A Dual-band Architecture for Multi-Gbps Communication in 60 GHz Multi-hop Networks

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Abstract— **By utilizing abundant spectrum available at 60 GHz, millimeter wavelength (mmWave) radios can enable multi-gigabit per second (Gbps) link rates, but only over short distances. The limited range of mmWave radios can be extended to provide high throughput coverage to an entire home or office network using multi-hop communication. In this paper, we present a dual-band architecture that leverages the significant range advantage of low-cost commodity WiFi radios to control and coordinate scheduling/routing on a 60 GHz multi-hop network. The high pathloss and directionality of mmWave radio create significant opportunities for spatial reuse in these mmWave networks. By realizing these spatial reuse gains through effective scheduling/routing, this dual-band architecture can enable multi-Gbps end-to-end throughput in 60 GHz multi-hop networks.**

Index Terms— **multi-Gbps, multi-hop, 60 GHz, WiFi, WPAN, WLAN, multi-band**

I. INTRODUCTION

Next generation wireless local area network (WLAN) and personal area networks (WPAN) will require multi-giga bit per second (multi-Gbps) throughput for applications such as high definition (HD) video streaming, cable replacement, and bulk data transfer. Table I summarizes the requirements of some of these applications. Curent state-of-the-art WLAN technology, namely IEEE 802.11n, can provide link level data rates up to a few hundred Mbps. These systems will be unable to provide multi-Gbps throughput as they are limited by, among other things, the bandwidth available in WLAN/WPAN spectrums. The order of magnitude improvement in throughput required for next generation networks cannot be achieved without utilizing a considerably larger bandwidth. The abundance of unlicensed spectrum allocated at 60 GHz has garnered interest by multiple standards bodies and industry consortiums [1]–[4]. With up to 7 GHz of spectrum available at this frequency, millimeter wavelength (mmWave) technologies serve as a compelling vehicle for enabling multi-Gbps wireless systems.

TABLE I: Wireless HD Video Requirements from [7]

Application	Data Rates Required
Uncompressed 1080p	1.12 – 2.98 Gbps
Uncompressed 1080i	1.1 – 1.4 Gbps
Uncompressed 720p	0.5 – 1.3 Gbps
File transfer of DVD movie in < 1 minute	0.7 – 1.4 Gbps
Wireless PC display	0.5 – 2.6 Gbps

Recent advances in building inexpensive mmWave transceivers in silicon have prompted industry to begin to commercialize and productize 60 GHz radios for high bandwidth applications [5]. This is evidenced by standardization efforts such IEEE 802.15.3c [1] and WirelessHD$^{\text{TM}}$ [2]. Researchers in industry and academia have targeted 60 GHz communication for enabling multi-Gbps link rates in WPAN applications. As such, much of the attention on 60 GHz communication has been focused medium-access control (MAC) and physical layer (PHY) design for point-to-point communication [1]–[3]. Because of the severe attenuation and pathloss characteristics at 60 GHz [6], the multi-Gbps data rates promised by emerging standards, such as IEEE 802.15.3c or WirelessHD$^{\text{TM}}$, will only be possible at short distances of a few meters. Multi-hop communication can be used to extend this limited range 60 GHz communication to cover an entire home or office network. Doing so will enable a variety of multi-Gbps WLAN applications.

This paper proposes the design of a dual-band architecture to enable multi-Gbps end-to-end throughput in 60 GHz multi-hop communication. This dual-band design will leverage the range advantage of commodity WiFi hardware to coordinate the high-bandwidth directional communication of mmWave radios. We describe the features of the dual-band design, and discuss opportunities and challenges in using this approach to enable multi-Gbps throughput in WLAN.

Recently, the IEEE 802.11ad task group (TGad) was formed to define a standard that would enable WLAN operation in the 60 GHz band to exceed 1 Gbps [4]. Although our proposed dual-band design is similar in many ways to these efforts, it differs in two primary ways. First, we advocate the use of commodity WiFi hardware as an integral part of our architecture (as opposed to enhancement of WiFi). Second, we are focused on facilitating central coordination of the multi-hop flows in a 60 GHz network (as opposed to single-hop traffic or two-hop relays).

