

# QoS-Guaranteed Polling-Based 2-Layer Integrated Multihop Scheduling Algorithm for Wireless Ad Hoc Networks

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**Abstract**—In this paper, with removing the global synchronization that are usually assumed, we use the concept of relative timing between neighboring clusters and the concept of rendezvous windows for the gateway nodes to rendezvous with its connected clusters for timing conversion to overcome the synchronization problem in wireless multihop ad hoc networks. To be able to schedule both intra-cluster and inter-cluster traffic sources in the assumed 2-layer network hierarchy, we propose a QoS-guaranteed polling-based 2-layer integrated multihop scheduling algorithm that schedules both intra-cluster and inter-cluster packets based on a preset service priority. The delay and jitter for intra-cluster and inter-cluster connections are analyzed and are used as the admission criterion for connection setup requests.

**Keywords**—ad hoc networks, connectivity, power conservation

## I. INTRODUCTION

In the recent years, the topic of wireless ad hoc networks has received increasing attention e.g. [1]. A wireless multihop ad hoc network is a wireless network without existence of fixed infrastructures. As a consequence, delivering QoS guaranteed multimedia traffic sources over the multihop wireless ad hoc networks are much more complex than that in conventional communication networks. The key design issues to support QoS guaranteed multimedia services in the multihop ad hoc networks are network architecture, rendezvous window, synchronization and multihop scheduling. The network architecture of wireless ad hoc network is generally regarded as *flat* or *hierarchical*. In the flat network architecture, nodes are assumed to have the same capabilities and peer-to-peer communications are used. In the hierarchical architecture, the entire network is organized into set of clusters. Each cluster is controlled by a clusterhead (CH) and clusters are connected by gateways (GW). Links connect CHs and GWs constitute a virtual backbone. Nodes that are neither CH nor GW are regarded as ordinary nodes. In the wireless multihop ad hoc networks, regardless the network architecture, packets are basically multihopped to the intended receivers. To provide QoS guaranteed multimedia services, a multihop scheduler is thus necessary to schedule packets to (from) the downstream (upstream) nodes. In other words, an admitted packet must be forwarded to the next hop before the required QoS provisions are violated. This requires GW to schedule rendezvous window with neighboring clusters at the right time and last for a sufficient period of time to satisfy the required QoS provisions.

To achieve this, certain degree of network synchronization is needed. However, without the help of infrastructure, there is no centralized timing source to synchronize the entire wireless multihop ad hoc network. This paper addresses the above issues and proposes a 2-layer integrated QoS guaranteed multihop scheduling algorithm as the solution in designing QoS-guaranteed wireless multihop ad hoc networks. The rest of the paper is organized as follows. In Section II, the related assumptions and models are presented. Section III discusses the proposed algorithm and Section IV provides the related QoS analysis and Section V presents the initial connection setup procedure and admission control. Section VI concludes this paper.

## II. OPTIMUM TRANSMISSION RANGE AND NETWORK CONNECTEDNESS

### A. Basic Assumptions

The wireless multihop ad hoc network is assumed to be connected, and a topology control scheme e.g. [2] is used to maintain the connectedness of the network. There also exists an underlying ad hoc routing protocol to provide routing information from the source node to the destination node. The wireless multihop ad hoc network is organized into a hierarchical architecture with set of clusters by a clustering algorithm e.g. in [3], the resulting cluster architecture possesses minimum number of orphan clusters, and thus, the total number of generated clusters is minimized. In this clustered wireless multihop ad hoc network, nodes are classified into CH, GW and ordinary nodes and all communications are required to go through the CH even though the source node and the destination node are directly connected.

### B. Traffic Model

The characteristics of the traffic sources we considered are stated below.

