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REVIEW

Survey of scheduling algorithms in IEEE 802.16 PMP networks

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Abstract IEEE 802.16 standard has been proposed to support wide-range wireless broadband access. It is based on a common medium access control (MAC) protocol compliance with several physical layer specifications and operates in two modes Point-to-multipoint (PMP) and mesh mode. Physical layer specifications and MAC protocol signaling are already well defined for the standard. But, scheduling policies for IEEE 802.16 have been left as open issue to be explored by equipment manufactures. The objective of this survey is to investigate scheduling issues to ensure quality of service (QoS) support for WiMAX networks. Design issues for the development of schedulers have been presented. Classification and characteristics of various techniques based on their fundamental working principle are considered and summarized. Impact-able future issues in the area of QoS support for WiMAX have also been discussed.

Contents

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1. Introduction

The communication systems over the past have been changed by rapid advances in Wireless and mobile networks. Additional demand for high speed wireless internet access, voice and multimedia applications has revolutionized growth of Internet. This ever increasing need had led to the popularity of technologies like 3GPP, LTE, 3GPP2, and IEEE 802.16 that provide broadband data rates to wireless users.

IEEE 802.16 also known as WiMAX (Worldwide Interoperability for Microwave access Networks) has been designed to provide wireless and wired broadband access with QoS guarantees in Metropolitan area networks [1]. This standard initially specified a frequency range of 10–66 GHz with a theoretical maximum bandwidth of 120 Mb/s and maximum transmission range of 50 km and supported only line-of-sight (LOS) transmission. Since its inception standard had undergone several amendments and evolved to the 802.16-2004 standard [2] (also known as 802.16d) together with convergence of WiBro [3] from Korea. A variant of the standard, IEEE 802.16a-2003, approved in April 2003, can support non-LOS (NLOS) transmission and adopts OFDM at the PHY layer. It also added support for the 2–11 GHz range. Further extensions to the standard were made in the form of advancements IEEE 802.16b and IEEE 802.16c for providing QoS guarantees, priorities for real-time applications, and differentiation of service classes for different traffic types. It also provided provisions for addition of more devices to the standard. Lack of mobility support was one of the major hindrances to its deployment compared to IEEE 802.11 WLAN which was added by IEEE 802.16e standard released in 2005.

Table 1 lists currently active standards and portraits major amendments and ongoing developments of the standard. Table 2 provides a comparison of WiMAX with competitive technologies like 802.11 and 802.20. While some consider mobile WiMAX as a candidate for 4th generation of mobile networks, others view it as the first generation of mobile Internet technologies emerging from a wider ecosystem targeting to extend success of WiFi over wide area networks supporting mobility [4,5].

The goal of this paper is to study the various available scheduling techniques for IEEE 802.16 networks in PMP mode. Similar studies like [6–10] do not contribute enough on certain issues. While Miray et al. [6] has covered schedulers in mesh mode, the main focus of other studies [7–9] is on traditional schedulers like RR, WRR, FQ, WFQ only where as there are relevant number of studies available on other working principles also. Lamia Chhari et al. [10] has covered very few hierarchal and dynamic schedulers while none of them had considered scheduling as a cross layer approach or as an optimizing problem. Present study focuses on factors effecting scheduling in WiMAX and includes all the categories in which scheduling algorithms can be divided. Present study includes cross layer and soft computing (neural network, fuzzy logic etc.) based schedulers along with traditional, hierarchal and dynamic schedulers as compared to previous studies. Some of the theoretically and practically proven scheduling techniques like [11,12] which can suitably be applied/migrated to WiMAX are also included. Table 3 justifies purpose of current study.

The audience for this paper includes practitioners and researchers in the field of wireless communication who shall view it as summarization of current practices as well as broader audience of scientific professionals who may view it as an introduction to a mature field.

This paper is organized as follows. Following this introductory part section two discusses about Quality of Service in WiMAX and section three is devoted to studies available in literature. These studies are appropriately divided into different types so as to enable the readers have a fair understanding about problem of scheduling from different prospective. Following this part analysis and inferences are specified and some thoughts that may lead to new future directions in the current field are discussed. Although attempt has been made to explore all possible studies as per the understanding of the authors but this study shall not be in any sense considered exhaustive.

2. QoS in WiMAX

WiMAX supports connection-oriented MAC which is further subdivided into three different sublayers namely: Convergence, Common part and security sublayer [1,2,13,14]. Connections are referenced with 16-bit connection identifiers (CIDs) and may require continuously granted bandwidth or bandwidth on demand. There are two types of connections: Data and Management.

