Protocols and Algorithms Supporting QoS in an Ad-hoc Wireless ATM Multihop Network*

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Abstract **The Ad-hoc Wireless ATM Multihop (AWAM) network described in this paper is decentrally organized and can be rapidly deployed. To support a real time variable bit rate (VBR) service with stringent QoS requirements, together with a delay insensitive available bit rate (ABR) service, protocols and algorithms for adaptive medium access control, logic link control and call admission control have been developed. The complementary packet delay distribution function under various loads has been analyzed through the computer simulation based on a formal protocol specification in SDL.**

I. INTRODUCTION

Ad-hoc networking, which is self-organized and could be rapidly deployed, is a topic of growing interest in wireless communication areas [1]-[4]. In most cases, it is infeasible, if not impossible, to implement a central control in an ad-hoc networking environment, so we have no central control support in the AWAM network. This is worth emphasizing because most of the research in Wireless ATM (W-ATM) so far is based on a central control.

Another element of the AWAM network which we should mention is multihop communications. W-ATM systems [5][6] will use 5 GHz or higher frequencies which have a very limited ability to penetrate obstructers and exhibit a severe atmospheric attenuation. So we have a networking environment in which the maximum communication distance between any two stations would be less than 500 meters, and the communication zone would be strongly deformed by shadowing. As such, we may not be able to place all wireless stations (WSs) within range of each other. Thus, multihop communications (with typically a few hops only) must be considered by providing the relay function for WSs. The limited transmission path length gives the benefit of battery power conservation, less interference to other transmissions and spatial reuse of scarce radio resources, resulting in a reduction of the channel spectrum required. On the other hand, however, it is much more difficult to support a QoS guarantee in multihop environments with the hidden station problem than in single-hop fully connected systems.

Another challenging problem we face in the AWAM network is the statistical multiplexing of bursty traffic with diverse QoS requirements in a fully distributed manner. Based on the observation that ATM might be ubiquitous in wired networks, it would be very advantageous that W-ATM systems could be transparently integrated with standard ATM networks. Therefore, W-ATM systems should support the same traffic as that of wired ATM networks. Statistical multiplexing can be realized in wired ATM networks by bandwidth managing at ATM switches [7]. In the AWAM network, however, traffic sources are distributed in WSs which are not coordinated by a central control. As such, adaptive protocols and algorithms must be developed to realize statistical multiplexing and to use the radio resources efficiently.

II. SYSTEM ARCHITECTURE AND PROTOCOL STACK

The proposed network, shown in Fig. 1, consists of portable or movable WSs, such as laptops, not moved during communications. So we can call them semi-mobile stations [8]. WSs may be able to communicate with each other directly or due to limited communication distance may need to be relayed to reach their destinations. They can also be integrated transparently into a wired ATM network through an access point (AP).

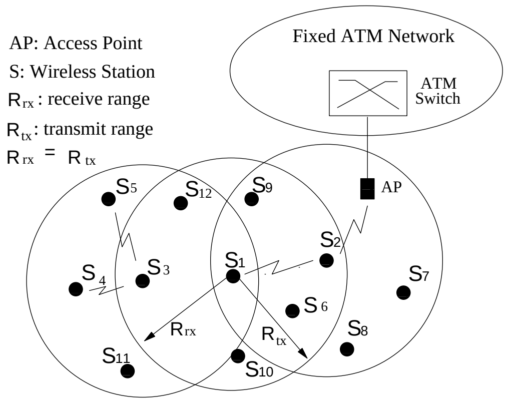

Fig. 1. AWAM network system architecture

The AWAM network protocol stack is shown in Fig. 2. We have used standard ATM protocols and interfaces as much as possible to reduce the network developing cost

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and to enlarge the application range of such a network. Of course, an additional protocol stack which is specific to the AWAM network, including a network layer (NL), a data link layer consisting of a medium access control (MAC) sublayer and a logical link control (LLC) sublayer, and a wireless physical layer (W-PHY) is still necessary to connect the wireless terminal adapters (WA) and the AP.