TABLE II: Maximum Data Rate for WLAN/WPAN Technologies

WLAN/WPAN Technology	**Maximum Achievable Link Rate**	**Bandwidth**
Bluetooth	$1-3$ Mbps	~ 1 MHz
IEEE 802.11g	54 Mbps	20 MHz
Multiband OFDM (UWB)	480 Mbps	528 MHz
IEEE 802.11n	288.9/600 Mbps	20/40 MHz
IEEE 802.15.3c	3.0 Gbps	1.728 GHz
WirelessHD^{TM}	25 Gbps[1]	1.76 GHz

The remainder of the paper is organized as follows. Section II describes the relevant characteristics of 60 GHz communication that impact our dual-band approach. In Section III, we introduce the dual-band architecture by presenting a brief overview of the design and potential benefits of this approach. Next, in Section IV, we discuss the research opportunities and challenges associated with this new architecture. Section V presents prior work related to our proposed dual-band design; and Section VI concludes the paper.

II. CHARACTERISTICS OF 60 GHZ COMMUNICATION

Table II shows the maximum data rates of some popular and emerging WLAN and WPAN standards. It is clear that emerging mmWave standards, namely IEEE 802.15.3c and WirelessHD^{TM}, outperform their WLAN/WPAN peers by an order-of-magnitude or better. By utilizing abundantly available spectrum at 60 GHz, these mmWave technologies can provide multi-Gbps link rates. Making 60 GHz a commercially viable technology required addressing many physical layer and circuit design issues [6]. Making 60 GHz a viable technology *in WLAN*, however, will require addressing additional challenges caused by the limited range of millimeter wavelength communication.

Consider the free space pathloss model, which predicts the pathloss between a transmitter-receiver pair,

$$PL_{freespace} = \left(\frac{4\pi d}{\lambda}\right)^2,$$

where d is separation distance and λ is the wavelength of the carrier. From this model, 60 GHz communication will suffer 28 dB of additional pathloss compared to 2.4 GHz WiFi radios. This results in a significantly shorter communication range. The problem is exacerbated by the unique characteristics of 60 GHz transmissions, such as the difficulty penetrating through or diffracting around obstacles [5].

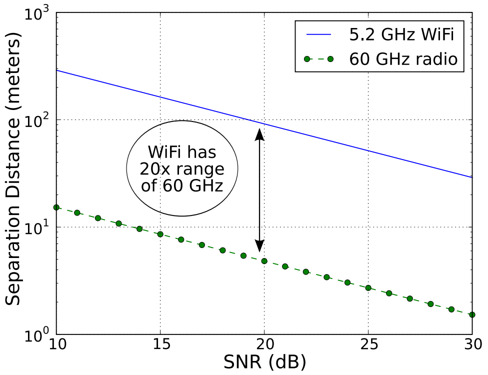

Fig. 1: Transmission distance vs. SNR for WiFi and 60 GHz. Radio parameters taken from [5].

To compensate for much of this loss, 60 GHz radios employ beam steering to create high gain directional links. The small millimeter wavelength at these high frequencies makes it possible to create small form factor antenna arrays with numerous antennas. For example, at 60 GHz a 5-by-5 square array of antennas could be created in a 2 cm^2 area and provide as much as 25 dB of beam forming gain (if used at both transmitter and receiver) [8]. Directional communication in 60 GHz networks, however, can also complicate MAC coordination, because it requires addressing issues such as deafness or hidden nodes [9]. In addition, broadcasting is very inefficient when using directional communication.

Even with the use of high gain directional links, emerging 60 GHz technologies still have a limited communication range of a few meters. Figure 1 plots signal-to-noise ratio (SNR) of a link versus the corresponding separation distance, using the freespace pathloss model. The plot, which uses 5.2 GHz WiFi and 60 GHz radio parameters from [5], illustrates how mmWave communication can have up to twenty times smaller range than WiFi radios even when using high gain directional antenna arrays. *In order to extend this limited range, 60 GHz networks will need to route and forward traffic over multiple hops.*

The high pathloss and directionality that limits the range of 60 GHz communication, however, also presents the opportunity to improve overall network performance through *spatial reuse*. Multiple mmWave radios can transmit simultaneously using high data rates if they can do so without significantly interfering with each other. The use of highly directional links will increase the likelihood that multiple distributed 60 GHz links can coexist. That is, they can simultaneously transmit at high data rates without emitting energy and interference, i.e. being *directed*, at one another. Furthermore, any excess energy directed at unintended receivers will undergo severe attenuation, which further reduces the potential for interference. Realizing these spatial reuse gains, however, will still require spatially-aware scheduling that considers the directionality of mmWave radios and accounts for interference relationships in the network.

