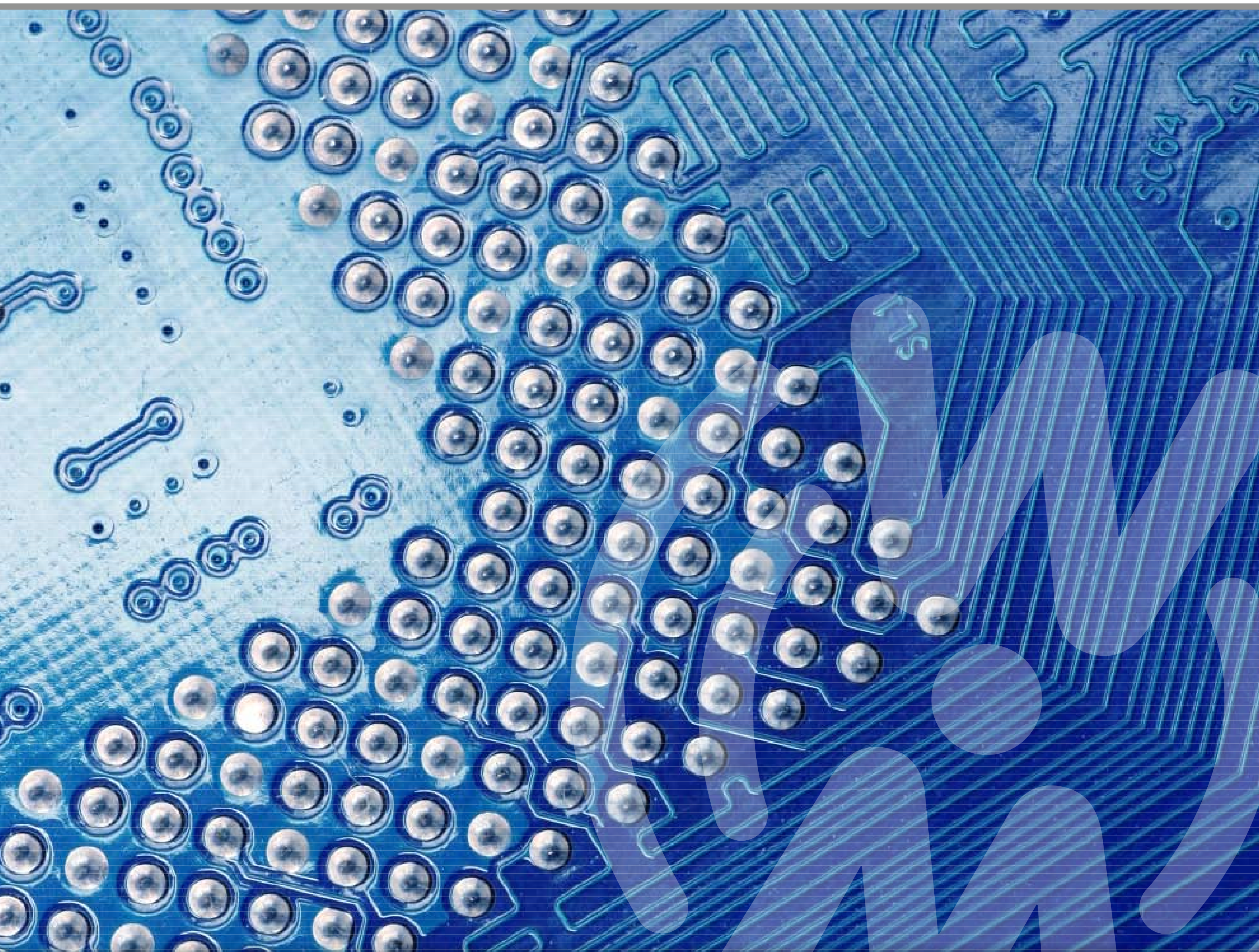
WiMedia ALLIANCE



# WiMedia Ultra-wideband:

## Efficiency Considerations of the Effects of Protocol Overhead on Data Throughput

Contributed by WiMedia member company

ellisys Better Analysis.


## Abstract

Today's wireless applications demand more bandwidth than ever. The WiMedia Ultrawideband (UWB) specifications are the most advanced high performance wireless specifications available for low cost, low power, consumer and information technology products.

Any communications scheme which transfers data across a network cannot expect to utilize the full bandwidth of the medium since some data is required to describe the content of the data, routing information and other protocol needs. This document investigates the sources of protocol overhead inherent in implementations of the WiMedia UWB specifications. We explain the structure of the Physical Layer (PHY) frame and how the Medium Access Control (MAC) protocol uses the frame to carry its very high performance data. We show how key components of the frame structure and MAC protocol overheads affect protocol efficiency and how they can be exploited to minimize their effects and maximize performance.

After you have read this paper you will:

- Understand the PHY frame structure and its timing
- Understand key aspects of the MAC protocol and its cost as overhead
- Know how to select optimal values for frame payload length
- Understand throughput available to an application


## Prerequisites

To get the most out of this publication it is recommended that the reader is familiar with the following documents:

- WiMedia MultiBand OFDM Physical Layer Specification (Version 1.2)
- WiMedia Distributed Medium Access Control (MAC) for Wireless Networks (Version 1.2)

These WiMedia specifications are also published by Ecma International as:

- Standard ECMA-368 High Rate Ultra Wideband PHY and MAC Standard, 2nd Edition / December 2007,



## Introduction

The WiMedia UWB specifications provide the technical details of the operation of a 480Mb/s PHY and a fully distributed MAC. The very high data rates are achieved at very low transmitted power by occupying very large amounts of spectrum but using very low power spectral density.

