AC 2009-2454: IEEE 802.11N WIRELESS LOCAL AREA NETWORKS STANDARD:

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IEEE 802.11n Wireless Local Area Networks Standard: A simulation model of PHY layer of Amendment Draft 3.0

Abstract

The IEEE 802.11n is a currently emerging Wireless Local Area Network (WLAN) standard capable of providing dramatically increased throughput, as well as improved range, reduced signal fading, over the existing IEEE 802.11a/g WLAN standards. These benefits are achieved through use of MIMO (Multiple-Input, Multiple-Output) technology. The latest draft for IEEE 802.11n describes rates up to 600Mbps, exceeding the maximum rate with the 11a/g standards by more than ten times. In addition, techniques such as space-time block coding and beamforming provide the potential of increasing signal strength at the receiver with optimal efficiency, based on the diversity order used.

In this paper, we present a brief historical narrative of the development of the standard, then we describe the three main proposals for the physical (PHY) layers in the original main proposals for the 11n amendment (the TGn Sync, WWiSE and TGn Joint proposals). The Joint Proposal was adopted and it reflects the current PHY layer architecture described in Draft 3.0 for the 11n amendment.

Several design choices were made in the TGn Joint proposal regarding the areas of channel estimation (considering the use of beamforming, channel smoothing), bit interleaving techniques (for maximizing coding gain under channels with high frequency diversity), space-time block coding (STBC) options (designed in an effort to achieve a good balance between achieving high diversity gain and low receiver design complexity), and pilot tone selection (for a reasonable tradeoff of robustness and link-level performance).

We have implemented a simulation model for the IEEE 802.11n standard using MATLAB/SIMULINK. Performance curves (based on simulation models) can be used for design exploration and for teaching purposes. This simulation model is a potentially great teaching tool for evaluating various aspects of the PHY layer of the IEEE 802.11n standard. We present examples of such exploration.

Our simulation model has since been made available for free download on Mathworks MATLAB Central. This simulation model is applicable for design space exploration for classroom/laboratory teaching of wireless communication courses at both undergraduate and graduate levels.

Introduction

The IEEE 802.11n is a currently emerging WLAN standard capable of providing dramatically increased throughput, as well as improved range, reduced signal fading, over the existing IEEE 802.11a/g WLAN standards. These benefits are achieved through use of MIMO (Multiple-Input, Multiple-Output) technology. The latest draft for IEEE 802.11n describes rates up to 600Mbps, exceeding the maximum rate with the 11a/g standards by more than ten times. In addition, techniques such as space-time block coding and beamforming provide the potential of increasing signal strength at the receiver with optimal efficiency, based on the diversity order used. Details of the 802.11n standard can be found in [1].

The process of developing the IEEE 802.11n (11n) amendment for the next generation of wireless local-area networks (WLAN) devices has encountered many hurdles, particularly in the initial stages, where the competing draft proposals from leading companies resulted in an overall inability to proceed with the standardization process.

With the latest draft of IEEE 802.11n (Draft 3.0), throughputs beyond 200Mbps are possible, based on physical layer (PHY) data rates up to 600Mbps. Techniques employing multiple transmit and receive antennas, referred to as MIMO (multiple input, multiple output) are used to achieve these rates. These MIMO techniques include spatial division multiplexing (SDM), transmitter beamforming, and space-time block coding (STBC), used either to increase throughput over single antenna systems (by two to four times) or to improve range of reception, depending on the environment. In this paper, the focus is on the PHY layer design, and thus no treatment of the Media Access Control (MAC) layer is given here.

This paper evaluates the architectural differences of the PHY layers in the TGn Joint, TGn Sync, and WWiSE proposals [2] for the IEEE 802.11n standard and provides key insights into the choices made. In Section II, we give a brief history of the development of the 11n amendment, the approaches for channel estimation, bit interleaving, space-time block coding, and pilot tone usage are analyzed in an effort to characterize the performance benefits of each proposed technique.

In Section III, we provide a brief description of the IEEE 802.11n PHY Layer and the key modifications. In Section IV, we give a summary of the comparison of the competing proposals that led to the Joint Proposal that was adopted in Draft 3.0 Amendment.

