Design and Evaluation of an Adaptive Data Link Control Protocol for Wireless ATM Networks[*]

Ricardo J. Sánchez, Fadi F. Wahhab,
Joseph B. Evans, Victor S. Frost and Gary J. Minden
{rsanchez, wahhab, evans, frost, gminden}@ittc.ukans.edu
Information and Telecommunications Technology Center
Department of Electrical Engineering & Computer Science
The University of Kansas
Lawrence, KS 66045-2228

To appear on proceedings of GLOBECOM '98, Sydney, Australia, November 1998

Abstract – This paper describes the design of an adaptive data link control (DLC) protocol for wireless ATM networks and measures its performance in a locally deployed testbed implemented by the *RDRN* ***(Rapidly Deployable Radio Network) project. Our DLC protocol provides quality of service (QoS) support for ATM-based virtual connections by distinguishing between delay-sensitive and loss-sensitive traffic over the wireless portion of the network. Delay-sensitive traffic that is received with errors is dropped while loss-sensitive traffic that is lost or received with errors is selectively retransmitted using a go-back-N ARQ scheme. To overcome the unreliability of a wireless link, the DLC protocol exploits adaptation techniques that utilize channel state information to maximize the performance of individual connections. Our experiments shows that the adaptive data link control protocol under consideration is more robust at dealing with lossy wireless links than its non-adaptive counterpart version; we have achieved TCP/IP throughput speedups of up to 4 times in our adaptive protocol implementation for virtual connections established over both delay-sensitive and loss-sensitive channels across impaired wireless links.***

1 Introduction

Growing demand for ATM-based technology and recent proliferation of wireless access technologies have motivated researchers to examine the feasibility of extending the ATM paradigm from the wireline to the wireless domain and create a new research area known as Wireless ATM (WATM) [Toh97]. Dealing with lossy wireless links, characterized by limited bandwidth and high, bursty error rates, breaks the main assumption of conventional ATM systems which is that of using *no-errors* fiber links. Therefore, WATM systems must provide a transparent mechanism to ensure reliable end-to-end data transmission over the wireless portion of the network. We identify a wireless-specific data link control (W-DLC) layer, sitting between the traditional ATM layer and a wireless-specific medium access control (W-MAC) layer, as the responsible entity for guaranteeing the quality of service (QOS) requested by individual ATM-based virtual connections . Further, we claim that smart (adaptive) DLC protocol operations are key to making over-the-air data transmission more resilient to the dynamics of the wireless channels. Our focus is thus to explore the benefits of adaptive techniques in DLC protocol design for Wireless ATM network systems.

In particular, this paper describes the design and evaluation of the adaptive data link control protocol im-

---

[*] This work is partially funded by ARPA contract number J-FBI-94-223 and Sprint under contract CK5007715.

plemented for the Rapidly Deployable Radio Network (RDRN) project. The goal of the RDRN project [S$^+$97] is to develop an adaptive high speed ATM-based wireless communication system that is mobile capable, rapidly deployable, easily reconfigurable, and seamlessly integrated to end-to-end ATM LANs and WANs. The two key features of our W-DLC protocol are:

1. Data link level support for ATM services like available bit-rate (ABR) data, constant bit-rate (CBR) voice, and variable bit-rate (VBR) video traffic by implementing two link-level traffic classes that enable delay-sensitive and loss-sensitive W-DLC protocol operation. Retransmissions are only required for loss-sensitive traffic and are implemented using a *go-back-N* automatic-repeat-request (ARQ) scheme.

2. State-based adaptive W-DLC protocol operation that utilizes current channel conditions to maximize performance of individual connections across impaired (lossy) radio links. Delay-sensitive traffic is optimized by dynamically varying the length (i.e., number of ATM cells) of the wireless ATM (WATM) frame. Loss sensitive traffic, on the other hand, is optimized by combining the adaptive WATM frame length scheme with the amount of error control provided by an N-copy scheme.

The rest of the paper is organized as follows. In Section 2, we discuss relevant related work. The design of our adaptive W-DLC protocol is presented in Section 3. Section 4 reports the results obtained from our experimental testbed and provides a discussion of issues related to our DLC protocol implementation. Finally, in Section 5 we present our conclusions and provide suggestions for future work.

