8.9 The FlexLink Standard

The FlexLink standard is an open physical layer, PHY, and media access controller layer, MAC, specification of a packet based OFDM radio link used for applications where the transceiver stations may be in motion and/or stationary. The time division duplex, TDD, link will support point to point and point to multipoint communication. The specification originally took shape to provide the framework for a radio link that supports video transmission from fast moving terminals such as drones. However, in general, the specification provides for both high reliability and high throughput transmission between multiple terminals whether in motion or stationary.

Whereas modem specifications, such as 3GPP's 5G New Radio or IEEE 802.11 WLAN, already exist for similar applications, they have certain drawbacks that FlexLink attempts to sidestep. The following table attempts to provide a brief overview of the features of the different technologies, and how FlexLink stands apart.

Table 8-1: Comparison of Different Standards

	5G New Radio	**WiFi 6 / 7**	**FlexLink**
Data Throughput	Low to Very High < 100KBPS to > 1GBPS	Medium to Very High 6MBPS to > 1GBPS	Low to High < 1KBPS to > 125MBPS
Mobility	Yes	No	Yes
Data Transfer	Cellular Network Based	Packet Based	Packet Based
Implementability	Extremely Difficult	Very Difficult	Reasonable
Documentation	Extensive but Awful	Reasonable	Very Good

The 4G LTE and 5G New Radio specifications are designed from the ground up to support communication in a mobile environment. FlexLink borrows many concepts from these standards but fundamentally differs from them given that it does not operate in a cellular environment and uses packet based communication. In this, it resembles the IEEE Wifi technologies, which unfortunately make almost no effort to support communication with terminals that are in motion and neglects high reliability / low throughput transmission. The Wifi standards are designed specifically to deliver very high throughput to many different stationary users. Flexlink is designed to remedy the short comings of these technologies, but refrains from implementing extreme throughput capabilities, which are not needed for its application. Another advantage that FlexLink will provide is its documentation. The FlexLink specification is not simply a dry explanation of how to generate a transmit signal, but rather teaches the technology in a concise way such that a small team of engineers can implement it. In addition to the written documentation, FlexLink is supported by a full suite of Python scripts, which model its performance.

8.9.1 Features that Drive the FlexLink Specification

FlexLink is designed to act as a point-to-point link, where a service terminal controls and communicates with a client terminal. Either terminal may be in motion or stationary. A point-to-mulitpoint configuration is also supported were a service terminal controls and communicates with several clients at once. Again, any of the terminals may be in motion or stationary.

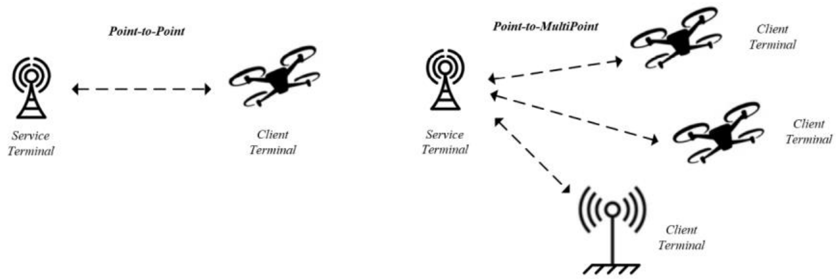


Figure 8-102: Point-to-Point and Point-to-Multipoint Configurations

Mobility

Given the fact that the terminals may be in motion dictates that the method of modulation should be either OFDM or SC-FDMA, which is used in 4G/5G uplink. The ease of equalization and straight forward use of multiple antennas offered by these modulation techniques make them the only viable option for this application. Whereas SC-FDMA signals do feature better peak to average power ratio than OFDM and therefore facilitate more efficient power amplification, both link directions were chosen to use OFDM modulation in order to minimize the complexity of the specification and subsequent implementation effort. In order to ensure that the frequency response remains flat over as single subcarrier, the subcarrier spacing was chosen to be 20KHz.

Data Throughput

The FlexLink technology does not require the massive data throughput offered by modern 5G and WLAN specifications. A maximum theoretical throughput of about 130MBPS allows us to use a standard 20MHz channel and avoid the use of spatial multiplexing MIMO. This simplifies the standard as RF radio components with this channel size are readily available and the lack of spatial multiplexing MIMO significantly eases the implementation effort. Also note that spatial multiplexing MIMO is only a realistic option when both terminals are stationary and multipath conditions are well behaved. The lack of spatial multiplexing is not a significant hinderance as multiple antennas at the transmitter and receivers can equivalently be used to boost throughput via the use of transmit and receive diversity.

Robust Transmission

The FlexLink technology can process low data rate information in poor signal to noise ratio conditions. This feature extends the useful range of the link and allows terminals to receive and successfully decode control information even if the user data information can not be retrieved. This requirement dictates the use of both robust and generous synchronization and reference signal design and layout. In order to support both high and low throughput, the construction and layout of the synchronization and reference information is very flexible.

Multiple Antennas Layout

The FlexLink technology stipulates the use of one or two transmit antennas. The use of two transmit antennas provides transmit diversity via space frequency block coding. The number of receive antennas may be any number. At a minimum, a single receive antenna is required and any futher antenna / receiver port may be used to enable receive diversity via maximum ration combining or any other combing scheme. The figure below illustrates the standard antenna configuration for a link featuring no more that two antennas at each terminal. Clearly, FlexLink support the SISO (single input single output) configuration as this is the most basic setup needed to establish an RF link. Whereas technically, FlexLink does not mandate any additional antennas, a 2x2 MIMO configuration using transmit and receive diversity via SFBC (space frequency block coding) and MRC (maximum ratio combining) is recommended. Given that a second transmit antenna is an option in the specification, all FlexLink receivers needs to be able to decode the space frequency block coding at each receiver path.

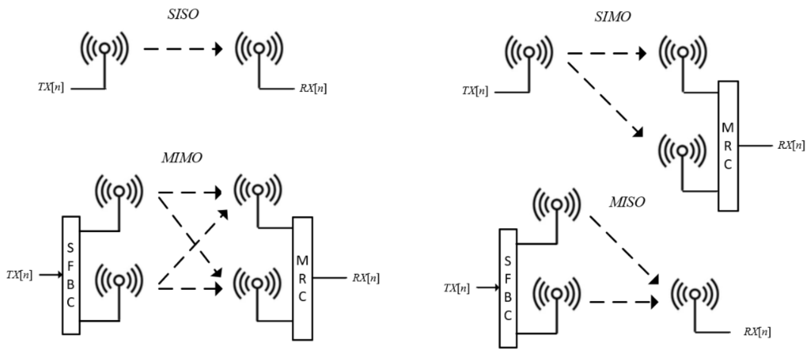


Figure 8-103: Basic Standard Antenna Configurations

Packet Transmission

The link is packet based meaning that all synchronization and data information is contained within a bound time period.

8.9.2 Specification Overview in Tabular Form

The following table provides a brief overview of some of the physical layer parameters of the FlexLink Specification. These specifications will be explained in more detail over the following pages.

Specification	Comments
Method of Modulation	Orthogonal Division Multiplexing (OFDM)
Base Sample Rate	20MSPS / 40MSPS (Oversampled)
I/FFT Size	N = 1024 / N = 2048 (Oversampled)
Subcarrier Spacing	20MHz/1024 = 19.53125KHz
OFDM Symbol Length No CP	50e-6 Seconds
CP Length	5e-6 sec (100 Samples)
Bandwidth WLAN Mode	841 Subcarriers ≈ 16.5MHz
Bandwidth LTE Mode	913 Subcarriers ≈ 17.9MHz
Reference Symbol Periodicity	Every 1st, 3rd, 6th, 12th OFDM Symbol
Reference Signal Spacing	Every 3rd, 6th, 12th, 24th Subcarrier
FEC (Payloads A and B)	LDPC / Polar Coding
FEC (Signal Field)	Polar Coding
QAM Constellations	BPSK, QPSK, 16QAM, 64QAM, 256QAM
Max Data Rate	130 MBPS (LTE BW) / 122 MBPS (WLAN BW)
Min Data Rate	260KBPS / 238KBPS

8.9.3 Packet Construction

The FlexLink specification dictates a TDD type link that will transmit packets in both the forward and reverse direction.

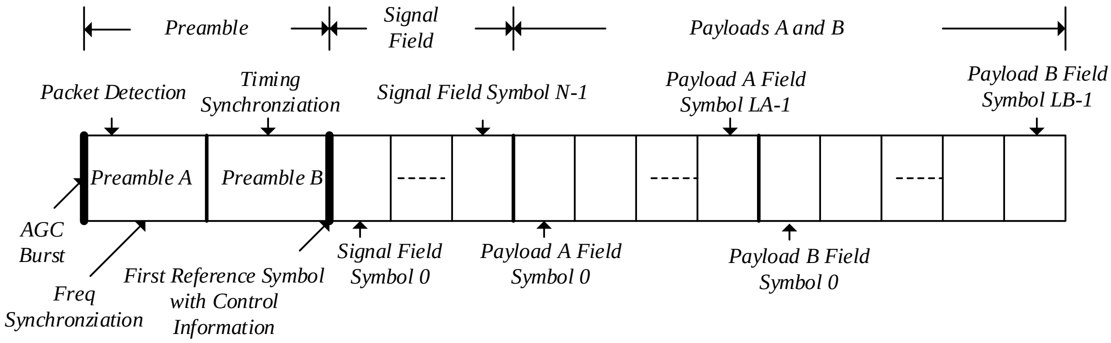


Figure 8-104: Basic Packet Structure for FlexLink

The FlexLink specification provides a preamble, a signal field as well as two payload fields: Payload *A* and *B*. The payloads are separated such that each can have a different modulation and coding schemes and the packet can thus convey two messages with different reliability. For example, payload *A* can feature control information that is more important for the receiver than data information in payload *B*. In the drone application, the drone can send GPS data and other telemetry data in payload *A* and video in payload *B*.

8.9.3.1 The Preamble

The preamble is composed of three separate portions each providing different synchronization.

<u>AGC Burst</u>

→ The initial portion of the preamble is a four microsecond long wideband AGC (automatic gain control) burst that facilitates the acquisition of all gain stages in the analog radio portion of the modem with the goal of providing IQ data that is within the proper ADC input range.

<u>Preamble A</u>

→ Packet detection – This algorithm discerns a FlexLink packet from any other that might legally be transmitted in the band.
→ Frequency offset acquisition – The frequency offset must be acquired and corrected in order to avoid loss of orthogonality in the OFDM demodulator.

<u>Preamble B</u>

→ FFT Timing determination – Preamble *B* will consist of a sequence that will have excellent autocorrelation properties with distinct peaks that allows the receiver to determine the arrival time of the strongest RF path.

8.9.3.2 The Resource Grid

The resource grid is a convenient construct allowing us to organize information for subsequent OFDM modulation. The figure on the following page illustrates the resource grid specified by the FlexLink standard. FlexLink supports two bandwidths that may be considered as a 20MHz channel. The first bandwidth is composed of 913 subcarriers, which at a subcarrier spacing of 20MHz/1024, or 19.53125KHz, covers a bandwidth of 17.84MHz. The second bandwidth is composed of 841 subcarriers and covers a bandwidth of 16.43MHz. These layouts are chosen to be compatible with RF chip sets and filters used for LTE and WLAN. Note that the resource grid is further devided into resource blocks and triplets, where each triplet is composed to three subcarriers. No information of any kind is provided at the DC subcarrier.

→ LTE Variant: 913 subcarriers, (913 – 1)/3 = 304 triplets, (913 -1)/12 = 76 resource blocks
→ WLAN Variant: 841 subcarriers, (841 – 1)/3 = 280 triplets, (841 -1)/12 = 70 resource blocks

The first Reference Symbol with Control Information

The first reference symbol constitutes the first opportunity for the receiver to observe reference signals from both transmit ports. It allows the receiver to compute a high accuracy channel estimate and SNR value for both transmit paths. The first reference symbol features a **static** subcarrier arrangement (see figure) of reference signals and control information, but no user data.

Control information is embedded within the first demodulation reference symbol. The information is embedded this way so that the transmitting MAC can control some aspects of the link on the fly, without previously having to inform the receiver of the configuration change. This is also important so that the transmitter can communicate in an ad hoc manner with unknown receivers. Control information, which is BPSK encoded, is transmitted on **TX port 0 only** and must be equalized using reference signals associated with TX port 0 before being decoded.

