Extended DQRAP (XDQRAP)
A Cable TV Protocol Functioning as a Distributed Switch

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Abstract*[1] - *XDQRAP, an extension of DQRAP (Distributed Queueing Random Access Protocol), is a multiple access protocol that like DQRAP offers a throughput equal to the offered traffic up to a load of one and with a lesser delay than any other multiple access protocol. XDQRAP, as does DQRAP, provides this performance for all values of "a", i.e., the size of the network is immaterial. XDQRAP also functions as a distributed switch in that the segments of variable length packets in a slotted system do not require encapsulation, i.e., an adaptation layer is not required. XDQRAP is described and simulation results are presented. The argument is presented that community networks should utilize random access of a shared medium on the inbound channel(s) at the MAC layer and that these community networks should utilize XDQRAP to support all voice and data transmission.

I. INTRODUCTION

XDQRAP is an extension of DQRAP (Distributed Queueing Random Access Protocol). DQRAP was the result of a directed research effort at IIT [1] to transfer the concept of distributed queuing as utilized by DQDB [2] to a multiple access protocol suitable for the tree-and-branch topology of a typical cable TV system. DQRAP was proposed to IEEE 802.6 in July 1993 as a standard that would address the "last mile" of a MAN in a typical CATV environment [3]. This was the catalyst that triggered the establishment of an IEEE 802.6 study group charged with preparing a PAR (program authorization request) to be submitted to the IEEE 802 Executive Committee requesting the formal establishment of a Working Group charged with defining a Cable TV Protocol [4].

XDQRAP can best be explained by first describing DQRAP in the context of existing contention-based multiple access protocols. Multiple access of a shared channel started in the late 1960s with Aloha [5], a protocol with no rules, i.e., transmit when ready. Aloha is inherently unstable but when a suitable backoff algorithm is employed it does provide 18.4% (1/2e) throughput. Slotted Aloha, [6], introduced only a single rule, i.e., transmit only on a slot boundary, but did improve throughput to the well-known 36.8% (1/e). More improvement is gained by using the CSMA protocols, i.e., having a station "listen before talking". For systems where "a" (ratio of propagation delay to transmission time of the frame) is less than 1, the CSMA protocols provide effective throughput into the 50%-60% range but for networks where a > 1, Slotted Aloha or scheduling protocols remain as the main options [7].

The Aloha protocols, including CSMA, have a basic rule that ready stations continue to retransmit after collisions, subject to back-off rules, until successful. The tree protocols based upon the work of Capetanakis [8] block all new arrivals after a collision occurs. The best of the tree protocols provides a throughput of 0.487 [9] but they have not proved practical. Control minislots were introduced into the tree protocols with the goal of reducing the occurrence of collisions in the dataslot and on paper provide throughput superior to the Aloha and the basic tree protocols. The best of these, AARA [10] achieves a throughput of 0.85 with three control minislots, albeit with long delay at that throughput. But in common with all previous protocols using control minislots AARA includes a statement to the effect "and with an infinite number of control minislots a throughput of one is achieved." But even with an "infinite" number of control minislots these protocols still utilize dataslots for the final resolution of a collision. Control minislots have in practice only proved useful in satellite networks, mainly in variations of reservation protocols based upon Slotted Aloha .

DQRAP achieves 100% utilization of available dataslots for all values of "a". The delay characteristics approach that of an ideal protocol for a < 0.5 and then increases linearly with increased propagation delay .

To be precise, in DQRAP when at least three minislots are utilized along with the two queues the controlling algorithm ensures that an arrival of multiplicity N is resolved in less than N dataslots thus providing a throughput of one [11]. We fall back on a well known result to provide a more intuitive explanation. One minislot in our gateway will allow a maximum throughput of 1/e, our well known Slotted Aloha result described above. Two minislots widen the gateway and provide a throughput of 2/e and then with three minislots we obtain 3/e or 110% thus breaking the 100% barrier. Going beyond three minislots provides a

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marginal reduction to the delay but does not improve throughput since occupancy of the data slots is limited to 100%.