The WiMedia UWB specifications include:

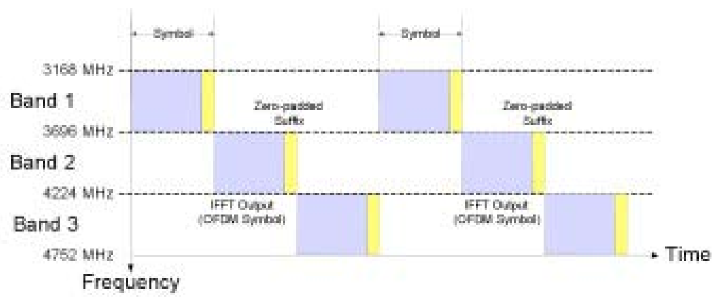
- A PHY specification describing the structure of transmission on the radio channel
- A MAC specification describing how devices use a radio channel to establish communications amongst them.

## The WiMedia PHY Channel

The WiMedia PHY transmits a waveform constructed from the output of an IFFT function to produce an ODFM symbol. All symbols are the same length and have an effective raw data rate of 640Mb/s. Coding of the inputs to the IFFT provides a range of coded data rates (53.3, 80, 106.7, 160, 200, 320, 400 and 480 Mb/s). Data is coded across the carriers of the OFDM symbol and also across blocks of 6 consecutive symbols. Consequently, symbols are always transmitted in blocks of 6.

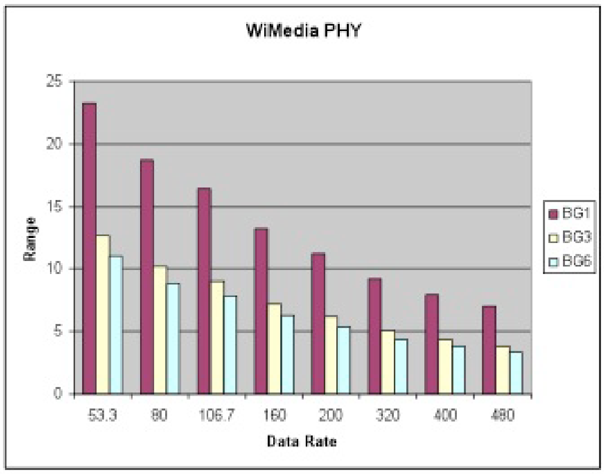
Between each symbol, the PHY may change frequency so that sequential symbols are transmitted in a channel consisting of 1, 2 or 3 adjacent bands. The bands are 528MHz wide. The set of 3 bands defines the Band Group. The order of use of the bands defines the PHY channel. The following figure shows a 3-band hopping channel in Band Group 1 — the order Band 1, Band 2, Band 3 is defined by the PHY specification to be TFC-1 (Channel 9).

### Figure - 1 PHY Symbols and Bands



As all symbols carry data at the same raw rate (640Mb/s), the payload data rates are obtained by redundantly coding the data over the OFDM symbols. Higher redundancy improves the probability of successfully decoding the data at the cost of a lower data rate. The resultant gain gives a rate-range curve of the form shown in Figure 2.

**Figure 2 Rate - Range plot for 3-Band TFC, Path Loss Exponent=2**




## The WiMedia Frame Structure

Information sent over the WiMedia PHY is organized in sets of symbols forming frames. Figure 3 below shows the general structure of a WiMedia frame:

**Figure 3 – WiMedia Frame Structure**


Frames are made up of three parts (see PHY Layer Overhead section for details):

- A Standard or Burst PLCP[1] Preamble (Green);
- A PLCP Header (Red);
- An optional PSDU[2] that contains the Payload, FCS[3] and Tail/Pad bits (Blue)

Frame drawings throughout this document use different heights to reflect the difference in nominal bit rates. The PLCP Header is always sent at 39.4 Mb/s. The PSDU is sent at a rate that is specified in the header and can be any rate defined by the WiMedia PHY specification. Figure 3 shows a Payload sent at 480 Mbps.

The *Preamble* is sent to inform receiving devices that they will take delivery of a frame and help them to synchronize to it. Frames can use standard preambles or burst preambles. Standard preambles are used in most cases and burst preambles can be used in bandwidth-critical applications where the overhead of a standard preamble would be too large.

The *Header* contains information about the nature of the frame and how to process it. It specifically targets one receiving device or a group of devices, gives information on the sender and indicates if this frame is part of a sequence of frames.

The *Payload* contains the actual data to be transmitted. For non-data frames it may contain information that supports the protocol layers in various tasks. For data frames its content depends on the application and can be a part of a file, video or anything else that an application needs to transmit. The payload can vary from 1 byte to 4095 bytes or can even be completely omitted if it is not useful in a given context. When an application needs to transmit more than 4095 bytes, it has to split the total amount into several frames. An FCS is added at the end of the payload, unless the payload is omitted, to help detect transmit errors.

