Physical Layer Analysis of Emerging IEEE 802.11n WLAN Standard

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Abstract - **In January 2004 IEEE announced that it had formed a new 802.11 Task Group N (TGn) to develop a new amendment to the 802.11 standard for wireless local-area networks that will be known as IEEE 802.11n standard. The real data throughput will be at least 100 Mbps, with possibility of even higher raw data rate at the physical layer (PHY), and should be up to 5 times faster than 802.11a or 802.11g, and perhaps 25 times faster than 802.11b in mandatory modes of operation. It is projected that 802.11n will also offer better operating distance and full compatibility with current WLANs. There are two competing proposals of the 802.11n standard, expected to be ratified: WWiSE and TGnSync. This paper on PHY compares new technical solutions of these two proposals believing that the best of these proposals will be incorporated in 802.11n standard. We also emphasize features and technical solutions on PHY that inevitably will be built in emerging 802.11n standard**.

1. Introduction

Wireless local-area networks (WLAN) are evolving towards the development of broadband applications, including multimedia services in a way to compete with wired LAN systems. It is expected that rapid growth of mobile users will eventually demand the development of new applications with broadband access and bit rates higher than 54 Mbps, what is currently offered by IEEE 802.11a and g standards. Only 50-60% of that nominal bit rate is devoted to user traffic, due to the overhead imposed by physical-layer (PHY) frame header, preamble transmission and requirement that each sent frame must be acknowledged. Therefore, the aim of today's research effort is to provide high bandwidth WLAN communication system with similar performance, reliability and security compared to its wired counterpart. As WLAN technology matures, newer features and functionality will continue to be made available. Standardization organizations, like IEEE are providing continuous effort to meet new demands from users by introducing new standards as well as minimizing shortcomings of the previous standards [1, 7].

In January 2004 IEEE announced that it had formed a new 802.11 Task Group N (TGn) to develop a new amendment to the 802.11 standard for wireless local-area networks [6, 7, 8]. TGn's goal is to achieve 100 Mbps net throughput, after subtracting all the overhead for protocol management features like preambles, interframe spacing, and acknowledgments. There are two approaches to achieve 100 Mbps throughput: improve the efficiency of the MAC, increase the peak data rate well beyond 100 Mbps - or both. Between many partial and few complete proposals submitted for ratification to IEEE 802.11 TGn, support has coalesced around two main competing proposals, from groups named TgnSync and WWiSE (World-Wide Spectrum Efficiency), where the third group named MIMOT had also highly ranked proposal [2, 3, 6]. The core of WWiSE group is composed of companies including Broadcom, Airgo networks, Conexant Systems, AT&T, HP, Texas Instruments, STMicroelectronics with Nokia and Motorola joined to the group later [2]. TgnSync group is backed by Atheros, Agere, Marvell, Qualcomm and Intel Corporation. However, quite a few manufacturers of electronic devices that might use 802.11 (Cisco, Nortel, Philips, Samsung, Sanyo, Sony, Panasonic, Mitsubishi, Hitachi…) have also become part of the effort, and they are disproportionately represented in TgnSync group [3]. The standardization process is expected to be completed by the end of 2006.

According to the vote support in IEEE TGn, TGnSync proposal will probably be the basis for the 802.11n specification, but some solutions trading will likely result in a WWiSE or even a few MIMOT features being incorporated. Thus, it is to be expected that final standard will have some resemblance to both of competing standards, and will likely choose features from each in order to bring new standard that will be known as IEEE 802.11n specification. As a result, this paper describes PHY of both of the main competing proposals, emphasizing elements that inevitably must be built in future standard. Since many new basic concepts are shared between the two proposals, our goal is to describe these basic concepts and predict what best features of every main proposal will be incorporated in new standard. Detail technical realization of some concepts will not be presented in this paper because proposals themselves may have slightly changed since the drafts upon which this paper was based were written. The main contribution of this paper is presentation of new concepts, features and technical solutions that will be, in our opinion implemented in emerging 802.11n standard.

