THE PURSUIT OF TENS OF GIGABITS PER SECOND WIRELESS SYSTEMS

CARLOS CORDEIRO, INTEL CORP.

INTRODUCTION

More than any time ever before, today technology has a significant impact on people's lives. The proliferation of slim, mobile, and portable devices such as notebooks, ultrabooks, tablets, and smartphones is a clear testament to the importance of computing and communication in modern society. In the particular case of wireless systems, this explosive growth has led to an insatiable need to constantly boost capacity so that innovative uses can be offered to consumers. This vicious cycle has brought to market many innovative wireless solutions including the IEEE 802.11 family of standards, third generation (3G), and fourth generation (4G), to name a few.

When it comes to wireless systems with data rates greater than 1 Gb/s at a few meters, the most notable examples include the IEEE 802.11ac and IEEE 802.11ad amendments to the base IEEE 802.11 standard [2], with key parameters summarized in Table 1. Several companies have announced products implementing these technologies, with a few of those products already available, or soon to be available, to consumers.

The data rates offered by IEEE 802.11ac and IEEE 802.11ad can meet the needs of many applications, with replacement of wired digital interface (WDI) cables arguably the most prominent new use of these technologies. This includes replacing WDI cables used between a notebook/tablet/smartphone and certain display (e.g., HDMI, DisplayPort) and IO (e.g., USB) devices, thereby enabling a fully wireless user experience [4].

THE EVOLVING LANDSCAPE IN WDIS

The vicious cycle of technology permeates both wired and wireless interfaces. Since replacement of WDI cables is the primary use of this new wave of multi-gigabit per second wireless systems, it is important to understand how prominent WDIs are expected to evolve over time. This is illustrated in Table 2, which focuses primarily on the approximate maximum data rates currently supported by each of the corresponding WDI. Future versions of these WDIs are under development and promise to offer even higher data rates.

Supporting the data rates outlined in Table 2 over a wireless system is nontrivial. While IEEE 802.11ac and IEEE 802.11ad are able to support degrees of these WDIs, when it comes to supporting, say, the high-end data rates for certain WDIs shown in Table 2, it becomes apparent that there is still a performance gap. This gap is only expected to grow larger, given the rapid evolution in WDI speeds – clearly, this is one of the major drivers of the vicious cycle behind multi-Gb/s wireless technologies. As such, we can conclude that next generation wireless systems needs to support data rates in the order to tens of Gb/s to be able to keep up with the evolution of WDI speeds.

THE WAY TOWARD TENS OF GIGABIT PER SECOND WIRELESS

So far today, there has been little discussion in the industry on ways to achieve tens of Gb/s wireless speeds with ranges of a few meters. Despite that, there is growing consensus being formed that the only practical way of getting there is through the use of higher frequencies, with 60 GHz being the starting point.

The amount of unlicensed spectrum in frequencies below 6 GHz is very limited. Even though there are ongoing efforts to allocate additional unlicensed spectrum in the 5 GHz band, the added capacity will be far short of allowing tens of gigabits per second rates to be offered at ranges of 5–10 m. As such, the 60 GHz frequency band, with its vast bandwidth of around 7 GHz, is currently seen as the only viable solution to achieve those goals. Referring back to Table 1, this implies that reusing and extending IEEE 802.11ad is the way toward tens of gigabits per second wireless, since this technology operates in the 60 GHz frequency band. Arguably, unlicensed bands higher than 60 GHz (e.g., terahertz) could also be used to achieve tens of gigabits per

Parameter		IEEE 802.11ac	IEEE 802.11ad
Approx. max. theoretical data rate (Gb/s)	Per device	3.5 (4× 4, 160 MHz channel)	6.8
	Aggregate	6.95	
Range at max data rate (m)		Few (< 10)	
Channel bandwidth (MHz)		20/40/80/160	2160
Number of channels in the US		Five 80 MHz	Three
Frequency band (GHz)		5	60
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Table 1. *Brief comparison between two > 1 Gb/s systems.*

WDI	Version	Approx. max. data rate (Gb/s)
DisplayPort	1.0–1.1	8.6
	1.2	17.3
HDMI	1.0–1.2a	5
	1.3–1.4a	10.2
USB	2.0	0.48
	3.0	5
Thunderbolt	1.0	10