Another remarkable feature of DQRAP, its claim to a throughput of one at offered loads of one or greater, can also be explained using another well known result and again some intuition. As mentioned above newly ready stations can transmit in both a control minislot and a data slot when the global queues are empty. If two or more stations arrive in the same time period a collision occurs in the data slot. There may or may not be collisions in the minislots but we refer the reader to [1] for a discussion of that part of DQRAP. The key point here is that a collision occurs in a data slot only when the data transmission queue is empty. A well known result in queuing theory states that when the offered traffic approaches a load of one the length of the queue grows without bound. Equally so in our distributed queue, when the offered load reaches one the queue grows without bound. The only circumstance under which a collision occurs in a dataslot in DQRAP is when the data transmission queue is of length zero but since the queue is never empty when the offered load is one, all slots are occupied and thus we have a throughput of one. Our throughput of one refers to the percentage of available slots utilized - there is the overhead of the control minislots. The reader is referred to [1] and [11] for details.

One other observation before getting on with XDQRAP. We stated that the global data transmission queue in DQRAP grows without bound as the offered load reaches and passes one. However in DQRAP the growing queue is simply a counter that is being incremented. The actual data buffers are disbursed over scores or even hundreds of stations, thus requiring minimal storage at each station. This is the reason that in the coming years DQRAP will most likely be the chosen mechanism to carry the voice, data, and video packets that currently by default is assumed to be the province of ATM.

There have been several announcements by RBOCs that billions will be spent in building new plant consisting of fiber to a hub and thence coax to the home. Our brief review of the state of the art of existing contention protocols showed that when "a" > 1, the general condition in cable networks, the practical throughput for randomly arriving traffic remains at 37.8%. Thus despite the expectation that traffic at least on the inbound channel(s) of the new systems will be random in nature there has been little consideration given to using a contention protocol. FDM and adaptive TDM are winning by default, until now.

II. HOW XDQRAP WORKS

We introduce Extended DQRAP (XDQRAP), a multiple access protocol that enables a cable TV-based data network to operate as a distributed switch. We use the term switch in the sense of a device where external control is used to establish a path from an input port to an output port thus permitting a segment of data to pass through the switch without modification or requiring encapsulation. An XDQRAP MAC layer will accept IP datagrams, IEEE 802.X frames, MPEG cells, SMDS frames and PPP frames, segment them, and transmit the segments without any additional overhead. A priority mechanism in XDQRAP allows single slot messages to preempt multiple slot messages in the midst of transmission [12]. XDQRAP in a cable TV environment retains the excellent characteristics of DQRAP described in [3]. XDQRAP, as does DQRAP, supports voice either with synchronous DS0 or by using virtual voice packet circuits [13].

What changes have been made to DQRAP? Just two. The size of the control minislot is extended and the immediate access feature is dropped.

In DQRAP the control minislot ideally consists of a single bit. All that is required is that the receiver be able to detect amongst three states: the absence of a signal, the arrival of a single bit, or the simultaneous arrival of two or more bits, i.e., a collision. Detecting the first two conditions is straightforward, detecting a collision in an environment such as rf is a non-trivial task that has been addressed in [14]. In XDQRAP we increase the size of the control minislots to include destination and reservation fields as shown in Fig. 1. Increasing what appears to be overhead is counter-intuitive but we will show that there is a payoff. The address field in the control minislot along with the length field containing the number of slots required alerts the destination station to the arrival of a multiple slot message. All stations, including source and destination stations, upon receiving the feedback from the successful transmission of a control minislot, increment their copies of TQ, the counter representing the number of slots required for pending transmissions. The source and destination stations each calculate, using the value of TQ before incrementing, the slot number to start transmitting and reading respectively. The destination station knows exactly when the multiple slots carrying the message will arrive thus the segments can be reassembled. The adaptation layer joins the ranks of the unemployed.

Dropping the immediate access feature turns XDQRAP into a reservation protocol. But it is a reservation protocol unlike any other. High priority messages can preempt transmission of multiple slot messages thus as is shown by the simulation results excellent performance with respect to delay is provided for shorter messages.

