for single-radio multichannel WMNs called Multichannel MAC (MMAC). The solution avoids network partition and hidden terminal issues by periodically having a rendezvous time interval during which the transceiver of each node is tuned to a common channel to negotiate channel access for the rest of the duration. The channel negotiations and consequent communications on different channels are all based on DCF random access principles. At the same time, this solution requires a time synchronization mechanism to synchronize the rendezvous intervals among nodes. Hence a trade-off between network *throughput* and lower *complexity* of the solution exists.

Several multiradio multichannel solutions are being proposed based on DCF principles as a way to improve *throughput* as well as *scalability* [Kyasanur et al. 2006; Wu et al. 2000]. The hybrid multichannel protocol proposed in Kyasanur et al. [2006] fixes one receiver interface per node on a channel and each neighbour node chooses a different channel whenever possible or a channel with the lowest usage. All other interfaces switch to reach their neighbours' fixed interfaces. Due to this switching and an unknown past history of the switched channel, the hidden node problem persists in this solution. On the other hand, the proposal in Wu et al. [2000] stipulates an interface per node, fixed on a common and dedicated control channel, and the rest of the interfaces are left to switch between remaining channels for data transactions as negotiated over the control channel. In this solution, dedicating a channel for control purposes is inefficient when there are a low number of channels. Note that all of the multichannel solutions use a Preferable Channel List (PCL) in their random handshakes to select the best possible channel [Kyasanur et al. 2006; So and Vaidya 2004; Wu et al. 2000].

The study Mo et al. [2008] categorizes random access-based multichannel schedulers into single-rendezvous and parallel rendezvous schemes, and then the single-rendezvous schemes further into dedicated control channel, common hopping, and split-phase schemes. It evaluates the performance of eight MMAC schemes for *throughput*, *delay*, and *complexity* with the help of analytical models and simulations under different traffic conditions, topologies, and channel availabilities.

Backoff adaptation algorithms have been proposed to calculate CW, of (1) to improve the delay measures and other *service levels* at the MAC layer. The study in Kim et al. [2009] extensively analyzes the effects of binary exponential backoff, multiple increase exponential decrease, exponential increase exponential decrease, determinist contention window algorithm, and adaptive backoff algorithm on end-to-end packet delivery delays and packet delivery ratios against varying traffic load conditions over WMNs. On another angle, Lee et al. [2010] propose an adaptation scheme to determine CW based on the number of leaf nodes of spanning tree networks. These studies on backoff mechanisms generally cover both *throughput*, *delay*, and *other service-level* attributes.

Kyasanur and Vaidya [2005] show the unfairness between nodes due to their location in the network. This location-based contention leads to *service-level* degradation in some nodes while the other selfish nodes take advantage. A receiver-based penalty scheme is proposed to impede nodes from taking unfair advantages.

The study in Tan et al. [2010] provides a detailed comparison of performance measurements obtained through computer-based simulation tools and testbed-based experiments. Findings include how differently the physical, MAC, and networking layers behave, and how they affect traffic flow in WMNs that are based on random access schemes.

The developments on IEEE 802.11s for Wireless Local Area Network (WLAN) mesh are discussed in Hiertz et al. [2010]. The authors discuss advances in the random access scheme to improve *delay* and *service-level* guarantees and measure *throughput* over an 802.11s pro-type-based nodes.

Aziz et al. [2011] succinctly reveal the instability of DCF-based WMNs of three or more hops affecting *scalability* and effective *throughput*. In their study, probabilistic modelling and testbed-based measurements are used to prove that there is a significant probability of congestions and deadlocks when three or more bandwidth-greedy nodes exist in a network. To improve the performance, a cross-layer flow-control mechanism is being proposed.

A comprehensive survey of Kumar et al. [2006] on DCF-based Media Access Control (MAC) protocols provides a very good insight of the early random access solutions.

Mechanisms to improve *energy efficiency* such as scheduling with transmission power controls, scheduling with adaptive modulation and coding, management of sleep and wake-up statuses of interfaces are being proposed among asynchronous random access sechemes [Nieminen et al. 2010; Qiao et al. 2003]. Furthermore, the IEEE 802.11s task group has made *energy efficiency* as one of the prime goals in the design of MAC for WMNs. Note that the energy efficiency is improved at the cost of increased delays, processing power, asymmetric links creating hidden terminals, and synchronization requirement. Hence a trade-off between *energy efficiency*, *throughput*, *delay*, and *other service levels* has to be chosen carefully.

Synchronous random access schemes

While the vast majority of random access-based research works are focused on adding some advancements on top of asynchronous DCF schemes that are readily supported by WiFi equipment, some research is also being carried out on slotted time-based random access schemes for WMNs [Zhu and Corson 1998; Marina et al. 2001]. An important feature of these schemes is that they use separate subframes for reservation and user-data transmissions where slots within a reservation subframe are randomly accessed to reserve slots within a user-data subframe. Thereby, contention is limited to reservation subframes and slots within user-data subframe are broadcast in a collision-free manner. While Zhu and Corson [1998] use an adaptation mechanism, based on the number of contending neighbours, to limit the probability of a node accessing a slot within the reservation subframe to minimize collisions, Marina et al. [2001] propose repeated transmissions of request messages to improve the probability a request message is being received by the intended node. These schemes, which are meant for control message exchange to establish cyclic access within a user-data subframe, pave the way for further research on the number of reservation subframes required for different neighbourhood densities.

A similar contention-based synchronous and distributed random access scheme was proposed in Ju and Li [1998]. The proposal improves on the lower bound of *throughput*, and requires the size of the network and the maximum degree of a node in the network beforehand for its operation.

Wu et al. [2007] investigate the capacity region of a distributed greedy algorithm to schedule packets as part of *throughput* analysis. In addition, they derived the necessary conditions to be met by the traffic patterns for network stability.

Another prominent example for the use of synchronous random access schemes exists within the IEEE 802.16-2004 coordinated distributed scheduling framework, where the *MSH-NENT* messages in network control subframes are scheduled in a random manner. Wang et al. [2007] succinctly identify the possible deadlocks caused by the hidden terminal problem in the network establishment processes involving *MSH-NENT* and *MSH-NCFG* MAC management messages affecting *autonomous operation*. Extensions to network control messages are devised to overcome ambiguities in link establishment, expediting link establishments in dense network scenarios. Here, scheduling *MSH-NCFG* is carried out in a pseudo-random fashion.

