Adaptive Frequency Hopping and Other Co-Existence Mechanisms for CC85xx

Kjetil Holstad

ABSTRACT

This application report provides operational details of the RF System that are used in the PurePath Wireless family of devices (CC85xx).

Contents

List of Figures

List of Tables

All trademarks are the property of their respective owners.

1 Introduction

The CC85xx is specifically designed to stream audio in the 2.4 GHz ISM band. The ISM frequency band is a license-free, worldwide frequency band. This also means that the frequency band is crowded by other devices transmitting, including but not limited to WLAN, Bluetooth devices, 802.15.4 (ZigBee) and a whole range of proprietary products.

In order to establish a reliable wireless audio link, mechanisms must be in place to make this a robust and drop-out free experience for the end user in order to motivate them to replace a wired product.

The PurePath Wireless protocol has been engineered with several mechanisms to ensure a robust audio link while at the same time co-exists peacefully with other products using the same band.

1.1 Acronyms

Table 1. Acronyms Used in This Document

AFH	Adaptive Frequency Hopping
FH	Frequency Hopping
FSK	Frequency Shift Key
ISM	Industrial, Scientific and Medical (Referring to the 2.4GHz band)
PPW	PurePath Wireless
QoS	Quality-of-Service
RF	Radio Frequency

2 RF Parameters

The CC85xx RF radio communication system is designed to stream uncompressed audio with as little bandwidth used as possible. This is achieved by implementing a shaped 8 Frequency Shift Key (FSK) modulation capable of 5 Mbps throughput.

The nature of *any* RF device is that it can be interfered. How easily it can be interfered depends on a lot of things all the way down to the physical RF interface. The most obvious interference is products or devices trying to operate in the same frequency band or even at the exact same frequency.

Table 2. Some Selected RF Parameters for the CC85xx Radio

Parameter	Test Condition	MIN	TYP	MAX	UNIT
Output power	Maximum output power setting		3.5		dBm
Receiver sensitivity	5 Mbps 2 Mbps		-83 -86		dBm
Saturation (maximum input level)	5 Mbps 2 Mbps		-2 6		dBm
Selectivity	Adjacent channel, ±4 MHz, wanted 3 dB above sensitivity. 5 Mbps Adjacent channel, ±4 MHz, wanted 3 dB above sensitivity. 2 Mbps		8 20		dB
	Adjacent channel, ±8 MHz, wanted 3 dB above sensitivity. 5 Mbps Adjacent channel, ±8 MHz, wanted 3 dB above sensitivity. 2 Mbps		35 43		dB
Occupied bandwith	99% energy bandwith. 5 Mbps 99% energy bandwith. 2 Mbps		3.8 3.2		MHz

Selectivity is a parameter that tells something about a RF device capability to cope with interferers that is not on the wanted frequency. It measures how large the signal in a channel outside the channel can be while still receiving your signal. As an example, the CC85xx can tolerate a signal 35dB (2000x) larger that the input signal at ± 8 MHz offset from the desired frequency.

The 2.4 GHz ISM frequency band is from 2400 to 2483 MHz and for any device operating in this band the major trade-off is to occupy as little bandwidth as possible while on the other hand getting the throughput needed for the application. The CC85xx radio communication system with its shaped 8-FSK modulation with a 5 Mbps RF capacity only requires a bandwidth of 3.8 MHz at any given time. This compares to other technologies:

- Bluetooth: 1.0 MHz (measured at 20 dBc)
- Bluetooth EDR: 1.5 MHz (measured at 20 dBc)
- 802.11b / g: 22 MHz (measured at 30 dBc)
- 802.11n: 20 / 40 MHz (measured at 30 dBc)

For the PurePath Wireless family, the 3.8 MHz occupied bandwidth results in a theoretical possibility to divide the 2.4 GHz band into 20 channels. Due to regulatory demands (ETSI, FCC and so forth), the channels closest to the band edge is often omitted to reduce the out-of-band emissions.

Tips and Tricks

For some applications that do not require the full audio bandwidth that the 5 Mbps 8-FSK signal is given, there is an option to run the radio in a 2 Mbps 2-FSK mode resulting in slightly less occupied bandwidth at 3.2 MHz with a greater sensitivity and selectivity performance.

For more information and limitations using this 2 Mbps mode, see the PurePath Wireless Configurator help system and 'Advanced Options' **(located where?)**.