This paper is organized as follows: section 2. outlines MIMO operation and transmission of single data stream across multiple antennas. In Section 3., we briefly describe operating channel structure of both proposals. Modulation types and data rates of two main proposals are pointed out in section 4. Section 5. describes different transmission modes. Finally, section 6. emphasizes enhancements in improving MAC efficiency that are incorporated inside proposals.

2. MIMO systems

New 802.11n standard builds upon previous 802.11 standards, especially 802.11a standard by adding MIMO (Multiple-Input/Multiple-Output) operation. So far, most of

802.11 devices had a single antenna, or even two antennas in a diversity configuration, but the basis of diversity is that the "best" antenna is selected. In diversity configurations, only a single antenna is used at any point. Although there may be two or more antennas, there is only one set of components to process the signal, or RF chain. The receiver has a single input chain, and the transmitter has a single output chain. The next step beyond diversity is to attach an RF chain to each antenna in the system. This is the basis of MIMO operation. Each RF chain is capable of simultaneous reception or transmission, which can dramatically improve throughput. Furthermore, simultaneous receiver processing has benefits in resolving multipath interference, and may improve the quality of the received signal far beyond simple diversity. Each RF chain and its corresponding antenna are responsible for transmitting a spatial stream. A single frame can be broken up and multiplexed across multiple spatial streams, which are reassembled at the receiver [1, 5]. MIMO operation will be built in new standard since it is reliable technology for boosting data rate through parallel transmission of multiple spatial streams proposed by both groups.

In most cases, an antenna will be used for each spatial stream what is defined as basis in both of proposals. However, there may be cases when the number of antennas is greater than the number of spatial streams. Thus, it is important to emphasize the difference between the number of transmit antennas and the number of spatial streams, where the number of spatial streams (will probably be equal to 1,2,3, or 4) must be less than or equal to the number of transmission antennas. Support for at least two spatial streams will probably be mandatory. If, for example, most APs wind up using three antennas while clients only use two, there is an "extra" transmit antenna, and the two spatial data streams need to be assigned to the three antennas. Transmitting a single spatial stream across multiple antennas will be used in some transmission modes of new 802.11n devices.

Space-time block coding (STCB) is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. The fact that transmitted data must traverse a potentially difficult environment with scattering, reflection, refraction and so on as well as be corrupted by thermal noise in the receiver means that some of the received copies of the data will be 'better' than others. Thus, STBC combines all the copies of the received signal in an optimal way to extract as much information from each of them as possible [5]. When there are extra antennas, the WWiSE proposal mandates that a single spatial stream is transmitted on only 2 antennas using basic STBC rule also called Alamouti code [4, 2]. If the number of spatial streams is less than the number of transmit antennas, a TgnSync proposal defines usage of spatial steering matrix in order to assign bits to transmission antennas for some transmission modes. The unitary matrices are presented in TGnSync proposal for construction of spatial spreading antenna map enabling transmission of single spatial stream over 2, 3 or 4 antennas without usage of classical STBC codes [3]. Although unitary matrices of TGnSync proposal enables that each spatial stream maps equal energy to each antenna, space-time block codes have low cost, wide flexibility, and no overhead. We give advantage to classical STCB coding with possibility of single spatial stream transmission over 2, 3, and 4 antennas with equal energy.

MIMO antenna configurations are often described with the shorthand "YxZ", where Y and Z are integers, used to refer to the number of transmitter antennas and the number of receiver antennas. For example, both WWiSE and TGnSync require 2x2 operations, which have two transmit chains, two receive chains, and accordingly to that two spatial streams multiplexed across the radio link [1, 2, 3]. Thus 2x2 operation will probably be mandatory operation for every 802.11n device. Both proposals also have additional required and optional modes. Therefore, it is likely that most products that are based on the eventual 802.11n standard will support additional required modes and at least some of the optional modes. It is likely that the common hardware configuration will require operating in a two-transceiver mode on the client side to save cost and battery power, while access points (AP) will have more transceivers (antennas). Basic APs may have only two, while the most expensive enterprise-class APs will probably have three or four transceivers (RF chains, antennas). Configurations that will be mostly found on the market would use 2x2 (1x2), 2x3 (1x3), 2x4 (1x4) MIMO operation for its uplink communication (from mobile clients to AP), and 2x2 (2x1) 3x2 (3x1), 4x2 (4x1) MIMO operation on the downlink (from AP to mobile clients). The fact that more antennas are feasible at AP and fewer at mobile clients implies that asymmetric way of working will be built in new standard.