2 Related Work

Several data link control (DLC) protocol procedures have been proposed to provide reliable data transmissions over impaired radio links. A common theme present in all the proposals is the use of error detection with retransmissions for link level error recovery. Specifically, almost all of them use automatic-repeat-request (ARQ) with selective repeat mechanisms supplemented by forward error correction (FEC) coding schemes. Early proposals, such as the Radio Link Protocol (RLP) [N$^+$94] and AIRMAIL [A$^+$95], provided the basic principles to design DLC protocols in former cellular wireless networks. Recent approaches targeting DLC protocol design for Wireless ATM networks are found in [A$^+$96][E$^+$95][PA95][X$^+$95]. In all these approaches the main focus is on the reliability aspects of the protocol in question. However, they all fail to address the performance aspects of the protocol when operating over lossy links. Wireless channels are usually time-varying and the channel bit error rates vary as the surrounding environment changes. Since these factors put in jeopardy the performance of the DLC protocol (and higher layer end-to-end protocols at large), additional link-level mechanisms are required for improving the performance while still providing reliability over impaired radio links.

In [CI97], it is pointed out that errors in the wireless channel significantly affect the performance of end-to-end protocols (like TCP) mainly because of the losses over the radio link. This observation motivated the design and implementation of the snoop protocol [B$^+$95] which indeed improved the performance of TCP connections on networks with wireless links. However, the snoop scheme requires the use of transport-level hints to detect losses plus modifications to the IP layer at the base station to perform local retransmission across the wireless link.

Is it possible to provide reliable transmission and optimal performance across wireless links by using a link layer protocol? Can this protocol operate independently of higher layer protocols and make decisions to adapt its behavior based on the current state of the wireless channel? We believe the answer is yes and that our W-DLC implementation represents an attempt to achieve these goals under the strict constraints imposed by impaired wireless links.

3 Adaptive DLC Protocol Design

Figure 1 shows the protocol stack organization in the RDRN architecture. The adaptive wireless-specific data link control (W-DLC) layer is introduced between the wireless-specific medium access control (W-MAC) layer and the ATM layer. ATM cells to be transmitted over the air are passed to the W-DLC layer and then encapsulated within a WATM frame. Figure 2 shows the structure of a WATM frame in the RDRN architecture. Basically, a WATM frame contains one or more standard ATM cells and/or special (e.g., W-MAC level or W-DLC level) control information. The W-DLC protocol allows standard ATM QOS requirements to be extended over the wireless portion of the network by distinguishing between VCs carrying delay-sensitive traffic like voice and video from those carrying loss-sensitive traffic like data. ATM cells from multiple VCs are allowed to be encapsulated in the same WATM frame as long as they belong to the same W-DLC traffic category. WATM frames carrying delay-sensitive traffic are dropped when received with errors while WATM frames carrying loss-sensitive traffic are retransmitted when lost or received with errors. Retransmissions are implemented using an sliding window and a go-back-N automatic-repeat-request (ARQ) scheme that guarantee in-order delivery of ATM cells to the upper ATM layer at the receiver.