As shown in Fig. 1 we abandon the 53-octet ATM cell size of the original DQRAP proposal for the Cable TV protocol in [3] and instead adopt a 64 octet data slot plus approximately 16 octets for preamble and two extended control minislots (there is no free lunch). Each of the control minislots support a 12-bit address field and an 8-bit request field. The former support up to 4096 virtual addresses and the latter permits up to 256 64-octet dataslots to be reserved (16384 octets). Both could be modified up or down in implementation.

Fig. 2 shows the layout of the slots in a typical cable system. Multiple slots on both the inbound and outbound channels indicate that "a" > 1 thus interleaving is in use.

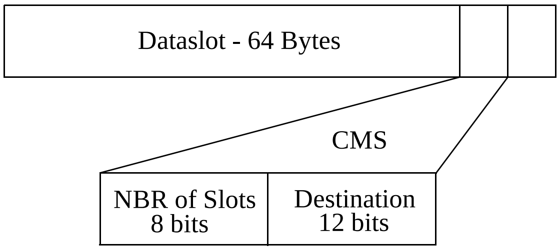

Figure 1 XDQRAP - Dataslot and Control Minislots

Fig. 2 could also represent an asymmetric system. For instance the inbound channel could be 2.048 Mbps and the outbound channel could be 10.240 Mbps. The outbound channel is in a state of continuous transmission thus there are no constraints on the size or form of the packets - all that is required is that the control and feedback information be inserted at the proper intervals.

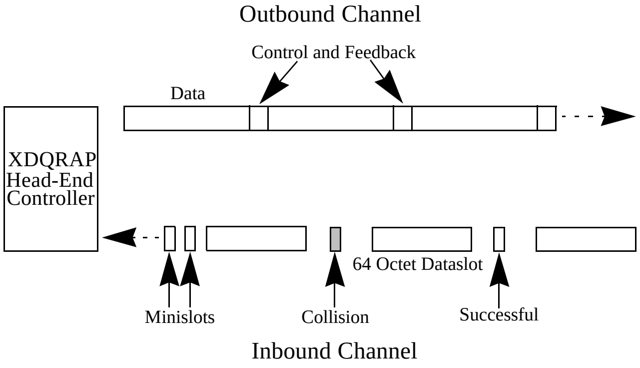

Figure 2 Dataslots and Control Minislots in Context of Inbound and Outbound Channel

A 64-octet data slot increases the assembly delay for voice packets to eight milliseconds from the six milliseconds of the ATM cell but this two millisecond increase is more than offset by the advantages of accommodating a minimum size IEEE 802.3 frame or TCP/IP/PPP frame with a reasonable amount of payload.

Some readers will note that Figs. 1 and 2 show two control minislots. What happened to the argument presented above that three control minislots are required to support a throughput of one in the dataslots? Remember that we pointed out that two control minislots provide for a throughput of 2/e (75%) in the dataslots. This means that if the average reservation request in XDQRAP is for 100/75 = 4/3 slots or higher, then the dataslots will be 100% utilized and so two control minislots will do the job.

III. SIMULATION

The operation of XDQRAP was simulated using Watcom "C" for a variety of loads, mix of traffic, and values of "a". In common with other protocols XDQRAP accommodates values of "a" > 1 by utilizing interleaving, i.e., establishing a frame of size equal to or greater than 2a + 1 and then subdividing the frame into slots. Simulations were run with interleaving factors of 1, 5, and 20, two packet sizes, and two mixes of traffic. The simulation followed the rules of XDQRAP by running a pure reservation system. Two packet sizes were used: one slot and 30 slots. The priority feature of PDQRAP [12] was utilized to assign a high priority to all single slot messages. The priority feature employs two transmission queues, a high priority queue and a normal priority queue. Data is always transmitted from the high priority queue before any transmission of waiting segments on the normal priority queue. In most priority systems short messages of high priority still must wait till long messages of normal priority finish transmitting. The priority feature in XDQRAP allows a high priority message to preempt the ongoing transmission of a normal priority multislot message. This, as we shall see, ensures great performance for high priority messages. The values for delay include service time for the messages.

