Implementing 'Diversity' Using Low Power Radios

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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

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.

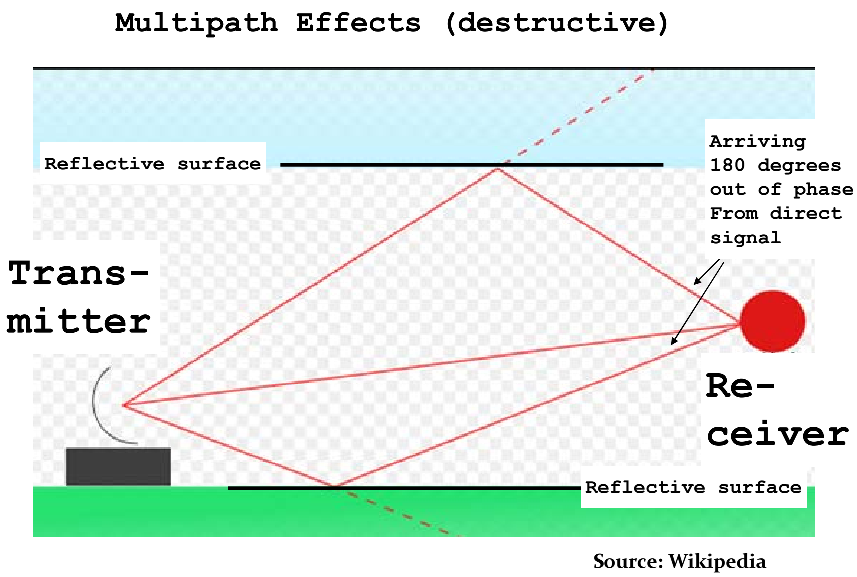

Figure 1 - Multipath Effects

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.

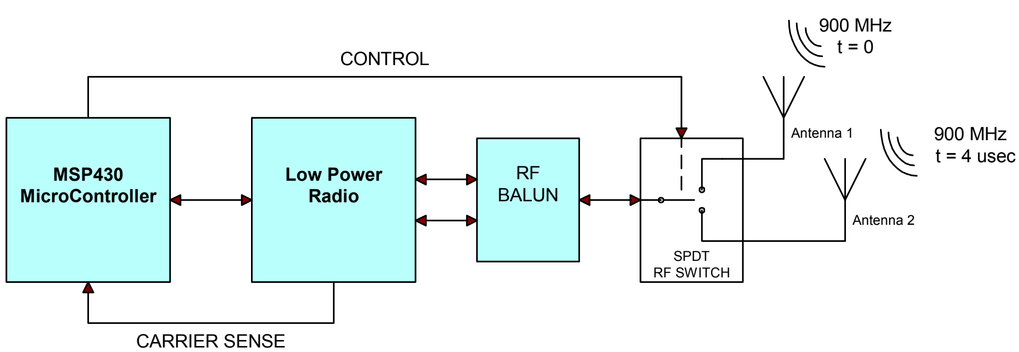

Figure 2 - Single Radio Amplitude-Based Antenna Diversity

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
2. 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.

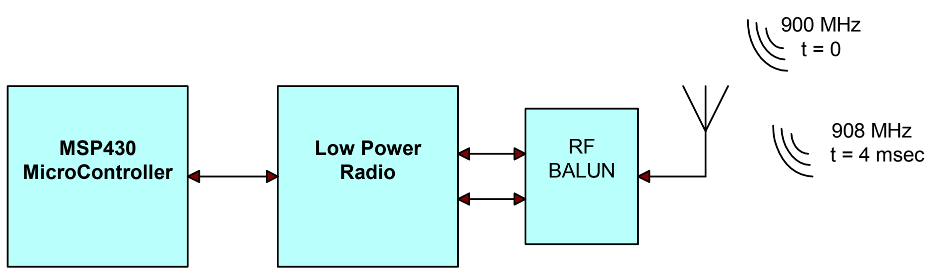

Figure 3 - Single Radio Frequency Diversity

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.

