High Definition Video in Multi-User WPANs

Sandra Scott-Hayward† **and Emiliano Garcia-Palacios***

Institute of Electronics, Communications and Information Technology (ECIT)
Queen's University Belfast, Belfast, BT3 9DT, Northern Ireland

E-mail: †`sscotthayward01@qub.ac.uk` *`e.garcia@ee.qub.ac.uk`

Abstract — **The IEEE 802.15.3c standard for millimeter-wave-based high-rate wireless personal area networks (WPANs) was approved in September 2009. The 7 GHz of spectrum available for unlicensed use in the 57-64 GHz band is ideally suited to multimedia applications with high data rate requirements. High-Definition (HD) video is one such potential application. A simulation model for the IEEE 802.15.3c hybrid medium access protocol (MAC) has been developed. The simulation is used to study the transmission of a series of H.264/SVC (MPEG-4 Part 10) HD video sources. Clear throughput losses due to static channel time allocation are identified. The model will be further used to explore resource allocation methods for the mm-Wave network.**

Keywords — **IEEE 802.15.3c, WPAN, HD-Video, VBR Traffic, Throughput**

I INTRODUCTION

The demand for high speed, high bandwidth wireless communications is growing as the use of multimedia applications increases. Current wireless technologies support multi-Megabit per second (Mbps) data rates over varying ranges. However, many applications require Gigabits per second (Gbps). An example is HD video streaming. The data rate requirement for an uncompressed HD video stream 1920*1080 (frame size) with 24 bits per pixel (colour support) and 60 frames per second (frame rate) is approximately 3 Gbps. Current standards in frame size, colour support and frame rate give a range of HD data rates from 0.5 Gbps to 5.5 Gbps [1]. Other widely discussed applications requiring Gbps or multi-Gbps data rates are rapid upload/download file transfers and wireless gaming or projection. A complete list of the usage models for high data rate communication is included in [2].

The provision of high data-rate, high quality of service (QoS) applications is supported by bandwidth. In 2001, the Federal Communications Commission (FCC) allocated 7 GHz of spectrum in the 57-64 GHz band for unlicensed use. This band supports high data rate, short range, line-of-sight (LOS) directional transmissions, which falls into the category of WPANs.

The IEEE 802.15.3c standard [3] was approved in September 2009. It supports a range of data rates as high as 5 Gbps. While these data rates can be achieved at the physical layer (PHY), the actual throughput at the MAC layer in a network is always less than the PHY throughput. This is due to overheads introduced at the MAC layer for data packetising and error-checking, for example. In addition, and quite significantly, when multiple devices attempt to transmit in a shared medium, they are competing for the limited bandwidth available. Collisions occur when devices try to access the medium simultaneously and this results in loss of data packets, waste of bandwidth and, as a result, reduction in MAC throughput. The IEEE 802.15.3c standard defines improvements to the existing 802.15.3 MAC to support the new mm-Wave PHY. For example, frame aggregation techniques and block acknowledgment are introduced as means to reduce the MAC overhead.

Considering an indoor WPAN such as a living room, multiple high data rate applications will have to co-exist. Several research questions arise when characterising such coexistence. In an attempt to satisfy bandwidth demands, terminals will compete for bandwidth in a selfish manner. What are the consequences of this competitiveness to access the medium? How are transmissions to be scheduled to use the bandwidth most efficiently? Can service provision be guaranteed and with what quality of service?

Performance analyses of the IEEE 802.15.3c standard have to date focussed on simplistic traffic models. Multiple devices in a network transmit the same amount of data at a constant rate enabling static scheduling of a CTA for the duration of the transmission [4, 5]. However, in reality devices will have heterogeneous traffic, which will likely vary over time. In this work, a model of the IEEE 802.15.3c hybrid MAC protocol is developed. The impact of transmitting realistic video traffic over this network is studied.

The rest of this article is organised as follows: in Sect. II the IEEE 802.15.3c MAC protocol is introduced. In Sect. III we highlight related work in this area. In Sect. IV variable bit rate (VBR) video traffic is discussed. Section V introduces the model and simulation parameters and in Sect. VI the results are presented. Finally, in the conclusion the results are summarised and our proposed further work on this topic is identified.

II IEEE 802.15.3c MAC Protocol

An 802.15.3c network, or piconet, is a wireless adhoc data communications system in which a number of independent devices communicate with each other in a peer-to-peer fashion [3]. In the 802.15.3c protocol, medium access is controlled by a piconet controller (PNC). This role can be held by any device in the network and is usually allocated to the first member of the network. Medium access is based on a frame structure, as shown in Fig. 1.

