Application Report
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AN124 – Autonomous High Density Streaming Protocol

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ABSTRACT

This application report describes a new high density streaming protocol that was developed for the new series of ultra-low cost 2.4 GHz System-on-Chip (SoC) devices called CC2543/4/5. With this protocol, it is possible to setup a large number of point-to-point links in the same physical environment. Examples of applications where such a protocol could be used are patient monitoring systems, remote controls for various type radio controlled cars and airplanes or other remote controlled toys, and even various educational tools.

The spreadsheets discussed in this application report can be downloaded from the following URL: http://www.ti.com/lit/zip/swra433.

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1 Introduction

A typical approach of multiple user access to a shared medium is “Listen Before Talk”. This type of system works well up to approximately 50% load and then collisions start to happen so frequently that the overall level of service is degraded.

To avoid this, a simple time-based approach is devised, where each user gets a time slot and a certain frequency where it will operate. These types of systems are called Time Division Multiple Access (TDMA).

Typical examples of TDMA systems are GSM-based cellular networks and DECT home cordless phones. They each setup TDMA schedules where each user is allocated a time slot and this is where the user will operate.

The great advantage of this type of system is that each user gets a “clean” piece of spectrum and time; therefore, the quality of service is assured all the way up to the maximum capacity of the overall system.

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Table 1. Abbreviations

SoC	System-on-Chip
DSSS	Direct Sequence Spread Spectrum
EIRP	Equivalent Isotropically Radiated Power
EM	Evaluation Module
EVM	Error Vector Magnitude
ISM	Industrial, Scientific, Medical
FCC	Federal Communications Commission
FHSS	Frequency Hopping Spread Spectrum
LNA	Low Noise Amplifier
PA	Power Amplifier
PCB	Printed Circuit Board
PSD	Power Spectral Density
RF	Radio Frequency
RSSI	Receive Signal Strength Indicator
RX	Receive, Receive Mode
TX	Transmit, Transmit Mode
TDMA	Time Division Multiple Access

2 System Requirements

A system is needed that allows for many users to be in the same physical space while ensuring that each user gets a good reliable bidirectional link of data at a certain speed and interval.

The actual amount of data needed in both directions and the interval at which each frame is being transmitted are dependent on top level system requirements for the system integrator, and the wireless protocol described here can adapt to these system integrator needs within limits.

This example is designed for:

- 500 or more pairs running at the same time
- 50 ms packet repetition interval
- 32 bytes forward payload each time
- 32 bytes reverse payload each time

To implement this system, considerable thought has to be put into how to allocate the available frequency spectrum and time between in excess of 500 simultaneous users.

3 System Resource Allocation Plan

The overall goal with the system resource allocation plan is to devise a scheme in which can accommodate as many users in the same environment at the same time as possible. The issue that needs to be resolved is how to assure a certain level of performance for all users.

A typical approach of multiple user access to a shared medium is “Listen-Before-Talk”. This type of scheme is widely used in TCPIP networks and also low power wireless networks like Zigbee. These types of systems work well up to approximately 50% load and then collisions start to happen so frequently that the overall system degrades, see http://nms.lcs.mit.edu/papers/hbhfc-sensys04.pdf.

To avoid this, a simple time-based approach is considered, where each user gets a time slot and a certain frequency where it will operate. A system utilizing this scheme implements a scheduled system that looks like has a User Allocation Plan as shown in Table 2.

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Table 2. User Allocation Plan

T/F	2402	2403	2404	2405	2406	2407	2408	..	2482
0	UID1	UID5							
1	UID2								
2	UID3								
3									
4	UID4								
5									
6									
7									

In Table 2, the allocated time slot is on the vertical axis and the allocated frequency of operation is on the horizontal axis. The number of frequency channels and time slots in a given system depend on the band of operation and timing needs of the top level system.