Then in Section V, we describe the simulation models developed in MATLAB/SIMULINK which are useful for performance verification of the IEEE 802.11n standard and can also be used as a teaching tool. This simulation model is a potentially great teaching tool for evaluating various aspects of the PHY layer of the IEEE 802.11n standard. The simulation model has since been made available for free download on Mathworks MATLAB Central [3].

Finally, we make some concluding remarks.

Historical development of the IEEE 802.11n

The initial development of the IEEE 802.11n amendment began towards the end of 2003. At this time, the IEEE (Institute of Electrical and Electronics Engineers) formed the TGn task group to begin work on the specification. The initial goal was to achieve effective throughputs of at least 100Mbps, which would more than double the existing throughput for the 802.11a/g specifications. It is important to note that this 100 Mbps throughput goal represents the overall throughput, which includes all protocol overhead, i.e., the MAC as well as PHY layers overhead.

At one point, as many as 61 draft proposals were submitted to the IEEE, originating from a variety of hardware and networking companies [4]. However, by February of 2005, they were effectively narrowed down to two. One was by the WWiSE (World Wide Spectrum Efficiency) group, which included companies such as Airgo Networks, Broadcom, Motorola, and Texas Instruments. This proposal suggested the use of channels with similar bandwidth to the existing 11b/g networks (20MHz), as well as the use of multiple transmit and receive antennas, or MIMO technology, to achieve throughput rates of around 135Mbps in real-world conditions.

The other proposal was by the TGn Sync group, which consisted of Atheros Communications, Intel, Philips, Sony, among others. The proposal suggested doubling the bandwidth to 40MHz, to essentially double throughput. In addition, other, more sophisticated processing techniques allowed the TGn Sync devices to transmit data at rates up to 315Mbps.

Over the following months, the two proposals evolved to form the main competing proposals for IEEE 802.11n standard. Both offered MIMO communications capability, with up to four transmit and four receive antennas. Both also supported an optional 40MHz bandwidth mode. The two proposals differed, however, in areas such as data interleaving, space-time coding, and channel estimation. The TGn Sync proposal included approaches for transmit beamforming and spatial spreading.

Although the TGnSync proposal enjoyed a majority of the ballot voting compared to WWiSE, the proposal was not able to obtain the 75% vote necessary to be accepted as the initial 11n amendment draft. In July 2005, however, a group consisting of members of both proposals agreed to form a joint proposal group, which submitted a new proposal to the TGn workgroup in January 2006. This proposal, referred to as the TGn Joint proposal, combined the benefits of the other proposals, and formed the basis of the current drafts for the 802.11n standard.

IEEE 802.11n PHY Layer Description

To achieve the increased throughput and range envisioned for IEEE 802.11, the 11n amendment describes enhancements to both the physical (PHY) and medium access control (MAC) layers. Modifications to the MAC include the addition of frame aggregation (ie. sending multiple MAC frames in one PHY layer packet, to reduce overhead), block ACK enhancements (acknowledging frames in blocks, also to reduce overhead), a reverse-direction (RD) protocol (allows the transmit station currently holding the air channel to efficiently transfer control to another station, without the need for the other station to initiate a data transfer), as well as schemes for co-existence with legacy devices.

Other modifications include:

- Quality of Service (QoS) features, to support delay-sensitive applications such as Voice over WLAN (VoWLAN) and multimedia streaming (described in 802.11e)
- power save multi-poll (or PSMP) feature, a battery saving feature for WLAN in handheld devices
- extended channel switch announcement, ie. allowing an AP to switch between support of 20MHz only, and 20MHz / 40MHz (described in 802.11y)
- improved radio resource management, ie. efficient use of multiple APs within a network (described in 802.11k)
- support for fast roaming, ie. fast handoffs between base stations, intended for use in supporting mobile phones using VoIP and wireless networks instead of cellular networks (described in 802.11r).

The modifications to the PHY layer include:

- Use of multiple transmit and receive antennas (known as MIMO)
- Channel bonding (ie. use of two 20MHz bandwidth streams)
- Advanced coding (ie. low-density parity check, or LDPC, codes)

Figures 1 and 2 show block diagrams of general MIMO transmit and receive datapath structures for an IEEE 802.11n PHY layer.