Management connections can be either basic (urgent), primary(less urgent) or secondary and used to transfer management messages such as RNG-REQ/REP-RSP/RST etc. These three connections reflect the three different QoS requirements used by different management levels. Basic connection is used to transfer short, time-critical MAC and radio link control (RLC) messages while Primary management connection is used to transfer longer, more delay-tolerant messages, such as those used for authentication and connection setup. The secondary management connection transfers standards-based management messages such as Dynamic Host Configuration Protocol (DHCP), Trivial File Transfer Protocol (TFTP),

Table 1 IEEE 802.16 standard developments.

Active standards	Superseded standards	Amendments made	Pre-Draft stage
IEEE 802.16.2012 Revision of IEEE 802.16, including 802.16h,802.16j,802.16m	IEEE Std 802.16-2009 Amended by IEEE 802.16j-2009, 802.16h-2010, 802.16m-2011	IEEE 802.16m-2011 (amendment to IEEE 802.16-2009) Advanced Air Interface	Project P802.16q Multi-tier Amendment
IEEE 802.16.1 2012 As amended by IEEE 802.16.1b,802.16.1b	IEEE Std 802.16-2004 Amended by IEEE 802.16g-2007,802.16f-2005,802.16e-2005, IEEE 802.16-2004/Cor1/2005	IEEE 802.16h-2010 (amendment to IEEE 802.16-2009) Improved Coexistence Mechanism for license exempt operation	Project 802.16r Small Cell backhaul with Ethernet
IEEE 802.16k-2007 Bridging of IEEE 802.16	IEEE Std 802.16.2–2001 Amended by 802.16a-2003 (NLOS: 2–11 GHz) 802.16c-2002	IEEE 802.16j-2009 (amendment to IEEE 802.16-2009) Multi-hop Air Interface for Broadband Wireless Access Systems	Project P 802.16.3 Mobile Broadband Network Performance Measurement
IEEE Std 802.16.2-2004 (reaffirmed for 5 years)	IEEE 802.16.2–2001 LOS: 10–66 GHz	IEEE 802.16g-2007 (amendment to IEEE 802.16) Management plane Procedures and Services	
IEEE Std 802.16/ conformance 04-2006		IEEE 802.16f-2005 (amendment to IEEE 802.16) Management Information Base	

Table 2 Properties, evolution and comparison of WiMAX with IEEE 802.11 and 802.20.

IEEE standard	802.11b	802.11g	802.11 a	802.16	802.16a	802.16e	802.20
Date ratified	1999/9	2003/6	1999/9	2001/12	2003/1	2005/6	2006
Access Type	LAN			MAN			WAN
Mobility support	Portable			Fixed	Portable	Pedestrian speed (< 150 kmp h)	Vehicular speed (< 250 kp h)
Channel conditions	NLOS			LOS	NLOS	NLOS	NLOS
Max cell range	100 m	50 m	50 m	2–5 km	7–10 km(ma × 50 km)	2–5 km	20 km
Spectrum	License exempt	License exempt	License exempt	License and license exempt			Licensed
Frequency Band	2.4 GHz	2.4 GHz	5 GHz	10–66 GHz	2–11 GHz	2–6 GHz	< 3.5 GHz
Max Data rate	11 Mbps	54 Mbps	54 Mbps	32–134 Mbps in 28 MHz	Upto 75 Mbps in 20 MHz	Upto 15 Mbps in 5 MHz	> 4 Mbps
Channel Bandwidth	20 MHz			20,25,28 MHz	1.25–20 MHz	1.25–20 MHz	1.25–40 MHz
Spectrum Efficiency (bps/Hz)	0.55	2.7	2.7	4.8	3.75	~3	> 1
Modulation	DSSS	OFDM	OFDM	QPSK, 16QAM and 64QAM	OFDM 256 carriers plus QPSK 16 QAM, 64QAM and OFDMA 2048 carrier		OFDMA
QoS	802.11e(not ratified) will introduce QoS functionality			Yes			Yes
Mesh	Mesh			No	Yes	Yes	No

Table 3 Comparison of surveys on WiMAX PMP mode schedulers.

Study	Origin & amendments to WiMAX standard	Design issues affecting scheduling performance	Comparing WiMAX with similar technologies	Traditional Approaches like (RR,WRR, FQ, WFQ etc.	Hierarchal Approach	Dynamic/Channel Aware schedulers	Cross Layer Schedulers	Soft Computing Approaches
[7]	No	No	No	Yes	No	No	No	No
[8]	No	Yes	No	Yes	No	No	No	No
[9]	No	No	No	Only proportional fair scheduler	No	No	General approach presented; no study explored	No
[10]	No	No	No	No	Yes	Yes	No	No
Current study	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

and Simple Network Management Protocol (SNMP). A management CID is bi-directional and can be used for both uplink and downlink transmission. Every BS-SS pair will require at least a basic and primary management connection identifier to communicate.