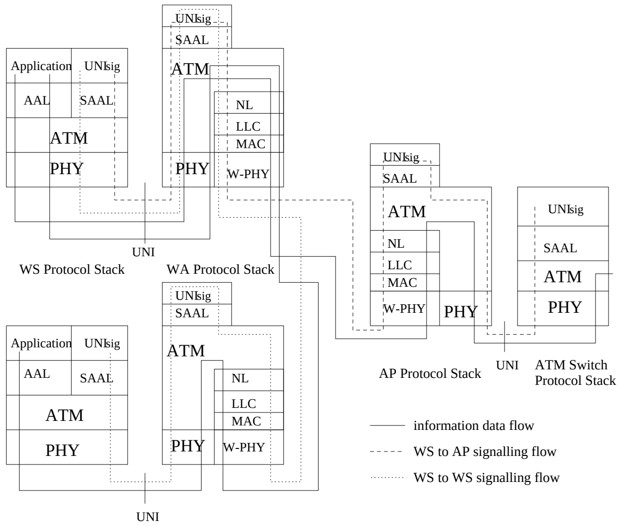

Fig. 2. AWAM network protocol stack

The key component of the AWAM network protocol stack is the MAC protocol. It has to overcome the hidden station problems. It must realize statistical multiplexing of bursty traffic in the radio link. It must be able to reserve sufficient bandwidth for real time (rt) traffic at short time. Because of unreliable radio transmission, an automatic repeat request (ARQ) protocol is necessary in the LLC sublayer.

The NL performs routing and network management functions, such as maintaining connectivity and routing information. It performs also call admission control and user parameter control to guarantee the QoS of the established virtual connections.

Signal flows of signaling data and user data are also depicted in Fig. 2. The NL of WA in the WS supports transparent transport of standard ATM cells. If two WSs communicate with each other, the WA performs the network side UNI signaling. If a WS accesses to a wired ATM network, seamless interworking between an AWAM network and a wired ATM network is achieved.

III. ADAPTIVE MEDIUM ACCESS CONTROL

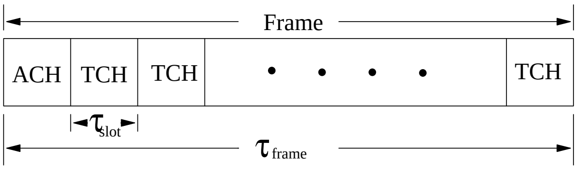

Fig. 3. Channel access frame

The transmission time scale in the MAC layer is organized in frames, each containing a fixed number of time slots, see Fig. 3. All WSs of the network are synchronized on a frame and slot basis, which can be realized by using a synchronization scheme [4]. To use channel resources more flexibly for heterogeneous applications, slots might be divided further to support several logical channels (LCH) [3]. To simplify the description, we use one slot every frame for a LCH in this paper. The first slot of the frame is used as an access channel (ACH), in which a number of binary energy signals and a signaling packet (*s-pkt*) can be transmitted. The other slots are used as traffic channels (TCH), each able to carry one data packet. A TCH can be also dynamically defined as an ACH dependent on the current traffic load on the ACH. A data packet consists of one standard ATM cell and a packet overhead containing information specific to the AWAM network, such as packet identifier, sequence number, time information, etc.. A WS might be the source, a relay or the sink of a burst.

A. Dynamic Channel Reservation

When it has channel reservation requests from the LLC layer, the MAC layer of e.g. S_1, see Fig. 1, selects the access request with the minimum access deadline and contends for transmitting an access (*acc*) *s-pkt* via the ACH using the distributed access priority, see Section III-C. The *acc s-pkt* contains a set of free LCHs which could be used in the view of S_1. There is always a free LCH available for rt-VBR service as long as the system is not overloaded, see Section III-E and V. In the event that S_1 did send the *acc s-packet*, and the addressed station, e.g. S_2, could successfully receive this *acc s-pkt* and could find at least one of the channels proposed by S_1, to be free in the view of S_2, it responds to S_1 with an acknowledgment (*ack*) *s-pkt* via the selected LCH. After this procedure, a LCH to be used is reserved between S_1 and S_2. All other WSs in the transmit range of S_1 and S_2 will mark this LCH as reserved, so that the hidden station problem is eliminated. At the end of its information burst (called a train in [3] and a block in [9]), S_1 stops transmitting in its reserved channel. This stimulates S_2 to send a release (*rel*) *s-pkt* on the reserved LCH to indicate this LCH available again. WSs in the range of S_1 and S_2 which either receive the *rel s-pkt* or detect the end of transmission of S_1 will also mark this LCH free again. This protocol is closely related to R-ALOHA [10] and PRMA [11]. It differs from R-ALOHA and PRMA by its ability to operate in multihop environments and in a fully distributed manner. It can be viewed as a combination of the IEEE 802.11 MAC protocol [2] and PRMA. Details of this protocol can be found in [3].