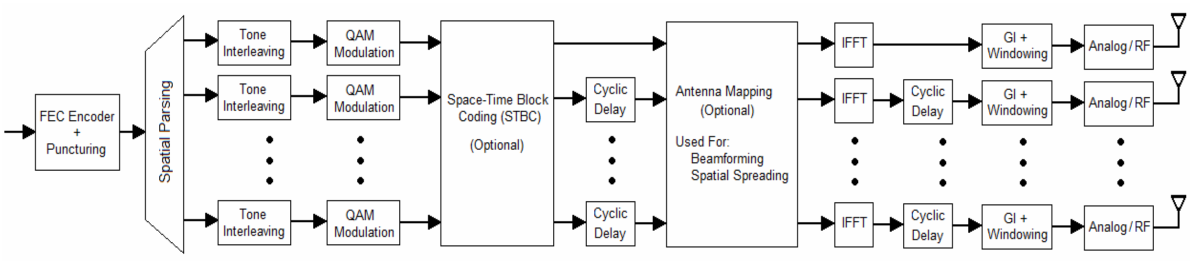

Figure 1: General MIMO TX Datapath

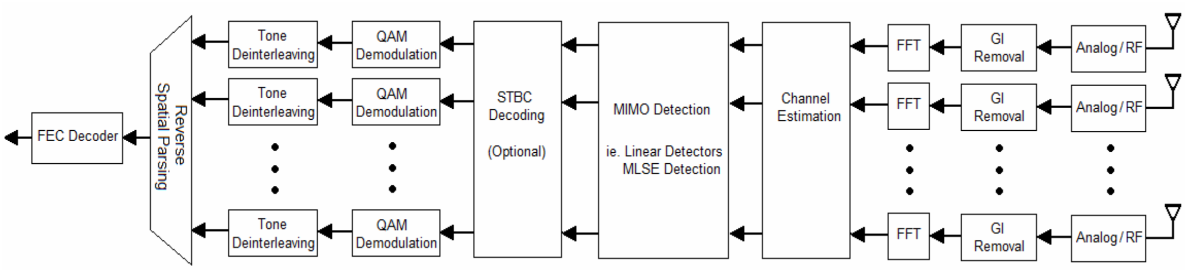

Figure 2: General MIMO RX Datapath

Summary Comparisons of Competing Proposals

In this section, we summarize the comparisons of competing proposals (WWiSE and TGn Sync proposals) and consider the choices made in the TGn Joint proposal. More details are in [2].

First, we discuss the channel estimation performance results for the three proposals. Consider that the derived MSE for the TGn Joint proposal differs from the WWiSE proposal only by the term ¼. This was due to the benefit of channel smoothing described previously. Considering that this channel smoothing, time-domain windowing, can be used with the TGn Joint proposal as well, the performance using the TGn Joint proposal training should be the same as with the WWiSE. However, unlike the WWiSE training, the TGn Joint does not require the use of these algorithms (which require a high correlation between adjacent sub-carriers). Thus, there exists a tradeoff between the use of channel smoothing or SVD-based beamforming. The TGn Joint proposal eventually handled this issue by incorporating a training sequence which allows for the use of either channel smoothing or beamforming. The TGn Joint proposal also includes an extra bit in the preamble which specifies whether the training sequence was beamformed in a manner suitable for channel smoothing. This allows for implementation flexibility, providing support for the approaches considered by both the WWiSE and TGn Sync groups.

For the bit interleaving, the approach used by the TGn Joint proposal is the same as the TGn Sync proposal. These proposals differ from the WWiSE proposal in the spatial parsing (WWiSE maps alternating bits across spatial streams, while the TGn Sync, TGn Joint proposals map groups of bits). They also differ in the process of interleaving the bits across sub-carriers. However, the choice of interleaving parameters for the TGn Joint proposal was based on the number of pilot tones selected, in addition to the benefits for frequency diversity.

