Implementing 'Diversity' Using Low Power Radios

By Mike Burns and Tim Starr

Keywords

- Antenna Diversity
- Amplitude Diversity
- Frequency Diversity
- CC1100
- CC1101

- CC1110
- CC1111
- CC1100E
- CC430

1 Introduction

In this context, the term diversity is used to describe various strategies for choosing the best of two (or more) paths (or channels) for transmitting and/or receiving an RF signal in order to maximize the likelihood that a packet will be correctly received. This note describes techniques for implementing 'Single Radio Amplitude Based Antenna Diversity' (two antennas, one radio), 'Dual Radio Antenna Diversity' (two antennas, each connected to a radio), and 'Single Radio Frequency

Diversity' (one antenna, one radio, two frequencies). All of these techniques can be implemented using one or two low power radio(s), a low power microcontroller, and, if required, an external RF switch.

This design note uses CC1101 as an example, but it is also applicable for CC1100, CC1100E, CC1110, CC1111, and CC430.



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2 Abbreviations

AGC	Automatic Gain Control
CRC	Cyclic Redundancy Check
dB	Decibel
dBm	Decibel (referenced to one milliWatt)
EVM	Evaluation Module
kbps	kilo bits per second
MHz	Megahertz
mW	milliWatt
PER	Packet Error Rate
RF	Radio Frequency
RSSI	Received Signal Strength Indication (usually in dB)
μs	Microseconds



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3 Multipath Effects

Multipath is a phenomenon which occurs when electromagnetic waves bounce off of surfaces and arrive either in phase (constructive) or out of phase (destructive interference). See Figure 1. This can be problem for stationary transmitters and receivers, but is nearly always an issue for moving radios, which will experience areas of good reception and bad reception as they move in an echoic environment. Since the earth is itself a reflector, most 'real world' environments are echoic.

Reflective surface Reflective surface Arriving 180 degrees out of phase From direct signal Re Ceiver Reflective surface Source: Wikipedia

Figure 1 - Multipath Effects

4 Single Radio Amplitude-Based Antenna Diversity

In this approach, a single radio is used to receive from 2 or more antennas. These antennas can be placed at right angles to one another to hedge against polarization effects for a given position, or they can be physically separated, such that as one antenna is experiencing destructive interference, the other is likely to be experiencing constructive interference. See Figure 2.

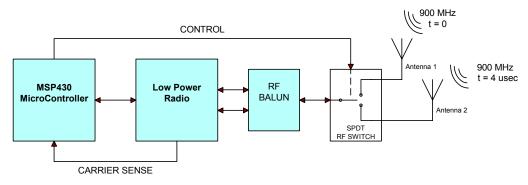


Figure 2 - Single Radio Amplitude-Based Antenna Diversity

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Selection of the antenna to be used for reception of a packet is based on the signal strength observed during the 'preamble' portion of a packet. During the preamble, the Received Signal Strength Indication (RSSI) value is measured using one of the two antennas. The measurement is then repeated using the other antenna. The antenna giving the larger RSSI value is then used for reception of the remainder of the packet.

The difficult part of this algorithm is deciding which antenna to select first (before carrier is sensed). Several possibilities exist, including:

- 1. Always use the same antenna
- Use the antenna that had the higher signal level (RSSI) during the last received packet
- 3. Alternate between the two antennas until carrier is sensed

Experimentally, approach 2 gives the best results, especially when the signal levels approach the lower limit of detection. Approach 3 is not practical when using a CC1101 transceiver, due to the length of time required for the signal strength value (RSSI) to stabilize.

In order to implement this algorithm, the preamble needs to be long enough so that the RSSI value has time to be read and evaluated by the microcontroller. The time required is dependent upon several variables, including data rate, receiver bandwidth, and the AGC time constants. Refer to Application Note DN505 for details [2].

5 Single Radio Frequency Diversity

In this approach, the packet is transmitted at one frequency and then repeated at a different frequency immediately afterwards. The idea is that if destructive interference is occurring for the first frequency, constructive interference is possible (or even likely) at the other. Refer to Figure 3.