Common assumptions

The following are the common assumptions made in many of the random access-based simulation studies, in addition to the lists of assumptions that are given in Section 2.6: (i) interfaces can distinguish between no packet reception, packet reception, and collision, and (ii) transceivers are kept in receive mode except during the transmitting durations.

4. PSEUDO-RANDOM ACCESS SCHEMES

In this section we give a brief overview of distributed pseudo-random access schemes for WMNs and a well-known example, namely Election-Based Transmission Timing mechanism (EBTT) of IEEE 802.16-2004. Then we discuss the research progress including early pseudo-random access schemes, control channel and data channel scheduling solutions as well as the common assumptions found in the literature.

4.1. Continuous Distributed Prediction

A pseudo-random access exhibits a nearly random sequence of channel accesses by each node, while the sequence is governed by an algorithm such as *Mesh_Election* of IEEE 802.16-2004. Through fan-in and fan-out of seed values carrying scheduling information predictability is incorporated to the scheduler. It is basically a synchronous access scheme where the distributed algorithm is executed on each node with locally available data to determine its own and neighbour nodes' schedulings. Figure 8 shows the basic principle of the pseudo-random scheme where the shared algorithm determines the winning *CONDITION*s of nodes in a locality.

The algorithm decides the winning node among two-hop neighbours with inputs such as node IDs, available data on neighbours' scheduling, intended time slot, and

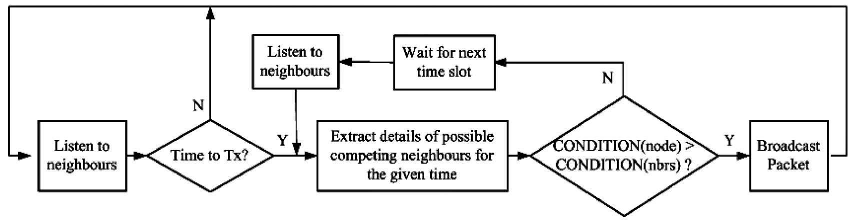


Fig. 8. Continuous distributed prediction based on locally available data.

priority of nodes. The primary objectives of these schemes are minimizing collisions and making decisions based on updated local information to adapt to traffic and topology changes. In pseudo-random access, while distributed algorithms play a primary role in determining the transmission opportunities, protocols such as three-way handshakes of request-grant-acknowledge messages might be used for secondary slot allocations.

4.2. Mesh Election-Based Coordinated Distributed Scheduling

The Coordinated Distributed Scheduling (CDS) framework of the IEEE 802.16-2004 mesh mode proposed a pseudo-random *mesh election* subroutine to determine the transmission timing of control messages [Cao et al. 2005]. This scheme is essentially a slotted time system where time is divided into frames, frames are divided into subframes, and subframes are further divided into slots. Time slots within the control subframes are called *Transmit Opportunities* (*TOs*) and slots of data subframes are known as *Mini Slots* (*MSs*). As shown in Figure 4(b), the scheme is meant to locally coordinate the broadcasts of *MSH-DSCH* and *MSH-NCFG* control messages within the control subframes in a collision-free manner. While the broadcast sequence of a node does not have a fixed sequence or repetition, each node can predict its own and its two-hop neighbours' transmission timings using a shared algorithm.

According to the standard, each node should maintain two-hop neighbourhood information composed of neighbours' unique node identities (NodeId), next possible transmission interval, hop count, and the time of the last update about the neighbours, exchanged over *MSH-DSCH* and/or *MSH-NCFG* messages. Note that this pseudo-random access scheme is mainly used for control packets over *TOs* only, and the scheduling of data packets over *MSs* is left open for another scheme.

Figure 9 shows the fundamental operational principle of this scheme. When a TO is about to begin, each node recalls its last decision on the next transmission timing to determine whether it is going to occupy the TO. If the previous decision suggests that the TO belongs to the node, the concerned node has to complete a *Mesh Election* procedure to determine its subsequent transmission and include that detail within the *MSH-DSCH* message the node is about to broadcast. The determination of a next TO starts by setting a temporary transmit opportunity (*tempXT*) deferring by a period called *holdoff time (H)* from the current transmit time (*cxt*). Then the node extracts the set of possible competing 2-hop neighbours at *tempXT* from the available neighbourhood information, and the pseudo-random *Mesh Election* subroutine is called for comparison. If the node wins TO at *tempXT*, then the particular *tempXT* will be the node's next transmit time. Else, the *mesh election* process is repeated for subsequent transmit opportunities by incrementing *tempXT* with a renewed set of competing nodes, until the node finds its next transmit opportunity. The next *MSH-DSCH* message transmission time is presented as relative time information with respect to the current time and is advertised as an interval instead of an exact TO. These timing intervals are expressed using the *Next Xmt Mx (nxm)* and *Xmt Holdoff Exponent (exp)* variables which hold

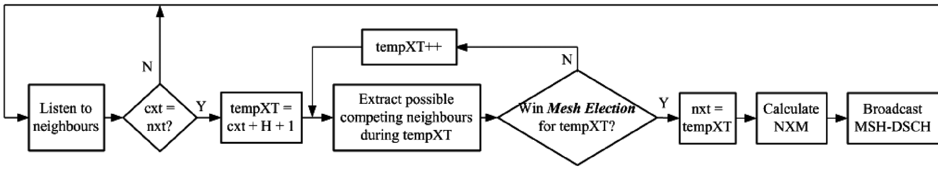


Fig. 9. IEEE 802.16-2004 *mesh election*-based coordinated distributed scheduling.

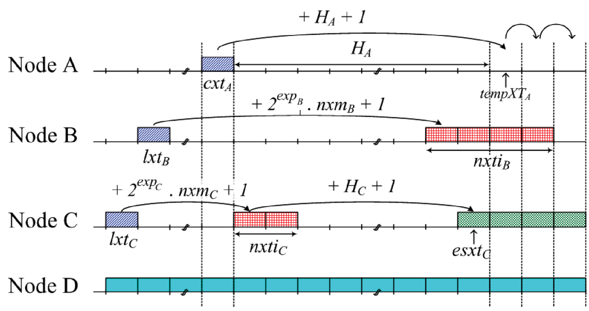


Fig. 10. Possible ways of competition for a TO.

five bits and three bits of information, respectively. In addition, the node has to relay its first-hop neighbours' next transmission timings within each *MSH-DSCH* message.