By utilizing the tremendous spectrum available at 60 GHz, employing multi-hop communication, and exploiting spatial reuse opportunities, we can enable multi-Gbps end-to-end throughput in 60 GHz networks. *However, this will require coordinated scheduling and an efficient broadcast mechanism to communicate control information.*

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[1] Theoretical maximum for distances of less than 1 meter.

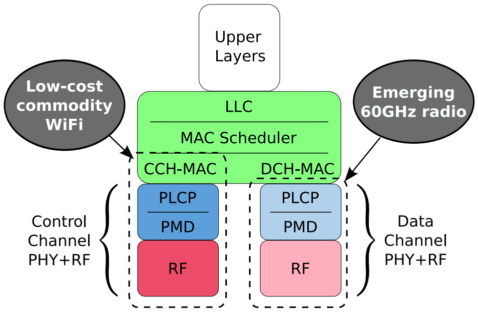

Fig. 2: Dual-band Protocol Stack

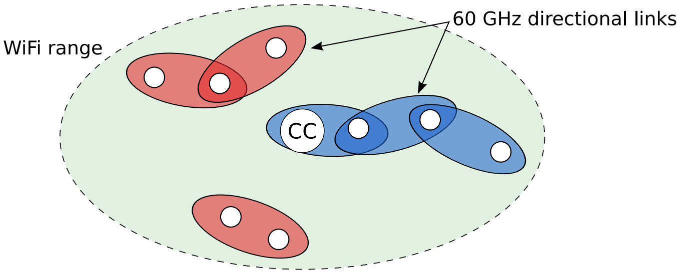

Fig. 3: Dual-band Operation. All nodes are in the WiFi broadcast range of the CC and use directional 60 GHz radios for data.

III. DUAL-BAND MULTI-GIGABIT WLAN

A. Usage Scenarios

Our dual-band design is primarily motivated by future applications in indoor home and office networks. Before we proceed, let us consider a typical usage scenario. Consider a home network in which a media server streams HD video content to multiple devices in the home. There may also be concurrent wireless traffic from a variety of other sources, such as: wireless PC displays, portable handheld devices synching audio and video files in a few seconds, or Internet traffic to a laptop. This diverse assortment of applications will require a network capable of supporting multiple concurrent multi-Gbps traffic flows. Other applications which motivate multi-gigabit WLAN include cable replacement technology for everything from simple mice and keyboards to high bandwidth HDMI cables.

B. Design Overview

As discussed previously, in order to enable multi-Gbps end-to-end throughput over 60 GHz multi-hop networks, we must exploit spatial reuse opportunities and enable efficient broadcast of control information. Low-cost commodity WiFi radios are capable of long-range omnidirectional communication at data rates below 100 Mbps, while emerging 60 GHz radios can provide short-range directional communication at multi-Gbps data rates. Our dual-band architecture leverages the complimentary nature of these two technologies to enable high throughput multi-hop communication. Each node in the network is equipped with a WiFi radio and a 60 Ghz radio as depicted in Figure 2. This dual-band architecture retains standard abstractions to upper layer protocols while managing new interfaces to support these radios. The control channel (CCH) will be built using low-cost commodity WiFi hardware operating at 2.4 or 5 GHz. The data channel (DCH) will be implemented using the PHY and radio front-end (RF) of a 60 GHz radio.

Figure 3 illustrates the typical operation of our dual-band design. The central coordinator (CC) manages the operation of the 60 GHz network via an efficient broadcast control plane built on the *longer*-range omnidirectional communication of commodity WiFi radios. More specificially, this low-cost WiFi control plane coordinates multi-hop scheduling/routing to exploit spatial reuse opportunities in the high-bandwidth directional 60 GHz network. We assume that all nodes in the network are within the same collision domain for the broadcast WiFi control channel.

The control and data plane each utilize separate MAC protocols that are managed by the same scheduler. The WiFi control plane is built on top of the point-coordination function (PCF) of IEEE 802.11 [10]. This gives the CC priority on the control channel and provides contention-free support for polling, admission control, and efficient broadcast of scheduling/routing control messages. It also allows contention-based access to the WiFi network, e.g. for announcing control messages or as an alternate mechanism for sending data (see below). The data plane operates in a TDMA fashion based on the schedules distributed by the central coordinator.