Data connections are also known as service flows and are identified by 32-bit number called SFID or service flow ID and is assigned whenever a data service/connection is created and lasts for the entire life of service. Each service flow could be in any one of the three types (or modes): Provisioned, admitted or active. Both SS and BS can set the type of a service flow through DSA or DSC three-way handshaking procedure.

Mapping of SFID to CID Number of SFID (2ˆ32) is very large as compared to number of CID (2ˆ16) because SFID is assigned to every service flow where as CID is only assigned to a service whenever it is active or admitted mode i.e. only those SFID are mapped to CID who are in active or admitted mode. Eg for BS-SS to transmit data, at least 4 CIDs are required: one each for basic and primary management connection and one each for downlink and uplink data transmission.

QoS architecture in IEEE 802.16 is dynamic means that the QoS parameters in a connection i.e. latency, jitter etc. can be changed during a connection by associating packets to a Service flow ID (SFID). It is accomplished by 3-way handshaking messages using DSA-REQ, DSA-RSP, DSC-REQ, DSC-RSP, DSD-REQ and DSD-RSP MAC management messages. A newly arrived connection is entertained by CAC (call admission and control) module and is admitted only if the required resources are available for this new connection as well as to entertain previous requests. There are 5 types of service classes supported by the recent WiMAX standard namely UGS, ertPS, rtPS, nrtPS and BE (Table 4).

2.1. Issues and challenges for IEEE 802.16 scheduling

Scheduling is the method by which data flows are given access to system resources (communications bandwidth in this case). This is usually done to load balance a system effectively and/or achieve a target quality of service. In theory, there are 3 schedulers needed for IEEE 802.16, one for outbound transmission scheduling at the Base Station for downlink another for uplink burst scheduling at the BS and last is the outbound transmission scheduling at the SS. The goal of this section is to provide better understanding about the issues for the design of schedulers. Since WiMAX has to deal with heterogeneous traffic therefore the major design issues concerning the development of schedulers may be stated as under

1. Guaranteeing a certain degree of **fairness to the subscribers and different types of flows.** However ensuring fairness to every node or flow may not be always easy as it may be conflicting with efficiency.
2. **Guaranteed delivery of QoS requirements** that are negotiated at the time of connection establishment.
3. **Effective Channel utilization:** It may be measured in terms of throughput, in order to improve channel utilization several other factors like AMC, MIMO techniques and fragmentation mechanism needed to be explored.
4. **Complexities** associated with the implementation of algorithm shall be small.
5. Good **bandwidth- request strategy** i.e. it shall be able to choose whether to piggyback, multicast, broadcast or send

Table 4 Different traffic classes for IEEE 802.16.

	UGS	rtPS	nrtPS	BE	ertPS
Service	CBR flows	Real-time VBR flows	Require better than best effort service	Best effort service	Real time variable size flows with guaranteed data rate
Bandwidth Request	Not required	Contention-free (Unicast Polling)	Contention-free or contention	All types	Polling and Uplink allocation
Uplink Scheduling	Fixed number of time slots in a frame	Not Defined	Not Defined	Not defined	Not defined
Min reserved traffic rate	Yes	Yes	Yes	–	Yes
Max latency	Yes	Yes	–	–	Yes
Tolerated jitter	Yes	–	–	–	Yes
Traffic priority	–	Yes	Yes	–	Yes
Example	VoIP	MPEG video	FTP	HTTP, SMTP	VoIP with silence suppression

stand alone messages to request more bandwidth. This could add a substantial burden to the resources if not handled carefully.

6. **Efficiency** in terms of delay, throughput, scalability, robustness and graceful degradation of scheduler.
7. In TDD mode the amount of **bandwidth allocated** shall be adapted **dynamically** by the scheduler.
8. Focus of schedulers is being shifted to the study of **congestion and other network layer parameters** and scheduler may make its scheduling decision based on congestion, routing or queue lengths.

3. Scheduling in IEEE 802.16

WiMAX has two modes of operation: Point to Multi Point (PMP) mode and Mesh mode. PMP mode consists of one BS and multiple SS, communication between different SS takes place only through BS whereas in mesh mode SS have the ability to communicate among themselves i.e. every node may be treated as BS. A central node connected to outside world may be considered as mesh BS. In Mesh mode the scheduling is either central in which the mesh BS schedules all SSs or distributed scheduling in which transmissions in two hop neighborhood are coordinated to avert collisions. This study focuses on PMP mode for the majority of time. The approaches as applied to scheduling in PMP mode may be divided into following sub categories:

1. Traditional
2. Hierarchal
3. Cross Layer Approaches
4. Dynamic Schedulers
5. Soft Computing based

3.1. Traditional schedulers

Traditional Schedulers are those borrowed from studies of Operating systems like Round Robin (RR) scheduler that was used to nullify the decision time required to be taken to schedule every packet. It distributes equal channel resources to all the SSs without any priority. However, this technique is not suitable for systems with different levels of priority and systems with strongly varying sizes of traffic [15,16]. Weighted Round Robin (WRR) scheduler is based on static weights in which weights are assigned to every flow/queue. The weights determine the bandwidth allocated to that particular flow. Flows are scheduled in accordance with these weights [16] but Sayenko et al. [17] insisted that WRR because of its work conservative behavior is not fit for IEEE 802.16 networks as weights are floating numbers while slots allotted are integers.

DRR scheduler as proposed by Shreedhar et al. [18] associates a fixed quantum and a deficit counter with each flow/queue. Deficit counter is incremented by a fixed amount after each round for every flow. A comparison between deficit counter and length of packet decides whether the head of the $(\text{queue})_i$ will be de-queued or not and if de-queued, counter is decremented by length of packet. It puts a limitation that only one packet at most can be sent for each flow. It provides fairness for variable length packets but the major problem in DRR is calculating the size of head of queue packet which was not possible for uplink traffic and i.e. why DRR had been implemented for downlink and SS schedulers in most of the studies.

Table 5 Comparison of hybrid scheduling strategies.

Study	Scheduling	Phase	UGS	rtPS	nrtPS	BE
[26,27]		1	Fixed			
		2		EDF	WFQ	RR
[28]	BS	1	Guaranteed bandwidth	Grant bandwidth request opportunity at connection setup		
		2		Guarantee min reserved rate		
		3		WFQ		
	SS		Fixed bandwidth	Fixed Priority		
[30]		1	Assigned to high priority queue	Intermediate queue		Low priority queue
		2		migrate to high priority queue		
[32]	SS	1	slots given to each time sensitive connection			
		2	Remaining slots distributed in Round robin fashion			
[31]	BS	Tier 1	Fixed Bandwidth	Priority based on queue length		
	SS	Teir 2	Fixed Bandwidth	Fairness Queuing		WRR
	per class flow	Tier 3	——————	EDF		Shortest length
[29]	Scheduler 1	EDF used for UGS, rtps, nrtPs and BE				
	Scheduler 2 (nrtPs only)			WFQ(bandwidth request)		
	Scheduler 3(BE only)					WFQ (traffic priority)
[34]	Phase I	Modified SFQ(start time fair queuing)	MCFQ with start/finish time stamping			BE served only when no traffic of other classes. Starvation avoided using admission control and traffic shaping. WRR used among various BE flows.
	Phase II	Priority scheduler with priority in order UGS/ertPS > rtPs/nrtPS				

The maximum Signal-to-Interference Ratio (mSIR) scheduler is based on the allocation of radio resources to subscriber stations which have the highest signal-to-interference Ratio (SIR) but it may lead to starvation of the flows having lower SIR as no mechanism had been proposed to deal with such situations [19,20]. A new variant of DRR scheduler that handles latency critical applications has been proposed by Rath et al. [21] namely Opportunistic Deficit Round Robin (O-DRR) scheduler in which BS polls subscribers periodically and includes SSs into a set based upon different conditions and selects one SS from this set.

Loutfi Nuaymi et al. [22] argued that a proportional Fair (PF) scheduler should in theory result in better throughput than the various variants of DRR schedulers because the PF scheduler assigns slots first to those connections that have the best ratio of current achievable rate to averaged rate and incorporates the aspect of fairness among different flows. Ball et al. [23] specified temporary Removal Scheduler (TRS) that involves identifying the packet call power, depending on radio conditions, and then temporarily removing them from a scheduling list for a certain adjustable time period T_R. Reference of few more scheduling algorithms like Drop tail queue, random early detection and random early detection with IN/OUT may be found in [24] in which comparisons between various scheduling techniques have been carried out. WFQ (weighted fair queuing) one of the most common variant of fair queuing has been utilized as its default scheduler in Qualnet simulator for WiMAX Networks [25].

3.2. Hybrid schedulers

Hybrid Schedulers combine several scheduling techniques in order to meet the particular needs of different traffic classes. Resources are distributed as first level of hierarchy and employ different types of techniques to schedule different types of service flows. Usually traditional approaches are combined with a certain level of admission control to avoid starvation. Table 5 lists the major studies in this direction.