Table 8-2: Understanding Control Information

Information	Number of Bits	Description
Reference Symbol Periodicity in OFDM Symbols	2 bits	[0, 1, 2, 3] →1, 3, 6, and 12 OFDM Symbols
Reference Signal Spacing	2 bits	[0, 1, 2, 3] → Every 3rd, 6th, 12th, 24th Subcarrier
Number Signal Field Symbols	2 bits	[0, 1, 2, 3] → The number of OFDM symbols for the signal field: 1, 2, 3, or 4
Signal Field Format	2 bit	0/1/2/3 – Format 1 / Format 2 / Format 3 / Format 4
BPSK [0] / QPSK [1] in Signal Field	1 bit	Use QPSK in the signal field for links with reasonable SNR in order to occupy fewer OFDM symbols.
Number of Tx Antenna Ports	1 bit	[0, 1] → 1 or 2 Transmit antennas
Point to Point or Point to Multipoint Mode	1 bit	[0, 1] → Point to Point / Point to Multipoint
DC Subcarriers	1 bits	[0, 1] → 1 Subcarrier / 13 subcarriers
	12 bits	

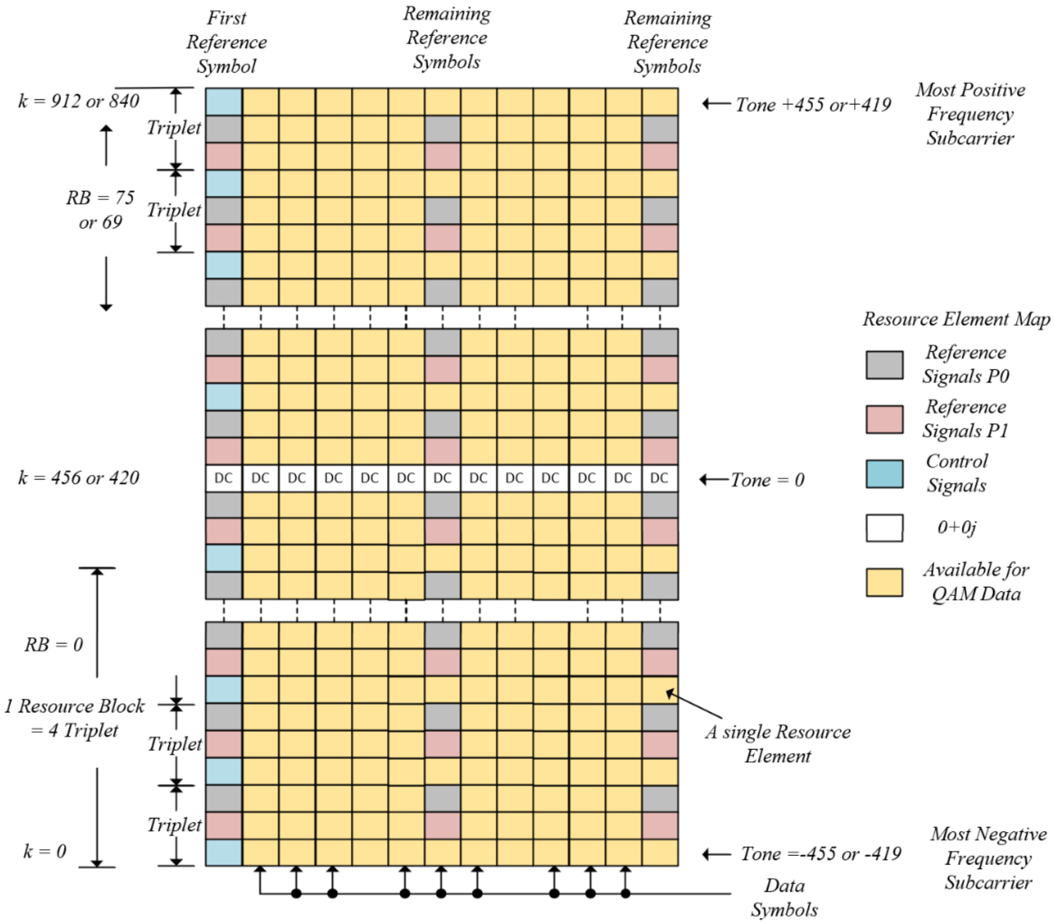


Figure 8-105: Resource Grid Layout for FlexLink Channel

Before explaining how the reference signals are arranged and what the meaning of the control information is, please note the following nomenclature related to the resource gried. Subcarriers are enumerated via the variable *k*, as done in LTE. The figure also provides the IEEE convention, which identifies the subcarriers as tones.

Table 8-3: Nomenclature Related to the Resource Grid

Term	Explanation
Resource Grid	A convenient construct used to organize information into OFDM Symbols.
Resource Element	An element in the resource grid holding a single QAM value at a single subcarrier and OFDM symbol.
Resource Block	A collection of 4 Triplets = 12 Subcarriers (76 LTE RB, 70 WLAN RB)
k	The subcarrier index as defined in the 3GPP specifications.
Tone	The subcarrier index as defined in the IEEE specifications.
P0 / P1	Port 0 / Port 1 refers to the first and second TX Antennas respectively
Reference Signal	A resource element with a value known to the receiver ahead of time. Reference signals are used for channel and SNR estimation.
Reference Symbol	An OFDM symbol that contains reference signals.
Data Symbol	An OFDM symbol that exclusively holds user data.

<u>*Reference Symbol Periodicity*</u>

The reference symbols may be spaced at a periodicity of 1, 3, 6 or 12 OFDM symbols. The previous figure shows a periodicity of 6 OFDM symbols. The faster the relative motion of the different terminals, the faster the multipath condition change. This requires a tight spacing of reference symbols.

→ A spacing of 1 OFDM symbols is primarily used with a high reference signals spacing of 12 or 24 subcarriers. This arrangement can be used for stationary terminals that only need to track phase walk and timing drift, but no actual change in multipath conditions. This arrangement is similar to pilot tone construction in 802.11 OFDM modems.

→ A spacing of 3 OFDM symbols is appropriate for very fast moving terminals such as high speed drones.

→ A spacing of 6 or 12 OFDM symbols is used for terminals that move with progressively less velocity.

A larger spacing of reference symbols frees up more resources for user data. However, a larger spacing than 12 OFDM symbols provides a neglible increase in user data resources, and the control information therefore does not accommodate it. Including the reference symbol periodicity in the control information is important as a terminal in motion can thus autonomously change the spacing as it changes velocity and thus Doppler conditions.

The reference symbol spacing needed to resolve Doppler, or the equivalent frequency offset, can be determined by first understanding the kind of Dopper we will face. For the drone application, we may assume that the maximum doppler will be related to a maximum speed, i.e. 300Kph, or 54 m/sec. The maximum Doppler frequency at a center frequency of 5.9GHz is computed as follows:

$$F_{Doppler} = F_{Center}\frac{V_{max} m/s}{300e6 m/s} Hz = 5.9e9\ \frac{84}{300e6} Hz = 1652 Hz$$

The maximum absolute Doppler frequency that can be resolved by a reference signal spacing of T seconds is proportional to the Nyquist BW of 1/T Hz. Therefore, for a spacing of 3 OFDM symbols, where each OFDM symbol features a period of 55 microseconds, the maximum detectable Doppler is ±1/(2·T) = ±1/(2·3·55e-6) ≈ ± 3KHz. Note that these calculations assume that the terminals are moving toward or away from one another in a straight line. Any other motion produces less Doppler. See section 7.3.2 for a more detailed description of the effect of calculations regarding Doppler.

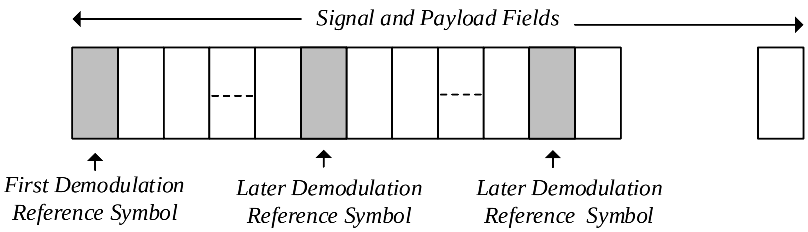


Table 8-4: Repetition of Reference Signal OFDM Symbols

Reference Signal Spacing along the Frequency Axis

Reference signal may be spaced every 3rd, 6th, 12th, and 24th subcarrier. Note that the first reference symbol is **always** set to every 3rd subcarrier. There are two aspects of the link that influence the reference signal spacing. The larger the delay spread of the multipath channel, the more quickly the frequency response changes across the bandwidth of the channel. Large delays between paths, which occur for outdoor communication and are typically worse in rural than urban environments, thus require a tighter reference signal spacing than indoor scenarios where the paths will arrive at the receiver with small delays due to the small distance between terminals. A second aspect is the desire for very accurate determination of the frequency response and signal to noise ratio. The larger the number of reference signals to which the receiver has access, the more accurately the frequency response of the channel and the signal to noise ratio may be estimated.

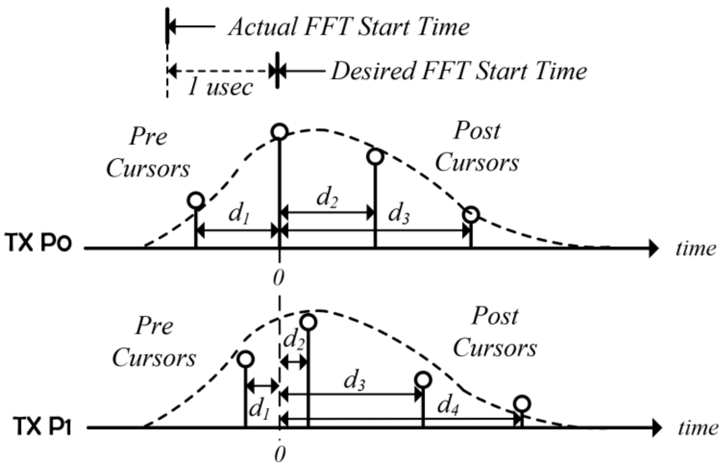


Figure 8-106: Channel Impulse Response Due to TX Ports P0 and P1

To better understand how tightly reference signals need to be placed along the frequency axis, let's consider the figure above, which shows the impulse response of the two channels that FlexLink supports. The first channel exists between transmit antenna port P0 and a single receive antenna, whereas the second channel exists between transmit antenna port P1 and that same receive antenna. Note that preamble *B* is used for timing synchronization, meaning that once we have seen the maximum correlation peak produced by the strongest path emanating from transmit port P0, then we will also know when the strongest copy of the first OFDM symbol from that port begins. In the figure above, we indicate that moment as *time* = 0. The frequency response changes at a rate that is proportional to the delay between desired FFT start time (indicated as *time* = 0) and the start time of the IFFT portion of the OFDM symbol of the various paths.

From section 8.1.3.2, we know that the frequency response for a single OFDM symbols is defined as follows.

$$FreqResponse(f) = \sum_{p=0}^{P-1} C_p \cdot e^{-j2\pi d_p f}$$

The next figure shows the frequency responses due to three paths. The top most plot is the frequency response of the strongest path, at which we want to start the FFT operation. Let's assume that we can't estimate that moment perfectly and some very small amount of delay remains. The second plot represents the frequency response due to a precursor that arrives 0.5 microseconds ahead of the strongest path. The third plot represents the frequency response of a post cursor arriving with a delay of 2 microseconds. The total frequency response is the summation of the constituent responses due to each path.

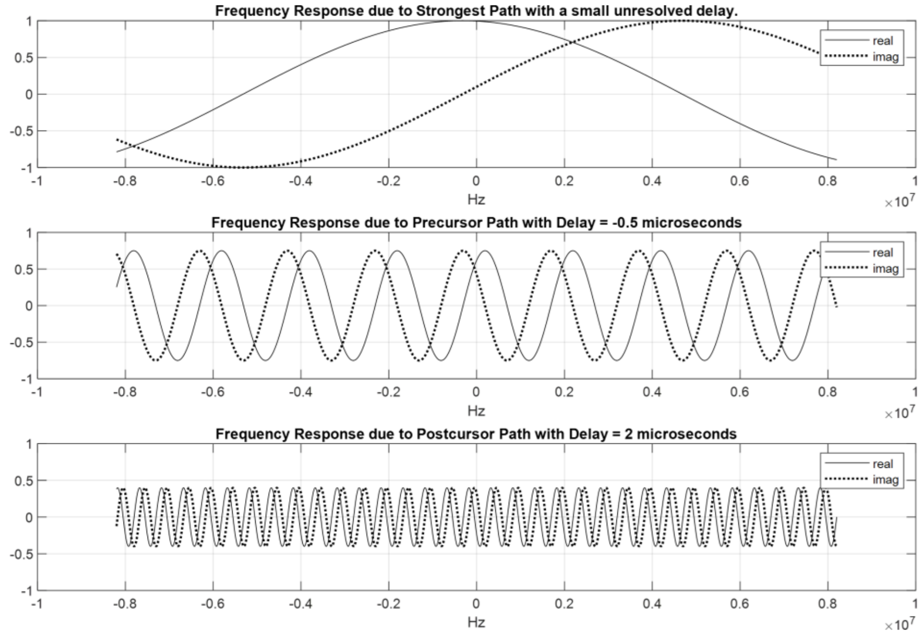


Figure 8-107: Frequency Response due to Three Separate Paths

The reference signals along the frequency axis must be spaced so that they can properly sample the frequency response that oscillates at the highest rate. The Nyquist theorem tells us that we must sample a time domain signal at twice its highest frequency component. For the complex sinusoid, the minimum sampling rate would be $2f_o$ Hz, with the sample period being $1/(2f_o)$ seconds.

$$ComplexSinusoid(t) = C \cdot e^{-j2\pi d f_o t}$$

In our case, the complex sinusoid extends over frequency rather than time. Whereas this seems a bit awkward as we don't usually encounter signals that change as a function of frequency, the concept is exactly the same. Therefore, the sampling rate is at least $2d_p$, with a sample period no larger than $1/(2d_p)$. FlexLink is set up to handle an absoluate maximum delay of 5 microseconds, which is the cyclic prefix length. A larger delay would definitely cause intersymbol interference.

$$FreqResponse(f) = C_p \cdot e^{-j2\pi d_p f}$$

The minimum sample period for the maximum delay is therefore 1/(2·5e-6) = 100KHz. The tightest available spacing in FlexLink is 3 subcarrier · 20KHz = 60KHz, which is better than what we need.

Changing from the Desired to the Actual FFT Start Time

Remember that an OFDM symbol is composed of the output of an IFFT operation and a cyclic prefix that is meant to avoid intersymbol interference. Once we have acquired timing via the correlation against the preamble *B* sequence, we know where in the received signal the IFFT portion of the first OFDM symbols starts. That moment would appear to be the right moment to start reading in samples into the FFT buffer. For this reason we call it the desired FFT start. However, if a precusor exists, then that precursor overlays the end of the IFFT portion of the strongest path as shown in the figure below. We must therefore choose a different time, the actual FFT start, at which we begin reading samples into the FFT buffer.