Typical examples of TDMA systems are GSM-based cellular networks and DECT home cordless phones. They each setup TDMA schedule where each user gets an allocated time slot and this is where the user will operate. GSM uses a 576 µs time slot interval and DECT uses a slightly shorter slot time of 417 µs. In order to make the protocol implementation simple and the requirements on the used crystals slightly lower, it is chosen to go with slower slot times as compared with what is used in GSM and DECT and also use both forward and reverse links within the same “on time”.

In the tested configuration, the frame time is 25 ms and the slot time is 3.125 ms, or 8 time slots per frame. Each time slot includes both forward and reverse data packets.

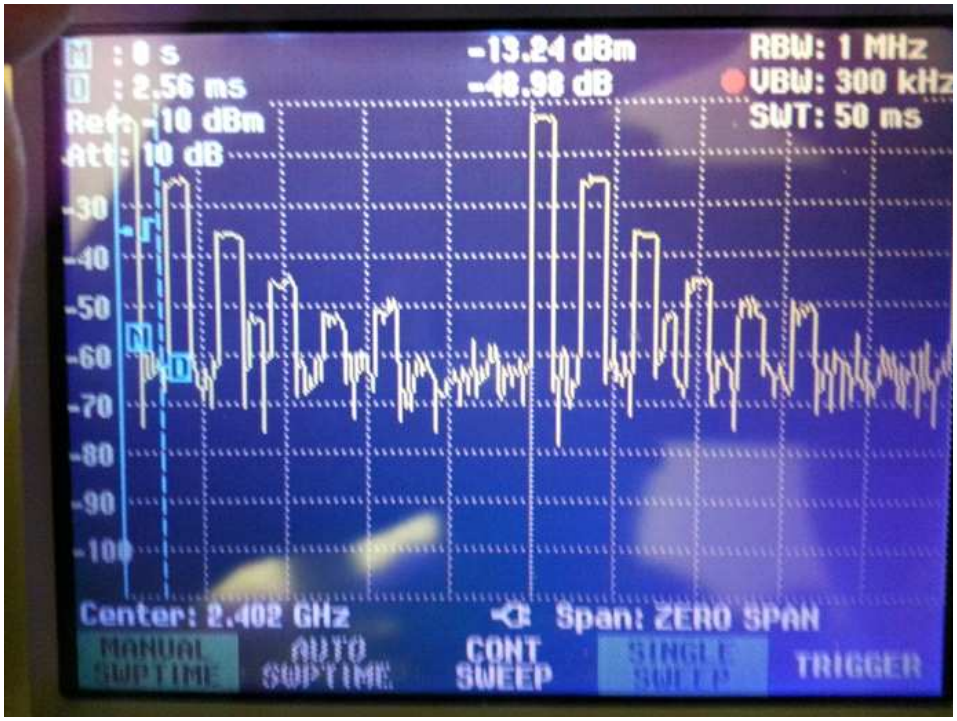

Figure 1. Six Forward Packets can be Seen and One Reverse Packet (slightly shorter)

The remaining five reverse links were too weak to be picked up by the spectrum analyzer.

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4 Radio Payload Structure

To make the system robust and flexible, some housekeeping overhead is required for the protocol to work as intended. The dark blue fields are required by the radio hardware to function correctly, the lighter blue colors represent field used by the protocol to establish and maintain a connection between a given transmitter and receiver.