1. A CBR source  $i$  is modeled by  $(r_{e,i}, j_i)$ , where  $r_{e,i}$  is the average rate and  $j_i$  is the maximum tolerable jitter. Each CBR packet generated from an admitted CBR source is temporally stored in its Ready-To-Transmit (RTT) buffer. The jitter is defined as the difference between the instant that two consecutive packets departing from the RTT buffer and the instant that two consecutive packets

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- arriving at the RTT buffer. Besides, all inter-cluster connection in this paper are assumed to be CBR sources.
- A VBR source  $i$  is modeled by  $(r_{v,i}, b_i, d_i)$ , where  $r_{v,i}$  is the average rate,  $b_i$  is the maximum burstiness and  $d_i$  is the maximum tolerable delay. The first two parameters are obtained by regulating the  $i$ -th VBR source through a  $(b_i, r_{v,i})$ -leaky bucket where  $r_{v,i}$  is the token generation rate and  $b_i$  is the token buffer size. Each VBR packet output from the leaky bucket is also temporally stored in a RTT buffer. Another VBR regulation technique proposed in [4] and [5] is to locate the leaky bucket at the CH. However, since CH has no knowledge about the arrival process of the VBR source, an extra separated signaling channel or extra state transition is needed to obtain the VBR arrival process. The delay of a VBR packet is defined as the difference between the instant that it arrives at the CH and the instant that it arrives at the RTT buffer.
  - An ABR source is considered as a Poisson process. The ABR sources have neither jitter constraint nor delay constraint. ABR sources share fairly and efficiently the remaining bandwidth of the inter-cluster connections, CBR and VBR sources. Besides, all connection request packets are also regarded as ABR packets.

### C. The System Model

The system is modeled as follows. In the clustered network hierarchy, each CH is categorized into Home CH (HCH), Visiting CH (VCH) or Destination CH (DCH). The HCH is the CH of the cluster where a connection is originated. The DCH is the CH of the cluster where the connection is terminated. In addition to HCH and DCH, the CHs that a connection traverses are regarded as VCHs. There are two types of polling tokens (PT) in the system: inter-cluster PT and intra-cluster PT. The inter-cluster PT consists of Home Token (HT), Remote Token (RT) and Virtual Token (VT). All HTs and RTs are further classified into incoming PTs (I\_HT and I\_RT) and outgoing PTs (O\_HT and O\_RT). The I\_HT is located at the HCH and is used to represent an inter-cluster packet at the source node. The O\_HT is also located at the HCH but it represents an outgoing inter-cluster packet at the HCH is ready to be forwarded to the downstream GW. The RT can be located at the GW, VCH or DCH. An I\_RT located at the VCH or DCH represents an incoming inter-cluster packet at the upstream GW. An O\_RT located at the VCH or DCH represents an outgoing inter-cluster packet is ready to be forwarded to the downstream GW or destination node respectively. An I\_RT located at the GW represents the GW is ready to receive an inter-cluster packet at the upstream HCH or VCH. An O\_RT in the GW represents the GW is ready to forward an inter-cluster packet to the next downstream VCH or DCH. VT only locates in the CH and represents the GW that the VT directed is busy in servicing a connection that does not traverse the CH. The intra-cluster PTs consist of PTs for CBR, VBR and ABR sources. We assume that the channel access priority of inter-cluster PTs prevail over the intra-cluster PTs and among the inter-cluster PTs, incoming PTs are with higher priority than outgoing PTs. As to the intra-cluster PTs, the CBR PTs are with the highest priority then the VBR PTs and the ABR sources are with the lowest priority. An example of the system model for two clusters connected by a GW is illustrated in Figure 1. In this figure, there are two inter-cluster connections originating from Cluster1 and terminated at Cluster2, one inter-cluster connection originating from Cluster2

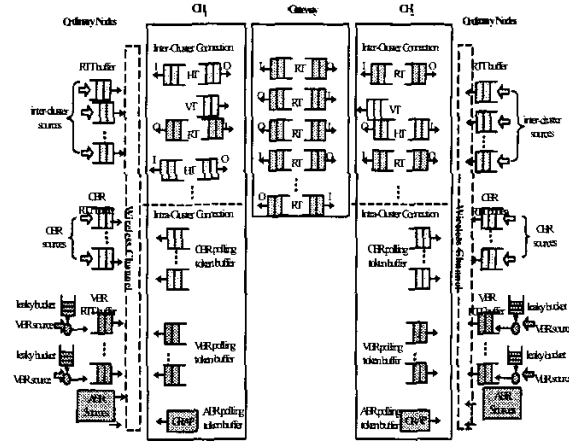


Figure 1 An example of the system model with two clusters connected by a GW.

and terminated at Cluster1 and one inter-cluster connection that passing through the GW to a cluster other than Cluster1 and Cluster2. The two HT PT buffers in CH1 and two RT PT buffers in CH2, one RT PT buffer in CH1 and one HT PT buffers in CH2 and one VT PT buffer in both CH1 and CH2 are the PT buffers corresponding to the inter-cluster connections.