The WiFi control plane is a key contribution of our proposed dual-band architecture, as it provides a low-cost mechanism to enable the feedback and coordination needed for effective scheduling/routing of directional 60 GHz communication. The control plane must facilitate three tasks.

1) CSI: First, the control plane must be able to measure, collect, and learn channel state information (CSI). That is, nodes must be able to *measure* CSI by overhearing traffic or through an explicit channel sounding/probing procedure. The central coordinator (CC) must *collect* this CSI to aid in scheduling/routing. As nodes move, routes change, or traffic starts/stops, the CC must be able to *learn* about these changes through incremental updates.

2) Scheduling/Routing: The second task the WiFi control channel must facilitate is the ability to *coordinate scheduling/routing*. After computing routes/schedules that exploit spatial reuse opportunities, the CC must be able to distribute these scheduling/routing decisions and manage 60 GHz activity (i.e. starting, stopping, and coarsely synchronizing communication on the data channel).

3) Feedback: The final task the control plane must enable is the ability for nodes to *report feedback* about scheduling/routing decisions. In particular, if a route or schedule is ineffective or erroneous, the node must be able to notify the CC about this failure.

C. Benefits of Dual-band Approach

The main advantages of this dual-band architecture are:

1) WiFi Know-How: The dual-band design utilizes low-cost commodity WiFi hardware. The wealth of engineering knowledge and intuition about WiFi in industry and academia will ultimately help to reduce the cost and development time for implementing a dual-band system.

2) Multi-Gigabit WLAN: Proper scheduling and routing that exploits spatial reuse opportunities in the 60 GHz multi-hop networks can enable multi-Gbps end-to-end throughput for next-generation home and office networks.

3) Interoperability: Since the WiFi control plane is built on top of the PCF mode of IEEE 802.11, it will be able to interoperate with other 802.11 networks using CSMA/CA, i.e. IEEE 802.11 a/b/g/n.

We reiterate the importance of spatial reuse in our dual-band approach. Without significant spatial reuse, the end-to-end throughput of multi-hop flows in the 60 GHz network would rapidly diminish with the number of hops in the network, i.e. $O(1/N)$. Our intuition, however, is that the high pathloss and directionality of 60 GHz communication will create significant spatial reuse opportunities that will enable multi-Gbps WLAN.

IV. CHALLENGES AND OPPORTUNITES

A. Challenges

Practical implementation of the dual-band architecture will require addressing a number of research challenges. The most pressing challenge is the resource allocation problem. This is the question of how to optimally allocate space/time/frequency resources through routing and scheduling. Solving this combinatorial optimization problem in general is difficult, and can require large amounts of CSI and significant computation [11]. Finding reduced complexity approaches, heuristics, and low-overhead methods to solving this problem is a key research challenge. Spatial and temporal scheduling of links *must* exploit spatial reuse opportunities in order to provide multi-Gbps end-to-end throughput to multi-hop 60 GHz networks.

Another practical issue for implementation is the design of a formal protocol for the dual-band operation. Although we have described some of the schemes that might be employed in such a protocol, standardization will require complete description of a dual-band protocol. In order to commoditize this architecture, engineers will also need to address issues pertaining to placing these disparate RF chains on a single chip design (i.e. System on a Chip, SoC). Growing multi-gigabit 60 GHz networks beyond the single collision domain of one central coordinator will require innovative approaches to scaling, such as imposing hierarchical structure as in mesh networks. Other areas of research related to the dual-band architecture might also include: quality-of-service (QoS) provisioning, security, and power-aware protocol design.

B. Opportunities

The dual-band architecture provides a key opportunity to extend the functionality of the control plane. In particular, non-control traffic could be sent over the WiFi network to address various QoS needs and to improve the utility of the WiFi and 60 GHz channels. For example, we might employ a traffic-splitting scheme to support the following traffic classes on either WiFi or 60 GHz channels:

- delay sensitive, low rate (e.g. VoIP) → WiFi
- persistent, high rate (e.g. streaming HDTV) → 60 GHz
- bursty, low rate (e.g. TCP setup/tear-down) → WiFi

One way this traffic-splitting approach improves the utility of the dual-band system is by scheduling bursty traffic on the WiFi channel, thereby avoiding the overhead required for scheduling/routing on the 60 GHz channel.