3   Timeslot Architecture

PurePath Wireless (PPW) divides time into so-called timeslots, during which all nodes in the audio network operate on the same RF channel and each node transmits one packet. The duration of a timeslot is nominally 2.5 msec, but this parameter depends on the protocol master's configuration and can be between 1.5 and 5.75 msec.

To achieve robustness against interference, each successive timeslot is transmitted at a different RF channel following a deterministic sequence. For more details, see Section 4.

Figure 1. Anatomy of a Timeslot With 1 Master and 2 Slaves (not drawn to scale)

The start of a timeslot is defined as the point in time when the protocol master has just transmitted its packet synchronization sequence. The protocol master dictates the timing within each timeslot and informs the protocol slaves if and when they may transmit and when the next timeslot will start. The sequence of events during a timeslot is illustrated in Figure 1 and summarized below for a three-node audio network:

- Frequency synthesizer calibration is performed just prior to the start of the timeslot
- The protocol master performs an energy measurement in the RF channel to see whether it is already in use (see Section 5)
- If the energy is below a threshold, the protocol master transmits its packet. This marks the start of the timeslot. The protocol master packet contains:
  - Information about the audio network
  - Data side-channel datagram to a single protocol slave, if any
  - Audio slice acknowledgments for each audio channel the protocol master consumes
  - Audio slices for each active audio channel that the protocol master produces
- Following the protocol master packet is the slave join packet slot. This is reserved for protocol slaves that wish to join the audio network. If the audio network has the maximum number of supported slaves this slot is removed

- Then each of the protocol slaves transmits their packets at the time offset in the timeslot announced by the protocol master in its packet. Each protocol slave packet contains:
  - Remote control information
  - Data side-channel datagram to the protocol master, if any
  - Audio slice acknowledgments for each audio channel the protocol slave consumes
  - Audio slices for each active audio channel that the protocol slave produces

Did you know!

Due to the timeslot architecture, there will be power-pulling from the CC85xx radio being turned on/off at $1\,{}^{1}\!/_{2}$ *timeslot period*. At the nominal 2.5 msec timeslot period this results in a pulling-frequency of 400 Hz and if picked up by the audio path results in audible noise. Proper star-routing with as much separation between RF power and Audio power is needed and care needs to be considered for proper decoupling, length of sensitive traces, antenna positioning and so forth.

The RF active duty-cycle of a device will, as can be seen from the above, depend on configuration and timeslot as well as the number of slaves participating in the network. For devices that are audio producers, the amount of time spent in transmit vs. receive is higher unless the audio link is bi-directional.

The timeslot is always fixed length for any given configuration, thus, you should carefully set up the configuration to the minimum required for any applications (for example, if the application is point-to-point only, 1 slave should be able to connect to the master so that there is as little idle time within a timeslot as possible).

4 Adaptive Frequency Hopping and Frequency Planning

The purpose of using frequency hopping in a radio system is to provide diversity that allows data throughput to be maintained even if interfering radio systems or the physical environment (multipath fading) renders some RF channels unusable. In the 2.4 GHz ISM band, the sheer amount of radio systems and the severity and dynamic nature of indoor fading phenomena in typical operating environments require the use of this kind of diversity if a minimum data throughput is to be assured (as audio streaming requires).

Frequency hopping systems can either implement a fixed sequence of channel hops or adapt its hopping sequence dynamically to the changing environment it operates in. In order to maximize its own chances of delivering audio data in time and to co-exist amicably with other fixed-frequency or adaptive frequency-hopping systems, PurePath Wireless uses an advanced adaptive frequency hopping (AFH) scheme that adapts to changing conditions within tens of milliseconds.

Did you know!

The AFH implementation in PPW is not as specified in the European regulatory EN 300 328 v1.8.1 and, therefore, you cannot certify this as a frequency hopper nor as an adaptive wide-band system. To pass this ETSI regulatory, you need to declare it as other wide band modulation with a maximum output power less than 10 dBm e.i.r.p.

The PurePath Wireless RF Communication System divides the 2.4 GHz ISM band into 18 RF channels with 4 MHz bandwidth. The protocol master controls the adaptive frequency hopping scheme for the audio network, and maintains a table with an entry for each RF channel and an associated quality-of-service (QoS) estimate for each. Each time an RF channel is used the QoS estimate is updated based on what happens during the timeslot.