### III. 2-LAYER INTEGRATED QoS-GUARANTEED MULTIHOP SCHEDULING ALGORITHM

Based on the flat network architecture and the global synchronization assumptions, scheduling packets traverse the wireless multihop ad hoc networks are generally classified into node scheduling [6] and link scheduling [7]. The main objective of these two scheduling schemes is to find a conflict-free schedule that maximizes the system throughput. However, in [6] the problem of determining transmission schedules with optimal throughput is shown to be NP-complete. In the flat network architecture, the available network bandwidth is highly depends on the frequency of network topology dynamics since any network topology update must be distributed to all nodes in the network. Besides, the global synchronization assumption requires each node to synchronize with a fixed absolute timing source that is not realistic in network without the infrastructure such as wireless multihop ad hoc network. In this paper, with clustering assumption, the available network bandwidth is increased since the local network topology updates need only be forwarded to the local CHs. Furthermore, the global synchronization issue can be reduced to the intra-cluster and the inter-cluster synchronization problems. For the intra-cluster synchronization, all nodes in the cluster follow the CH timing. For the inter-cluster synchronization, the relative timing or the timing offset between the connected clusters is used for GW to forward packet between clusters.

For the 2-layer clustered network architecture, the general design approach of a multihop scheduling algorithm is to design two schedulers to schedule intra-cluster and inter-cluster communications individually. In the following, we present a novel 2-layer integrated multihop scheduling algorithm that can both schedule intra-cluster and inter-cluster communications.

The following algorithm is executed at each CH to schedule QoS guaranteed packets according to the preset priority.

```

Procedure Clusterhead()
  Generates PT of each admitted connection based on the required average rate;

```

```

While (CH senses the channel idle){
  selects the pending PT (excluding the VTs) with the highest priority;
  if (an I_HT is found){
    polls the corresponding source node to send a packet;
    removes the I_HT from the PT buffer;
  }
  if (an O_HT is found){
    if (HCH==DCH){
      polls the destination node;
      sends the packet to the destination node;
      removes the O_HT from the PT buffer;
    }
    else{
      if (a Hello packet from the downstream GW node is received){
        polls and sends a packet to the downstream GW node;
        removes the O_HT from the PT buffer at the CH;
        removes the corresponding I_RT from the PT buffer at the
        downstream GW node;}}
  }
  if (an I_RT is found){
    if (a Hello packet from the upstream GW node is received){
      polls the upstream GW node to send a packet;
      removes the I_RT from the PT buffer at the CH;
      removes the corresponding O_RT from the PT buffer at the
      upstream GW node;}}
  }
  if (an O_RT is found){
    if (VCH==DCH){
      polls the destination node;
      sends the packet to the destination node;
      removes the O_RT from the PT buffer at the CH;
    }
    else{
      if (a Hello packet from the downstream GW node is received){
        polls the downstream GW node to receive a packet;
        removes the O_RT from the PT buffer at the CH;
        removes the I_RT from the PT buffer at the downstream GW
        node;}}
  }
  if (a CBR token is found){polls the corresponding CBR source to send a
  packet;
  removes the token form the corresponding PT buffer;}}
  if (a VBR token is found){polls the corresponding VBR source to send a
  packet;
  if (the corresponding RTT buffer is not empty)
    the VBR source sends out a packet;
  else
    the VBR source sends an End-Of-File (EOF) signal;
  if (CH receives an EOF signal from a VBR source){
    removes the token form the corresponding PT buffer;
    schedules the generation of the next PT after  $p$  seconds;}}
  if (there is no higher priority PT found)
    run GRAP1 to service the ABR sources;}}

```

The following algorithm is executed at each GW to rendezvous with clusters.

```

Procedure Gateway(){
  While (the channel corresponds to the highest priority PT is sensed idle){
    if (this PT is I_RT or O_RT)
      sends a Hello packet to the corresponding CH to signal its appearance
      (or return) from other CH;
    else
      takes turn to rendezvous with all the connected CHs;}}