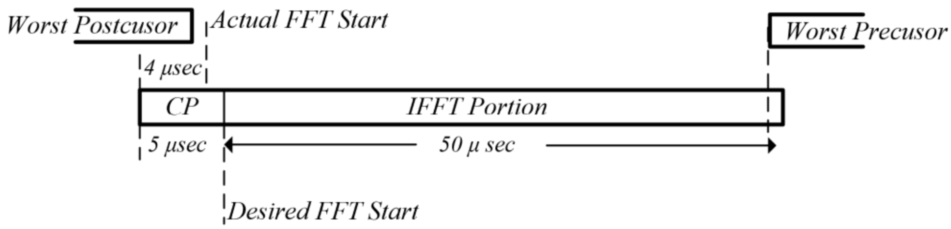


Figure 8-108: Desired vs Actual FFT Start Time

Common sense indicates that the strongest signal will arrive earlier than the weaker ones as those travelled further and thus experience more attenuation. However, the strongest path only arrives first if there is a direct line of sight. As a rule of thumb, we move the FFT start time 1 microsecond into the cyclic prefix in order to avoid precosurs of the next OFDM symbol and post cursors of previous OFDM symbol. Starting the FFT at an earlier time makes it appear as if we are processing a delayed copy of the OFDM symbol, and we must therefore correct the FFT outputs as follows.

$$FFT\_Output(f) = FFT\_Output_{1\mu sec}(f) \cdot e^{-j2\pi(-1e-6)f}$$

Now that the FFT outputs have been corrected, the delay range that we can handle extends from -1 microsecond to 4 microseconds.

Arrangement of Reference Signals

In addition to the previously discussed factors that influence reference symbol periodicity and reference signal spacing, there is another component to the way the reference signals are spaced across the resource gird. They are evenly spaced in both the frequency and in the time domain. This is not the case for LTE, which heavily supports mobility. The reason for the even spacing is to enable the use of the discrete Fourier transform in both frequency and time direction to accurately estimate the frequency response and the signal to noise ratio. We will see how this work later.

Signal Field

The signal field defines the amount of information transmitted in *payloads A* as well as the manner in which this information is error encoded and mapped into QAM constellations. The information in the signal field may be spread across 1, 2, 3, or 4 OFDM symbols and be mapped into BPSK or QPSK constellations. After the control information, the signal field is the one with the most error protection as without it, *payload A* can not be decoded. There are two configuration in which the signal field may be constructed.

TX Antenna Ports

The FlexLink may operate with either one TX (port P0) or two TX antennas (ports P0 and P1). In the case of two TX antenns, space frequency block coding shall be used to provide transmit diversity. The number of receive antennas is not defined and one may be used or several receive antennas may be employed to add receive diversity via maximum ratio combining.

Point-to-Point and Point-to-Multipoint Configuration

The basic link configuration consists of two terminals, a service and a client, communicating with one another in an exclusive manner. However, the standard also includes a configuration that allows a single service terminal to serve as a central station that exchanges data with several client terminals of which some, all or none are in motion. This service terminal may itself be in motion or stationary.

DC Subcarriers

Similar to the LTE specification, the FlexLink standard does not transmit any data at the DC subcarrier. This is done as most Zero-IF receiver must suppress DC offsets in its analog components, and are thus unable to process information at the exact center frequency of the signal. In addition, in order to remain compatible with RF chipsets designed for WLAN applications, FlexLink will forgo transmitting user data on the four inner triplets, or the 12 subcarriers closest to the DC subcarrier. The WLAN standard forgoes placing data at its DC subcarrier as well, but given that it uses a subcarrier spacing of 312.5KHz rather 19.53125KHz, the FlexLink will avoid data mapping in the central 13 subcarriers.

8.9.3.3 Mapping between the Resource Grid to the FFT/IFFT Inputs

Whereas the core sample rate of the FlexLink modem is 20MHz, the analog-to-digital and digital-to-analog converters need to operate at least twice as fast in order to make analog filtering at the ADC inputs and DAC outputs practical. In the transmit direction, the resource grid may be fed to a 1024-point or 2048-point IFFT depending on the manner of Upsampling desired. If an IFFT of size 2048 is used, the output sequence is automatically upsampled to 40MHz, whereas the use of an IFFT of size 1024 will require an upsampling step (see section 3.4.1).

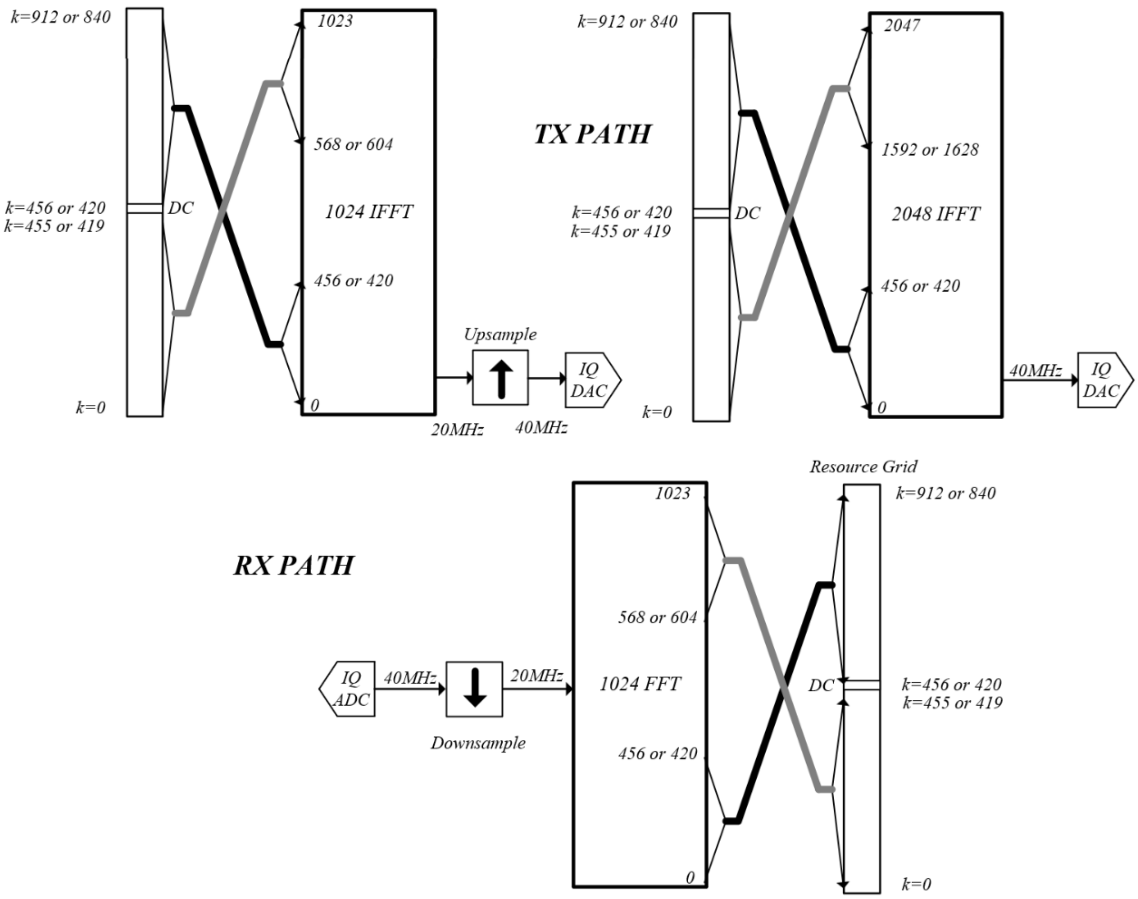


Table 8-5: FFT/IFFT Mapping to Resource Grid

Similarly, at the receiver, the analog signal needs to be sampled at a rate of at least 40MHz, and then downsampled (see section 3.4.2) to 20MHz before being provided to the FFT input buffer.

Otherwise the mapping itself is very straightforward with the positive frequencies mapping to the lower I/FFT input ports, whereas the negative frequencies connect the upper I/FFT input ports, as dictated by Nyquist's aliasing rules.

Table 8-6: FFT/IFFT Mapping to Resource Grid

Subcarrier Index k	IFFT Port Indices N =1024 / 2048	Frequencies	Bandwidth
0:455	568:1023 / 1592:2047	(-456:1:-1)·SC = -8.90625MHz : -SC	LTE
456:912	0:456	(0:1:456)·SC = 0Hz : 8.90625MHz	LTE
0:419	604:1023 / 1628:2047	(-420:1:-1)·SC = -8.203125MHz : -SC	WLAN
420:480	0:420	(0:1:420)·SC = 0Hz : 8.203125MHz	WLAN

8.9.3.4 The Signal Field

The signal field defines the amount of information transmitted in payloads A and B as well as the manner in which this information is error encoded and mapped into QAM constellations. Two payloads exist in order to accommodate the transmission of more critical control information and pure user data information. For the drone application, the ground station may not necessarily be able to receive a video stream anymore, but the telemetry information exchange should stay in takt. Therefore, Payload A can feature far better error correction than Payload B if so desired. The information in the signal field is provided by the media access controller, or MAC.

Format 1

Format 1 of the signal field is the simplest configuration in which FlexLink can operate. In this mode, only payload *A* is transmitted and specified. We may use either polar or low density parity check coding and only a single transport block is transmitted. The transport block is broken up into a certain number, *NCB A*, data blocks which become data words and code words once the encoding and rate matching is added respectively. See the next section for a definition of the various types of data units that are processed in the bit encoding chain.

Table 8-7: Signal Field Description Format 1

Information	Number of Bits	Description
FEC Mode A	1	0/1 – LDPC Coding / Polar Coding
Code Block Size (CBS) A	2	Encoded block size (648, 1296, 1944 bits, 1944) if LDPC Encoded block size (256, 512, 1024, 2048) if Polar Code
NCB A	14	The number of code blocks to be sent in the payload.
FEC A	3	(0, 1, 2, 3, 4, 5, 6, 7) LDCP ½, 2/3, ¾, 5/6, ½, ½, ½, (0, 1, 2, 3, 4, 5, 6, 7) Polar ¼, 3/8, ½, 5/8, ¾, 7/8, ¼, ¼
RM A	3	The amount of rate matching (0, 1, 2, 3, 4, 5, 6, 7) C2 = 0.5, 0.75, 1, 2, 3, 7, 15, 31
BPS A	2	Bits Per Symbol (QAM) 0, 1, 2, 3 = BPSK, QPSK, 16QAM, 64QAM
Num OFDM Symbols	14	The number of OFDM symbols in the packet including the signal field.
Reference Clock Count	14	A counter needs to be attached to the 20MHz Reference oscillator. This value is the remainer of the integer division of CounterValue and 2^{14}, at the moment when the first AGC Burst sample reaches the IQ DACs.
User Bits	3	User defined bits.
CRC	8	Cyclic Redundancy check bits that protect the 72 signal field bits
	64	

The bit stream of the format 1 signal field must be encoded using a ¼ rate N = 256 Polar code and the encoded bits repeated until they fill the number of OFDM symbols indicated in the control information.

Format 2

Format 2 of the signal field follows the same pattern as format 1 except that it provides

Information	Number of Bits	Description
FEC Mode A	1	0/1 – LDPC Coding / Polar Coding
Code Block Size (CBS) A	2	Encoded block size (648, 1296, 1944 bits, 1944) if LDPC Encoded block size (256, 512, 1024, 2048) if Polar Code
NCB A	14	The number of code blocks to be sent in the payload.
FEC A	3	(0, 1, 2, 3, 4, 5, 6, 7) LDCP ½, 2/3, ¾, 5/6, ½, ½, ½, (0, 1, 2, 3, 4, 5, 6, 7) Polar ¼, 3/8, ½, 5/8, ¾, 7/8, ¼, ¼
RM A	3	The amount of rate matching (0, 1, 2, 3, 4, 5, 6, 7) C2 = 0.5, 0.75, 1, 2, 3, 7, 15, 31
BPS A	$76 \cdot 3 = 228$	The number of bits per QAM symbol for each resource blocks: 0, 1, 2, 3, 4, 5, 6, 7 = 0bits, 1bit, 2bits, 4bits, 6bits, 8bits, 10bits, 10bits
Num OFDM Symbols	14	The number of OFDM symbols in the packet including the signal field.
Reference Clock Count	14	A counter needs to be attached to the 20MHz Reference oscillator. This value is remainer of the integer division of CounterValue and 2^{14}, at the moment when the first AGC Burst sample reaches the IQ DACs.
User Bits	1	User defined bits.
CRC	10	Cyclic Redundancy check bits that protect the 72 signal field bits
	290	

The bit stream of the format 2 signal field must be encoded using a N = 1024 Polar code (approximately rate ¼) and the encoded bits repeated until they fill the number of OFDM symbols indicated in the control information.

The vector BPS A (of length 228 bits) indicates the QAM constellation for the data resource element values of each of the 70 (WLAN BW) or 76 (LTE BW) resource blocks. If the first three bits of the vector are 011, then all data resource elements in resource block 0 will be 16QAM modulated as this constellation represents 4 bits. The total number of useful bits will be either $70 \cdot 3 = 210$ or $76 \cdot 3 = 228$. For the case of the WLAN bandwidth, the last 18 bits of the vector are undefined.

8.9.3.5 Synchronization Strategy Using the Preamble and Signal Field

Synchronization is a collective term used to describe the activities in the receiver that facilitate the proper demodulation of the signal. Therefore, synchronization and demodulation are separate processes, with the former happening first. When developing synchronization sequences for the FlexLink standard, the overriding constraints were that FlexLink should enable synchronization at very low signal to noise ratio (close to -10dB) and work using inexpensive reference oscillators with reasonable stability. When using less expensive reference crystal osciallators whose stability is larger than 1ppm, the receiver will see very significant frequency offsets embedded in the received signal as well as timing drift, which is generally less of a problem.

As an example, assume that reference crystal oscillators with a stability of 10ppm (part per million) at the transmitter and receiver are used to establish a link at 2.4HGz. The frequency error seen at the receiver may be as bad as 2.4e9Hz · 2 · 5e-6 = 48KHz. Not correcting this error would make our OFDM demodulator, which works with 15KHz subcarrier spacing, completely deaf. We need to detect and correct this error even at poor SNR. The following activities are part of the synchronization process.

Automatic Gain Control (AGC)

AGC is the process of detecting the average magnitude of the incoming signal and readjusting its size such that clipping does not occur in the analog to digital converters. FlexLink provides an AGC burst at the beginning of the preamble to facilitate this process. The AGC burst is a Zadoff-Chu sequence that is spread across the entire bandwidth of the signal. The low peak to average power ratio of the Zadoff-Chu sequence, and the fact that it is a wide-band signal, makes it the perfect sequence for this task.