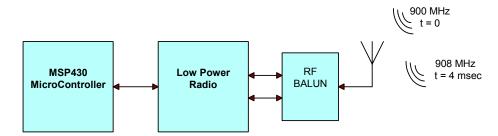


Figure 3 - Single Radio Frequency Diversity

Frequency diversity is actually a degenerate form of frequency hopping, or, when done at a slow rate, frequency agility. More than 2 frequencies can be used, and the criteria for hopping can differ from system to system. This technique has the added advantage of being less susceptible to interference from other transmitters, assuming that the interference occurs on only one of the frequencies in use.

6 Dual Radio Two Antenna Diversity

In this approach, each antenna is connected to a radio. This allows each path to be evaluated independently and at the same time. This removes the need to retransmit the packet, or to extend the preamble, as was the case when a single radio is shared between the antennas. It also avoids the need for an RF switch, but at the cost of an additional radio. Refer to Figure 4.



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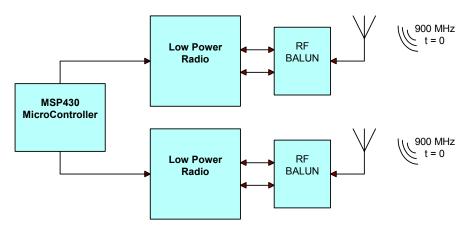


Figure 4 - Dual Radio Two Antenna Diversity

7 Experimental Results

Experiments were performed to analyze the effectiveness of the three approaches to antenna diversity described above. In the experiment, the transmitter was placed in the main hallway of the Texas Instruments office located in Rochester, Minnesota. The receiver was placed approximately 150 feet away, behind a 6 foot high cubicle wall. There are multiple 'dry wall' style walls, metal studs, metal doors, cubicle walls, etc, in the path between the transmitter and receiver.

The receiver is mounted to the moving platform of a 60 inch linear actuator. The speed of the actuator is set such that the receiver will move 60 inches in the time it takes to transmit 1000 data packets. In Dual Radio and Amplitude Based Antenna Diversity modes, 1000 packets are transmitted in 10 seconds, and the receiver is moved at a rate of 6 inches per second. In Frequency Diversity mode, 1000 packets are transmitted in 20 seconds, and the receiver is moved at a rate of 3 inches per second.



Figure 5 - 60 inch Linear Actuator with EVM

In the photo, the EVM is located at the 'zero' (leftmost) position.

7.1 Amplitude Based Antenna Diversity Mode

The following data was taken using a single radio and two antennas, at a frequency of 900 MHz. The antennas are oriented at an approximate 45 degree angle with respect to the EVM card, and 90 degrees with respect to each other. They are spaced 3.5 inches apart (approximately ½ wave length) at their bases.



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Figure 6 - Antenna Diversity EVM, Rev B. One Radio Amplitude Based Antenna Diversity

Mode

Test results are shown in Figure 7, below.

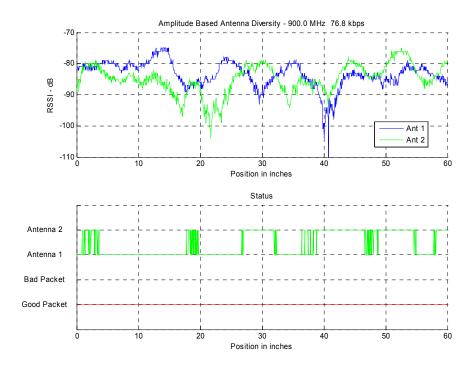


Figure 7 - Amplitude Based Antenna Diversity, 900 MHz, 76.8 kbps



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Packets Received	10	00
Packets Lost	()
Packets Received with No	1000	
Errors		
Packet Error Rate (PER)	0.0%	
Antenna Used	Antenna	Antenna
	1	2
	565	434
Errors	CRC	Other
	0	0

Table 1 - Amplitude Based Antenna Diversity Test Results (76.8 kbps)

In the top plot of Figure 7, the blue trace shows the signal strength received by the rightmost antenna (Ant 1) as a function of position along the linear actuator. The green trace shows the signal strength received by the leftmost antenna (Ant 2).