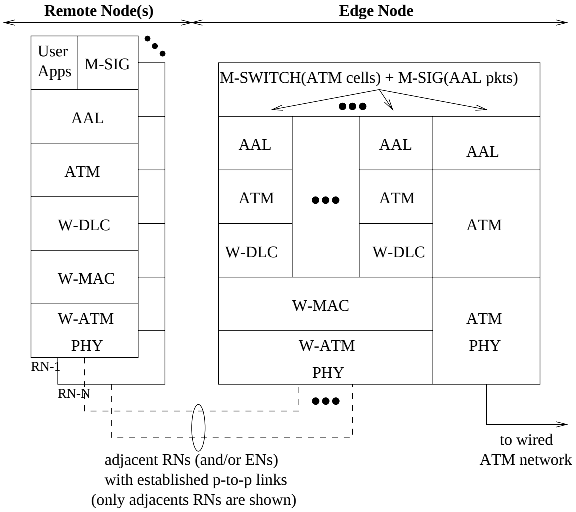

Figure 1: RDRN Protocol Stack Architecture

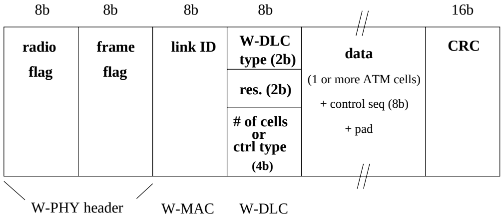

Figure 2: Wireless ATM Frame Format

The novel feature of the W-DLC protocol is the adaptive control it provides. By using a two-state channel model, the wireless channel is treated as a link with either a high bit error rate (HBER) or a low bit error rate (LBER). The objective is to estimate the right state of the wireless channel to adapt the operation (and parameters) of the W-DLC protocol accordingly. For example, when the channel is in the LBER state, the throughput can be maximized by encapsulating several ATM cells in each WATM frame. However, when the channel is in the HBER state, most WATM frames are received in error; hence, it is best to encapsulate fewer ATM cells. Also, retransmissions in the HBER state can be reduced by transmitting more than one copy of each frame at a time. In our design, the wireless channel state is estimated at the receiver based on the ratio of the number of WATM frames received with and without errors. This state information is then communicated back to the transmitter which adapts accordingly to the prevailing link conditions.

3.1 W-DLC Frame Types

There are three types of W-DLC frames: information frames, supervisory frames, and unnumbered frames. The essence for W-DLC frame operation is derived from the HDLC protocol [Sca88].

Information frames (IF) contain data to be transmitted as encapsulated ATM cells. Two types of IF frames are used: one for delay-sensitive traffic (DS) and another for loss-sensitive traffic (LS). Sequence numbers are maintained for LS frames. N(S) is the sender's sequence number for each transmitted frame. N(R) is the receive sequence number and denotes the sequence number of the next expected received frame. N(R) thus serves to acknowledge all received frames up to N(R)-1.

Supervisory frames (SF) provide link control functionality such as acknowledging or requesting retransmission of IF frames. Two types of SF frames are used: the RR (Receive Ready) frame and the REJ (Reject) frame. The RR frame is used to acknowledge properly reception of up to N(R)-1 IF frames and to indicate the ability to receive more IF frames. The REJ frame is sent when frames are received out of sequence at the receiver and is used to request retransmission of IF frames starting with frame N(R). Any frames that were sent with a sequence number of N(R)-1 or less are implicitly acknowledged. The reject condition is cleared by the proper reception of IF frames up to the IF frame that caused the reject condition to be initiated.

Unnumbered frames (UF) allow exchange of additional control information beyond what is accomplished with SF frames. Three types of UF frames are used: link activity frames (LA), reset frames (RES), and unnumbered acknowledgement frames (UA). LA frames are sent when there is no traffic observed on the link for a certain period of time. They are used to elicit a response from the node at the other end of the link and to determine if the link is indeed still up. The RES frame is sent when a frame is received with a receive sequence number outside the sending window and is used to recover from such an abnormal operating condition. The receipt of an RES frame forces the remote end to reset its state since peer W-DLC layers must be synchronized. This synchronization takes place when an UA frame is received from the peer end confirming that it has also reset its state.

3.2 Wireless Channel State Estimation

The interesting aspect of the W-DLC protocol is its ability to adapt the frame length and retransmission mechanism based on the wireless channel conditions. This requires an estimate of the wireless channel conditions at frequent intervals.

The estimation method is based on a ratio of the total number of frames received without errors to the total number of frames received with errors during a given time period. Since the channel is slowly varying, we used an estimation interval over which the channel state is assumed to remain unchanged. The ratio number is computed at the end of each estimation interval. The computed ratio is compared against computed upper and lower bound error thresholds. Using these two threshold values in the estimation process prevent the estimated state to continuously oscillate between the HBER (i.e., good) and LBER (bad) states.

3.3 Adaptive Frame Length

The design of the wireless frame format allows for a variable number of ATM cells to be encapsulated within each frame. Ideally, encapsulating a larger number of cells in each frame would yield an increase in data throughput. However, considering that random and independent bit errors are present in the LBER state, an increase in frame length causes an increase in frame error rate for a give bit error rate. Hence, a higher frame error rate yields lower throughput. We believe that there is an optimal frame length that yields the best throughput under given conditions in wireless links. This procedure requires computation of the optimal frame length for the LBER and the HBER state in a way similar to the slow-start TCP/IP algorithm [Ste94]. This implies the use of different frame lengths for the LBER and the HBER state.