Packet Detection

Some mechanism must exist to determine that a FlexLink packet has arrived as compared to some other type of signal radiating within the RF channel. The packet detector described in 8.9.4.2 can detect the *PreambleA* at signal to noise ratios close to -10dB and at frequency offsets far exceeding those of the examble above. The *PreambleA* may feature a length of either 50 or 250 microseconds. The first 50 microseconds are sufficient for task of packet detection.

Frequency Offset Acquisition

Whereas the packet detector can indicate the arrival of the packet and do so at very large frequency offsets, we need a mechanism to actually compute the frequency offset and then correct for it. Latent offset after frequency offset correction will cause loss of orthogonality in the OFDM demodulator, which will make the signal to noise ratio at the FFT output worse. The frequency detector will be able to determine the frequency offset to enough accuracy to avoid the effects of loss of orthogonality. In order to compute the frequency offset, the *PreambleA* must feature a length of 250 microseconds. During normal scenarios, the long version of the *PreambleA* would only be used when the two terminals make initial contact.

Timing Acquisition

Timing acquisition is the process of determining the start of the OFDM symbols and therefore which sections of the received IQ sequence should be read into the FFT buffer of the OFDM demodulator. The receiver will use the *PreambleB*, which is a Zadoff-Chu sequence with very good auto-correlation performance. It is the sequences auto-correlation properties, not its low peak to average power ratio, that are used for this purpose.

This specification requires a uniform clocking strategy, which features a single reference oscillator (usually a TXCO) that provides a single reference clocks to the base band processor, the mixed signal converters (ADCs / DACs), and to the synthesizer that generates the local oscillator, LO, signals that up and down convert the IQ information between baseband and RF frequencies. This is done in order to simplify synchronization as frequency offset and timing drift will now track one another (see 7.3.2).

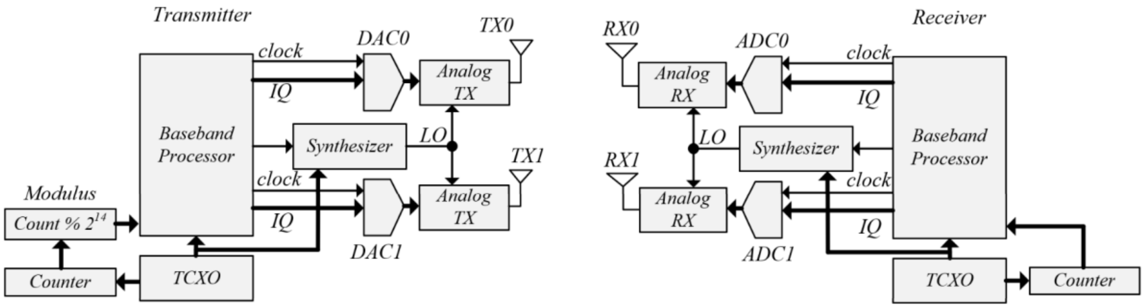


Figure 8-109: Unified Clocking Strategy

<u>Timing Drift and Frequency Offset Tracking</u>

As mentioned in section 7.3.2, the unified clocking strategy links the timing drift of the IQ signal to the frequency offset. We can deduce one by knowing the other. As the frequency of the 20MHz reference clock can drift with temperature, it is important to be able to reacquire the frequency offset from time to time. We could occasionally transmit the long version of *PreambleA*, but we will use a different scheme that is far more accurate.

Note that the signal field contains a 'Reference Clock Count'. This reference clock count is equal to the value of the transmit modulo counter (see figure above) at the moment that when the transmitter begins to read out the preamble and passes it to the digital to analog cenverters. In the figure above, we can see the counter and modulo operation providing the baseband processor with a *mod*(Count, 2^{14}) value that changes with every clock. The transmitter provides this value in the signal field and once two packets have arrived at the receiver, the receiver can compute the difference in count values for the two packet. The receiver keeps a count of its own reference clock as well, and assigns a reference count at the time that a peak is detected during the *preambleB* processing of the two packets. The ratio of the transmit and receive count differences is equivalent to the difference in time base between the transmitter and receiver. With this information at hand, processing of additional long *preambleA* sequences is not longer necessary.

8.9.3.6 Payload A and B

The payload is divided into two different fields, *A* and *B*, to give the modem the opportunity to transmit data with different amounts of protection or MCS (modulation and coding scheme). The data sent in each payload consists of a certain number of blocks, whose sizes are defined by the FEC encoding that is used.

Transport Block

A transport block is a set of MAC bits that is protected by a single 24 bit CRC, features a common error encoding method and is mapped in a sequential manner to a distinct area in the resource grid. A *transport word* is simply the concatenation of the transport block and its 24 bit CRC. The transport word size is thus 24 bits larger than the transport block size.

$$TWS = TBS + 24$$

Data Blocks

The transport word needs to be divided into data blocks which have the correct size to be FEC encoded. Each data blocks is first appended with an 8 bit CRC to become a *data word*, and it is this *data word* that is FEC encoded. The data block and data word sizes are as follows.

$$DWS = DBS + 8$$

Figure 8-110: Data Word Sizes vs Code Block Sizes for LDPC ½, 2/3, ¾, 5/6 Rate Encoding

DWS (data word size)	CBS (code block size)
324	LDPC ½ - 648
648	LDPC ½ 1296
972	LDPC ½ - 1944
432	LDPC 2/3 - 648
864	LDPC 2/3 - 1296
1296	LDPC 2/3 - 1944
486	LDPC ¾ - 648
972	LDPC ¾ - 1296
1458	LDPC ¾ - 1944
540	LDPC 5/6 - 648
1080	LDPC 5/6 - 1296
1620	LDPC 5/6 - 1944

Figure 8-111: Data Word Sizes vs Code Block Sizes for Polar Encoder

DWS (data word size)	CBS (code block size)
128	Polar 1/4 - 512
256	Polar 1/4 - 1024
192	Polar 3/8 - 512
384	Polar 3/8 - 1024
256	Polar 1/2 - 512
512	Polar 1/2 - 1024
320	Polar 5/8 - 512
760	Polar 5/8 - 1024
384	Polar 6/8 - 512
768	Polar 6/8 - 1024
448	Polar 7/8 - 512
892	Polar 7/8 - 1024

Code Blocks

For LDPC, the code block sizes are fixed at 648, 1296, and 1944 bits, whereas for the polar codes the size is either 512 or 1024. In order to be able to decode signals with low signal to noise ratio, we repeat the bits in the code blocks a certain number of times to form the *code word*. The receiver may therefore sum the repeated softbits to the received code word soft bits before executing the FEC decoder. The code word size, CWS, is computed as follows.

$$CWS = CBS + NumRepeatedBits$$

$$NumRepeatedBits = CBS \cdot RepetitionFactor + NumFillerBits$$

The repetition factor will be provided and is a constant for each transport block, whereas the number of filler bits is such that the code word will fill an integer number of resource blocks. In this way, each successfive code word will always start at the beginning of a resource block.

Resource Element Blocks

A resource element block is a sequence of QAM symbols holding the code word. The resource element block size must be an integer multiple of 12 as the code word must fill an integer number of resource blocks. The resource element block is then either encoded via SFBC, space frequency block coding, and then passed to the two resource grids for OFDM modulation and transmission via antenna port P0 and P1, or it is directly passed to the resource grid for P0 only.

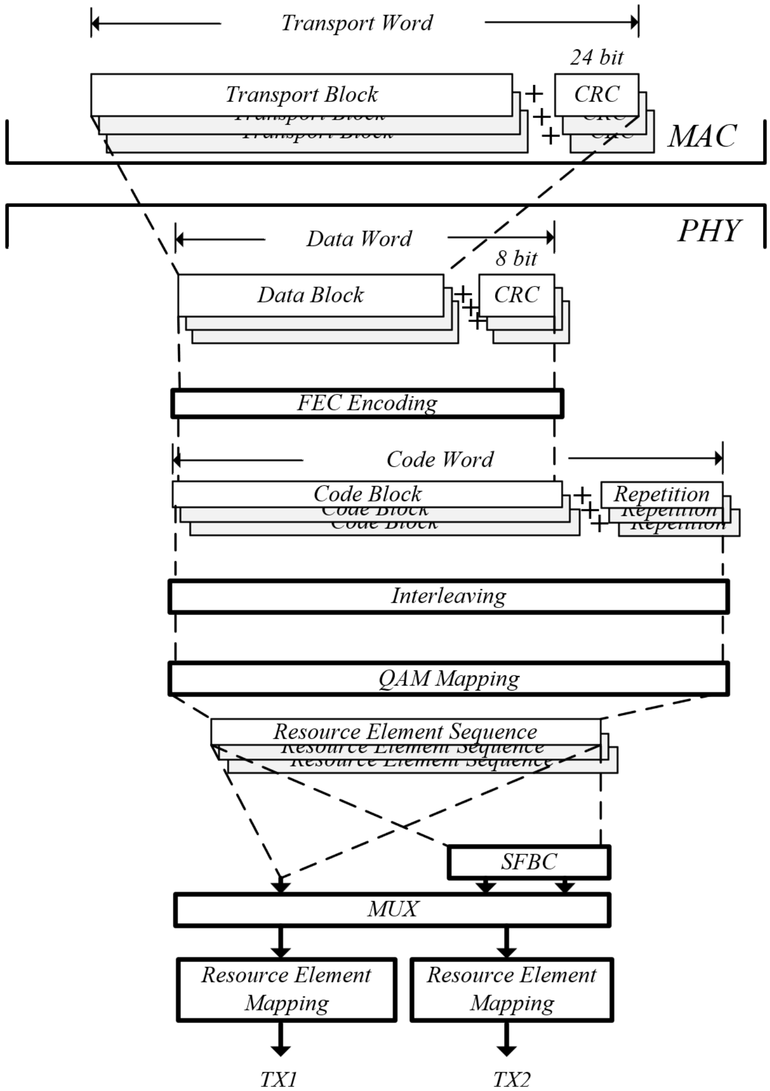


Figure 8-112: Processing Chain for Data Bits and Resource Elements

Vertical vs Block Mapping

There are two types of resource element mapping available. *Vertical mapping* will map all resource element blocks belonging to a transport block in a vertical fashion starting at subcarrier k = 0 to k = 912 or 840, depending on the channel configuration (LTE / WLAN configuration). Vertical element mapping is the only mapping method available for payload *A*. *Block mapping* will map all resource element blocks belonging to a single transport block into a rectangular region in the resource grid. Both vertical and block mapping are available in payload *B*. In the figure below, both mapping techniques are shown for the case where payload B uses block mapping (left image) and vertical mapping (right image). Note that the resource element sequences 0 and 1 for payload *A* both cover a full OFDM symbol plus one resource block. This is to be expected given that they represent two code words with identical number of bits.

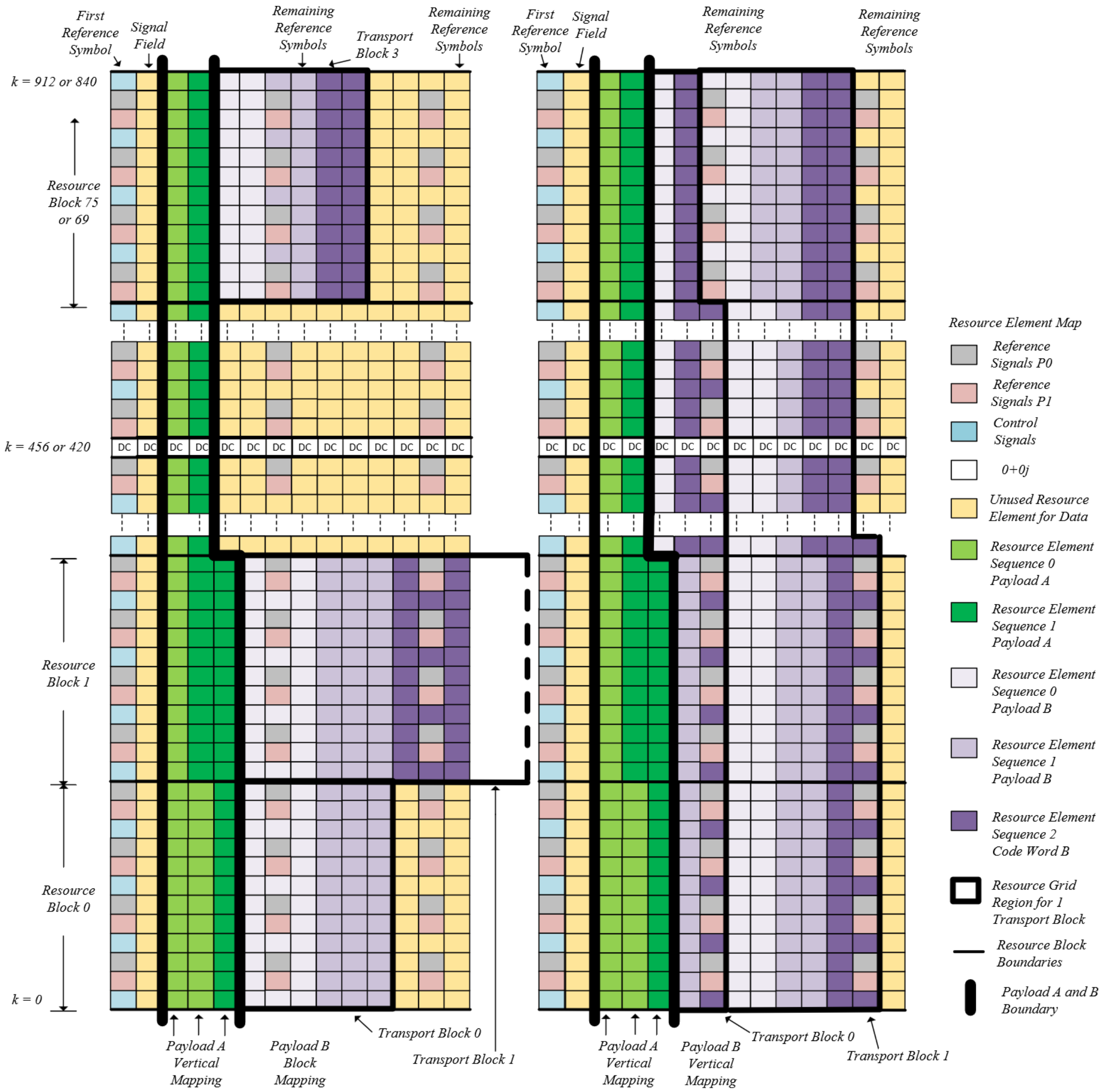


Figure 8-113: Vertical and Block Mapping in Payload A and B

Block mapping is used when the transmitter knows the frequency response that the receiver will see, a fact that is only possible if both stations are relatively stationary, which gives the receiver time to convey the frequency response back to the transmitter before it changes. With this information, the transmitter can properly place encoded bits belonging to each transport block thus optimizing the overall throughput.

