MA-FEC: A QoS-Based Adaptive FEC for Multicast Communication in Wireless Networks

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Abstract—
Wireless channels are highly affected by unpredictable factors such as cochannel interference, adjacent channel interference, propagation path loss, shadowing and multipath fading. The unreliability of media degrades the transmission quality seriously. Forward Error Correction (FEC) schemes are frequently used in wireless environments to reduce the high bit error rate of the channel. In this paper, we propose an adaptive FEC scheme for multicast communication in wireless networks based on dynamic variation of coding parameters as a function of the channel bit error rate, desired QoS in terms of reliability, number of receivers and efficiency in terms of bandwidth use. Reed-Solomon erasure codes are used throughout this study because of their appropriate characteristics in terms of powerful coding and implementation simplicity. We make a numerical analysis of a set of Reed-Solomon erasure codes. The observations made throughout this numerical analysis are the basic principals of our adaptive FEC scheme. Numerical results show that our adaptive scheme provides the best trade-off between transmission overhead and guaranteed QoS.

Keywords—**Wireless networks, Multicast communication, FEC, QoS.**

I. Introduction

Multicasting is the process of delivering a packet to several destinations using a single transmission. Multicast communication involves more than two users wishing to exchange information [1]. The advantage of multicast communication is its efficient savings in bandwidth and network resources since the sender can transmit the data with a single transmission to all receivers. Multicast applications are becoming more and more popular. Examples of such applications include audio and video conferencing, distributed games, and computer supported collaborative work (CSCW). We also see the emergence of data dissemination systems where an information source distributes the same information to a group of subscribers. The key idea of these systems is in multicast data transmission. Due to these advantages, it is important that future wireless networks can support multicast communications.

Most of the work done for multicast communication has been based on a fixed Internet environment. In fixed Internet, packets are most likely dropped due to congestion while in wireless, the unreliability of media is the major factor causing packet loss. In fact, wireless channels are highly affected by unpredictable factors such as cochannel interference, adjacent channel interference, propagation path loss, shadowing and multipath fading. End-to-end error recovery mechanisms do not necessarily work well in presence of wireless links and different kinds of mechanisms are required to guarantee reliability at the traversed wireless links. These are our basic motivations for the study of error recovery mechanisms for multicast communication in wireless environments.

Basically, there are two main error recovery mechanisms: Automatic Repeat Request (ARQ) and Forward Error Correction (FEC). ARQ tries to retransmit the lost packets while FEC transmits some redundant data with the original ones. FEC is frequently used in wireless environments but it can not assure full reliability unless coupled with ARQ.

Most of the reliable multicast protocols propose the use of ARQ [2], [3]. However, the use of simple ARQ for reliable multicast transmission towards a large group may cause a high retransmission rate at the sender even if each receiver has a low error rate. The use of FEC in this case can reduce the retransmission rate tremendously [4], [5] but its redundancy level must be carefully chosen according to network state. A FEC scheme with an optimal behavior during normal operation of a network may not necessarily work well during temporary degradation of the network. Adaptive FEC schemes for multicast communication have already been proposed but in other environments [6] [7].

In this context, we focus on FEC mechanisms in order to achieve error recovery based on the use of Reed Solomon Erasure (RSE) codes. In fact, the challenge is to design an error control technique which satisfies different Quality of Services (QoS) with an efficient use of available resources. We study an adaptive FEC scheme combined with ARQ for multicast communication over wireless networks. We call this scheme Multicast Adaptive FEC (MA-FEC). The scheme is capable to tune its error control parameters according to channel state. We take the packet loss rate of the multicast channel as our QoS metric throughout this paper.

The rest of the paper is organized as follows. Section II provides a brief description of packet level FEC and Reed-Solomon erasure codes. Section III points out the advantages of FEC for multicast communication in the context of wireless networks based on numerical analysis. The effect of changing the parameters of FEC is outlined in this section. Section IV studies the effect of FEC on packet loss rate of a multicast channel. Section V details our proposed adaptive FEC scheme. The performance of our adaptive scheme is compared to other FEC schemes in section VI. Finally, section VII provides concluding remarks.

