VIDEO-STREAMING APPLICATIONS ENABLED ACROSS BLUETOOTH V. 2.0 INTERCONNECTS

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ABSTRACT

Bluetooth v. 2.0's enhanced datarates bring quality video streaming within scope. To harness that capacity in the presence of RF noise, various techniques should be applied. Dynamic packetization of an encoded video stream improves throughput and meets playout deadlines. Datarate swapping reduces RF loss and obviates the need for ARQ. Bluetooth's ARQ is shown to be unhelpful for video streaming unless the re-transmission policy adapts to buffer fullness. PSNR measurements demonstrate high-quality reception when all the techniques are applied.

KEYWORDS

ARQ, Bluetooth, packetization, video streaming

1. INTRODUCTION

IEEE 802.15.1, Bluetooth version 1.0 [7] in the unlicensed 2.4 GHz band, has received comparatively limited investigation as a way of streaming video across a wireless interconnect. Research papers that do investigate Bluetooth v. 1.0 streaming include [3][8][9]. The Enhanced Data Rate (EDR) of Bluetooth v. 2.0 [15] has a peak user payload of 2.2 Mb/s, which is the same rate offered by interactive IP-TV. WiMedia with Bluetooth v. 3.0 framing, by virtue of Ultra Wideband (UWB) in the 3.1-10.6 GHz band is projected to be able to support High Definition TV (HDTV) [1] but, in the meantime, many cell 'phones in Europe include Bluetooth v. 2.0 or earlier as a default option, and Bluetooth-based video is desirable for applications such as wearable computers and in-car entertainment. Bluetooth's key advantage is low-power transmission [6], typically consuming 1-35 mA, as opposed to 100-350 mA for IEEE 802.11 systems.

Bluetooth employs variable-sized packets up to a maximum of five frequency-hopping slots of 625 μs duration. To stream video, an efficient packetization scheme for a video stream is required to maximize the achievable data rate. Static packetization schemes preserve slice boundaries, minimizing the propagation of channel errors. Dynamic packetization, packing less than one, or one or more slices per packet without preserving slice boundaries, can improve the net video quality, compared to a fixed packetization scheme. However, the presence of Radio Frequency (RF) noise [16], especially for multi-slice packets may upset the video quality. The goal of this paper is to show that dynamic packetization, combined with adaptive datarate swapping, is an effective antidote to RF noise. The result is high-quality video across a Bluetooth interconnect. Adding adaptive Automatic Repeat Request (ARQ) timeouts brings video quality above that normally expected on mobile devices.

Two options[1] exist in Bluetooth v. 2.0 to counter-act the impact of RF noise. The first is to reduce the raw data rate from 3.0 Mb/s with eight phase Differential Phase Shift Keying (8-ary DPSK) modulation to 2.0 Mb/s with pi/4 Rotated Differential Quaternary Phase Shift Keying ($\pi/4$QPDSK) [15]. In this paper, the channel quality parameter that the Bluetooth module employs for adaptive frequency hopping introduced in version 1.2 encourages consideration of datarate swapping between 3.0 Mb/s and 2.0 Mb/s. In simulations, a two state channel model allows datarate swapping to be investigated. The second option is to employ link layer stop-and-go ARQ [2] after a cyclic redundancy check (CRC) reveals the need. For video streams, the ARQ retransmission limit should be set for real-time delivery (25 frame/s herein). In this paper, the interaction of ARQ with static and dynamic packetization is investigated. In an extension, adaptive ARQ timeouts are advocated. To determine the adaptive threshold, a cross-layer approach based upon transmit buffer fullness monitoring [14] is employed.

In summary, the contribution of the paper is a scheme for video streaming over Bluetooth in which: firstly an appropriate packetization strategy is selected; secondly the datarate is adaptively selected to gain a much improved video quality; and thirdly the addition of adaptive ARQ increases the Peak Signal-to-Noise Ratio (PSNR) still further. A by-product of the research is that the selection of Bluetooth packet types is simplified and the potential improvement from leased time slots is confirmed.