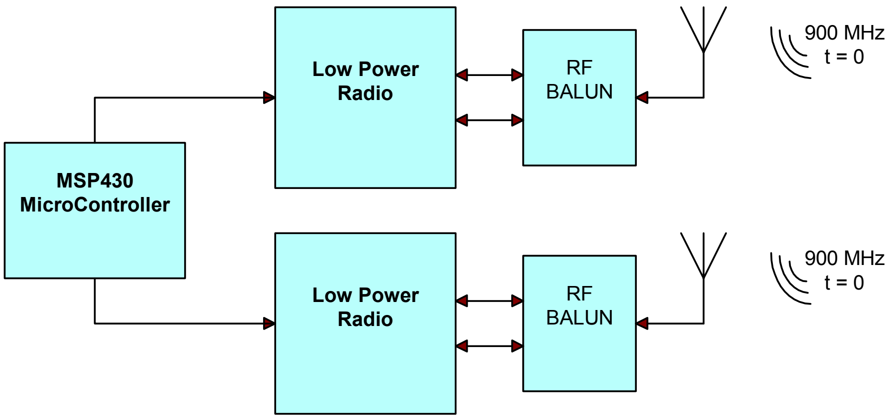

Figure 4 - Dual Radio Two Antenna Diversity

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.

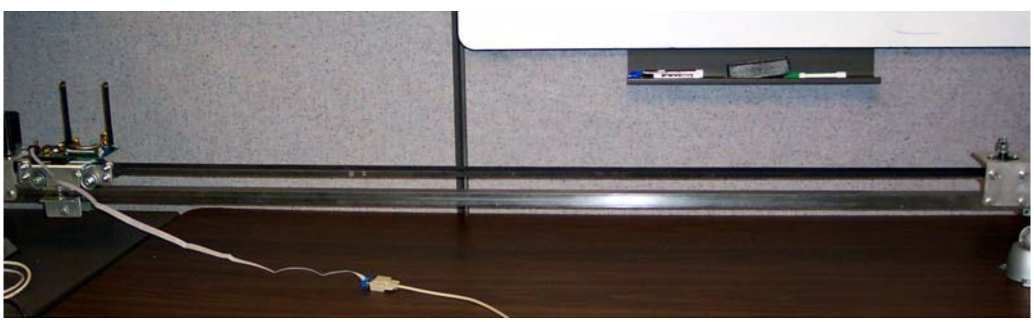

Figure 5 - 60 inch Linear Actuator with EVM

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 ¼ wave length) at their bases.

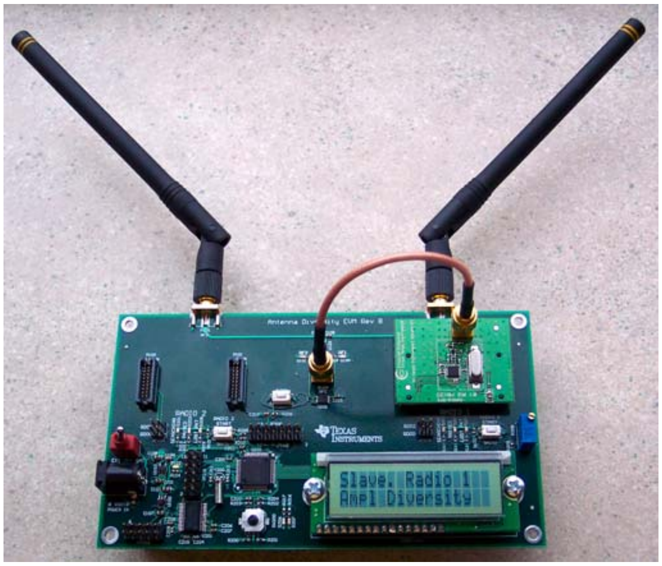

Figure 6 - Antenna Diversity EVM, Rev B. One Radio Amplitude Based Antenna Diversity Mode

Test results are shown in Figure 7, below.