The relationship between parameters *Xmt Holdoff Time (H)*, *Next Xmt Mx (nxm)*, and *Xmt Holdoff Exponent (exp)* are defined in the standard as

$$H = 2^{exp+4}, \tag{2}$$

and

$$2^{exp} \cdot nxm < nxt \leq 2^{exp} \cdot (nxm + 1), \tag{3}$$

where *nxt* denotes next transmit time.

If the current transmit time is *cxt*, then Eq. (3) can also be stated in absolute time as: $cxt + 2^{exp} \cdot nxm < nxt \leq cxt + 2^{exp} \cdot (nxm + 1)$, or as a time range $nxti = [cxt + 2^{exp} \cdot nxm + 1, cxt + 2^{exp} \cdot (nxm + 1)]$, where *nxti* is the next transmit time interval in absolute time.

Figure 10 illustrates an example of competition and the relevant calculations where txt_A indicates the initial *TempXmtTime* of node *A*. In this process, node *A* is competing with a set of neighbours $\{B, C, D\}$ to get its next TO. Neighbours are considered as competitors in the following scenarios: if (i) node *B* whose next transmission time interval ($nxti_B$) includes txt_A, (ii) node *C* whose earliest subsequent transmission time, $esxt_C \leq txt_A$, or (iii) node *D* whose next transmission time interval is unknown.

Note that, unlike random access schemes, pseudo-random access schemes primarily depend on algorithms such as hashing sequences and mesh elections to determine which node is going to access the channel.

4.3. Progress in the Research of Pseudo-Random Access Schemes

The concept of pseudo-random algorithms for scheduling packetized wireless solutions was initially proposed for radio frequency identification (RFID)-based tag access and satellite networks [Rozovsky and Kumar 2001; Chlamtac et al. 1997a, 1997b]. In those solutions, a base station having a fair amount of seed information about other terminals (RFIDs or satellites) decides which terminal is to communicate next. Rozovsky and Kumar's [2001] "SEEDEX" extended the pseudo-random scheduling solution for multihop communication in a distributed manner. In SEEDEX, a fan-in and fan-out procedure is proposed to exchange seeds within a two-hop neighbourhood and the output of a pseudo-random routine for these seed values is used to choose the probability of a node's transmission for a given time slot to minimize collisions. The solution is extended in Bao and Garcia-Luna-Aceves [2001] for collision-free node or link scheduling in WMNs. Improving *throughput*, *delay* measures, and *energy efficiency* are objectives of this solution.

The CDS scheme based on the IEEE 802.16-2004 standard - "Air interface for fixed broadband wireless access systems" is a concrete pseudo-random access framework which provides a great range of supporting functions required for a mesh operation, such as network synchronization, network entry procedures, scheduling, network security, and quality of service. The standardization of mesh operation and strength of WiMAX certified equipments in terms of bandwidth and coverage have drawn significant research interest to this channel access framework [Ali et al. 2008; Ghosh et al. 2008]. Moreover, with well-defined operational frequencies, frame lengths, modulation schemes, and forward error correction schemes, performance attributes can be realistically measured for IEEE 802.16-2004-based CDS schemes using either a simulation environment or a real deployment of WiMAX[1] certified wireless nodes in mesh mode.

In CDS, the *Mesh_Election* subroutine governs the collision-free scheduling of *MSH-DSCH* and *MSH-NCFG* MAC management packets over control subframe TOs in a pseudo-random fashion. The scheduling scheme for MS allocations over data subframes for a user-data packet is left open in the standard. Even though the MS scheduling can be of any algorithm, the effect of pseudo-random scheduling will affect MS scheduling as well.

Scheduling control packets

Early proposals such as Cao et al. [2005] and Bayer et al. [2006] on CDS are intended to develop an *interoperable* working model supporting *autonomous operation* based on the framework stipulated in the IEEE 802.16-2004 standard. Cao et al. [2005] explain the use of a *Mesh_Election* subroutine for the pseudo-random operation, determination of competing neighbours, and the three-way handshake of *MSH-DSCH* messages required to allocate user-data packets. In addition, Cao et al.'s [2005] bifaceted study evaluates delay performances using a stochastic model and simulation results. The study in Cao et al. [2007], an improved version of Cao et al. [2005], also provides evaluation-based stationary and ergodic renewal processes and a simulation tool with a different network topology being investigated.

The research study in Bayer et al. [2006] on CDS proposes an effective way to uniquely identify the crucial TO number for execution of the *Mesh Election* subroutine. It includes a simulation results for a neighbourhood density of 12 neighbours per node in studying the performance measure of Election-Based Transmission Timing (EBTT) mechanism using the *Mesh Election* subroutine.

Expediting three-way handshakes of *MSH-DSCH* messages is considered as a way to accelerate data slot allocations and hence reduce the end-to-end delay [Vijayalayan et al. 2010; Wang et al. 2008a; Cicconetti et al. 2007b]. Collision avoidance in *MSH-DSCH* scheduling, dynamic allocation, or usage-based selections of *Xmt Holdoff Exponents*, and adjustment of *Holdoff Time* were investigated in this regard.

The simulation study in Cicconetti et al. [2007b] measures the inter-transmission intervals of nodes in various neighbourhood densities. In addition, the effect of *Xmt*

[1]WiMAX forum issues WiMAX certifications for IEEE 802.16 standard complying devices.

Holdoff Exponent on the neighbourhood is also analyzed. Studies in Bayer et al. [2007] and Wang et al. [2008a] explain the need for proper selection of *Xmt Holdoff Exponent* values for nodes based on the role of the node and traffic requirements. The authors in Wang et al. [2008b] also point out the delay caused by *Holdoff Time* and present a dynamic method of calculation.

The work in Vijayalayan et al. [2010] reveals the existence of collisions, its adverse effect on the *delays* of data slot allocations, and proposes a simplified solution to overcome the issue. The authors show that optimization can be achieved by adjusting the *Holdoff Time* for low neighbourhood densities, achieving faster data channel establishments. Moreover, the effect of increased neighbourhood density on channel establishment delays was studied in detail for *scalability* considerations.