Wongthavarawat et al. [26,27] were the first to introduce the concept of hierarchal schedulers for scheduling problem of WiMAX. They performed the scheduling of different service classes using different algorithms. UGS was allotted fixed time slots, rtPS was scheduled using Earliest Deadline First (EDF), nrtPS uses Weighted Fair Queuing (WFQ) while BE class was scheduled using Round Robin(RR) algorithm. The inter-class scheduling follows fixed priority with UGS having highest priority followed by rtPS, nrtPS and BE. Every SS is made to follow a traffic contract to avoid starvation and this contract is included in each SS however only uplink scheduling has been considered.

Sun et al. [28] proposed two different schedulers for BS and SS. Priorities to UGS and bandwidth request opportunities for rtPS and nrtPS connections were assigned at the time of connection setup. Data for these classes were scheduled taking into account bandwidth request information. Fixed priority was implemented at SS for BE, nrtPS, rtPS and UGS service classes respectively. UGS is allocated guaranteed bandwidth at the first instant, deadlines for rtPS packets were then calculated based on arrival time and tolerated delay and were scheduled on the basis of approaching deadlines.

Liu et al. [29] presented another scheme that uses combination of three different schedulers to meet Qos requirements. Scheduler I serves time sensitive traffic streams and uses EDF algorithm. WFQ was used to schedule minimum bandwidth reserving flows like nrtPS while BE also employs WFQ scheduling technique. Weights in both these cases comprise of requested bandwidth and traffic priorities as were specified by each BE connection respectively and these schedulers were served in fixed priority order with scheduler I being assigned highest priority.

Juliana Freitag et al. [30] used the concept of high, intermediate and low priority queues to handle varying types of traffic. High priority queue is used to handle flows that must be scheduled in next frame which includes UGS packets and uni-cast request opportunities for rtPs and nrtPS flows. Intermediate and low priority queues were used to handle rtPS, nrtPS and BE flows respectively. Queues were served using strict priority however starvation was handled as request whose deadline is going to expire is migrated to high priority queue. Significant overhead was added as queues need to be checked time and again to for deadline expiry.

Maode Ma et al. proposed in [31] a three-tier scheduling framework in which DL and UL respective loads could be left unbalanced. They divided scheduling scheme into 3 tiers, Tier 1 scheduling scheme exists at BS only. It performs bandwidth allocation coarsely across service class and across SS. Tier 2 scheduler determines the number of time slots granted by the BS for different connections within each service class at each SS. Tier 3 scheduling is to determine the transmission priorities of packets in each connection at each SS. [32] further extended the concepts of Juliana et al. to incorporate the issue of scalability and used GPSS(Grant per subscriber Station) mode for data grants instead of GPC (grant per connection) which the authors thought to be of major hindrance to scalability issue. The scheduler used is at SS only whose job is to distribute the granted slots to different connections. Slots are first given to each time sensitive connection and the remaining slots were distributed in a round robin fashion, first to the UGS and rtPS flows needing additional airtime, then to the nrtPS connections and finally to the BE connections. Settembre et al. [33] proposed a scheduler that combined fixed priority among different service categories and used following queuing principles for different traffic classes: fixed bandwidth for UGS, WRR for rtPS and nrtPS and RR for BE however no admission control mechanism was described to guarantee minimum bandwidth requirements.

Fallah et al. [34] proposed different scheduling architectures for BS and SS. They proposed combination of scheduling schemes for Real–time multimedia support in IEEE 802.16 networks. The scheduling process is divided into two phases. Phase 1 uses three different scheduling algorithms where flows with similar characteristics use same type of scheduler. UGS and ertPS uses modified start-time fair queuing to increase temporal fairness; rtPS and nrtPS classes require BW guarantee and uses multi-class fair queuing algorithm whereas BE traffic can use any scheduler since no QoS guarantee is required for BE. BE is scheduled only when there is no QoS for other classes and may at times face starvation. Starvation for BE class was avoided using admission control and traffic shaping. WRR was also employed among similar BE flows. Phase II was used to handle packets selected in phase-I using a priority based scheduler where UGS and ertPS enjoy higher priority than rtPS and nrtPS. The drawback of this method in the inherent complexity associated with this algorithm and starvation of BE flows which at times may account for large amount of traffic.

3.3. Cross layer schedulers

The objective of cross layer scheduling techniques is to optimize communication among various layers of network architecture. Liu et al. [35,36] introduced a priority-based scheduler at the medium access control (MAC) layer for multiple connections with diverse QoS requirements and where each connection employs adaptive modulation and coding (AMC) scheme at the physical (PHY) layer. A priority function (PRF) was defined for each connection admitted in the system and it was updated dynamically depending on the wireless channel quality, QoS satisfaction, and service priority across layers. Number of time-slots to UGS were fixed and all non-UGS connections were assigned slots with priority as rtps > nrtps > BE. Priority Function (PRF) was used to allocate the left over time-slots according to the one having highest value. The technique proposed is simple and easy to implement but it schedules only one non-UGS connection per frame that can cause delay and may also lead to starvation for low priority flows.