The space-time coding options supported by the TGn Joint proposal were shown to include the STBC options described by the other proposals. Thus, the TGn Joint proposal supports all the STBC modes of the other proposals, as well as additional modes (based on choice of spatial mapping matrices).

Finally, it was shown that the choice of four pilot tones for 20 MHz mode is preferred, on the basis of robustness. This was illustrated with the case where one pilot tone undergoes fading, and considering the minimal throughput improvement with two pilot tones (around 4%). Four pilot tones are used with the TGn Joint and TGn Sync proposals, compared to two pilot tones for the WWiSE.

Thus, for all areas discussed above, the choices made in the Joint proposal yield similar or better performance compared with the other proposals. Table 1 summarizes these results.

	WWiSE	TGn Sync	TGn Joint
Channel Estimation (effective SNR, Rx output)	$\rho_{eff,dB} = \rho_{d,dB} - 10\log\left(1 + \tfrac{1}{4}(N_{STS} / N_{DLTF})\right)$	$\rho_{eff,dB} = \rho_{d,dB} - 10\log\left(1 + (N_{STS} - \tfrac{1}{2})\right)$	$\rho_{eff,dB} = \rho_{d,dB} - 10\log\left(1 + (N_{STS} / N_{DLTF})\right)$ Performance is similar to WWiSE if same techniques are used (windowing, smoothing)

Bit Interleaving	Data carriers used: 54 - Bits mapped to every 9th carrier for 6 carriers (then back to next bit of 1st carrier) - Shift across spatial streams: For 1st SS : 0 carriers For 2nd SS : 5 carriers For 3rd SS : 10 carriers For 4th SS : 15 carriers Provides advantage if tones are highly correlated only within 9 carriers. However, every N_{SS}*6th bit has similar reliability. The carrier shifts across spatial streams should ensure consecutive bits have different reliability, however this should depend on channel	Data carriers used: 52 - Bits mapped to every 4th carrier for 13 carriers (then back to next bit of 1st carrier) - Shift across spatial streams: For 1st SS : 0 carriers For 2nd SS : 22 carriers For 3rd SS : 11 carriers For 4th SS : 33 carriers Can result in consecutive bits of similar reliability if tones are correlated further than 4 carriers. However, only every N_{SS}*13th bit has similar reliability. Carrier shifts for spatial streams should ensure consecutive groups of bits have differing reliabilities, however depends on channel	Data carriers used: 52 - Bits mapped to every 4th carrier for 13 carriers (then back to next bit of 1st carrier) - Shift across spatial streams: For 1st SS : 0 carriers For 2nd SS : 22 carriers For 3rd SS : 11 carriers For 4th SS : 33 carriers Benefit same as TGn Sync
Space Time Coding	Coding options: N_{SS}=1 to N_{STS}=2,3,4 N_{SS}=2 to N_{STS}=3,4 N_{SS}=3 to N_{STS}=4 The options N_{SS}=1 to N_{STS}=2 and N_{SS}=2 to N_{STS}=4 are the same as TGn Sync. Also uses a circulation pattern across antennas for N_{SS}=1 to N_{STS} =3,4	Coding options: N_{SS}=1 to N_{STS}=2 N_{SS}=2 to N_{STS}=4	Coding options: N_{SS}=1 to N_{STS}=2,3,4 N_{SS}=2 to N_{STS}=3,4 N_{SS}=3 to N_{STS}=4 For options N_{SS}=1 to N_{STS}=3,4 the circulation pattern across antennas with WWiSE is not present. However, pattern can be performed using spatial mapping matrices.

Pilot Tones	Pilot tones used: 2 Allows for higher data rate (4% rate increase), however benefit lost if either pilot tone is corrupted, resulting in loss of clock frequency, carrier phase offset tracking (even with MIMO).	Pilot tones used: 4 Data rate lower (by 4%), however the use of 4 pilot tones is more robust against corruption of pilot tones for clock frequency and carrier phase offset tracking.	Pilot tones used: 4 Benefit same as TGn Sync

Table 1: Comparison Summary of WWiSE, TGn Sync, and TGn Joint Proposals

The Simulation Model as a Teaching Tool for Communications

Our MATLAB/SIMULINK model simulates the PHY layer. The simulation model we developed can be used as a teaching tool for wireless communications and networking courses. The top-level block diagram of the SIMULINK/MATLAB simulation tool is shown in Figure 3.

