

MIT Open Access Articles

PRAC: Exploiting partial packets without cross-layer or feedback information

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Angelopoulos, Georgios, Anantha P. Chandrakasan, and Muriel Medard. "PRAC: Exploiting Partial Packets Without Cross-Layer or Feedback Information." 2014 IEEE International Conference on Communications (ICC) (June 2014).

As Published: <http://dx.doi.org/10.1109/ICC.2014.6884247>

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Persistent URL: <http://hdl.handle.net/1721.1/99924>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Terms of use: Creative Commons Attribution-Noncommercial-Share Alike



PRAC: Exploiting Partial Packets without Cross-layer or Feedback Information

Georgios Angelopoulos, Anantha P. Chandrakasan and Muriel Médard
Department of EECS, MIT, Cambridge, USA

Abstract—This paper proposes a partial packet recovery scheme, called Packetized Rateless Algebraic Consistency (PRAC). PRAC exploits intra and inter-packet consistency to identify and recover erroneous packet segments, *without* recourse to cross-layer or detailed feedback information. In the absence of cross-layer coordination or detailed feedback, the prevailing methods proposed in the literature have discarded packets with errors. PRAC uses a rateless linear packet code for data encoding and an iterative decoding process consisting of a search algorithm and an algebraic consistency rule (ACR) check. It allows, but not relies upon, the use of any PHY FEC code, requires no feedback other than a notification of completion and, in the absence of partial packets, incurs no overhead. Our implementation and experimental results in a 7-node indoor testbed using wireless boards equipped with CC2500 radio transceivers reveal that PRAC offers an average throughput gain of 35% compared to a baseline ARQ scheme discarding partial packets and 13% compared to an ideal genie-aided HARQ (iHARQ) scheme. Specifically for links with high PERs, PRAC significantly enhances their robustness and its maximum throughput gain is 148% and 34% compared against the baseline and iHARQ schemes, respectively.

I. INTRODUCTION

A majority of current wireless communication systems use physical layer (PHY) FEC schemes to correct errors introduced during data transmission, and error detection codes at the data link layer to prevent propagation of erroneous information to higher layers of the protocol stack. A received packet is called *valid* and is pushed to higher layers if, after having been processed by a FEC code, it contains no erroneous bits; otherwise, it is called *partial*. Most of current wireless packet-based networks tend to operate in an “all-or-nothing” mode, completely discarding partial packets regardless of the number of correct bits contained in them.

However, dropping a partial packet and requesting the retransmission of the entire packet is highly suboptimal because partial packets usually contain large amount of useful information, especially in wireless networks. In order to take advantage of partial packets, several techniques have been proposed, which mostly fall into the following two broad categories: FEC codes [1], [2] combined with rate adaptation techniques [3], [4] whose goal is to eliminate any bit error exclusively at the PHY, and cross-layer or combining schemes, with soft PHY information [5], [6] or without [7], [8], [9], in which corrupted packets are recovered synergistically across multiple layers.

In this paper, a new partial packet recovery technique is proposed, called Packetized Rateless Algebraic Consistency

(PRAC), which leverages the correct information contained in partial packets, reducing the overall number of retransmissions. The main challenge in any partial packet recovery scheme is the identification of correct information within a partial packet. Cross-layer information (e.g. PHY soft information [5] and confidence hints [6]), multiple CRCs [10], pilot bits within a packet [8], detailed feedback information [9] and redundancy enabling error estimation codes [11] have been proposed as potential solutions. PRAC does not use any of these methods. Instead, transmitted data are encoded using a rateless linear cross-packet code and correct information is harnessed from partial packets making use of PRAC’s algebraic consistency rule (ACR) check. ACR checks exploit the property of linear (n, k) codes, according to it any k out of the n symbols are sufficient to decode the initial data and the other $(n - k)$ can be expressed as linear combinations of them. The recovery process is performed iteratively using an optimized search algorithm, ACR checks and CRC updates.

The main characteristics of the proposed scheme are the following:

- Cross-layer information is not required to be exposed to higher layers, making the proposed algorithm easily deployed in current wireless networks¹.
- PRAC’s encoding process incurs no transmission overhead for correctly received packets.
- PRAC requires minimal feedback information since it can operate with only a notification of completion.
- The computational requirements of PRAC’s recovery algorithm can be easily adapted to the available resources, balancing the recovery performance with the algorithmic complexity.