The superframe is initiated by a beacon from the PNC. A contention phase known as the contention access period (CAP) follows the beacon. It is essentially a CSMA/CA (Carrier-Sense Multiple Access/Collision-Avoidance) phase for command and data exchanges using the Binary Exponential Backoff (BEB) mechanism.

In 802.15.3c, devices compete during the CAP to transmit a request for dedicated channel time during which the application data can be transmitted. The time slot is called a CTA (channel time allocation) and occurs during the channel time-access period (CTAP), which follows the CAP.

The CTAP operates under the TDMA (Time Division Multiple Access) principle. In this phase, a time slot or CTA is assigned to any devices that have requested an access period, provided the time is available. Management transmissions (MCTAs) are also allocated time in the CTAP.

For asynchronous data e.g. a one-off file transfer request, the assignment of channel time is indicated in the subsequent beacon. The asynchronous request is assigned a single CTA for the total amount of time needed for the data transfer. The assignment is scheduled in the superframe on a best effort basis. If additional data is to be sent, the user must request another CTA.

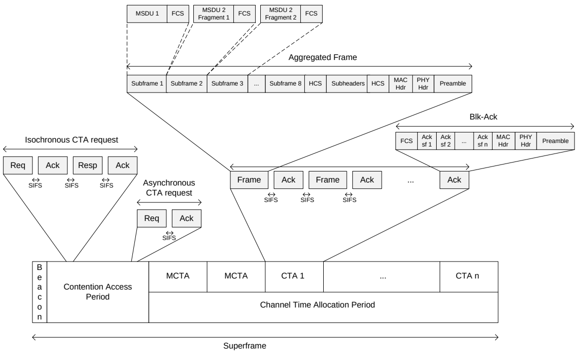

Fig. 1: Superframe structure, Frame aggregation and Block acknowledgment in IEEE 802.15.3c

For isochronous stream requests such as a video stream transmission request, the PNC replies to the CTA request in the CAP with a CTA response. If resources are available, the isochronous request is then assigned a CTA in each subsequent superframe for the duration of the video. The isochronous stream does not expire until it is terminated either by the source device, the destination device or the PNC.

In order to improve the MAC efficiency, frame aggregation and block acknowledgment are supported by the standard. Frame aggregation involves fragmenting and mapping MAC Service Data Units (MSDUs), as received from the upper layers, into multiple subframe payloads. The subheader for each subframe is combined to form the MAC sub-header and up to 8 subframes are aggregated into a single frame thus increasing throughput. Standard and low-latency aggregation mechanisms are defined [3]. The low latency version limits transmission delay under low traffic load by transmitting empty subframes of zero length if sufficient MSDUs are not received. A block acknowledgment (blk-ack) is sent for the aggregated frame, within which each subframe is acknowledged. The standard aggregation method along with the blk-ack frame is shown in Fig. 1.

The benefit of these mechanisms is improved efficiency by reducing frame/ack overhead. However, the loss of a large frame can be critical to quality of service so that when selecting subframe- and frame size, the wireless channel condition should be considered [6].

III Related Work

As presented in Sect. II, the IEEE 802.15.3c standard has a hybrid medium access protocol, where hybrid refers to the combined CSMA/CA(CAP)-TDMA(CTAP) MAC.

The coordination between the CAP and the CTAP for the 802.15.3 (2.4 GHz) protocol is studied in [7]. Network performance is improved by varying the retry limit and the length of the CAP and allowing simultaneous transmissions between non-interfering devices.

For the mm-Wave IEEE 802.15.3c standard, Pyo and Harada [4] consider the overall network throughput based on contention in the CAP for transmission of CTA requests and the resulting allocation of CTAs for high-speed data transmission in the CTAP. The effect of varying the time allocated to the CAP is studied. The CAP must not be so large as to cause low data transmission time in the CTAP, nor so small as to limit successful transmission requests. Throughput improvement is proposed by providing an optimum access time for the CAP based on the number of devices in the network and through a private channel-release time, which provides a dedicated time for the device to send its CTA release request. The latter method avoids the possibility of collision/delay while contending to send the CTA release request during the CAP, which could result in an unused CTA for one or a number of superframes.

