Rateless Coding on a Wearable Wireless Network for Augmented Reality and Biosensors

R.Razavi, M. Fleury, and M. Ghanbari
University of Essex, Wivenhoe Park, Colchester CO4 3SQ, United Kingdom

***Abstract*— This paper introduces a block-based form of rateless channel coding that minimizes energy consumption by reducing the overhead and latency from channel coding. Consequently, results from a Bluetooth (IEEE 802.15.1) wearable wireless network for Augmented Reality (AR) show a consistent reduction in energy consumption compared to Bluetooth FEC schemes. AR relies on video transmission across a wearable network. Block-based rateless coding resulted in around 5 dB improvement compared to block-based FEC in video quality at a head-mounted display in the face of worsening channel conditions. System modeling took into account cross-traffic resulting from biosensors that moderate the AR display according to the cognitive load of the wearer.**

I. Introduction

We model a wearable wireless network to find the impact of data traffic from biosensors upon an Augmented Reality (AR) video stream passing from a camera worn on the operative to a Head-Mounted Display (HMD). A central, wearable computer processes incoming encoded video from the camera unit, adding additional information from an internal source and/or transferred from an external wireless source. The video is then re-transmitted in compressed form to the display device. For this system, we selected Bluetooth (IEEE 802.15.1) v. 2.1 with Enhanced Data Rate (EDR), for which, according to modulation type and channel conditions, the gross (shared) air rate is 3.0 Mbps which equates to 2.2 Mbps mean gross user payload.

The paper proposes that a proposed block-based scheme of rateless channel erasure coding [1] will reduce the impact of wireless channel errors on the AR video streams, while also reducing energy consumption taken up in their transmission. Currently, Bluetooth offers block-based Forward Error Control (FEC) and the paper compares variants of this scheme to rateless erasure coding. In comparison, simple packet-based rateless coding decreases energy efficiency in worsening channel conditions, while other forms of Bluetooth FEC lead to increased latency, which is undesirable for delay-intolerant video in general and a real-time application in particular. In the proposed block-based rateless coding scheme, each packet contains $k(1+\varepsilon)$ blocks, where ε is a small fractional overhead, typically 5%, to ensure with high probability that all k information blocks are decodable if received without error (rateless codes are constructed in probabilistic fashion). Raptor rateless codes have constant time coding and linear decoding computational complexity, though additional pre-coding is performed prior to formation of the rateless code. Consequently, we remark that rateless codes also will help reduce processor energy consumption.

With the proposed block-based method of rateless coding redundancy is also reduced in comparison to simple packet-based coding because the unit of coding is not a packet but a block within a packet. By piggybacking redundant blocks onto newly transmitted packets, redundancy is incrementally achieved until either a prior video-bearing packets received in error are reconstructed or the display deadline of the frame of which that packet is a part expires.

For a wearable AR system, energy consumption is important because batteries are carried upon the person and cannot easily be replaced in stressful scenarios. In [2], it was reported that there is approximately a linear relationship between bitrate and energy consumption and in [3] it was shown that transmission accounts for more than a third of the total energy consumption in communication on a mobile device, which is one reason why Bluetooth's stop-and-wait Automatic Repeat reQuest (ARQ) is unsuitable.

AR allows a video display of the outside world to be supplemented with computer-generated graphics, annotations, instrument readings, and other sources of information [4]. The display for emergency workers is typically on an HMD and may be partially mediated, i.e. the subject is also able to view the outside world directly. Unfortunately, the level of information may saturate (cognitive overload) owing to the limited capacity of human memories [5], causing an operative's performance to deteriorate [6]. In augmented cognition, biosensors upon the person feedback information to the AR unit and these act to reduce the level of viewable information. In augmented group cognition, that information may be transmitted from other personnel. AR wearable wireless networks have applications for emergency and medical workers, in the military, and in the maintenance of large vehicles. Bluetooth can now support video transmission and is similar in star topology, spread spectrum, and Time Division Duplex (TDD) TDMA to BBN's BodyLAN [7], also intended as a wearable AR system, though without the need to support augmented cognition.