## Protocol layers

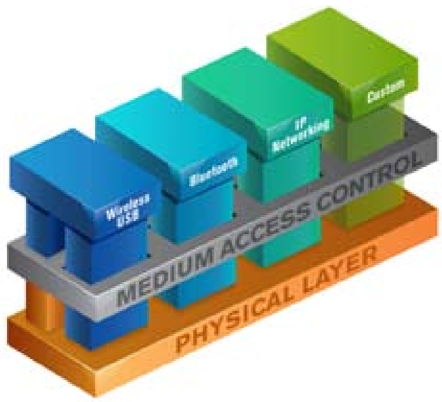
All communications systems are organized in layers with each lower layer providing services and features used by the layer above. The cost of the services and features is the overhead paid to encode them.

The WiMedia UWB specifications define MAC and PHY layers, as shown in Figure 4 below. These lower layers provide the services and facilities to support application- oriented protocols such as Wireless USB (WUSB), Bluetooth, and WLP.

The PHY layer defines the OFDM waveform used to carry information on the UWB WiMedia channels. The MAC layer

[1] PLCP stands for PHY Layer Convergence Protocol
[2] PSDU stands for PHY Service Data Unit – the PHY Layer "packet"
[3] FCS Stands for Frame Check Sequence

Figure 4 – WiMedia Protocol Layers




beacon protocol defines the control channel used to ensure orderly channel access by all WiMedia compliant systems. It also defines WiMedia data transfer and systems management services and a Private Reservation mechanism that allows customized medium access rules to be used in place of those of the WiMedia MAC in a well-defined and orderly manner.

For more information on protocols supported by WiMedia UWB specifications please go to www.wimedia.org

## Channel Access Control

The WiMedia architecture divides time into superframes. A superframe has a nominal duration of 65536 us. Each superframe is sub-divided into 256 Medium Access Slots (MAS) of 256 us each. A device can use the Distributed Reservation Protocol (DRP) to reserve MAS for exclusive or shared use. It can also use the Prioritized Contention Access (PCA) protocol to transmit frames without reservations.

## Beacons

WiMedia devices announce their presence and capabilities through the use of a special frame called a Beacon, which must be sent in a beacon slot by each active device once in every superframe. The first two beacon slots of each superframe are reserved for beacon protocol signaling purposes and are followed by a variable number of other beacon slots depending on the number of active devices in a beacon group. The beacon protocol requires beacon group members to adjust their superframe start time every superframe to maintain superframe and MAS boundary alignment for resource sharing. The Beacon Period overlays the first N MAS with fixed length Beacon Slots of 85us each. Any residual time between the end of the last Beacon Slot and the end of the MAS in which it falls is unused.

Via the beacon protocol, WiMedia UWB devices access the UWB PHY channels in an orderly manner without any centralized coordination or control. The WiMedia architecture is a fully de-centralized communications architecture.

## Frames

A WiMedia frame contains several protocol elements that identify the nature of the frame, its source and destination, and several other fields used in various tasks. A data frame is a specialized frame that also contains data useful for a given application.

## Other Features

The WiMedia specifications provide a range of additional services and facilities including:

- Unacknowledged or acknowledged data transfer services with prioritized contention access (PCA) or distributed reservation protocol (DRP) management
- Power Savings mechanisms to allow devices to enter and exit low power modes and conserve battery power
- Non-secure and secure, authenticated frame exchange

Having introduced the fundamental concepts of the WiMedia UWB MAC & PHY specifications, we can now look at some of the inherent overheads associated with them and calculate the effective performance of the WiMedia UWB standard.

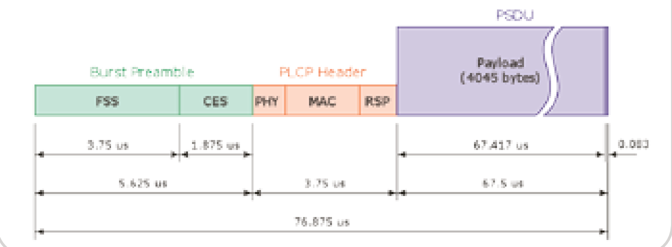
# PHY Layer Overhead

## PLCP Overhead

When the PHY is instructed to send a frame over the air it automatically concatenates the necessary PLCP elements — including the preamble, the header and the payload — so that the receiving PHY component can decode them. In general, information is carried in the payload and so we can consider everything else to be overhead.

We can easily compute this overhead at 480 Mbps with the timing values given in Figure 5.

**Figure 5 – Burst Frame Elements Duration at 480 Mbps**[4]




A simple calculation gives a rough overhead of:

$$\frac{\textit{Total duration} - \textit{Payload duration}}{\textit{Total duration}} = \frac{76.875\ \mu s - 67.417\ \mu s}{76.875\ \mu s} = 12.3\%$$

or an effective equivalent bit rate of 420.9 Mbps, without taking into account any other overhead.

The same can be computed at 53.3 Mbps, as shown in Figure 6.