```

#### IV. QoS ANALYSIS

In this section, based on the analyses in [9], we provide the mathematical analyses of the packet delay and delay jitter at each CH and GW along the path of an admitted connection. Let  $\tau'_{data} = \tau_{poll} + \tau_{packet}$  be the time to send a packet at the first and last hop, i.e. from the source node to the HCH and from the DCH to the destination node respectively,  $\tau_{data} = \tau_{offset} + \tau_{Hello} + \tau'_{data}$  be the packet transmission time at the remaining hops of the considered path where  $\tau_{offset}$  is the offset time from the instant that a CH wants to forward a packet to a GW to the instant that the CH receives a Hello packet from the GW. We further classify the PTs into four classes. Those I\_HT at the HCH and O\_RT at the DCH are Class 1 PTs. Ignoring all lower priority VTs in the same CH that direct to different GW, those O\_HT and O\_RT that are followed by a VT or an I\_RT that directs to the same GW are Class 2 PTs. According to the definition of VT, when determining the delay/jitter of a specific PT, VTs that satisfy one of the following two conditions are ignored: (i) If a Class 1 PT is considered, all consecutive higher priority VTs between this Class 1 PT and the last higher priority O\_HT or O\_RT are ignored. (ii) If an I\_RT is considered, all higher priority consecutive VTs between this I\_RT and the last O\_HT or O\_RT that direct to different GWs are ignored. As a result, those VTs that are actually considered are regarded as Class 3 PTs. The rest of PTs are Class 4.

<sup>1</sup> For the detail operation of the GRAP wireless access protocol, please refer to [8].

assume for each considered PT, the number of higher priority Class 1, Class 2, Class 3 and Class 4 PTs are  $h_1, h_2, h_3$  and  $h_4$  respectively. For the intra-cluster communications, we assume there are totally  $N_C$  CBR sources and  $N_V$  VBR sources.

Lemma 1: Let  $V$  be the total bandwidth consumed by all higher priority PTs than the considered I\_HT in the HCH or O\_RT in the DCH, i.e. Class 1 PT. The delay of a Class 1 I\_HT in the HCH (i.e. the first hop),  $d_S^{(c)}$ , of connection  $c$  is

$$d_S^{(c)} \leq \frac{h_1 \tau'_{data} + (2h_2 + h_4 + 1) \tau_{data}}{1 - V}. \quad (1)$$

Also, the delay of a Class 1 O\_RT at the DCH (i.e. the last hop),  $d_D^{(c)}$ , of connection  $c$  is

$$d_D^{(c)} \leq \frac{h_1 \tau'_{data} + (2h_2 + h_4 + 1) \tau_{data}}{1 - V}, \quad (2)$$

where

$$V = \sum_{m=1}^{h_1} r_m^{(1)} \tau'_{data} + (2 \sum_{m=1}^{h_2} r_m^{(2)} + \sum_{m=1}^{h_4} r_m^{(4)}) \tau_{data}. \quad (3)$$

*Proof.* To show  $d_S^{(c)}$ , we assume a marked Class 1 I\_HT is generated at time 0. Consider the case that on arriving of the marked I\_HT, HCH is transmitting a packet. In this case, the marked I\_HT at most must to wait  $\tau_{data}$  for this packet to complete its transmission. After that, according to the preset service priority, the marked I\_HT still have to wait for service until all higher priority PTs are depleted. Since the inter-cluster packet transmission at the first hop and the last hop is equivalent to an intra-cluster packet transmission, there is no Class 3 PT. The number of higher priority Class 1, Class 2, and Class 4 PTs generated in  $d_S^{(c)}$  are upper bounded by