II. Methodology

The Bluetooth network in Fig. 1 contains two biosensors, a video camera source and an HMD, along with an external source which may act as a means of exchanging biosensor data with other operatives and as a source of external sensor data. The video source is assumed to be of variable bit-rate (VBR) to ensure higher quality than constant bit-rate (CBR), within the restrictions of the available bandwidth. The encoded video is transferred to the central node, where, after decoding. augmentation of the display takes place, along with moderation of that display in line with interpretation of biosensor data. Notice that if the display contains text then good resolution is needed.

The Electroencephalography (EEG) and Electrocardiography (ECG) biosensors are assumed to be CBR sources. The external source was modeled as an on-off source in the ratio 1 s on to 2 s off with its bitrate divided equally in the two directions. However, polling packets from the master node and null return packets to the external source will occupy a significant portion of the available bandwidth when the external source is off. The assumed data rates of the sources are detailed in Table I along with packet sizes. ECG, EEG, and the external source all used Bluetooth's largest packet size of type 3DH5 packets (5 time slots and one reply slot, user payload 0-1021 B, max. asymmetric rate 2178 kbps) [8].

The video-bearing Bluetooth 3DH packet payload was partitioned into three parts, Fig. 2: 1) a variable-sized redundant block portion, with the blocks within this portion generated by the rateless algorithm from prior packets; 2) the data of the next packet divided into blocks with an additional ε blocks generated by the rateless algorithm, as k(1+ε) blocks are required for reconstruction of the original *k* blocks with high probability; 3) a Cyclic Redundancy Check (CRC) which is a default part of a Bluetooth packet but which we assume is applied to the decoded *k* blocks of the current packet. Upon failure of the CRC, additional blocks are requested from the sender and these are sent in the first part of the next packet together with any other blocks from yet to be reconstructed packets.

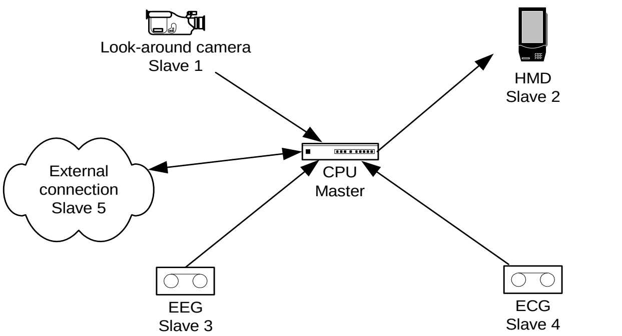

Fig. 1. Bluetooth wireless wearable network, showing master and slave nodes

TABLE I. TRAFFIC FLOWS ACROSS THE WEARABLE NETWORK

Comms.	Mean bitrate	Type (packet size)
S1 to M	256 kbps	VBR
M to S2	256 kbps	VBR
S3 to M	1000 kbps	CBR (800 B)
S4 to M	3.6 kbps	CBR (800 B)
S5 to M	50 kbps	CBR (800 B)

(From Fig. 1, S1 = Slave 1, S2 = Slave 2, … M = Master node).

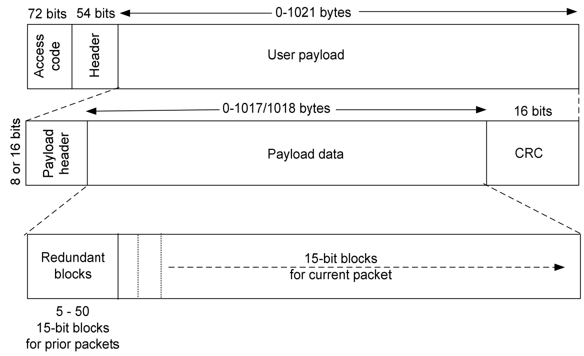

Fig. 2 Bluetooth packetization structure showing the incorporation of redundant blocks into the payload.

