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A Dynamic Frame Partitioning Scheme for IEEE 802.16 Mesh and Multihop Relay Networks

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***Abstract*—The IEEE 802.16 standard, also known as WiMAX, defines flexible frame structures to support applications classified into different WiMAX traffic classes. The standard defines two types of scheduling to guarantee the Quality of Service (QoS) requirements of these applications – centralized and distributed. However, the standard does not specify how the frame can be dynamically partitioned among its centralized and distributed schedulers or uplink and downlink schedulers. Through efficient partitioning that dynamically adapts the partitioning based on demand, network can support more user applications with different QoS requirements, and hence increase the revenues of service providers. In this paper, we propose a novel and general dynamic frame partitioning scheme for IEEE 802.16 mesh and IEEE 802.16j multi-hop relay networks. The scheme uses a dynamic Markov model that studies the frame utilization over current frames to predict efficient partitions for future frames. Simulation results show that the proposed scheme improves average frame utilization and decreases packet dropping.**

***Index Terms*—Frame partitioning, QoS scheduling, 802.16 mesh, 802.16j**

I. INTRODUCTION

The IEEE 802.16 standard [1] defines one of the most prominent broadband wireless technologies today. It is characterized by its high speed, wide coverage, flexible design, relay networking and mobility. One of its main features is proposing an infrastructure to provide differentiated QoS guarantees for different types of applications. QoS management is affected by many mechanisms which include call admission control (CAC), scheduling and frame partitioning. The CAC ensures that the QoS requirements of a connection can be supported by the network once accepted. The scheduler controls the resource provisioning among different connections based on the various QoS constraints. The main objective of dynamic frame partitioning is managing bandwidth allocations efficiently, thus optimizing resources' utilization while meeting users' traffic requirements. Optimizing frame utilization facilitates accepting more connections with different QoS requirements.

The 802.16 standard defines two network architectures: the single hope Point-to-multi-point (PMP) architecture, and the multihop that includes the mesh and tree based 802.16j architecture. In PMP, nodes are organized in a cellular-like structure consisting of a base station (BS) and multiple subscriber stations (SS). Communication can only occur between the BS and SSs, where downlink (DL) refers to data transmission from the BS to the SS, and uplink (UL) to data transmission in the reverse direction. In the multihop mode, communication is allowed between subscriber stations. Unlike PMP, in the mesh mode of multihop architecture, channel access is not limited to the centralized management at the BS, as the management can be distributed among nodes in the network. The communication is link based, i.e. there is no differentiation between UL and DL. However, in the 802.16j mode of multi-hop relaying there is differentiation between uplink and downlink communication as well as centralized and distributed communication. This is due to the fact that the main objective of the 802.16j extension is the backward comparability between the PMP and multi-hop architecture besides extending the cell coverage and enhancing the support of mobile nodes. Therefore, the 802.16j frame is a compound of both the PMP and mesh frame structures, where the frame is divided into UL and DL, with the presence of the centralized and distributed schedulers.

In this paper, we present a novel scheme for dynamically partitioning a WiMAX frame. The scheme is general in the sense of its equal applicability of partitioning PMP frame into uplink and downlink subframes as partitioning an 802.16 mesh or 802.16j frames into centralized and distributed subframes. However, for ease of presentation we will focus on the later case. The importance of this work is due to the fact that the standard allows dynamic partitioning, whereas, it is based on fixed partitioning. Fixed partitioning can either result in under-utilizing one of the frame portions, or un-satisfying the need of one of the schedulers. Hence, in our scheme we avoid these two scenarios by dynamically partitioning the frame based on the demand of the different types of applications admitted to the network over a large window using a Markov model.

Our contributions in this work can be summarized as follow: providing an alternative more efficient partitioning scheme to address the void of the current fixed scheme of the standard, presenting a scheme which is general in the sense that it can be extended from the centralized/distributed model, to any frame structure that is controlled by two separate entities. Finally, prove the effectiveness of the scheme in optimizing the network resource utilization while meeting applications QoS requirements through extensive simulation. The simulation

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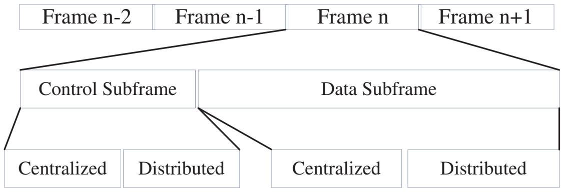


Fig. 1: 802.16 Mesh Mode Frame Structure

shows that our scheme achieves higher utilization and lower packet dropping compared to the available schemes.