B. Reservation Conflict Resolution and Channel Handover

If one or more LCHs in the set of proposed channels in the *acc s-pkt* of S_1 are already reserved by another station in the transmit range of S_1, say S_3, see Fig. 1, for rt-VBR traffic, S_3 will send a conflict resolution *s-pkt* via the ACH. Such a case can happen if S_1 did not receive *ack s-pkt* of S_3 before. For example, if S_3 sent its *ack s-pkt* when S_4 was transmitting, S_1 was interfered and could not receive any packet. After receiving the conflict resolution *s-pkt*, S_1 will not transmit in the conflict channel even if S_2 has selected it. If S_2 did select the conflict channel, S_1 has to repeat the channel reservation procedure described in Section III-A.

Channel handover is necessary when S_1 sends packets in the conflict channel later. This may happen if: (1) S_1 is not able to receive the conflict resolution *s-pkt* of S_3; (2) S_3 does not send conflict resolution *s-pkt* as it is receiving ABR traffic in the conflict channel; (3) S_3 does not receive the *acc s-pkt* of S_1. Thus, S_3 will be interfered in the reserved LCH and can no longer receive any packet in this LCH (if packet capture is neglected). At this time, S_3 will send a handover request *s-pkt* with a set of free channels, which could be used in the view of S_3, via the ACH to the former partner station, e.g. S_5. If it could successfully receive this handover request *s-pkt* and could find one of the channels proposed by S_3, which is also free in the view of it, S_5 responds to S_3 on the selected LCH with a handover *ack s-pkt*. After receiving this *s-pkt*, S_3 sends a handover confirm *s-pkt* on the same LCH in order that WSs in the transmit range of S_3 can mark the LCH as reserved. After that, S_5 will resume sending information packets in the new LCH and the handover procedure is completed. Channel handover might be also necessary due to degrading channel quality.

C. Distributed Access Priority

As described above, the AWAM network must support a rt-VBR service. We defined the QoS of the rt-VBR service in terms of a maximum tolerable packet delay D_{max} and a packet dropping probability P_{drop}. Packets with delay exceeding D_{max} are useless and will be dropped in the LLC layer. Thus, a rt-VBR information burst requires prompt packet delivery. Among VBR bursts, each might have a different access deadline. To give the most urgent information burst a higher priority, we use the distributed access priority algorithm specified as follows:

```
if (D_acc − now()) < T_limit and B_type is VBR
    then P_acc = P_max
else if (D_acc − now()) > T_limit and B_type is VBR
    then P_acc = Rand(P_ABR + 1, P_max)
else P_acc = Rand(0, P_ABR)
```

where *now*() returns the current time; D_{acc} is the access deadline scheduled in LLC; T_{limit} is an access time limit; B_{type} is the service type of the information burst; P_{acc} is the access priority calculated by this algorithm; P_{max} is the maximum access priority with the greatest priority value; P_{ABR} is the maximum access priority for ABR service; *Rand*(*x*,*y*) is a discrete uniform distribution function which returns random integer value between *x* and *y*; T_{limit}, P_{ABR} and P_{max} are design variables. We have used T_{limit} = 100 [τ_{slot}], P_{max} = 15, P_{ABR} = 3 in this paper.

The distributed access priority is realized by using a combination of several binary energy signals, a procedure similar to EY-NPMA [1]. For example, if it contends for ACH with maximum priority 15, a WS sends four binary energy signals (1111) before transmitting *acc s-pkt*.