2. METHODOLOGY

Bluetooth employs Time Division Media Access with scheduling by a master to up to seven slaves, though we assume a single traffic source. A data frame across a Bluetooth link in asymmetric mode consists of an Asynchronous Connection-Less (ACL) packet occupying one, three or five time slots and at least a single slot reply, with either master or slave as receiver. Time Division Duplex allows send/receive separation and makes for a single chip implementation. Because of packet quantization effects, the Bluetooth packet sizes become significant and their effect on user payload are summarized in Table I for a single master-slave ACL link. In Section 3, it is demonstrated that the plethora of packet types in Table 1 is surplus to requirements, except at low SNRs. However, the variety of packet types plays a role in avoiding partial payloads. The assumed Bluetooth controller behavior is that, given a maximal Bluetooth packetization scheme, for example 3DH5 or 3DH3, packets up to the maximum user payload will be formed. However, if the arriving packets do not justify the pre-set maximal scheme, then a reduced scheme is used. For example, the controller swaps from 3DH5 down to 3DH3 or even 3DH1.

The simulations were carried out with input from an MPEG-2 encoded bitstream. For static packetization, a single slice per Bluetooth packet was allocated. Maximum slice extent in MPEG-2 is limited to a single macro-block row-sized slice, but in the H.264/AVC codec, with more flexible slice format, the same problem occurs, as it is difficult to predict in advance the optimal slice size. This is because when a Bluetooth master acts as an access base station, cross-traffic within a multi-source piconet [7] arriving at the master's buffers can lead to overflow if the master cannot meet servicing deadlines [13]. Therefore, the results are equally applicable to the H.264/AVC, which may well replace the widely deployed MPEG-2 codec. PSNR was found by reconstructing with a reference MPEG-2 decoder.

Assuming the maximum asymmetric rate, with or without fully-occupied packet payload, a single-slot return packet is returned to the sender, which may be an ARQ. An ARQ may occur in the following circumstances [16]: a) failure to synchronize on the access header code; b) header corruption detected by a triple redundancy code; c) payload corruption detected by CRC; d) failure to synchronize with the return packet header; e) header corruption of the return packet. Notice that a faulty ARQ packet can itself cause retransmission. Though not investigated further herein, there is a power usage implication from excessive re-transmissions.

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[1] A third option, Forward Error Control (FEC), is available [15] as an expurgated (15,10) Hamming code after CRC for single-slot DM packet payloads modulated at the basic data-rate of 1 Mb/s but this is best applied at low (< 11 dB) E_s/N_0.

The default value of the ARQ retransmission timeout (RTO) in most Bluetooth chipsets is set to infinity. In [2], a fixed RTO and an adaptive RTO are considered. The disadvantage of a fixed RTO is that it is difficult to arrive at a value that avoids either excessive delay or excessive packet drops in all circumstances. The adaptive RTO, which is upper- and lower-bounded, is based on a smoothed round-trip time. The RTO is adapted downwards or upwards if the new round-trip time respectively is less than or more than the previous smoothed round-trip time. In [14], buffer fullness was preferred as a measure of impeding congestion in a Bluetooth piconet as it is more immediate than packet delay (or packet loss). The same may apply for a single interconnect when determining the RTO and, hence, we prefer to change thresholds based on buffer fullness.

Table 1. Packet types showing user payload and bitrates

Packet type	**User payload in bytes Bluetooth v.2**	**Asymmetric max. rate in kb/s Bluetooth v. 2**
DMI	0-17	108.8
DM3	0-21	387.2
DM5	0-224	477.8
2DH1	0-54	345.6
2DH3	0-367	1174.4
2DH5	0-679	1448.5
3DH1	0-83	531.2
3DH3	0-552	1776.4
3DH5	0-1021	2178.1

Length and master to slave bitrates, for a single ACL master-slave logical link, with DM = Data Medium Rate (no EDR) and DH = Data High Rate, *e.g.* 2DH3 is 2.0 Mb/s datarate with a three time-slot packet

To determine when to change the datarate, a measure of the channel bit-error rate (BER) is required. The Bluetooth specification requires a value between 0 and 255 to be returned from a call across the Bluetooth Host-Controller-Interface (HCI) to the Bluetooth module. In the widely deployed Cambridge Silicon Radio chipset, there is an almost linear relationship between link quality and BER, which may be used to determine datarate swapping. The precise relationship appears in [2], though the same research points out that there is a risk that this value may oscillate widely, making deriving a smoothed value difficult. A noise value was also the basis of robust video streaming in [10], with the value determining the ARQ threshold.