3. Channel structure

IEEE 802.11b,a,g standards currently use 20 MHz channels because that is the channel bandwidth allowed by all regulators worldwide. Doubling the channel bandwidth to 40 MHz doubles the theoretical information capacity of the channel. Also, 40 MHz channels are only supported in the 5 GHz band because it is not possible to squeeze multiple 40 MHz channels into the 2.4 GHz ISM band. Although promising for the future, some regulators do not currently allow 40MHz channel operation. Japan is the most notable exception. We are sure that support for 20 MHz channels will be mandatory for backward compatibility with older standards, but support for 40MHz channels will also be built in new 802.11n standard. Reasons for that perception lie in the fact that both proposals define usage of 20MHz and 40 MHz channels, and because usage of 40MHz channels redoubles peak bandwidth. Both proposals are slightly evolution of 802.11a, using MIMO technology. Thus, orthogonal frequency-division multiplexing (OFDM) used in 802.11a,g technologies is also basic channel coding and transport mechanism of two proposals and it will be built in new 802.11n standard.

WWiSE proposal uses both 20 MHz and 40 MHz channels, without defining usage of 40MHz channels as mandatory [2]. 40 MHz operation may be through a single 40 MHz channel, or through a 20 MHz channel pair in which both channels are used simultaneously for data transmission.

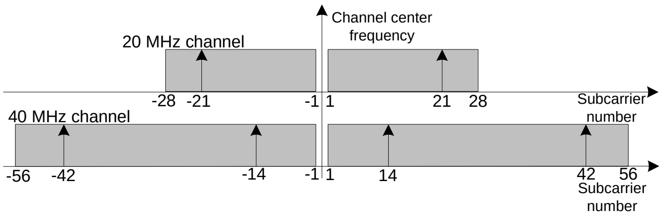

Fig. 1. 20MHz and 40 MHz Channel Structure of WWiSE Proposal

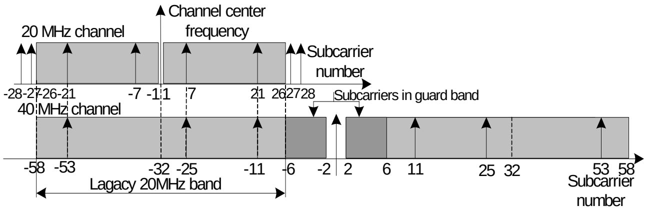

Fig. 2. 20MHz and 40 MHz Channel Structure of TGnSync Proposal

One channel is designated as the primary channel, and operates normally. The secondary channel is used only for channel aggregation (for "overflow" from the primary), and does not have stations associated on it. Although the first TGnSync proposal makes 40MHz channel support mandatory, harmonization between the two proposals has occurred imposing only optional usage of 40MHz channel band, what is originally defined in WWiSE proposal. Thus, TGnSync chipset would support work in 20 MHz channel band as mandatory operation while work in single, continues 40 MHz channel band will be optional. The TGnSync proposal also has MAC features that enable the use of networks with both 20 MHz and 40 MHz-capable stations. When stations have large amounts of data to transmit, it is possible to negotiate a temporary use of a wider channel before falling back to 20 MHz operation [1, 3]. In both proposals, 20 MHz and 40 MHz channels have subcarrier frequency spacing equal to 0.3125 MHz, just as in 802.11a standard. These frequency spacing are obtained by dividing 20 MHz channel with 64 and 40MHz channel with 128 possible subcarrier frequency slots. It is to be expected that new standard will impose the some subcarrier frequency spacing in both bands equal to 0.3125 MHz.