We continue by presenting an overview of the 802.16 mesh and relay frame structures in Section II. In section III and IV, we present our partitioning scheme model and our simulation results. Finally, we highlight the conclusions and possible future work.

II. OVERVIEW OF THE 802.16 MESH FRAME STRUCTURE

The 802.16 mesh mode uses Time Division Multiple Access (TDMA) medium access protocol for controlling channel access. The radio channel is divided into frames, which are further divided into time slots that are assigned to different nodes. Every time slot is composed of a fixed number of Orthogonal Frequency Division Multiplexing (OFDM) symbols. Every frame is composed of two integral subframes: *Control* and *Data*. The control subframe carries regular configuration messages for controlling the coordinated scheduling of frames. The coordinated scheduling can be either centralized controlled by the BS, or distributed controlled by all nodes in the network. When a node is granted a slot in the control subframe from either schedulers, it sends its bandwidth request for a specific link to the BS or to the neighboring nodes depending on the scheduling method. After predefined multiples of four frames unit, the control subframe carries special periodic broadcast messages that include the updated network parameters. The data subframe succeeds the control subframe, in the form of a sequence of fixed-size mini-slots. The mini-slots carry the physical transmission bursts of the BS and different SSs. The coding and modulation schemes determine the data rate attainable for different mini-slots. The data subframe is also shared between the centralized and distributed schedulers, where the centralized subframe proceeds the distributed. A graphical representation of the 802.16 mesh frame is shown in Figure 1.

The centralized scheduler is used for scheduling data traffic generated by SS to nodes outside the WiMAX network; i.e. the Internet traffic, thus it has to go through the BS. The BS calculates a global topology tree and broadcast it to the SSs. Once, all nodes receive the topology, the nodes calculate their transmission opportunities through the following procedure

- starting from the BS, nodes that are i hops away from the BS shall transmit before nodes that are $i+1$ hops away.
- the uplink should always precede the downlink.
- If nodes are of equal distance, then nodes with lower *Node ID* shall transmit first.

When the BS receives all bandwidth requests, it calculates the grants for different nodes, and broadcast the bandwidth allocation in a special message. Nodes which received the bandwidth allocation determine their allocation in the data subframe using a common algorithm that proportionally divides the frame to the flow assignments [1].

The distributed scheduler is designed to schedule the *intranet* traffic among different nodes. All nodes including the BS are treated equally. Each node coordinates its scheduling with its neighbors which are two-hops or less away from the node. This process allows spatial reuse. The distributed scheduling can be either coordinated or uncoordinated. The coordinated method includes nodes competing in their neighborhood through a global common algorithm called the *election algorithm* [1] [2]. Using this algorithm, every neighboring nodes contend for a specific transmission opportunity, and if a node wins, it backlogs for a specific time to increase the probability of other nodes seizing transmission opportunities. The uncoordinated scheduler uses contention for the unallocated time slots in both the data centralized and distributed subframes. For more information, studies on the mesh centralized and distributed schedulers can be found in [2], [3], [4].

There are some recent proposals for dynamic frame partitioning for the 802.16 PMP mode [5] [6] [7]. Most proposals which provide PMP partitioning schemes follow asymmetric approaches where they assign more slots to the downlink than the uplink. However, these schemes cannot be adapted in the multihop architecture, since careful consideration is required regarding the variations of demands among the centralized and distributed scheduled traffic. Moreover, our work presents more general model for the 802.16 PMP, mesh and multihop relay frame structure, while the aforementioned works are limited to the PMP mode. Other works focused on the 802.16j frame structure can be found in [8] [9] [10]. The multihop relay frame structure is similar to the PMP by having same frame structure. And similar to mesh frame structure by having the centralized and distributed frame support. The 802.16j documents are currently in the draft stage. In reference [11], the authors addressed the issue of centralized/distributed frame partitioning but from the objective of finding the minimum partition for supporting a specific single QoS requirement. The authors of [12] studied the mesh centralized and distributed schedulers, by highlighting the main design and open research issues and presenting a review of the state of the art works. The authors considered the absence of a frame partitioning scheme, which is the focus of this paper, as one of the design and open research issues.

III. OVERVIEW OF DYNAMIC FRAME PARTITIONING SCHEME

We propose a partitioning frame scheme with the following objectives: (i) increase the overall frame utilization, (ii) dynamically partition the frame to adapt to the changes to the traffic demands of nodes, (iii) and avoid starving one of the two schedulers. The standard currently has a fixed partitioning scheme, which results in under-utilizing the frames, or practically unsatisfying one of the schedulers. Our scheme studies the statistical behavior of the nodes' demand over a current time window, using a Markov model, and predicts efficient partitioning for frames in the following window. The details of the scheme are presented in the following section.