Tables I (a), (b), and (c) show the delay for interleaving factors of 1, 5, and 20 respectively for an offered traffic consisting of 50% high priority messages of one slot length and 50% normal priority messages of length 30 slots (1920 octets). This represents typical bimodal traffic where for each longer message transmitted there is a short acknowledgment. Tables II (a), (b), and (c) show the results when 90% of the offered messages are high priority single slot messages and the remaining 10% consists of 30-slot messages. Table II results represent the situation where the short messages could also include requests for various interactive services and possibly even ongoing phone conversations using a "transmit only when sound is present" scheme

Tables I and II present delay in terms of slots but these results can be used to determine the actual delay that would be encountered in real cable systems. We stated that interleaving is necessary when the propagation delay for a round trip from the most distant station to a central point exceeds the length of the slot. In practical terms this means that XDQRAP with an interleaving factor of 1 will support

Table I (a) 50%/50% Combination, Interleave Factor= 1

Load	Delay (in Slots)		
	High	Normal	Average
0.10	2.51	33.41	18.10
0.20	2.51	35.26	19.01
0.30	2.52	38.01	20.10
0.40	2.54	41.71	22.08
0.50	2.54	46.58	24.60
0.60	2.55	54.53	28.42
0.70	2.56	66.08	34.38
0.80	2.56	95.64	49.41
0.90	2.58	192.29	97.70
0.95	2.59	306.16	154.01

Table I (b) 50%/50% Combination, Interleave Factor= 5

Load	Delay (in Slots)		
	High	Normal	Average
0.10	6.55	37.42	22.12
0.20	6.54	39.30	23.04
0.30	6.60	42.08	24.17
0.40	6.62	45.80	26.17
0.50	6.64	50.68	28.70
0.60	6.69	58.70	32.57
0.70	6.72	70.24	38.54
0.80	6.75	99.89	53.63
0.90	6.83	196.49	101.93
0.95	6.84	310.54	158.33

Table I (c) 50/50 Combination, Interleave Factor=20

Load	Delay (in Slots)		
	High	Normal	Average
0.10	21.70	52.45	37.21
0.20	21.64	54.39	38.14
0.30	21.82	57.40	39.45
0.40	22.00	61.13	41.52
0.50	22.23	66.16	44.23
0.60	22.23	74.30	48.14
0.70	22.42	85.94	54.24
0.80	22.42	115.63	69.33
0.90	22.74	212.34	117.81
0.95	22.84	326.35	174.23

Table II (a) 90%/10% Combination, Interleave Factor= 1

Load	Delay (in Slots)		
	High	Normal	Average
0.10	2.55	33.66	5.70
0.20	2.58	35.86	5.90
0.30	2.62	38.99	6.21
0.40	2.67	43.16	6.69
0.50	2.72	48.73	7.32
0.60	2.76	56.76	8.16
0.70	2.81	68.96	9.45
0.80	2.87	96.49	12.23
0.90	2.93	199.16	22.64
0.95	2.98	303.26	32.88

Table II (b) 90%/10% Combination, InterleaveFactor= 5

Load	Delay (in Slots)		
	High	Normal	Average
0.10	6.65	37.72	9.81
0.20	6.79	40.04	10.10
0.30	6.91	43.23	10.49
0.40	7.07	47.58	11.09
0.50	7.23	53.19	11.83
0.60	7.36	61.37	12.76
0.70	7.49	73.62	14.12
0.80	7.69	101.23	17.04
0.90	7.85	204.27	27.57
0.95	7.91	308.45	37.84

Table II (c) 90/10 Combination, Interleave Factor=20

Load	Delay (in Slots)		
	High	Normal	Average
0.10	22.04	53.14	25.19
0.20	22.50	55.90	25.82
0.30	23.01	59.35	26.59
0.40	23.60	64.04	27.61
0.50	24.21	70.02	28.79
0.60	24.67	78.75	30.08
0.70	25.13	91.40	31.78
0.80	25.77	119.62	35.16
0.90	26.42	224.12	46.27
0.95	26.65	326.89	56.55

a system operating at 2.048 Mbps over a radius of 20 Km. This result is obtained by calculating the transmission time of a 64 octet slot (250 microseconds) and dividing by the propagation delay in cable (approximately 5 microseconds/km) to obtain 50 km. Divide by two and reduce by 20% to allow for buffering and we get 20 Km.