Static and Adaptive Vertical Mapping

Vertical mapping may be subdivided into static an adaptive modes. As mentioned above, if the terminals are not moving and the frequency responses remain stable, the receiver will estimate the CINR for every resource block and convey this information back to the transmitter. This will allow the transmitter to select the proper QAM constellation when mapping data into each resource block. Resource blocks for which the CINR is low require stronger protection than those that feature strong CINR. We cannot change the FEC configuration within a single resource block, but we can assign the bits to a custom constellation for every resource block. Those resource blocks with poor CINR will use a more robust mapping such at BPSK or QPSK, whereas those with good CINR may use a higher constellation map. This technique called *adaptive mapping* allows us to use less FEC protection than in the case were we did not have the CINR information and were forced to use a static QAM constellation (*static mapping*) thus requiring more conservative FEC strength.

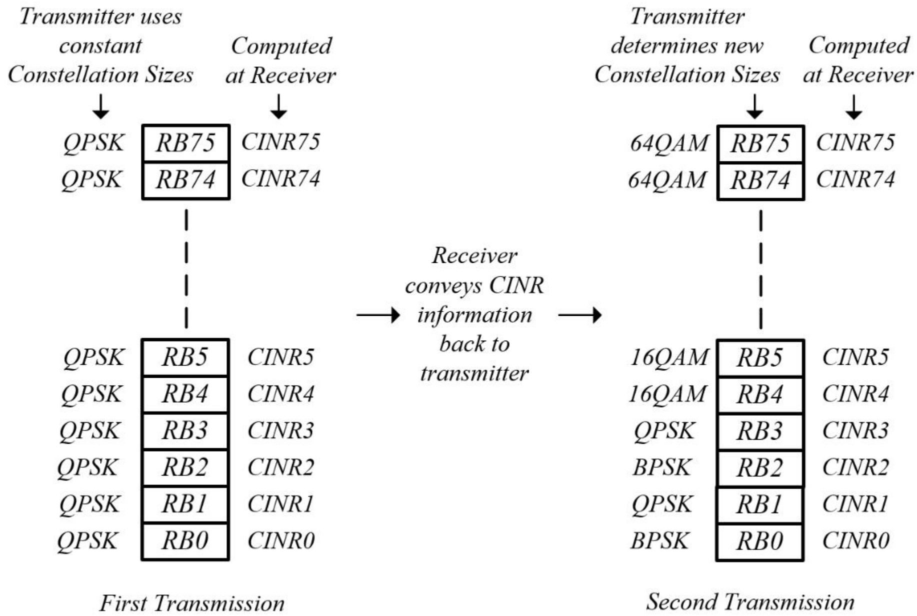


Figure 8-114: Static versus Adaptive Mapping

Note that block mapping only makes sense if we have the CINR information thus allowing us to place transport block data in optimal locations. In this case, not just can we change the QAM constellation for each block, we can also adjust the FEC strength, thus giving the transmitter even more flexilibity and better throughput.

If the terminals are in motion and the frequency response changes, then conveying CINR measurements from the receiver back to the transmitter is not adviced as the frequency response and thus the CINR values of the different resource blocks changes too quickly. In that case, both payload *A* and *B* may stick with static vertical mapping.

8.9.4 Preamble Construction

The following section will discuss the requirements and design of the different preamble components. The preamble is only transmitted from antenna port 0. In situations where both transmit antenna ports have a clear line of site to the other terminal, then it is possible that sending identical information from both antenna ports with destructively interfere at the receiver antannas, thus decreasing the signal to noise ratio significantly. The payload will not have this issue due to space frequency block coding.

8.9.4.1 Construction and Processing of the AGC Burst

The purpose of the AGC burst is to present the receiver with a waveform that allows for fast detection of the signal magnitude. As such, the waveform should be wideband and feature a low peak to average power ratio. The AgcBurst shall occupy 5 microseconds, which at 20MHz yields 100 samples. The AgcBurst is a Zadoff-Chu sequence defined as a time domain sequence that is generated via the step below. Note that the actual parameters used for the Zadoff-Chu sequence are not critical. There are many variations of this sequence that can be used for the AGC burst.

The derivation of the AgcBurst begins with the expression of a Zadoff-Chu sequence. The length of the sequence shall be N_{zc} = 887, the root index u = 34 and the discrete time index spans n = 0, 1, … N_{zc}-1.

$$\boxed{zc[n] = \exp\left(-j\frac{\pi u n(n+1)}{N_{ZC}}\right)}$$

We now take the N_{zc} = 887-point discrete Fourier transform.

$$FFT\_Output[m] = \frac{1}{N_{ZC}}\sum_{n=0}^{N_{ZC}-1} zc[n]\cdot e^{-j2\pi nm/N_{ZC}}$$

By definition, we will have a certain number of positive frequency subcarriers, m = 0, 1, …*ScPositive*-1 and a certain number of negative frequency subcarriers, $m = N_{zc}$ - *ScNegative*, … N_{zc}-1.

$$ScPositive = ceil\left(\frac{N_{zc}}{2}\right) = 444$$

$$ScNegative = floor\left(\frac{N_{zc}}{2}\right) = 443$$

The FFT output shall be mapped into a length 1024 or 2048 IFFT input buffer depending on the desired output sample rate. The indexing into the input buffer is based on the tone convention.

$$IFFT\_Input[1\colon ScPositive] = FFT\_Output[1\colon ScPositive]$$
$$IFFT\_Input[1024 - ScNegative\colon 1023] = FFT\_Output[N_{zc} - ScNegative\colon N_{zc} - 1]$$
or
$$IFFT\_Input[2048 - ScNegative\colon 2048] = FFT\_Output[N_{zc} - ScNegative\colon N_{zc} - 1]$$

The DC tone, *Tones*[0], remains unmapped as it will not survive the zero-IF down conversion process in the receiver. Execute the IFFT and retain the first 100 samples.

8.9.4.2 Construction and Processing of PreampleA

Preamble A is transmitted only from TX antenna port P0 and enables the following synchronization processes at the receiver.

→ *PreambleA* is used to detect the presence of a FlexLink packet.
→ *PreambleA* is used to determine the frequency offset in the packet.

Defining and Detecting the PreambleA

To define the equation the PreambleA, let's restate the base sample rate of 20MHz and the FFT size of 1024 used during the OFDM modulation process which together yield a subcarrier spacing of 20MHz/1024 = 19.53125KHz. Subsequently, the equation of the *PreambleA* is as follows.

$$PreambleA(t) = \frac{1}{4}(\cos\left(2\pi \cdot 32\frac{20e6}{1024} \cdot t\right) + \cos\left(2\pi \cdot 96\frac{20e6}{1024} \cdot t\right))$$
$$= \frac{1}{4}(\cos(2\pi \cdot 625000 \cdot t) + \cos(2\pi \cdot 1875000 \cdot t))$$

The *preambleA* is defined as the super position of two cosine waveforms at 625KHz and 1.875MHz respectively. The waveform is period with a period of 1/625KHz = 1.6 microseconds, or 32 samples. Compared to the single sided bandwidth of the overall waveform, which is just shy of 10MHz, these tones feature relatively low frequencies. This is done in order to apply low pass filtering and significantly decrease noise present in the channel. The noise reduction and thus increase of signal to noise ratio is approximately equal to 10e6Hz/2.5e6Hz = 4, or 6dB.

The structure of the packet detector seen below is almost identical to what was used in the 802.11A modem discussed in section 8.3.2. The autocorrelation $x[n] \cdot conj(x[n\text{-}32])$, or $x[n] \cdot x[n\text{-}32]^*$, will will average to constant, sizable real value as $x[n]$ and $x[n\text{-}32]$ are equal during the preamble. When PreambleA is not present, $x[n]$ and $x[n\text{-}32]$ are unrelated and $x[n] \cdot x[n\text{-}32]^*$ will average toward zero. The variance is computed in the lower branch of the structure in order to normalized the auto correlation to a maximum value of 1.0. The main differences between this version and the one used in the 802.11A example are the addition of the low pass filtering process and the potentially much larger averaging length *N* of 512, which enables us to detect packets with signal to noise ratios down to -10dB. When SNR conditions are known to be reasonably good, then *N* may be reduced in order to increase the speed of the packet acquisition

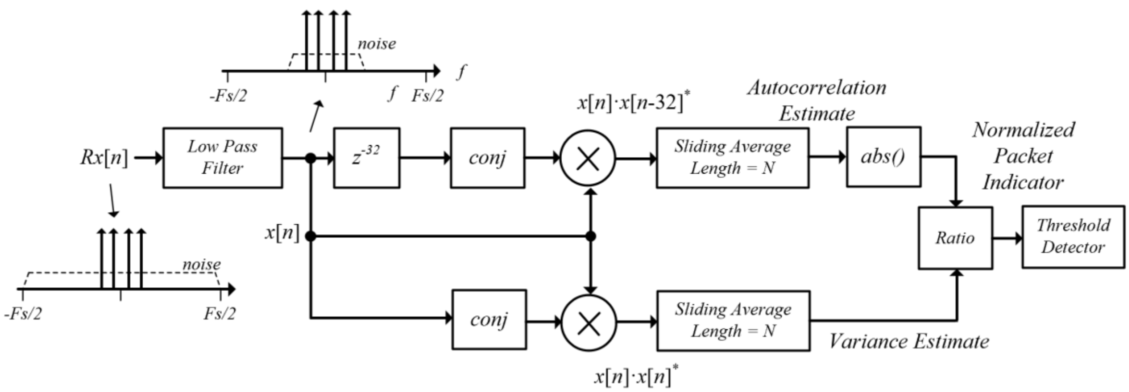


Figure 8-115: FlexLink Packet Detector

The figure below illustrates the situation where the signal to noise ratio is 0dB and the averaging length is N = 512. The sequence being passed through the detector consists of noise until sample 500, when the PreambleA arrives. N = 512 samples, 25.6 microseconds, later, the ratio value has reached its peak. For a low signal to noise ratio of -10dB, detection can be determined by observing 200 consecutive ratio values larger 0.18.

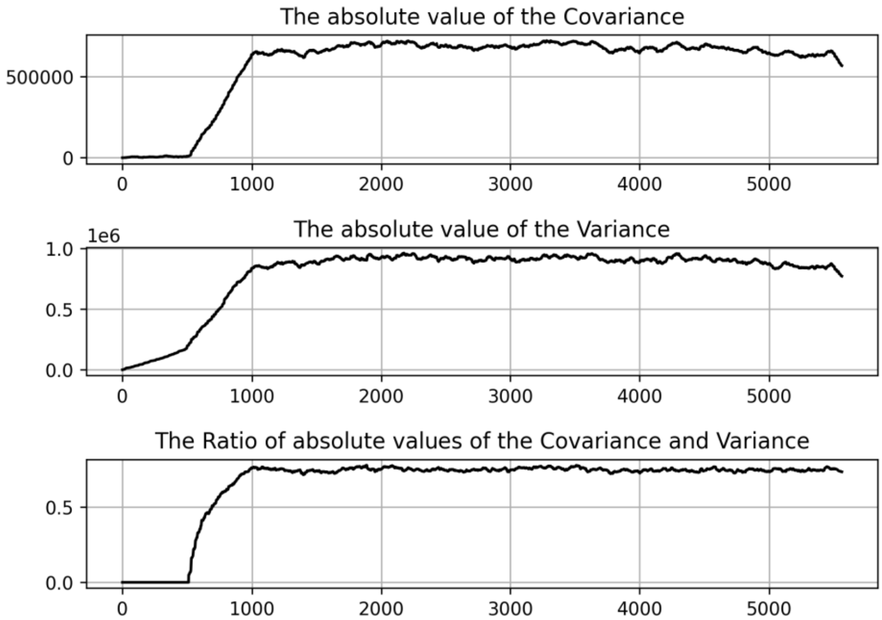


Figure 8-116: PreambleA Detector Performance for an SNR = 0dB and N = 512

Length of the PreambleA

The FlexLink transmitter can elect PreambleA lengths of 50 or 250 microseconds depending on the SNR conditions. If no contact has yet been made with the receiver, then the length should default to 250 microseconds, which allows the frequency offset detector, which we will discuss next, to determine frequency error at a low signal to noise ratio. However, once the offset has been determined by the respective receivers, there is no need to maintain the 250 microsecond length as the difference in LO frequencies between the terminals is now know and will not change significantly. The transmitter therefore has to make a choice as to the length of the PreambleA, and the natural question beckons as to how the receiver will know the transmitter's selection ahead of time. In the absence of any information exchanged previously, the receiver needs to run the *PreambleB* detector at the same time as packet and frequency offset detectors. If the algorithm detects the PreambleB within 100 microseconds of the packet detection, then the PreambleA was set to 50 microseconds.

Frequency Offset Estimation

The difference between the center frequency of the transmitted signal and the local oscillator frequency, which is used to down convert the receive signal from the RF to the base band domain, consists of two factors.

First, there is the unavoidable mismatch in the temperature compensated crystal oscillators (TCXO) that provide the reference clock to both the synthesizer, base band processor and mixed signal converters (ADCs/DACs). Each oscillator will produce a reference frequency that will have a range of some number of parts per million, or ppm. For example, two 20MHz TCXO with a deviation of ±1ppm, may produce reference frequencies errors of 20e6 ·±1e-6 Hz = ±20Hz, which does not sound like a lot. However, once these references are used to generate local oscillator frequencies at 5GHz, the frequency error in these LO signals ballons to 5e9 ·±1e-6 Hz = ±5KHz. In the worst case, the frequency error can compound at the receiver to a total of 10KHz, which would completely invalidate the orthogonality of the signal when we take the FFT during OFDM demodulation. After all, the subcarrier spacing is only 19.53125KHz. See section 8.1.3.3 for a thorough explanation of loss of orthogonality in OFDM receivers. The frequency offset that our OFDM demodulator can easily tolerate when receiving 64QAM is on the order of ±250Hz. We therefore need a frequency offset detector that can resolve the error to within 250Hz in good SNR conditions, which are required when receiving 64QAM.