We test and evaluate the performance of the proposed partial packet recovery mechanism in a 7-node indoor static testbed over fixed rate and transmission power links of one or two-hop length with deterministic routing. In our testbed, boards with CC2500 radio transceivers are used [12], connected to a PC, implementing an IEEE 802.15.4-like protocol. Data traces are collected and processed off-line. PRAC’s throughput performance is compared against a baseline ARQ scheme which discards partial packets and an ideal genie-aided HARQ (iHARQ) scheme whose performance, in the absence of detailed feedback, is an upper bound on all cross-layer schemes.

¹To the best of our knowledge, none commercial wireless card exposes cross-layer information, such as symbol-level PHY soft information, at the driver level. Schemes which do not comply with this restriction can only be implemented using certain SDR platforms.

Our measurements verify that leveraging information from partial packets can significantly benefit wireless networks. Compared to the baseline ARQ scheme, PRAC's observed average throughput improvement across our testbed is 35%, while its maximum throughput benefit on high PER links is 148%. In addition, PRAC performs better compared to iHARQ; it has a throughput improvement of 13% on average and 34% in challenged links. Finally, PRAC guarantees that all links reliably meet a minimum throughput requirement, contrary to the other two schemes, which fail to do so.

II. BACKGROUND AND RELATED WORK

The exploitation of correct information contained in partial packets in order to increase performance of wireless networks has attracted extensive attention. In the following subsections, we present some of the main approaches.

A. PHY FEC Codes and Rate Adaptation Techniques

One widely used approach for increasing reliability of links in wireless networks and eliminate errors occurred during data transmission is the use of FEC codes at the PHY. The literature on this topic is vast and some of the codes are described in [1]. Different channel conditions require different amounts of redundancy, since fixed code rate FEC schemes can operate well only within a specific SNR regime. Having a PHY equipped with a powerful FEC scheme could potentially eliminate the occurrence of partial packets and the need of retransmissions. However, since the quality of the wireless channel fluctuates and is unpredictable, designing codes for worst-case scenarios can be quite inefficient because, most of the time, extra bits will be transmitted but not used at the recovery process, reducing the effective throughput.

Rate adaptation techniques seek to estimate the channel quality and adapt the modulation and coding rate accordingly [3], [4]. A trade-off exists between the amount of associated overhead (i.e. probing or channel state feedback) versus the accuracy of the measurements. In general, the incorporation of channel measurement mechanisms increases system's complexity, and, in mobile environments, a rate adaptation mechanism might be inefficient to track changes of a wireless fast-varying channel [13]. For this reason, rateless codes, which do not require a priori knowledge of the channel quality, have been proposed. For instance, coding schemes described in [14], [15] achieve the capacity of binary erasure channel (BEC) without knowledge of the erasure probability. More recently, scheme have been proposed practical rateless codes for binary symmetric and AWGN channels [16], [17], [18].

B. Cross-layer Schemes

Recovery mechanisms have also been proposed to operate at the data link or higher layers, independently or in synergy with the PHY. When they operate in synergy, cross-layer information, such as PHY soft information, is provided to higher layers in addition to its estimate about received bits to express how close the bit passed to them was to the received channel value corresponding to it, as shown in Fig. 1. For

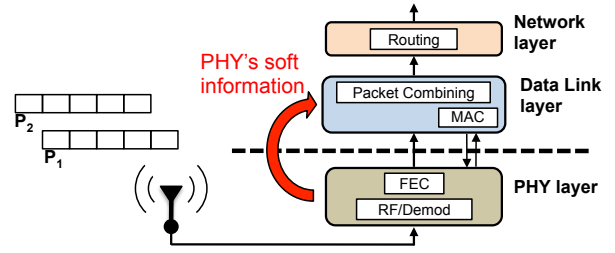


Fig. 1. Simplistic block diagram of a protocol stack in a receiver using a cross-layer packet combining scheme with propagation of soft information from the PHY to higher layers.

instance, hybrid ARQ (HARQ) schemes [19] combine the advantages of both FEC codes and packet retransmissions (ARQ) by accumulating PHY soft information corresponding to incoming and previously received partial packets in an incremental way, increasing the probability of a successful reception. Cross-layer schemes, such as the ones presented in [5], [20], [21], annotate every decoded bit from the PHY with a confidence hint in order to enable the link layer to identify which chunks of a packet have higher probability of being erroneous and request, through detailed feedback information, only these chunks.