Unlike Liu et al. who had restricted their cross layer architecture to layer 1 and layer 2 authors of [37,38] emphasized the need of involvement of layer 3 and layer 2 for better QoS service since some very important information is available at these layers that can help in scheduling process. They included mapping between L3 and L2 QoS where Intergrated and differentiated services are mapped to 802.16 MAC service classes. The authors defined a frame control mechanism to group fragments of same IP packet to be treated as single unit by MAC layer and a new flow was only admitted when remaining link capacity is more than the requirements.

One more cross layer mechanism that communicates with application layer has been proposed by Triantafyllopoulou et al. [39,40]. The proposed scheduler works at BS and SS and it communicates with application layer as part of optimization process. Although the technique benefits in terms of QoS and system capacity but it adds a lot of complexity at BS.

3.4. Dynamic schedulers

Mukul et al. [41] argued that this process of bandwidth request and scheduling can be adaptive and proposed a stochastic adaptive scheduler for rtPS traffic based on the prediction of the rtPS packets arrival. BS allocates bandwidth for rtPS traffic after receiving a bandwidth request. During this period of request and grant it is possible that SS may receive from upper layers new rtPS packets which may aggregate bandwidth requirement. However these packets need to wait till the next request is sent. The basic idea is to predict the arrival of more rtPS packets so that subscriber can request time slots for the currently present rtPS data and also for the data which can arrive during this request-response time. A staircase function is proposed and a network calculus method has been used to analyze the proposed method. The authors had tried to reduce delay and length of the queue however for simulations the data flow has been assumed to be generic and no statistic on data entry was taken. Pheng et al. [42] tried to improve upon the work proposed by Mukul and others considering queue length factor and Lagrange's Interpolation function to estimate the value of time width and data arrival rate. Authors had proposed a variable to estimate the proportion of values of estimation function and the value of this variable changes dynamically however the simulations are based on the same model and other traffic classes have not been considered.

Jin-Yup Hwang et al. [43] divided traffic models into two types namely NRTV for real time and FTP for non real time traffic and stated another adaptive traffic allocation scheduling scheme that provides priority to a traffic class group and to SSs belonging under that class group. This priority is based on traffic type and maximum allowed delay time. The Real time traffic is scheduled using RR and non real time using Proportional Fair algorithms, similarly real time packets are preferentially allocated. Ruangchaijatupon et al. [44] tried to impart fairness to the adaptive scheduling scheme by using the concept of priority queuing and deficit queuing and used an adaptive deficit quantum to handle priority queue. This quantum was based on current queue size and channel capacity and the algorithm assigns this quantum to a particular flow depending upon whether the traffic is in burst or non-burst state.

In [45] an adaptive queue-aware algorithm is proposed for uplink bandwidth allocation and rate control mechanisms in a SS for polling services in a GPSS system. This scheme helps to adjust the amount of bandwidth allocated for polling service dynamically as per variations in traffic load, channel quality, and queue length at SS at the same time maintaining QoS performances such as protocol data unit delay and protocol dropping probability at desired level. However the approach draws no boundaries between real-time and non real-time services and fails to exploit QoS factors like latency in scheduling. The authors of [46] Raghu et al. proposed a queue based algorithm in which adaptability is implemented by defining a parameter X defined as the ratio of the maximum time a rtPS or nrtPS MPDU can wait in the queue (i.e. max_mpdu_delay) to the maximum latency specification of the real-time flows. This parameter was used to control the QoS given to real-time and non real-time services and varied to obtain the desired delays for real-time and non real-time traffic flows. Kim et al. [47] argued that a bandwidth-request grant mechanism used in IEEE 802.16 may not be effective for TCP flows because of the dynamic nature of sending traffic and had proposed a scheme for TCP traffic that does not need any bandwidth request process for allocation. Instead, it estimates the amount of bandwidth required for a flow based on its current sending rate.

One of the most recent work in the field of dynamic scheduling has been done by Fathi et al. [48] where a joint scheduling and CAC method is proposed. The whole process is divided into two stages, in stage one weighted fair queuing is used to assign initial weights to different traffic classes in the order rtPS > nrtPS > BE and bandwidth allocated is calculated as function of packet dropping probability, average arrival and departure rates of a class. Law of moving averages was employed to calculate new arrival and departure rates. New portion of bandwidth was allocated to any flow at stage II and then an appropriate scheduler was employed to schedule packets.

3.5. Soft computing based

This category of scheduling strategies tends to formulate scheduling problem as an optimization problem that aims to optimize resource allocation to different SS/service flows. Since soft computing techniques like Genetic Algorithm, Neural Networks, game theory etc. are potential candidates for solving such problems therefore these techniques have been successively applied to solve such problems.