Table 2. *Evolution of prominent WDIs.*

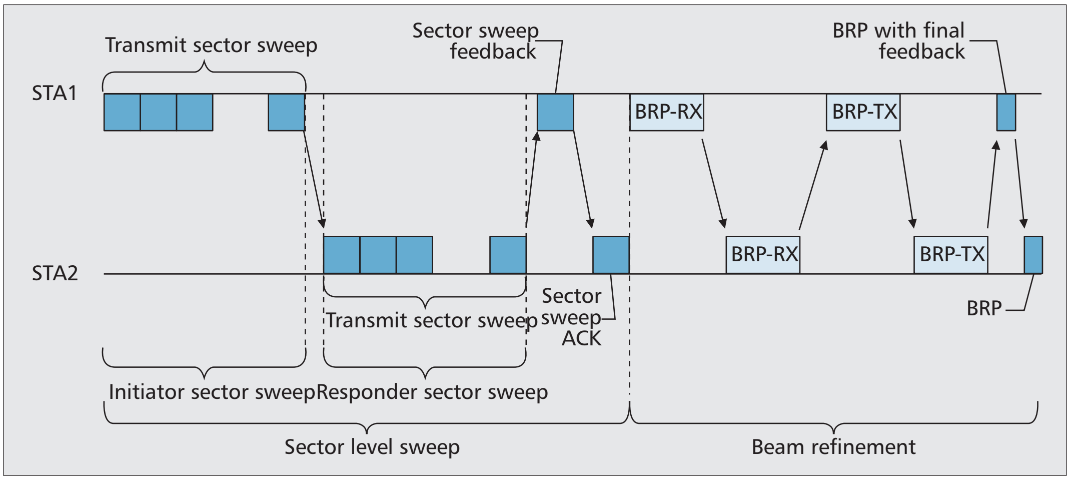

Figure 1. *Beamforming protocol in IEEE 802.11ad.*

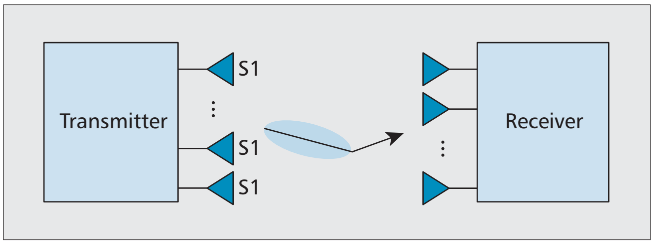

Figure 2. *IEEE 802.11ad beamforming: single RF path.*

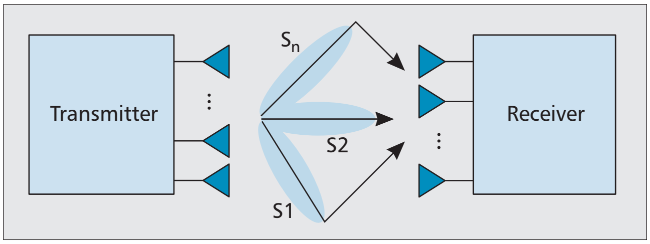

Figure 3. *Next generation 60 GHz beamforming: > 1 RF path.*

second wireless, but technologies operating at these frequencies are nowhere near commercialization.

REVIEW OF BEAMFORMING IN IEEE 802.11AD

An overview of the IEEE 802.11ad standard is given in [3]. The unique feature of this standard is the fact that communication in 60 GHz requires the use of high gain directional antennas in order to compensate for the large path loss [1]. While directional communication addresses the link budget issue, it introduces the need for finding the direction of communication with a neighbor. This is addressed by a novel beamforming (BF) protocol.

BF is the process used by a pair of stations to achieve the necessary link budget for subsequent communication. In IEEE 802.11ad, BF consists of two phases, as depicted in Fig. 1: sector level sweep (SLS) and beam refinement phase (BRP). SLS enables a pair of devices to establish the initial (coarse) direction of communication. At the end of SLS, a pair of devices determines the best transmit sector for communication with each other. BRP is used for receive antenna training and to fine tune antenna settings to improve the quality of directional communication, and hence obtain a multi-gigabit-per-second link.

One of the most important characteristics of the BF protocol in IEEE 802.11ad is that it is capable of discovering a single radio frequency (RF) path for communication between a pair of devices. Thus, this means that even if a device possesses more than one antenna array, only one of those antenna arrays is used for communication between any transmitter-receiver device pair. This is depicted in Fig. 2.