$\sum_{m=1}^{h_1} \lceil r_m^{(1)} d_S^{(c)} \rceil$ ,  $2 \sum_{m=1}^{h_2} \lceil r_m^{(2)} d_S^{(c)} \rceil$ , and  $\sum_{m=1}^{h_4} \lceil r_m^{(4)} d_S^{(c)} \rceil$  respectively. Note that the number of higher priority Class 2 PT is doubled. According to the proposed algorithm, the next lower priority VT or I\_RT to this Class 2 PT will receive service only when a Hello packet from a GW is received. Since the Class 2 PT generates two PTs, I\_RT and O\_RT, in the GW, the GW will send a Hello packet to the CH for the next lower priority VT or I\_RT to this Class 2 PT after the two PTs are services. Thus, the equivalent number of PT of a Class 2 PT is doubled. Therefore, the delay bound for this marked I\_HT is

$$d_S^{(c)} \leq \tau_{data} + \sum_{m=1}^{h_1} \lceil r_m^{(1)} d_S^{(c)} \rceil \tau'_{data} + (2 \sum_{m=1}^{h_2} \lceil r_m^{(2)} d_S^{(c)} \rceil + \sum_{m=1}^{h_4} \lceil r_m^{(4)} d_S^{(c)} \rceil) \tau_{data}. \quad (4)$$

Using the fact  $\lceil x \rceil \leq x + 1$ , we have

$$d_S^{(c)} \leq \frac{h_1 \tau'_{data} + (2h_2 + h_4 + 1) \tau_{data}}{1 - V},$$

where  $V$  is defined as in (3). Following the same derivations, (2) can be obtained. Q.E.D.

Lemma 2: Let  $W$  be the total bandwidth consumed by all PTs with higher priority than a marked PT at the CH of the  $n$ -th hop of connection  $c$ , the delay of the marked PT is

$$d_n^{(c)} \leq \frac{h_1 \tau'_{data} + (2h_2 + 2h_3 + h_4 + 1) \tau_{data}}{1 - W}, \quad (5)$$

where

$$W = V + 2 \sum_{m=1}^{h_3} r_m^{(3)} \tau_{data}. \quad (6)$$

*Proof.* Assume the marked PT is generated at time 0. Consider the case that on arriving of this marked PT, the CH is

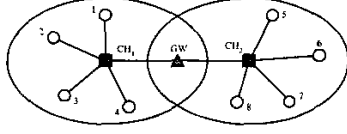


Figure 2 Two clusters connected by a gateway node.

transmitting a packet. In this case, the marked PT at most has to wait for  $\tau_{data}$  for the CH to finish this transmission. In addition, according to the service priority, the marked PT has to wait for depletion of all higher priority PTs. Let the delay bound of the marked PT  $d_n^{(c)}$  be the maximum waiting time to deplete all higher priority tokens. The number of higher priority Class 1, Class 2, Class 3 and Class 4 PTs generated in  $d_n^{(c)}$  are upper bounded by  $\sum_{m=1}^{h_1} [r_m^{(1)} d_n^{(c)}]$ ,  $2 \sum_{m=1}^{h_2} [r_m^{(2)} d_n^{(c)}]$ ,  $2 \sum_{m=1}^{h_3} [r_m^{(3)} d_n^{(c)}]$  and  $\sum_{m=1}^{h_4} [r_m^{(4)} d_n^{(c)}]^2$  respectively. Also, with the fact  $\lceil x \rceil \leq x+1$ , the delay bound for this marked PT is

$$d_n^{(c)} \leq \frac{h_1 \tau'_{data} + (2h_2 + 2h_3 + h_4 + 1) \tau_{data}}{1 - W},$$

where  $W$  is defined as in (6). Q.E.D.

**Theorem 1** The end-to-end delay of a connection  $c$  along a path with  $g^3$  hops to the destination is

$$d_{ETE}^{(c),g} = d_S^{(c)} + \sum_{n=2}^{g-1} d_n^{(c)} + d_D^{(c)}. \quad (7)$$

*Proof.* For  $g=2$ , it is basically an intra-cluster connection. The end-to-end delay is equal to the delay incurred from the source node to the HCH and the delay from the DCH to the destination<sup>4</sup>. As stated in Lemma 1, the end-to-end delay is  $d_S^{(c)} + d_D^{(c)}$ . For  $g>2$ , in addition to the delay incurred at the first and the last hops, the delay incurred at each intermediate hop should also be included. Thus, based on Lemma 1 and Lemma 2, the end-to-end delay of a connection  $c$  along a path with  $g$  hops to the destination is

$$d_{ETE}^{(c),g} = d_S^{(c)} + \sum_{n=2}^{g-1} d_n^{(c)} + d_D^{(c)}. \quad \text{Q.E.D.}$$