A number of performance analyses demonstrate the benefit of implementing frame aggregation and block acknowledgment in IEEE 802.15.3c [8–11]. A 30% MAC efficiency gain by using blk-ack or NACK for the aggregated frames is presented in [8]. In [9] the results show that using the standard frame aggregation mechanism with a large subframe length improves system throughput. In [10] the authors consider the limitation that the PHY frame size places on the aggregated frame size. The proposal is to overcome this by adding a PHY frame sequence number to the MAC header such that an aggregated frame can be transmitted via multiple PHY frames. A combination of frame aggregation, Dly-ACK (similar to the blk-ack mechanism), and an Improved-Back-off Algorithm (IB) is used in [11] to increase the throughput of the WPAN MAC.

High data rate applications are proposed for the 60 GHz WPAN. However, the models developed to date and discussed here predominantly analyse the performance of the WPAN MAC with constant frame length/frame payload for each device. This does not match with the variety of multimedia applications identified in Sect. I and their realistic traffic profiles. The specific case of HD video traffic is explored in the next section.

IV VBR Video Traffic Requirements

Operating at a high PHY data rate, such as possible at mm-Wave frequencies, the transmission of uncompressed HD video is possible in a WPAN. The constant bit rate of uncompressed HD video simplifies the PNC scheduling task. However, the associated high bandwidth requirement (0.5-5.5 Gbps [1]) results in little resource availability for other network applications. In contrast, using an encoding scheme to compress the video means that good video quality can be provided at substantially lower data rates. For example, using a coding scheme such as H.264/MPEG-4 Part 10 can reduce the bandwidth requirement to between 64 kbps and 240 Mbps, depending on the application. For HD formats (Level 4), the maximum compressed bit rate is 20-50 Mbps [12]. Compression to produce constant quality video results in highly variable traffic. The difference in peak and mean frame bit rate for the set of video traces [13] used in the simulation is shown in Table 1. Clearly, a simple, constant CTA as used with uncompressed video will not suit the VBR of compressed video. The question is how much bandwidth is wasted in this scenario and how can the network efficiency be improved.

Table 1: Statistics of Video Traces

	Mean Frame Bit Rate (Mbps)	Peak Frame Bit Rate (Mbps)
Transporter2	27.945	110.922
Blue Planet	13.153	145.948
Finding Neverland	15.515	92.683
Speed	21.530	92.352
The LakeHouse	13.839	132.999

In order to satisfy the quality of service (QoS) of multiple device requests with heterogeneous traffic, bandwidth must be dynamically allocated. For example, allocating bandwidth to match the peak bit rate should be avoided as this will lead to unused bandwidth during many portions of the transmission when the actual bit rate is well below the peak. This is highlighted in [14].

Some resource management methods have been proposed. In [5] a method to support Internet Protocol TV (IPTV) flows, which require high data rate and high QoS is presented. This method takes advantage of simultaneous transmissions using directional antennas. The successful transmission of multiple flows of a HDTV format video is demonstrated in the simulation. However, competition for resource from other applications with different parameters is not considered. A set bandwidth is reserved per flow, which does not focus on the variance in frame size within that flow.

Resource allocation for this type of traffic has also been explored in [15, 16] using variable stepsize least-mean square traffic prediction and a scene change detection algorithm. Results are presented for a single device transmitting a VBR video to another device and do not account for contention with other devices competing for the available bandwidth. Two issues can be identified with this proposal. The first is that the device sends a request in every CAP (or in an MCTA for increased reliability) identifying its bandwidth requirement for the next superframe. For a large number of devices in the network, this will significantly reduce the available data transmission time. Secondly, what happens if the requested bandwidth is not available in the next superframe?

In this work we study the transmission of compressed HD-video using the IEEE 802.15.3c protocol. The impact of the VBR traffic on the network throughput is identified and the requirement for a dynamic scheduling mechanism to support this is highlighted. This contrasts with the static scheduling or single device resource allocation assumed in previous research.

V Simulation Model

A MATLAB simulation of the IEEE 802.15.3c MAC protocol has been developed. The network consists of a PNC plus devices. In the 802.15.3c standard a common mode signalling is defined based on the single carrier (SC) PHY, supporting coexistence and interoperability. The mandatory modulation and coding schemes are used (see Table 2). An ideal channel is assumed. This means that the packets dropped in the contention access period can be attributed to collisions alone and are not a result of varying channel conditions.