II. Coding Aspects

A. Bit-level versus Packet Level FEC

In a system that uses FEC for error control, the sender and the receiver use a mutually agreed code to protect the data. This code can be represented by $C(n, k)$. The code adds $h = (n-k)$ redundant symbols to the k information symbols in order to correct the errors found in the received codeword of n symbols. *Redundancy* of a coding scheme is defined as the ratio of h/k and it represents the amount of redundancy added to the original information.

Forward error correction can be done at many levels from bit level up to packet level. In a bit level FEC, a bit is considered as a symbol while in packet level FEC, a symbol is a packet. Bit level FEC is basically implemented at the physical layer of almost all wireless networks. It is typically done by means of a Digital Signal Processor (DSP) chip or a specific Integrated Circuit (IC). It is designed to correct bit errors as its name indicates.

Packet level FEC consists of producing h redundant packets from k original ones. Packet level FEC is based on erasure coding. In coding theory, an error is defined as a corrupted symbol in an unknown position while an erasure is a corrupted symbol in a known position. The error correcting capability of a code can be increased if the decoder can exploit the erasure information [8].

Packet level FEC is mostly interesting in the context of multicast communication. Its interest lies on the fact that a single redundant packet can recover the loss of different information packets at different receivers.

B. Reed-Solomon Erasure Code

A Reed-Solomon erasure (RSE) code is a Reed-Solomon code with symbols defined over the Galois Field $GF(2^m)$, designed to correct only erasures. It has the capacity to correct h erasures with only h redundant symbols. This characteristic makes this kind of code particularly powerful to combat transmission packet losses.

We take k data packets of length L each. In the sender side, the RSE encoder takes these k packets and generates h redundant packets to form a code block of $n = k + h$ packets. If the receiver receives correctly at least k packets out of $k + h$ transmitted packets, it can reconstruct the original data. Here the loss unit is a packet and a packet payload is considered as a symbol. Thanks to the packet sequence numbers, the location of lost packets can be easily detected.

C. Implementation Issues

RSE coders with large symbol size are difficult to implement. McAuley proposed a hardware architecture for RSE codes in [9] using a symbol size $m = 8$ and $m = 32$. Rizzo proposed a software implementation of RSE codes in [10]. The maximum efficiency of his coding scheme is achieved with a symbol size not larger than half the word size of the processor due to fast table lookups.

Normally, the packet size is on the orders of hundreds or thousands of bits. In this case, we need to consider a packet size of $L = l.m$ where l is an integer. The coding can then be implemented using parallel RSE coders.

Since the number of elements of the $GF(2^m)$ with a symbol size of m is limited to 2^m, it is important to choose a RSE code with $n < 2^m$. If we take $m = 8$, we will have a maximum block length $n = 255$.

In order to have variable error correcting capabilities, we are interested to modify the coding parameters k and h of an RSE code. This is feasible by using *shortening* and *puncturing* techniques [8]. Shortening consists of adding a certain number of information symbols equal to zero to the original information in the encoding phase. Let's consider a Reed Solomon erasure code of $RSE(n, k)$. We can generate a set of shortened code $RSE(n-b, k-b)$ with $1 \leq b \leq k-1$ and an error correcting capability, h', equal to h. These shortened codes have their b high order information symbols equal to zero. Code puncturing involves not transmitting (deleting) certain redundant symbols. Puncturing allows an encoder/decoder pair to change their code rates, i.e., error correcting capabilities. The shortened and punctured codes can use the same encoder/decoder pair as their original code.

III. FEC in the Context of Multicast Communication

We take *efficiency* as a measure of performance of the scheme and we define it as the inverse of the average number of transmissions required by all receivers to receive a packet correctly. The efficiency gives us an indication of the used bandwidth. For our analysis, we take a Binary Symmetric Channel (BSC) model for wireless link where bit errors occur independently. We assume that all bit errors in a received packet are detected thanks to Cyclic Redundancy Check (CRC) field. The packet loss rate p is then calculated as:

$$p = 1 - (1 - p_b)^L \tag{1}$$

where p_b is the bit error rate of the wireless link and L is the packet length.