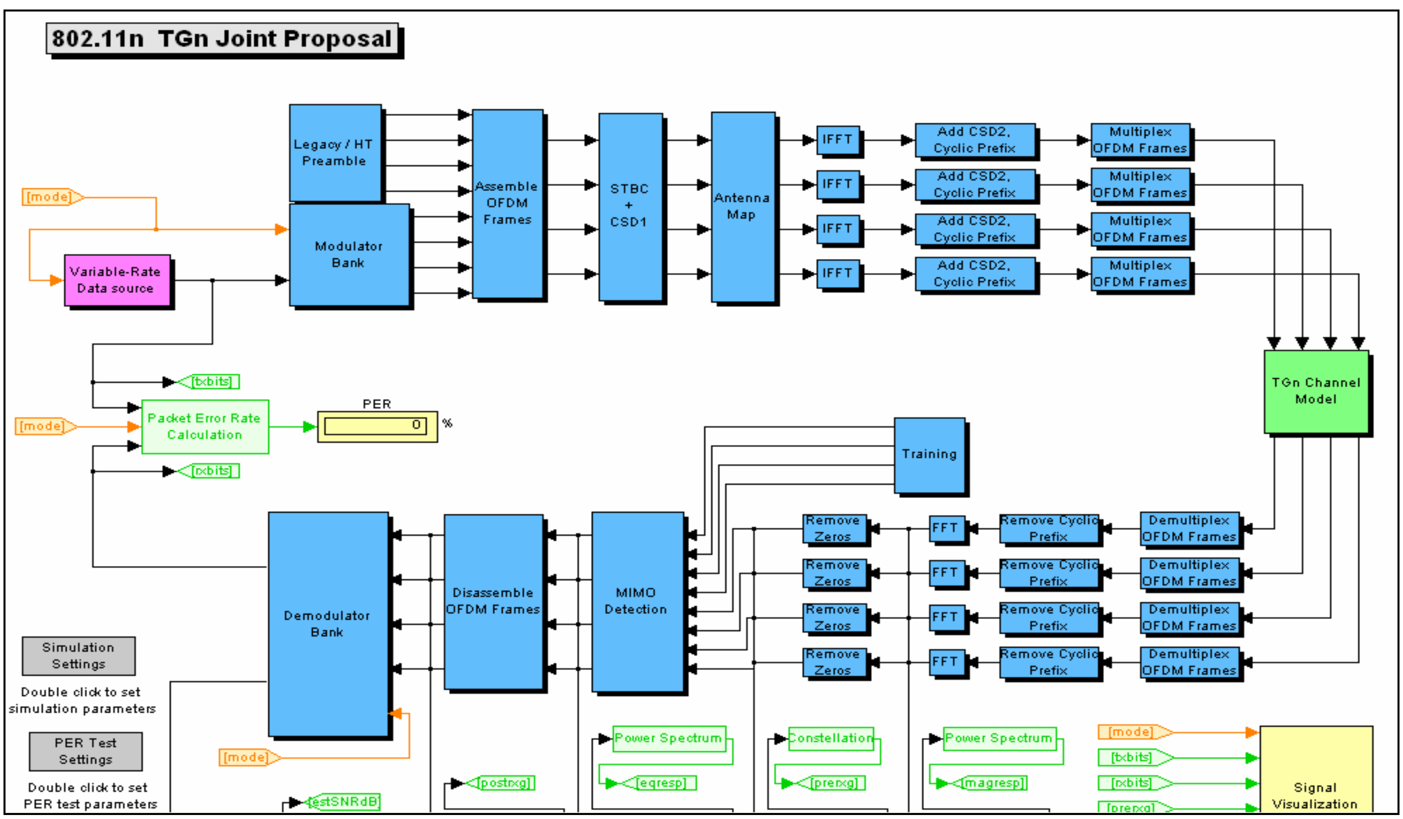

Figure 3: MATLAB/SIMLINK Block Diagram for the IEEE 802.11n Standard

Settings can be set as follows for the performance tests:

- Receiver type: MMSE detector
- Payload Size: 1000 bytes
- AWGN, Ch D (nLOS) channels (no impairments)
- Per-tone channel est. (no smoothing)

Various configurations can also be set for the simulation environment. Examples are:

- AWGN, 2x2 Direct-map
- Ch D (nLOS), 2x2 Direct-map
- Ch D (nLOS), 2x2 Beamforming
- Ch D (nLOS), 4x2 STBC

The PER (packet error rate) vs. SNR results for the various configurations can be compared. This serves a powerful purpose of design exploration in the context of teaching.

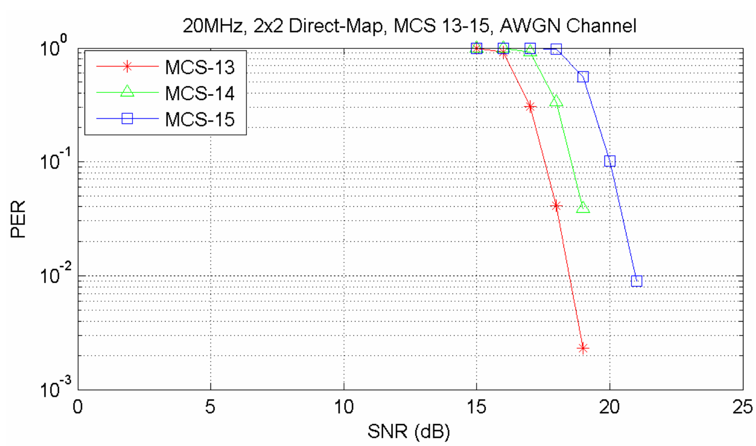

Figure 4: IEEE 802.11n PHY: AWGN, 2x2 Direct-Map

The PER curves in Figure 4, show the performance of the 11n PHY layer and an Additive White Gaussian Noise (AWGN) channel. The curves should directly reflect the MCS settings used. Note these modulation settings are similar to IEEE 802.11a/g.

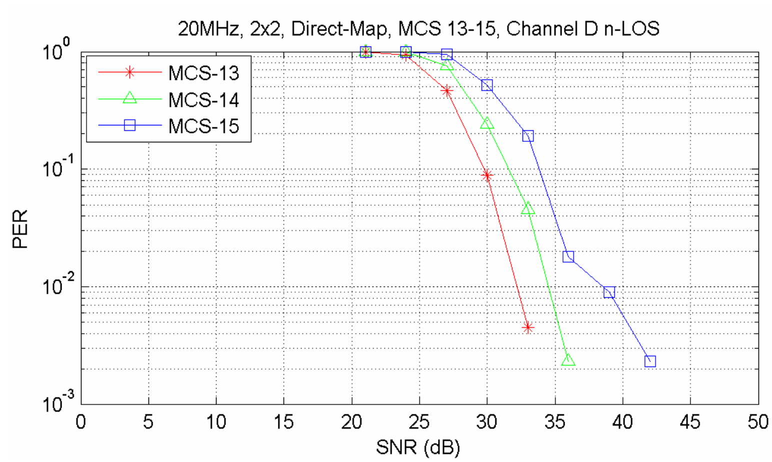

Figure 5: IEEE 802.11n PHY: Ch D, nLOS, 2x2 Direct-Map

In Figure 5 (Channel D, nLOS), a delay spread channel (reflecting a typical office-type environment) is simulated, leading to frequency-selective fading. For this type of channel, the SNR varies across data carriers, and the PER is dominated by the low SNR carriers. Thus, a higher average SNR is required to achieve the same PER as for the AWGN channel.