D. Adaptive Back-off

In spite of using the distributed access priority, a collision may still happen if: (1) two WSs use the same priority; (2) contending WSs are hidden to each other, such as S_1, S_5 in Fig. 1. To avoid repeated collisions, we use an adaptive back-off algorithm specified below:

```
if (D_acc − now()) < T_limit and B_type is VBR
    then T_b = Rand(0, T_b1)
else if (D_acc − now()) > T_limit and B_type is VBR
    then T_b = Rand(T_b1 + 1, T_bVBR)
else T_b = Rand(T_bVBR + 1, T_bmax)
```

where T_b is the back-off time calculated by this algorithm; T_{b1} is the upper bound back-off time of the most urgent access request; T_{bVBR} is the maximum back-off time of VBR service; $T_{b\max}$ is the maximum back-off time. We have used T_{b1} = 2 [τ_{frame}], T_{bVBR} = 4 [τ_{frame}] and $T_{b\max}$ =7 [τ_{frame}] in this paper.

E. Adaptive Interruption of ABR Transmission

ABR traffic will be multiplexed with VBR Traffic in the air interface. To use bandwidth efficiently, ABR service will use bandwidth resources which are temporarily not used by VBR service. As WSs reserve LCHs in an unco-ordinated manner, an algorithm is needed to ensure that a VBR burst can always find a free LCH when it arrives in the WS. Otherwise, this VBR burst may encounter excessive access delay and be dropped in the LLC layer. Therefore, it is necessary to interrupt ABR transmissions adaptively according to the algorithm specified as follows:

```
if N_free < N_limit and N_ABR > N_min
and if there are one or more LCHs
    reserved for ABR service by this WS
then release one LCH by this WS
```

where N_{free} is the number of free LCHs seen by a WS at the beginning of each frame when this algorithm is executed; The Algorithm needs to be executed by all WSs which have one or more ABR VCs. N_{limit} is the number of free LCHs which should be available for coming VBR bursts; N_{ABR} is the number of LCHs reserved for ABR service; N_{min} is the minimum number of channels allocated for ABR service. N_{limit} and N_{min} are design variables. We have used N_{limit} = 2 and N_{min} = 2.

The interrupted ABR transmission is resumed according to the channel reservation procedure described in Section III-A, when $N_{free} > N_{limit}$ again.

IV. Access Deadline and Logical Link Control

In Section III, access deadline D_{acc} is used by the distributed priority algorithm and adaptive back-off algorithm. This parameter is calculated in the LLC layer as follows:

For VBR service :

$$D_{acc} = (D_{\max} - L_b * N) / N_h + (N_h - 1) * \gamma_h * (D_{\max} - L_b * N) / N_h + now() \qquad (1)$$

(in source WS)

$$D_{acc} = (D_{pkt} - now() - L_b * N) / N_h + now() \qquad (2)$$

(in relay WS)

For ABR service:

$$D_{acc} = D_{\max}^{acc} \quad / N_h + now() \qquad (3)$$

(both in source WS and relay WS)

where D_{acc} is the access deadline (nominated in τ_{slot}); D_{pkt} is the packet deadline; D_{max} is maximum tolerable delay of VBR service; L_b is the burst length (number of packets); N is the number of slots each frame; N_h is the number of the remaining hops; *now*() is current time nominated in τ_{slot}. γ_h

is a value between 0 and 1, which is a design variable. $D_{\max}^{acc}$ is maximum access delay for ABR service. As we assume that ABR service is delay insensitive, we use $D_{\max}^{acc}$ as a loose delay bound for ABR service.

If the MAC layer can not reserve a LCH for a burst before D_{acc}, the entire burst will be dropped. This is based on the consideration that it is useless to deliver part of the burst which would be discarded in the destination. Such a consideration that QoS should be provided to bursts other than packets can also be found in [12][7]. We do use burst length in eq. (1) and (2). This should not be a problem for video application because even with live video capture, the burst length is known as soon as the video source has encoded a picture [12].

As WSs support multimedia traffic and have relay functions, it is possible that more than one virtual connection (VC) exists at the same logical link between two WSs. In this case, statistical multiplexing of ABR service and VBR service can be realized more efficiently by using a scheduler in each LLC entity instance existing for communications with a neighbor WS, see Fig. 4. If a VBR burst arrives when ABR traffic is being sent, the ABR transmission is interrupted and the VBR burst will be sent immediately. The transmission of ABR burst will resume at the end of the VBR burst. If an ABR burst arrives and there already exists a reserved LCH, the LLC entity instance will not request more LCH unless the queue length of the ABR traffic has exceeded a predefined bound.