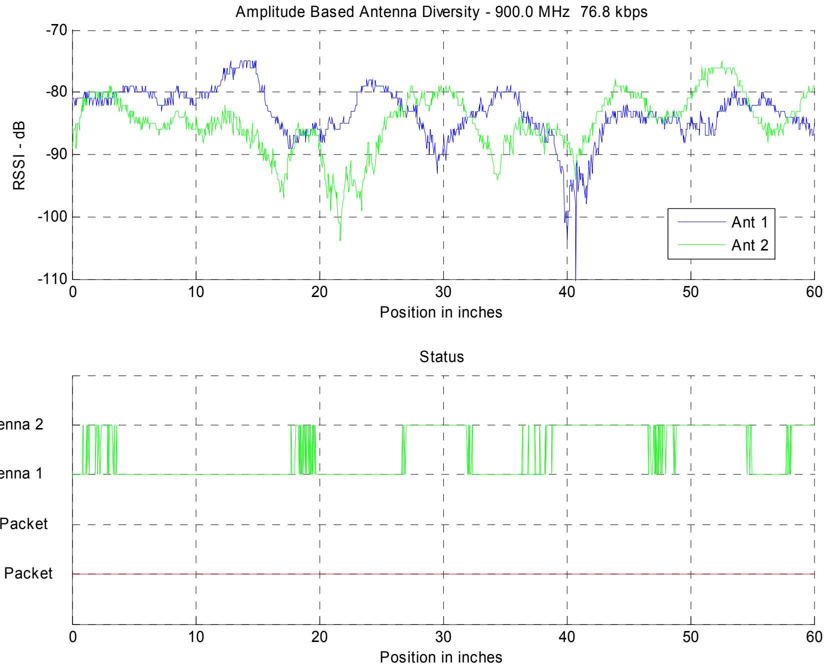

Figure 7 - Amplitude Based Antenna Diversity, 900 MHz, 76.8 kbps

Packets Received	1000	
Packets Lost	0	
Packets Received with No Errors	1000	
Packet Error Rate (PER)	0.0%	
Antenna Used	Antenna 1	Antenna 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, 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.