The frequency hopping algorithm separates the 18 RF channels into two sets:

- A set of 4 *active channels*
- A set of 14 *trial channels*

The active channel set contains the preferred RF channels that have proven that they provide sufficiently good quality-of-service. The trial channel set contains the remaining RF channels that are only evaluated occasionally in order to be able to maintain an accurate picture of their quality-of-service. If the QoS estimate of an RF channel in the active set goes beyond a minimum threshold this channel is swapped out with the RF channel in the trial channel set that has the best QoS estimate. Other factors play in when selecting a new RF channel to the active channel set, such as trying to maintain a certain minimum distance in frequency between the different active channels.
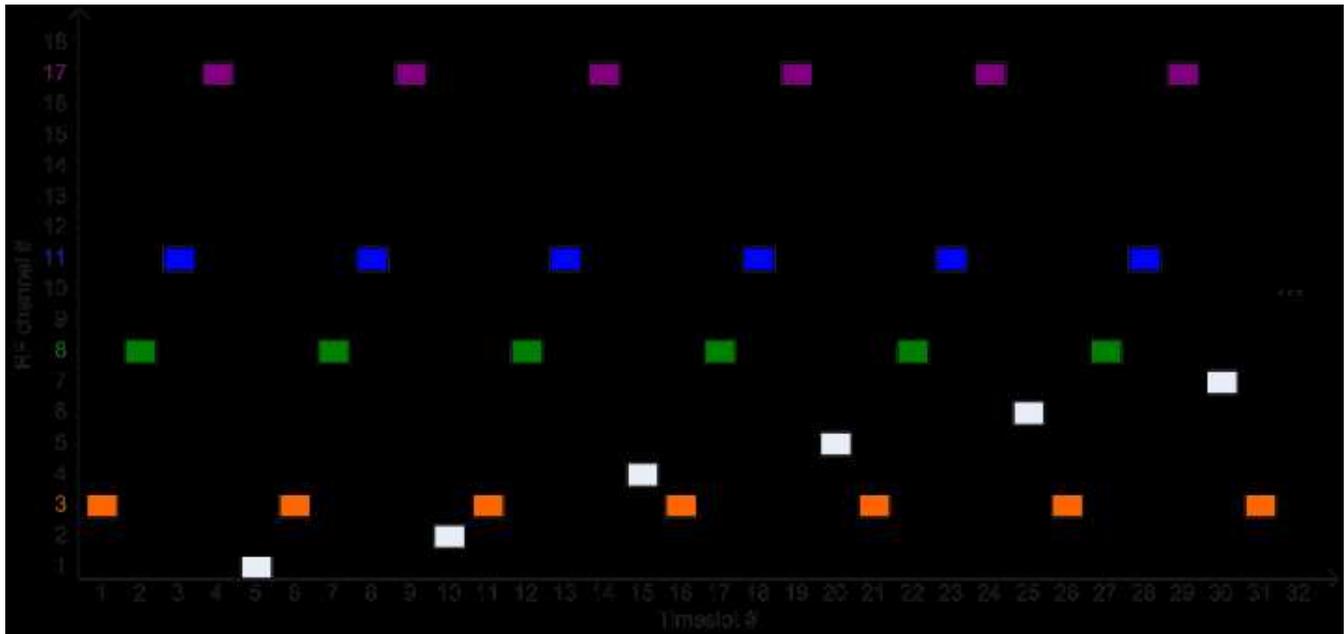
Figure 2. Example of AFH Hop Sequence

The frequency hopping algorithm, employs the following macrosequence, when no swaps between the active and trial channel sets occur, it goes through a sequence of 70 frequency hops over the course of which every RF channel has been used.

- This 70-hop macrosequence consists of 14 repetitions of:
  - 5-hop microsequence during which:
    - Each of the four active RF channels are used once
    - One of the trial RF channels is used once (cycling through all trial channels over the course of a macrosequence)

Table 3 illustrates this concept. This gives an average steady-state RF channel usage in an audio network of:

- Each of the four active channels are used 20% of the time
- Each trial channel is used 1.43% of the time

The 18 channels are set to the frequencies shown in Table 3.