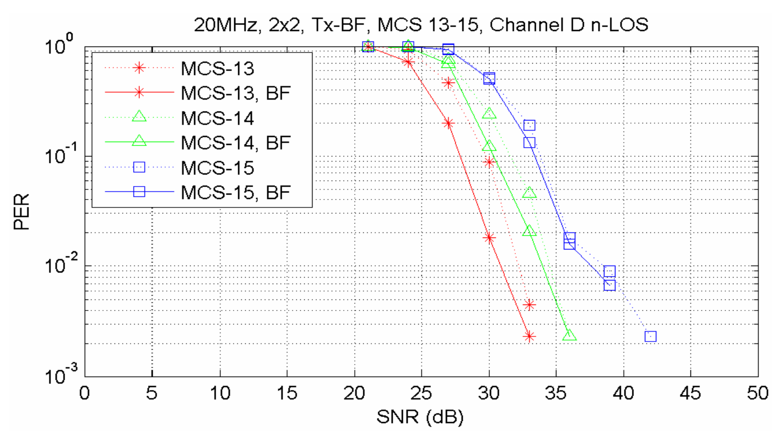

Figure 6: IEEE 802.11n PHY: Ch D, nLOS, 2x2 Beamforming

Figure 6 shows the benefit of beamforming (use of eigenmodes for transmission). Note that the gain is modest (only around 2dB), since same number of Tx antennas as spatial streams is used (2x2 MIMO). Thus, the diversity order is not increased. The benefit originates solely from channel diagonalizing (ie. use of orthogonal transmission modes). Since Ch D (nLOS) is a Rayleigh fading MIMO channel, the benefit of diagonalizing channel is modest.

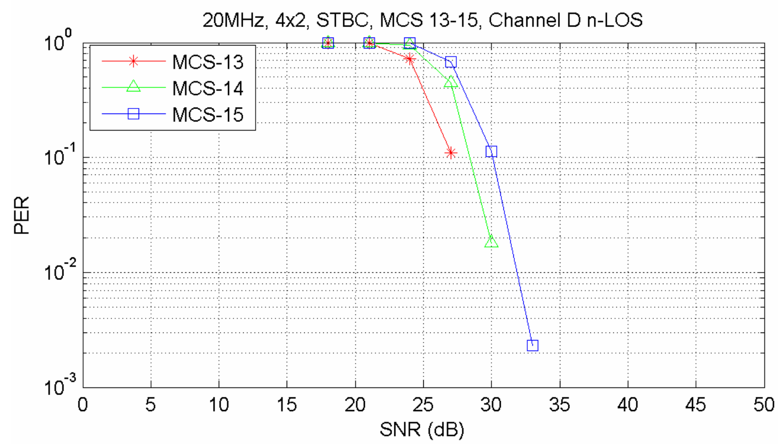

Figure 7: IEEE 802.11n PHY: Ch D, nLOS, 4x2 STBC

In Figure 7, we show the benefit of 4x2 STBC (2 spatial streams, 4 space-time streams). Note the significant improvement (about 8dB) compared to 2x2 direct-map and beamforming, due to the additional transmit diversity order, which is used to provide STBC coding for each of the transmitted spatial streams.

In order to better compare the various PHY layer configurations for the IEEE 802.11n amendment, Figure 8 shows simulation results of the average throughput versus distance under an office-type environment (Channel D). Note, for each of these tests, that the focus is on PHY layer performance, and the influence of the MAC layer on throughput (also considering frame aggregation) was approximated to provide suitable results.

The following IEEE 802.11 PHY layer configurations were tested:

- IEEE 802.11a/g (as reference)
- SISO
- 2x1 STBC
- 2x2 SDM
- 2x2 SDM+Beamforming
- 4x2 STBC
- 4x4 SDM+Beamforming