**Theorem 2** Let  $Y$  be the total bandwidth used by the inter-cluster connections and the first  $i-1$  CBR sources. The jitter of the  $i$ -th intra-cluster CBR source is

$$d_i^{CBR} \leq \frac{(h_1 + i - 1) \tau'_{data} + (2h_2 + h_4 + 1) \tau_{data}}{1 - Y}, \quad (8)$$

where

$$Y = V + \sum_{m=1}^{i-1} r_{c,m} \tau'_{data}. \quad (9)$$

*Proof.* Assume a marked PT of the  $i$ -th CBR source is generated at time 0. The waiting time in the worst case for the marked PT to access the channel consists of the time for the channel to be idle, the time for all Class 1, Class 2 and Class 4 PTs to deplete their PT buffers and the time for the first  $(i-1)$  higher priority CBR PTs to deplete their PT buffers. Let the jitter bound of the marked PT be  $d_i^{CBR}$ . Based on the assumed service priority, the marked PT has to wait for depletion of all higher priority PTs. The number of higher priority Class 1,

Class 2, Class 4 and previous  $(i-1)$  CBR PTs generated in  $d_i^{CBR}$  are bounded by  $\sum_{m=1}^{h_1} [r_m^{(1)} d_i^{CBR}]$ ,  $2 \sum_{m=1}^{h_2} [r_m^{(2)} d_i^{CBR}]$ ,  $\sum_{m=1}^{h_3} [r_m^{(4)} d_i^{CBR}]$ , and  $\sum_{m=1}^{i-1} [r_{c,m} d_i^{CBR}]$  respectively. With the fact  $\lceil x \rceil \leq x+1$ , the jitter bound for this marked PT is

$$d_i^{CBR} \leq \frac{(h_1 + i - 1) \tau'_{data} + (2h_2 + h_4 + 1) \tau_{data}}{1 - Y}$$

where  $Y$  is defined as in (9). Q.E.D.

**Theorem 3** Let  $Z$  be the total bandwidth used by all inter-cluster connections, all CBR sources and the first  $i-1$  higher priority VBR sources. The delay of the  $i$ -th VBR source is

$$d_i^{VBR} \leq p_i + \frac{1}{1 - Z} \left[ (h_1 + N_C + \sum_{m=1}^{i-1} (b_m + 1)) \tau'_{data} + (2h_2 + h_4 + 1) \tau_{data} + (i-1) \tau_{empty} \right], \quad (10)$$

where

$$Z = V + \left( \sum_{m=1}^{N_C} r_{c,m} + \sum_{m=1}^{i-1} r_{v,m} \right) \tau'_{data} \quad (11)$$

*Proof.* Due to the preset service priority, the  $i$ -th VBR source will receive service after the channel is free and all inter-cluster connections, all  $N_C$  CBR sources and all the first  $i-1$  VBR sources finish services. The busy hour for the  $N_C$  CBR sources in  $(t_1, t_2)$  is bounded by  $\sum_{m=1}^{N_C} (r_{c,m} (t_2 - t_1) + 1) \tau'_{data}$ . Then, with considering the maximum delay for each of the first  $i-1$  VBR source, the busy hour for the first  $i-1$  VBR sources is bounded by

$$\sum_{m=1}^{i-1} [(t_2 + d_m^{VBR} - t_1) r_{v,m} + b_m + 1] \tau'_{data}. \quad (12)$$

In addition, we need to further consider the busy period provided by the EOF signal caused by polling the empty VBR RTT buffers. This busy period can be upper bounded by  $\tau_{empty} \sum_{m=1}^{i-1} (\frac{t_2 - t_1}{p_n} + 1)$  where  $\tau_{empty}$  is the time to transmit an EOF signal and is defined as  $\tau_{empty} = \tau_{poll} + \tau_{EOF}$ . Thus, the available service time for the  $i$ -th VBR source in  $(t_1, t_2)$  is