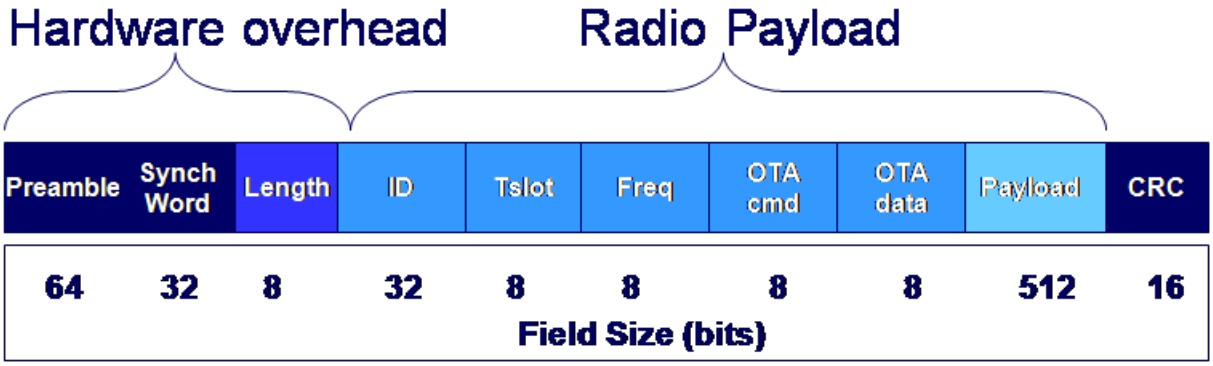

Figure 2. Complete Radio Data Structure, Hardware Overhead, System Overhead and Payload Fields

The following is a description of each field in the data structure.

- **The Preamble**: The preamble is required for the receiver to be able to setup the gain settings of the receiver correctly and to achieve synchronization with the bit timing of the transmitter.
- **The Sync Word**: The sync word is used to figure out when the exact start of a radio payload begins and when it ends. The sync word can be used to separate two systems from each other, because the receiver hardware is looking for a specific sync word and will wait until it finds it. In this system this feature has been utilized to separate all Forward links from all reverse links.
- **The Length**: The length byte is required by the receiver to figure out how many bytes to expect behind the Sync word.
- **The ID**: The ID is a unique identifier transmitted with every message. This enables the receiver of the message to ensure that the message being processed is actually intended for the receiver and not someone else.
- **The Time Slot**: The time slot of operation is used to indicate to any other system that is trying to join the network that this particular packet was transmitted in time slot X. This enables the new system to figure out which times slots are occupied and which ones are empty.
- **Frequency**: Simply transmits the frequency of operation. This is used for cases where it is possible the a receiver at an adjacent channel accidentally gets a message not intended for it. **(not sure what is being said here)**
- **OTA Command**: This data field implements the command field of a simple over-the-air command protocol between the transmitter and the receiver in the system. This enables features, like the transmitter, to move time slots and frequency of operation during run-time.
- **OTA Data Field**: This field is the data that corresponds to the OTA command described above.
- **Payload**: Is the customer payload field that can be any size up to the limit of the physical size of the transmit and receive buffers. On the CC2544, the buffers are 128 bytes, given the radio overhead. This gives a maximum payload length of 116 bytes.
- **CRC**: A two byte CRC is automatically generated and checked by the hardware to ensure correct data inside the packet.

This means that the actual data length of a packet going out over the radio interface is substantially longer than the actual payload. It important to understand the exact duration of the radio on time to establish a solid TDMA structure.

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4.1 Timing Analysis of a TDMA Time Slot

To ensure that the TDMA structure will work, a timing scheme needs to be devised that allows for enough time for the payload in both directions and any hardware related overhead (read TX/RX turnaround time) that needs to be added.

4.1.1 Choosing the System Data Rate

The particular radio used in this example is capable of various data rate; choosing the data rate becomes a compromise between the number of channels in the system and the range of the each node. Here is a list of the available data rates:

- 250 kbps 80 channels
- 500 kbps 80 channels
- 1000 kbps 40 channels
- 2000 kbps 40 channels

For this system, 500 kbps and 80 channels were chosen.

4.1.2 Actual Payload Length of for a TX Payload

The actual payload length of a Forward frame is a combination of hardware related overhead, protocol overhead and check sum needs.

- Radio hardware overhead :12 bytes
- Protocol overhead : 9 bytes
- Payload : 32 bytes
- CRC : 2 bytes

This gives a grand total of 55 bytes of data and at 500 kbps this takes exactly.

- 55 * 8 / 500 = 0.90 ms

4.1.3 Actual Payload Length of for a RX Payload

The actual payload length of a Reverse frame is a combination of hardware related overhead, protocol overhead and check sum needs.