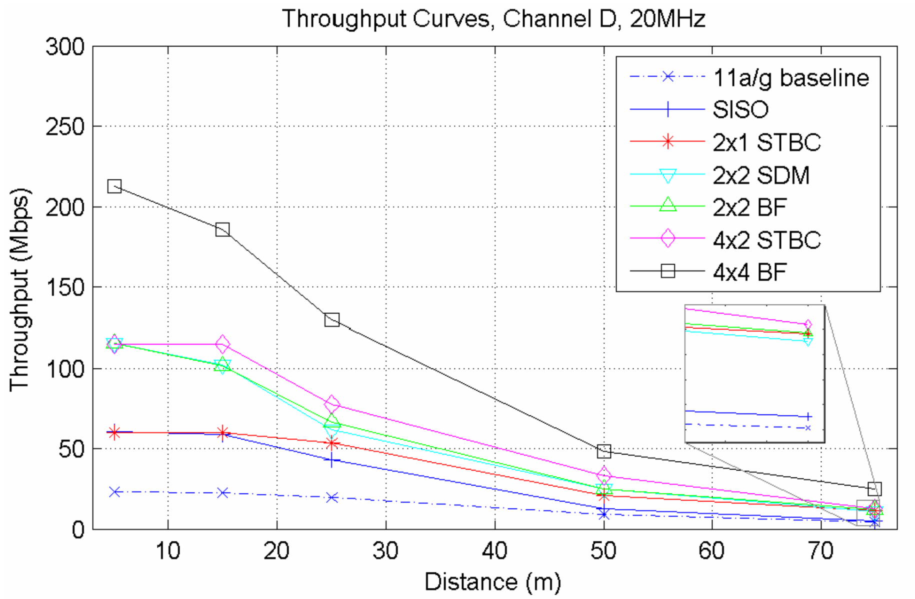

Figure 8: IEEE 802.11n PHY: Throughput vs. Ch D, Various Config.

These graphs show the increase in throughput obtained using multiple spatial streams (the last three tests). For the 2x2 and 4x4 tests, we see that the throughput is generally double (or four times with 4x4) that of the SISO case for shorter distances (less than 20m). However, at larger distances, note that the 2x2 SDM throughput reduces to levels similar to SISO, and below 2x1 STBC. This is due to the fact that, at these distances, the low SNR affects MIMO detection (note MIMO detection balances noise whitening, interference cancellation), resulting in a reduced ability to perform interference cancellation for the spatially-multiplexed streams. Note the performance is slightly better for 2x2 SDM with beamforming, as the use of orthogonal transmission modes improves the signal strength at the receiver.

However, for the results with 2x2 SDM with beamforming, the overall performance gain is modest (less than 5 Mbps), for the same reasons described previously for Figure 6. Finally, regarding the use of 4x2 STBC, note the general performance benefit over both the 2x2 SDM and 2x2 SDM+beamforming tests, again due to the additional transmit diversity order.

One final area to consider is the performance of the 802.11a/g baseline. We see that, at close distances, the performance of the 11a/g baseline is around half that of the IEEE 802.11n SISO. This is mainly due to the frame aggregation used with 11n, which allows the practically achievable throughput to approach the actual PHY layer data rate. At larger distances, however, the performance gap between the 11a/g and the 11n SISO case reduces considerably. This is due to the fact that very low data rates are used at this range, significantly increasing the packet duration (the data portion of the packet), thus reducing overhead, as well as the need for frame aggregation. However, even at large distances, some benefit from the use of frame aggregation can be observed.

From the above tests, we can see the benefits provided by the IEEE 802.11n PHY layer, in terms of both range and throughput, over the 11a/g PHY layer. We also note that the use of frame aggregation was required to reduce packet overhead sufficiently to achieve throughputs approaching the PHY layer rate (we can compare the 11a/g and 11n SISO results to observe this) [5,6,7].

Conclusions

In this paper, we presented a brief historical narrative of the development of the standard, then we compared the three main proposals for the physical (PHY) layers that led to the development of the main proposal for the 11n amendment known as the Joint proposal.

We described a MATLAB/SIMULINK based simulation model for the PHY layer of the Joint Proposal. Several design choices were made in the TGn Joint proposal regarding the areas of channel estimation (considering the use of beamforming, channel smoothing), bit interleaving techniques (for maximizing coding gain under channels with high frequency diversity), space-time block coding (STBC) options (designed in an effort to achieve a good balance between achieving high diversity gain and low receiver design complexity), and pilot tone selection (for a reasonable tradeoff of robustness and link-level performance).

Our simulation model has been used for design exploration and can also be effectively used as a teaching tool in Communication courses. Examples of the performance curves (based on simulation models) were given. This simulation model is an extremely useful teaching tool for evaluating various aspects of the PHY layer of the IEEE 802.11n standard. We present examples of such exploration.

Our simulation model has since been made available for free download on Mathworks MATLAB Central [3].

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