$$\begin{aligned} A_{v,i} &\geq (t_2 - t_1) - \tau_{data} - \sum_{m=1}^{h_1} (r_m^{(1)} (t_2 - t_1) + 1) \tau'_{data} \\ &\quad - 2 \sum_{m=1}^{h_2} (r_m^{(2)} (t_2 - t_1) + 1) \tau_{data} - \sum_{m=1}^{h_3} (r_m^{(4)} (t_2 - t_1) + 1) \tau_{data} \\ &\quad - \sum_{m=1}^{N_C} (r_{c,m} (t_2 - t_1) + 1) \tau'_{data} - \sum_{m=1}^{i-1} d_m^{VBR} r_{v,m} \tau'_{data} - \sum_{m=1}^{i-1} (b_m + 1) \tau'_{data} \\ &\quad - \sum_{m=1}^{i-1} \tau_{empty} - (t_2 - t_1) \left( \sum_{m=1}^{i-1} r_{v,m} \tau'_{data} + \frac{\tau_{empty}}{p_n} \right). \end{aligned} \quad (13)$$

The total number of packets for the  $i$ -th VBR source generated in  $(t_1, t_2)$  is upper bounded by  $r_{v,i} (t_2 - t_1) + b_i + 1$ . Thus the workload for the  $i$ -th VBR source in  $(t_1, t_2)$  is

$$W_{v,i}(t_1, t_2) \leq (r_{v,i} (t_2 - t_1) + b_i + 1) \tau'_{data}. \quad (14)$$

Since the offered load must less than the system capacity and, thus, we can obtain the delay bound for the  $i$ -th VBR source

$$\begin{aligned} d_i^{VBR} &= p_i + \frac{1}{1 - Z} \left( (h_1 + N_C + \sum_{m=1}^{i-1} (b_m + 1) + \sum_{m=1}^{i-1} d_m^{VBR} r_{v,m}) \tau'_{data} \right. \\ &\quad \left. + (2h_2 + h_4 + 1) \tau_{data} + (i-1) \tau_{empty} \right), \end{aligned}$$

where  $Z$  is defined as in (11). Q.E.D.

<sup>2</sup> The reason for doubling the number of Class 3 PT is similar to the case in doubling the number of Class 2 PT discussed in the proof of Lemma 1.

<sup>3</sup>  $g$  is an even number due to the CH-GW forwarding approach.

<sup>4</sup> In this case, the HCH is equivalent to the DCH.

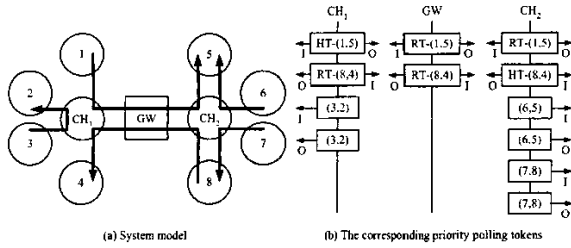


Figure 3 Intra-cluster and inter-cluster connection in the network shown in Figure 2 and the corresponding PTs at CHs and GW.

TABLE I THE END-TO-END DELAY AND DELAY SUFFERED AT EACH HOP.

Connection Type	Connection ID c	QoS provisions	$d_s^{(c)}$		$d_d^{(c)}$		$d_{ETE}^{(c)}$	
			$d_s^{CBR} / d_s^{VBR}$	$d_s^{(c)}$	$d_d^{CBR} / d_d^{VBR}$	$d_d^{(c)}$	$d_{ETE}^{CBR} / d_{ETE}^{VBR}$	$d_{ETE}^{(c)}$
Inter-cluster	CBR (1,5)	(0.04, 10, 50)	2.2	3.45	2.2	4.83	12.7	
Inter-cluster	CBR (8,4)	(0.024, 15, 70)	6.34	7.84	9.87	13.6	37.7	
Intra-cluster	CBR (3,2)	(0.015, 20, 40)	15.7	N/A	N/A	17.7	33.4	
Intra-cluster	CBR (6,5)	(0.01, 25, 40)	11.2	N/A	N/A	12.7	23.9	
Intra-cluster	VBR (7,8)	(1.27x10 <sup>-3</sup> , 8, 100)	14.3	N/A	N/A	38.8	53.1	

