To be Published in ICC'99 Proceedings

Punctured Convolutional Codes for Supporting PCS Access to ATM Networks

Melbourne Barton
Bellcore
331 Newman Springs Road
Red Bank, NJ 07701-5699, USA
Tel: +1-732-758-3081
Fax: +1-732-758-4372
Email: mbarton@bellcore.com

Abstract— **A personal communications services (PCS) system that provides access to, and interworks with, the ATM network will have the capability to support future multimedia services. PCS access to fixed ATM networks is one of the wireless access scenarios being considered by the ATM Forum for standardization. This paper provides a system level description of a PCS-to-ATM interworking scenario. It proposes a variable-rate forward error correction (FEC) coding scheme for the wireless physical (PHY) layer that is based on rate-compatible punctured convolutional (RCPC) coding. Through numerical analysis, using a two-ray Rayleigh fading channel model, it is shown that RCPC coding at the wireless PHY layer can be effective in providing reliable PCS access to the ATM infrastructure network. RCPC coding at the wireless PHY can be augmented with ARQ at the data link control layer (DLC) to form a hybrid ARQ/FEC protocol.**

1 INTRODUCTION

The current network for supporting personal communications services (PCS) is narrowband integrated services digital network (ISDN), with network intelligence based on advanced intelligent network (AIN), and a signaling system based on signaling system 7 (SS7) network architecture. The core network is expected to evolve to asynchronous transfer mode (ATM) over time, and provide the capability to integrate a wide range of network services onto a single ATM transport network platform. This will eliminate the need for an overlay network for PCS. In anticipation of these developments, international standards bodies such as the ATM Forum are working to develop specifications and requirements to allow PCS systems to provide access to, and interwork with, the ATM infrastructure network. These specifications will facilitate the use of ATM as an efficient and cost-effective infrastructure network for next generation PCS (and other non-ATM and ATM-based wireless access systems).

In this paper, the term PCS is used in a generic sense to mean emerging digital wireless systems that support mobility in microcellular and other network environments. They include: i) low-tier PCS systems described in [1], ii) digital cellular systems, which are becoming known in the United States as high-tier PCS, especially when implemented in the 1.8-1.9 GHz PCS frequency bands, and, iii) cellular radio systems at 800-900 MHz that have evolved to digital in the form of Global System for Mobile Communications (GSM) in Europe, Personal Digital Cellular (PDC) in Japan, and IS-136 (formerly IS-54) Time Division Multiple Access (TDMA) and IS-95 Code Division Multiple Access (CDMA) in the U.S.

Adding PCS mobility support over fixed ATM networks as described in [2], will require effective strategies to manage the changing quality of service (QoS) levels that are inherent in the wireless access environment. For example, error control beyond that which is provided by current ATM standards are likely to be required on the PCS access segment in order to realize reliable communications. Attempts to provide end-to-end QoS performance for a PCS-to-ATM networking system that is similar to that provided for fixed access ATM networks will not be cost effective, and might lead to low spectral efficiencies on the PCS access segment. Instead, we differentiate between multimedia service types, and their QoS requirements, and tailor the level of error protection to the service type requirements, the relative importance of different parts of the wireless protocol data unit (PDU), and the radio channel characteristics.

In this paper, we investigate the performance of a variable-rate, forward error correction (FEC) coding scheme that is based on rate-compatible punctured convolutional (RCPC) coding at the wireless physical (PHY) layer of a PCS system that provides access to an ATM transport network. The rate-compatibility restriction is imposed on the codes to insure that a single encoder/decoder that provides a range of code rates can be implemented at the PCS PHY layer. It is assumed that the multipath fading channel exhibits both Doppler and time delay spread. This work extends results presented in [3] that focus on a single-path Rayleigh fading channel exhibiting Doppler spread. This is the first step towards developing a hybrid automatic repeat request (ARQ)/FEC protocol for error control of the wireless link, with FEC at the PHY supplemented by ARQ at the DLC layer. A comparison of commonly used FEC and ARQ techniques and their potential application to WATM is presented in [4].

The rest of this paper is organized as follows. The PCS-to-ATM system model is presented in Section 2. The RCPC coding concepts is developed in Section 3. Numerical results are presented in Section 4, and conclusions presented in Section 5.