A. System Model

The proposed partitioning scheme considers partitioning the data subframe between the centralized and distributed schedulers as a proof of concept, same argument applies for uplink and downlink partitioning in PMP and relay frames. Let the size of the frame be L time slots, the size of the control subframe L_C, and the size of the data subframe L_D, such that $L = L_C + L_D$. Also, let the size of the centralized portion of the data subframe be L_{DC} and the distributed size L_{DD}, such that $L_D = L_{DC} + L_{DD}$, where L_{DC}, L_{DD} ϵ $[L_{Dmin}, L_{Dmax}]$, where L_{Dmin} is the minimum size allowed for the centralized subframe and L_{Dmax} is the maximum allowed size. Our objective is to find the optimum values for L_{DC} and L_{DD} in the given range, such that the utilization is maximized. We assume that the control subframe has a fixed size, where the problem of finding an optimum partition between the control and data subframes is beyond the scope of this work. Because of the TDMA nature of the frame, where the centralized portion proceeds the distributed, the standard allows the distributed scheduler to utilize the unused slots in the centralized, but the reverse process is not practically possible. Therefore, we give higher priority to the centralized scheduler shubframe, and we make our partitioning decisions based on the data collected from the centralized portion of the data subframe.

The proposed scheme is generic and independent of CAC and scheduling schemes. The frame duration can be set to any value allowed by the standard (i.e. 2.5, 4, 5, 8, 10, 12.5, 20), without affecting the functionality of the scheme. For every frame, the BS calculates the demand of all bandwidth requests received by the control messages scheduled in the control subframe. The demand undergoes the scheduling process to determine the expected occupancy of the frame. We denote the number of expected occupied symbols in frame i, as determined by the scheduler, by λ_i. The value of λ_i can be calculated as:

$$\lambda_i = \sum_{n=0}^{N} \lambda_{ni} \tag{1}$$

Where N is the total number of nodes in the network, λ_{ni} is the number of symbols requested by node n for frame i. Note that the value of λ_i, for any frame i, is strictly equal to or larger than L_{Dmin}, because nodes will always request time slots, regardless of having current data to send or not [1] [12]. If the scheduling process results in allocation that is larger than the available slots in the data subframe, the allocation can be either *scaled down* proportionally to bandwidth requests, or spanned over a long frame (two-frames) as explained in the standard [1].

We divide the time domain into time windows, each includes a large number of frames. According to our simulations, a size of 1,600 frames or more is necessary for acquiring stable results. Statistics are collected for every window and used by the Markov model described in the following subsection. The partitioning decision is taken at the end of the current window, and applied for all frames in the following window.

B. Mathematical Model

We use a discrete Markov Chain (DMC) to model the expected frame occupancy (λ_i) based on the nodes' bandwidth requests. We denote the Markov chain as D. Every state represents the aggregate number of symbols requested by all nodes per frame. For example, if the system is in state 100, it means that all nodes have requested 100 symbols in the last frame. The number of states in the chain D_s can be found through the following equation:

$$D_s = \frac{L - L_C - \lambda_{min}}{\psi} \tag{2}$$

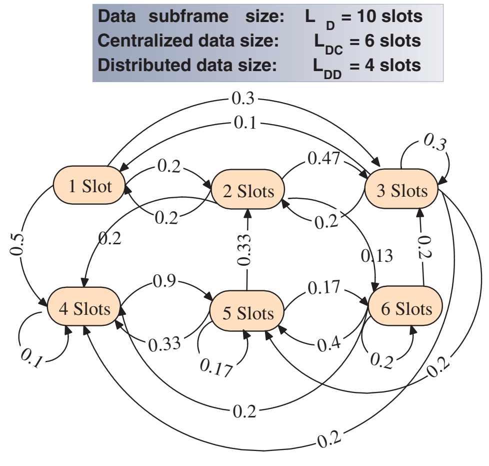
Where L and L_C are the the length in symbols of the whole frame and control subframe consecutively. The parameter ψ represents the granularity of the system, which is a fixed number of symbols. The complexity of the scheme is inversely proportional to the system granularity.