- Radio hardware overhead :12 bytes
- Protocol overhead : 9 bytes
- Payload : 32 bytes
- CRC : 2 bytes

This gives a grand total of 47 bytes of data and at 500 kbps this takes exactly.

- 55 * 8 / 500 = 0.90 ms

The next item is the turnaround time between TX and RX. It was measured on the existing implementation that it takes approximately 400 µs to turn around from TX to RX. Most of this time is spent by the 8051 microcontroller to figure out if the ID was correct and copied payload from various buffers to other buffers. Over all, this could be optimized to get into the sub 300 µs range, but it was decided it was not in the best interest of the project to spend time on this topic.

Therefore, the time slot is allocated as follows:

- TX packet : 0.90 ms
- TX/RX turn : 0.40 ms
- RX packet : 0.90 ms

This gives a total of 2.20 ms, where earlier 16 times slots were selected in a 50 ms frame for a total time slot duration of 3.125 ms. So, there is approximately 900 µs “slop in the system”.

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The developed spreadsheet can be used to figure out if a certain set of TDMA parameters will work. It is very simple to use, just type in values for the five values highlighted in yellow. The values include the wanted frames rate, number of time slots, data rate, forward and reverse payload. The spreadsheet will estimate all the required system overheads, then calculate whether the system will fit within the time allotted or not.

Table 3. TDMA Timing Analysis Spreadsheet (included in software package on the web)

Configuration	Frame Rate	50	ms
	Timeslots	16	
	Data rate	500	kbps
	Forward data	32	bytes
	Reverse data	32	bytes
System	Hardware overhead	12	bytes
Calculations	System overhead	12	bytes
	TX/RX turnaround	0.4	ms
	TX/TX slop needed	0.2	ms
	Timeslot time	3.125	ms
	bits/timeslot	1562.5	bits
	Total Forward bytes	56	bytes
	Total Reverse bytes	56	bytes
	Forward (in bits)	448	bits
	Reverse (in bits)	448	bits
	Turn around (in bits)	200	bits
	Slop time (in bits)	100	bits
Overview	Total available	1562.5	bits
	Total needed	1196	bits
	Total Remaining	366.5	bits
Final Status	Status	OK	

The spreadsheet shown in Table 3 will automatically evaluate a set of TDMA parameters to see if they can run.

There is one more hardware limitation that is not taken into account and that is the resolution and depth of the timer that is running the TDMA structure. TimerA is in use in the CC2544, which is a 40-bit timer and results in incredible flexibility. In the particular configuration it is being used in, this application will provide the possibility of running the controlling of the system with 0.1 ms resolution and with up to 1677721 millisecond maximum frame length (or 27 minutes).

5 Autonomous TDMA Protocol

The innovative feature of this implementation is that is does not require a system master or some kind of system controller. Each system is responsible for its own timing requirements and also responsible for keeping timing to its neighbor system. This is achieve by “sniffing” other time slots for activity.

For an autonomous TDMA protocol to work, a number of different issues have to be considered and solutions needed to be found. Consider the following normal use cases:

- How is timing achieved
- A new transmitter needs to join the network
- A receiver needs to find its paired transmitter
- A system leaves the network

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5.1 How is Timing Achieved

In any TDMA-based system, the timing of each of the nodes to all other nodes is critical. In order to create a system that is autonomous, but has tight timing, something has to be done.

The concept of reference nodes is introduced, for each frequency, the system that operates in time slot 0 becomes the reference node for the rest of the systems operating in that channel. This system works great as long as the node in time slot 0 does not leave the environment. But to make the system truly autonomous there can be no requirement that time slots 0 remains in play at all times. Therefore, a secondary mechanism for always making sure that someone is operating in time slot 0 needs to be implemented.

We call this system “Automatic defragmentation”, in order to make sure that time slot 0 is always full; all nodes will run a scan for empty slots and then move into the empty slots as needed. The details of this algorithm are explained further in Section 5.2.