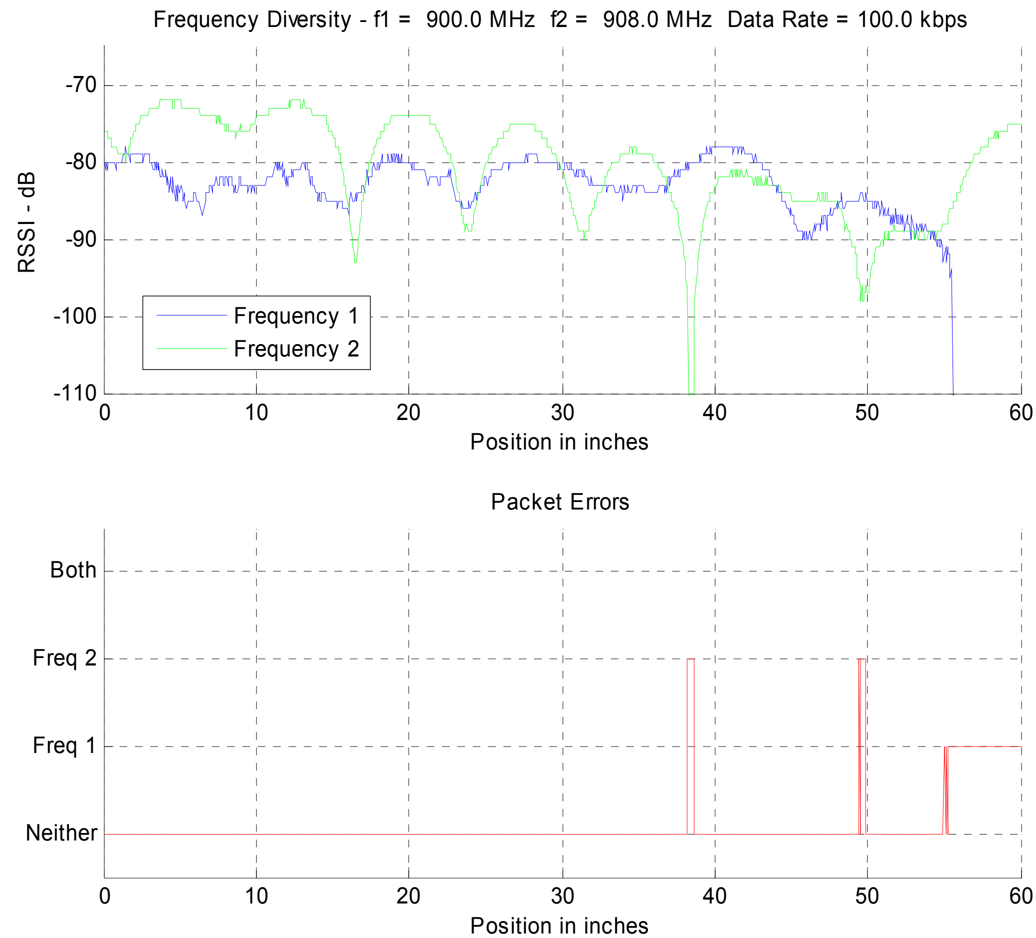

Figure 9 - Frequency Diversity, 900\908 MHz, 100 kbps

Good Packets	Either	900 MHz	908 MHz
	1000	918	985
Packet Error Rate (PER)	0.00%		
CRC Errors	900 MHz	908 MHz	
	7	8	
Other Errors	900 MHz	908 MHz	
	75	7	
Average RSSI	900 MHz	908 MHz	
	-82.7 dBm	-80.4 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 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.