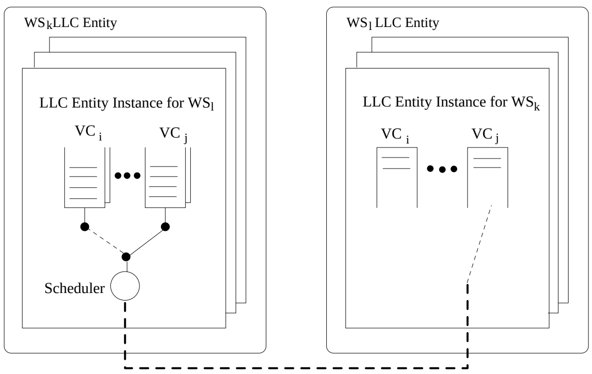

Fig. 4. Scheduler in LLC entity instance

Each transmit queue has a back-up queue, which is used by the ARQ protocol. The packets transmitted will remain in the back-up queue until the next burst is transmitted. Based on the same consideration that QoS should be provided to bursts other than packets, a burst-based ARQ protocol has been developed for the AWAM network. For ABR service, delay is of less interest than packet loss rate. In most cases, the packet loss rate of ABR service should equal zero as the whole data burst might be destroyed if one of its packets is lost. Therefore, the LLC layer performs a burst-based selective-repeat (SR) ARQ protocol for ABR service according to the ACK or NAK received at the end of the burst. If it does not receive an acknowledgment at the end of the burst, the sender will poll the receiver. Such a procedure will be repeated until the whole burst is received correctly. In contrast to ABR service, delay is critical for rt-VBR service. So the retransmission request will be sent via the ACH by the receiver using the highest priority as soon as it detects an error in the burst. If the retransmission is not successful, the ARQ procedure will not be repeated. If it does not receive any retransmission request, the sender will assume that the burst has been received correctly. The ARQ protocol for the rt-VBR service can be regarded as an as-soon-as-possible ARQ protocol.

V. CALL ADMISSION CONTROL

A call admission control (CAC) function must be applied to avoid network congestion and to support rt-traffic in packet switched networks. Many kinds of CAC algorithms have been studied for fixed ATM networks and centrally organized W-ATM systems. However, such kinds of CAC algorithms could not be applied in the AWAM network, as bandwidth resources of the AWAM network are shared in fully uncoordinated manner. To overcome this problem, we have developed a novel CAC algorithm which is implemented distributedly in each WS in the AWAM network.

For rt-VBR service, the total bandwidth allocated is divided into C LCHs. The source, relay, and destination WSs as well as all other WSs which are in the transmit or receive range of these three kinds of WSs allocate n LCHs to a VBR VC in the local bandwidth management table if they observe a requested call (n is according to the peak rate of this virtual connection and access delay needed in MAC layer to contend for these LCHs). The bandwidth resources which are temporarily not used by VBR virtual connections will be multiplexed by ABR service. We specify the CAC algorithm as following:

<u>VBR_CAC</u>(C_{VBR} , λ_{peak})

1 let n meet
2 $(n-1)c < \alpha(\lambda_{peak} + \gamma * \lambda_{peak} * N_h) <= nc$
3 if $(C_{VBR} - n) > 0$
4 then accept the call
5 $C_{VBR} := C_{VBR} - n$
6 else reject the call

α = 1 for source/destination WS and α = 2 for relay WS.

<u>procedure update</u>(C_{VBR})

1 $C_{VBR} := C_{VBR} - n$

(executed each time when a VBR call is accepted by a neighbor WS)

where C_{VBR} is the number of available LCHs for VBR service, and is initialized to C, the maximum number of LCHs allocated for VBR service; c is the bandwidth of one LCH; n (≥1) is the number of LCHs needed by this call; λ_{peak} is the peak rate of a VBR VC; N_h is the number of hops of the connection. γ is a design variable, which reflects the necessary access delay in the MAC layer. In our research, we find that $\gamma = 0.16$ is appropriate.

For ABR service, the admission control is based on the total sum of required minimum rates of all the virtual connections which are in the receiving and transmission range of this WS. The ABR minimum rate is the bandwidth which must be always available for an admitted

ABR connection [13]. As no flow control mechanism is considered in the paper, we have used the mean rate of the ABR service instead of the minimum rate.

