STREAMING UNCOMPRESSED HD OVER WIRELESS CHANNELS

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ABSTRACT

Emerging high-throughput wireless LANs, especially those operating in the 60 GHz band, provide sufficient bandwidth to transport uncompressed HDTV. Of these IEEE 802.15.3c is promising as it was specifically designed for device-to-device communication. 60 GHz LANs must still solve the problems associated with limited indoor range and directed beam transmission. This paper offers a network architecture for HD streaming, which extends IEEE 802.15.3c's small-scale, personal area network structure so that it can accept connections initiated elsewhere in a large building or vehicle. In doing so, IEEE 802.15.3c is supplemented with an out-of-band control channel. The paper also compares wireless options for uncompressed HD streaming.

INTRODUCTION

Uncompressed High Definition (HD) video streaming via a High Definition Multimedia Interface (HDMI) wired connection avoids the need for compatible decoders at display devices. However, in large buildings such as airline terminals there is a wiring and flexibility problem when there are multiple receiver positions and/or access points. Wireless HDMI distribution can potentially overcome this problem and extend streaming across just a single link to networked distribution of uncompressed HD video. A wireless connection also facilitates rapid switching between devices.

A wireless network, nonetheless, must meet HD video quality requirements. Emerging uncompressed video data rates (see Table 1) are between 0.5 and 5.6 Gbps for resolutions ranging from 1280×720 pixel/frame at 24 frame/s to 1920×1080 pixel/frame at 90 frame/s. At these resolutions, quality imperfections are readily apparent to the viewer and consequently latencies should be in the tens of milliseconds, and error rates as low as 10^{-12}. However, with the emergence of high-throughput wireless solutions, it could be that, despite the volume of HDMI units already shipped, a wireless HDMI solution will be preferable in the long run. Compressed HD IPTV could also benefit from high-throughput wireless distribution, as identified by Cai et al. (1), but IPTV system requirements are similarly stringent (packet loss rates of 10^{-6} and path latency of 50 ms).

There is a number of contending high-throughput indoor wireless standards, as summarized in Table 2. Both IEEE 802.11n and IEEE 802.11ac employ 802.11 Medium Access Control (MAC) in the 5 GHz band, as does the proposed IEEE 802.11ad standard (2) at 60 GHz, and they can, therefore, be characterized as WiFi extensions. The IEEE

802.15.3c, Baykas et al. (3), MAC considered herein is organized as a small-scale, ad hoc network and does not use the negotiable, distributed data access of WiFi. In fact, though the IEEE 802.11e QoS extension with centralized access control is available to WiFi systems, it is unlikely to be always activated on devices, putting WiFi at a disadvantage for real-time multimedia applications. The Time Division Medium Access (TDMA) scheme of IEEE 802.15.3c for data is further discussed later in this article. Due to TDMA, the beacon-based superframes of IEEE 802.15.3c result in lower latencies, increasing the throughput of real-time video transmission. The high-throughput WiFi extensions may be more suitable for applications such as wireless desktop and wireless LAN bridge, whereas 802.15.3c has been designed from the start as a multimedia network between consumer devices.

Table 1 - Data-rates for emerging and projected uncompressed HDTV formats according to frame rate and bits per channel per pixel for a progressive display.

Pixels per line	Active lines per picture	Frame rate per second	No. of bits per pixel	Data rate (Gbps)
1280	720	24	24	0.531
1280	720	30	24	0.664
1440	480	60	24	0.995
1280	720	50	24	1.106
1280	720	60	24	1.327
1920	1080	50	24	2.488
1920	1080	60	24	2.986
1920	1080	60	30	3.732
1920	1080	60	36	4.479
1920	1080	60	42	5.225
1920	1080	90	24	4.479
1920	1080	90	30	5.599

Table 2 - Characterization of indoor high-throughput IEEE wireless standards (there are also ECMA 387 and WIGWAM standards).