The probability matrix of the Markov chain is of size $D_s \times D_s$, which is sensitive to ψ. The value $P_{j,k}$ represents the probability that the system requests k ψ units for the current frame, if the request of the previous frame was j ψ units, i.e. $P(\lambda_i = k | \lambda_{i-1} = j)$. At the beginning of every long window, all values of $P_{j,k}$ are initialized to 0. After every frame where λ_i is found, a relevant counter for the occurrence of that event is incremented. These counters represent the random variable of the Markov chain, where the time is the length of the current window. At the end of the window, the counters are used to calculate the $P_{i,j}$ probabilities. The probabilities are used to compute the stationary distribution π. Our partitioning decision is made by setting L_{DC} to the maximum value in the stationary distribution. This choice represents the long run behavior of the system, as most frames are expected to be occupied by ψ symbols equal to this value. A simplified graphical example of this Markov model is shown in Figure 2, where the size of data subframe is 10 slots, ($L_{DC} = 6$ and $L_{DD} = 4$). In this example, if the stationary distribution is equal to [0.13, 0.17,0.21,0.31,0.37,0.18], then the partition is set to 5 slots.

IV. PERFORMANCE EVALUATION

A. Simulation Model

We implemented our scheme on an in house simulator for the 802.16 standard. The frame structure and the two schedulers were fully implemented alongside the basic networking functionalities. The network is composed of a single BS and 8 to 24 SSs, depending on the experiment. The mesh network is



Markov Chain

$$D = \begin{vmatrix} 0.00 & 0.20 & 0.30 & 0.50 & 0.00 & 0.00 \\ 0.20 & 0.00 & 0.47 & 0.20 & 0.00 & 0.13 \\ 0.10 & 0.20 & 0.30 & 0.20 & 0.20 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.10 & 0.90 & 0.00 \\ 0.00 & 0.00 & 0.20 & 0.20 & 0.40 & 0.20 \end{vmatrix}$$

Probability Matrix

Fig. 2: Frame Partitioning Markov Model

a tree rooted in the BS, and is composed of nodes that are at least 2 hops away from the BS. We use two traffic models: (i) homogenous, where all nodes generate traffic of the same class (ii) heterogeneous, where different nodes generate different classes of traffic. The implemented traffic classes are the traffic classes defined by the standard: real-time polling service (rtPS) simulated as video streaming, non-real-time polling service (nrtPS) simulated as FTP, extended real-time polling service (ertPS) simulated as VoIP, and best effort BE simulated as HTTP. We assume that a node can only generate one type of traffic, and in the heterogeneous model, the traffic is distributed as: 10% ertPS, 30% nrtPS, 40% rtPS, and 20% BE [13]. The Rayleigh distribution is used as the channel model for the adaptive modulation and coding schemes (AMC) [14]. The fixed and variable parameters are shown in Table I.

TABLE I: Simulation Parameters

Fixed Parameters	**Value**
Physical Layer	WirelessHUMAN
Symbol Duration	12.5 us
Frame Size	256 slots
Control subframe size	15 time slot
Symbols per control slots	7 symbols
System Granularity (ψ)	1 time slot
Minimum Scheduler Size	24 time slots
Long window size	4,800 frames
Variable Parameters	**Value**
Frame Duration (ms)	4,5,8,10,12.5,20
Traffic Types	ertPS, rtPS, nrtPS, Be, mixed
Number of SS	4,8,12,16,20,26
Fixed algorithm size	50,100,150,200 slots
AMC (random)	QPSK(1/2), QPSK(3/4), 16QAM(1/2), 64QAM(2/3), 64QAM(3/4)

We compare our scheme with two other schemes. The first is the standard's *fixed partitioning* scheme, which we evaluate under different fixed partitions. The second is a *probabilistic partitioning* scheme, where the partition is set to most frequent number of slots in the previous window. The simulation is multi-threaded to the three schemes to ensure that all schemes are run under the same system conditions.

B. Simulation Metrics

We use *utilization* and *Overflow Probability* as our performance metrics. The utilization measures the number of utilized ψ units with respect to the capacity of the centralized portion of the data subframe. A utilized unit ψ^1 is a unit where all symbols are utilized, and an unutilized unit ψ^0 is defined otherwise. The utilization of a frame can be calculated as:

$$U_i = \frac{\sum_{k=0}^{L_{DC}} \psi_k^1}{L_{DC}} \tag{3}$$

Where L_{DC} is the size of the centralized portion of the data subframe in units of ψ. The overflow probability (δ) for a frame is defined as the ratio of the unallocated ψ due to the small size of the current partition for that frame to the difference of the maximum and minimum possible scheduler sizes, as shown in the following equation:

$$\delta_i = \begin{cases} 0 & \text{if } \lambda_i \leq L_{DC} \\ \frac{\lambda_i - L_{DC}}{L_{Dmax} - L_{Dmin}} & \text{if } \lambda_i > L_{DC} \end{cases} \tag{4}$$

The overflow probability is designed to check whether the current partitioning is too small to satisfy the centralized scheduler, while the utilization checks if it is too large. For every frame, we compute the utilization and overflow probability, and we compute the average at the end of the simulation for all frames. Our objective is to maximize the average utilization and minimize the average overflow probability.