PHY-independent schemes typically identify correct segments by either introducing some overhead within the transmitted packets (e.g. pilot bits), modifying the feedback mechanism to include detailed information in the acknowledgment frames (e.g. multiple CRCs), using cross-packet coding methods on top of PHY FEC codes, such as packet erasure codes, or a combination of them [7], [10], [8], [9], [11].

C. PRAC as a Partial Packet Recovery Scheme

PRAC's core component is a cross-packet random linear rateless code [22] which enables its optimal operation without knowledge of the channel quality. The encoding process introduces no fixed overhead to any transmitted packets, such as multiple CRCs per packet and known pilot bits for BER estimation. The detection of correct and erroneous parts of partial packets is performed with a mechanism based on the cross-packet algebraic consistency of a linear code (ACR checks), followed by an iterative correction algorithm.

PRAC is a PHY-independent process compliant with the abstraction layering convention and operates without modifications to the traditional interfaces between PHY and data link layer. In addition, it can be transparent to higher layers; the only consideration is that packets are delivered to them in a batch mode, right after a successful decoding. These two features enable PRAC's implementation as a driver extension or firmware patch without access to PHY soft information, applicable to several existing wireless systems.

III. HARNESSING PARTIAL PACKETS WITH PRAC

A. Packet Erasure Coding Schemes

Packet erasure codes can be used in PHY-independent partial packet recovery schemes as a mechanism to detect

and correct erroneous information. The performance of these coding schemes and their interaction with the PHY has been studied in the literature [23], [24], suggesting that spreading the transmitted redundancy across and within packets significantly outperforms the case in which only one method is used, especially for wireless fading channels [25], [26], [27].

Although a fixed-rate code, such as Reed Solomon (n, k) code, can be used to introduce the cross-packet dependency, the use of a rateless code may be preferable since it does not require knowledge of the channel characteristics in order to select the appropriate rate. Fountain codes, such as LT [14] and Raptor [15], are excellent rateless code candidates with low encoding and decoding complexity requirements. However, these codes do not perform well with short block lengths and a coding overhead (ϵ) is associated with them. If k initial packets are encoded together, approximately $k(1 + \epsilon)$ correct packets are required on average to be received for successful decoding. Although this overhead asymptotically approaches zero as $k \rightarrow \infty$ for appropriately designed degree distributions, in most practical scenarios ϵ has a non-negligible value since latency requirements of data link or higher layers limit the number of packets (k) buffered and coded together (in our experiments $k < 10$). Thus, coding overhead results in transmission of extra packets which negatively affects the achieved network performance. A family of codes with the desired characteristics of being rateless, performing well over small block lengths and having zero coding overhead are random linear codes. Although these codes do not provide similar encoding/decoding complexity guarantees as Fountain codes, they are selected as PRAC's core coding component.

B. PRAC's Encoding Process

The encoding process is performed upon groups of packets; the size (k) of these groups is called in the rest of the paper as generation size. Let P_i , where $i = 1, 2, \dots, k$, be an uncoded packet for transmission, consisting of l blocks. These blocks (p_{ij} , where $j = 1, 2, \dots, l$), are called symbols, have q bits length and are considered as elements from the finite field $\mathbb{F}(2^q)$. We assume that all packets have the same length of ql bits; if not, zero padding is applied. Using matrix notation, the uncoded packets can be represented as a $k \times l$ matrix \mathbf{P} , whose entries are the symbols p_{ij} . The encoding process transforms the k initial packets into m coded ones by the matrix multiplication, performed over finite field operations:

$$\mathbf{P}' = \mathbf{C} \times \mathbf{P}, \quad (1)$$

where \mathbf{C} is a randomly generated matrix of coefficients c_{ij} over $\mathbb{F}(2^q)$, with $i = 1, 2, \dots, m$, $j = 1, 2, \dots, k$ and $m \geq k$, and \mathbf{P}' is a matrix with the coded packets. Each coded packet is associated with a set of coefficients [22] which can be conveyed with the packet transmission (e.g. in the header) or locally produced at the receiver by random generator in sync with one at the transmitter. For the rest of the description, we assume that they are locally produced and error free.