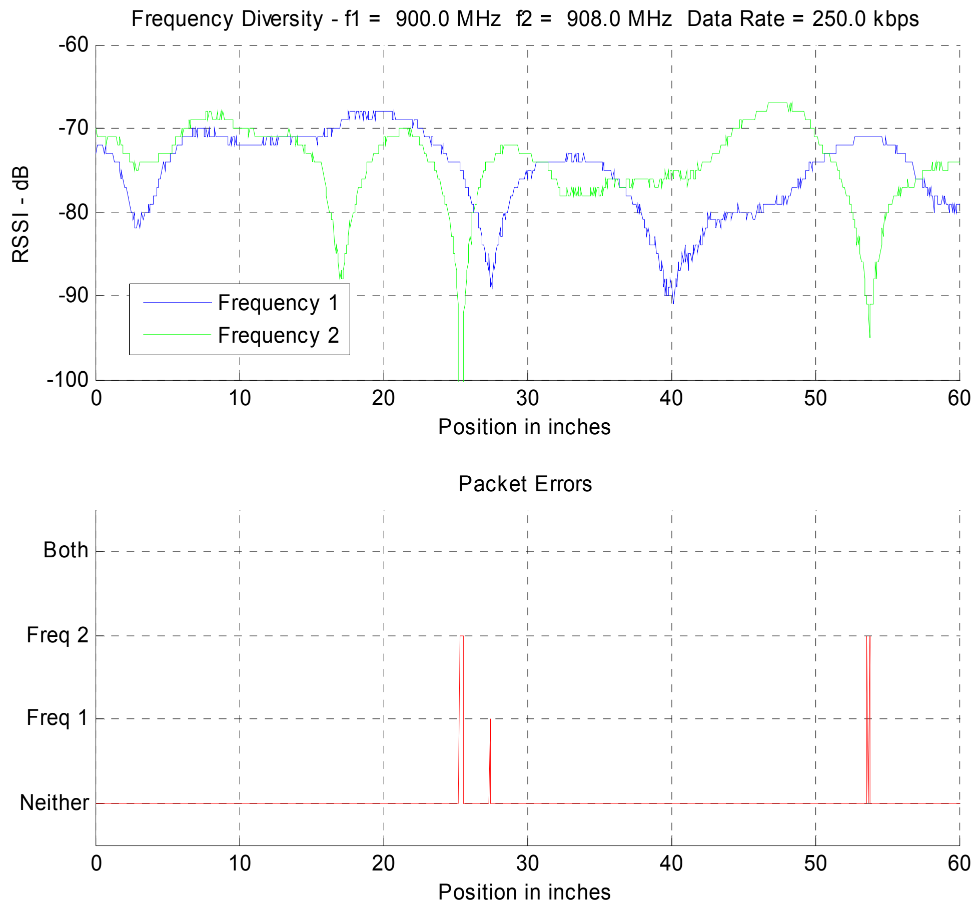

Figure 10 - Frequency Diversity, 900\908 MHz, 250 kbps

Good Packets	Either	900 MHz	908 MHz
	1000	999	993
Packet Error Rate (PER)	0.00%		
CRC Errors	900 MHz	908 MHz	
	1	2	
Other Errors	900 MHz	908 MHz	
	0	4	
Average RSSI	900 MHz	908 MHz	
	-75.2 dBm	-74.3 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