C. Simulation Results

We have performed two extensive experiments to compare the performance of our scheme with the fixed and probabilistic schemes, under different traffic loads and traffic classes. We notice from Figure 3 that the dynamic scheme outperforms the other schemes by achieving 80-90% utilization, while 65-80% for the probabilistic scheme and 50-70% for the fixed scheme. For the overflow probability, the dynamic scheme achieves less than 4%, and the probabilistic 8% on average and the fixed scheme more than 10%. It is also noticed that using the ertPS and rtPS traffic types, the dynamic scheme clearly achieves lower overflow probabilities compared to the other two scheme. This is important because in ertPS and rtPS, packet dropping/delay is critical, and having high overflow severely degrades the performance of its applications.

In Figure 4, we present the simulation results for evaluating the schemes under networks with different number of nodes. Similar to the first experiment, the dynamic scheme achieves the highest average utilization (85-95%) and lowest average overflow probability ($< 4\%$). The fixed scheme suffers from low utilization under low traffic loads, and high overflow

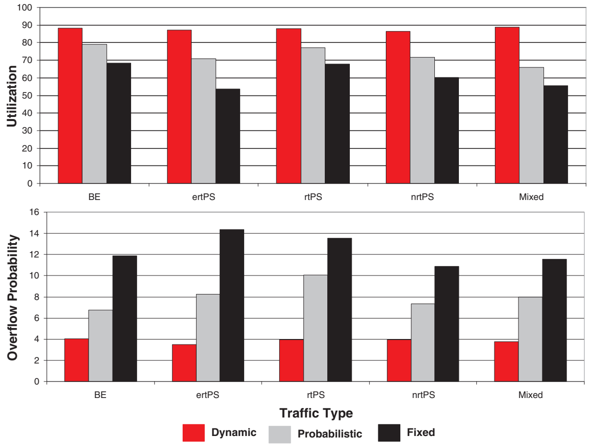


Fig. 3: Scheme Comparison (Traffic Type)

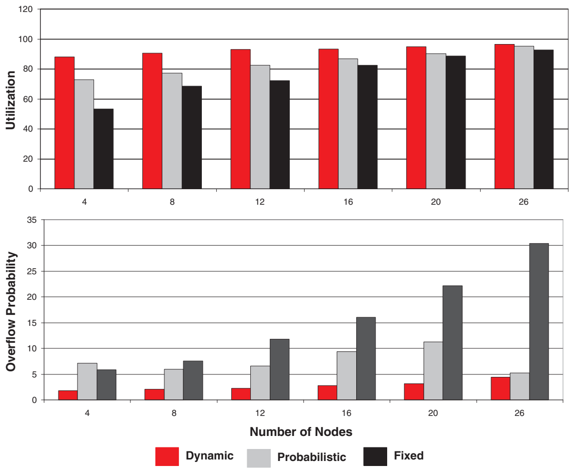


Fig. 4: Scheme Comparison (Congestion)

probability with large number of nodes. The probabilistic scheme performs lower utilization and higher overflow probability in networks with lower number of nodes. As the number of nodes increases, the utilization increases and so is the overflow probability. Towards the point of saturation, the probabilistic scheme performs similar to the dynamic scheme, since both schemes allocate large partitions for the centralized data subframe.

V. CONCLUSION AND FUTURE WORK

We proposed a novel dynamic frame partitioning scheme for the 802.16 mesh and 802.16j frame structures. The scheme efficiently partitions the frame into centralized and distributed subframes. The scheme is designed based on a Markov chain, which calculates the steady state probability of the network demand over a long time window. The output of our scheme is the length of the centralized subframe which is the maximum value of the Markov chain's stationary distribution. Our simulations showed that our scheme produced higher overall utilization and less packet dropping, compared to the fixed scheme available in the standard.

As for the future work, we will enhance our scheme by fine tuning the long window decisions through statistical study of multiple fine (small) windows. This should add more flexibility to the partitioning decisions, and improve the system response to the traffic changes.

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