We further assume that each receiver has a probability of packet loss p which is independent of other receivers. Let us consider first the scenario where a sender multicasts data to R receivers. The sender retransmits the original packet if there is at least one receiver that has not received the packet correctly. In [11], an expression is derived for average number of packet transmission in a multicast group. From there, we can calculate the efficiency of the scheme, Eff, as follows:

$$Eff = \frac{1}{E[M]} = \frac{1}{\sum_{m=1}^{\infty} \left(1 - (1 - p^{(m-1)})^R\right)} \tag{2}$$

Now, we consider the case where the sender uses a coding scheme $RSE(n, k)$. In this case, the sender sends k original packets followed by h redundant ones. Each receiver can recover from loss if it receives correctly k packets out of $k+h$ transmitted packets, otherwise it asks for a retransmission. [4] made a complete analysis of average number of packet transmissions in this case. The perceived packet loss rate by each receiver, q, and the efficiency of the scheme are calculated as follows:

$$q = p\left(1 - \sum_{j=0}^{n-k-1} \binom{n-1}{j} p^j (1-p)^{n-j-1}\right) \quad (3)$$

$$Eff = \frac{1}{E[M]} = \frac{k}{n} \frac{1}{\sum_{m=1}^{\infty} (1 - (1 - q^{(m-1)})^R)} \quad (4)$$

In order to better understand the effect of changing the coding parameters on the overall performance of the system, we took a large set of RSE codes with different values of k and h for our analysis. The packet length L is 1024 bits. Fig. 1 shows the efficiency as a function of bit error rate in a group of 1000 wireless receivers for three different codes as well as a pure ARQ scheme. The efficiency as a function of number of wireless receivers for a bit error rate of 5×10^{-5} is depicted in fig. 2. From these figures, the advantages of FEC for multicast communication are evident.

Based on these results, we can make the following conclusions:

- There is not one best code. Depending on the bit error rate, the efficiency of a code varies. Therefore, we can only designate one best code for a certain range of bit error rates. If the bit error rate changes, the choice of best code changes also. This motivates the use of adaptive FEC schemes where the parameters of FEC vary dynamically according to the wireless channel state.
- If the bit error rate goes very high, even a coding scheme can not help. A code is operational up to a certain bit error rate. Our set of codes are operational up to a bit error rate of 10^{-3}.

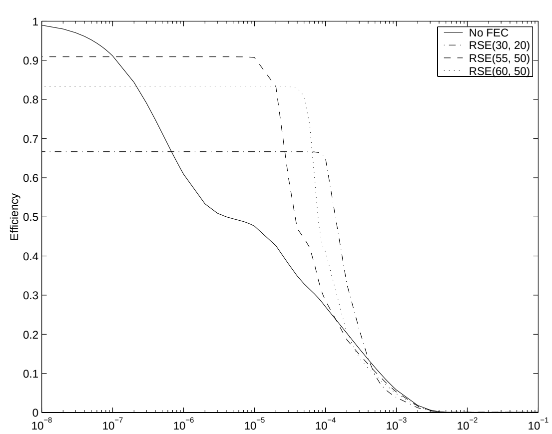

Fig. 1. Efficiency as a function of bit error rate with R=1000

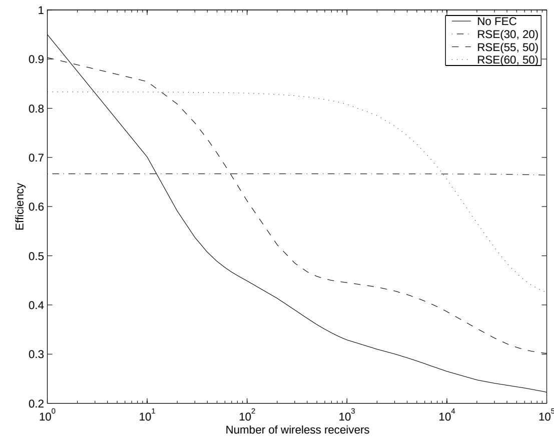

Fig. 2. Efficiency as a function of number of receivers, $p_b = 5 \times 10^{-5}$