Similar calculations show that a 10.24 Mbps system utilizing an interleaving factor of 20 could serve an area of 80 Km radius. The IEEE 802.x Cable TV Protocol Study Group has stated that the final protocol must serve an area of radius 80 Km.

The throughput of XDQRAP is equal to the offered load up to an offered load of one and thence remains at one. Thus the delay characteristics of Tables I and II suffice to describe the performance of XDQRAP. Table I shows that the delay for the high priority traffic is reasonably constant at approximately 2.5 slots for all offered loads. This corresponds to an average delay of slightly under 650 microseconds in a 20 Km system. The average delay in our 20 Km system for the 30 slot transmissions ranges from 8.3 ms at a load of 0.10 to 76.3 ms at a load of 0.95.

Now let us look at the delay for a 10.24 Mbps system operating over 80 Km. The theoretical interleaving requirement is 80*5/51.2 = 15.6 but we increase this to 20 to satisfy practical requirements. Table I (c) indicates that the delay for the high priority transmissions of one slot length are less than 23 slots, under 1.2 ms. And this over the entire range of offered loads. When the percentage of short messages is increased to 90% the delay at 0.95 load as shown in Table II (c) is 26.65 slots which is still under 1.4 ms. The normal priority messages of 30 slots length experience delays ranging from 2.7 ms at a load of 0.10 to approximately 16 ms at a load of 0.95 in both Tables I (c) and II (c).

IV. DISCUSSION OF SIMULATION RESULTS

The delays of the high priority messages do not change appreciably over the entire offered load. This is due to two factors: (a) the efficiency of the priority mechanism, and (b) the fact that even at an offered load of 0.95 the arrival rate of the short messages represents less than 3% of the total capacity at a 0.5/0.5 split of traffic. In XDQRAP it is the traffic offered to the control minislots in the form of requests, not the amount of offered data, that most affects the performance. Even with a 0.9/0.1 split of traffic the short messages still represent under 12% of available slots at a total load of 0.95. We will encounter the 2/e barrier discussed in Section II with a split of 0.98/0.02 for single slot messages and 30-slot messages at an offered load of one. This is unlikely in practice since even with a 64-octet slot there will be sufficient short messages of two or three slots in length to lower the request rate below 2/e. However it is a matter for further study and simulation.

V. IMPLEMENTATION CONSIDERATIONS

In Section I we emphasized that DQRAP (and of course XDQRAP) is based upon the ability of a receiver to detect a collision in a control minislot. In a digital WAN environment using DS0, DS1, etc., the simultaneous arrival of two bits at two inputs of a logic gate is easily identified as a collision. The task is not much more difficult in some baseband environments, including fiber, where the power budget can be used to establish equal signal strength for arriving signals. In both these cases the overhead for a 64-octet slot will be 2 x 20 = 40 bits as shown in Fig. 1. By coincidence this is equivalent to the five octets overhead of an ATM cell thus XDQRAP in a digital environment will require no more overhead than ATM and yet eliminates the adaptation layer.

Community networking will in all likelihood, at least for the next two or three decades, utilize a hybrid fiber/coax plant similar to that shown in Fig. 3. Detecting a collision in the rf environment of the coax used in the last mile is more challenging. We will not address the technical details but instead make general arguments about the amount of overhead that will permit the task to be accomplished.

In DQRAP it must be remembered that the control minislots carry no intelligible information. This means that conventional preamble, synchronizing, etc., are not required. This has been addressed in [14] where a scheme of assigning each station a unique pattern such that the overlapping of two or more of the patterns is discernible thus enabling collision detection. This scheme can be implemented with the equivalent of approximately double the number of bits. Thus in DQRAP three minislots each consisting of the equivalent of a 12 bit pattern plus say 5 bits for guard band will occupy 2 x 3 x (12 + 5) = 102 bits. Let us be conservative and round this up to the equivalent of 128 bits or 16 octets for an overhead factor of 16/(16+64) = 20%. A not onerous figure given the performance available with DQRAP.