3.4 Pre-emptive Retransmissions

For loss-sensitive traffic, it is possible that a frame may need to be retransmitted more than once due to a high error condition in the wireless channel. The pre-emptive retransmission or *N-copy* scheme is an attempt to reduce the number of such occurances. The basic idea is to send multiple successive copies of each frame at each transmission and retransmission instead of just one copy as in normal *go-back-N*, with the hope that at least one of these copies is received error-free. This may reduce the number of retransmission requests, especially for entire windows of frames, and yield an increase in data throughput. However, the use of such an scheme is advised only in the HBER state since in the LBER state the extra overhead (due to the multiple redundant copies) may reduce the effective throughput. The computation of the optimal value of N for the LBER state is indeed a hard problem; however, we provide estimates through a series of experiments in the next section.

4 Results and Analysis

4.1 Experimental Setup

This section presents a performance evaluation of the W-DLC protocol implemented in a real RDRN testbed. The configuration used for all the experiments is shown in Figure 3. The testbed includes Toshiba Tecra laptops running Linux with extensions for ATM and WATM support. The setup involves a combination of wired ATM-based OC-3 technology (maximum nominal speed = 155 Mb/s) and beamforming antenna technology for the wireless link [S^{+}97] (maximum nominal speed = 1 Mb/s). Each experiment involves traffic flowing from the RDRN fixed node (FN) to the RDRN remote node (RN) across the RDRN edge node (EN). A single virtual circuit was setup between the FN and the RN with specific QOS parameters as required for the experiment in question. The EN and RN were positioned very closed to ensure an error-free wireless link. In order to control the bit error rates introduced in the wireless channel a random bit error rate generator was instrumented at the link level prior to transmission to the W-MAC layer. A modified version of the *ttcp* program was used to compute average throughput where needed. For the purposes of this study, it is assumed that a channel BER of 10^{-5} or lower means that the channel is in the good state (i.e., LBER) while a BER higher than 10^{-5} denotes a bad state (i.e., HBER).

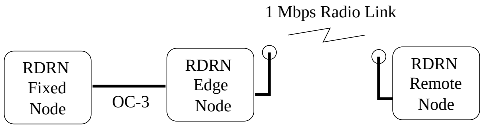

Figure 3: Experimental Setup

4.2 Effect of Adaptive Frame Lengths on N_Copy Mechanism on Throughput

In Figure 4, we plotted end-to-end TCP throughput performance versus WATM frame size for delay-sensitive traffic under different bit error rate conditions. It can be seen that the optimal frame size for the ideal case (i.e., no errors) is very high and approximates a maximum attainable throughput of 0.9 Mb/s as expected. On the other hand, for a BER equals to 10^{-5}, a maximum throughput is achieved at 9 cells per frame. As the number of encapsulated cell increase, the effect of the frame overhead decreases yielding an increase in throughput. However, as the frame size becomes larger the resulting frame error rate also increases and this has an adverse impact on the throughput. A similar reasoning applies to the case when BER equals 10^{-4} and the results are plotted in Figure 5. As the figure shows the maximum throughput is obtained with a frame size of 6 cells per frame with a big decrease in throughput for larger sizes. Similar experiments were done for the loss-sensitive traffic and the results are shown in Figure 5. Note that the optimal frame size numbers are lower than for the delay-sensitive case. This is due to the retransmissions performed for this operation mode. All these results indicate that the performance of data transport over lossy links can be achieved by adapting the frame length to its optimal value.