**Figure 6 – Standard Frame Elements Duration at 53.3 Mbps**

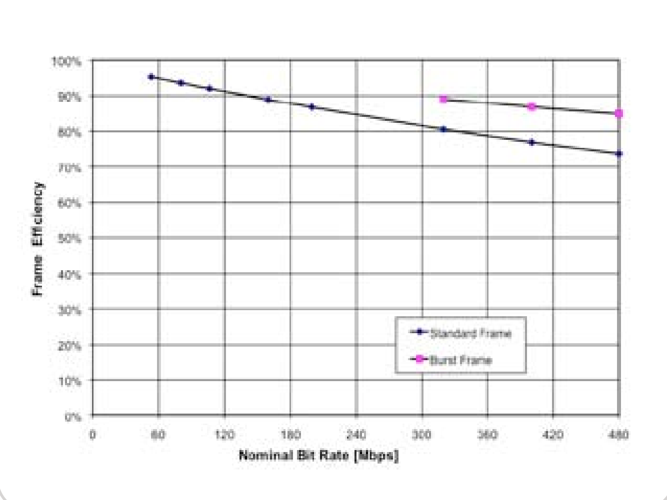

In this case the rough overhead is:

$$\frac{\textit{Total duration} - \textit{Payload duration}}{\textit{Total duration}} = \frac{628.125\ \mu s - 615\ \mu s}{628.125\ \mu s} = 2.09\%$$

or an effective equivalent bit rate of 52.2 Mbps.

Figure 7 shows the underlying protocol efficiency for a maximum length payload for each standard nominal data rate, including standard and burst preambles. Note that burst preambles are only permitted for payload data rates above 200Mb/s.

**Figure 7 – Underlying protocol efficiency**




Unfortunately the lower the payload data rate is, the longer it takes to send the frame. Figure 8 below represents a maximum length frame sent at 53.3 Mbps.

**Figure 8 – Maximum length frame at 53.3 Mbps**

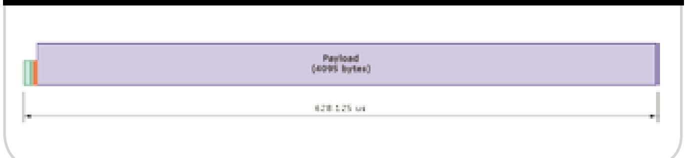
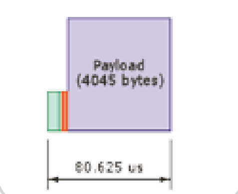



Figure 9 represent a maximum length frame sent at 480 Mbps.

**Figure 9 – Maximum length frame at 480 Mbps**




Since the time needed to transmit the preamble and header does not vary with payload data rate it constitutes a proportionally larger portion of frames sent at higher data rates. This explains why the efficiency decreases with the nominal data rate, and why burst preambles are important at high data rates.

[4] In Figure 5 and Figure 6, FSS Stands for Frame Synchronization Sequence, CES for Channel Estimation Sequence and RSP for Reed-Solomon Parity

# MAC Layer Overhead

## Beacon Period Overhead

Not all the superframe is available for transmission. The beginning of the superframe contains the beacon period, which is reserved for sending beacons. In the simplest case we will need only two beacons, each to identify a single device. These two beacons will use two beacons slots, to which we add two extra beacon slots reserved for signaling beacons. These four beacon slots will take 4 * 85 us = 340 us.

These slots will occupy the first two MAS that we then cannot use for data transmission. However we can use all the remaining 254 MAS. See Figure 11 below.

**Figure 10 – Four beacon slots with two beacons**

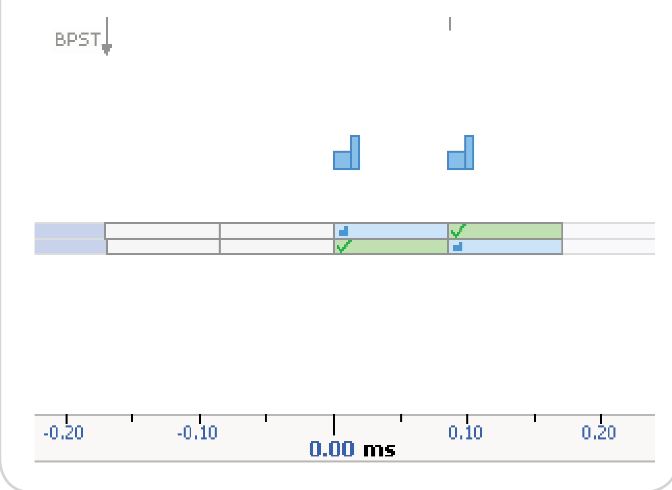
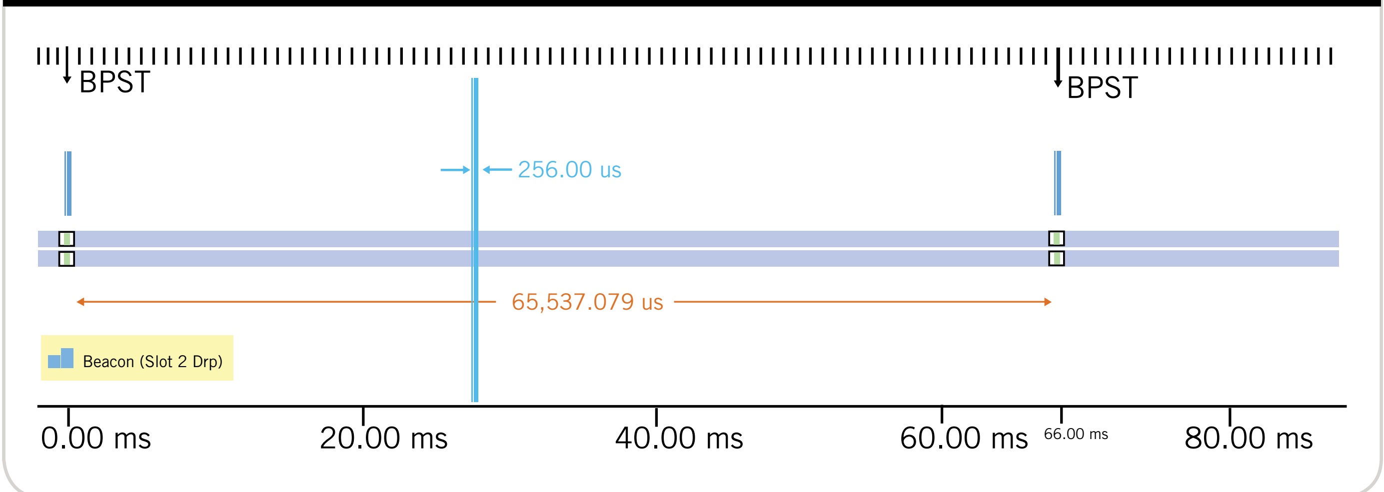