5.2 A New System Needs to Join the Network

A pair needs to joins the network, the pair consists of one Forward link device (transmitter) and one Reverse link device (Receiver). The transmitter is powered up and will need to initiate a search of all valid frequencies and all time slots.

The first thing that has to happen is that the new device needs to find the beginning of a Forward packet, such that it can achieve time slot synchronization. When this has been achieved, it continues to search all available time slots and tabulate which ones are available and which ones are occupied. If a certain frequency is fully occupied, it will search the next frequency in the list until all frequencies have been exhausted. (At this time it will not be able to join).

If the transmitter finds an available time slot, it will align itself in the time domain to the TDMA frame time using the information found in the device transmitting in Time Slot 0. The new device wanting to join can identify the Time Slot 0 device by parsing the content inside the protocol overhead information, as described in Section 4. After the timing has been achieved, the new device will start transmitting beacons on that time slot and frequency.

5.3 A New Receiver Needs to Join the Network

This task is somewhat simpler in that the receiver will scan all frequencies and all time slots continuously until it finds a beacon package with the corresponding unique ID in the payload. It then uses the slot number identifier in the package to setup its clock system to the frame structure and starts transmitting reverse payload packets just behind the forward link packet.

It checks for valid unique ID for every packet received; this ensures the receiver is always getting the correct data and not accidentally jumped onto someone else transmit slot.

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5.4 A System Leaves the Network

This is very simple because the system that leaves the network stops transmitting packets. In most systems, there are physical on and off switches; therefore, a system needs to be implemented that can accept the systems pairs abrupt disappearance.

For the remaining systems, this poses a pretty important and complicated question. What can be done with empty time slots and why is this even important to consider? Consider Table 4 where it can be seen that “UID4” has an empty time slot just before itself.

Table 4. Concept of Autonomous TDMA Structure

T/F	2402	2403	2404	2405	2406	2407	2408	..	2482
0	UID1	UID5							
1	UID2								
2	UID3								
3									
4	UID4								
5									
6									
7									

6 Automatic Defragmenting

Automatic defragmentation becomes required when considering the standard use cases for autonomous TDMA system where it allowed that system can leave and join the network arbitrarily.

As explained earlier time slot 0 becomes the reference node for the remaining systems in the same channel. All other systems are required to keep precise delay between the start time of time slot 0 and start time of time slot X, where “X” is the number of the slot that the particular system is operating in.

To implement this concept the radio will always wake up at time slot 0 so it can be aligned with time slot 0. This then puts a requirement on the system that time slot 0 is always occupied.

To achieve this, each of the nodes are also responsible for making sure that the time slot just in front of itself is occupied. see Table 4.

In this case our system is UID4:

- UID4 wakes up at T0 and aligns itself with the Forward burst in that time slot. It does not need to know who is in the time slot just that it is in time slot 0
- UID4 also wakes up in T3, to make sure that there is someone in there. In the setup of the system, one can define how many times UID4 will accept an empty slot before moving in there. The default configuration is that it will wait for 100 times a frame length or 2.5 seconds.
- UID4 lastly wakes up in its own time slot and performs normal data operation.

In the special case of UID1 being in time slot 0 it will actually use 1 burst time every 128 burst to keep itself aligned with other time slot 0 in other frequency channels.

There is not defragmentation in frequency as this was not needed for this system to remain stable.