2 PCS-TO-ATM SYSTEM MODEL

A system level architecture to support PCS-to-ATM interworking is described in this section, along with the PHY layer characteristics of the coded PCS access system. In the network architecture shown in Figure 1, the ATM user network interface (UNI) is located at the base station controller (BSC). The BSC acts as the PCS-to-ATM gateway[1]. On the access network side, existing PCS signaling and user data transfer protocols are used, while on the fixed network side, both data and signaling traffic uses the ATM protocol. Communications between the BS and BSC is specific to the PCS access network, and could be a proprietary interface. Compared with existing/emerging PCS systems, additional protocol layer functionality is required in the BSC to provide ATM to PCS PDU conversion, and a limited amount of ATM multiplexing/demultiplexing capabilities.

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[1] If the PCS system does not explicitly support a stand-alone BSC, then the gateway could be moved to the BS.

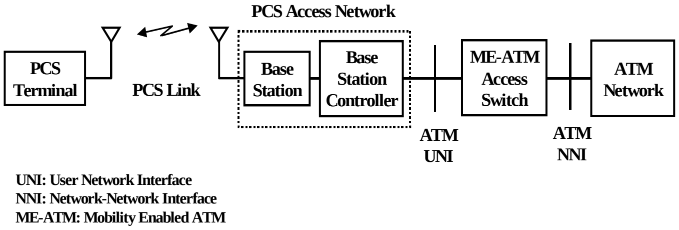

Figure 1. Block diagram of system level architecture to support PCS access to ATM network.

The BSC is connected to the ATM network through a mobility enabled ATM (ME-ATM) access switch which provides switching and signaling protocol functionality to support ATM connections along with mobility and location management functions. The mobility and location management functions could be integrated in the ME-ATM switch or implemented in a server that is physically separate from, but logically connected to, the ME-ATM switch. On the fixed network side, traditional ATM signaling is carried in the control plane (C-Plane), and PCS signaling is carried in the C-Plane, or as user traffic in the user plane (U-Plane).

2.1 PCS Access System

A block diagram of the PHY layer of the PCS access system model is shown in Figure 1. We assume a differential quadrature phase-shit keying (DQPSK) modulator, and a raised cosine transmit filter. The channel is modeled as a two-ray Rayleigh fading channel to approximate the multipath delay spread. The rays are assumed to be two independent complex Gaussian stochastic processes with equal average powers. The propagation delay between the rays is twice the root-mean square (RMS) delay spread. A time division multiple access (TDMA) channel access strategy is assumed. The design goal is to provide enough error protection on the radio access layer (RAL) so that the PCS access link does not unduly impact the end-to-end QoS performance of the PCS-to-ATM interworking system.

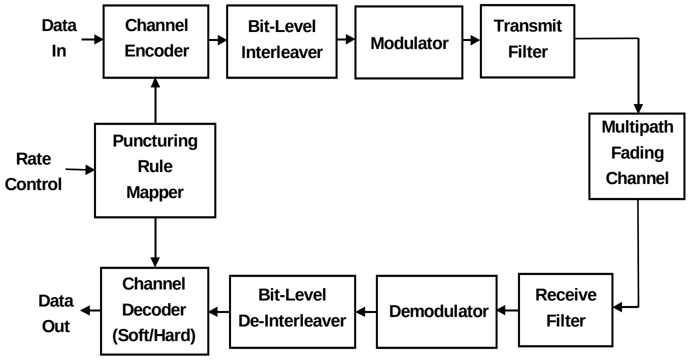

Figure 2. Block diagram of coded PCS access system.

At the receiver, the channel output is demodulated and de-interleaved before being passed to the RCPC channel decoder. An important design problem that is not the focus of this paper concerns implementation of the rate control mechanism for the RCPC encoder, and the method used to provide this information to the decoder. The design should be based on source significant information, the desired level of protection, and the state of the communication channel. The rate adaptation algorithm could be based in part on information that is fed back to the transmitter, using an FEC/ARQ protocol, for example.

The size and structure of the wireless PDU format for over-the-air transmissions should be closely aligned with the fixed ATM network cell format, to minimize incompatibilities between them, and reduce the amount of gateway processing required at the PCS-to-ATM network interface, i.e., the BSC shown in Figure 1. For example, the wireless PDU should include: i) additional error control in the PDU header to prevent mis-routing of cells in the fixed ATM network, ii) a compressed ATM cell header, if required, and iii) a full 48-byte ATM cell information payload (or some sub-multiple thereof), in the PDU information payload.