To maintain an even number of slots in a Bluetooth frame width there is always a reply slot, whether ARQ is turned on or not. In [18], a general scheme for slot leasing by a master to a slave so that direct slave-to-slave communication can take place. We have adapted this scheme for ARQ slot leasing. The advantage is enhanced utilization of the Bluetooth shared channel and we assume ARQ time-slot leasing in some simulations (Section 3).

A Gilbert-Elliott [4] two state discrete-time Markov chain modeled the wireless channel error characteristics between a Bluetooth master and slave node. The original design of Bluetooth assumed a burst error channel [11]. Work in [19] established the validity of employing a first-order Markov chain is a good approximation in modelling the error process in a fading channel, for example in an indoor environment due to the motion of people. By adopting this model it was possible to simulate non-independent burst errors of the kind that cause problems to an ARQ mechanism. In the simulations (Section 3), the mean duration of a good state, T_g, was set at 2 s and in a bad state, T_b, was set to 0.25 s. In units of 625 μs (the Bluetooth time slot duration), T_g= 3200 and T_b= 400, which implies from

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

that, given the current state is g,„Pgg, the probability that the next state is also g , is 0.9996875 and Pbb, given the current state is b, the probability that the next state is also b, is 0.9975. At 3 Mb/s, the BER during a good state was set to 10^{-5}, and during a bad state to 10^{-3}. The transition probabilities, Pgg and Pbb, as well as the BER, are approximately similar to those in [17], but the mean state durations are adapted to Bluetooth. The two states result in SNRs of respectively 15.97 and 13.02 dB.

Figure 1 plots the BER for the two EDR modulation schemes in an Additive White Gaussian Noise (AWGN) channel. By means of the equations governing these plots [12] the equivalent BER for a 3.0 and 2.0 Mb/s datarate is found. Figure 2 illustrates the definite advantage of switching in an AWGN channel from one packet type to another and from one datarate to another. Fig. 2 extends the analysis that [16] supplies for the Bluetooth basic rate. At any one value of E_s/N_0 a particular type of packet gives optimal throughput. For example, at a point around 15 dB and above 3DH5 gives better throughput than all other schemes. Interestingly, 3DH3's throughput is less than 2DH5 at SNR's lower than 15 dB. This implies that for dynamic packetization schemes, either 3DH5 or 2DH5 packets should be selected for higher SNR (above 11 dB) scenarios. The Gilbert-Elliott model's two states fall conveniently within the two optimal packet type regimes. The main area where a practical noise sensing mechanism may result in a sub-optimal solution is at the crossover point at around 15 dB.

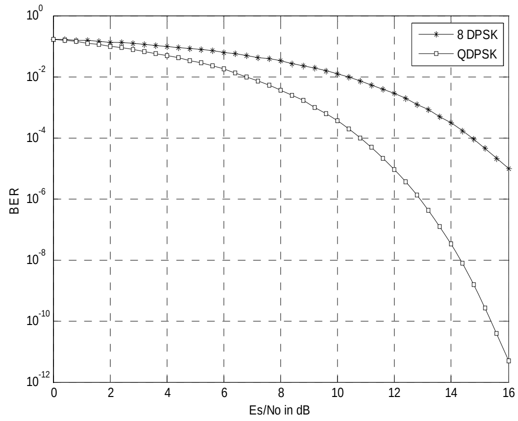

Figure 1. BER against SNR for 8DPSQ at 3.0 Mb/s and QDPSK at 2.0 Mb/s

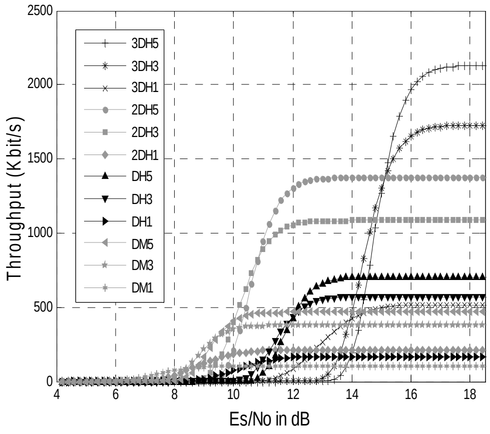

Figure 2. Average throughput of Bluetooth ACL packet types in AWGN for differing Bluetooth modulation modes