The 20MHz radio channel in WWiSE proposal uses 56 operational subcarriers, and 40 MHz channels, which are optional in WWiSE proposal uses 112 operational subcarriers (Figure 1). As in 802.11a OFDM, few subcarriers are set aside as pilots to monitor the performance of the radio link. Theoretically, fewer pilot carriers are needed in a MIMO system because the pilot carriers run through as many receiver chains. A 20 MHz 802.11a channel uses four pilot subcarriers. In the WWiSE proposal, a 20 MHz channel requires only 2 pilot carriers because each pilot is processed by 2 receiver chains, which has the same effect as 4 pilots processed by a single receiver chain. With fewer pilots, more subcarriers can be devoted to carrying data. 20 MHz WWiSE channels have 54 data subcarriers and 40 MHz channels with 4 pilots have exactly twice as many equal to 108 (Figure 1.). These data subcarriers provide separate pathways for sending the user information in parallel fashion based on OFDM technology also used in 802.11a,g standard.

In the first TGnSync proposal, 20 MHz channel was identical to an 802.11a channel structure requiring 52 operational subchannels with 4 pilots subchannels. But, convergence between group proposals results in TGnSync 20MHz channel structure proposal with equal number of operating subcarriers (56) like in WWiSE proposal. Two extra data subcarriers are added at the ends on each side from the center of the legacy (802.11a) 20 MHz channel, creating 20 MHz channel structure with 56 operational subcarriers (Figure 2.). Only difference when compared to WWiSE proposal is the number of pilot subcarriers equal to 4, since TGnSync channel structure proposal was based on 802.11a channel structure (Table 1.). The 40 MHz channel proposed by TGnSync is a modification of the 20 MHz structure (Figure 2.). Two 20 MHz channels are bonded together, and the resulting spectral band uses 114 operational subchannels. The center frequencies of the old 20 MHz channels are located at +/–32th subcarrier of the new 40MHz channel with the number of center null subcarriers equal to 3 (-1, 0, 1). The legacy channels (802.11g,a) apply a spectral mask from –6 to +6 and roll off the amplitude of transmissions at the end of the bands. With a single continuous 40MHz channel, however, there is no need to use a spectral mask, and the middle of the band can be used at full strength. To further boost throughput, one of the pilot carriers from the 20 MHz channel is removed, so a 40 MHz channel has 6 pilot carriers instead of 8 (Figure 2). Rather than simply double the throughput as in case of WWiSE proposal, a 40 MHz channel in TGnSync proposal with 108 data subcarriers provides throughput equal to 2.0769... (108/52) times higher then 20 MHz channel with 52 data subcarriers.

Spectral usage was the first major point of contention between the two groups, with main question of defining usage of 40MHz channels mandatory or not. If the usage of 40 MHz would be ratified as mandatory, it would lead to chipsets that are always capable of 40 MHz operation, adding extra cost and complexity, even though regulators may not allow them. Also mandatory usage of 40 MHz channels to improve the data rate before improving efficiency will be a waste of scarce unlicensed spectrum. Since both groups agreed upon usage of 20 MHz channel mode as mandatory and 40MHz channel mode as optional, we strongly believe that this channel mode usage will be incorporated in new 802.11n standard. In countries where 40 MHz channels are allowed, the extra speed would be welcome and 40 MHz channels will be used. Also, in areas where 40 MHz channels are disallowed, the reduction in extra costs which might be caused by optional 40MHz channel operation will be gladly accepted. Since WWiSE 20 MHz channel structure proposal has only 2 pilot subcarriers, the number of subcarriers dedicated to data transmission is slightly higher then in TGnSync proposal. But, quantitative analyses show that usage of only 2 pilots causes significant performance degradation what is not justified by the less than 4% data rate increase. Also, WWiSE proposal merely doubles throughput in their 40 MHz mode where TGnSync squeezes more than double (2.0769... times) of the capacity out in the 40MHz channel. For these reasons we believe that TGnSync 20 and 40MHz channel structure proposal with or without some

Table 1. Mandatory/Optional Cannel Parameters and Modulation Techniques of Both Proposals