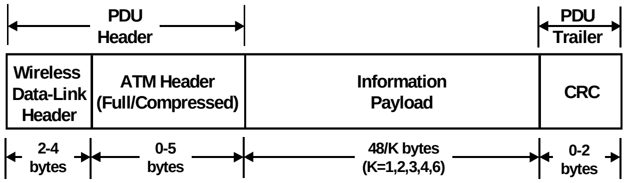

Figure 3. Example of a PCS access system PDU format.

One example of the PCS PDU format is shown in Figure 3. It shows an adjustable-size PDU with: i) a PDU header comprising a 2-4 byte wireless-specific segment and a 0-5 byte compressed (or full) ATM header, ii) a 48/K-byte PDU information payload, where K=1,2,3,4, or 6, and, iii) a 0-2 byte PDU trailer, e.g., a cyclic redundancy (CRC) block. This PDU structure can accommodate a 10- to 59-byte packet containing an 8- to -48-byte information payload. The RCPC code can be used to provide different levels of error protection for the PDU header, information payload, and trailer. Some of the implications on system performance of transmitting a compressed ATM cell header, and minimum functionality that might be defined in the wireless-specific PDU header are discussed in [3].

3 RCPC CODING

One immediate impact of providing PCS access to the fixed ATM infrastructure network is the need to manage the range of QoS that are inherent in a mobile environment. Variability in QoS might be due to the type of multimedia traffic, vagaries of the wireless link, re-routing of traffic due to handoff, and limited channel bandwidths. QoS metrics include: i) throughput, ii) delay sensitivity, iii) loss sensitivity, and, iv) BER performance. Issues relating to end-to-end QoS provisioning in multimedia wireless networks are discussed in [5] and articles therein. Here, the focus is on BER maintenance in the context of PCS-to-ATM interworking using RCPC coding at the radio PHY layer. This type of coding scheme can: i) support a broad range of QoS levels consistent with the requirements of multimedia services, ii) minimize the loss of information on the wireless access segment, and, iii) prevent mis-routing of cells in the fixed ATM network. Code rate puncturing is a procedure used to periodically discard a set of predetermined coded bits from the sequence generated by an encoder for the purposes of constructing a higher rate code. With the rate-compatibility restriction, higher rate codes are embedded in the lower rate codes, allowing for continuous code rate variation within a data frame.

It is assumed that the source encoder provides information about the relative importance, or susceptibility to errors, of certain groups of bits at the input to the RCPC encoder. This information might include the required BER for each block of bits at the output of the decoder. Furthermore, the receiver might also feed back to the transmitter information concerning the state of the channel, e.g., the channel fade rate, signal-to-noise ratio (SNR) (or signal-to-interference-to-noise ratio (SINR)), or delay spread. The RCPC encoder design objective is to find the RCPC code, with code rate *R*, puncturing period *P*, and memory length *M*, which satisfies the target BER for each block of bits associated with the wireless PDU. The design steps are described in [3].

3.1 Performance Analysis

The performance of RCPC codes on a multipath fading channel is difficult to analyze satisfactorily except under certain ideal conditions such as the assumption of infinite interleaving. The theoretical BER performance results that are presented in this paper assume hard and soft decision decoding, and knowledge of the channel state information (CSI). To accommodate soft decision decoding and CSI, a maximum likelihood decoder is required. This is implemented using a Viterbi decoder. The Viterbi upper bound on the decoded BER is given by [6]:

$$P_b \leq \frac{1}{P} \sum_{d=d_f}^{\infty} \beta_d P_d \tag{1}$$

where *P* is the puncturing period, β_d is the weight coefficient of paths having distance *d*, P_d is the probability of selecting the wrong path, and d_f is the free distance of the RCPC code. Tables for determining β_d are presented in [7]. Assuming sufficient interleaving to achieve statistical independence of the data streams at the input to the Viterbi decoder insures that there is no correlation between symbols entering the Viterbi decoder. In this case, the Viterbi decoder performs maximum likelihood decoding based on minimum error probability decoding rules, and only knowledge of the statistics of the demodulated symbols, conditioned on the transmitted symbols, is required in order to compute theoretical performance results.