3. Results

This research employed the University of Cincinatti Bluetooth (UCBT) extension[2] to the well-known ns-2 network simulator (v. 2.28 used). The UCBT extension has the advantage that it supports Bluetooth EDR but is also built on the air models of previous Bluetooth extensions such as BlueHoc from IBM and Blueware. Unlike earlier models, the UCBT extension also takes account of clock drift.

An MPEG-2 CIF-sized encoded video `news clip' at 1.2 Mb/s, with Group of Picture (GOP) structure of N=12, M=3 was selected as input. The duration of the `news clip' was 40 s, being selected as it is longer than that of standard test sequences. The news clip[3] features medium motion consisting of an announcer with a changing background. Higher motion clips accentuate the effects reported herein but results are not included for reasons of space.

In Fig. 3, a fixed single-slice per packet scheme was simulated at the maximum EDR datarate, with a Gilbert-Elliott channel but with no ARQ. 3DH5 packets were selected as the default. The PSNR verges on the acceptable, with a PSNR between 25 and 28 dB being preferable for a mobile device. Delay is low, Table 2, resulting in no loss to missed playout deadlines. If ARQ is added, with default infinite RTO, Fig. 4, then delay increases resulting in losses due to late arrivals. The retransmitted packets also contribute to increased buffer overflow, Table 3. The mean PSNR is somewhat reduced when ARQ is introduced and, therefore, ARQ in its default setting cannot be recommended.

When dynamic packetization is introduced (see Section 1), with 3DH5 packets, the mean PSNR now becomes acceptable for a mobile device, Table 4, with dips in quality, Fig. 5, being caused by scene changes. Delay is further reduced, Fig. 5, over the fixed packet scheme. Therefore, in these simulations, the risk of temporal error propagation was less than the advantage gained by more flexible packetization. When dynamic packetization was applied with ARQ then similar effects occurred as with the static scheme, causing the total loss rate to increase to 0.1735 and the mean PSNR to drop to 26.99 dB. When the EDR was reduced

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[2] Download is available from `http://www.ececs.uc.edu/~cdmc/ucbt/`.

[3] Viewable at `http://www.essex.ac.uk/ese/research/vidnet_lab/ex4wireless.shtm`

to 2 Mb/s, with 2DH5 packets, Fig. 6, the RF packet loss rate dropped to such an extent that the addition of ARQ made little difference to the results. Compared to Fig.5, the instantaneous PSNR was similar, resulting in a similar mean PSNR, Table 5. Delay was constrained to between about 0.16 and 0.8 s, tightly oscillating between these limits, resulting in no loss due to the late arrival of packets, Table 5. Therefore, dropping to the lower data-rate reduces RF packet loss and preserves similar video quality. ARQ in its default setting should be turned off.

Table 2. Statistics for the stream of Figure 3

Total loss rate	0.35783
RF loss rate	0.10311
Loss rate due to buffer overflow	0.25471
Loss rate due to late arrival	0.00
Mean PSNR (dB)	23.89
Mean delay (s)	0.1479

Table 3. Statistics for the stream of Figure 4

Total loss rate	0.3994
RF loss rate	0.00
Loss rate due to buffer overflow	0.3685
Loss rate due to late arrival	0.0308
Mean PSNR (dB)	23.07
Mean delay (s)	0.2034