To get a solution to optimization problem Mohammadi et al. [49] had used the concept of dynamic programming. A linear programming based approach with a complexity of $O(n^3.m^3.N)$ where N, n, and m denote the number of slots, number of SSs and number of sub-channels is proposed. However authors have suggested the use of heuristic algorithm with complexity $O(n.m.N)$ to solve the problem and proved that the proposed algorithm will optimize the overall system performance but may result in unfairness. The authors of [43] defined the problem of scheduling as achievement of two goals namely maximizing the total number of packets and number of UGS packets sent. They tried to formulate problem as 0–1 Knapsack problem which is NP hard problem and therefore argued that the concept of dynamic programming can be applied to optimize such problem. To achieve second goal authors assigned more priority to packets belonging to UGS class. However the mechanism to calculate this value is not specified and induction based theorems has been stated as a proof for the applicability of dynamic programming metaphor.

The concepts of Genetic Algorithm as a solution to scheduling problem have been proposed by [50]. Authors proposed a cross layer APP-MAC-PHY scheduling algorithm based on genetic algorithm that uses information at the application layer together with AMC properties of WiMAX aiming to provide optimal scheduling. The algorithm works by having current rate allocations as initial population of two chromosomes at a specified time. Weight of each user was taken as a function of modulation scheme index, packet error rate (PER), SNR and QoS parameters which depend upon different types of services. Fitness function considers minimization of aggregation of weight multiplied by the chromosome's varying over the rate limit. The selection operator is priority based and suitable crossover and mutation operator have been used to allocate bandwidth to different users. However the simulations are provided only for a small number of nodes and only BE traffic class has been considered for performing simulations. Gunasekaran et al. [51] had also utilized the genetic metaphor to solve the broadcast scheduling problem in WiMAX networks. They had represented the network as graph with nodes as stations and edges as connection between nodes. They found set of nodes such that all the nodes in that set could transmit at same time without any conflict. Authors tied to find an optimal TDMA frame represented in the form of M*N matrix where M is number of time slots in frame and N is the number of nodes based on satisfaction of constraints like each node must be activated at least once and that no node can receive and transmit data at same time followed by reception of data by two nodes at same time.

In case of multiple solutions utilization index defined as ratio of total number of nodes activated to total number of slots available is considered. The genetic algorithm was applied to maximize value of utilization index where chromosomes are represented as M*N matrix having values [0, 1] where each row corresponds to time slot and column represents a node. Value of 1 indicates that corresponding node is active at specified time. The chromosome population is generated by converting different permutations into required 2D matrix by assigning suitable position. Two chromosomes having good fitness scores are selected for crossover with a predefined crossover probability. Mutation is applied with a probability .005 to incorporate randomness into the solution.

Niyato et al. in [52,53] applied the concepts of non-cooperative game theory for admission control and scheduling in IEEE 802.16 networks. Players in game are the rtPS and nrtPS connections that want to maximize their QoS performance while total utility of both ongoing connections is regarded as playoff. The problem is to find equilibrium point between the two types of connections so that a new connection may be offered bandwidth while meeting the QoS requirements of both ongoing and new connection.

Neural networks have also been proposed to solve bandwidth allocation and scheduling problem by [54]. A feed forward neural network with a single scalar output had been chosen to make the decision of allocating bandwidth needs of different users. The authors of [55,56] have used the neuro-fuzzy based methods to provide QoS and solve scheduling problem. They divided the scheduling problem in two stages. In first stage fuzzy logic is used to provide priorities to different services based on queue size and second stage uses a multi layer neural network for scheduling. The input to the first layer of neural network is the output of fuzzy network while layer two and three comprises of Kohenen and Grossberg neural layers respectively.

Raliean et al. [57] had used the theory of neural networks to predict the traffic characteristics in WiMAX. ANN has been associated with Stationary Wavelet Transform to predict traffic time series. The main focus of their study is to compare the quality of forecasting obtained using different configurations of the ANN and testing these configurations using real traffic data from a WiMAX Network developed by Alcatel. This is the rarest of the work in which data taken is the real world data. Comparisons are drawn at the end with previous techniques to show the performance of the technique.