Notice how the RSSI value varies by over 15 dB as the radios are moved along the actuator, and that the two amplitude plots are more or less out of phase. That is, while the amplitude received from Antenna 1 is decreasing, that received from Antenna 2 is increasing. This is partially due to the choice of antenna spacing (approximately ¼ wavelength apart), but is highly dependent upon the environment in which the radios are operating. From this plot it is a clear that amplitude based antenna diversity should significantly improve PER.

In the bottom plot, the red trace shows whether or not a packet was successfully received. The green trace shows which antenna was selected. The data presented here was developed using a CC1101 and a software based antenna selection algorithm. See Appendix.

7.2 One Radio, One Antenna, Frequency Diversity Mode



Figure 8 - Antenna Diversity EVM, Rev B. One Radio. One Antenna, Frequency Diversity Mode

Results using Frequency Diversity are dependent upon the difference in frequency at which the two repeated transmissions are made. In the following figure, frequencies of 900 MHz and 908 MHz were chosen, in part because 908 MHz was less 'busy' in the Rochester office. We are located about 1/4 mile away from a USPS (US Postal Service) distribution center,



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which apparently uses two way radios operating in the 915 MHz ISM band. Even though the signal level of this interference is very low (between -80 and -90 dBm), it's enough to affect the accuracy and repeatability of measurement results.

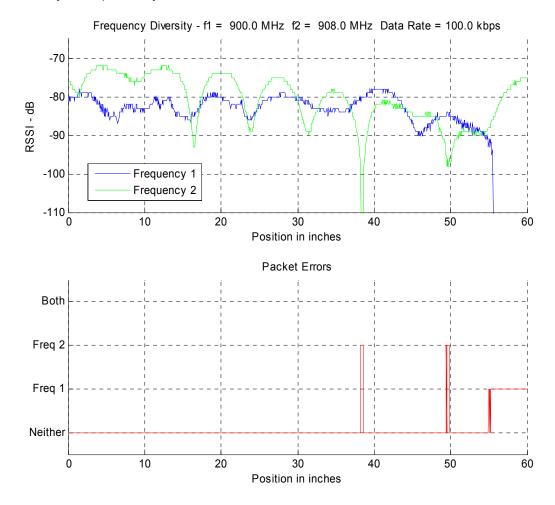


Figure 9 - Frequency Diversity, 900\908 MHz, 100 kbps

Good Packets	Either	90	00	908
		MI	Ηz	MHz
	1000	91	18	985
Packet Error Rate (PER)		0.	.00%	
CRC Errors	900 MHz 9		9	08 MHz
	7			8
Other Errors	900 N	1Hz	90	08 MHz
	75			7
Average RSSI	900 N	1Hz	90	08 MHz
	-82.7 c	lBm	-80	0.4 dBm

Table 2 - Frequency Diversity Test Results (100 kbps)

In the top plot of Figure 9, the blue trace shows the signal strength received at Frequency 1 (900 MHz) as a function of position along the linear actuator. The green trace shows the signal strength received at Frequency 2 (908 MHz). In the bottom plot, the red trace shows



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packet errors, and has a value of 'Freq 1' when the packet received by on Frequency 1 was in error (lost or contained a CRC or length error), a value of 'Freq 2' when the packet received on Frequency 2 was in error, and a value of 'Both' if packet could not be successfully received on either frequency. Note that RSSI fell below -95 dBm at 900 MHz when the receiver was located near its rightmost position (greater than 55 inches), while that at 908 MHz approached its maximum value.

Results at a data rate of 250 kbps are similar; again, all 1000 packets were successfully received, despite changes in amplitude of more than 20 dB over the length of the actuator.