In Zhang et al. [2008], the authors develop a probabilistic model to find necessary and sufficient conditions for collision-free operation. Their study also shows that the collision-free property is not unconditional over CDS.

Scheduling data packets

Scheduling of both *TOs* and *MSs* have to be studied in a combined manner for the completeness of a study on a pseudo-random access scheme. Some of the *MS* allocation solutions that emerged after some preliminary publications on *TO* scheduling, such as Mogre et al. [2009] and Kapoor and Ribeiro [2010], investigated the MS allocation in isolation of TO allocations and hence the secondary effects of the pseudo-random algorithm were ignored. Teng et al. [2008] focus on the number of *MSs* to be allocated with a three-way handshake of *MSH-DSCH* for *throughput* efficiency, consider the best-case scenario on MS allocations where the requesting node is granted with all the requested *MSs*, always.

Wang et al. [2008b] provide a good insight of MS allocations. It includes a mechanism to estimate a suitable slot for starting MS with respect to TO in which an *MSH-DSCH:Request* was received. Limitations of the existing framework on MS allocations such as inability to support multiple chunks of *MSs* with a single control message handshake and noninclusiveness of flow information are identified and solutions are proposed.

Similarly, a Fair-End-to-end Bandwidth Allocation (FEBA) scheme [Cicconetti et al. 2009] proposed for *MS* scheduling includes enhanced measures to minimize waste of *MSs* in the slot reservations. Estimations of “schedule horizon”, that is, time between two consecutive *MSH-DSCH* transmissions by a node, and “grant horizon”, that is, time between a request message and corresponding grant, improve bandwidth utilization through appropriate starting point of *MSs* and reallocation of unestablished *MSs*.

In Xuekang et al. [2009], the effect of single and multiple MS allocations over a single three-way handshake of *MSH-DSCH* messages are studied on a realistic radio-wave environment. Under simulation study, a basic cross-layer CDS mechanism is evaluated over a small tree-type network comprising five nodes. Note that these different MS allocation proposals are based on intensive calculations increasing the *complexity* of the hardware and create issues on *interoperability*.

Short surveys in Ghosh et al. [2008] and Ali et al. [2008] cover early research on IEEE 802.16-based WMNs. The study in Ghosh et al. [2008] provides a comparison of mobile multihop relay networks versus WMNs, and differences between scheduling techniques: centralized scheduling, coordinated distributed scheduling, and uncoordinated distributed scheduling, on generic aspects. It also summarizes several proposals on centralized scheduling. On the other hand, the study in Ali et al. [2008] analyzes the operational and performance aspects of centralized scheduling and coordinated distributed scheduling in a detailed and balanced manner, with various quality of service attributes, scalability, frame and message formats, and synchronization discussed.

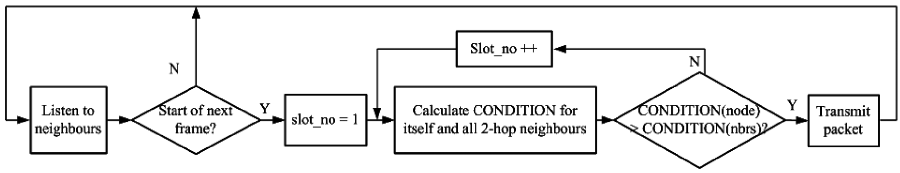


Fig. 11. Cyclic access scheme with one time slot per frame.

The recent survey on IEEE 802.16 mesh mode schedulers [Kas et al. 2010] also summarizes some of the distributed scheduling proposals in addition to the centralized ones. The study categorizes the proposals on distributed scheduling schemes into Election-Based Transmission Timing (EBTT) proposals and algorithms for MS allocations. Moreover, the survey provides a comparison of the research proposals based on performance metrics.

Common assumptions

The following are the common assumptions made in many of the pseudo-random access-based simulation studies, in addition to the lists of assumptions that are given in Section 2.6: (i) all nodes are using the same set of algorithms in random number generation, seed value exchange, and comparison, (ii) nodes know the identities of their two-hop neighbours (the minimum), (iii) network changes are learned through some other mechanisms, and (iv) the strongest modulation and coding schemes are used for control messages and modulation and coding schemes with highest possible bit-rate are used for user data (in case of IEEE 802.16-2004).

5. CYCLIC ACCESS SCHEMES

In this section, we first give a brief overview of distributed cyclic access schemes for WMNs and a well-known example. The last subsection discusses the progress in research of cyclic access schemes, covering node scheduling solutions, link scheduling solutions, and the common assumptions found in the literature.

5.1. Achieving the Lowest Cycle Length

Cyclic access schemes follow the typical round-robin algorithms of TDMA architecture of many point-to-multipoint solutions, where time is divided into slots of fixed size and slots are grouped into frames that are repeated. Either nodes [Chlamtac and Pinter 1987; Gronkvist et al. 2004] or links [Djukic and Valaee 2007; Jayachandran and Andrews 2010] are allocated with a certain number of slots and the positions of those slots within frames remain the same over a length of time. Here, all nodes in a network execute the same algorithm with locally available information to achieve a conflict-free scheduling cycle.

The primary objectives of these schemes are improving the spatial reuse of frequency channels and assuring QoS attributes such as end-to-end delay, delay jitter, and throughput [Ramanathan and Lloyd 1993]. The problem is approached as either a node scheduling problem or a link scheduling problem that can be compared with vertex-colouring and edge-colouring problems of graph theory, respectively.

Achieving the lowest possible cycle length is considered as the measure of performance of the scheduling scheme proposed. Since finding an optimal scheduling solution for a mesh network is NP-complete, various heuristic-based algorithms are being investigated to obtain a shorter cycle length [Chlamtac and Pinter 1987; Ramanathan and Lloyd 1993].

A basic cyclic scheme to schedule broadcast of nodes is given in Figure 11, where nodes are assumed to have knowledge of scheduling of nodes within a two-hop neighbourhood by some means and have a prefect time synchronization globally. Nodes continuously monitor the broadcasts of neighbours and wait for their opportunity within a frame until the neighbours with higher priority or "preferable condition" have broadcasted their packets. The cycles/frames are repeated by tracking the broadcast completion of lower-priority nodes within the neighbourhood.