A. Rayleigh Fading Channel

Closed-form expressions are presented in [3], [7], [8] for P_d, for three combinations of CSI (i.e., Rayleigh distributed channel amplitude), and quantization options for the decision variables at the decoder. In this case the channel is modeled as a correlated Rayleigh fading channel, with a time-varying envelope having a complex Gaussian distribution (and thus its amplitude has a Rayleigh distribution). The mathematical expressions for P_d for hard decision decoding with no CSI available at the receiver, denoted by YHAN, is given by:

$$P_d = \begin{cases} \displaystyle\sum_{j=(d+1)/2}^{d} \binom{d}{j} P_0^{\,j} (1-P_0)^{d-j}, & d \text{ odd} \\ P_{d-1}, & d \text{ even} \end{cases} \tag{2}$$

For an L-diversity-branch Rayleigh fading channel, with fading processes on the *L* branches that are mutually statistically independent, the raw (theoretical) BER on the channel is given by [6]:

$$P_0 = \frac{1}{2}\left[1 - \rho \sum_{k=0}^{L-1} \binom{2k}{k} \left(\frac{1-\rho^2}{4}\right)^k\right]. \tag{3}$$

An approximate expression for the cross-correlation coefficient ρ for the Rayleigh fading channel is [8]

$$\rho = \frac{\mu R_1}{\sqrt{2 - \mu^2 R_1^2}} \tag{4}$$

where

$$\mu = \frac{\gamma_s}{1+\gamma_s}. \tag{5}$$

$R_1 = J_0(2\pi f_D T_s)$ is the normalized correlation coefficient between consecutive samples of the received signal at the output of the channel, γ_s is the average channel SNR per transmitted symbol, f_D is the maximum Doppler frequency, T_s is the symbol interval, and J_0 is the Bessel function of the first kind and zero order. The second combination of CSI and decoding option that is considered is soft decision decoding with no CSI available at the receiver, denoted by YSAN. In this case P_d is given by:

$$P_d = \left(\frac{1-\rho}{2}\right)^{2d-1} \sum_{j=0}^{d-1} \binom{2d-1}{j} \left(\frac{1+\rho}{1-\rho}\right)^j. \tag{6}$$

The third combination of CSI and decoding option that is considered is soft decision decoding with knowledge of the CSI available at the receiver. This is denoted by YSAS. For YSAS, P_d is upper bounded by

$$P_d = \left(\frac{1}{2}\right)\left(\frac{1}{1+\gamma_s}\right)^d. \tag{7}$$

B. Two-Ray Channel Model

The impulse response of a multipath fading channel generally exhibits both Doppler shift and time delay spread. In a digital communication system, delay spread causes intersymbol interference (ISI), and results in an irreducible BER. The extent of the delay spread is usually characterized by the root mean-square (RMS) delay spread τ_{rms}. The channel is modeled as a wide-sense stationary (WSS) uncorrelated scattering Rayleigh fading channel [9]. If the two-ray model is used to approximate the multipath delay spread, then the impulse response of the channel can be written as

$$h(t,\tau) = \beta_0(t)\delta(t) + \beta_1(t)\delta(t-\tau) \tag{8}$$

where the weights $\beta_0(t)$ and $\beta_1(t)$ are two independent complex Gaussian processes with equal average powers, $\delta(\cdot)$ is the Kronecker delta, and the propagation delay $\tau = 2\tau_{rms}$.

The derivation of mathematical expressions for P_d for the two-ray channel model follows the same procedure described above for the single-path Rayleigh fading channel model. Without loss in generality, we assume that $\beta_0(t)$ and $\beta_1(t)$ are approximately constant over the symbol interval T_s. We further assume sufficient interleaving to achieve statistical independence of the data streams at the input to the Viterbi decoder. For DQPSK modulation with Gray code mapping of pairs of input bits into phases, it is easy to show that the expressions for P_d for YHAN, YSAN, and YSAS are of the same form as presented above. However, for the two-ray channel model and a raised cosine transmit pulse shaping filter with impulse response $p(t)$, the expression for μ in (5) is replaced by:

$$\mu = \frac{\alpha_1 \gamma_s}{\sqrt{(1+\alpha_2 \gamma_s)(1+\alpha_3 \gamma)}} \tag{9}$$

where

$$\begin{aligned}\alpha_1 &= 1 + p^2(\tau) + \sum_{k \neq n-1} p(nT_s - kT_s - \tau)\, p(nT_s - kT_s - T_s - \tau) \\ \alpha_2 &= 1 + \sum_{k} p^2(nT_s - kT_s - \tau) \qquad (10) \\ \alpha_3 &= \alpha_2 + 2R_1\, p(\tau)\, p(T_s + \tau)\end{aligned}$$

If $\alpha_2 \approx \alpha_3$, then the average effective SNR is defined to be $\bar{\gamma}_s = \alpha_2\, \gamma_s$.