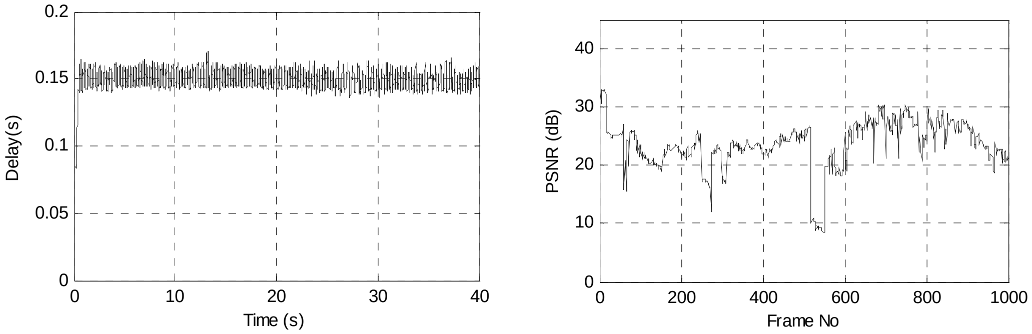

Figure 3. Delay and video quality for a 3 Mb/s datarate, without ARQ, using a single slice per Bluetooth packet

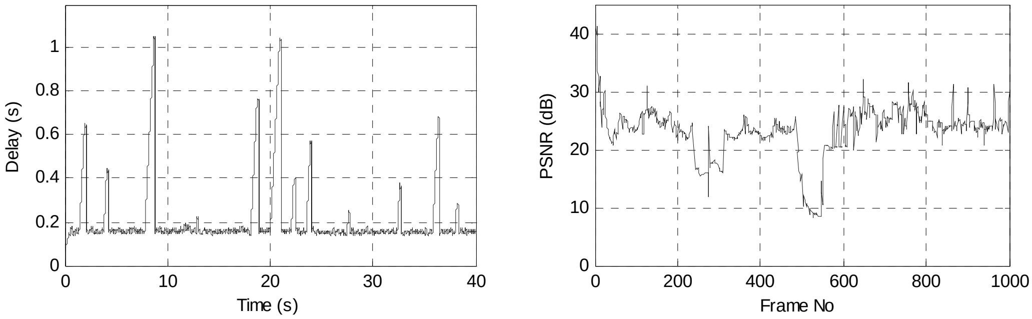

Figure 4. Delay and video quality for a 3 Mb/s datarate, with ARQ, using a single slice per Bluetooth packet

The relative immunity of the EDR $\pi/4$QPDSK modulation to RF noise can be traded against delay to adaptively switch between the 3.0 Mb/s and 2.0 Mb/s data-rates. In simulations, the two datarates were swapped when the Gilbert-Elliott model states changed, selecting the 2.0 Mb/s datarate, when the lower SNR was entered. Fig. 7 shows the behavior over time, while Table 6 summarizes. It is evident that, when combined with dynamic packetization, an adaptive scheme produces a vastly improved video quality.

The ARQ RTO can also be adaptively selected in terms of number of retransmissions needed to successfully transmit a packet. A threshold is set that is the maximum number of retransmissions allowed when the buffer is empty. The maximum number of retransmissions is subsequently changed by a factor depending on the buffer fullness reported by the Bluetooth module. Propagation delay is taken into account at all times. As mentioned in Section 1, this is a form of cross-layer interaction over the Bluetooth HCI.

Table 4. Statistics for the stream of Figure 5

Total loss rate	0.1504
RF loss rate	0.1504
Loss rate due to buffer overflow	0.00
Loss rate due to late arrival	0.00
Mean PSNR (dB)	27.39
Mean delay (s)	0.0073

Table 5. Statistics for the stream of Fig. 6.

Total Loss rate	0.1632
RF Loss rate	0.0037
Loss due to buffer overflow	0.1594
Loss rate due to late arrival	0.00
Mean PSNR (dB)	27.36
Mean delay (s)	0.1762