In XDQRAP the same mechanism could be used to arrive at total overhead of 2 x 2 x (20 + 5) = 100 bits. Again we round up to 16 octets. However there is a fundamental difference in the use of the control minislots in XDQRAP. At the basic request level it is still required that a collision be detected in a minislot. However, if there is no collision there is information in each minislot that must reach all stations, i.e., an address and a count. This and the fact that only two minislots are required presents the option that the control minislots utilize conventional frame transmission techniques with preamble, sync, etc. Assuming a forty bit overhead for the conventional overhead including probably a 6 bit CRC then we arrive at an overhead of 2 x (20 + 40) = 120 bits or 16 octets. The detection in a cable environment of the arrival of two or more such minislots will be detected by the presence of rf, failure of CRC, etc.

If we assume the equivalent of a 16 octet overhead for a data slot then to net 2.048 Mbps the bit transmission rate must be 2.560 Mbps. The authors argue that even if the requirement turned out to be higher a careful comparison with all alternatives will show XDQRAP to be the optimum choice.

Fig. 3 shows another feature of the recommended deployment of XDQRAP. We recommend serving each cluster of homes with a unique XDQRAP channel. This means that at the head-end of the cable plant there will be a system of N XDQRAP controllers, one for each cluster of homes. The individual XDQRAP channel for a cluster of homes would be carried to a regional hub it one was being used.

VI. XDQRAP IN A COMMUNITY NETWORK

XDQRAP supports the same applications as does DQRAP as described in [3]. The highlights are presented.

A. Video-on-Demand

VOD is probably the most discussed potential application for a community network. VOD is the ultimate in an asymmetrical application and XDQRAP is ideal for the support of this service. Aside from using XDQRAP in the last mile the authors also propose that XDQRAP be utilized in a backbone that connects cable system XDQRAP channels to hundreds or even thousands of low-cost VOD storage devices as shown in Fig. 3. Delivering compressed digital video via what is effectively a LAN allows VBR (variable bit rate) compression to be fully utilized thus improving the quality of the received video for a given average transfer rate.

B. Information/Message Systems

The numbers of subscribers to Prodigy, Compuserve, and the multitude of database/message servers now in operation, plus professors, students, and workers calling in via modem to their place of work or study or to access the Internet is probably in the five million range and increasing rapidly. All are potential customers for what would be the equivalent of an economical 2 - 10 Mbps LAN service. FAX service at these rates will prove very attractive.

C. Synchronous Service

DQRAP is unique amongst contention-based random access protocols in that synchronous channels are supported. The network manager, on request, will inform all stations that a repeating slot is removed from contention. This slot, allocated to the requesting station, will support a

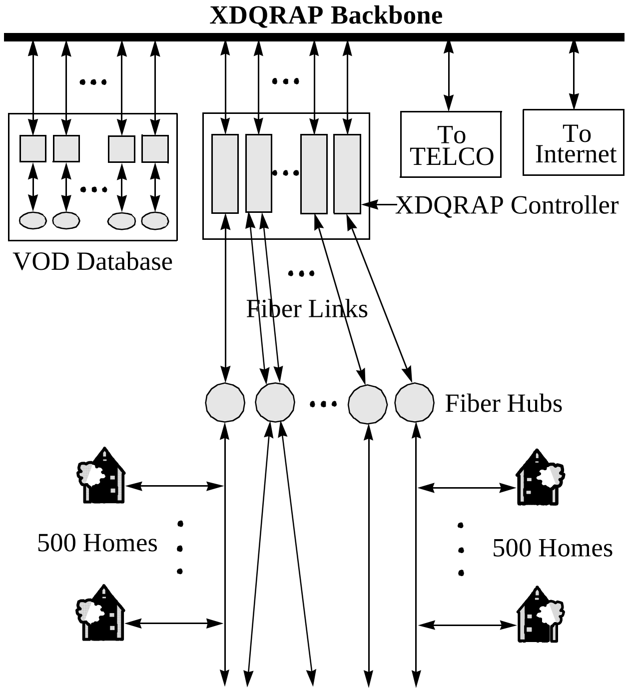

Figure 3 XDQRAP in a Fiber-Coax Community Network

synchronous channel at DS0, DS1, or any speed up to the capacity of the channel.