5.2. Node-Id-Based Cyclic Access Scheme

The main challenge of gathering information of a whole topology, set of ready nodes, intended receivers, and changes in network topology is infeasible to achieve with cyclic schemes. Hence, Cidon and Sidi [1989] proposed a solution where all the nodes in a network are given with sequential identifiers (Ids) starting from 1, and each node i broadcasts within the i'th control slot. It is assumed that the node Ids are preprogrammed in the nodes and the total number of nodes in the network, N, is known to all the nodes.

Time is divided into a control channel and data channel, where the control channel is divided into request and confirmation segments. Each segment is further divided into N slots. A node i having a data packet to be sent to a neighbour generates a request in the i'th slot, and if there is no denial during its first half of the i'th confirmation slot, then it confirms the transmission during the later half.

Even though the solution is simple, there is no spatial reuse of the channel within control segments, slots might be wasted when there is no traffic, and data transmission is prone to delay variations. Furthermore, the necessity to know the total number of nodes reduces the scalability. These shortcomings are addressed in the later proposals that are given in the following subsection.

5.3. Progress in the Research of Cyclic Access Schemes

Research on cyclic access schemes are mostly based on graph-colouring techniques or opportunistic scheduling with proportional fairness, and are intended to fit all the TDMA-based wireless broadband solutions without confining to any standard that may change over time [Ramanathan and Lloyd 1993; Djukic and Valaee 2007]. The problem of improving the spatial reuse of the frequency spectrum is generally approached as maximizing the simultaneous utilization of time slots. When graph theories are used, the network is mapped into connectivity graphs and conflict graphs are derived. Then, vertex-colouring or edge-colouring algorithms are used to colour either nodes or links in the connectivity graph in a collision-free manner [Max et al. 2007].

Based on the primary selection of the network entity, cyclic access solutions can be categorized into node scheduling and link scheduling schemes. In node scheduling, time slots are allocated to nodes where each time slot can be simultaneously used by nodes that are separated by a minimum of two intermediate nodes (3 hops away) for their broadcasts. On the other hand, in link scheduling, links (denoted by node pairs) are allocated with time slots with simultaneous allocations avoided for conflicting links.

Node scheduling

Since finding an optimal cycle length is an NP-complete problem, various heuristics are being proposed to achieve near-optimal cycle lengths. Chlamtac and Pinter [1987] propose a simple node scheduling heuristic of the lowest node Id first in deciding the node sequence within frames. They also come up with an upper bound of their scheduling cycle: $min(K^2 + 1, |V|)$, where K is the maximum degree of a node in the network and $|V|$ is the number of nodes in the network. Their solution is given as an algorithm to handle a graph and details of how the timing of a second-hop neighbour's transmission are learned by a node are left open for another scheme. The study in Cheng et al. [2008] extends the preceding solution as One Neighbour Per Cycle (ONPC) and

All Neighbours Per Cycle (ANPC) for node scheduling and link scheduling purposes for added multiradio multichannel scenarios.

Cunningham and Cahill [2002] propose a combined solution of random access and cyclic access to guarantee end-to-end delays. The network coverage area is split into cells, and nodes within a cell access the channel in a contention-free and cyclic manner using random access-based negotiations over the contention period. The solution has issues such as conflicting simultaneous requests over the contention period and intercell communication, which may affect *autonomous operation, throughput, scalability*, as well as *delay* measures.

In Zhu et al. [2008], authors propose an alternative solution to schedule IEEE 802.16-based mesh networks, a cyclic access scheme, where bits are allocated for each node over a preconfigured scheduling cycle. They propose a fixed scheduling cycle where all nodes are preprogrammed with neighbourhood information.

The authors of Calamoneri et al. [2011] propose a distributed version of a range assignment schedule to improve *energy efficiency* by partitioning the network and reducing mesh topologies into tree topologies; a trade-off with *throughput*. The solution has a prerequisite on knowing the number of nodes in the network and geographical location of nodes at each node.

More recently, the IEEE 802.11-2012 standard defined a Mesh Coordination Function (MCF) of hybrid nature called MCF-Controlled Channel Access (MCCA) that can help a limited number of nodes reserving transmission opportunities for repetitive broadcasts. Here, MCCA is established with the help of a random access mechanism. The standard suggests the use of MCCA on a subset of nodes in a WMN requiring stricter QoS guarantees, and defines an MCCA Access Fraction Limit (MAF Limit) parameter to limit usage of the spectrum for MCCA.

Link scheduling

A link scheduling solution based on a distributed Bellman-Ford algorithm over a conflict graph is proposed by Djukic and Valaee [2007]. A wave-based termination routine initiated by a control node is included to look for the changes required on the scheduling cycle. The resulting schedule reduces the mesh network into a tree network.

The study in Salonidis and Tassiulas [2005] also proposes a cyclic link scheduling solution over mesh topologies reduced into tree networks. The solution supports multiple slot allocations to cater for the bandwidth requirements and an asynchronous random access scheme is incorporated to negotiate the scheduling cycle. The proposal also includes the convergence time estimation for various network densities. While their solution attempts to maintain *service levels*, the network *throughput* is affected by the channel negotiation at higher node densities.

Jayachandran and Andrews [2010] use the *maximum independent set for unit-disk graphs* principle to achieve a low-delay scheduling over a geometric graph. Similar to Cunningham and Cahill [2002], the area is divided into squares and the scheduling problem is decomposed into grid schedules.

The optimality of node scheduling and link scheduling solutions is investigated in detail in Ramanathan and Lloyd [1993]. The study also derives a relationship between expectable optimality and the network's thickness based on maximum node degree. Moreover, tree networks are found optimally scheduleable in a distributed fashion. Ramanathan [1997] provides a generalization for cyclic access schemes that can be used for TDMA, FDMA, or CDMA solutions. However, a distributed implementation of these schemes is limited due to the prerequirement for network knowledge.

While these scheduling schemes have been proposed as a solution for slotted time wireless unit-based WMNs for some time, they remain theoretical models. In addition, a priori knowledge of global network parameters, such as the number of nodes in the network and the maximum number of neighbours a node has, are difficult to predict and may change with time [Chlamtac et al. 2003].