Another approach to improving utility in the dual-band system is through frame aggregation. By fragmenting, aggregating, and reassembling packets efficiently, we can combine different classes of traffic to produce a single stochastically stationary data stream that can be more easily scheduled.

In order to gain traction in home and office networks, this technology must be cost effective and require little to no maintenance. One feasible option for deployment in indoor networks could be in power-outlets throughout the home (or office). As these are usually placed at regularly spaced intervals and appear in every room in the home (or office), this deployment could robustly maintain connectivity and access to power. This would effectively create a high-bandwidth data plane that could be accessed anywhere in the indoor network.

V. RELATED WORK

Interest in 60 GHz communication from academia and industry has led to a variety of results addressing physical layer and circuit design challenges (see [6] and references therein). Also, a variety of channel measurement studies has improved our understanding of the multipath and pathloss characteristics of 60 GHz wireless channels [12]–[14].

We are primarily motivated in our approach by the spatial reuse opportunities present in 60 GHz networks. The relationship between spatial reuse and interference has been studied in a number of different ways. In [9], Alawieh, et al. survey MAC techniques for improving spatial reuse in ad hoc wireless networks. The authors identify problems that can mitigate the spatial reuse gains associated with the use of directional antennas, including: deafness, hidden terminals, exposed terminals, and queueing issues. Many of these issues stem from the lack of global coordination and incomplete channel knowledge among nodes in the network.

Park and Gopalakrishnan examined the spatial reuse charateristics of 60 GHz single-hop links in a densley packed office environment [8], [15]. They studied the impact of interference on the number and quality of wireless links that can be simultaneously active. This latter work is particularly relevant to our approach as it furthers our understanding of the spatial reuse opportunities in 60 GHz networks. Singh, et al. developed a protocol to utilize directional communication to route around blocked LOS paths in an in-room 60 GHz network using a multi-hop relay [16]. They show that a small number of relays in the network can effectively reduce outages in the network.

Some recent results on jointly utilizing $2.4/5$ GHz and 60 GHz bands are similar in scope to the dual-band architecture we have presented in this paper. Daniels and Heath argued that enhancing physical layer throughput in WLAN will require significant increase in bandwidth [17]. They proposed a multi-band solution that required joint PHY and MAC design across $2.4/5/60$ GHz bands. Yang and Park introduced the concept of multi-band gigabit mesh networks in [5]. As with their work, we advocate the use of existing WiFi radios and the latest in 60 GHz radios. Our paper builds upon the results of [5]. Moreover, our work advances this research topic closer towards protocol design and addressing implementation details for multi-Gbps WLAN.

Although not using 60 GHz communication, Kyasanur, et al. developed a protocol based on a dual-band architecture that also leveraged the propagation characteristics of two disparate frequencies [18]. They proposed a Control Channel-based MAC protocol that utilized a low bandwidth radio operating below 900 MHz to perform the MAC coordination for an IEEE 802.11a WiFi network. By leveraging the extended range of the 900 MHz control channel and an advanced reservation scheme, they showed that their MAC scheme outperformed conventional WiFi protocols.

VI. CONCLUSION

In this paper we presented a dual-band architecture to enable multi-Gbps throughput in WLAN. The key intuition that has motivated our dual-band design is that because of high pathloss and directionality, there is significant spatial reuse opportunity in 60 GHz multi-hop networks. The main features of the dual-band system include: (i) high bandwidth directional 60 GHz radios, (ii) multi-hop communication, (iii) a control plane built on low-cost commodity WiFi, and (iv) scheduling to exploit spatial reuse opportunity.

Multi-hop communication in 60 GHz networks will not be able to provide multi-Gbps end-to-end throughput without realizing spatial reuse gains through effective spatial and temporal scheduling. We are currently designing and implementing scheduling algorithms to address this need along with a dual-band protocol to enable these algorithms in our proposed architecture. Future work must address this and other resource allocation issues presented in this paper, namely effective routing. The feasibility of our proposed architecture hinges on two key issues: (i) the aforementioned scheduling/routing design; and (ii) protocol design that can efficiently utilize the WiFi control plane to implement the feedback and coordination required for effective spatial reuse in the 60 GHz multi-hop network.

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