IV. DECODING PROCESS

Upon the reception of a new coded packet (P'_i), its CRC status is checked and it is properly buffered as valid or partial. When the number of received (valid and partial) packets exceeds the used generation size (k), PRAC's recovery process is initiated. This process is performed column-wise over the matrix of received packets (\mathbf{P}') in a sequential manner. The correct and erroneous information are distinguished using an algebraic consistency rule (ACR) checks, and the identified errors are corrected by an iterative process consisting of an optimized search algorithm and ACR checks.

A. Algebraic Consistency Rule Check

PRAC identifies correct information within partial packets by taking advantage of the algebraic consistency of the encoded packets, property of (n, k) linear codes: any set of k out of the n valid symbols can be used to decode the initial data and the rest $(n - k)$ symbols will be a linear combination of them. Assume the generation size is k and x packets have been received ($x > k$), including partial and valid ones. The steps of the ACR check for column j are the following:

Step 1 - Create a set of $(k + 1)$ symbols which contains the symbols belonging to valid packets.

Step 2 - Pick randomly k symbols out of this set and multiply them by their inverted coefficients matrix to estimate the values of the uncoded symbols:

$$\begin{bmatrix} p_{1j}^* \\ \vdots \\ p_{kj}^* \end{bmatrix} = \begin{bmatrix} c_{11} & \dots & c_{1k} \\ \vdots & \ddots & \vdots \\ c_{k1} & \dots & c_{kk} \end{bmatrix}^{-1} \times \begin{bmatrix} p'_{1j} \\ \vdots \\ p'_{kj} \end{bmatrix}, \quad (2)$$

where “ $*$ ” denotes recovered symbol values.

Step 3 - Re-encode the estimated symbol values with the coefficients associated with the $(k + 1)$ th packet:

$$p'_{(k+1)j} = [c_{(k+1)1} \dots c_{(k+1)k}] \times \begin{bmatrix} p_{1j}^* \\ \vdots \\ p_{kj}^* \end{bmatrix}. \quad (3)$$

and compare the result with its value.

Step 4 - If equality holds ($p'_{(k+1)j} = p'_{(k+1)j}$), the set of the $(k + 1)$ symbols is consistent with high probability and the initial packet symbols of column j are the recovered symbols p_{ij}^* from Eq. 2. If not, PRAC's correction process is triggered.

When the result of the ACR rule for a column indicates consistency, there is also a probability for a false positive event (p_{fpe}), as with any other checking rule. Assuming that the effect of the channel on the received packets is uniform, the false positive event rate depends only on the value of field size (2^q) used. Thus, by increasing the field size, p_{fpe} can be set under any desired threshold. However, increase in the field size, increases exponentially the complexity of PRAC's correction process. An alternative way to lower p_{fpe} is by executing multiple ACR rounds (step 1 to 4) for the same column with considering a different set of $(k + 1)$ symbols each time.

If q is the length of each symbol and r is the number of consistency check rounds, the probability of a false positive event (p_{fpe}) of our check rule is:

$$p_{fpe} = \left(\frac{1}{2^q}\right)^r. \quad (4)$$

This means that, by using a field size of eight and two ACR rounds for each column, p_{fpe} equals $1/2^{16}$, which is the same as the false negative event rate of 16-bit CRC rule. The desired value of p_{fpe} is an application specific choice and can be adjusted depending on the available computational resources and the desired algorithmic performance.

B. Correction Process

When ACR detects an erroneous column, PRAC's correction process is initiated to correct its erroneous symbols. This is an iterative process and each iteration involves ACR checks, a search algorithm and CRC updates. The search algorithm attempts to identify the correct symbols until ACR check for the specific column is satisfied. At the end of the correction process, the CRC status of the partial packets with corrected symbols is updated before the recovery algorithm processes the next column, gradually reducing the number of partial packets.

Since no cross-layer information exists indicating potential erroneous bits, an exhaustive search algorithm is the optimal strategy in terms of recovering performance, whose complexity grows exponentially with the field and generation size. A reduced-complexity search algorithm is used in PRAC's correction process, examining first symbols with minimum Hamming distance from the received ones and setting a limit on the maximum number of trials. This provides a reduction on the average searching time and a tradeoff between recovery performance and processing time, respectively.