It is noteworthy that the fixed-length cyclic access schemes require the assistance of either a random access scheme or a pseudo-random access scheme to handle network topology changes. Hence, a cyclic access scheme can only partially fulfill *autonomous operation* and *scalability* in its own.

Common assumptions

The following are the common assumptions made in many of the cyclic access-based simulation studies, in addition to the lists of assumptions that are given in Section 2.6: (i) nodes know the identities of their two-hop neighbours (the minimum), (ii) network information such as number of nodes in the network and maximum number of 1-hop neighbours a node has (i.e., degree of the network) are known to all the nodes a priori, (iii) completion of transmission by a second neighbour can be learned through some mechanism, and (iv) messages arrive on each link in the order in which they are sent and are processed in the same order.

6. COMPARISON OF MAJOR TYPES OF DISTRIBUTED SCHEDULING SCHEMES

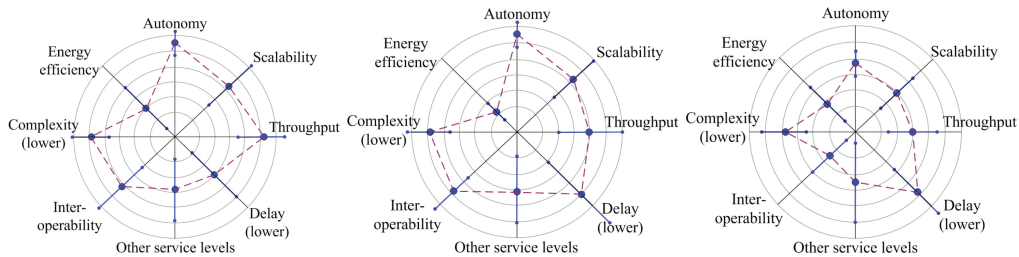
Based on the indicators of key attributes of WMN scheduling schemes tabulated in Table I, a summary of the current status of the three distributed scheduling schemes is provided in Table II. It is evident that due to the support of standardization for some years, the random access and pseudo-random access schemes have the advantage of frameworks that are implementable for the entire WMNs over widely accepted wireless equipment like WiFi and WiMAX. In addition, it can be observed that cyclic access schemes lag behind the other schemes on key attributes such as *autonomous operation*, *scalability*, and *interoperability* for full network-wide WMN operation.

Among the forefront solutions, DCF-based random channel access solutions are being deployed over real-world WMNs. Due to the inherent ability to support changes in the network topologies, these random access schemes are suitable for mobile applications and highly varying environments. Nevertheless, the high contention due to the use of unlicensed frequency spectrum, deadlocks due to backoffs, lesser coverage distance of WiFi, and lack of QoS guarantee remain as limitations.

Encouraged by the strengths of the WiMAX air interface and relative newness, *Mesh Election*-based coordinated distributed scheduling schemes have received significant interest among researchers. Moreover, pseudo-random schemes can adapt to changes in the network topology provided that the updated two-hop neighbourhood of each node is known. With predictability of transmissions and relaying of schedule information, pseudo-random solutions are favourable for synchronous wireless equipment to support dynamic traffic and radio-wave propagation conditions. In addition, through predictability they improve energy efficiency by avoiding waste of energy in collisions and continuous receiver up time.

However, the random nature of TO scheduling results in complications on allocating mini slots for user data packets relative to the control packet handshakes. In addition, guaranteeing upper time limits for data packet delivery, as required by certain data applications, remains a tedious goal. Furthermore, pseudo-random schemes are dependent on random access schemes to learn about the addition of new nodes to a network. Multiradio multichannel scheduling schemes are yet to be developed that comply to distributed and pseudo-random criteria.

Cyclic access schemes face issues on establishing cycles in their own as nodes cannot predict their second-hop neighbours' transmissions. For example, knowing the existence of second-hop neighbours only is not sufficient to continue with the scheduling process. For a given node, unless an intermediate node confirms completion of



(a) research focus in random access schemes (b) research focus in pseudo-random access schemes (c) research focus in cyclic access schemes

Fig. 12. Summarized view of degree of focus on crucial attributes of scheduling schemes.

transmission of a second-hop neighbour with higher preference, the first node will have to wait indefinitely, causing deadlocks (if the intermediate node has lesser preference). Such deadlocks are uncommon in random access and pseudo-random access schemes.

Despite the practical difficulties in implementing cyclic access schemes for WMNs, increasing QoS requirements on network traffic necessitates the cyclic access schemes. Hence, a cyclic solution with random or pseudo-random schemes to learn topology changes is inevitable for certain application domains such as voice/video over Internet protocol.

6.1. Research Focus of the Selected Literature

In addition to the comparison given in Table II, we also quantitatively compared the research focus given on the eight key attributes for major scheduling schemes. This process was carried out on the literature referred to in this survey that are selected based on the criteria given in Section 1.5. If a research proposal significantly considers a performance attribute, then we gave one mark for the paper on that attribute. Partial and insignificant considerations were given 0.5 and 0 marks, respectively. Based on this, mean values and standard deviations of marks on each attribute were taken for each major distributed scheduling solution. Figure 12 shows the degree of focus given by the research on the three major types of scheduling schemes based on our quantitative study. In these graphs, the smallest circle denotes lowest or no focus and the largest circle denotes all of the developments considered or some new noteworthy contribution in the area.

From the web charts in Figure 12, it is evident that in random access and pseudo-random access schemes more focus is given on *autonomous operations*, *interoperability*, and *throughput* whereas cyclic access schemes pay more attention to *delay*. This trend matches the strengths of the corresponding schemes. Furthermore, there appears to be scope for more contributions in *energy efficiency* of pseudo-random access solution designs.

7. DEVELOPMENTS IN WIRELESS STANDARDS

7.1. IEEE 802.11 Family Standards

The ubiquitous WiFi technology is based on the IEEE 802.11 family of standards that has been evolving since 1999. DCF, part of IEEE 802.11-1999, is a foundation for many variants of distributed schedulers. Enhanced Distributed Channel Access (EDCA) is an enhanced variant of DCF defined in the IEEE 802.11-2007, supporting multiple data packet transfers per *RTS*/*CTS* handshake and priority data traffics for *throughput* and *service-level* enhancements.