TGnSync proposal (Draft details August 2005)									WWiSE proposal (Draft details August 2005)							
Channel band (MHz)	No. of possible special streams	Modulation type	Coded bits/ Subcar.	Code rate	Modulat.options	ABM Code rate	Mand.	Opt.	Mand.	Opt.	Channel band (MHz)	No. of possible special streams	Modulation type	Coded bits/ Subcar.	Code rate	Modulat.options
							Number of speciel strems									
							1and2	1to4	only2	1to4						
20, 40	1,2,3,4	BPSK	1	1/2	2×4=8		Number of transmit antennas				40,20*	1*,2,3,4	BPSK	1	1/2	1×4=4
20, 40	1,2,3,4	QPSK	2	1/2	2×4=8	1/2	2	1to4	2	1to4	40,20*	1*,2,3,4	BPSK	1	3/4	1×4=4
20, 40	1,2,3,4	QPSK	2	3/4	2×4=8	3/4	Chennelisatin bandwidth (MHz)				40,20*	1*,2,3,4	QPSK	2	1/2	1×4=4
20, 40	1,2,3,4	16-QAM	4	1/2	2×4=8	1/2	20	40	20	40	40,20*	1*,2,3,4	QPSK	2	3/4	1×4=4
20, 40	1,2,3,4	16-QAM	4	3/4	2×4=8	3/4	Number of occupied subcarriers				40,(20*)	1*,(2,3,4)	16-QAM	4	1/2	4+3=7
20, 40	1,2,3,4	64-QAM	6	2/3	2×4=8		56	114	56	112	40,(20*)	1*,(2,3,4)	16-QAM	4	3/4	4+3=7
20, 40	1,2,3,4	64-QAM	6	3/4	2×4=8	1/2,3/4	Number of data subcarriers				40,(20*)	1*,(2,3,4)	64-QAM	6	2/3	4+3=7
20, 40	1,2,3,4	64-QAM	6	5/6	2×4=8		52	108	54	108	40,(20*)	1*,(2,3,4)	64-QAM	6	3/4	4+3=7
20, 40	1,2,3,4	256-QAM	8			1/2,3/4	Number of pilot subcarriers				40,(20*)	1*,(2,3,4)	64-QAM	6	5/6	4+3=7
Number of modulation options-basic advanced mod					64	94	4	6	2	4	Number of modulation options-basic(advanced)mode					49 (9*)
Guard interval (ns)							800	400	800	800	Guard interval (ns)					

changes will be incorporated in new standard.

On the other hand, ratification of 40MHz channel usage as optional, opens possibility that two types of 802.11n devices will be present on the market: devices that support operation in 20 MHz channel mode only, and devices that support operation in both channel modes (20/40). First one can reach peak data rates of 270Mbps (WWISE) or 260/288.89 Mbps (TGnSync), for maximum parameters currently defined in every standard (4 special streams, 64-QAM with 6 coded bits per carrier and 3/4 code rate). We express our fear that different types of devices ratified by the same standard might cause confusion between average customers, appealing on manufacturers, vendors and regulatory bodies to simply and clearly define differences between various devices. We also worn about the fact that price gap between two types of devices might discourage costumers in purchasing 2 (20/40 MHz) mode devices in areas where 2 mode operation is allowed, declining benefits of more then double peak data rates that future 802.11n standard in 2 mode operation will probably offer.

4. MIMO modulation rates

There are 24 data rates defined by the WWiSE PHY proposal, with 49 different modulation options in mandatory and optional basic mode of working (Table 1.). Extra advanced optional working mode defines 9 additional modulation options with STBC coding (* in Table 1.) [2]. On the other hand, basic mandatory and optional modes of TGnSync PHY proposal define 32 different modulation and coding pairs what equals to 64 modulation options (Table 1.). Advance beamforming mode (ABM) of TGnSync offers 94 extra modulation options in mandatory and optional working modes [3]. Devices that will work accordingly to new 802.11n standard will use basic formula for data rate calculation that will be similar to this one:

Data rate (Mbps) = *K*×*channel bandwidth factor*×*number of spatial streams*×*coded bits per subcarrier*×*code rate*×*guard interval factor*