V. IMPLEMENTATION AND EXPERIMENTAL TESTBED

A. Implementation of PRAC and Parameters Selection

PRAC is implemented as a software module and its performance is evaluated by processing stored data traces offline. Small values of field size reduce the probability of a column containing erroneous symbols and the search space of the correction process but increase ACR's false positive event probability. In terms of the generation size, increasing its value up to a certain value increases the channel diversity gains but it also exponentially increases the correction process's search space. Finally, number of ACR rounds lowers the false positive probability of the check rule but increases the required computations. In our experiments and performance comparison, a field size of eight is used, a generation size of five and two ACR rounds, keeping the overall computational load of the CPU used in minimal levels.

PRAC's encoding process has minimal computational requirements. The recovery process exhibits higher complexity but it can be adjusted depending on the desired performance. Its implementation in resource constrained devices can be challenging. However, due to its inherent parallelism, it can be efficiently mapped to a multithreaded computing platform

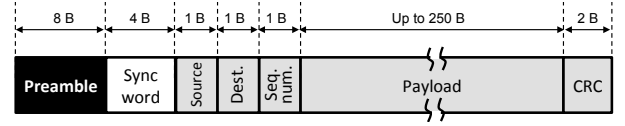


Fig. 2. Packet format used in our experiments.

or application specific circuit architecture, aspects which go beyond the scope of this paper.

B. Experimental Setup

A static, indoor 7-node testbed is used, with fixed transmission rate links and deterministic routing. Commercial boards [12] with CC2500 radio transceivers are used in the experiments, communicating at 2.4 GHz band. The nodes are connected to a central PC, storing data traces and other link statistics and operate in a centrally-controlled time division manner. Throughout all of our experiments, FSK modulation, 500 Kbps transmission rate, +1 dBm output power (maximum supported) and payload of 250 bytes length are used, unless otherwise specified. A rate 1/2 convolutional encoder, a Viterbi decoder and an interleaver are also used. The packet format contains: 8-byte preamble, 4-byte synchronization word, up to 253 bytes payload and 2-byte CRC check, as shown in Fig. 2. It should be emphasized here that PRAC is PHY-independent and any implementation platform can be used for evaluation without affecting its performance.

In the feedback mechanism 6-byte acknowledgment frames are used, transmitted upon the reception of a packet, indicating only its CRC status. No detailed feedback information about which segments of a packet are corrupted or how many errors exist in a packet is required. Data packets, including the retransmitted ones, have the same length. Although PRAC is a rateless code and feedback reduction techniques [28], [29] could be applied, we use the traditional per-packet acknowledgment throughout our experiments, for all recovery schemes tested, in order to decouple the benefits of harnessing partial packets from feedback suppression methods.

C. Channel Measurements

Our testbed consists of links with wide range of link qualities; packet error rate (PER) varies from 0.1% to 68%, with an average value of 14%. Channel measurements are taken across several days and hours in a typical office environment. PER accounts for both completely erased (not received at all) and partial packets. However, the benefit of any partial packet recovery scheme depends only on the percentage of partial packets since erased ones are not captured at all. Upper Fig. 3 shows the PER of three randomly selected links. The transmitter output power is varied in order to emulate the behavior of links across the whole PER spectrum values. The ratio (η) of the number of partial over erased packets is plotted in the lower Fig. 3, in which it can be observed that the number of partial packets is significantly higher (on average $5.2\times$ more) than the number of erased ones across the whole range of transmitter output power, or equivalently across links of