This synchronous capability means that a community network utilizing DQRAP can provide services equivalent to conventional phone system digital channels. This, however, would for all practical purposes be replicating the switched system in what is a natural multi-access environment. The next section presents a better way of getting the job done.

D. Mixed Voice/Data

One of the more exciting of the potential applications that has been investigated by the DQRAP Research Group at IIT is the support of voice packet transmission. It has been known for years that the active period on voice channels is around 40% or less [16]. However, very little has been done to take advantage of this phenomenon. The reason of course is that, as discussed in section I, an effective multiple access protocol was not available. Research by Lin and Campbell [13] indicates that a common broadcast channel operating under DQRAP requires approximately 16 Kbps capacity per voice channel.

The strict synchronicity required to transmit voice is somewhat relaxed when using voice packets but a problem could still arise when mixing voice and data packets. At high offered loads the voice packets could be delayed by the typically longer data packets. The solution is the priority scheme previously discussed. Table II (c) shows the results of what could be described as a mixed voice/data system where the voice packets are assigned high priority. As discussed previously the average delay of what would be a voice packet at 0.95 load is under 1.5 ms. Comments on the advantages of a packet based voice system are presented in [3]. One of the conclusions reached by the authors in that article is that the efficiency of DQRAP would result in minimal usage of resources by the voice circuits (the voice packets would be transparent to the system) thus a cable company, if it so desired, could offer "free" phone service in the local community area without being subject to charges of cross-subsidization.

V. CONCLUSIONS

RBOCs such as Bell Atlantic, Pacific Telesis, and Ameritech have recently announced plans to rebuild their physical plant such that POTS (plain old telephone service) would be provided, along with conventional TV service, VOD, etc., by means of a hybrid fiber-coax plant. This adaptation of a shared physical medium, coax, to provide communication services to residences offers a great opportunity to extend the dominance of the LAN approach of moving data in the campus environment to an equal dominance for the transmission of both voice and data in the community.

We showed in Section I that there until now there was no suitable multiple access protocol for any network where "a" > 1. But for those networks where "a" < 0.5 random access protocols such as CSMA/CD and Token Ring [2] totally dominate the market for movement of data. The availability of XDQRAP for a community network, certainly an "a" > 1 environment, means that advantage can be taken of the efficiencies of statistical multiplexing of offered data and voice in the community environment. We include voice since it is possibly the most "bursty" of all forms of data. The economies of transmitting voice only when there is sound was not feasible in the all analog world of telephony till the arrival of digital telephony in the 1960s. It was still not feasible for the next 30 years because of the lack of a protocol that supported the efficient sharing of a common access physical medium. DQRAP removes that obstacle. The already announced plans described above to utilize a shared coax cable to provide communications to the community mean that all the pieces are in place to complete the process started by the use of LANs in the office environment and to move to a system where all traffic moves in packets. Unlike ATM, DQRAP/XDQRAP supports packet "collection" at the edge of the web as well as supporting packet switching inside the web.

We conclude by once again stating that XDQRAP provides a throughput equal to the offered load up to an offered traffic of one and with lesser delay than any other multiple access protocol. XDQRAP, operating as the functional equivalent of a distributed switch, supports the transmission of variable length packets without the need of an adaptation layer. XDQRAP supports the synchronous circuits that will be utilized in the transitional period before packet communications becomes dominant. Any plan for community networking should start with the assumption that (a) random access will be the basis of operation for the network, not synchronous FDM/TDM, and, (b) XDQRAP will be the multiple access protocol used at the MAC layer .

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