VI. COMPUTER SIMULATION

As discussed in the previous sections, there are different design variables that must be considered in the AWAM network. For the purpose of performance evaluation of the protocols and algorithms, a simulation tool, shown in Fig. 5, has been developed. The protocol stack is formally specified in the Specification and Description Language (SDL). With the C++ code generator SDL2SPEETCL [14], the protocol stack can be embedded in the C++ SDL simulation environment. By adopting read-in files, the simulation tool can evaluate the performance of any kind of network topology, traffic characteristic, and VC configuration of the AWAM network without the need to recompile the software.

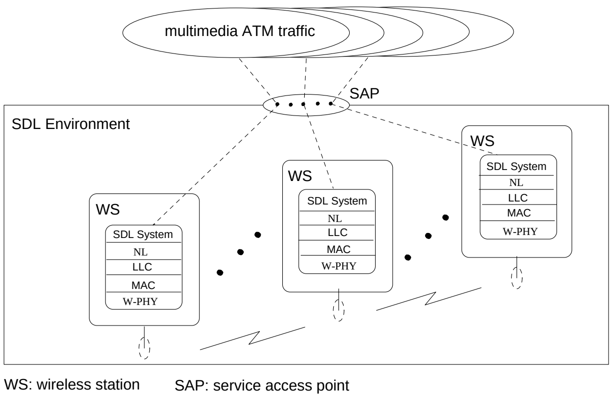

Fig. 5. AWAM network simulation model

The simulation tool has been used to evaluate protocols and algorithms proposed in previous sections. The network under study consists of 20 WSs. For the simplicity of description, these WSs are regularly placed in a square, with 1*M* meter distance between any two neighbor WSs, Fig. 6. We assume that the transmit range R_{tx} as well as receive range R_{rx} is $\sqrt{5}\,M$ meter. Although the capture may improve the system performance, no capture is considered in this paper. So any collided packet will be destroyed. Except for collisions, error free transmission is assumed.

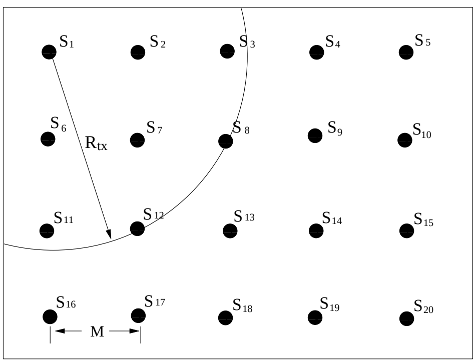

Fig. 6. Simulation scenario

In this research, we use a frame length $N = 16$ [τ_{slot}], and a slot length to carry one packet of τ_{slot} = 20 μs, which can be achieved with a channel rate 34 Mb/s [6].

Traffic sources are activated in the initialization phase and remain active during the rest of simulation time. A WS randomly selects a destination WS as a traffic sink. If the destination WS is not a neighbor WS, the end-to-end VC must be relayed by one or more WSs which are selected according to the minimum hop routing algorithm.

The burst length of rt-VBR traffic is modeled by an autoregressive Markovian process [15] with a mean burst length of 35 packets and a maximum burst lengths of 70 packets, yielding a burstiness factor of 2. The VBR traffic source produces 30 bursts per second (simulating a video codec which produces 30 pictures per second). The VBR service has two QoS requirements: maximum delay D_{max}=*1500* [τ_{slot}] (30*ms*) and packet dropping probability P_{drop} < 1%. The burst length of the ABR traffic is 60 packets. The inter arrival time of ABR bursts is negative exponentially distributed, with a mean value 3000 [τ_{slot}] (60*ms*). Although ABR service is delay insensitive, we have used a maximum access delay $D_{\max}^{acc} = 15000$ [τ_{slot}] in order to evaluate the performance of the ABR service. If it encounters an access delay exceeding $\lfloor 15000 / N_h \rfloor \tau_{slot}$, an ABR burst will be dropped.

Table I provides one result of our experiments with the throughput of 69.1%, defined as the number of all successfully transmitted user data packets divided by the number of simulated slots. Here we can see that there are in total 24 end-to-end VCs at the same time. The number of received VBR packets are 0.005% less than that transmitted because the as-soon-as-possible ARQ protocol described in Section IV can not ensure that every retransmission is successful. The VBR packet dropping probability is P_{drop}=0.6%<1%. The mean delay of VBR packets is about 8 ms. Contrarily, the number of received ABR packets is the same as that transmitted because of the burst-based SR ARQ protocol. Only 0.02% ABR packets are dropped. The mean delay of the ABR packets is about 21 ms.