Table 3. Channel Frequencies

Channel 1	2406 MHz
Channel 2	2410 MHz
Channel 3	2414 MHz
Channel 4	2418 MHz
Channel 5	2422 MHz
Channel 6	2426 MHz
Channel 7	2430 MHz
Channel 8	2434 MHz
Channel 9	2438 MHz
Channel 10	2442 MHz
Channel 11	2446 MHz
Channel 12	2450 MHz
Channel 13	2454 MHz
Channel 14	2458 MHz
Channel 15	2462 MHz
Channel 16	2466 MHz
Channel 17	2470 MHz
Channel 18	2474 MHz

Four active channels are selected randomly at start-up seeded by a unique 32-bit device address, which is stored in the hardware by Texas Instruments during chip production.

4.1 Frequency Planning

At configuration time, the available channels can be limited in the configurator tool. This is very useful if the environment is static in such a way that frequency planning is beneficial. This can either be multiple known PurePath Wireless networks in close proximity or a nearby WiFI is operating at a known channel.

Figure 3. Available Channels Limited to Channel 1 Through 9

In host-controlled mode, this can be dynamically altered run-time with the *NWM_SET_RF_CH_MASK EHIF* command [2], this is extremely powerful where the system or host MCU knows something about the RF environment. Most typical use-case is where the system also contains a WiFi device and the host MCU knows the channel this is operating at and can set up PPW with no overlapping channels.

In the case the full channel set of 18 channels is further limited using frequency planning, the scheme with four active channels and a set of trial channels remains the same. The minimum number of channels that can be selected is 6 resulting in 4 active channels and two trial channels.

Tips and Tricks

When using CC85x1 USB applications, the RF channels can be controlled using a SET_MEM command as defined in the USB Audio Class with the following parameters:

- wValue = 0x0000
- wIndex = 0x0000
- wLength = 0x0004

And the following four data bytes:

Figure 4. Byte 0

7	6	5	4	3	2	1	0
CH 7	CH 6	CH 5	CH 4	CH 3	CH 2	CH 1	Reserved

Figure 5. Byte 1

7	6	5	4	3	2	1	0
CH 15 Enable	CH 14 Enable	CH 13 Enable	CH 12 Enable	CH 11 Enable	CH 10 Enable	CH 9 Enable	CH 8 Enable

Figure 6. Byte 2

7	6	5	4	3	2	1	0
Reserved	Reserved	Reserved	Reserved	Reserved	CH 18 Enable	CH 17 Enable	CH 16 Enable

Figure 7. Byte 3

7	6	5	4	3	2	1	0
Reserved	Reserved	Reserved	Reserved	Reserved	Reserved	Reserved	Reserved

If no channels are selected, RF will shut down until it has a valid channel mask of minimum 6 channels.

5   Active Channel Selection / Listen-Before-Talk

In addition to AFH, listen-before-talk (LBT) is used by the master at the start of every timeslot to determine the energy in the current channel and these measurements are compared against a threshold and are used to detect a "bad" channel. In addition, at the end of every timeslot one will detect if one or more slave packets are missing.

In LBT, the energy level is measured and compared against a threshold which at power-up is set to be -65 dBm. Based on the result the device will:

- If LBT fails, the master will not transmit in the current timeslot. Since the PurePath Wireless has a fixed latency, the protocol will ensure that the master always sends its packet in the next two timeslots after a failing one. In these next two timeslots, the energy in the channels is still measured.
- Two failing LBTs in a row for a given channel will mark the channel as "bad" / occupied.
- Three failing LBTs during the last five timeslots at a given channel will mark the channel as "bad" / occupied.

At the end of the timeslot the Master will also count to see if one or more slave packets are missing:

- If three timeslots in a row for a given channel has missing slave packets, the channel is marked as bad

These results are stored in a historical table to at all times give a complete picture of the performance of each channel and the energy level in the 2.4 GHz spectrum.

If any of the active channels are marked as bad they are replaced by the best channel that is furthest away from the remaining three good channels.

Tips and Tricks

In some applications, the PurePath Wireless network should have priority over other 2.4 GHz devices and the LBT threshold can be disabled or altered to facilitate this.

To change the LBT:

1. Open the master's device configuration file (.ppwcfg) in a text editor (.xml syntax highlighting helps).
2. Search for "Normal LBT threshold" and find the following section:

```
<name>Normal LBT threshold </name>
<value> –65</value>
```

Copyright © 2015, Texas Instruments Incorporated

3. Change the value to the desirable setting. A threshold of 20 dBm (remember to remove the minus sign) is in practice the same as disabling the LBT altogether.