Assume initially that just the one prior packet has failed then redundant blocks are now piggybacked upon the current packet to add to the original *k(1+ε)* blocks already transmitted in order to increase the probability of a successful decode. After an attempted decode, the CRC of that prior packet is applied to establish whether there has been an erasure. If there is an erasure additional blocks are requested through Bluetooth's TDD mechanism, unless the duration of block retransmissions already exceeds the display deadline of the video frame of which that packet's data forms a part. The display deadline in the simulations was set to a constant *d* number of retries.

Critical to the operation of rateless error correction is the number of blocks contained in part 1 of a Bluetooth packet payload. If redundant blocks are to be sent then a minimum and a maximum number of 15-bit blocks are defined, being 5 and 50 respectively in the simulations. Leaving aside initialisation packets, the starting number of redundant blocks was the minimum number (five blocks) in our simulations. Upon receipt of a consecutive sequence of *n* successfully-transmitted packets, 100 in the simulations, then the limit is reduced by one. Upon a failure to reconstruct any packet after the d^{th} transmission of its blocks then the number of redundant blocks included in a packet is increased for the future by a factor α, set to 1.5 in the simulations. This conservative policy for a volatile channel results in a rapid increase in redundancy when un-correctable errors first occur.

If more than one prior packet of the same frame type has errors then the redundant block allowance is split according to the proportion of retransmissions remaining for each packet, allowing for some irregularity due to the need to apportion an integer number of blocks. The ratio is calculated as a proportion of factor *d.* A simple acknowledgment of the differing importance of frame types was made by altering the allocation in the ratio 3:2:1 for I-, P-, and B-frame packets respectively. Other priority-based schemes are possible.

A Gilbert-Elliott two state discrete-time, ergodic Markov chain models the wireless channel error characteristics between a Bluetooth master and slave node. The mean duration of a good state, T_g, was set at 2 s and in a bad state, T_b was set to $a \times T_g$, where a is a parameter which is varied to alter the duration of bad states. In units of 625 μs (the Bluetooth time slot duration), T_g = 3200 which implies from:

$$T_g = \frac{1}{1 - Pgg}, T_b = \frac{1}{1 - Pbb}$$

that, given the current state is good (g), Pgg, the probability that the next state is also g, is 0.9996875. Both good and bad state is modeled with a Rayleigh channel with the mean SNR being 35 ± 1 dB and 25 ± 1 dB in the g and b states respectively. Calculated packet loss rate/s [11] for Rayleigh SNRs of 35 and 25 dB are 0.5431 and 0.0081 respectively.

We employed the University of Cincinatti Bluetooth (UCBT) extension to the well-known ns-2 network simulator (v. 2.28 used). The UCBT extension supports Bluetooth EDR but is also built on the air models of previous Bluetooth extensions such as BlueHoc from IBM and Blueware. All links were set at the maximum EDR 3.0 Mbps gross air rate. Simulation runs were each repeated 100 times and the results averaged to produce summary statistics.

The simulations were principally carried out with input from an MPEG-2 encoded bitstream at a mean rate of 256 kbps for a 30 s video clip with moderate motion. PSNR was found by reconstructing with a reference MPEG-2 decoder. The 25 frame/s display rate resulted in 750 frames in each run. The source video was Common Intermediate Format (CIF)-sized (352 × 288 pixels) with a GOP structure of N = 12, and M = 3. In [9] it was demonstrated that forming fully-filled Bluetooth packets outweighed the need to preserve MPEG-2 slice boundaries, which over the fixed Internet are preserved for error-resilience purposes. Therefore, fully-filled packets of the 3DH type are formed from the arriving encoded video stream.