K is constant and equals 0.675 in WWiSE proposal or 13 in TGnSync proposal. *Channel bandwidth factor* is equal to either 20 for 20 MHz channels, or 40 for 40 MHz channels or channel pairs in WWiSE proposal. 20 MHz channels are the baseline, and are assigned a channel bandwidth factor of 1 in TGnSync proposal and 40 MHz channels carry more than twice the data, and are assigned a channel bandwidth factor of 2.0769 in TgnSync proposal. The *number of spatial streams* can be equal to 1, 2, 3, or 4 and it must be less than or equal to the number of transmission antennas in both proposals. *Coded bits per subcarrier* is either 6 for 64-QAM, 4 for 16-QAM, 2 for QPSK, or 1 for BPSK, whereas in WWiSE proposal BPSK and QPSK are only supported for 20MHz optional channel mode with 1 spatial stream (* in Table 1.). The *code rate* may be 1/2, 3/4 (only WWiSE proposal) when used with BPSK ; 1/2 or 3/4 when used with QPSK or 16-QAM; or 2/3, 3/4, 5/6 when used with 64-QAM. The guard interval factor is parameter used only in TGnSnc proposal. The basic guard interval equals 800 ns, and is assigned the factor 1. 400 ns guard intervals increase throughput slightly, and are assigned a factor of 1.1111.

Combination of different number of spatial streams, coded bits per subcarrier and code rates for two types of channel bands as previously described will lead to different data rates that will be defined by 802.11n standard (Table 1.). We presume that some data rates will be mandatory and some will be optional, like in 802.11a standard, where 6,12, 24 Mbps data rates are mandatory and 9, 18, 36, 48 or 54 Mbps are optional. By combining parameters that have influence on the value of data rate, there may be multiple ways to get to the same data rate. Also, with appropriate combination of described parameters new standard will offer data rates compatible with old 802.11 devices in 2.4 and 5 GHz band.

In a basic 20 MHz channel mode with a single spatial stream and 3/4 cod rate (which are most similar to the legacy radio channel transmission), channel capacity is slightly higher in WWiSE (60.75 Mbps) and TGnSync proposal (65/72.22 Mbps) than in 802.11a standard (56 Mbps) because 4 extra data and fewer pilot subcarriers are used. But, advantage of the TGnSync proposal is that these basic mode is mandatory instead of being optional like in WWiSE proposal. Because of that, another disadvantage of WWiSE proposal shows up, offering data rates lower then 54 Mbps only as an option while they are mandatory offered in TGnSync proposal. WWiSE proposal scores highest channel capacity for every 20MHz channel modulation when compared to TgnSync proposal, because it uses fewer (only 2 instead of 4) pilot subcarriers and higher number of data subcarriers (54 instead of 52). But TGnSync proposal attain approximately 10% higher channel capacity when short guard interval is used in both bands. When short guard interval is not used, 40 MHz channel capacity is identical in both proposals since they have equal number of data subcarriers. By using all the highest throughput parameters (four 40 MHz spatial streams, with 64-QAM and a 5/6 code rate), in basic mode WWiSE proposal has a maximum throughput of 540 Mbps and TGnSync proposal has a maximum throughput of 540/600 Mbps (higher value of channel capacity is obtained using a short guard interval). Besides basic modes of operation both proposals also offer additional modes. Additional ABM mode of TGnSync with mandatory and optional modulation rates offers one new constellation: 256-QAM, which transmit 8 coded bits per subcarrier with 1/2 and 3/4 code rate, enabling maximum data rates equal to 648/720 Mbps (Table 1.). Additional single stream STBC mode of working in 20 MHz channel band is only offered as optional mode in WWiSE proposal.

It is notable that types of modulation constellations and number of coded bits per subcarrier of new standard would be equal to the one used in 802.11a standard, with exception of ABM mode (256-QAM) proposed by TgnSync, if it will be ratified. However, coding in the new standard will be enhanced, where new convolutional code rates equal to 5/6 will be built in new standard and added to the 1/2, 2/3 and 3/4 code rates defined and used by 802.11a. In addition to the convolutional code supported by the original OFDM specification, the new standard will probably support additional error correction code known as low density parity check (LDPC) code the usage of which is proposed by both groups.