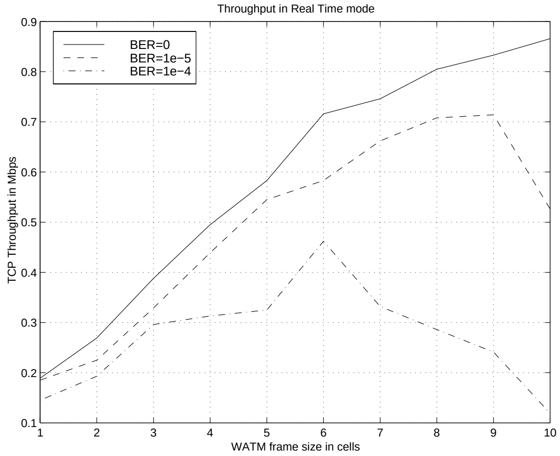

Figure 4: Delay-sensitive Traffic: TCP Throughput vs. WATM frame size

Having determined the optimal frame sizes in the good and bad states, we now evaluate the effect of adapting the frame size to the current channel state. For the purpose of these experiments we assume a BER of 10^{-5} in the good state and a BER of 10^{-4} in the bad state. By using the estimated optimal frame size for each state, we use a frame size of 9 cells per frame in the good state and a frame size of 6 cells per frame in the bad state for delay sensitive traffic. In each of the following experiments, the BER is varied between 10^{-5} and 10^{-4} once every 10 seconds.

The plot in Figure 6 shows the variation of throughput versus time as the error rate changes with and without any frame length adaptation for the delay-sensitive traffic. The throughput is measured every second over the duration of the test. Region A and C of Figure 6 correspond

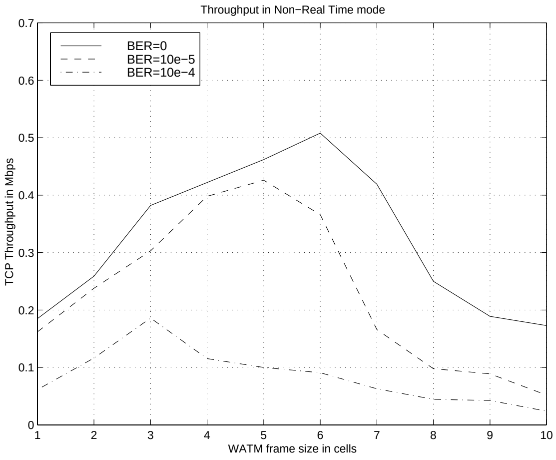

Figure 5: Loss-sensitive Traffic: TCP Throughput vs. WATM frame size

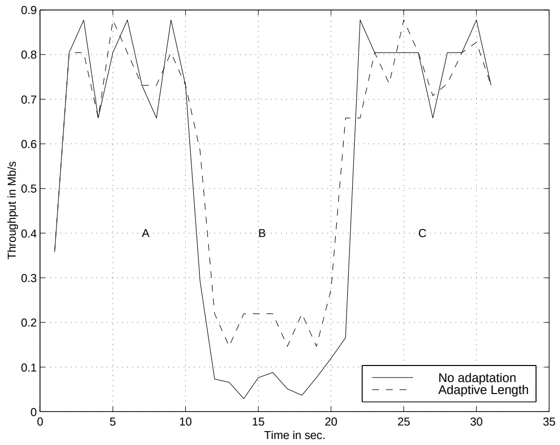

Figure 6: Throughput Adaptation in delay-sensitive traffic

to the good state while region B corresponds to the bad state. Note the increase in performance in region B for the adaptive length case: as much as twice the throughput without adaptation. Similar experiments were conducted for the loss-sensitive case. The results are shown in Figure 7 with no adaptation, adaptive length, n_copy ($n = 2, 3$), and a combination of n_copy ($n = 2$) and adaptive length. Note that the 3-copy mechanism clearly delivers the best performance in region B in all cases: as much as 4 times throughput speedup compared to the non-adaptive case. In all cases, it can be seen that the adaptive mechanisms offer no noticeable improvements when the channel state is good (region A and C) compared to the non-adaptive case.

5 Conclusions and Future Work

This paper described the design and evaluation of an adaptive data link control protocol for wireless ATM networks. The protocol handles error recovery and control over the wireless channel and provides the ATM layer with a more reliable transport medium. It provides a delay-sensitive and a loss-sensitive operation mode to facilitate the extension of standard ATM QOS parameters over the wireless portion of the network. A simple channel state estimation algorithm is also implemented at the data link level. The channel estimation algorithm is used to adapt the DLC protocol operation to current channel conditions. Our implementation is scalable since requires minimal state information to be maintained at adjacent peers. It also operates independently of higher layer protocols.