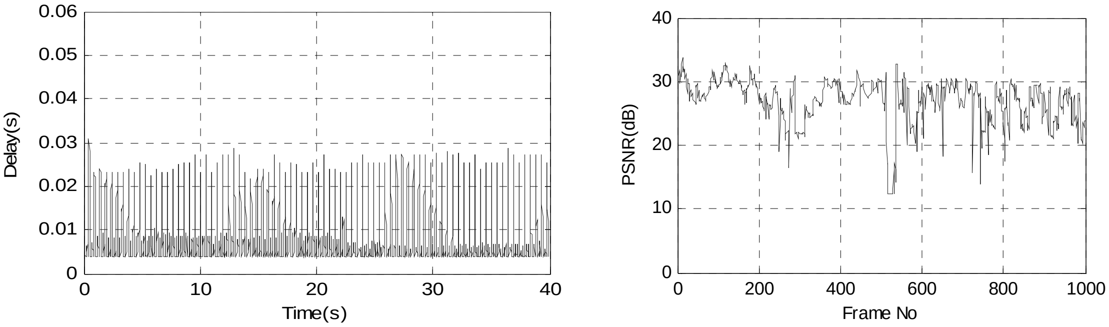

Figure 5. Delay and video quality for a 3 Mb/s datarate, without ARQ, using dynamic allocation of slices to Bluetooth packets

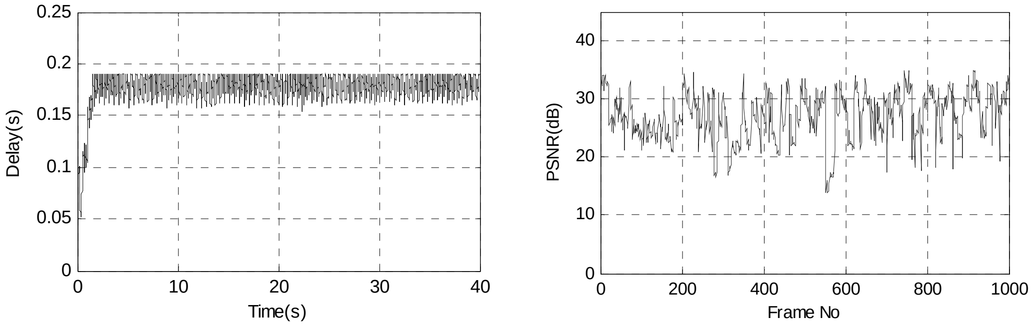

Figure 6. Delay and video quality for a 2 Mb/s datarate, without ARQ, using dynamic allocation of slices to Bluetooth

Table 6. Statistics for the stream of Figure 7

Total loss rate	0.0907
RF loss rate	0.0907
Loss rate due to buffer overflow	0.00
Loss rate due to late arrival	0.00
Mean PSNR (dB)	37.36
Mean delay (s)	0.0162

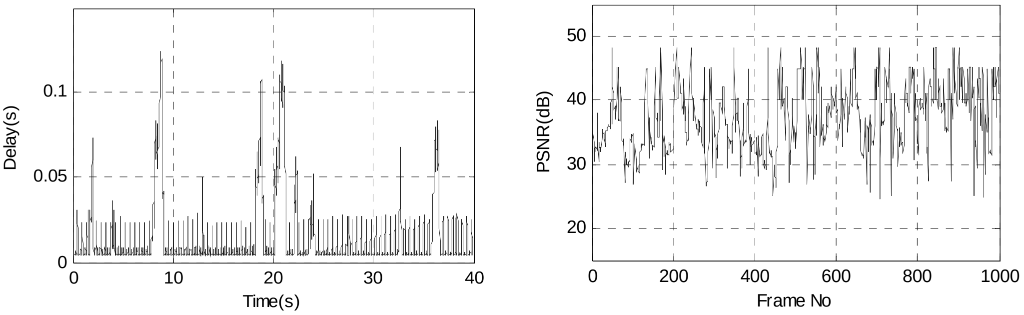

Figure 7. Delay and video quality with an adaptive datarate, without ARQ, using dynamic allocation of slices to Bluetooth packets