TGnSync proposal achieves higher peak data rates what is probably reflection of TgnSync group goals to support new networked devices and services in the home like sending HDTV or DVD video streams across wireless networks. More aggressive coding, including a larger constellation, and a reduced guard interval are present to improve the data rate in optional mode of TGnSync proposal when compared to WWiSE proposal. Although, TGSync group is heavily oriented towards achieving higher data rates, one element in improving MAC efficiency is usage of a short guard interval. In the 802.11a,g standards as well as the WWiSE proposal, the guard interval is 800 ns and it should be two to four times the delay spread. An 800 ns guard interval allows a 200 ns delay spread, which is much higher than was observed in many environments. Most offices and homes have much smaller delay spread, on the order of 50–100 ns. As we previously notice, if usage of a 400 ns guard interval is built in new standard, it will boost throughput by approximately 10%.

5. Transmission modes

Previous 802.11 PHY specifications had fairly simple transmission modes. The WWiSE proposal has 14 basic transmission modes, depending on 3 items:

1. The number of transmit antennas. It ranges from 1 to 4, although a single antenna is only supported for 40 MHz channels. All 20 MHz channels must use at least two transmit antennas, though they may have only one spatial stream.
2. Whether the frame is used in a greenfield or mixed mode environment. Mixed mode transmissions use physical headers that are backwards-compatible with other OFDM PHYs, while greenfield transmissions use faster physical header.
3. The channel bandwidth, which may be 20 or 40 MHz.

Thus, usage of 2 to 4 antennas for 20 MHz channels in a greenfield and mix mode defines first 6 modes of transmission, where number of spatial streams must be equal to the number of antennas. Usage of 1 to 4 transmit antennas for 40 MHz channels in a greenfield and mix mode defines 8 rest modes of transmittion.

There are three transmission modes that the TGnSync proposal calls for. In the mandatory basic MIMO mode, the number of spatial streams is equal to the number of antennas. Each spatial stream is modulated and transmitted identically. Each channel is coded using the same modulation, and sent with the same transmission power. Any changes in transmission rate are based on the implicit feedback of lost acknowledgments. Two optional modes known as basic beamforming and advanced beamforming MIMO (ABM) mode are also proposed by TGnSync, taking advantage of information learned about the radio channel, which is referred to as “closed-loop” operation.

In the basic beamforming MIMO mode, every channel must be coded the same way. Before beginning transmission, TGnSync devices send “sounding” frames to each other to measure the performance of the link. Based on the information gathered from sounding and calibration, beamforming can be used to boost signal quality. Higher signal quality means that a given data rate can be used at longer range. Based on the information from the sounding exchange, the power and coding for the spatial streams is selected. Basic beamforming mode requires that all spatial streams be transmitted at the same power with the same coding. In this mode signal processing advantages are most evident when the number of antennas transmitting a signal is greater than the number of receiving antennas. If the number of spatial streams is less than the number of the transmit antennas, a spatial steering matrix mentioned in second section is used to assign bits to transmission antennas. Third optional ABM mode works in a manner similar to the basic beamforming mode, but with the additional capability of using different transmission power on each transmit stream, as well as the possibility of using a different modulation and code rate on each spatial stream. Like the basic beamforming mode, it requires the gathering of radio status information to calibrate the channel. An optional mode in the advanced beamforming mode allows beamforming to occur in both directions if it is supported in both directions [1, 2, 3].

Although, TGnSync transmission mode proposal requiring closed-loop operation is much more advanced and sophisticated then WWiSE proposal, hardware realization of the closed loop operation in silicon might be quite challenging task. Concept in which sounding frames must be used to measure the channel, and responses must be collected to calibrate the radio channel will impose lot of research effort and higher development price with higher cost of final 802.11n product. On the other hand, the WWiSE proposal uses only open loop operation, which is less sophisticated but simpler and cheaper to implement. The WWiSE proposal also offers the ability to spread a single encoded stream across multiple antennas without using closed-loop operation. If closed-loop operation were to be problematic to implement in silicon, compromises must be engaged to resolve this issue.