**Figure 11 – A superframe with its 256 MAS**

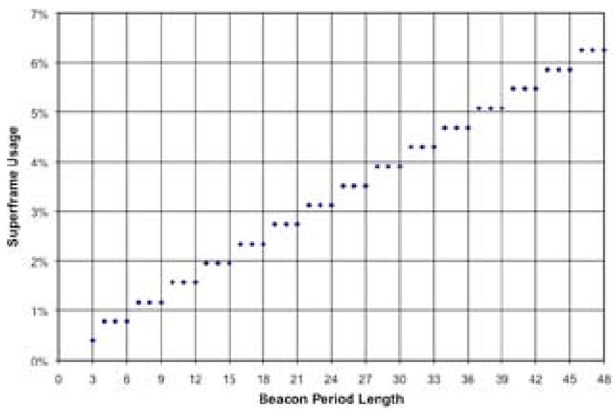



Since each MAS lasts 256 us we have 254 * 256 us = 65024 us available to transmit frames. In other words, 0.8% of the superframe is unavailable for application data.

Adding devices to a beacon group will add beacons to the beacon period. A beacon period is limited to 48 beacon slots, totaling 48 * 85 us = 4080 us, or 16 MAS. In this worst case example, 6.25% of the superframe is unavailable for application data.

Figure 12 on the next page shows the overhead caused by the length of the beacon period.

Figure 12 – Superframe usage due to the presence of devices




As we can see, the overhead due to the presence of devices is quite small when only a few devices are active. It can become more significant when many devices are operating in the same beacon group, but as we will see below, other factors will further impact transmission anyway.

## Frame Bit Rate

Although the PHY layer supports 480 Mbps payload data rate in theory, the distance separating the communicating devices, as well as the local electromagnetic environment, will determine the signal to noise ratio (SNR) required to decode the data. Redundantly coding the data provides an effective processing gain and lowers the signal energy required to satisfy the SNR requirement.

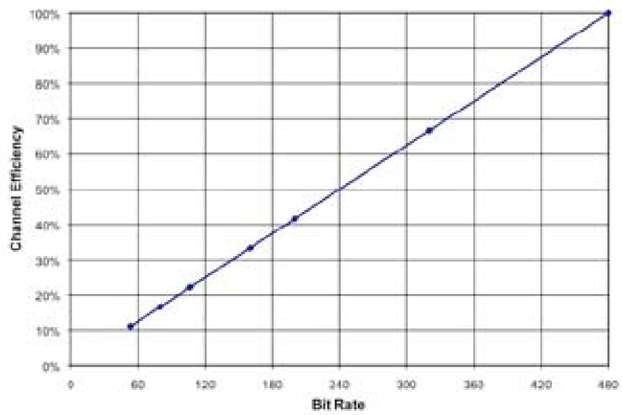
Consequently, choosing a lower payload data rate may be a good strategy in some cases. For example, it can help to create a more reliable link by reducing the frame error rate when two devices are far from each other, or when the electromagnetic environment is noisy. Since the error rate will be higher at 480 Mbps than at 53.3 Mbps, an application may choose to reduce the frame data rate until the signal to noise ratio becomes acceptable.

However, transmitting a frame at 53.3 Mbps when the medium allows transmission at 480 Mbps consumes more bandwidth than transmitting packets at higher data rates.

We can compare the efficiency of frames sent at different nominal bit rates. We define a frame sent at 480 Mbps on a channel with a maximum nominal data rate of 480 Mbps to have an efficiency of 100%. A frame sent at 240 Mbps takes roughly twice the time and thus has an efficiency of only 50%. A frame sent at a low data rate on a channel does not use all the capabilities of this channel and thus reduces its potential:

Note that this expression ignores the fixed PHY overhead for the preamble and PLCP Header.

Figure 13 – Channel Efficiency as a Function of Frame Bit Rate




Transmitting frames at a low data rate prevents other devices from using the medium during this time and thus reduces the available capacity of the channel. It is always better to transmit information at the highest available data rate but it is not always possible. Transmitting at the highest possible data rate also minimizes the energy per bit consumed.

## Frame Length

Most applications can freely choose the length of the frames they send. Although the number of useful bytes can be chosen, the lower layers sometimes need to add utility bytes and thus adjust the actual numbers of bytes sent.