The traffic in the simulation is a set of H.264/SVC (MPEG-4 Part 10) HD video sources [13]. MPEG-4 is selected for its high compression efficiency and suitability for HD content transmission. Some statistics of the video traces are listed in Table 1.

The video traffic is represented by a stream of frames of varying size, as produced by the MPEG-4 codec. This traffic is then packetised into RTP (Real-Time Protocol) packets as described in RFC 3016 [17]. For the high data rate, mm-Wave network represented, one frame or fragment of a frame is contained in one RTP packet. The RTP header is 12 bytes.

This traffic is then encapsulated in 4096-byte UDP packets, which introduce an additional 8-bytes header. The value of 4096 bytes has been chosen to take advantage of the larger fragment size (maximum of 1 MB) allowed in the 802.15.3c protocol, which reduces overhead, but also to limit the impact of frame loss, as identified in [6]. With large frame sizes, higher SNR (signal-noise ratio) is required to maintain a certain PER (packet error rate). The IP packet is created by adding a 20-byte IPv4 header to the UDP datagram.

Table 2: Parameters for Throughput Analysis

Parameter	Value
Number of devices, N	2-40
Preferred Fragment Size	4096 Bytes
Data Rate	1.65 Gbps
Basic Rate, Beacon Rate	12.5 Mbps, 25.8 Mbps
Length of Beacon	(27+(7*N)) Bytes
SIFS, MIFS	2.5 μs, 0.5 μs
CCA Time	4 μs
Channel Time Request, T_{req}	24.36 μs
Channel Time Response, T_{resp}	19.24 μs
Length of Imm-Ack, $T_{\text{imm-ack}}$	10 Bytes
Length of Blk-Ack, $T_{\text{blk-ack}}$	7+(2*No. Subframes) Bytes
Length of frame, T_{frame}	Preamble(1.96 μs) + Header(9.6 μs) + T_{payload}

Typically, the encoded audio is packetised independently from the video so that two separate streams are used to transport the data in an IP environment. MPEG-4 High Efficiency Advanced Audio Coding (HE-AACv2) can be used with H.264 video and can offer "good" audio quality at 16-24 kbps Mono [18]. In the simulation, a 5-channel audio stream of 120 kbps accompanies each video.

The IP packets are the MSDUs (MAC service data units). In accordance with the standard aggregation technique, as described in Sect. II and shown in Fig. 1, the MSDUs are fragmented or mapped into subframes. The subframe is based on the preferred fragment size identified by the device when associating with the piconet. In this work it is set to the UDP/IP packet size. Provided the frame deadline will not be exceeded, the frame can also be split across multiple superframes/CTAs. The MPDU (MAC protocol data unit) is produced at the MAC layer ready for transmission at the PHY layer.

The parameters used in the simulation are listed in Table 2.

VI Results

To study the throughput of VBR traffic in the 802.15.3c WPAN, each device has a video to transmit and sends an isochronous stream CTA request. The CTA request is based on the mean bit rate of the relevant video, as per Table 1, and calculated with respect to the superframe duration. A device would not know the mean bit rate of the video in advance but this value is used for comparison. The video traffic is generated from the video trace [13] and packetised as described previously. Repeated simulation runs of 15 s duration were made.

For each of the selected videos, the expected throughput based on N devices successfully receiving a CTA to transmit at the mean bit rate is plotted. This is compared with the actual throughput based on N successful devices transmitting within their allocated CTA according to the VBR of the video trace. The results are shown in Fig. 2. The maximum number of devices that can be allocated a CTA under the given system settings varies but it is seen that for a video such as *Transporter2*, the limit is 28 devices/flows. For the lower mean bit rate videos, such as *The LakeHouse*, a limit is reached at around 55 devices/flows.

The reduction in actual throughput compared with expected throughput varies between 10% and 30% across the five videos. The difference can be attributed to the variation in frame size leading to either allocated CTA time being underused or insufficient. The penalty for inappropriate provisioning is both waste of bandwidth, due to underused CTAs, and loss of quality, due to frames that can't be transmitted within their deadline being dropped.