6. MAC enhancements

Although, the aim of this paper is presentation of PHY enhancements that will be incorporated in new 802.11n standard, basic MAC enhancements that will be built in emerging standard will also be described. Both TGnSync and WWiSE adopt techniques to improve the efficiency of the radio channel. Concepts are similar, but the details differ. Both offer some form of block ACKs called frame bursting. By removing the need for one acknowledgment frame for every data frame, the amount of overhead required for the ACK frames, as well as preamble and framing, is reduced. Block acknowledgments will be incorporated in new 802.11n standard. Frame aggregation is also part of both proposals. Many of the packets carried by 802.11 are small. Interactive network sessions, such as telnet and SSH, make heavy use of rapid-fire small packets. Small packets become small frames, each of which requires physical-layer framing and overhead [1, 2, 3]. Combining several small packets into a single relatively large frame improves the data-to-overhead ratio what is important element that must be built in new standard. Frame aggregation is often used with MAC header compression, since the MAC header on multiple frames to the same destination is quite similar. Frame aggregation is an important part in reaching high data rates of 100Mbps and beyond.

Aggregation as designed by the protocol is a bit more intelligent in TGnSync, although this is only a minor advantage. WWiSE's proposal only allows aggregation when the first address field in the MAC header is the same. In an infrastructure network, that address field is the basic service sat identifier. All frames from a station to an AP can be aggregated, so the two proposals are identical in the upstream direction. In the downstream direction, WWiSE must use a physical-layer frame burst to change directions. Each new direction must have a new physical layer convergence protocol header. TGnSync can reduce overhead by using a multiple-receiver aggregate frame, and collecting responses from each receiver in the aggregate. Taking full advantage of aggregation opportunities requires more intelligent queuing than is currently implemented. Whether 802.11n offers a huge increase in speed it is likely to depend a great deal on how well improved queuing algorithms are able to coalesce collections of small packets into large aggregates. Since, neither proposal specifies queuing, it will be very useful to define powerful queuing algorithms in both proposals. This will enable incorporation of queuing in new standard, avoiding different queuing performance between vendors.

7. Conclusion

At a very high level, both proposals are similar, though they differ in the emphasis on increasing peak data rates versus improving efficiency. Although, the goal is 100 Mbps net throughput, the final proposal seems certain to blow past that number, and offers many times (up to 6 or 7) that throughput in maximum configurations. MIMO operation shows up as straightforward, reliable, and suitable technology in realization of these height throughput goals. Each of proposals makes use of MIMO technology in several configurations and provides for backwards compatibility with older (legacy) systems in the same frequency band. Future 802.11n standard will be based on MIMO operation and OFDM technology as channel coding and transport mechanism. Space time block codes will be used for the transmission of a single spatial stream across multiple antennas in some transmission modes of new 802.11n devices. Both proposals support operation in the current 20 MHz channels, with provisions to use double-width 40 MHz channels for reaching extra throughput. It is to be expected that new standard will define work in 20 MHz channels as mandatory, while work in 40 MHz channels will be optional. Combination of different number of spatial streams, coded bits per subcarrier and code rates for two types of channel bands will lead to much higher number of different data rates when compared to older 802.11a,g standards. We presume that some data rates and working modes will be mandatory and some will be optional, like in previous standards. Also, mandatory modes will offer backwards compatibility and interoperability with existing Wi-Fi devices in the 5 GHz and 2.4 GHz bands to ensure strong support of legacy deployments. Besides classical convolutional code rates used in older (802.11a standard), new convolutional code rate 5/6 will probably be incorporated in new standard. In addition to the convolutional code supported by the original OFDM specification, the new standard will probably support additional error correction code known as low density parity check (LDPC) code. On MAC level, block acknowledgments and frame aggregation will be incorporated in new 802.11n standard. TGnSync proposal compared to WWiSE proposal offers the most extensible PHY with higher peak data rates, larger number of different data rates, advanced transmission modes and slightly better PHY hardware realization. These advantages are main reasons why we give little overall advantage in treatment of TGnSync proposal as basis for new standard.

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