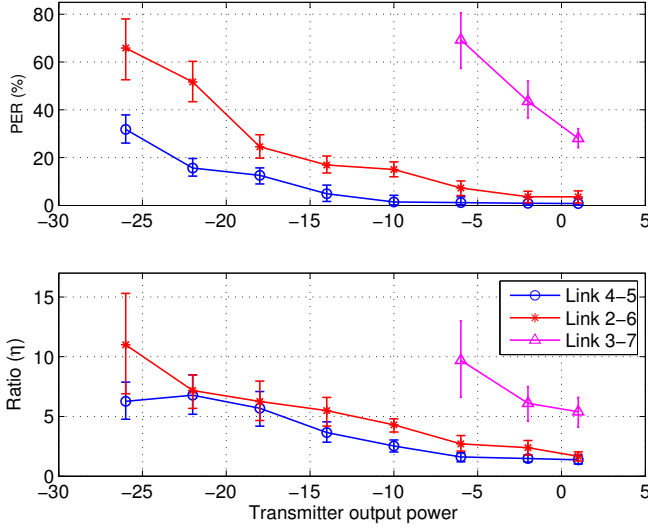


Fig. 3. Packet error rate (upper figure) and ratio (η) of the number of partial over erased packets (lower packets) as a function of the output transmitter power for three links in our testbed (link $i-j$ corresponds to link from node i to node j).

any PER. This verifies the potential improvement in network's performance from a partial packet recovery mechanism.

VI. PERFORMANCE EVALUATION

A. Compared Schemes

PRAC's performance is compared against a baseline ARQ scheme, which discards partial packets, and a genie-aided ideal HARQ scheme, called iHARQ, which exploits partial packets by combining them with their retransmitted copies. A significant difference between PRAC and iHARQ, which will be shown that has a major effect on performance, is that PRAC encodes and recovers a group of packets synergistically, while iHARQ processes and recovers individual packets. In more details, PRAC's performance is evaluated against:

- (i) **Baseline ARQ scheme** - It is composed by the combination of a convolutional code of rate 1/2 and an ARQ mechanism. When a partial packet is detected, it is discarded and a new retransmission is requested.
- (ii) **Genie-aided iHARQ** - This hypothetical scheme represents an ideal recovery mechanism with the ability to recover any received packet with at most one retransmission, if needed. In case of a packet is detected as partial, it is buffered and a genie guarantees that, with its upcoming retransmitted copy, successful recovering will take place, even if the second retransmitted packet is partial as well. As it becomes obvious, this is an upper bound on the performance of partial recovery schemes operating without detailed feedback.

B. Evaluation Results

The performance evaluation of the aforementioned schemes is shown in upper Fig. 4. The achieved end-to-end throughput of 40 randomly picked source-destination pairs is plotted for each scheme. The baseline ARQ scheme performs well in links with low PERs but its performance degrades drastically in less

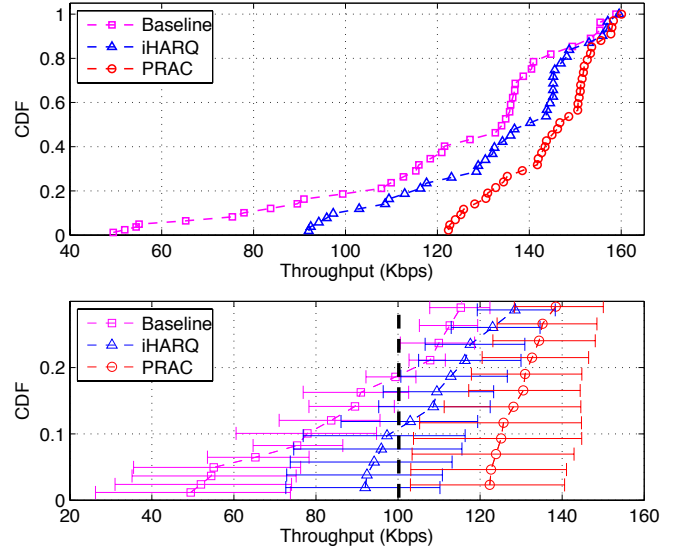


Fig. 4. Performance comparison among the baseline ARQ scheme, iHARQ and PRAC, for 40 randomly picked source-destination pairs in our testbed (upper figure) and zoomed view including the error bars (lower figure).

robust links. This is explained by the “all-or-nothing” operation of FEC codes; they perform well up to a certain channel SNR and poorly beyond that. A rate adaption algorithm would limit the performance degradation but it is not included in any of the considered schemes.

The bottleneck in any wireless network comes from links of high PER, which usually limit the overall network performance. For instance, in our testbed, the baseline ARQ and iHARQ schemes fail to provide guarantees of robust connectivity across all nodes for an application of 100 Kbps information rate, as shown in lower Fig. 4. The error bars reveal that only 65% and 77% of the links in our testbed will always support the required throughput threshold, for baseline and iHARQ schemes respectively. However, PRAC significantly enhances the robustness of low quality links and, as shown from the error bars, guarantees that 100% of links meet the throughput requirement, enabling all nodes to reliably operate without communication outages.