4. Save the file and re-open the configurator (which will load the new and modified .ppwcfg file).

5. Go to the flash programming panel and flash the master again for the new settings to take effect.

6 Co-Existence With Other PurePath Wireless Network

In an ideal world where all networks have perfect clocks, similar sized timeslots and are perfectly time-synchronized to each other (synchronized to not send at the same channel at the same time), the theoretical limit of PurePath Wireless networks that can co-exist in close proximity are limited by the number of channels in the frequency hopping algorithm namely 18 (unless limited further using frequency planning). Such a perfect world does not exist though and other interference and noise as well as drifting clocks will reduce this number significantly.

Due to clock drift, different energy measurements during the masters listen-before-talk and various level of interference this number will go down and vary over time. The length of a timeslot will also influence this to some degree.

The AFH algorithms with its four active channels and one trial channel tells a more realistic picture of what can be achieved. With 18 channels total and five channels being used per PurePath Wireless network the number is somewhere between 3-4 networks.

Other aspects influencing this are the number of slaves and audio channels in the network as well as the streaming format for the audio. Increasing the number of slaves and number of audio channels makes co-existence more challenging while using SLAC compression instead of PCM16 makes co-existence easier.

With this many parameters influencing the performance, the only way to say something about this is to test in a realistic user scenario in realistic environment for a given product.

Table 4 shows through some practical testing that the realistic number of networks that can co-exists is in most cases less than 4 as the mean-time-between-dropout [MTBD] will significantly decrease with more networks than this.

Table 4. Mean-Time-Between-Dropouts for PurePath Wireless With 1 Master and 1 Slave

MTBD [hour]	Number of PurePath Wireless Networks	Distance Between Networks [cm]
20	3	40
0,69	4	40

7 Co-Existence With Bluetooth/Bluetooth EDR

Bluetooth is also a relatively narrow band solution that has frequency hopping (EDR uses Adaptive Frequency Hopping) so co-existence between PurePath Wireless networks and Bluetooth networks depends on the probability that the hopping algorithms align themselves in frequency and time over a period of time.

As can be seen by Table 5, the two technologies co-exist well with each other in a controlled environment.

Table 5. Bluetooth EDR Throughput With PurePath Wireless (with 1 master and 4 slaves)

Bluetooth Throughput [Mbit/s]	MTBD [hour]	Number of PurePath Wireless Networks	Distance to Interference [cm]
1,3	no dropouts	1	40
1,3	no dropouts	1	∞

Similar or better performance is expected when looking at other "narrow-band" proprietary technologies that have frequency hopping implemented.

8   Co-Existence With WLAN (802.11) and Static Interferers

WLAN is a wide-band interferer with potentially high data rates and duty-cycle. Various 802.11 protocols exists with the 802.11n being the among the latest one. To secure a robust audio experience, care has to be taken to avoid channels used by close-by WLAN networks.

The adaptive frequency hopping as implemented by the PurePath Wireless is designed to co-exist well with relatively static interferers like WLAN. The active channel selection mentioned in Section 4 will detect and avoid WLAN channels so that the active channels used are outside the channels occupied by WLAN itself.

It is important to note that WLAN itself have listen-before-talk implemented and besides certain flavors of 802.11n does not transmit its data back-to-back. Due to this it's perfectly fine for a PurePath Wireless timeslot to start in-between WLAN transmissions as the WLAN will hold back its transmission until the PurePath Wireless timeslot is over at the cost of only a minor reduction in throughput for WLAN.