Standard (Industry version)	Features	Modulation	Spectrum band	Max. gross datarate
IEEE 802.11n (WiFi)	MIMO up to 4 streams, 40 MHz channels	OFDM	2.4 GHz, 5 GHz	288.9/600 Mbps (20/40 MHz channels)
IEEE 802.11ac (WiFi)	80-160 MHz channels, up to 256-QAM, MIMO up to 8 streams	OFDM	5 GHz	1 Gbps
IEEE 802.11ad (WiGig™)	Beam-forming	OFDM	60 GHz	Upwards of 1 Gbps
IEEE 802.15.3c (WirelessHD™ for AV OFDM)	Beacon with superframe MAC	OFDM (HSi and AV), SC-SDE	60 GHz	5.28 Gbps (SC-FDE), 25 Gbps (WirelessHD™ for < 1m)

SC-FDE = Single-Carrier Frequency Division Equalization, HSI = High Speed Interface, AV=Audio Video)

IEEE 802.15.3c operates within the 60 GHz band. Directed beams are almost obligatory for effective 60 GHz transmission and as a result connection access then becomes more complex. Consequentially, out-of-band solutions with conventional 802.11 WiFi systems and 802.15.3c transmission become attractive, as we consider in this paper. This is especially so if the small-scale, ad hoc network structure of IEEE 802.15.3c is to be extended to provide a more general solution that can be applied to large buildings. Though the range of 60 GHz can undoubtedly be extended through the use of specialist antennas, it is inherently 20 times less than 5.2 GHz 802.11 systems, Park and Yang (4), and may ultimately require a multi-hop extension, Madke and Nettles (5).

Madke and Nettles (5) was an early exploration of an out-of-band (or dual-band) solution to the problem of 60 GHz directional beams and their limited range. However, though many useful suggestions were made, their plan involves the user devices themselves being connected in multi-hop fashion, whereas that is not a reliable commercial solution. Indeed, the 'sea of cubicles' scenario within an open-plan office of the IEEE 802.11 Very High Throughput Study Group, Miles and de Vegt (6)[1] is nearer to being feasible. In that scenario, a desktop display in each cubicle is updated with uncompressed HD video via a 60 Hz beam linking to an adjacent cubicle. Consequently, the connection mechanism in that scenario does not rely on the ad hoc arrival of 60 GHz devices to establish multi-hop communication.

Inter-access-point 60 GHz links may be possible by placing transceivers close to ceilings to achieve line-of-sight communication but this is not a convenient way to co-ordinate remote access to a service. In fact, indoor directed beams are very prone to blocking by obstructions, as they suffer from weak diffraction, Smulders (7), which suggests that some form of beam-swapping mechanism is advisable. People passing across a beam are the most obvious form of obstruction. They could easily interrupt viewing of a movie, unless an alternative, reflected beam became available. Additionally, multicast distribution of video, Kim et al. (8), at an access point is also problematic without prior localization of each receiver. It may also be advisable to swap between frequency bands, Park and Yang (4), if one band presents difficulties in terms of channel conditions or device capability, and to that end WiGig™ propose a tri-band structure (2.4, 5, and 60 GHz). Some way to enable a transition to a conventional 802.11 interface may also become necessary for IEEE 802.15.3c. Video resolution transcoding would be needed to compensate for the reduced bandwidth at the lower frequencies. These reasons again suggest that IEEE 802.15.3c may be insufficient in itself, without an auxiliary out-of-band channel.

For IEEE 802.15.3c distribution over 60 GHz channels low-cost and low-energy single-carrier (SC) transmission (without Orthogonal Frequency Division Multiplexing (OFDM) and its high peak-to-average power ratio) has been demonstrated to work within a car, without the need for equalization, Sawada et al. (9). However, a beam-forming antenna is needed to exploit usable paths without reflection, Sawada et al. (9). Because of the short wavelength (around 5 mm), on chip or package antenna arrays are indeed possible, Daniels et al. (10), and can be fabricated in Silicon Germanium (SiGe) with CMOS logic, Guttierez et al. (11), rather than the more expensive Gallium Arsenide (GaAs). This has resulted in single-hop wireless HDMI systems within the home, as well as the first laptops with a 60 GHz interface.

Apart from remedying potential weaknesses of IEEE 802.16.3c, an out-of-band channel may be helpful in enabling dual-mode connection with DisplayPort, Kim et al. (12), or HDMI. License-free DisplayPort is the main alternative to HDMI and may use Display Port

[1] In later versions, Miles and de Vegt refined their scenarios but the original topology and the transfer of uncompressed or lightly compressed video remained.