WiMedia PHYs implement a bit scrambler that needs a predefined number of bits to operate correctly. To ensure a

PSDU can be properly encoded, the PHY adds a certain number of pad bits after the payload. The formula below shows how to calculate $N_{PAD}$, which is the number of pad bits:

$$N_{PAD} = N_{IBP6S} * \left\lceil \frac{8 * Length + 38}{N_{IBP6S}} \right\rceil - (8 * Length + 38)$$

Where:

- Length is the number of bytes in the payload, excluding the FCS.
- $N_{IBP6S}$ is the number of information bits per 6 symbols, as defined in Table 1.

**Table 1 – Number of Information Bits per 6 Symbols**

| Data Rate [Mbps] | $N_{IBP6S}$ |
|---|---|
| 53.3 | 100 |
| 80 | 150 |
| 106.7 | 200 |
| 160 | 300 |
| 200 | 375 |
| 320 | 600 |
| 400 | 750 |
| 480 | 900 |

Incidentally the formula below defines $N_{FRAME}$, which is the number of OFDM symbols of the PSDU. The PSDU is constructed of blocks of 6 symbols since the PHY defines an interleave depth of 6 symbols:

$$N_{FRAME} = 6 * \left\lceil \frac{8 * Length + 38}{N_{IBP6S}} \right\rceil$$

Full details on these formulae can be found in the WiMedia Multiband OFDM Physical Layer Specification.

Using the two formulae defined above we can compute both $N_{FRAME}$ and $N_{PAD}$ for a given Length. Table 2 below gives some examples at 480 Mbps ($N_{IBP6S}$ = 900):

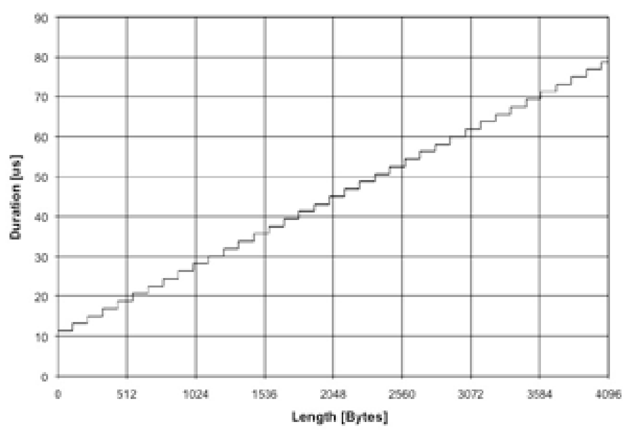
**Table 2 – $N_{FRAME}$ and $N_{PAD}$ for a given Length**

| Length [Bytes] | $N_{FRAME}$ [Symbols] | $N_{PAD}$ [bits] |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 6 | 854 |
| 2 | 6 | 846 |
| 3 | 6 | 838 |
| --- | --- | --- |
| 105 | 6 | 22 |
| 106 | 6 | 14 |
| 107 | 6 | 6 |
| 108 | 12 | 898 |
| 109 | 12 | 890 |
| 110 | 12 | 882 |
| --- | --- | --- |
| 1024 | 60 | 770 |
| --- | --- | --- |
| 4043 | 216 | 18 |
| 4044 | 216 | 10 |
| 4045 | 216 | 2 |
| 4046 | 222 | 894 |
| 4047 | 222 | 896 |
| 4048 | 222 | 878 |
| --- | --- | --- |
| 4093 | 222 | 518 |
| 4094 | 222 | 510 |
| 4095 | 222 | 502 |

These results show that PHYs send 6 symbols for a frame of any size between 1 byte and 107 bytes; sending a frame of 1 byte takes the same time as sending a frame of 107 bytes.

This creates a “stairway” effect that is clearly visible in a graph:

**Figure 14 – Duration of a 480 Mbps frame as a function of its length**




## Spacing between Frames

The PHY needs some time between the frames to properly send or receive them. To compute the actual throughput we have to take into account the spacing between frames. With burst preambles, the spacing is defined by the PHY at exactly 1.875 us. With standard preambles, it can vary depending on the application. We took 10 us for our computations.

## Channel Access Control

A device can use the Distributed Reservation Protocol (DRP) to reserve some MAS for exclusive or non-exclusive use. It can also use the Prioritized Contention Access (PCA) to transmit frames without reservations.

## Distributed Reservation Protocol

Two or more devices willing to communicate using DRP can negotiate to reserve some MAS. Depending on how they reserve these MAS, they may have exclusive or non-exclusive transmission rights during the reservation. The DRP mechanism itself uses very little bandwidth because DRP management information is carried in beacons.

The use of MAS successfully reserved in a DRP negotiation is respected by all WiMedia compliant devices, which respect the MAS boundaries of the reservation. The time defined by the reserved MAS is available for frame transmissions except for a small overhead at the end of a reservation block. Frames are not allowed to cross reservation block boundaries and so there may be some unused time at the end of each reservation block, depending on the length of the data frames and their transmission start times within the reservation block.

## Prioritized Contention Access

PCA is a random access scheme with a backoff mechanism used to resolve contention for the channel. The overheads associated with the backoff mechanism are dependent on the number of contending devices and the priority of the traffic being transmitted.

When the traffic profile is bursty, such as for web browsing, PCA can provide a more efficient use of the channel resource since the channel can be used by other devices when there is no traffic for a device to send. The WiMedia MAC specification defines 4 classes of priority to support a range of voice, video and data traffic types.