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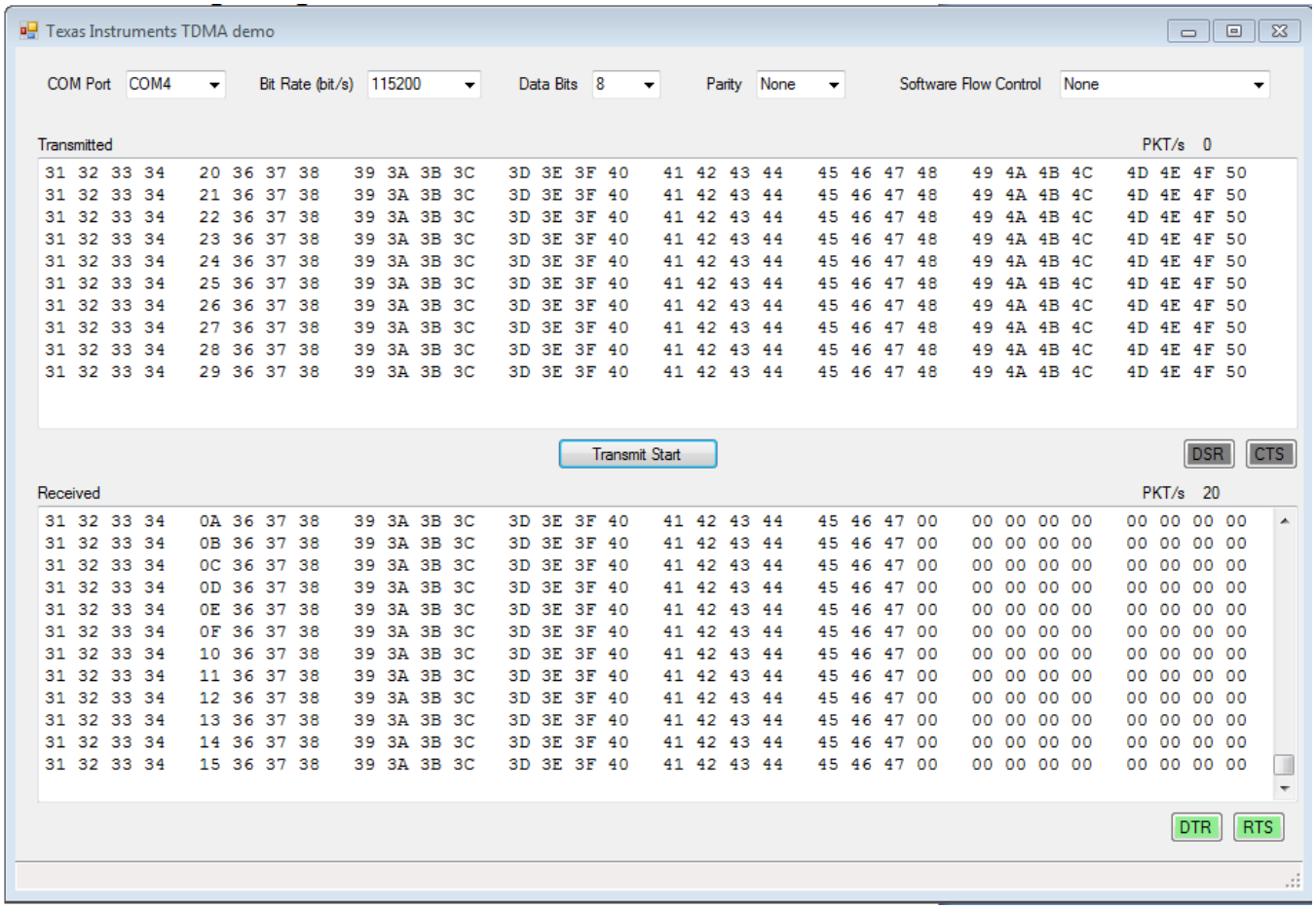
7 PC-Based Software for Demonstrating the System

A simple PC application has been created to demonstrate the data links successfully working. To really exercise this protocol many nodes needs to be created and many PC's needs to be sending data simultaneously.



This is a very simple demo. Simply start up the program on a standard Windows PC one of the available COM port. Nothing will get printed in the Recieved box until a second unit is transmitting data to it. But transmitting data is possible even before the pairs have been linked.

The standard settings used in this demo are 115200, 8N1 and no flow control.

8 References

Mitigating Congestion in Wireless Sensor Networks: http://nms.lcs.mit.edu/papers/hbhfc-sensys04.pdf

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