Figure 2 illustrates the case of homogeneous traffic in the network (all N devices use the same video source). Simulations of random video traffic in the network have also been performed. Over the course of a 1 minute simulation, each of the 40 devices in a network attempts to send a video flow. The start time, end time and duration of the flow are random. Similar to the single video examples, once a device's request to transmit is successfully received and provided there is sufficient time available in the CTAP, the CTA is assigned. The CTA duration is based on the request made by the device, which is, as previously, the mean bit rate of the particular video. In Fig. 3a the difference in actual and expected throughput over the course of the simulation is shown. The average difference in throughput is 12%. Also illustrated in Fig. 3b is the effect on the video application of limiting the CTA duration to the mean bit rate. The percentage of dropped frames varies between 1% and 60%. While some loss of B (bidirectional coded) and P (inter-coded) frames in the transmission may be tolerated, losing an average of 5% of I (intra-coded) frames will significantly reduce the quality of the video transmission.

The conclusions we draw from this analysis are that in order to maximise network throughput, CTAs must be adapted to suit VBR applications and to meet the quality of service requirements of individual applications.

VII CONCLUSION

In this paper, we have studied the suitability of the IEEE 802.15.3c mm-Wave WPAN standard for compressed HD video distribution. A MATLAB simulation modelling the hybrid CSMA/CA-TDMA MAC was developed.

The analysis shows that a significant loss in throughput and quality of service is experienced when a static channel time allocation is made in the network based on the mean bit rate of a variable traffic stream. The conclusion is that a dynamic system is required, which will link CTAs to the varying traffic stream. Shared knowledge in the network such as number of devices could be exploited to reduce the contention in the CAP. This would enable more devices to be allocated CTAs or the CAP duration to be reduced making an increase in the CTAP possible. Similarly private knowledge of a device regarding the contents and traffic type in its buffer could be used to assist the PNC in optimising resource allocation.

Our future work will explore resource allocation methods to support heterogeneous high data-rate traffic in a mm-Wave network with minimum computational overhead.

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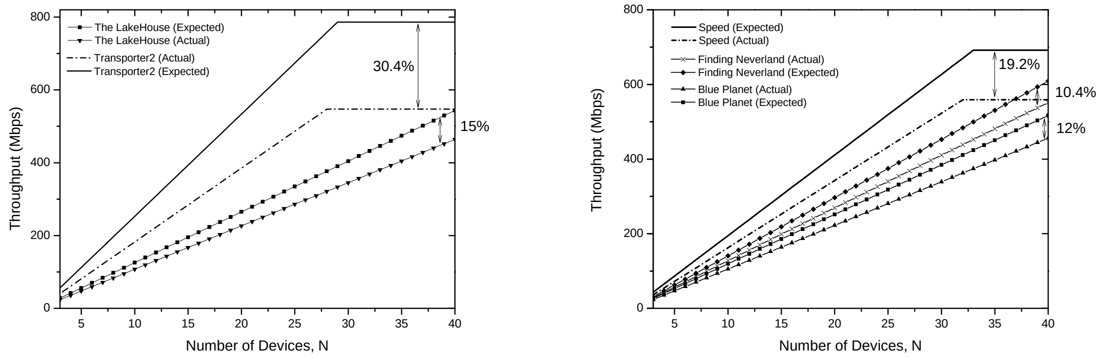
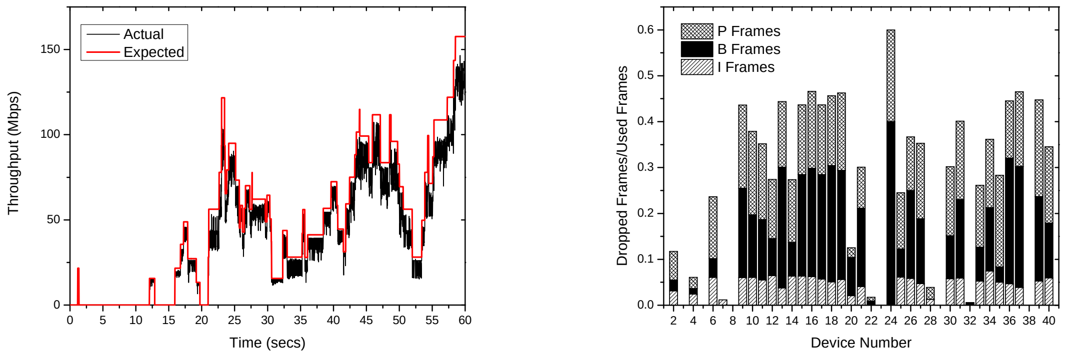


(a) (b)

Fig. 2: Actual Throughput vs. Expected Throughput for H.264/SVC HD video traces



(a) (b)

Fig. 3: (a) Actual vs. Expected Throughput for heterogeneous video traffic, (b) Percentage dropped frames per device

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