Fig. 5 plots the average throughput of links in our testbed with $PER > 3\%$. The iHARQ scheme achieves an average throughput gain of 17% over the baseline ARQ scheme, while its maximum observed throughput improvement is 82%. PRAC's outperforms on average the baseline by 35% and the iHARQ by 13%, while its maximum observed throughput improvement in the network is 148%. Although PRAC does not require use of cross-layer information, it outperforms the genie-aided iHARQ. Similarly to other packet erasure codes, PRAC's offered diversity benefits its performance, especially in channels with deep fades and strong interference [26], such as a typical indoors channel experienced in our testbed. Since every received packet equally contributes towards the recovery of an entire group of packets, PRAC's performance can tolerate a few bad channel realizations, since they are amortized

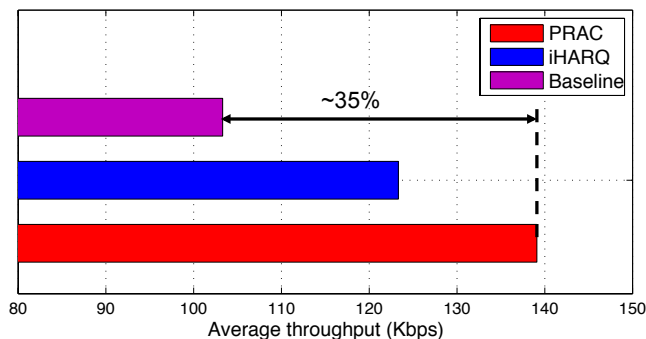


Fig. 5. Average throughput performance of the compared partial recovery schemes in links with PER > 3%.

across the entire group. In contrast, iHARQ's performance considerably degrades in these challenged channel conditions due to absence of diversity.

VII. CONCLUSION

The majority of current communication networks operate in an "all-or-nothing" mode, discarding partial packets. Because of the useful information contained in these packets, several schemes have been proposed in the literature to harness partial packets by either making use of cross-layer information, introducing some overhead in transmitted packets or increasing the feedback information sent to the transmitter. In this work, a novel partial packet recovery scheme is presented, called Packetized Rateless Algebraic Consistency (PRAC). PRAC exploits the intra and inter-packet algebraic consistency of a group of packets, introduced by a rateless linear code, to harmoniously recover them through an iterative decoding algorithm. Being PHY independent, it does not require recourse to cross-layer information. In addition, no overhead occurs in the absence of partial packets and minimum feedback information is required.

Our implementation and experimental results in a 7-node indoor testbed of fixed rate links demonstrate an average throughput improvement of 35% compared to a baseline ARQ scheme discarding partial packets, which can be up to 148% in challenged links. PRAC's performance is also compared against a genie-aided recovery scheme which represents the upper bound of performance for cross-layer schemes without detailed feedback, achieving an average throughput gain of 13% and 34% in high PER links.

ACKNOWLEDGMENT

The authors would like to thank Dr. X. Shi for useful discussions. Funding was provided by the Interconnect Focus Center, one of six research centers funded under the FCRP, an SRC entity, under Award Number: 017894-010.

REFERENCES

- [1] S. Lin and J. Costello, D. *Error Control Coding: Fundamentals and Applications*, 2nd ed. Prentice Hall: Englewood Cliffs, NJ, 2004.
- [2] R. Gallager, "Low-density parity-check codes," *Information Theory, IRE Transactions on*, vol. 8, Jan. 1962.
- [3] R. T. Morris, J. C. Bicket, and J. C. Bicket, "Bit-rate selection in wireless networks," Masters thesis, MIT, Tech. Rep., 2005.