TABLE I SIMULATION RESULT

	VBR service	ABR service
packets transmitted	932044	792346
packets received	931995	792346
packets dropped	5603	175
mean delay	402 [τ_{slot}]	1047 [τ_{slot}]
conflict resolution	704	
channel handover	517	
adaptive interruption	8067	
virtual connections	12	12
mean hops	1.5	1.33
simulation time	2.496×10^6 [τ_{slot}]	

Fig. 7 shows the complementary distribution function (CDF) of VBR and ABR packet end-to-end delay with the throughput of 69.1%. Here we see that delay of rt-VBR packets is strongly controlled and meets the QoS requirement.

Fig. 8 and Fig. 9 display the CDF of the VBR and ABR packet end-to-end delay under different network throughputs of 55.9%, 69.1% and 78.5%. Here we can see that the network load has less effect on the delay of VBR packets than on that of ABR packets. With a throughput of 55.9%, the network is low-loaded. At this load no packet is dropped. With the throughput of 78.5%, however, the network is overloaded and P_{drop}>> 1%. It is interesting that the network is still stable under overload condition although QoS requirements can no longer be met.

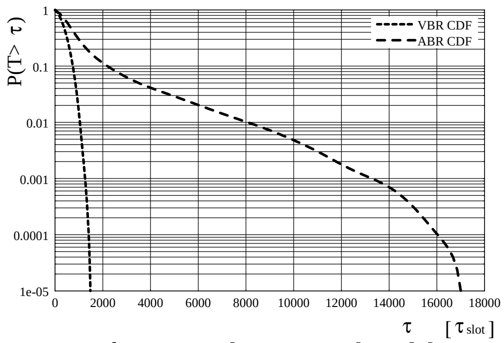

Fig. 7. CDF of VBR and ABR packet delay with the throughput of 69.1%. 2000 [τ_{slot}] = 40 *ms*.

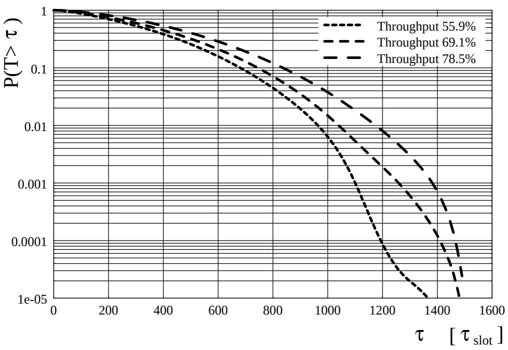

Fig. 8. CDF of VBR packet delay under throughputs 55.9%, 69.1% and 78.5%.

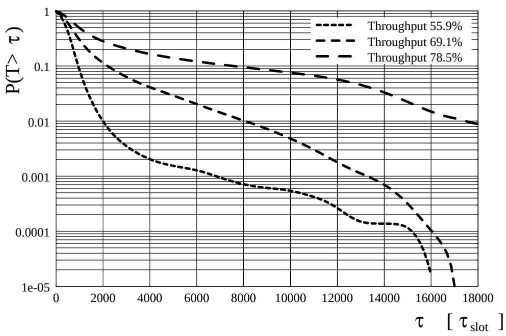

Fig. 9. CDF of ABR packet delay under throughputs 55.9%, 69.1% and 78.5%.

VII. CONCLUSIONS

In this paper, we have proven that rt-VBR traffic with stringent QoS requirements can be supported in a fully decentrally organized W-ATM multihop network by developing the necessary protocols and algorithms. This result is important not only for ad-hoc networking but also for other W-ATM systems. As W-ATM systems will use 5 to 6 GHz unlicensed frequency spectrum having very unpredictable propagation characteristics, frequency planning will be very difficult in such systems so that a central control might be difficult to implement. Furthermore, thanks to the spatial frequency reuse and dynamic channel allocation, there is some inherent property of frequency economy in the fully self-organizing wireless network. Therefore, the distributed, self-organized networking approach appears to be promising for future broadband W-ATM systems.

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