Content Protection (DPCP) rather than High-bandwidth Digital Content Protection (HDCP). An auxiliary channel can provide: a means of key exchange; a way of distributing Consumer Electronics Control (CEC) in the case of DisplayPort; as well as any other low-rate control functionality that may arise. In particular, future content protection schemes can operate, with authentication and subsequent exchange of security parameters taking place through this channel.

The paper now goes on to outline 60 GHz operation and its delivery through the IEEE 802.15.3c standard, before presenting out-of-band operation for an uncompressed HD distribution network.

60 GHz BAND OPERATION

The 60 GHz spectrum band is commercially attractive, as it is license-free and globally available with around 3 GHz of bandwidth at the same position in the spectrum (for a summary see Yong and Chong (13)). The bandwidth abundance implies that spectral efficiency can be lower and, unlike Ultra-Wideband, transmission power restrictions (-11 dBm) do not severely restrict the range. Table 3 is a comparison between other high-throughput wireless technologies at different frequency bands. The 60 GHz band is also less prone to the interference that, otherwise, occurs in the crowded unlicensed 2.4 GHz band. However, there is a reason for that, as oxygen absorption at 10 dB/km peaks at around 60 GHz and amplification is restricted both by practical considerations and national standards to around 10 dBm. This is assumed to restrict reliable indoor propagation without beam-forming to 10 m, though this depends on the extent of shadowing and the range might be extended to 20 m within a conference room. Other experimental systems suggest outdoor transmission much beyond that.

A simple free-space model suggests that 60 GHz communication suffers 26 dB additional pathloss compared to 2.4 GHz transmission. A 5×5 (or 6×6) antenna array can compensate by about 25 dB, Park and Gopalakrishnan (14), but this does not account for the effect of material absorption. The material concrete results in attenuation of up to 36 dB, Smulders (7), though glass only results in attenuation of between 3 and 7 dB. This implies that per room or area access points will be necessary, further creating a need to form a link between rooms in a large building.

Table 3 - Spectral efficiency of 60 GHz, multiband OFDM (UWB), and 5 GHz OFDM/MIMO technologies. (UWB is a frequency overlay.)

Technology	Bandwidth (Mbps)	Spectral efficiency to achieve 1 Gbps (bps/Hz)	Technology's target bitrate (Mbps)	Spectral efficiency required to achieve target bitrate (bps/Hz)
60 GHz	2000	0.5	4000	2.0
UWB	528	2.0	480	1.0
5 GHz OFDM	40	25.0	600	15.0

OVERVIEW OF IEEE 802.15.3C

The IEEE 802.15.3c MAC is based around a piconet controller (PNC) that schedules the access of piconet devices (DEVs) through a superframe. A piconet is a small scale, ad hoc wireless network arranged in a star-topology. Unlike the Bluetooth piconet system, the PNC is not also responsible for packet forwarding. Thus, once a PNC is selected, multimedia DEVs communicate during their allocated time slots in a DEV-to-DEV manner. A PNC should be connected to the mains power and be able to supply a security key, which implies it effectively acts as an access point. The PNC sends a beacon with access allocations at the start of a superframe (SF) (refer to Figure 1). The SF payload is divided into an optional Contention Access Period (CAP) with CSMA/CA and a Channel Time Allocation Period (CTAP) with TDMA suitable for delay-intolerant multimedia applications such as uncompressed HDTV. Multimedia DEVs acquire allocated CTAs within the CTAP from the PNC in order to communicate.

Consider a DEV that resets to find an existing piconet in operation, Pyo and Harada (15), then, after detecting a beacon and during the SF CAP, it associates with the piconet. Subsequently, it makes its request for a CTA to the PNC. The next beacon may contain its CTA for communicating with another DEV in the piconet. If so during the CTAP, multimedia streaming commences. At the end of streaming the CAP is used to disassociate from the piconet. Management CTAs (MCTAs) are also possible during the CTAP.