The formula employed is summarized as

$$N = round\left(\frac{m.(c-f)}{c}\right), \tag{2}$$

where N is the maximum number of retransmissions allowed -- the RTO, m is the maximum number of retransmissions allowed when the buffer is empty, f is the number of packets buffered in the send buffer (buffer fullness), and c is the buffer capacity (set to 50 in the simulations). The operator *round* returns the nearest integer. Fig. 8 shows the result of this scheme, where it is self-evident that the video quality is still further improved. The mean PSNR was 41.18 dB, the mean delay was 0.0171 s, and no packets were dropped due to buffer overflow or RF loss. In Fig. 9, the mean system throughput experienced by applications over the shared channel is shown with an AWGN channel model. The packet type was full-capacity 3DH5. It will be observed that turning on ARQ with the default infinite RTO actually decreases the throughput at lower SNRs (less than 17 dB). This is because errored ARQ packets result in re-transmission of packets, even if the original data packet was successfully received. The retransmitted packet delays reception of subsequent new data at the application. Lastly, if it is assumed that the ARQ single return slot is leased for some other direct slave-to-slave communication within a Bluetooth piconet [7] then the overall system throughput significantly increases. This assumes a piconet configuration in which there is one master-slave interconnect but also two other slaves communicate directly (Section 2). Optimal payloads are also assumed for the direct slave-to-slave link. Results for packet types 3DH3 and 3DH1 are similar in trend, except that the difference between the individual plots is accentuated. Therefore, in a multi-source Bluetooth piconet, modifying Bluetooth to lease slots is preferable if adaptive ARQ is not deployed.

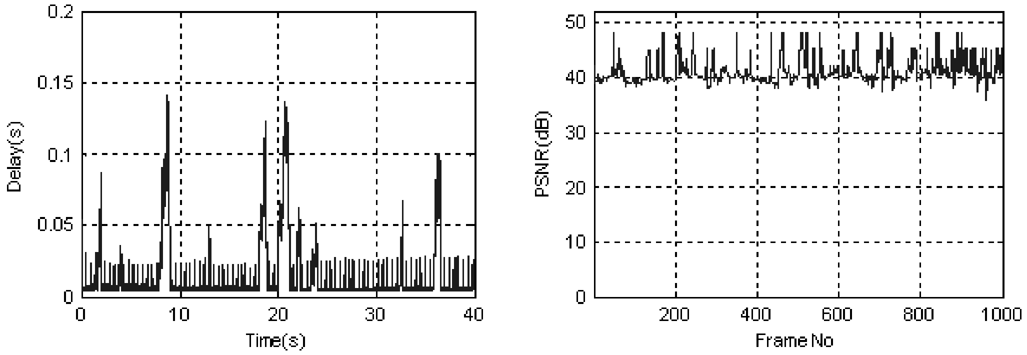

Figure 8. Delay and video quality with an adaptive datarate, with adaptive ARQ, using dynamic allocation of slices to Bluetooth packets

3. CONCLUSION

Streaming of personal video clips has long eluded the designers of short-range wireless interconnects with practical conference demonstrations being of disappointingly low quality. By two additional modulation schemes, Bluetooth v. 2.0 has provided the capacity for current devices to achieve high-quality streaming. However, this will not be achieved unless due attention is paid to video issues such as playout deadlines. The default Bluetooth settings are not suitable for video streams. This paper has demonstrated high-quality video streaming is possible if full advantage of the Bluetooth packet scheme is made. In practice, maximally sized packets should be selected and the bitstream should be dynamically packed into those packets. The default ARQ mechanism is only effective if it can be applied adaptively. However, the two modulation schemes do allow effective datarate swapping, which does counteract RF noise. When all these techniques are applied, video quality improves from being on the margins of acceptability, to acceptable for mobile device viewing, and finally to a quality similar to IP-TV. Further work would investigate adaptive ARQ in low SNR environments.

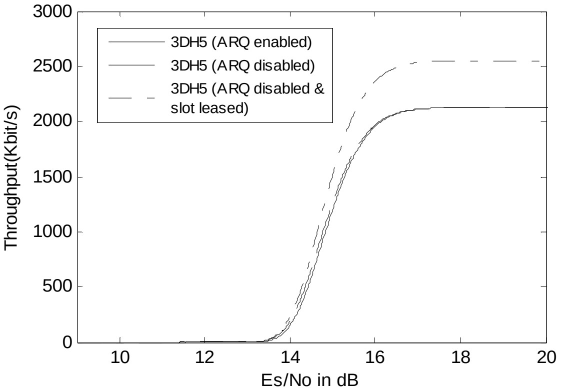

Fig. 9. System throughput, with and without ARQ, showing slot leasing.

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