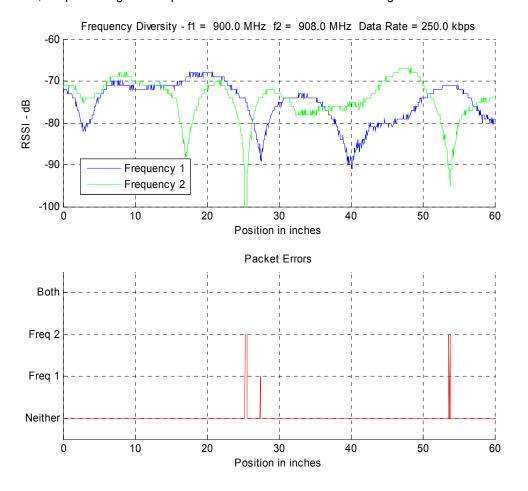


Figure 10 - Frequency Diversity, 900\908 MHz, 250 kbps



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Good Packets	Either	900		908
		M	Ηz	MHz
	1000	99	99	993
Packet Error Rate (PER)	0.00%			
CRC Errors	900 MHz 1		908 MHz	
			2	
Other Errors	900 MHz 9		90	08 MHz
	0			4
Average RSSI	900 N	1Hz	90	08 MHz
	-75.2 c	lΒm	-74	4.3 dBm

Table 3 - Frequency Diversity Test Results (250 kbps)

7.3 Dual Radio Antenna Diversity Mode

The following data was taken using 'dual radios' at a frequency of 900 MHz. Both antennas are vertically oriented and spaced 3.5 inches apart (approximately ¼ wave length).



Figure 11 - Antenna Diversity EVM, Rev B. Dual Radio Mode



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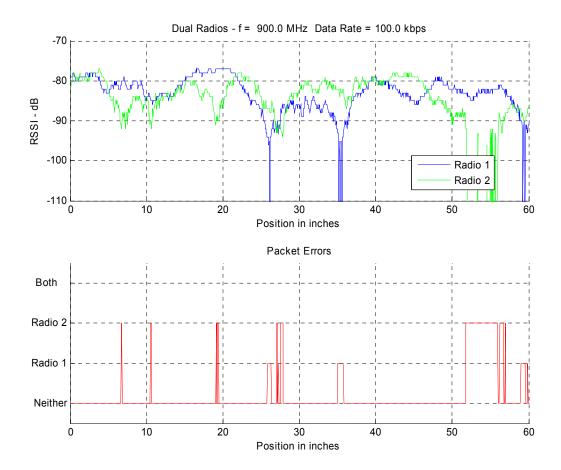


Figure 12 - Dual Radios, 900 MHz, 100 kbps

Good Packets	Either	Ra	dio	Radio
		1		2
	1000	96	67	906
Packet Error Rate (PER)		0.0	00%	
Lost Packets	Radio 1		Radio 2	
	8			59
CRC Errors	Radio 1		Radio 2	
	21		35	
Other Errors	Radio 1		Radio 2	
	4		0	
Average RSSI	Radio 1		Radio 2	
	-82.8 d	Bm	-83	3.1 dBm

Table 4 - Dual Radio Test Results (100 kbps)

In the top plot of Figure 12, the blue trace shows the signal strength received by the rightmost radio (Radio 1) as a function of position along the linear actuator. The green trace shows the signal strength received by the leftmost radio (Radio 2). In the bottom plot, the red trace shows packet errors, and has a value of 'Radio 1' when the packet received by Radio 1 is in error (lost or contained a CRC or length error), a value of 'Radio 2' when the packet received by Radio 2 is in error, and a value of 'Both' if both radios were unable to successfully receive



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the packet. In this case, this never occurred, even though both radios experienced 'dropouts' at some position along the actuator.

8 Qualifications

Please consider the results presented here as typical – in other words, your results will vary! Results are highly dependent upon the environment in which the tests are performed. For example, moving the location of the transmitter by as little as a few feet can change results substantially. The number, composition, and spacing of interior walls in the path between transmitter and receiver(s) greatly affects signal strength and the phase of reflections, as evidenced in the RSSI plots.

9 Conclusions

Several techniques for implementing diversity using one or two radios and one or two antennas have been described. All have been shown to be effective at minimizing multipath effects. Table 5 compares the pros and cons of the techniques.