The second factor influencing the frequency offset at the receiver is Doppler. The frequency error due to Doppler error is explained extensively in section 7.3.2 and reduces to the following expression, where *C*, F_{TX}, and *Vel* represent the speed of light, the signal's center frequency, and the terminals relative velocity toward one another respectively.

$$F_{Doppler} \cong F_{TX}(\frac{Vel}{C})$$

For a center frequency of 5GHz and a velocity of 200 Kph, or 55 meters per second, the Doppler shift yields a value of ±925Hz, depending on whether the terminals are moving directly toward or away from one another.

$$\pm 5GHz\left(\frac{55\, m/sec}{300e6\, m/sec}\right) \cong \pm 925Hz$$

The frequency detector will resolve both the natural frequency offset due to the mismatch and TCXO and Doppler simultaneously.

<u>When to Estimate the Frequency Offset</u>

Estimating the frequency offset in low signal to noise ratio conditions is much harder than detecting the presence of the FlexLink packet. When frequency offset detection is needed, the PreambleA length must always be 250 microsecond in length. The long PreambleA should be used to enable frequency detection for the following condition.

→ When the terminals make contact for the first time. (Point to Point)
→ When a terminal executes a significant change in velocity and/or direction. (Point to Point)
→ When a client terminal acts a a beacon for other terminals that want to access the serving terminal. (Point to Multipoint)

Clearly, the long PreambleA needs to be used by the transmitter to make initial contact with another station. The media access controller at the respective terminals needs to keep track of the motion of both terminals and reuse the long PreambleA each time a significant change in velocity or direction is detected that can affect the Doppler in a significant way. This is especially necessary when large QAM constallations are transmitted and a loss of orthogonality can't be tolerated due to the Doppler.

In a point to multipoint situation, where a new client terminal wants access to a distant serving terminal, it is helpful for other closer terminals to occasionally transmit the long PreambleA when communicating with the serving terminal.

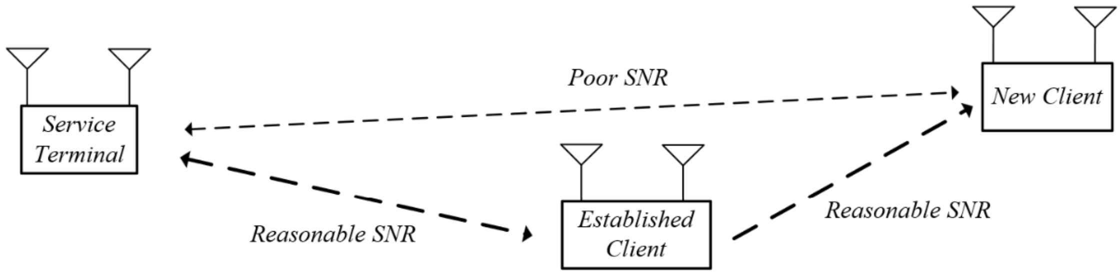


Figure 8-117: New Client Accessing the Serving Terminal

In the figure above, a new terminal with a poor SNR link to the serving terminal can estimate the frequency offset to a transmission of an established client rather than to the serving terminal. To make this possible, the established client must occasionally transmit the long PreambleA, as well as information (in Payload A) regarding its own relative frequency offset to the serving terminal that it has previously detected. With these two pieces of information the new client compute a better frequency offset to the serving terminal and establish communication with better synchronization.

Beyond frequency synchronization, established client can provide a weath of of access information to new clients, such as when the channel will likely be idle, at which point the new client can transmit an access request. This type of hand shaking is handled by the media access controller and related information should be provided in the more robust payload A data stream.

How to Detect Frequency Offset in Low SNR Conditions

Once the Packet has been detected, the receiver needs to read the next 4096 samples, which span over approximately 200 microseconds, into an FFT input buffer. The samples should be premultiplied by a Hanning window as they enter the buffer. The cosine waveforms of the PreambleA with frequencies of 625000Hz and 1875000Hz, will appear at tones ±128 and ±384 in the FFT output. The Hanning overlay will spread content from those tones to the neighboring tones but suppress the DFT leakage into all other tone. The content of the Hanning overlaid cosine waveforms is therefore nicely contained to with the center tones and the direct neighboring tones. This now allows us to zero out all other tones and take the inverse FFT, which recreates a hugely noise reduced version of the waveform that was in the FFT input buffer.

The procedure described above can be implemented in a variety of ways. In fact, there is no need to take the full FFTs or IFFTs to achieve the same results and estimate the frequency offset when we actually implement the detector in hardware.

8.9.4.3 Construction and Processing of Preample B

8.9.5 Resource Grid Construction

This section will define how data is mapped into the resource grid, whose columns are loaded into the IFFT input buffer as part of the OFDM modulation process. Whereas the mapping of reference signals and control data may not be completely obvious, there is a very simple rule that governs the mapping of QAM values into the resource grids for the case when we have one and two antennas. The following figure illustrate how data QAM values are mapped into a column of the resource grid that contains only data and one column that contains both data and reference signals. Note that resource grid P0 must not transmit any information where resource grid P1 would apply its **reference** signals and visa versa.

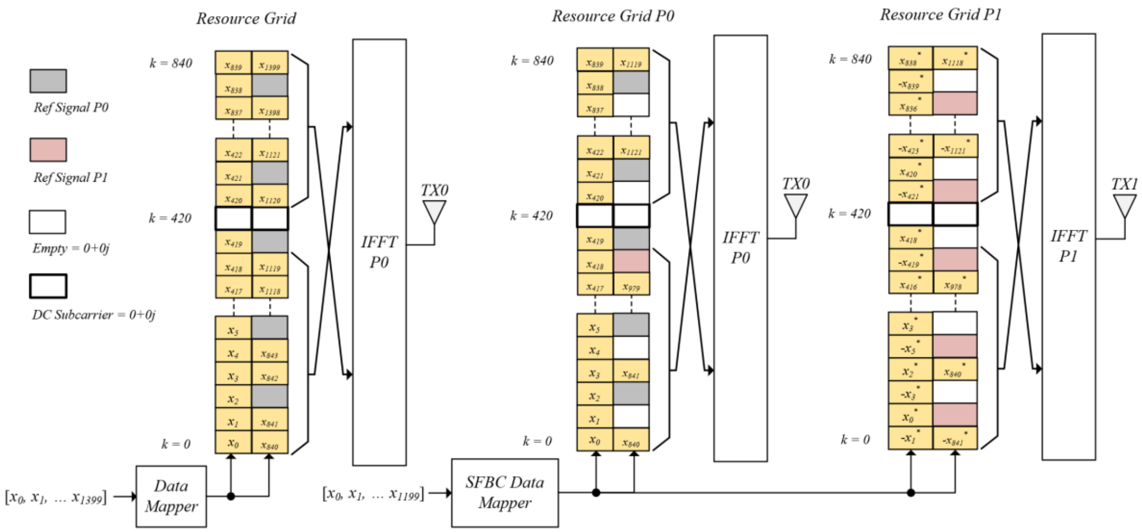


Figure 8-118: Data QAM Symbol Mapping for 1 and 2 TX Antennas (WLAN BW)

Rules for Mapping Reference Signals

There are two bits in the control information, which is embedded into the first reference symbol, that indicate the way reference signals should be placed into a column of the resource grid, which represents an OFDM symbol. These two bits represent the reference signal spacing, provides a distance between reference signals or a single port as every 3rd, 6th, 12th and 24th subcarrier. The table below indicates at which subcarrier indices, k, the reference signals should be spaced for and even distribution.

Table 8-8: Location of Reference Signals

Spacing	Expression P0	Expression P1
3	$k = 2 + n \cdot 3$	$k = 1 + n \cdot 3$
6	$k = 3 + n \cdot 6$	$k = 2 + n \cdot 6$
12	$k = 6 + n \cdot 12$	$k = 5 + n \cdot 12$
24 (WLAN)	$k = 6 + n \cdot 24$	$k = 5 + n \cdot 24$
24 (LTE)	$k = 12 + n \cdot 24$	$k = 11 + n \cdot 24$

Note that the variable n extends from 0 to what ever integer is required to fill the entire OFDM symbol (resource grid column).

<u>Reference Signal Orientation for Transmit Port 0 and Port 1</u>

Given the table above, we may compile the resource elements associated with either P0 or P1 into a list as we the subcarrier index, *k*, increases from 0 to 840 / 912. For P0, the resource elements on this list, starting with the resource element with the lowest *k*, shall be BPSK modulated with an alternating bit pattern equal to [0, 1, 0, 1, 0, 1, 0 ….]. For P1, the resource elements on this list, starting with the resource element with the lowest *k*, shall be BPSK modulated with an alternating bit pattern equal to [1, 0, 1, 0, 1, 0, 1 ….].

<u>Generating Basic Bit Capacity Tables</u>

Mapping QAM symbols into the resource grid takes a bit of planning, and constructing the following capacity tables ahead of time will save the computation unit, doing the mapping, some work. Therefore, given the resource block index, *R*, the bits per QAM symbol for that resource block, and the reference signal layout, compute the capacity as bits per resource blocks and write them into the following table.

Table 8-9: Capacity Table

R = Resource Block Index	Bits Per Symbol (BPS)	Capacity (Bits) Data Symbol	Capacity (Bits) Reference Symbol
0			
1			
2			
69 / 75			

For *PayloadA*, the bits per symbol for each resource block are provided in the signal field, and the reference signal spacing is provided in the control information. The bits per second may be constant for all resource blocks or they may vary. For *PayloadB*, the bits per symbol are indicated in MAC subheaders (Id2 / Id3), which appear in the *PayloadA*. We revisit this table when mapping the payloads.

8.9.5.1 Mapping and Construction of the First Reference Symbol

The first reference signal is provided to enable the receiver to determine the frequency response and signal to noise ratio associated with transmit ports P0 and P1, if two transmit antenna ports are being used. Note that one port must assign a 0 + j0 value to those resource elements used by the other port. There may be no overlap as is the case for data resource elements formed via SFBC.

<u>Control Information Bits</u>

Table 8-10: Control Bit Ordering

Bit	Description	Bit	Description
c_0	LSB – Reference Symbol Periodicity	c_6	LSB – Signal Field Format
c_1	MSB – Reference Symbol Periodicity	c_7	MSB – Signal Field Format
c_2	LSB – Reference Signal Spacing	c_8	Signal Field Format is BPSK/QPSK
c_3	MSB – Reference Signal Spacing	c_9	Number of TX Antennas Ports
c_4	LSB – Number Signal Field Symbols	c_{10}	Point to Point / Multipoint
c_5	MSB – Number Signal Field Symbols	c_{11}	DC Subcarrier

Whereas the table above only assigns control bit positions, the meaning of these bits is explained in table 8-2. Note that the control information is only transmitted from antenna port P0. We currently define 12 control bits, which shall be mapped as BPSK symbols as follows.

→ Starting at k = 0 and proceeding to k = 840/912, identify those resource elements reserved for control information using the index b. There is one control element opportunity, O_b, for every subcarrier triplet, which works out to 280 / 304 total opportunities for the WLAN / LTE bandwidths. As there are 12 control information bits, they will be assigned to opportunities, O_b, as follows.

$$O_b = c_{b\%12} \quad b = 0, 1 \dots 279 \; or \; 303$$

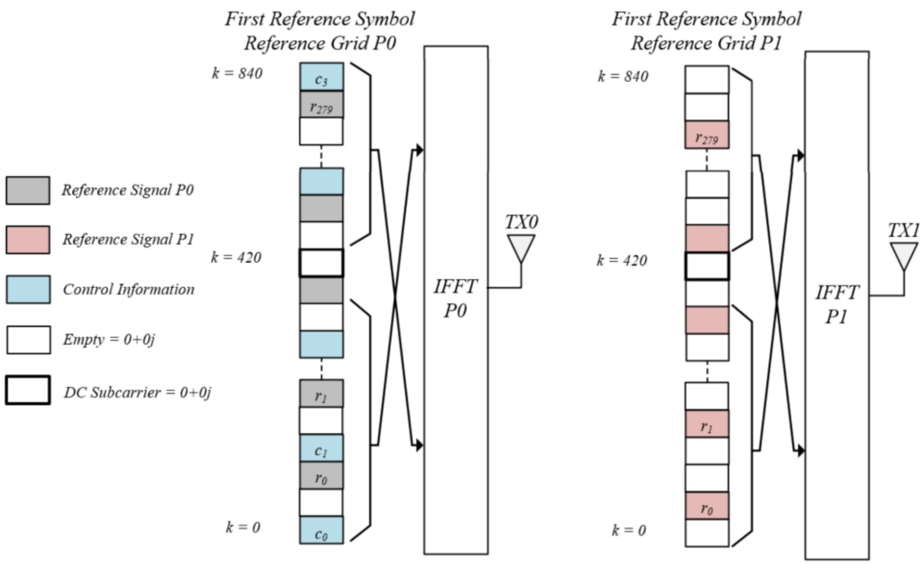


Figure 8-119: The First Reference Signal For Resource Grids P0 and P1 (WLAN BW)

In the figure above, showing the WLAN bandwidth scenario, the first control element opportunity, O_0, resides at subcarrier k = 0, whereas the last, O_{279}, resides at subcarrier k = 840. The control information bits mapped to these positions are $c_{0\%12} = c_0$ and $c_{279\%12} = c_3$.

8.9.5.2 Mapping and Construction of the Signal Field

Four control field quantities influence the construction and mapping of the signal field.