## Security

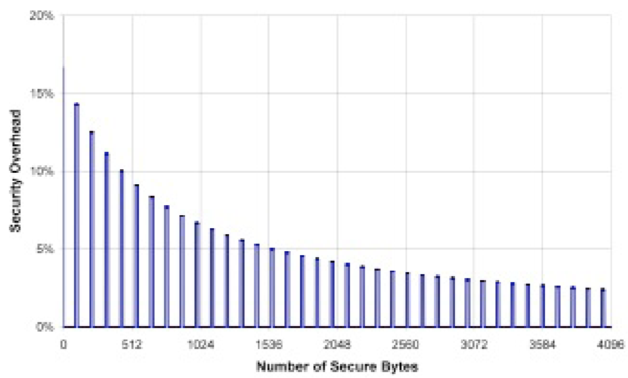
A frame payload can be secured in order to ensure it comes from the expected sender and has not been modified. Enabling security requires an exchange of keys — which is done only once — and 20 additional bytes sent in the payload of every secure frame. A secure payload begins with a Security Header of 12 bytes and ends with a Message Integrity Code (MIC) of 8 bytes. Everything else is the secure payload.

A non-secure frame can contain a payload of between 0 and 4095 bytes. Since the overhead of the security model is 20 bytes the secure payload is limited to 4075 bytes. In other words, a secure frame of N bytes needs N+20 bytes.

Since 20 bytes are required independently of the frame size the resulting overhead is quite large for small frames. However, earlier we have seen that, depending on the frame length, the PHY requires the addition of pad bits to fill the last interleaver block. If the frame length is chosen carefully, the security overhead can fit within the pad bits required by the PHY, effectively providing secure frame format at no cost.

Other frame lengths will still introduce an overhead when the pad bit area is not large enough to contain the 20 bytes needed for the security mechanism.

**Figure 15 – Overhead in secure frames**




We can see that more than 80% of payload lengths do not introduce any overhead for WiMedia security. About 20% of payload lengths add some overhead, which is less than 5% for frame lengths greater than 1536 bytes.

On average, the security layer adds less than 2% overhead for small frames and less than 0.5% for large frames. Remember that if you carefully choose the frame length then it does not introduce any additional overhead.

## Results

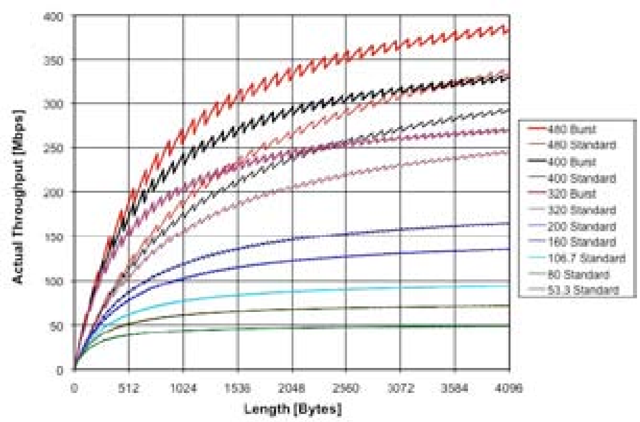
Combining all the overheads from the preceding analyses, Table 3 below shows the effective throughput of the WiMedia protocol for both burst and standard preambles for different payload lengths:

**Table 3 – Actual Throughput for a Given Frame Length**

| Frame Length [Bytes] | Actual Throughput [Mbps] @ 480 Mbps Burst | Actual Throughput [Mbps] @ 480 Mbps Standard |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0.6 | 0.3 |
| --- | --- | --- |
| 512 | 188 | 119 |
| --- | --- | --- |
| 1024 | 258 | 185 |
| --- | --- | --- |
| 2048 | 331 | 264 |
| --- | --- | --- |
| 4045 | 389 | 338 |
| --- | --- | --- |
| 4095 | 384 | 335 |

The complete table with all nominal bit rates drawn in the graph below reveals some interesting results:

**Figure 16 – Actual Throughput as a Function of Frame Length**



## A few observations:

- Using large frames is the dominant factor in attaining good performance. Using frames with 512 bytes or less is dramatically less efficient than using larger frames; they should be avoided in high-bandwidth applications.
- Throughput for short frames is largely independent of payload data rate.
- Higher payload data rates return greater throughput at all frame lengths. This is without taking into account any errors or retransmissions.
- Burst mode, using burst preambles is more efficient than using standard preambles.
- There is a ramp effect due to the addition of pad bits, which is more significant at higher nominal data rates rates because the frames are shorter giving a larger value of $N_{IBP6S}$.

If we take for example an application that needs to send a large amount of data at 480 Mbps it must carefully choose the frame length. With the "naïve" best choice of frames of 4095 bytes, which is the maximum, the application will not reach the optimal throughput. The best throughput at 480 Mbps is reached with frames of 4045 bytes, as shown in Table 3 and Figure 16.