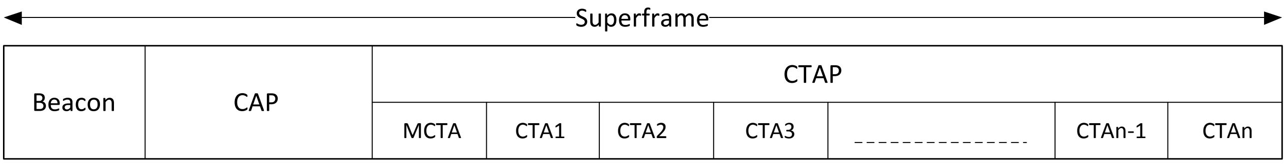

Figure 1 – IEEE 802.15.3c superframe format

The physical (PHY) layer of IEEE 802.15.3c has three modes: single carrier (SC) Frequency Division Equalization (FDE); high-speed interface (HIS); and audio/visual (AV). The AV mode is suitable for uncompressed, one-way HD video streaming. However, rather than employ OFDM, it could be that low-cost SC-FDE might be selected for communication to laptops, PDAs, and other smart devices. Table 4 is a summary of the differences between 802.15.3c's PHY modes.

To reduce header overhead, IEEE 802.15.3c has introduced to IEEE 802.15.3 (via IEEE 802.15.3b) frame aggregation. Sync frames also now serve to better distinguish between adjacent piconets.

Table 4 – IEEE 802.15.3c's PHY modes.

	SC-FDE	**HSI PHY**	**AV PHY**
Datarate range	0.3 Mbps-5.28 Gbps	1.54-5.78 Gbps	0.95-3.8 Gbps
Modulation	Single carrier	OFDM	OFDM
Forward Error Correction	RS, LPDC	LPDC	RS, convolutional
Block size/FFT size	512	512	512

RS = Reed-Solomon, LPDC = Low-Parity Density Check, OFDM = Orthogonal Frequency Division Multplexing

ENVISAGED OUT-OF-BAND OPERATION

The envisaged scenario in this Section is a large building such as an airport terminal within which it is simply not possible to operate a single IEEE 802.15.3c piconet to achieve coverage. It is assumed that there is a centralized source of uncompressed HD video but several PNCs throughout the building. The first issue to address is how to distribute uncompressed video to multiple PNCs from the centralized source, assuming that each PNC also acts as an access point. The most obvious means is through radio-over-fiber

(RoF) technology, Nirnalathas et al. (16). In fact, RoF is also a means to deliver compressed HD content to the centralized store, allowing remote update of the HDTV service. The work in Nirnalathas et al. (16) compares analog and digitized RoF for delivery to GSM and WiMAX terminals with a largely passive optical network using coarse or dense wave division multiplexing to mange flows. However, it is also possible to use direct 60 Ghz beam connection, provided the building geometry is suitable and provided line-of-sight (LOS) communication is possible. As previously mentioned, the most obvious way to do this is through a near-ceiling mounting to avoid obstructions. Despite the large bandwidth window available at 60 GHz, it is likely that only a few channels, Yong and Chong (13), of about 2 GHz in width will be available. This implies that spatial reuse, Park and Gopalakrishnan (14), will be necessary. However, that can occur only if the beam pattern is controlled to reduce interference between directed beams. Overall network control cannot be achieved by the PNCs themselves, as their ability to coordinate is limited by their short range and the likelihood that probing beams will cause interference to adjacent piconets.

Figure 2 shows an example scenario in which two of the PNCs are fed from an optical fiber transmitter, which is co-located with HD video data storage. Other PNCs are fed by directed beams that can be arranged in an inter-linked pattern. They can also direct their beams to users within the building under the centralized control of the 802.11 access point. Figure 2 also includes a conventional 802.11 access point (AP) which acts as an overall controller for the 60 GHz access network, with PNC devices being dual-homed in order to respond to control information. PNCs are assumed to be co-located with beam sources. As previously mentioned, the AP can also act to support HDMI and/or DisplayPort connectivity, providing supplementary functionality, lacking from each of these interfaces. In particular, it is likely that HD security parameters for content protection will be exchanged at access time.