4 NUMERICAL RESULTS

The PCS access system model shown in Figure 1 is used to obtain the PHY layer performance results for the RCPC coding scheme. The channel is modeled as a two-ray Rayleigh fading channel with a nominal RMS delay spread of 250 ns. The modulation format chosen is DQPSK modulation with Gray coding. The transmit filter is assumed to have a raised cosine spectrum with a 50% roll-off factor. A 2 GHz TDMA-based PCS system is assumed, operating in a microcellular environment, and providing access to an ATM infrastructure network. The frame length is 2 ms, with 8 time slots per frame, and a transmission rate of 512 kbps. The normalized RMS delay spread as $\Delta = \tau_{RMS} / T_s$, where the symbol period for 4-phase modulation is $T_s \approx 4\ \mu\text{s}$. The Jakes model [9] is used to obtain a discrete approximation of the autocorrelation function R_1 of the Rayleigh fading signal. The transmission model assumes perfect symbol and frame synchronization, and perfect frequency tracking.

An example set of three PCS PDU formats that are used in this study are presented in Table 1. They are derived from the PDU structure shown in Figure 3. PDU-3 shows encapsulation of the full 48-byte ATM information payload, along with wireless-specific overhead (and a full/compressed ATM header, if required by the mobile terminal), in the PCS PDU. The other two PDU's (PDU-1 and PDU-2) contain a sub-multiple of a 48-byte ATM information payload, along with wireless-specific overhead, and a compressed ATM header in the PCS PDU. Unless otherwise specified, the target BER for the PDU header and trailer is 10^{-7} or 10^{-9}, and 10^{-3} or 10^{-6} for the PDU information payload, depending on whether voice or data (including video) is transmitted. Associated with the target BER is a design goal of 20 dB for the SNR. The other base parameters are mother code rate $R = 1/3$, puncturing period $P = 8$, and memory length $M = 4 - 6$.

PDU Type	PDU Header (bits)	Information Payload (bits)	PDU Trailer (bits)	PDU Size (bits)
PDU-1	24	128	-	152
PDU-2	40	256	8	304
PDU-3	56	384	16	456

Table 1. Examples of wireless protocol data unit (PDU) formats with information payloads limited to sub-multiples of a 48-byte ATM cell information payload.

Figure 4 and Figure 5 show the BER performance of several RCPC codes as a function of the average SNR for DQPSK modulation. The BER is averaged over the multipath fading samples. The normalized RMS delay spread $\Delta \approx 0.06$. In Figure 4, the receiver uses hard decision decoding without any knowledge of the CSI (i.e., YHAN), and soft decision decoding (i.e., YSAN), in Figure 5. No diversity combining is assumed.

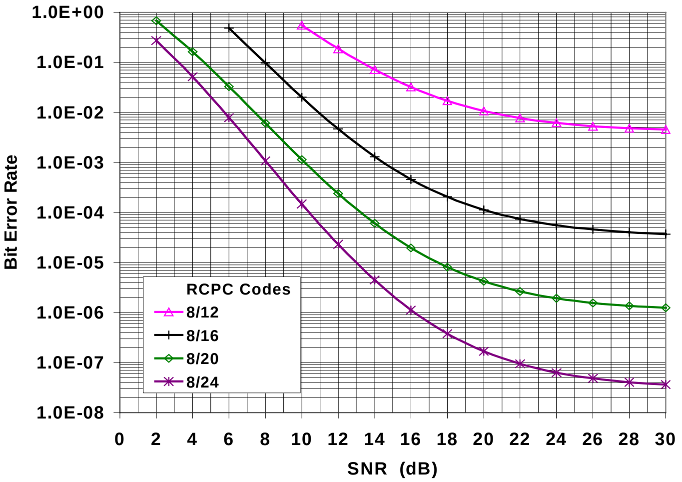

Figure 4. BER performance of RCPC codes for two-ray multipath Rayleigh fading channel model with DQPSK modulation, hard decision decoding, and no CSI.