III. Results

Experiments were conducted streaming the video of Section II. Metrics were recorded across both hops in Fig. 1 over which video was streamed. For example, packet loss is recorded as a total across both hops. A varying number of redundant blocks were included in the packet payload if one or more prior packets were found to have failed. For any one packet in error, retransmissions continued until the number of retransmissions, d, exceeded ten, assuming that after ten attempts at reconstructing the packet the display deadline would be exceeded. At a frame rate of 25 frame/s, a frame is displayed every 0.040 s, while ten retransmissions take 0.375 s. Assuming a worse case of each of 18 slices in an MPEG2 CIF-sized frame then a small playout buffer of about 20 frames is adequate even if all 18 were in error. Though in practice the display deadline is controlled by the size of a playout buffer at the receiver, in the experiments, the retransmission limit served as a gauge of the display deadline. After d is exceeded then the packet is declared as lost. A send buffer size of fifty packets was sufficient to avoid packet loss by buffer overflow, though increasing the video arrival rate could change that.

Fig. 3 shows how there is a sharp reduction in the packet loss ratio (the number of lost packets to the number of packets transmitted) at a given average SNR for a relatively small investment in redundant blocks. All loss occurred through exceeding the re-transmit limit of ten. Notice also that in Fig. 3 that there is a single-state Rayleigh channel, whereas later tests use the two-state channel model of Section II. Fig. 4 shows that as the retransmission depth, d increases then there is a higher chance of recovering a previously failed packet, as packet losses decline with d. However, d should match the playout buffer size, as an arbitrary choice can lead to missed display deadlines.

Bluetooth's already has FEC-bearing Data Medium (DM) packets [8], available at the basic rate of version 1 in the event of poor SNR. An expurgated (15, 10) Hamming code is applied to 15-bit blocks and can cope with burst sizes of two, depending on decoder [8]. As a point of comparison with rateless erasure codes, it is supposed that the DM packet scheme is extended to the EDR transmission modes. Additionally, an adaptive FEC-bearing scheme that assumes perfect channel knowledge was simulated. FEC-bearing packets are only selected when the channel enters a bad state. The adaptive scheme is introduced as it has the ability to save energy by reducing the overhead when channel conditions ease.

In Fig. 5, the augmented cognition traffic and the other traffic sources from Table I are turned on, while the

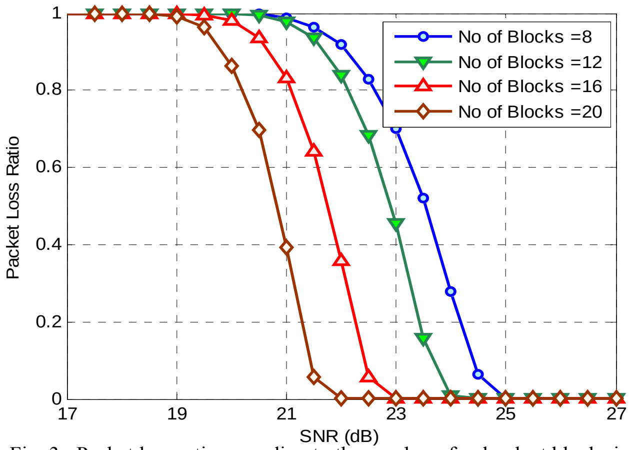

Fig. 3. Packet loss ratio according to the number of redundant blocks in a Rayleigh channel with varying SNR.