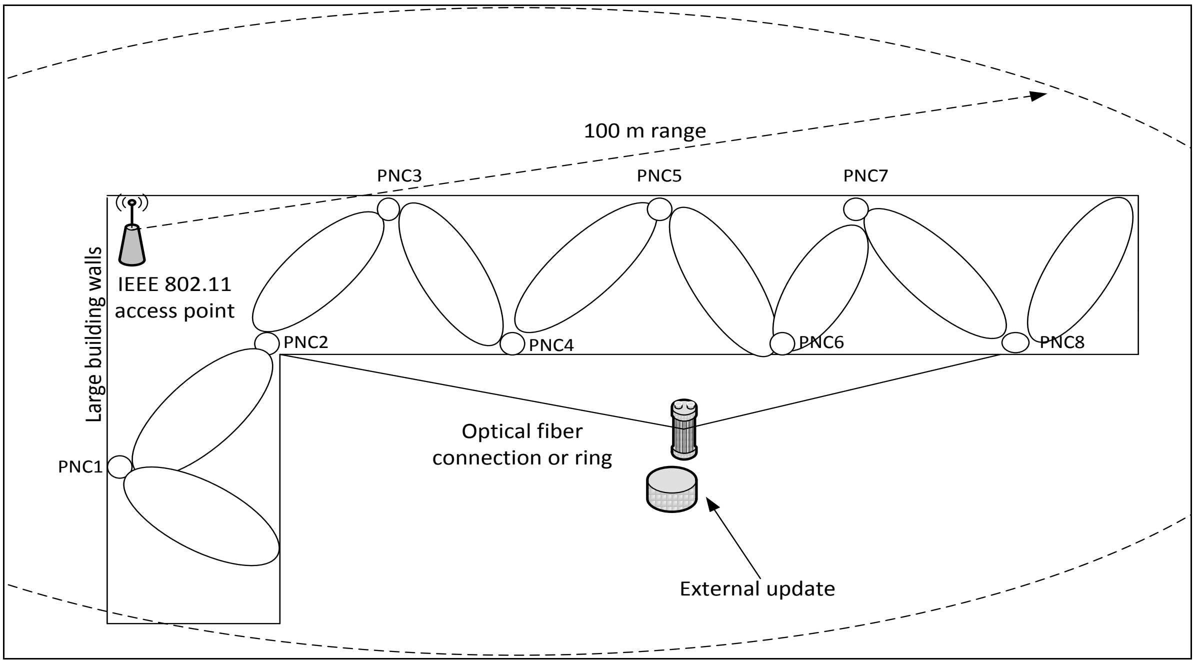

Figure 2 – Example large-building scenario for 60 GHz coverage

Not shown in Figure 2 are user devices, which are assumed to be present within the L-shaped building. These are also multi-homed devices with dual 60 GHz and 5 GHz or 2.4

GHz interfaces (or all three). It is also possible that coordination of access will be through a common MAC scheduler, with common upper layers of the protocol stack above the separate PHY layers and radio frontends (RFs). In the given scenario, user devices will be semi-static in position, as it is of course difficult to view TV on the move. Location information might be available from GPS, even though this is an indoor setting. However, the most likely way position can be established is through monitoring by the AP. Information that can be helpful is signal strength, angle of arrival measurement, and round-trip-times. Knowing the location of user devices opens up an interesting possibility, Madke and Nettles (5), that user devices themselves can act as multi-hop relay points but, as previously mentioned, this form of ad-hoc routing of uncompressed HD cannot be relied upon.

The role of the IEEE 802.11 AP in terms of routing can be summarized as: incremental update of PCN and user mobile devices locations in order to coordinate routing of uncompressed HD across the 60 GHz network; plan and arrange multi-hop routes; and receive and respond to requests for re-routing. In addition, the AP must manage exchange of the connection configuration.

CONCLUSION

As 60 GHz radio comes of age, it becomes feasible to move beyond single-hop transfer of files or streams. However, 60 GHz LANs may not be achieved by simply bolting on an alternative PHY and RF to an existing protocol stack, due to beam directionality and range. The paper has outlined how an out-of-band channel can coordinate multi-hop routes and provide a number of auxiliary functions to a multimedia network for streaming uncompressed video. Though IEEE 802.15.3c is already standardized as a 60 GHz multimedia network, it was designed in ad hoc mode and it does not natively operate in infrastructure mode. Therefore, its topology must be adapted to form a stable LAN that can be built up in piecemeal fashion by joining adjacent piconets. This paper has moved towards such a configuration by separating the control plane from the 60 GHz data plane. Future work will demonstrate video throughput and latency for a 60 GHz system with an IEEE 802.11 auxiliary channel. Fine tuning should take into consideration latency with and without protection features for uncompressed video such as pixel partitioning and multiple Cyclic Redundancy Checks (CRCs), Singh et al. (17). For compressed video, latency can be reduced by frame aggregation, while protection can be increased by turning on one of the ACK modes, Zhou et al. (18). In short, a rich research and development prospect exists on how best to offer video services over IEEE 802.15.3c.

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