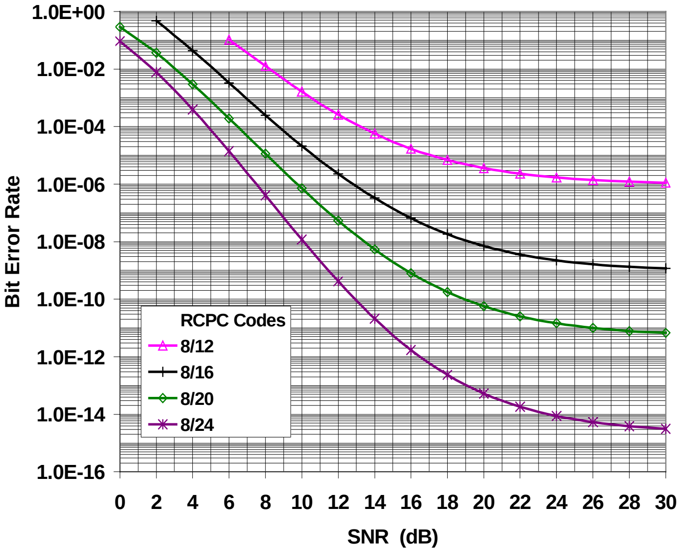

Figure 5. BER performance for RCPC codes on a two-ray Rayleigh fading channel model with DQPSK modulation, soft decision decoding, and no CSI.

Table 2 shows the average RCPC code rate associated with each of the three blocks of data in PDU-2, and the overall average effective code rate. The target BER for the information payload and PDU-2 overhead (header and trailer blocks) are fixed at 10^{-3} and 10^{-7}, respectively. The average SNR is fixed at 20 dB, and the $\Delta \approx 0.06$. The mother code rate $R = 1/4$, the puncturing period $P = 8$, and memory length $M = 4$. No diversity combining is assumed. The memory bits are required for proper termination of the decoding process.

Code Rate	Data Bits	Protection Bits	Memory Bits	Code Bits
8/15	256	224	-	480
8/32	40	120	-	160
8/32	8	24	16	48
0.44	304	368	16	688

Table 2. Example of three-level unequal error protection using RCPC coding and YHAN decoding option. Target BER for information payload is 10^{-3}. SNR is 20 dB.

Table 2 summarizes the average code rates for all three PDU's for the quantization and decoding options, CSI, and diversity combining schemes considered in this paper. The target BER for the overhead (header and trailer blocks) is fixed at 10^{-9}. The average SNR, mother code rate, puncturing period, and memory length are the same as those used to obtain the numerical results in Table 2.

Decoding and Diversity Options	Average Code Rate (10^{-3} BER Information Payload)			Average Code Rate (10^{-6} BER Information Payload)		
	PDU-1	PDU-2	PDU-3	PDU-1	PDU-2	PDU-3
YHAN – No Div.	0.43	0.44	0.44	0.32	0.32	0.32
2-Branch Diversity	0.70	0.72	0.72	0.54	0.55	0.55
YSAN – No Div.	0.68	0.70	0.70	0.53	0.54	0.54
2-Branch Diversity	0.82	0.83	0.83	0.82	0.83	0.83
YSAS – No Div.	0.79	0.83	0.81	0.63	0.76	0.64
2-Branch Diversity	0.86	0.88	0.88	0.86	0.88	0.88

Table 3. Average code rates for RCPC coding with various decoding options, decision variables, channel state information, and diversity combining for two-path Rayleigh fading channel model. Target BER for header and trailer blocks is 10^{-9}.

The numerical results in Table 3 show the following: 1) Hard decision decoding without diversity combining may not be a feasible RCPC coding strategy. 2) Soft decision decoding with/without knowledge of the channel can provide significant performance gains over hard decision decoding. 3) The use of 2-branch diversity can significantly improve the code rate performance. 4) The wireless PDU size (either full or a sub-multiple of a 48-byte ATM information payload) does not normally have any appreciable impact on code rate performance.

Adaptive FEC coding at the PHY layer using RCPC coding can be further enhanced by implementing an ARQ scheme at the DLC sublayer which combines FEC with ARQ to form an hybrid ARQ/FEC protocol. This approach allows adaptive FEC to be distributed between the wireless PHY and DLC layers.

5 CONCLUSIONS

The ATM Forum is developing specifications intended to facilitate the use of ATM technology for a broad range of wireless network access and interworking scenarios. The specifications will allow interworking of non-ATM wireless terminals with the fixed ATM network. This paper describes a PCS-to-ATM interworking scenario, and presents numerical results for a RCPC-coded unequal error protection scheme for the physical layer of the PCS access system, using a two-ray Rayleigh fading channel model. The results show the utility of using RCPC coding at the physical layer of the PCS access system to provide variable rate error protection for multimedia services that are likely to be encountered in future PCS systems that provide access to the ATM infrastructure network.

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