Table II. Comparison of Major Types of Distributed Scheduling Schemes

Attribute	Random Access	Pseudo Random Access	Cyclic Access
1. Autonomous operation			
1.1 Predictability of next transmission	Not possible	Predictable (Own, 1-hop, 2-hop)	Predictable (Own, 1-hop, 2-hop)
1.2 Adaptability to topology or traffic changes	Fast, no interruptions	Fast, no interruptions	Consumes time, possible interruptions
1.3 Support for unicast and/or broadcast	Broadcast of control messages and unicast user data	Broadcast of control messages and unicast user data	Node scheduling for broadcast and link scheduling for unicast
2. Scalability			
2.1 Effects of higher network densities	Deadlocks, increased av. delays and delay-jitter	Inability accommodate neighbours' details within control messages, increased av. delays and delay-jitter	Increased delays
2.2 Effects of multiple hops	Increased av. delays and delay-jitter	Increased av. delays and delay-jitter	Increased delays
2.3 Effects of network complexities	Deadlocks, increased av. delays, delay-jitter and location based contention	Increased av. delays, delay-jitter and location based contention	Increased delays
3. Throughput			
3.1 Mechanisms to minimize or avoid collisions	*RTS* & *CTS* handshakes, backoff mechanisms	Schedule information relaying and prediction	Schedule information relaying and prediction (limited no. of nodes)
3.2 Solution for exposed terminal problem	No practical solutions	Available	Available (under link scheduling schemes)
3.3 Availability of single-radio multi-channel scheduling schemes	Available	Framework available, convincing schemes are yet to be devised	No convincing frameworks or schemes
3.4 Availability of multi-radio multi-channel scheduling schemes	Available	Not available	Not available
3.5 Control overhead	Low, Generally fixed in length	High, Increases with the network density	High, Increases with the network density
3.6 Length of a transmission	Variable length	Fixed length (usually of slot length or multiples)	Fixed length (usually of slot length or multiples)
4. Delay (lower)			
4.1 End-to-end Delay Guarantee	Not guaranteed	Not guaranteed	Guaranteed
4.2 Delay jitter	Increases with neighbour density and path length	Increases with neighbour density and path length	Not exists
5. Other service levels			
5.1 Fairness	Statistically equal opportunity, affected by location based contention	Statistically equal opportunity, affected by location based contention	Equal opportunity, not affected by location based contention
5.2 Priority	Set on backoff mechanism	Set on seed-values e.g., *Xmt Holdoff Exponent*	Set on weights
5.3 Packet loss ratio	Low to high	Nil to low	Nil to low

Table II. Continued

Attribute	Random Access	Pseudo Random Access	Cyclic Access
6. Inter-operability			
6.1 Supporting wireless standards (mesh)	IEEE 802.11-2012 (EDCA)	IEEE 802.16:2004	IEEE 802.11-2012 (MCCA for limited no. of nodes)
6.2 Availability of message templates	Available	Available	Available (for limited no. of nodes)
7. Complexity (lower)			
7.1 Requirement for time synchronization	Generally not required	Required	Required
7.2 Computational complexity	Generally independent of neighbourhood	Depends on the neighbourhood	Depends on the neighbourhood
8. Energy efficiency			
8.1 Expected receiver uptime	Generally continuous, sleep and wake-up solutions are emerging	During control subframes and neighbours' predictable transmission periods	During neighbours' predictable transmission periods
8.2 Collision avoidance	The same as in 3.1	The same as in 3.1	The same as in 3.1

Even though DCF protocols readily support distributed scheduling for WMNs, task group *s* was formed in year 2004 to focus on enhancements required for WMN operations resulting in the IEEE 802.11s-2011 amendment [Hiertz et al. 2010]. Moreover, there have been noteworthy enhancements to WiFi technology brought in by recent amendments. More specifically, higher throughput in the order of 600 Mbps and a greater coverage of 5 km are made possible by the amendments IEEE 802.11n-2009 and IEEE 802.11y-2008 respectively.

The IEEE 802.11-2012, a revision of IEEE 802.11-2007, is the present active standard, that incorporates ten amendments that followed IEEE 802.11-2007 including *n*, *s* and *y*, mentioned earlier. This new standard provides major facilities on coordination function, discovery, peering management, beaconing and synchronization, power management, extended address frame formats, path selection and forwarding, intra-mesh congestion control, and security for mesh operations. Especially, the IEEE 802.11-2012 stipulates two distributed Mesh Coordination Functions (MCFs) for scheduling, namely Enhanced Distributed Channel Access (EDCA) and MCF-Controlled Channel Access (MCCA), a random access scheme and a cyclic access scheme, respectively [Khorov et al. 2011]. In here, MCCA requires a random access scheme to establish scheduling cycles and to adapt to changes, and only supports a limited number of nodes in a WMN.

7.2. IEEE 802.16 Family Standards

The WiMAX standard IEEE 802.16 continues to evolve by adapting the newer technological concepts and features of wireless data solutions, and by rolling up the previous standard with the enhancements that were later added to it as amendments to have consistency and to compete with other broadband access technologies. The current version of the standard is IEEE 802.16-2009, which is a roll up and revision of IEEE 802.16-2004 and its amendments IEEE 802.16e-2005, IEEE 802.16-2004/Cor1-2005, IEEE 802.16f-2005, and IEEE Std 802.16g-2007. In addition, enhanced Management Information Base (MIB) specifications and maintenance features were added in the newer version.

In the context of distributed scheduling for WMNs, a very significant change in the newer version of the WiMAX standard is that Section 6.2 - *mesh operation overview of MAC common part sublayer* of IEEE 802.16-2004 has been dropped and indicated as

“Reserved” in IEEE 802.16-2009. This means that the *Mesh Election* subroutine, the foundation for widely studied pseudo-random channel access scheme will not be a part of the newer version of WiMAX equipment. A discussion thread of IEEE 802.16 work group (IEEE C802.16maint-07/042) indicates that a mesh operation overview is being dropped due to the incomplete state and that the IEEE 802.16j amendment-based framework can be considered as an alternative solution in the mean time.