4. Analysis and inferences

In the previous sections design issues and some of the work done in the field of scheduling has been discussed. In this section, inferences from review of previous sections have been drawn. The main findings of the study may be summarized as:

1. Studies on **cross layer communication** based on network and physical layer information need to be explored further.
2. Scheduling must be supported by the concepts of **Call Admission and congestion control** since they go hand in hand such that more flows satisfying QoS requirements can be admitted.
3. Effect of different **routing schemes** on scheduling algorithms need to be studied. There has been negligible work in this direction. One of the few studies in this direction has been by Stephan Nosh et al. [58] who has used Interference Load Aware Routing (ILR) and Interference Load Aware Multipath Routing (ILMR) routing to improve acceptance ratio of flows that are served and class based scheduling to improve throughput and acceptance ratio.
4. **Availability of simulation tools:** designed for WiMAX mesh mode is a major hindrance in progress of research in this direction. Simulators for PMP mode are available [59–61] however, there are not many publicly available tools that support the mesh mode operation. One is

available at [62] but it has drawback in its inter operability with ns-2 routing algorithms. A simulation tool implemented on a widely used simulation environment such as Qualnet, OPNET or ns-2 with a pluggable 802.16 mesh architecture, would be extremely useful for the research community.
5. **Pricing issue** has not been studied by any of the researchers. To the best of authors knowledge no paper has been found that could have considered scheduling with pricing issues to achieve optimization of revenue and resources. All commercial implementations need this issue to be considered.
6. The problem of scheduling in NP-hard and therefore a soft computing technique like GA, Fuzz Logic and Neural Network is applicable whereby the given technique might be helpful in estimating, predicting or shaping the traffic patterns. This is one of the hottest area of research in WiMAX currently. Although enough studies are available but still it would be interesting to see how **AI techniques** perform in the field of scheduling.
7. Other **relevant fields** can also help to provide new innovation in this field for Example, ideas from hierarchical approaches for CAC in CDMA networks and neural networks for scheduling of multiple queues [11,12] could also be applied to IEEE 802.16 networks.
8. IEEE 802.16 networks can support different networks like IEEE 802.11, Ethernet etc. where 802.16 can serve as backbone and can work to overcome limitations of wired or wireless LANs and studies can be carried on such **hybrid networks**.
9. Moreover majority of the studies proposed have been tested without putting any restriction on the size of buffers which might not be always possible.
10. **Ordering** and size of the packets to be sent in a frame might also affect performance that is not considered, it is another area that has been left untouched.
11. Major emphasis has been laid on scheduling of rtPS class because of their bursty and sensitive nature thereby giving **unfair opportunities to nrtPS and BE** classes which might account for majority of the traffic in real world.

5. Conclusion and future directions of research

This paper at large discussed various issues of schedulers and explored various techniques presently available in literature. Although a number of methods are available but still there are some of the areas which are not quite explored namely the application of soft computing/optimization techniques like Genetic Algorithm, neural networks, fuzzy logic etc. Using these approaches together with information from higher layers can act as a major contributor in the field of scheduling. The issue of pricing into current or new techniques is still an open area. The ongoing popularity of WiMAX in developing countries is an indication that the future belongs to WiMAX technology. In the light of above it can be argued that scheduling and bandwidth allocation schemes are the heart of Quality of Service support and WiMAX performance. A lot of investigations had been made in this area however gaps in studies presented in this paper show that there is still strong scope for improvement.

Appendix A. List of Abbreviations and Acronyms

AMC	adaptive modulation and coding
BE	Best Effort
BS	Base Station
BWA	Broadband Wireless Access
CAC	call admission and control
CID	connection identifier
DCD	Downlink Channel Descriptor
DL	Downlink
DHCP	Dynamic Host Configuration Protocol
DRR	Deficit Round Robin
DSA	dynamic service addition
DSC	dynamic service change
DSD	dynamic service deletion
EDF	Earlier Deadline First
ertPS	extended real time polling service
FIFo	First in First Out
FQ	Fair Queuing
GPSS	grant per subscriber station
IEEE	Institute of Electronics and Electrical Engineers
IntServ	Integrated Services
LOS	Line of Sight
MAC	Media Access Control
MIMO	Multiple input and multiple output
NLOS	Non Line of Sight
nrtPS	Non real time polling service
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PDU	protocol data unit
PF	Proportional Fairness
PHY	Physical LAYER
PMP	Point to Multi point mode
RNG-REQ	Ranging Request
RNG-RSP	Ranging Response
RNG-REP	Range Response messages
RLC	radio link control
QoS	quality of service
RED	random early detection
RR	Round robin
rtPS	Real time polling service
SF	service flow
SFID	service flow identifier
SIR	Signal to Inference Ratio
SNMP	Simple Network Management Protocol
SS	Subscriber Station
TCP	Transmission Control Protocol
TDD	Time division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TFTP	Trivial File Transfer Protocol
UCD	Uplink Channel Descriptor
UDP	User datagram Protocol
UGS	Unsolicited Grant Service
VoIP	Voice over Internet Protocol
WFQ	Weighted Fair Queuing
WiMAX	Worldwide Interoperability for Microwave Access
WRR	Weighted Round robin

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