Another aspect to consider is that WLAN realistically rarely runs at maximum throughput and that the channels rarely are as wide as the specified 22 MHz (the occupied bandwidth of these are often ~16 MHz wide).
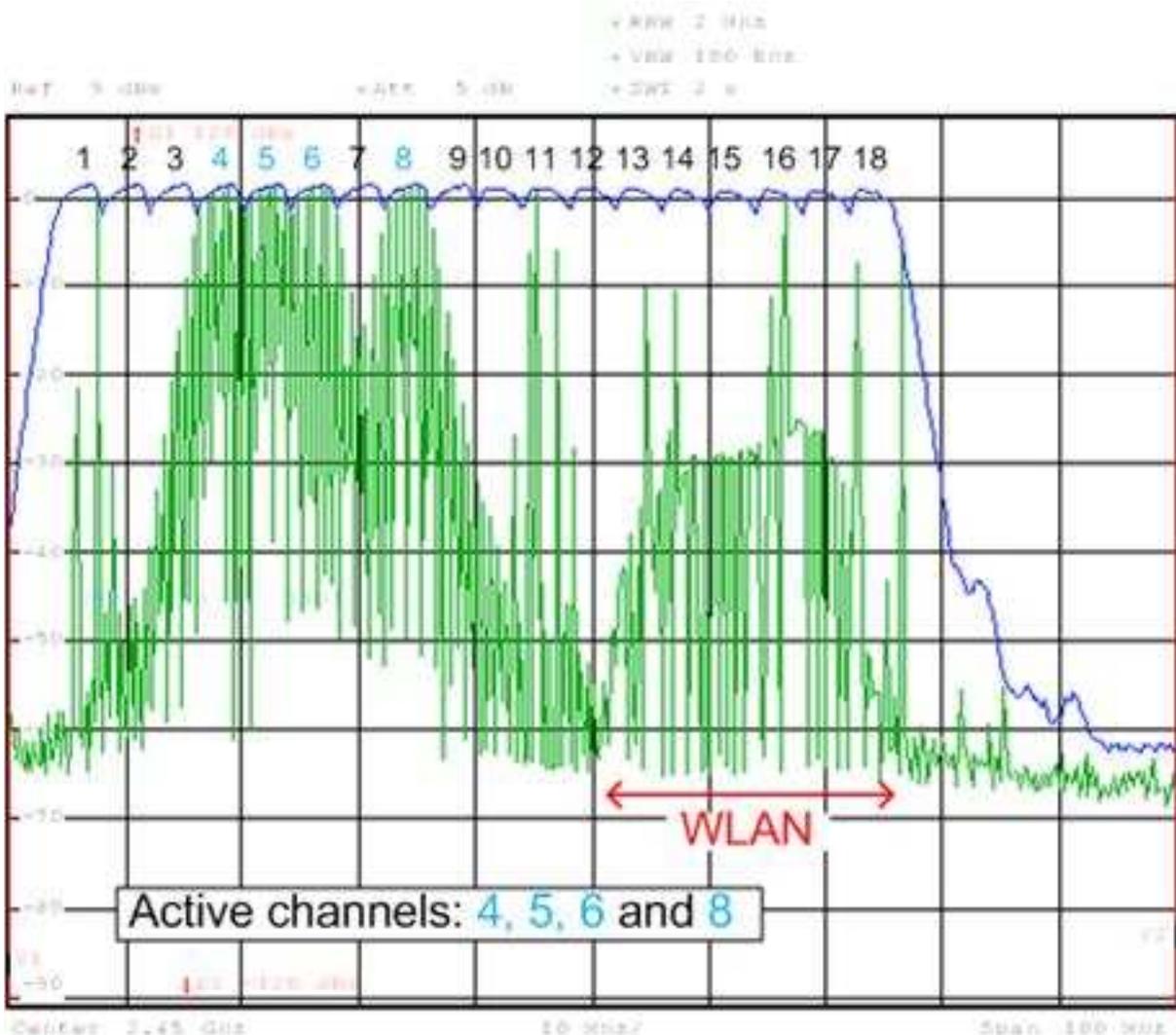
Figure 8. Adaptive Frequency Hopping in Practice

802.11 defines 13 overlapping channels in the 2.4 GHz band but due to the 22 MHz wide channels, channels 1, 6 and 11 are the most common ones to use. These channels correspond to the following center frequencies 2412 MHz, 2437 MHz and 2462 MHz accordingly. 802.11 also specify that the signal has to be attenuated by at least 30 dB from its peak energy at ± 11 MHz from the center frequency. For PurePath Wireless networks, this means that in practice the gap between these channels are bigger.

Distance, Router to laptop	Distance, M to laptop	Hardware used	Wi-Fi Throughput [Mbps]		# mute events	muted audio [%]	error concealment [%]
			no PPW	PPW			
10m	10cm	M: CC85XX+CC2590EM	50,0	47,7	0	0,00	0,00
		S: CC85XXEM	48,9	49,3	0	0,00	0,00
			51,3	50,2	0	0,00	0,00

Figure 9. 802.11G Throughput PurePath Wireless Master 10cm From Laptop (laptop 10 meters from router)

The adaptive frequency hopping is also a good mechanism to secure a robust audio performance in presence of other interferers like microwave ovens. Different models and types of ovens behave differently in radiated power, frequency of radiation and if the oven is of the non-inverter or inverter type (in effect saying something about the duty-cycle of the radiation).