→ The Signal Field Format (2 bits) 0/1/2/3 = Format 1/2/3/4

→ The Bit Per QAM Symbol (1 bit) 0/1 = BPSK / QPSK

→ The number of transmit antennas (1 bits) 0/1 = 1TX / 2TX Antennas

→ The number of signal field OFDM Symbols (2 bits) 0/1/2/3 = 1/2/3/4 OFDM symbols

Currently we define only two signal field formats, where the first format consists of 64 bits, and the second format consists of 288 bits as seen in section 8.9.3.4. The signal field using format 1 will be encoded using a 256 bit polar encoder resulting in a rate equal to ¼. The signal field using format 2 will be encoded using a 1024 bit polar encoder resulting in a rate close to ¼.

These 256 and 1024 bits are first interleaved and then repeated to completely fill between 1 and 4 OFDM symbols (columns in the resource grid). The receiver will sum the repeated bits back into a single set of 256 and 1024 encoded bits. This summing process raises the signal to noise ratio of each bit as $10\cdot\log_{10}$(Number of Copies) dB. Thus, if the set of 256 or 1024 encoded bits are repeated once, then two copies of the bits exist and the signal to noise ratio increases by $10\cdot\log_{10}(2)$ or 3dB prior to the polar decoding process in the receiver.

The media access controller continually observes the signal to noise ratio of the signal station(s), with which he is in contact, and will switch between BPSK and QPSK and alter the number of OFDM symbols in order to provide the appropriate protection.

8.9.5.3 Mapping and Construction of Payload A

PayloadA contains the MAC header and may contain user information. To generate and map *payloadA*, we first look at the number of data blocks and the FEC configuration, which the MAC has assigned and written into in the signal field. The first steps in the creation of payloadA is as follows:

→ Compute and attach the CRC to the provided data block thus producing data words.
→ Perform FEC encoding of all data words thus producing code blocks.

At this point, the code blocks should be written into code block memory as we do not need to and may not want to execute the next steps immediately. Therefore, the following steps may happen before the steps above, but it is more convenient to look at them at this time.

→ Given the amount of desired rate matching, the MAC computes the size of the code word.
→ The MAC now looks at the capacity tables introduced earlier in this section, and determines the number of resource blocks needed to store the code word. It does this by accumulating capacities of successive resource blocks starting with resource block 0 and ending at resource blocks 69 (WLAN) or 75 (LTE). If necessary, the MAC will continue by accumulating the bit capacities of the next OFDM symbol starting once again with resource block 0. As we will want to place a code word into an integer number of resource blocks, in all likelihood, the accumulated capacity in these resource blocks will be slightly larger than the projected code word size. In this case, we simply continue the repetition process and minimally increase the code word size until we fill the last resource block perfectly.

Once all this information is known, the base band processor can execute the following.

→ Interleave the code word.
→ Map the interleaved bits given the QAM constellation (BPS) of the resource block, into which we are currently mapping.
→ For the case of two transmit antennas, execute the SFBC algorithm and place the resource elements into the resource grid memory for transmit antenna ports 0 and 1. Otherwise, the SFBC block is bypassed and the resource element is mapped immediately into the P0 resource grid.

PayloadA always uses vertical mapping, which may be static or adaptive in nature. The figures in section 8.9.3.6 show exactly how the different blocks and words are related and how vertical mapping works. The term *static* simply indicates that signal field format 1 was used and a static QAM constellation was used for all resource elements. The term *adaptive* refers to the fact that signal field format 2 was used and the QAM constellations for each resource block are customized given the estimated SNR conditions of the channel within those resource blocks.

Talk about where the different data blocks start and stop in the figure.

8.9.5.4 Mapping and Construction of Payload B

8.9.6 Transmitter Architecture and Procedures

A lot of processes need to act in concert in order to produce the transmit waveform at the antenna port(s). To reduce the amount of coordination, the transmitter decouples certain processes that may execute and finish independently of one another.

The Preamble ROM

The preamble (AGC burst, *PreambleA*, and *PreambleB*) is a sequence of complex samples that never changes. It should therefore be prerendered and stored in memory to be read out via transmit antenna port 0 on demand.

FEC Encoding

In vitually all applications, the transmitter knows what it wants to convey to the receiver well ahead of the time of the actual RF transmission. At our leasure, we can therefore build and store some or all of the code blocks that are destined for the signal field and the two payloads. These code blocks can remain in the code block RAM until they are needed by the resource element mapper.

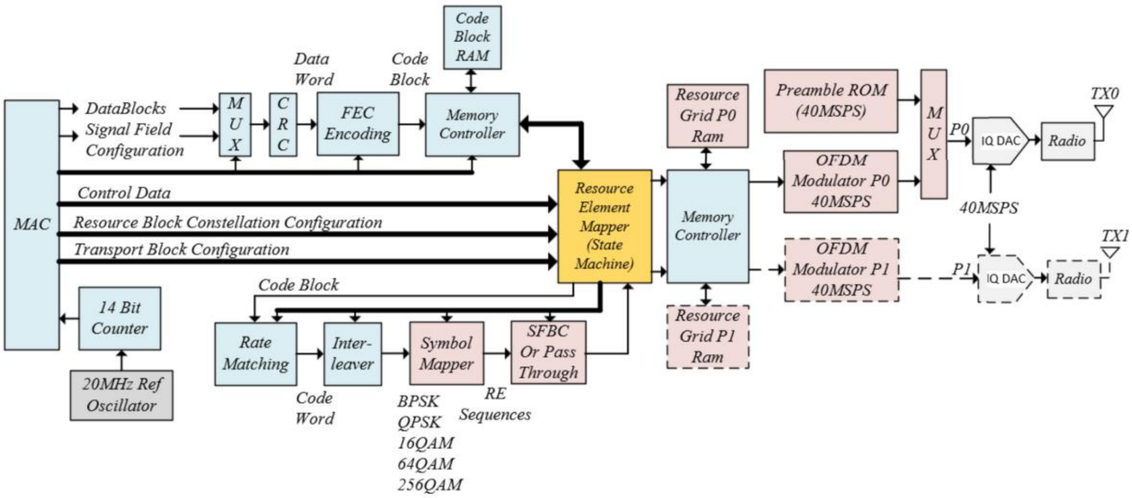


Figure 8-120: Conceptual Diagram of FlexLink Transmitter Implementation

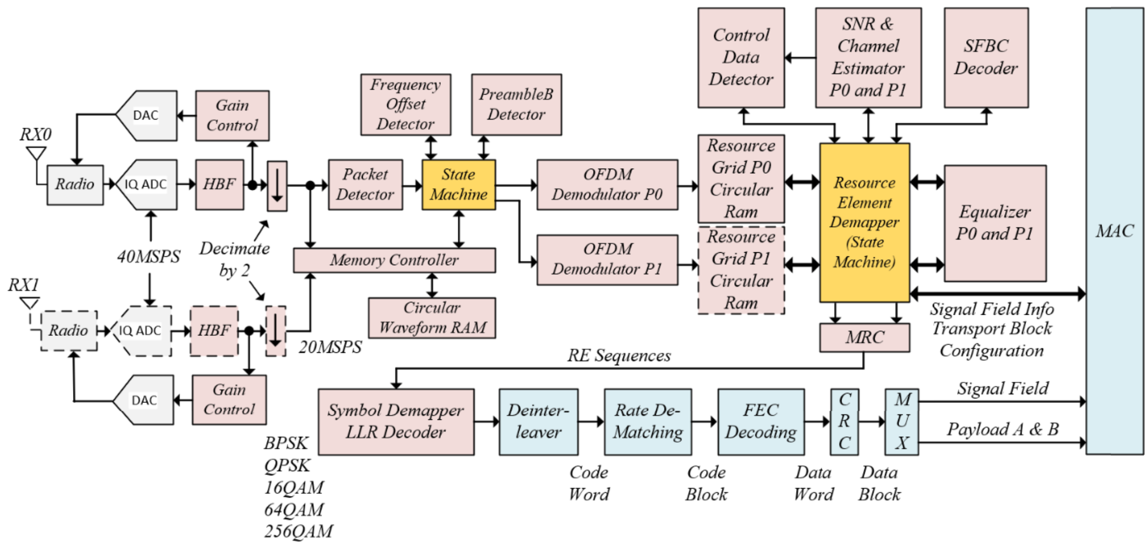
Resource Element Mapping

The resource element mapper is a state machine that is likely implemented as a combination of one or more CPUs and several finite state machines. It will have to extract the different code blocks from the code block RAM, apply rate matching, interleaving, symbol mapping and potentially SFBC encoding prior to placing them into the resource grid RAM modules. The overall encoding chain is broken up into two sections as the resource element mapper needs additional configuration information from the MAC in order to properly rate match the information.

To be continued

8.9.7 Receiver Architecture and Procedures

Under construction.



8.9.8 The Media Access Controller

8.9.8.1 MAC Header Information

The MAC Header is a sequence of bits that provides configuration information about the packet that is being sent. It consists of subheaders identified by an Id of length 5 bits. Note that the bit sequence representing subheader begins with the LSB of Oct 0 and ends with the MSB of the last octet.

Table 8-11: Address Subheader (Id = 0)

Bit	7 (MSB)	6	5	4	3	2	1	0 (LSB)
	Reserved		Id = 0 [5:0]					
Oct 0	24 Bit MAC Source Address							
Oct 1								
Oct 2								
Oct 3	24 Bit MAC Destination Address							
Oct 4								
Oct 5								

The Transport Block Subheader (Vertical Mapping) *PayloadA* defines the number and size of all transport blocks residing *payloadA*.
→ Each transport block block has an associated index, TbIndex, extending from 0 to $N - 1$.
→ Each transport block block features a certain number of data blocks equal to NumDB.
Given that the FEC configuration and number of bits per QAM symbol have been previously defined in the signal field, the number of data and encoded bits are easily found. The transport block subheader consists of O octets, where O is equal to the following expression.

$$NumOctets = O = \begin{cases} 2 + N \cdot \frac{3}{2} & for\ N\ even \\ 4 + (N-1) \cdot \frac{3}{2} & for\ N\ odd \end{cases}$$

Table 8-12: Transport Block Subheader (Vertical Mapping) Payload A (Id=1)

Bit	7 (MSB)	6	5	4	3	2	1	0 (LSB)
Oct 0	Reserved		Id = 1 [5:0]					
Oct 1	Number of Transport Blocks = N [7:0]							
Oct 2	Number of Data Blocks in TB 0 [7:0]							
Oct 3	Number of Data Blocks in TB1 [3:0]				Number of Data Blocks in TB 0 [11:8]			
Oct 4	Number of Data Blocks in TB 1 [11:4]							
Oct 5	Number of Data Blocks in TB 2 [7:0]							
:	:							
Oct O-2					Number of Data Blocks in TB N-1 [3:0]			
Oct O-1	Number of Data Blocks in TB N-1 (if N is even) [11:4]							

or

Oct O-2	Number of Data Blocks in TB N-1 (if N is odd) [7:0]							
Oct O-1	Reserved				Number of Data Blocks in TB N-1 [11:8]			

The Transport Block Subheader (Vertical Mapping) *PayloadB* defines the number and size of all transport blocks residing *payloadB*. The format is identical to the last subheader except for the fact that the bits per QAM symbol, as well as the forward error correction and rate matching can be defined separately.

$$NumOctets = O = \begin{cases} 3 + N \cdot \frac{3}{2} & for\ N\ even \\ 5 + (N-1) \cdot \frac{3}{2} & for\ N\ odd \end{cases}$$

Table 8-13: Transport Block Subheader (Vertical Mapping) Payload B (Id = 2)

Bit	7 (MSB)	6	5	4	3	2	1	0 (LSB)
Oct 0	BPS[0]	Reserved	Id = 2 [5:0]					
Oct 1	RM[2]	RM [1]	RM [0]	FEC[2]	FEC[1]	FEC[0]	BPS[2]	BPS[1]
Oct 2	Number of Transport Blocks = N [7:0]							
Oct 3	Number of Data Blocks in TB 0 [7:0]							
Oct 4	Number of Data Blocks in TB 1 [3:0]				Number of Data Blocks in TB 0 [11:8]			
Oct 5	Number of Data Blocks in TB 1 [11:4]							
Oct 6	Number of Data Blocks in TB 2 [7:0]							
Oct 7	Number of Data Blocks in TB 3 [3:0]				Number of Data Blocks in TB 2 [11:8]			
Oct 8	Number of Data Blocks in TB 3 [11:4]							
:	:							
Oct O-2	Number of Data Blocks in TB N-1 3:0]				Number of Data Blocks in TB N-2 [11:8]			
Oct O-1	Number of Data Blocks in TB N-1 [11:4] (if N is even)							

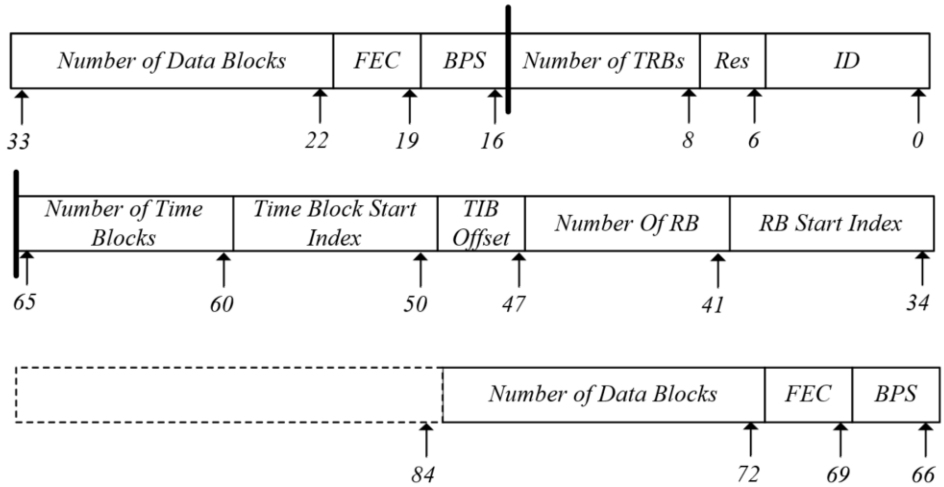
or

Oct O-2	Number of Data Blocks in TB N-1 **[7:0]** (If N is odd)							
Oct O-1	Reserved				Number of Data Blocks in TB N-1 [11:8]			

The transport block subheader (block mapping) *PayloadB* defines number, bit size and region in the resource grid for each transport block.