Diversity Technique	Cost/Size	Pros	Cons
HW implemented amplitude based one radio two antennas (Amplitude Diversity)	medium	No impact on data rate or packet length.	Requires two antennas and an external RF switch.
SW implemented amplitude based one radio two antennas (Amplitude Diversity)	medium	No impact on data rate or packet length. Algorithm easily changed in software.	Requires two antennas and an external RF switch. Requires a relatively long preamble ¹ .
Two radio two antenna (Dual Radio Antenna Diversity)	high	No impact on data rate or packet length. No external RF switch required.	Higher power consumption than Amplitude Diversity due to simultaneous use of two radios. Requires two antennas.
One radio, one antenna, dual frequency (Frequency Diversity)	low	Only a single antenna is required. Can be less sensitive to interference from other devices.	Effective data rate is 50% of set rate, since each packet must be sent twice. Higher power consumption than Amplitude Diversity due to packet repeat.

Table 5 - Diversity Techniques Comparisons

10 References

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based antenna diversity algorithm.

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¹ The length of the preamble must exceed twice the time required for the RSSI value to stabilize, which depends upon signal amplitude, data rate, RX filter Bandwidth and AGC settings, plus approximately 50 usec (algorithm overhead). Maximum preamble length is 24 bytes for the CC1101. This is sufficient for the single radio amplitude-

- [1] Design Note DN500 "Packet Transmission Basics" (http://www.ti.com/lit/swra109)
- [2] Design Note DN505 "RSSI Interpretation and Timing" (http://www.ti.com/lit/swra114)
- [3] CC1101 Data Sheet (http://www.ti.com/lit/swrs061)

11 Appendix

A code segment implementing one radio two antenna amplitude based antenna diversity using the MSP430 is provided below.

For this example, a data rate of 76.8 kbps was chosen, with a 12 byte preamble. Using values recommended by Texas Instrument's SmartRF Studio for the CC1101 for this baud rate, the receiver bandwidth (232.1 kHz), AGC Filter Length (2), and Wait Time (3), the CC1101 device requires approximately 310 microseconds to obtain a valid RSSI value after an antenna is selected and the carrier is sensed.

```
#define RF1 0
#define RF2 1
001 pktslost = csensed = 0;
002 usingRF1 = usingRF2 = 0;
003 no errors = crc errors = other errors = 0;
004 rssisum[RF1] = rssisum[RF2] = 0;
005 ant = RF1;
                                 // default to antenna 1 (RF1)
006 P10UT &= ~SW RF2;
007 P10UT \mid = SW \overline{R}F1;
008 for (pktattempts = 0; pktattempts < 2000; pktattempts++) {
      Strobe_Radio1_Reg(TI_CCxxx0_SRX); // Change state to RX
009
010
       TBCTI. \&= ~0 \times 0.030:
                                          // Stop Timer B
       TBCCR0 = 10000;
                                          // Set stop count (10 msec)
// Clear Timer B
011
       TBCTL |= TBCLR;
012
       TBCTL |= MC_1;
                                          // Set mode to UP
013
014
       csense = 0;
015
       while (1) {
                      // Loop until either SYNC is detected or Timer B exceeds 9 msec
016
       if (TBR > 9000) {
                                                 // Exit RX state (go to IDLE)
           Strobe Radiol Reg(TI CCxxx0 SIDLE);
017
           Strobe_Radio1_Reg(TI_CCxxx0_SFRX);
                                                     // Flush the RX FIFO
018
019
           pktslost++;
020
           syncdetected = 0;
021
          break;
                                          // beak out of 'while' loop (to line 073)
022
        if (csense == 0) { // if carrier has been sensed, skip this code segment
023
         if ((GDO2_Radio1_PxIN & GDO2_Radio1_PIN) > 0) { // if Carrier sensed
024
                                         // Mark the time
// See if CS remains high for 400 usec
025
             csense = TBR;
026
             do {
             027
028
                                          // beak out of 'do' loop (to line 036)
029
                break;
030
031
              if ((P3IN & GDO2_Radio1_PIN) == 0) { // if Carrier Sense drops
032
                csense = 0; // abort this code segment
                                          // beak out of 'do' loop (to line 036)
033
034
035
             } while (TBR < (csense + 400));</pre>
                                          // If CS has remained high for 400 usec
             if (csense > 0) {
037
               rssi = (signed char) Read Radio1 Status(0x34);
038
               rssidb1st = (rssi / 2) - 7\overline{4};
               rssisum[ant] += rssidbfirst;
039
040
               csensed++:
              ant^= 0x01;
if (ant == RF1) {
                                         // Swap antennas
041
042
                 P1OUT &= ~SW_RF2;
P1OUT |= SW_RF1;
                                              // Select Antenna 'RF2'
043
044
045
046
               else {
047
                 P1OUT &= ~SW_RF1;
                                              // Select Antenna 'RF2'
048
                 P1OUT |= SW \overline{R}F2;
```