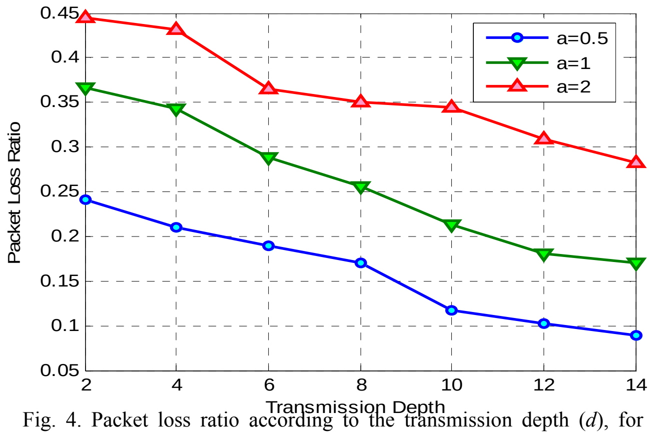

Fig. 4. Packet loss ratio according to the transmission depth (d), for varying duration (indexed by a) of bad state in a two-state Rayleigh channel.

packet loss ratio for each FEC-bearing scheme is compared with the proposed rateless coding scheme. The packet loss ratio is the ratio of packets lost against total packets transmitted in the video streams. The loss ratio is adjudged against worsening channel conditions as regulated by channel parameter *a* from Section II. From Fig. 5, it is apparent that the proposed rateless scheme outperforms the native schemes and increasingly so as the bad state durations increase.

The various schemes were also compared, Fig. 6, in terms of energy efficiency, which is the ratio the data successfully transmitted to the total data transmitted. (Recall from Section I that energy consumption is largely dependent on transmission.) Though the 'no FEC' plot involves no overhead from FEC, it still has a poor energy saving efficiency compared to the proposed scheme because of the fewer bits transmitted successfully. Adaptive FEC is relatively better at energy reduction than fixed FEC but, of course from Fig. 5, the number of unrecoverable packets is greater. In Fig. 7 a comparison between the delivered video quality for selected bad state durations for which Peak-Signal-to-Noise Ration (PSNR) is of a reasonable level. The Figure shows that in terms of delivered video quality the rateless scheme also outperforms the Bluetooth FEC scheme when applied to EDR packets. The relative improvement increases with worsening bad state duration.

IV. Conclusion

Wireless AR systems for wearable computers, as pioneering work by BBN Inc. recognized, have many applications in assisting what could broadly be termed emergency workers. As these operatives often work under stressful conditions, it becomes necessary to monitor the worker with biosensors, some of these having high bitrates. Through Bluetooth v. 2.1, it is now feasible to use wearable wireless networks with sufficient bandwidth capacity to also allow a video stream from camera to HMD. Rateless channel coding is well-suited to a Bluetooth wireless network, because of its centralized packet scheduling. We have proposed block-based rateless coding which from the paper's results can jointly improve energy consumption and delivered video quality compared to variants of native Bluetooth FEC.

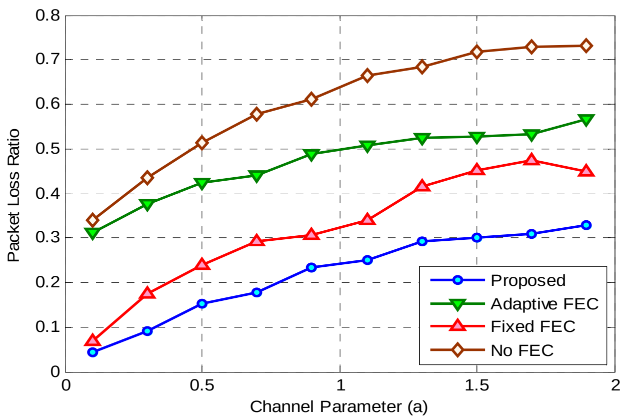

Fig. 5. Comparison of packet loss for rateless coding and various FEC-bearing streams with competing biosensor traffic, for varying duration (indexed by *a*) of bad state in a two-state Rayleigh channel.