9 Improving Link Performance, Co-Existence and Robustness

There are multiple factors influencing the overall robustness and co-existence performance of a PurePath Wireless network. Depending on the application, there can be trade-offs made to improve this.

The following is a list of some of the configuration parameters that can be adjusted and descriptions of the associated drawbacks. It is up to you to consider which, if any, can be applied to your product.

9.1 Number of Slaves in the Network

Always keep the number of slaves to the lowest possible for any given application. In a multi-cast protocol with fixed timeslot lengths as implemented in PurePath Wireless, time is set aside for each possible slave for potential re-transmissions. If only 1 slave is needed, robustness will be worse if one enables more slaves to join the network master.

9.2 Audio Sample Rate

Reducing the audio sample rate increases the total re-transmission capacity. However, if the audio latency setting (in number of samples) also is reduced by the same factor to maintain latency "in time", the maximum number of re-transmission attempts per audio slice is reduced.

9.3 Latency

Latency is a direct trade-off vs. robustness. One is directly trading re-transmission capacity / attempts for the lower latency. At the lowest setting, this goes towards zero re-transmission attempts and as a consequence the experienced range and robustness goes significantly down.

9.4 Number of Audio Channels

The number of audio channels supported will influence the robustness. The more channels supported, the more bandwidth is needed over the air and the less robust the link will be.

9.5 Direction of Audio

Typically audio sent from a master to a slave is better when having uni-directional audio. As an example, a microphone application could benefit from having the microphone as the master and the receiver as the slave (opposite of what one would "naturally" think). The directions are equally robust for bi-directional links.

9.6 Streaming Formats

The various streaming formats require different over-the-air bandwidth. The less bandwidth required, the more robust the link will be.

Table 6. Various Streaming Formats and Associated Bandwidth Requirements

Format	Description	Extra Delay	Data Rate @ 48 kHz
PCM16	Standard 16-bit Lossless 2's complement PCM samples	None	768 kbps
PCMLF	PCM16 decimated-by-four at producer and interpolated-by-four at consumer (for low frequency audio channels)	37 samples	192 kbps
SLAC	16-bit or 24-bit compressed full-fidelity audio stream using proprietary SLAC codec	None	232 kbps (average)
PCME24	24-bit comanded PCM samples, offering 15-bit signal-to-noises ration and 24-bit dynamic range	None	768 kbps

Note that PCM formats can be interpolated if there is a missing audio slice and that, in harsh environments, the PCM formats will give priority to even audio samples.

SLAC format do not have this possibility and a mute-event will occur as soon as there is a missing audio slice.

9.7 Output Power

Increasing the target output power and using the CC2590 range extender improves the range at the cost of power consumption and to some extent co-existence vs. equipment with less good selectivity and blocking performance. Also note that with very high output power, the link between two CC85xx devices can be saturated at very short distances.

9.8 Audio Fade-Out

By default, audio is faded in and out of mute events for a smooth and pleasant listening experience. This requires some buffer-capacity and disabling this under 'advanced options' in the configurator will slightly improve the re-transmission capability (equal to increasing the latency with one step).

9.9 Date Side-Channel

Enabling the use of the data-side channel in host controlled mode will set aside a good portion of the available bandwidth within a timeslot to data. This will significantly reduce the overall capacity for audio re-transmissions in the timeslot. Optimal setting is 'Autonomous' or 'Host control without data side-channnel'.

9.10 RF Data-Rate

In general the 2 Mbit setting is less vulnerable to RF multi-paths and improves sensitivity as well as selectivity performance. This will have a positive effect on range, but this mode is restricted to a very limited set of applications and use-cases. For more information, see configurator help system.

9.11 Antenna Diversity

If implemented on slaves, it will combat multi-path effects and improve the in-range performance. The cost is the actual cost of the external antenna switch and the attenuation introduced in the RF path by this switch. It is recommended implementing this for all applications that have the board space available.

10 References

1. *2.4 GHz RF SoC for Wireless Digital Audio Streaming CC8520, CC8521, CC8530 & CC8531 - PurePath™ Wireless Data Sheet* (SWRS091)
2. *CC85XX – RF SOC for Wireless Audio Streaming User's Guide* (SWRU250)

IMPORTANT NOTICE

Products		Applications	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		