Table 8-14: Transport Block Subheader (Block Mapping) Payload B (Id=3)

Bit	7 (MSB)	6	5	4	3	2	1	0 (LSB)
Oct 0	Reserved		Id = 3 [5:0]					
Oct 1	Number of Transport Blocks = N [7:0]							
Oct 2	Number of DB [1:0]		FEC[2]	FEC[1]	FEC[0]	BPS[2]	BPS[1]	BPS[0]
Oct 3	Number of Data Blocks (DB) [9:2]							
Oct 4	Resource Block Start Index (RBSI) [5:0]						Num of DB [11:10]	
Oct 5	TIB Offset [0]	Number of Resource Blocks [5:0]						RBSI [6]
Oct 6	Time Block Start Index [5:0]						TIB Offset [2:1]	
Oct 7	Number of Time Blocks [0:3]				Time Block Start Index [9:6]			
Oct 8	FEC[0]	BPS[2]	BPS[1]	BPS[0]	Number of Time Blocks [7:4]			
	:							


Number of Data Blocks
FEC
BPS
Number of TRBs
Res
ID
33
22
19
16
8
6
0
Number of Time Blocks
Time Block Start Index
TIB Offset
Number Of RB
RB Start Index
65
60
50
47
41
34
Number of Data Blocks
FEC
BPS
84
72
69
66

Bit	**7 (MSB)**	**6**	**5**	**4**	**3**	**2**	**1**	**0 (LSB)**
	# Transport Blocks		Id = 1					
Oct 0	Data Block Start Index							
Oct 1								
Oct 2	Number of Data Blocks							
Oct 3								

8.9.9 Overview of the Python Simulation Code

8.10 Exercises

1. Based on the tables for BPSK, QSPK, 16QAM, and 64QAM in section 8.2.5, present new tables for 256QAM and 1024QAM as well as their corresponding scaling factors.

References

[1] IEEE Std. 802.11a-1999 (1999), *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer in 5 GHz Band*, New York, September

[2] Heiskala, J. and Terry, J. (2001) *OFDM Wireless LANs: A Theoretical and Practical Guide*, Sams Publishing, Indianapolis, IN

[3] IEEE 802.11n-2009—Amendment 5: Enhancements for Higher Throughput. IEEE-SA. 29 October

[4] Fazel, K. and Kaiser, S. (2008) *Multi-Carrier and Spread Spectrum Systems: From OFDM and MC-CDMA to LTE and WiMAX*, Third Edition, John Wiley & Sons, New York

[5] Ergen, M. (2009) *Mobile Broadband – Including WiMAX and LTE,* Springer, NY

[6] Sesia, S., Toufik, I. and Baker, M. (2009) *LTE – The UMTS Long Term Evolution*, John Wiley & Sons, New York

[7] 3GPP TS36.211 Section 6.10 ‘Physical Channels and Modulation’ Version 14.2.0 Release 14

[8] 3GPP TS36.211 Section 9.8 ‘Physical Channels and Modulation’ Version 14.2.0 Release 14

9 An Introduction to Multiple Antenna Systems

This chapter is dedicated to Siavash Alamouti, an engineer and scientist born in Teheran, Iran, in 1962. His work led to the Alamouti code, which makes antenna diversity possible for cases where the transmitter rather than the receiver features multiple antennas.

Siavash Alamouti is an Iranian born engineer and scientist that was expelled from his home country during the cultural revolution of the 1980s. He moved to Canada where he continued his education and eventually worked for the cellular telephone industry. His major achievement is the invention of the Alomouti code, which is heavily used today in multiple antenna radio links. It improves the channel conditions of a radio link that uses two transmit antennas and a single receive antenna. This technique is used today to improve cellular communication between base stations, which can afford to boast multiple antennas, and smaller mobile devices, which due to cost and size constraints often feature only a single antenna. In effect, his invention provides transmit diversity for radio links in the form of space time and space frequency block coding (STBC / SFBC).

Multiple antenna techniques have been developed to mitigate the deleterious effects of multipath distortion and to increase data throughput over wireless communication links. Some of these techniques have been incorporated into recent OFDM based communication systems such as WiMAX [1], WLAN 802.11n/ac [2], and the 3GPP 4G long term evolution [3], and 5G New Radio cellular standard. Modern MIMO (multiple input/multiple output implementations have favored OFDM systems thanks to the per-subcarrier flat fading model, which may be utilized when equalizing and combining the signal streams arriving at multiple antennas. In this chapter, we will limit our discussion to three multiple antenna techniques that find utility in modern OFDM based communication systems. The techniques in question are receive antenna diversity, transmit antenna diversity, and spatial multiplexing. In the strictest sense, MIMO refers to the concept of spatial multiplexing or a combination of both transmit and receive diversity.

Receive Antenna Diversity (SIMO – single input/multiple output)

Receive antenna diversity utilizes a single transmit antenna and multiple receive antennas to mitigate the selective and flat fading effects of the multipath channel. Channel conditions at one receive antenna will be different from those at the other, and methods of optimally combining the received information will be presented in this chapter. The diversity combining effect produces an overall superior channel condition, which allows the link to use less forward error correction and/or higher symbol constellations, resulting in increased data throughput.

Transmit Diversity (MISO – multiple input/single output)

Transmit diversity utilizes multiple transmit antennas and a single receive antenna to achieve the same multipath benefit as is provided by receive antenna diversity. The original technique was pioneered by Siavash Alamouti [1] and focused on two transmit and one receive antennas. The goal, once again, is to establish a better-behaved multipath channel that allows the use of higher transmit constellations and/or less redundancy in the forward error correction algorithms. The two transmit diversity techniques we will get know are Alamouti's original space time block coding and space frequency block coding, which is used in LTE.

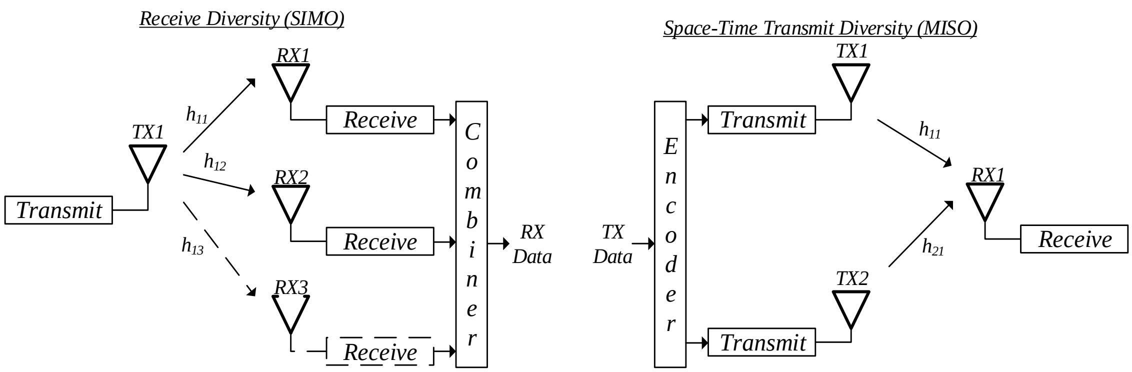


Figure 9-1: Basic Receive and Space-Time Transmit Diversity Scenarios

Spatial Multiplexing (MIMO – multiple input/multiple output)

This technique uses both multiple transmit and multiple receive antennas to send several data streams over the same RF channel. The resulting interference between these streams is removed via digital signal processing techniques at the receiver to yield the desired increase in data throughput. Strictly speaking, spetial multiplexing requires the same number of antennas at the transmitter and at the receiver. However, receive diversity may be easily added to the system to provide a better-behaved multipath channel that results in different numbers of transmit and receive antennas.

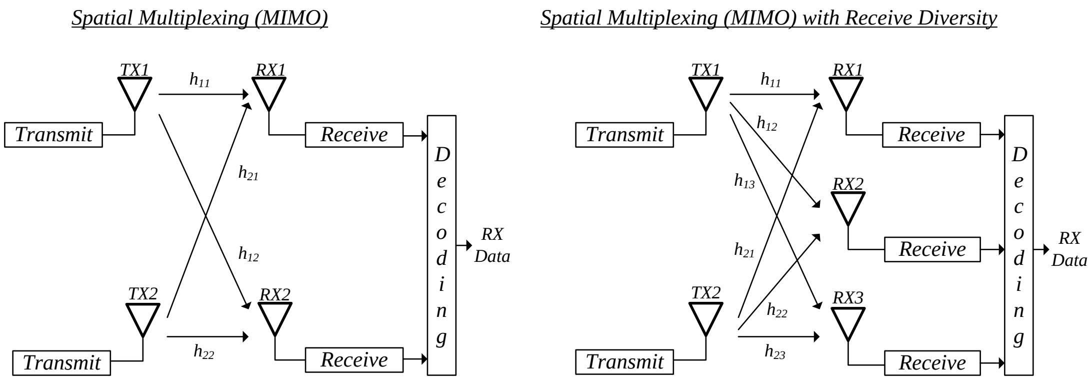


Figure 9-2: Spatial Multiplexing with and without Added Receive Diversity

The Selective Versus Flat Fading Model

The various antenna diversity techniques introduced above feature channel coefficients quantified as simple complex scalars, h_{ab}, where the variables a and b identify the transmit and receive antenna respectively. Channels that may be characterized by simple scalars are represented by the flat fading model, which assumes that the effect of the channel is uniform across the entire signal bandwidth. In chapter 6, we witnessed the harsh impact that selective fading conditions have on wide band signals. Luckily, although OFDM does feature a large bandwidth, it is subdivided into narrowband subcarriers, which may be individually modeled using the flat fading approach. It is for this reason that OFDM lends itself particularly well to the multiple antenna techniques discussed in this chapter. The techniques discussed here assume that all multipath channels, h_{ab}, are of the flat fading type and are known by the receiver after channel estimation is completed.

9.1 Receive Antenna Diversity

Receive antenna diversity has been around much longer than space-time transmit diversity or spatial multiplexing. For decades, we have seen the multiple receive antenna arrangements on cell towers, the roofs of buildings, and on the back of police vehicles. To introduce the idea of receive antenna diversity, let's assume that we have two observations, $y_1[n]$ and $y_2[n]$, of a transmitted symbol, $x[n]$, each featuring different amounts of noise, $v_1[n]$ and $v_2[n]$. It is our goal to find the coefficients of a linear combiner that will result in a final estimate of $x[n]$ that features the maximum possible signal to noise ratio.

$$y_1[n] = x[n] + v_1[n]$$

$$y_2[n] = x[n] + v_2[n]$$

The linear combiner, our estimator, is shown in the figure below and reduces to the following simple expression.

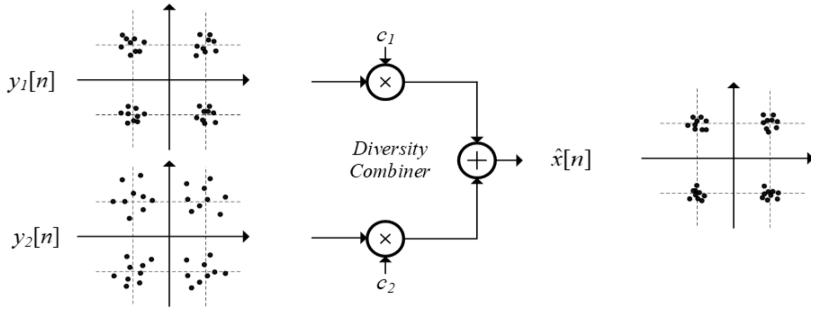


Figure 9-3: Linear Combination of Separate Observations

$$\hat{x}[n] = C_1 \cdot y_1[n] + C_2 \cdot y_2[n]$$
$$= C_1 \cdot (x[n] + v_1[n]) + C_2 \cdot (x[n] + v_2[n])$$
$$= (C_1 + C_2)x[n] + C_1 \cdot v_1[n] + C_2 \cdot v_2[n]$$

Assuming that our coefficients are real-valued, the signal to noise ratio of the estimate of x is as follows.

$$Signal\ Power = E(\,(c_1 + c_2)x[n] \cdot ((c_1 + c_2)x[n])^*) = \ |(c_1 + c_2)^2|\,\sigma_x^2$$

$$Noise\ Power = E(\,(c_1 v_1[n] + c_2 v_2[n]) \cdot (c_1 v_1[n] + c_2 v_2[n])^*\,)$$
$$= E(\,c_1^2\, v_1[n] \cdot\ v_1[n]^*)\ + E(c_1 c_2\, v_1[n] \cdot\ v_2[n]^*)$$
$$+ E(c_2 c_1\, v_2[n] \cdot\ v_1[n]^*)\ + E(c_2^2\, v_2[n] \cdot\ v_2[n]^*)$$
$$= c_1^2 \sigma_{v1}^2 +\ c_2^2 \sigma_{v2}^2$$

$$SNR_{final} = \frac{(c_1 + c_2)^2 \sigma_x^2}{c_1^2 \sigma_{v1}^2 +\ c_2^2 \sigma_{v2}^2}$$

Because $v_1[n]$ and $v_2[n]$ are uncorrelated, the terms $E(c_1c_2 \cdot v_1[n] \cdot v_2[n]^*)$ and $E(c_2c_1 \cdot v_2[n] \cdot v_1[n]^*)$ average toward zero, thus limiting the increase in noise power resulting from the diversity combination. This stands in stark contrast to the signal power calculation, in which all terms will add constructively to yield to positive values. Let's take a look at three combining schemes that have seen use in receive diversity combining applications.

9.1.1 Maximum Output Combining

The simplest of the three schemes, maximum output combining, picks the information at the antenna with the largest signal to noise ratio and ignores the other. If the information on antenna one features a larger signal to noise ratio, then c_1 = 1 and c_2 = 0. The technique is easy to implement and has been heavily used in older communication systems and situations where sophisticated DSP hardware isn't available.

$$SNR_{final} = maximum(SNR_1, SNR_2)$$