## V. INITIAL CONNECTION SETUP AND ADMISSION CONTROL

In this section, we present procedures to establish a new connection. As assumed Section II, all connection setup request (REQ) packets are regarded as ABR packets, i.e. the request packets can only access the channel when no pending higher priority token is found. As a CH receives a REQ packet, it determines if the requested QoS provisions can be honored based on Lemma 1, Lemma 2, Theorem 1, Theorem 2 and Theorem 3. Consider to setup an intra-cluster connection in the wireless multihop ad hoc network as depicted in Figure 2. Assume node 1 tries to establish an intra-cluster connection to node 2. Node 1 follows the GRAP protocol to send a REQ packet containing the required QoS provisions to CH<sub>1</sub>. CH<sub>1</sub> looks up the routing table and recognizes the requested connection as an intra-cluster connection and, then, calculates the available bandwidth to decide if admits the request. If CH<sub>1</sub> admits the request, the connection is setup and the required bandwidth is reserved. To setup an inter-cluster connection, a source node must first send out a REQ packet containing the required QoS provisions to the associated HCH. After receiving this REQ packet, the HCH based on Lemma 1, Lemma 2, Theorem 1, Theorem 2 and Theorem 3 to determine if the required QoS provisions can be met. If not, it rejects the request. Otherwise, it appends the calculated delay/jitter to the REQ packet and forwards this REQ packet to the downstream GW. The REQ packet is then forwarded to the VCH. Also, the VCH calculates and checks if it can honor the requested QoS provisions. The procedure repeats until the REQ packet reaches the DCH. If the DCH can also guarantee the requested QoS provisions, a reply (RPY) packet will be sent hop-by-hop back to the source node and the connection is established. After the connection is setup, the corresponding PTs described in Section II-C are generated at each CH and GW that the connection traverses. The entire network can be modeled like Figure 1. Note that forwarding the REQ and RPY packets can be simplified by piggybacking them into the general packet transmissions.

The system model and priority of PTs for an example of three intra-cluster connections (3,2), (6,5) and (7,8) and two inter-cluster connections (1,5) and (8,4) established in the wireless ad hoc network as shown in Figure 2 are shown in Figure 3. We assume the link speed is 10Mbps, the packet size is 1K bits, and the polling signal, EOF signal and the Hello packet are all 50 bits. Therefore, we have  $\tau_{packet}=0.1\text{msec}$ ,  $\tau_{poll}=\tau_{EOF}=\tau_{Hello}=5\mu\text{sec}$ . For simplicity, we let  $\tau_{packet}=1$  and normalize every parameter with respect to  $\tau_{packet}$ , i.e.,  $\tau_{poll}=\tau_{EOF}=\tau_{Hello}=\tau_{mark}=0.05$ ,  $\tau_{data}=2.2$ ,  $\tau_{offset}=1.1$ ,  $\tau'_{data}=1.05$  and  $\tau_{empty}=0.1$ . Assume there are three intra-cluster connections (3,2), (6,5) and (7,8) and two inter-cluster connections (1,5) and (8,4) established in the wireless multihop ad hoc network with two CHs connected by a GW. The corresponding system model and the priority of polling token for each connection are shown in Figure 3(a) and Figure 3(b). For each VBR source, we assume the parameter  $p_i=0.1d_{v,i}$ . The theoretical jitter and delay suffered in each hop and the end-to-end delay for each connection are listed in TABLE I. By verifying the calculated delay/jitter and the end-to-end delay, we find that the requested QoS provisions of all admitted connections are guaranteed and the requested connections are re established.

## VI. CONCLUSIONS

In this paper, without the global synchronization assumption that are usually made, we use the concept of relative timing between neighboring clusters and the concept of rendezvous windows for the GWs to rendezvous with its connected clusters for timing conversion to overcome the synchronization problem in wireless multihop ad hoc networks. To be able to schedule both intra-cluster and inter-cluster traffic sources, we propose a QoS-guaranteed polling-based 2-layer integrated multihop scheduling algorithm that schedules both intra-cluster and inter-cluster packets based on a preset service priority. We provide the end-to-end delay bound for inter-cluster connection, delay bound for VBR source and jitter bound for CBR source and these delay bounds are used as the criterion of admission control in order to achieve guaranteed QoS services.

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