Our main contribution is that adaptive DLC protocol operation over the wireless portion of the network can effectively improve the performance of end-to-end protocols under impaired radio links. We have presented results to evaluate the benefits of our ideas and the feasibility of our implementation. They show that under high bit error rate conditions, adaptive mechanisms such as frame length and *N_copy* can effectively yield an increase in throughput. In particular, experiments with adaptive frame sizes yield 2 times throughput speedup for the delay-sensitive traffic case. On the other hand, experiments with the adaptive N_copy scheme (N = 3) yield as much as 4 times throughput speedup.

The implementation described in this paper should serve as testbed for further work in software controlled adaptive protocols. There is a lot of scope for more work especially in the area of adaptive error control. Various FEC coding schemes can be incorporated, especially for use when the channel is in the good state, thus transforming the protocol to hybrid ARQ as opposed to regular go-back-N.

Another extension to consider is adding sequence numbers to wireless frames carrying delay-sensitive traffic.

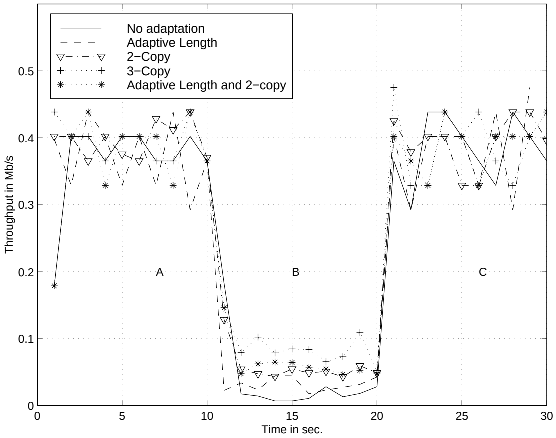

Figure 7: Throughput Adaptation in loss-sensitive traffic

This will enable the N_Copy scheme to be used for this type of traffic since it has been found to deliver the best throughput when the channel is in the bad state.

References

[A$^+$95] E. Ayanoglu et al. AIRMAIL: A Link-Layer Protocol for Wireless Nertworks. *ACM ACM/Baltzer Wireless Networks Journal*, February 1995.

[A$^+$96] Prathima Agrawal et al. SWAN: A Mobile Multimedia Wireless Network. *IEEE Personal Communications*, April 1996.

[B$^+$95] H. Balakrishnan et al. Improving TCP/IP Performance over Wireless Networks. In *Proc. ACM Mobicom ’95*, November 1995.

[CI97] R. Caceres and L. Iftode. Improving the Performance of Reliable Transport Protocols in Mobile Computing Environments. *IEEE Journal on Selected Areas in Communications,* June 1997.

[E$^+$95] K. Y. Eng et al. BAHAMA: A Broadband Ad-Hoc Wireless ATM Local-Area Network. In *Proc. Int’l Conf. on Commun. (ICC ’95)*, June 1995.

[N$^+$94] S. Nanda et al. A Retransmission Scheme for Circuit-Mode Data on Wireless Links. *IEEE Journal on Selected Areas in Communications*, October 1994.

[PA95] D. Petras and A.Hettich. Performance evaluation of the ASR-ARQ Protocol for wireless ATM. In *IEEE Wireless Communications Systems Symposium*, November 1995.

[S$^+$97] R. Sanchez et al. RDRN: A Prototype for a Rapidly Deployable Radio Network. *submitted to Mobile Computing and Communications Review*, November 1997.

[Sca88] E. Scace. Introducing System Description Language for AX.25 and Related Protocols. In *Proceedings of the 7th AARL Amateur Radio Computer Networking Conference*, October 1988.

[Ste94] R. Stevens. *TCP/IP Illustrated: The Protocols*, volume 1. Addison-Wesley Publishing Company, 1994.

[Toh97] C-K Toh. *Wireless ATM and Ad-Hoc Networks: Protocol and Architectures.* Kluwer Academic Publishers, 1997.

[X$^+$95] H. Xie et al. Data Link Control Protocols for Wireless ATM Access Channels. In *International Conference on Universal Personal Communications (ICUPC ’95)*, November 1995.