- The number of receivers has a big impact on the efficiency if only an ARQ scheme is used. The efficiency decreases sharply if the number of receivers increases a lot. The use of FEC reduces the impact of number of receivers on efficiency but its redundancy level must be chosen carefully. From fig. 2 we can observe that the RSE(30, 20) maintains a constant efficiency for different number of receivers while RSE(60, 50) is efficient only up to 1000 receivers.
- In general, we can deduce that if the bit error rate is not high, the best efficiency can be obtained by choosing the number of information packets k as high as possible with a few redundant packets. If the bit error rate goes high, the number of redundant packets must be increased. Nevertheless, if even the maximum number of available redundant packets can not increase the efficiency anymore, we must decrease the number of information packets k while keeping the number of redundant packets at its maximum. As an example, if we look at fig. 1, we observe that RSE(60, 50) works well up to 5×10^{-5} while RSE(30, 20) keeps the efficiency at a constant rate up to 10^{-4}.

IV. QoS Metrics

Generally, QoS requirements are expressed in terms of delay, jitter and reliability. Delay is the time between the generation of a packet at source up to its correct reception at the destination. Jitter is the variation of this delay and reliability is the delivery of all packets to the receivers in a correct order without any loss or bit errors. As stated before, we focus on reliability expressed by the packet loss rate of the multicast channel. In terms of QoS guarantees, we aim to choose an RSE code which minimizes the probability that the packet loss rate of the multicast channel exceeds a fixed threshold.

The packet loss rate of a multicast channel, p_g, is defined as the probability that at least one receiver can not receive a packet correctly. It is determined as follows:

$$p_g = 1 - (1-p)^R \quad (5)$$

where p is the packet loss rate of each receiver. In the case that we do not use FEC, p is the same as in (1). In presence of FEC, we have to replace p by q calculated in (3). In the following, whenever we use the term packet loss rate, we mean the packet loss rate of multicast channel.

Fig. 3 shows the packet loss rates of the same RSE codes used in the previous figures for a total of 1000 wireless receivers.

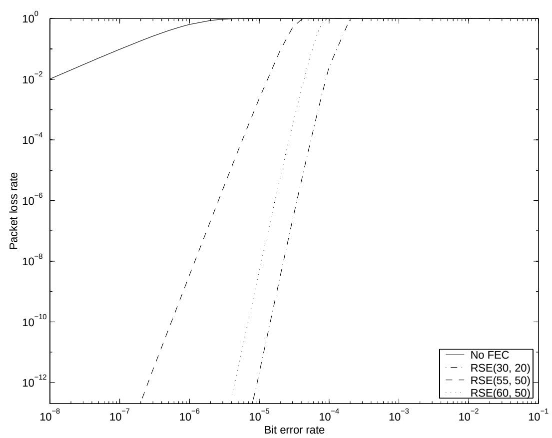

Fig. 3. Packet loss rate as a function of bit error rate with R=1000

From there, we can observe that:

- An RSE code can guarantee a packet loss rate up to a certain bit error rate.
- The more we increase the redundancy level of a code, the more a code is resistant to the increase of the bit error rate. For example, the RSE(30, 20) can guarantee a packet loss rate lower than 10^{-12} up to a bit error rate of 10^{-5} while RSE(55, 50) can guarantee the same packet loss rate up to a bit error rate of approximately 3×10^{-7}.
- A coding scheme that can guarantee a low packet loss rate is not necessarily the most efficient code. For example, the RSE(30, 20) maintains a packet loss rate lower than 10^{-12} up to a bit error rate of 10^{-5} while in terms of efficiency, it is not the best code for this range of bit error rates. Choosing a code is therefore a trade-off between a guaranteed packet loss rate and efficiency.

V. MA-FEC

Based on the conclusions taken from the numerical analysis, we propose an adaptive FEC scheme for multicast communications called Multicast Adaptive FEC (MA-FEC). Our proposed scheme attempts to increase the system efficiency as much as possible while maintaining the desired QoS in terms of packet loss rate. The adaptive algorithm consists of changing the block size k or the error-correcting capability h of RSE codes.