- [4] M. Vutukuru, H. Balakrishnan, and K. Jamieson, "Cross-layer wireless bit rate adaptation," in *SIGCOMM*, Aug. 2009.
- [5] K. Jamieson and H. Balakrishnan, "Ppr: partial packet recovery for wireless networks," in *SIGCOMM*, Aug. 2007.
- [6] G. R. Woo, P. Kheradpour, D. Shen, and D. Katabi, "Beyond the bits: cooperative packet recovery using physical layer information," in *MobiCom*, 2007.
- [7] H. Dubois-Ferrière, D. Estrin, and M. Vetterli, "Packet combining in sensor networks," in *SenSys*, 2005.
- [8] K. C.-J. Lin, N. Kushman, and D. Katabi, "Ziptx: Harnessing partial packets in 802.11 networks," in *MobiCom*, 2008.
- [9] B. Han, A. Schulman, F. Gringoli, N. Spring, B. Bhattacharjee, L. Nava, L. Ji, S. Lee, and R. Miller, "Maranello: practical partial packet recovery for 802.11," in *NSDI*, 2010.
- [10] R. K. Ganti, P. Jayachandran, H. Luo, and T. F. Abdelzaher, "Datalink streaming in wireless sensor networks," in *SenSys*, 2006.
- [11] J. Xie, W. Hu, and Z. Zhang, "Revisiting partial packet recovery in 802.11 wireless lans," in *MobiSys*, 2011.
- [12] "Ti products, cc2500/cc2550dk development kit." [Online]. Available: <http://focus.ti.com/docs/toolsw/folders/print/cc2500-cc2550dk.html>
- [13] J. Camp and E. Knightly, "Modulation rate adaptation in urban and vehicular environments: cross-layer implementation and experimental evaluation," in *MobiCom*, 2008.
- [14] M. Luby, "Lt codes," in *Proc. of the 43rd Symp. on Foundations of Computer Science*, ser. FOCS '02, 2002.
- [15] A. Shokrollahi, "Raptor codes," *IEEE/ACM Trans. Networking*, vol. 14, June 2006.
- [16] R. Palanki and J. S. Yedidia, "Rateless codes on noisy channels," in *ISIT*, 2004.
- [17] U. Erez, M. Trott, and G. W. Wornell, "Rateless coding for gaussian channels," *Information Theory, IEEE Transactions on*, vol. 58, no. 2, pp. 530–547, 2012.
- [18] A. Gudipati and S. Katti, "Strider: automatic rate adaptation and collision handling," in *SIGCOMM*, Aug. 2011.
- [19] J. Costello, D.J., J. Hagenauer, H. Imai, and S. Wicker, "Applications of error-control coding," *Information Theory, IEEE Transactions on*, vol. 44, no. 6, pp. 2531–2560, Oct. 1998.
- [20] S. Katti, D. Katabi, H. Balakrishnan, and M. Médard, "Symbol-level network coding for wireless mesh networks," in *SIGCOMM*, 2008.
- [21] W. Hu, J. Xie, and Z. Zhang, "pmore: Exploiting partial packets in opportunistic routing," in *GLOBECOM*, 2011.
- [22] T. Ho, M. Médard, R. Koetter, D. Karger, M. Effros, J. Shi, and B. Leong, "A random linear network coding approach to multicast," *Information Theory, IEEE Transactions on*, vol. 52, no. 10, pp. 4413–4430, oct. 2006.
- [23] D. S. Lun, M. Médard, R. Koetter, and M. Effros, "On coding for reliable communication over packet networks," *CoRR*, vol. abs/cs/0510070, 2005.
- [24] M. Vehkaperä and M. Médard, "A throughput-delay trade-off in packetized systems with erasures," in *ISIT*, 2005.
- [25] P. Wu and N. Jindal, "Coding versus arq in fading channels: How reliable should the phy be?" *Communications, IEEE Transactions on*, vol. 59, no. 12, pp. 3363–3374, 2011.
- [26] T. Courtade and R. Wesel, "Optimal allocation of redundancy between packet-level erasure coding and physical-layer channel coding in fading channels," *Communications, IEEE Transactions on*, vol. 59, no. 8, pp. 2101–2109, 2011.
- [27] G. Angelopoulos, A. Paidimarri, A. Chandrasekan, and M. Médard, "Experimental study of the interplay of channel and network coding in low power sensor applications," in *ICC*, 2013.
- [28] D. Lucani, M. Stojanovic, and M. Médard, "Random linear network coding for time division duplexing: When to stop talking and start listening," in *INFOCOM*, 2009.
- [29] P. A. Iannucci, J. Perry, H. Balakrishnan, and D. Shah, "No symbol left behind: a link-layer protocol for rateless codes," in *MobiCom*, 2012.