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```
049
                                                  // Mark the time
                csense = TBR;
050
                while (TBR < (csense + 400)); // wait 400 usec
051
052
                rssi = (signed char) Read_Radio1_Status(0x34);
                rssidb2nd = (rssi / 2) - 7\overline{4};
053
054
                rssisum[ant] += rssidb2nd];
055
                if (rssidb1st > rssidb2nd)
                                                  // if the RSSI from the antenna selected
                                                  // first is greater than that from the
                                                  // antenna selected second
                  ant^= 0x01;
                                                  // Swap antennas
057
                if (ant == RF1) {
058
                  P1OUT &= ~SW RF2;
                                                  // Select Antenna 'RF1'
                  P1OUT |= SW \overline{R}F1;
059
060
                  usingRF1++;
061
062
                else {
                  Plout &= ~SW RF1;
                                                  // Select Antenna 'RF2'
063
                  P10UT |= SW_RF2;
064
0.65
                  usingRF2++;
066
067
              }
                         // end of 'csense > 0' if
// end of 'csense == 0' if
068
069
         }
         if ((P3IN & GD00_Radio1_PIN) > 0) { // If GD00 of Radio 1 goes high // (SYNC detected)
070
            syncdetected = 1;
072
                                                  // beak out of 'while' loop (to line 075)
            break;
073
             // end of first 'while (1)' loop
                                                  // if no packet was detected
       if (syncdetected == 0)
076
         continue;
                                                  // go to end of 'for' loop
       TBCTL &= \sim 0 \times 0.030:
                                                  // SYNC has been detected - Stop Timer B
       TBCTL |= TBCLR;
078
                                                  // Clear Timer B
                                                  // Set mode to UP
079
       TBCTL |= MC 1;
                          // loop until either GDOO drops or Timer B exceeds
// SLAVE_RX_TIMEOUT_PER
080
       while (1) {
081
         if ((P3IN & GDOO Radio1 PIN) == 0) {
                                                           // If GDOO subsequently drops ...
082
           pktrcvd |= PKT RCVD Radio1;
                                                          // A packet was received
083
            rc = RFReceivePacket_Radio1((char *) &rxbufrp, &pktlen);
084
            switch (rc) {
085
           case 0:
                                                          // Good Packet
086
             no errors++;
087
             break;
088
           case 1:
                                                          // CRC error
089
             crc errors++;
090
              break;
091
                                                          // All other errors
           default:
092
             other_errors++;
093
              break:
           } // end of 'switch' statement
094
095
           TBCTL &= \sim 0 \times 0030;
                                                          // Stop Timer B
               // end of GDOO dropped 'if'
096
097
         if (TBR > slavetimeout[datarate]) {
            Strobe_Radio1_Reg(TI_CCxxx0_SIDLE);
Strobe_Radio1_Reg(TI_CCxxx0_SFRX);
098
                                                          // Abort RX
099
                                                          // Flush the RX buffer
                                                  // beak out of 'while' loop (to line 103)
           break;
                // end of timeout 'if'
102
            // end of second 'while (1)' loop
            // end of 'for' loop
```