We assume that the sender knows the channel bit error rate at any instant t. As already stated, we assumed that all receivers experience the same channel conditions for simplicity reasons. Therefore, all receivers have the same bit error rate at any instant t. We further assume that either the sender knows the number of receivers in advance or it can make an estimation of the number of receivers. The sender can then adjust the block size and the redundancy level of the RSE code according to the channel bit error rate, number of receivers, QoS requirements and efficiency of the scheme.

The time is divided into transmission rounds. Each transmission round corresponds to the transmission of a data block. A data block consists of $n = k + h$ packets in case of FEC and one packet in case of pure ARQ. A transmission round ends when the sender is informed about the reception states of all receivers. This can be done by receivers sending an ACK or NAK to the sender specifying the number of lost packets. The adaptive algorithm is repeated at the end of each transmission round.

The sender computes the efficiency and the packet loss rate of all the available coding schemes in the presence of different bit error rates of the wireless channel and different number of receivers. It then tries to find the coding scheme satisfying the packet loss rate for different bit error rates and number of receivers. In case it finds several entries satisfying the packet loss rate, it chooses the one with the highest efficiency. It then makes a table of optimal codes called FEC_TABLE. Basically, the algorithm goes through the following steps:

1. At the beginning of the algorithm, the sender computes the FEC_TABLE according to the desired packet loss rate. It then determines the number of wireless receivers for the session, the channel bit error rate and chooses the optimal code according to the FEC_TABLE. It proceeds to the first transmission round.
2. At the end of a transmission round, the sender again determines the channel bit error rate and number of receivers for the next transmission round. It makes a table lookup at FEC_TABLE in order to find the optimal coding scheme. It then adjusts its parameters for the next transmission round.

VI. Numerical Results

We take a series of codes with a maximum block size of $k_{max} = 20$ and maximum redundancy of $h_{max} = 20$. We fix the packet loss rate of the multicast group at 0.1%. The number of wireless receivers has been fixed at 1000. We analyze two adaptive schemes. The adaptive scheme I only tries to maximize the efficiency without taking into account the desired QoS. Adaptive scheme II corresponds to the MA-FEC protocol where we want to guarantee a loss rate less than or equal to 0.1%.

Fig. 4 shows the efficiency of these adaptive schemes as well as two fixed schemes. As we can see, both adaptive schemes have a better efficiency than the fixed schemes. Adaptive scheme II has a lower efficiency than the adaptive scheme I since its packet loss rate guarantee puts more constraints on its choices of best codes.

The packet loss rate of the adaptive schemes are compared with the same fixed schemes in fig. 5. We can observe that although the adaptive scheme I provides a better efficiency than the other schemes, it is not the best option in terms of packet loss rate,. We also observe that the packet loss rate of the adaptive scheme II does not exceed 0.1%, as it was expected. From

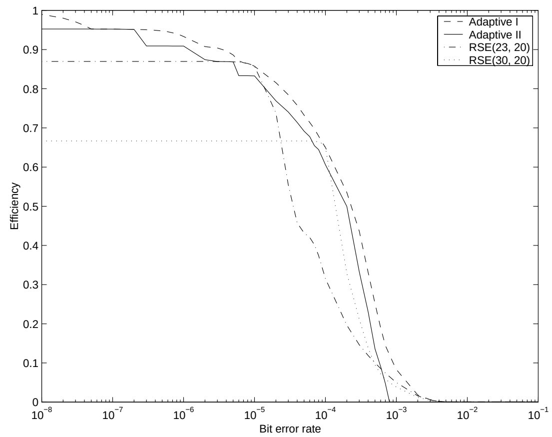

Fig. 4. Efficiency as a function of bit error rate with R=1000

these figures, we conclude that adaptive scheme II provides a good efficiency while respecting the desired packet loss rate.