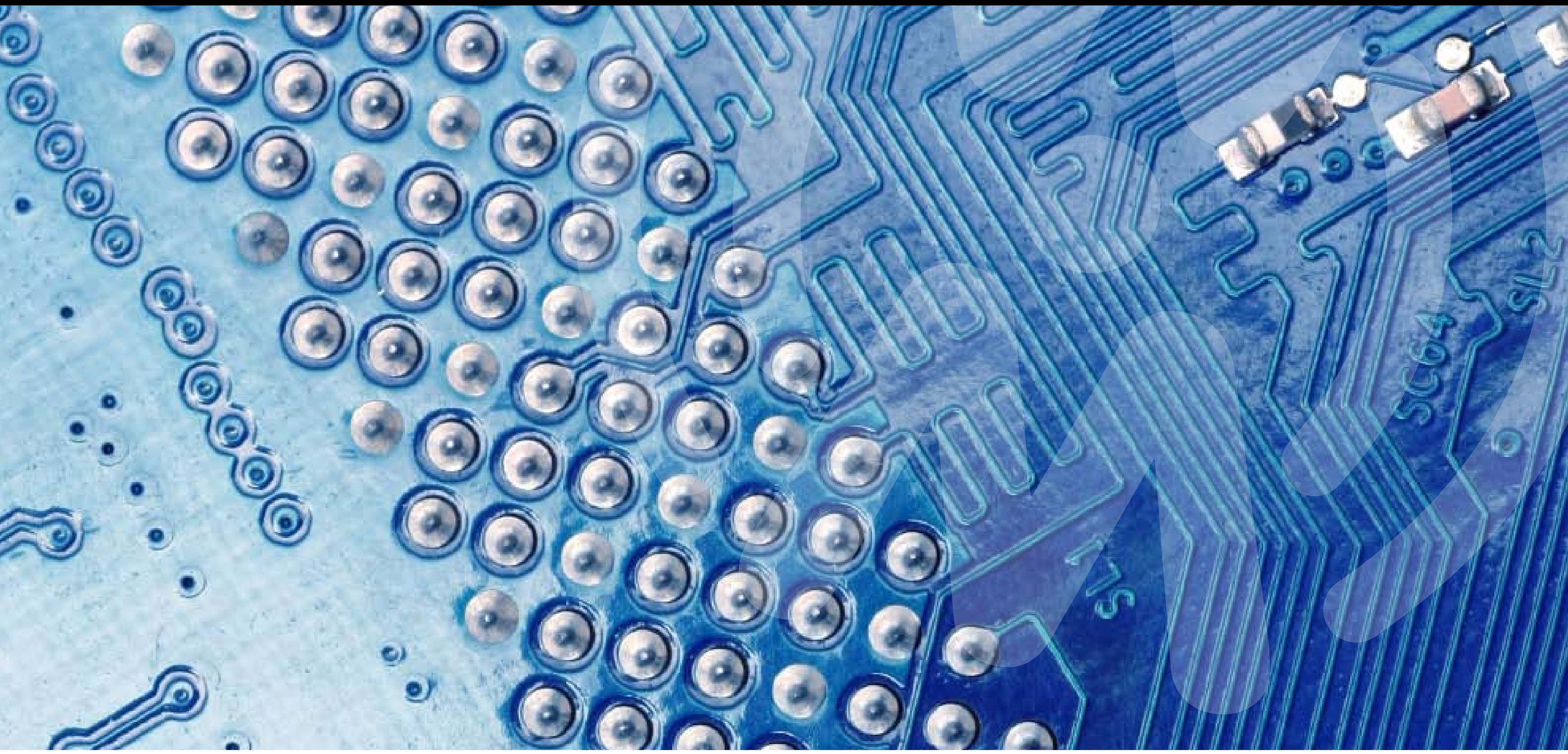
## Conclusion

In this paper we have introduced some of the fundamental concepts and structures of the WiMedia UWB specifications. We have explained the structure and cost of the PHY PLCP header and how it varies with payload length and data rate. We have also explained the overhead associated with the MAC superframe and beacon protocol and how careful choice of frame length can exploit the PHY frame structure to minimize the cost of the secure frame format.

We have calculated the effective throughput of the WiMedia MAC & PHY protocols and shown they can exceed 80% of the theoretical maximum data rate for near maximum length payloads at the highest PHY data rate. The state-of-the-art WiMedia protocol architecture ranks amongst the elite few designs offering such elevated channel efficienies and is uniquely placed to support very high performance wireless applications.

## Glossary

| | |
|---|---|
| **PLCP** | Physical Layer Convergence Protocol |
| **PSDU** | PHY Service Data Unit |
| **PHY** | Physical Layer |
| **MAC** | Medium Access and Control Layer |
| **FSS** | Frame Synchronization Sequence |
| **CES** | Channel Estimation Sequence |
| **RSS** | Reed-Solomon Parity Bits |
| **DRP** | Distributed Reservation Protocol |
| **PCA** | Prioritized Contention Access |
| **FCS** | Frame Check Sequence |
| **Beacon Period** | The initial part of the superframe forming a slotted Aloha communications channel for the transmission and reception of beacon frames |
| **Superframe** | The repeating 65,536us structure consisting of 256 MAS each of 256us forming the logical WiMedia communications channel |
| **Beacon Group** | A set of WiMedia devices that transmit and receive beacon frames between each other |



Ellisys is a Test & Measurement company committed to the design and timely introduction of advanced protocol analysis solutions for USB devices, Certified Wireless USB and UWB. For more information, please visit www.ellisys.com.

The WiMedia Alliance, a 350+ member global nonprofit organization, defines, certifies and supports enabling wireless technology for multimedia applications. The WiMedia Radio Platform represents the next evolution of wireless freedom and convenience. For more information visit www.wimedia.org