The algorithm makes use of the CC1101's 'Carrier Sense' and 'Sync Word Found' flags. These signals can be made available on the GDO0 and GDO2 pins through the IOCFG0 and IOCFG2 radio registers. See the 'Configuration Registers' section of the CC1101 Data Sheet.

The CC1101's 'GDO0' pin is connected to a DI pin on the controlling MSP430, and the IOCFG0 register is set such that the pin goes high after a valid SYNC field is detected and low after the packet is entirely received (IOCFG0 set to 0x06). Similarly, the CC1101's 'GDO2' pin is connected to another DI pin, and the IOCFG2 register is set (to 0x0E) such that the pin goes high when carrier is sensed (RSSI level is above a programmable threshold).



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Note that the amplitude at which the 'Carrier Sense' flag is raised is dependent upon the settings in CC1101 registers AGCCTRL2.MAX_DVGA_GAIN and AGCCTRL2.MAX_LNA_GAIN. See page 8 of DN505. For best performance in this application both AGCCTRL2.MAX_DVGA_GAIN and AGCCTRL2.MAX_LNA_GAIN should be set to zero.

For this implementation, SPDT RF switch is used. It is controlled by two MSP430 DO bits (bits 2 and 3 of P2).

The above code segment attempts to receive 1000 packets from a remote transmitter. The number of 'good' packets is calculated, along with the number of those with CRC and 'other' (length, filtering) errors. In addition, the number of times the 'RF1' (right) and 'RF2' (left) antennas were selected is calculated.

Details

Lines 6 – 7: Setting bits 2 and 3 of P2OUT to 01b selects Port 'RF1' of the RF Switch; setting bits 2 and 3 of P2OUT to 10b selects Port 'RF2' of the RF Switch.

Line 9: Turn on the Receiver.

Lines 10 – 13: Timer B is used in 'up' mode as a 'timeout' indicator. The timer counts up one count every usec. Register TBR holds the current 'tic' count.

Lines 15 – 74: Loop until one of two events occurs:

TBR exceeds a value of 9000. Lines 16 - 22. If neither Carrier nor SYNC is detected by this time, the packet is lost. The radio is forced into the IDLE state and the RX FIFO is flushed. SYNC is detected. Lines 70 - 73.

Lines 24 - 35: Once carrier is detected (the GDO2 line goes high), record the time (TBR) at which carrier is first sensed (line 25). Loop for 400 usec (lines 26 - 35), but abort the loop if SYNC is detected (GDO0 goes high) or Carrier Sense (GDO02) drops. If either of these two events occurs during the 400 usec period, csense will be re-set to zero.

Lines 36 – 68: Once it is verified that the Carrier Sense flag has gone high and remained high for a period of 400 usec (csense > 0), calculate 'rssidb1st', the RSSI value of the signal received using the currently selected antenna (lines 37 and 38). See DN505 for an explanation of the calculation. Swap antennas, wait an additional 400 usec to allow for the RSSI value to stabilize, and calculate 'rssidb2nd', the RSSI value of the signal received using this antenna (lines 50 - 54). If rssidb1st exceeds rssidb2nd, swap the antennas again (lines 55 - 56). Set the antenna switch and increment usingRF1 or usingRF2 as appropriate (lines 57 - 66).

Lines 75 and 76: If SYNC was never detected, jump to the 'end of the loop'.

Lines 77 – 79: If we get to this point in the code, SYNC has been detected. Reset Timer B.

Lines 80 – 102: Loop until one of two events occurs:

SYNC (GDO0) goes low, indicating that a packet has been received (lines 81 - 96). The Timer B tic count (TBR) has exceeded SLAVE_RX_TIMEOUT_PER. Should this condition occur, force the receiver into the IDLE state, flush the RX FIFO, and 'break' out of the loop (lines 97 - 101).

Lines 82 – 96: A packet has been received. Subroutine RFReceivePacket checks for packet errors (CRC, Packet Length, Address) and transfers data from the CC1101's RX buffer to MSP430 memory. The various counts are incremented as appropriate.



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Line 95: Stop Timer B.

12 Document History

Revision	Date	Description/Changes
SWRAxxx	yyyy.mm.dd	Initial release.



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