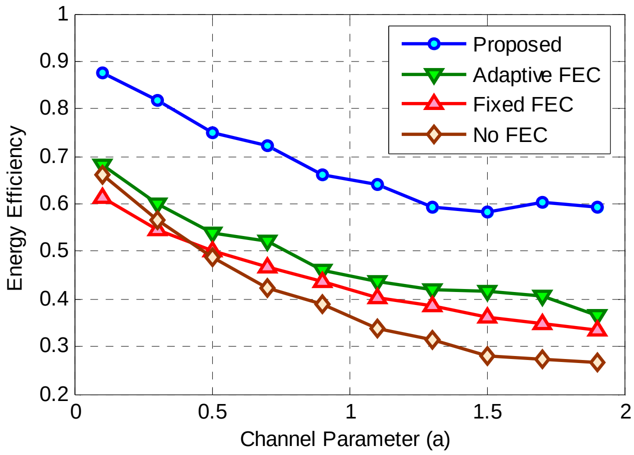

Fig. 6. Comparison of energy efficiency for rateless coding and various FEC-bearing streams with competing biosensor traffic, for varying duration (indexed by *a*) of bad state in a two-state Rayleigh channel.

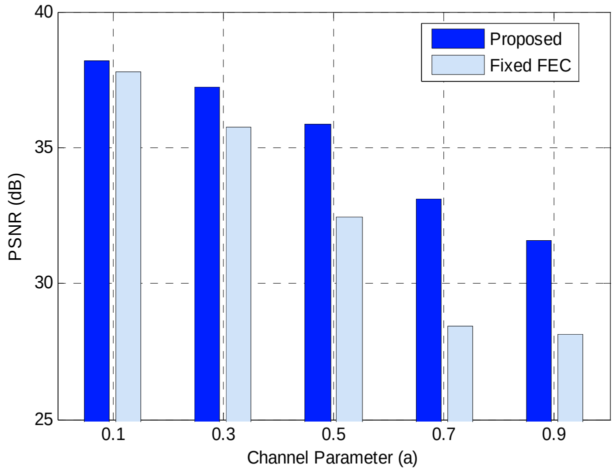

Fig. 7. Video quality comparison for transmission using the rateless coding scheme and the EDR FEC-scheme.

References

[1] D. J. C. MacKay, "Fountain codes", IEE Proceedings in Comm., vol. 152, no. 6, pp. 1062-1068, 2005.

[2] J. C. Chen, K. M. Sivalingam, P. Agrawal and S. Kishore, "A Comparison of MAC protocols for Wireless Local Networks based on Battery Power Consumption", IEEE INFOCOM, pp. 150-157, 1998.

[3] M. Tamai, T. Sun, K. Yasumoto, N. Shibata, and M. Ito, "Energy-aware Video Streaming with QoS Control for Portable Computing Devices", 14th Int. Workshop on NOSSDAV, 2004.

[4] J. P. Rolland and H. Fuchs, "Optical versus Video See-through Head-Mounted Displays", pp. 113-150, in "Fundamentals of Wearable Computers and Augmented Reality", Lawrence Erlbaum, NJ, 2001.

[5] J. Sweller, "Cognitive Load During Problem Solving: Effects on Learning", Cognitive Science, vol. 12, no. 1, pp. 257-285, 1998.

[6] M. Klan et al., "LifeNet An Ad-Hoc Sensor Network and Wearable System to Provide Firefighters with Navigation Support", 9th Int. Conf. on Ubiquitous Comp., pp. 124-127, 2007.

[7] R. LaRowe and C. Elliott, "Computer Networks for Wearable Computing", in "Fundamentals of Wearable Computers and Augmented Reality", Lawrence Erlbaum, New Jersey, pp. 715-745, 2001

[8] R. Razavi, M. Fleury, M. Ghanbari, "Correct Bluetooth EDR FEC Performance with SEC-DAEC Decoding", Electronic Letters, vol. 43, no. 22, pp. 1209-1211, 2007.

[9] R. Razavi, M. Fleury, E. Jammeh, and M. Ghanbari, "An Efficient Packetization Scheme for Bluetooth Video Transmission", Electronic Letters, vol. 42, no. 20, pp. 1143-1145, 2006.