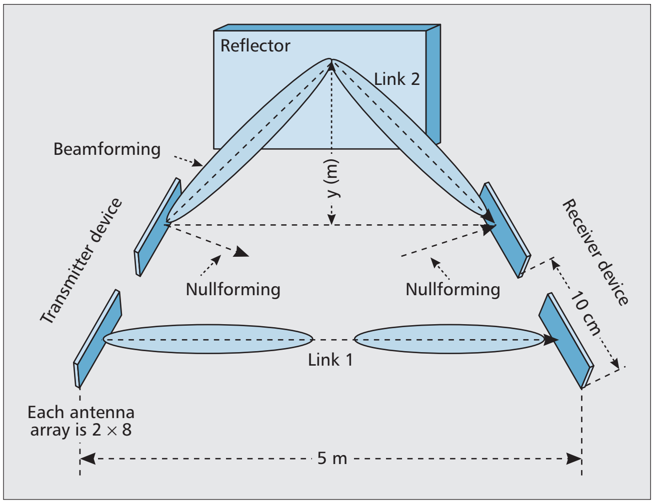

Figure 4. *Simulation scenario.*

ACHIEVING TENS OF GIGABITS PER SECOND WIRELESS

Similar to the evolution of IEEE 802.11a/b/g toward IEEE 802.11n, we believe that the next step in the evolution of 60 GHz standards beyond IEEE 802.11ad will include the introduction of multiple-input multiple-output (MIMO) and channel bonding capabilities. With MIMO, different signals are transmitted from different 60 GHz antenna arrays, as shown in Fig. 3. This results in an improvement in diversity and performance.

To illustrate the gains possible with MIMO in 60 GHz, we have simulated the scenario shown in Fig. 4, wherein

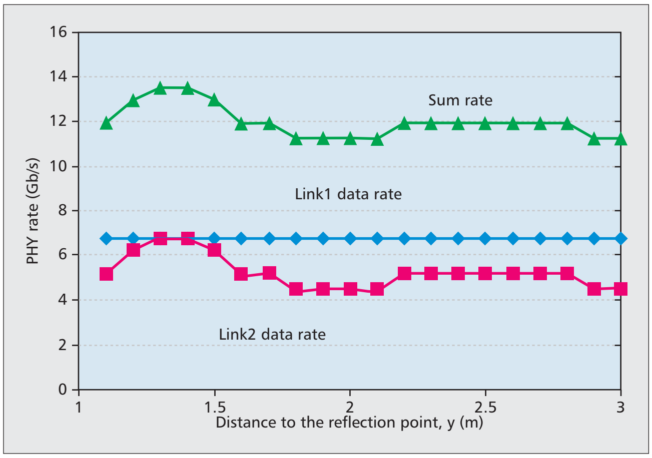

Figure 5. *Simulation results of MIMO with 60 GHz.*

two devices are separated by 5 m, and each device is equipped with two antenna arrays each with 2× 8 elements. The center of the two antenna arrays in a device are separated by 10 cm. A reflector with a reflection coefficient of 2 dB is placed next to the two devices to form a reflected path between the two devices. The distance to the reflection point (y) is varied from 1 to 3 m. The total transmit power of each antenna array is set to 10 dBm, and the noise figure and implementation loss are set to 15 dB. Both beamforming and nullforming techniques are used to enable two simultaneous data transmissions between the two devices over the direct path (i.e., link 1) and the reflected path (i.e., link 2). The MCS is chosen from MCS 13 (693 Mb/s) to MCS 24 (6.76 Gb/s) of IEEE 802.11ad based on the received signal-to-interference-plus-noise ratio (SINR). Figure 5 shows the results obtained, where an aggregate data rate of at least 11 Gb/s can be achieved with two simultaneous transmissions.

When coupled with channel bonding, the aggregate data rate is essentially multiplied. Therefore, MIMO with channel bonding can lead to data rates greater than 20 Gb/s for two bonded channels and 30 Gb/s for three bonded channels. The use of higher-order MIMO schemes and larger numbers of elements per antenna array than those shown in Fig. 4 can lead to even higher aggregate data rates.

CONCLUSIONS AND FUTURE DIRECTIONS

The next few years will experience a significant growth in the availability of commercial wireless technologies capable of multi-gigabit-per-second data rates. While this will provide a major technological advancement compared to the capacity of today's short-range wireless systems based on IEEE 802.11 [2], these speeds fall short of meeting the rates of future WDIs. The use of MIMO and channel bonding at 60 GHz frequencies is expected to provide the next major bump in wireless speeds that can lead to data rates on the order of tens of gigabits per second, thus serving as the path toward supporting the envisioned evolution in WDI speeds. That said, research is still in its infancy when it comes to the use of MIMO in 60 GHz, and further work is needed on developing this capability and proving its commercial feasibility.

ACKNOWLEDGMENTS

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