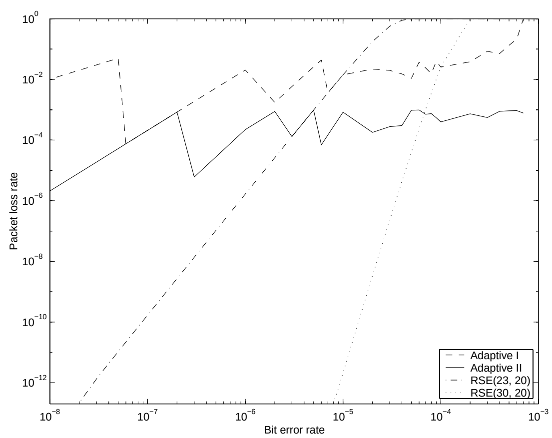

Fig. 5. Packet loss rate as a function of bit error rate with R=1000

VII. Conclusion

This paper presented a new adaptive FEC protocol for multicast communication over wireless links. According to the numerical results obtained for a large set of RSE codes, we observed that there is no unique best code. Depending on the bit error rate of the wireless channel, the efficiency of a code varies. Therefore, we can only designate one best code for a certain range of bit error rates. We observed that if the bit error rate is not high, the best efficiency can be obtained by choosing the number of information packets k as high as possible with a few redundant packets. If the bit error rate goes high, the number of redundant packets must be increased. Nevertheless, if even the maximum number of available redundant packets can not improve the efficiency, we have to decrease the number of information packets k while keeping the number of redundant packets at its maximum. We also observed that a coding scheme that can guarantee a low packet loss rate is not necessarily the most efficient code. Choosing a code is therefore a trade-off between a guaranteed packet loss rate and efficiency. These observations were the basic principals of our adaptive FEC algorithm, MA-FEC. We also compared the performance of MA-FEC with other schemes and we saw that it provides the best trade-off between efficiency and guaranteed loss rate.

References

[1] C. Diot, W. Dabbous, and J. Crowcroft, “Multipoint communications: a survey of protocols, functions and mechanism,” *IEEE Journal on selected areas in communications (JSAC)*, vol. 15, no. 3, pp. 277–290, April 1997.

[2] S. Floyd, V. Jacobson, C. Liu, S. McCanne, and L. Zhang, “A reliable multicast framework for ligth-weight sessions and application level framing,” *IEEE/ACM Transactions on Networking*, vol. 5, pp. 784–803, December 1997.

[3] S. Paul, K. K. Sabnani, J. C.-H. Lin, and S. Bhattacharyya, “Reliable multicast transport protocol,” *IEEE Journal on selected areas in communications (JSAC)*, vol. 15, no. 3, pp. 407–421, April 1997.

[4] J. Nonnenmacher, E. Biersack, and D. Towsley, “Parity-based loss recovery for reliable multicast transmission,” *IEEE/ACM Transactions on Networking*, vol. 6, no. 4, pp. 349–361, August 1998.

[5] Christian Huitema, “The case for packet level FEC,” in *Proceedings of IFIP 5th International Workshop on Protocols for High Speed Networks (PfHsn’96)*, INRIA, Sophia Antipolis, FRANCE, October 1996.

[6] A. Shiozaki, K. Okuno, K. Suzuki, and T. Segawa, “A hybrid ARQ scheme with adaptive forward error correction for satellite communications,” *IEEE Transactions on Communications*, vol. 39, no. 4, pp. 482–484, April 1991.

[7] P. Godlewski, M. Braneci, and A. Serhrouchni, “An error control scheme for multicast communications over an ATM network,” in *Proceedings of Singapore International Conference on Communication Systems (ICCS’94)*, Singapore, November 1994.

[8] S. Lin and D. Costello, *Error Control Coding: Fundamentals and Applications*, Prentice-Hall, Englewood Cliffs, New Jersey, 1983.

[9] Anthony J. McAuley, “Reliable broadband communication using a burst erasure correcting code,” in *Proceedings of SIGCOMM*, Philadelphia, Pennsylvania, September 1990.

[10] L. Rizzo, “Effective erasure codes for reliable computer communication protocols,” *Computer Communication review*, vol. 27, no. 2, pp. 24–36, April 1997.

[11] D. Towsley, J. Kurose, and S. Pingali, “A comparison of sender-initiated and receiver-initiated reliable multicast protocols,” *IEEE Journal on selected areas in communications (JSAC)*, vol. 15, no. 3, pp. 398–406, 1997.