Despite the changes on the IEEE 802.16 standard, researchers are continuing to work on *Mesh Election* subroutine-based scheduling to make it a complete channel access solution. Furthermore, the IEEE 802.16j-2009 framework only supports a tree topology-based multihop relay network and not the general mesh topologies [Ghosh et al. 2008].

The IEEE 802.16h-2010 proposes Cognitive Radio (CR) capabilities, that is, awareness of operational environment and internal state, and timely decision making, on the IEEE 802.16-based wireless units for improved coexistence mechanisms in license-exempt operation. The IEEE 802.16m-2011 provides enhancements for superior throughput of air interfaces to match with international telecom union’s IMT-advanced specifications. Hence, it can be concluded that IEEE 802.16-based WiMAX technology will continue as a potential fourth-generation wireless interface and a complete scheduling framework to turn them as constituent nodes for WMNs remains an interesting research topic.

7.3. Other IEEE 802 Family Standards

IEEE 802.15 Wireless Personal Area Network (WPAN) Task Group 5 is also working on physical-and MAC-layer sepcifications to bring mesh networking capability to WPAN products. The standard IEEE 802.15-2009 includes distributed scheduling as part of its MAC specifications and stipulates control message templates for random access and cyclic access schemes. Nevertheless, IEEE 802.15.5 concentrates more on basic network connectivity with route redundancy and improved battery life rather than network *throughput* as targeted in WMNs.

IEEE 802.20 mobile broadband wireless access systems supporting vehicular mobility is another emerging area that is being looked into for the possibilities of mesh networking [Bruno et al. 2005]. Considering the expected rapid change of topologies in mesh operations, distributed scheduling would certainly be of choice for multiple access.

IEEE 802.22 specifies MAC and physical layers for Regional Area Networks (RANs) with CR capabilities over television (TV) bands for point-to-multipoint connectivity. Considering the sizeable amount of spectrum released from disbanded analog TV broadcasts, their longer distance propagation properties, and strengths of CR, WMN solutions are emerging [Sengupta et al. 2008].

7.4. IETF’s Mobile Ad Hoc Network (MANET)

Internet Engineering Task Force’s (IETF) mobile ad hoc networks (MANET) working group is focused primarily on IP routing protocols for both ad hoc and wireless mesh networks. In addition, they have come up with standardizations of packet or message formats (RFC 5444), time representation formats (RFC 5497), jitter considerations (RFC 5148), and Management Information Bases (MIBs) that have to be considered in the implementation of distributed scheduling schemes for WMNs.

8. EMERGING TRENDS AND KEY RESEARCH PROBLEMS

WMNs are no longer confined to military applications and a multitude of applications are emerging that require focus on multiple aspects. Ideally, the scheduling schemes should meet all the attributes mentioned in Section 2 to the fullest. However, limited availability of information in distributed schemes, trade-offs in achieving two or more attributes, and cost factors make the scheduling schemes suboptimal in some aspects.

In addition, the wireless standards continue to evolve by adapting features of others. For example, IEEE 802.11s evolved with time synchronization and IEEE 802.11y serves larger coverage distances upto 4.5 km that were previously existing in IEEE 802.16 solutions. Similarly, IEEE 802.16j distributed scheduling is expected to be a cyclic access scheme. Moreover, *hybrid scheduling schemes* built as a mix of major scheduling schemes are becoming a common feature in the wireless standards. For example, the mesh coordination function of IEEE 802.11-2012 includes a random access scheme and a limited cyclic access scheme on top of it. In this scenario, random access is expected to handle changes in network topology and traffic, whereas cyclic access serves QoS provisions and energy saving with periodic scans for sleep-and-wake-up modes. Commercial WMN products such as Flashlinq and Tropos Networks also use combinations of two or more scheduling schemes of random and/or pseudo-random and/or cyclic accesses. Therefore it is highly beneficial to have an understanding of the fundamental principles behind major scheduling schemes.

Several cross-layer solutions are also emerging to make use of physical-layer, network-layer, and other higher-layer information with scheduling to further optimize performance. Adaptive channel coding and modulation schemes [Yip et al. 2011], queue management [Nieminen et al. 2010], routing [Hai-tao and Yue 2011], energy-aware routing [Calamoneri et al. 2011], and traffic admission control [Aziz et al. 2011] are some of the key cross-layer parameters that are being investigated jointly with scheduling. Additionally, cross-layer solutions such as directional or software-driven antennas and route-based link activation are emerging for further enhancements.

Since WMNs are being envisaged as an alternative to offer broadband connectivity in the places where wired solutions are unfavourable, achieving the near-optimal *throughput* will remain the predominant objective of any scheduling scheme, next to *autonomous operation*.

To meet the demands of popular network usage scenarios, such as voice and video transmissions, *delay* measures such as end-to-end delay and delay jitter have to be maintained within acceptable limits. Hence, these performance metrics have to be evaluated for different network topologies and traffic patterns.

For random access schemes maintaining the *delay* measures within acceptable limits remains a critical issue as guarantees are difficult to stipulate. In addition, continuous receiver up time for carrier sensing needs to be minimized to improve *energy efficiency* while maintaining delays within acceptable limits.

Pseudo-random schemes must also be optimized to maintain *delay* measures within limits under various network and traffic conditions. Investigations on optimal amount of seed data to be shared is another open challenge for researchers. Furthermore, a complete and convincing CDS scheme handling both control and user-data packets is yet to emerge.

The cyclic access schemes require further attention to formalize mechanisms to adapt topology and traffic changes. Detailed message templates serving the WMN control and user-data packets is another critical shortcoming of cyclic access schemes that need to be addressed.

9. CONCLUSION

In this survey, we discussed the fundamental ideas behind distributed scheduling schemes for WMNs and the key attributes of multiple access. We categorized solutions formulated in the literature as either random, pseudo-random, or cyclic, provided prominent examples and the latest research progress and methodologies. A comprehensive comparison on the major scheduling schemes was given with a breakdown on measures to judge the fulfilment of the objectives. This study also provides a comprehensive sample of research directions, major works, and recent developments. Considering the importance of wireless standards in real-world deployments of WMNs, we have also discussed the recent developments in the IEEE and IETF standards that will influence future WMNs. This survey provides a comprehensive guide for future researchers to understand the research area of distributed scheduling for WMNs.

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