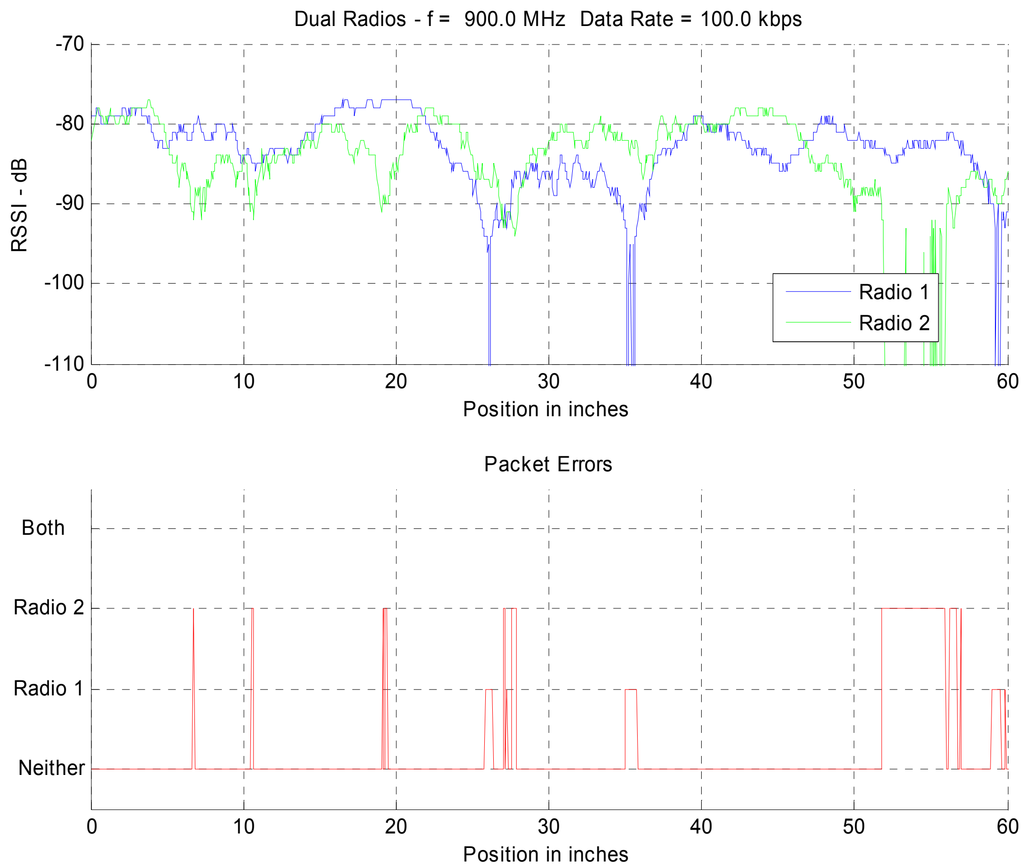

Figure 12 - Dual Radios, 900 MHz, 100 kbps

Good Packets	Either	Radio 1	Radio 2
	1000	967	906
Packet Error Rate (PER)	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 dBm	-83.1 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 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

[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-based antenna diversity algorithm.

[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 P1OUT &= ~SW_RF2;
007 P1OUT |= SW_RF1;

008 for (pktattempts = 0; pktattempts < 2000; pktattempts++) {
009    Strobe_Radio1_Reg(TI_CCxxx0_SRX); // Change state to RX

010    TBCTL &= ~0x0030;                 // Stop Timer B
011    TBCCR0 = 10000;                   // Set stop count (10 msec)
012    TBCTL |= TBCLR;                   // Clear Timer B
013    TBCTL |= MC_1;                    // Set mode to UP
014    csense = 0;

015    while (1) {    // Loop until either SYNC is detected or Timer B exceeds 9 msec
016      if (TBR > 9000) {
017        Strobe_Radio1_Reg(TI_CCxxx0_SIDLE);       // Exit RX state (go to IDLE)
018        Strobe_Radio1_Reg(TI_CCxxx0_SFRX);        // Flush the RX FIFO
019        pktslost++;
020        syncdetected = 0;
021        break;                        // beak out of 'while' loop (to line 073)
022      }
023      if (csense == 0) {      // if carrier has been sensed, skip this code segment
024        if ((GDO2_Radio1_PxIN & GDO2_Radio1_PIN) > 0) {       // if Carrier sensed
025          csense = TBR;               // Mark the time
026          do {                        // See if CS remains high for 400 usec
027            if ((P3IN & GDO0_Radio1_PIN) > 0) {   // if SYNC has been detected
028              csense = 0;                         // abort this code segment
029              break;                  // beak out of 'do' loop (to line 036)
030            }
031            if ((P3IN & GDO2_Radio1_PIN) == 0) {  // if Carrier Sense drops
032              csense = 0;             // abort this code segment
033              break;                  // beak out of 'do' loop (to line 036)
034            }
035          } while (TBR < (csense + 400));

036          if (csense > 0) {           // If CS has remained high for 400 usec
037            rssi =  (signed char) Read_Radio1_Status(0x34);
038            rssidb1st = (rssi / 2) - 74;
039            rssisum[ant] += rssidbfirst;
040            csensed++;
041            ant^= 0x01;              // Swap antennas
042            if (ant == RF1) {
043              P1OUT &= ~SW_RF2;             // Select Antenna 'RF2'
044              P1OUT |= SW_RF1;
045            }
046            else {
047              P1OUT &= ~SW_RF1;             // Select Antenna 'RF2'
048              P1OUT |= SW_RF2;
```

```
049            }
050            csense = TBR;                    // Mark the time
051            while (TBR < (csense + 400));    // wait 400 usec
052            rssi =  (signed char) Read_Radio1_Status(0x34);
053            rssidb2nd = (rssi / 2) - 74;
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
056              ant^= 0x01;                    // Swap antennas
057            if (ant == RF1) {
058              P1OUT &= ~SW_RF2;              // Select Antenna 'RF1'
059              P1OUT |= SW_RF1;
060              usingRF1++;
061            }
062            else {
063              P1OUT &= ~SW_RF1;              // Select Antenna 'RF2'
064              P1OUT |= SW_RF2;
065              usingRF2++;
066            }
067          }
068        }          // end of 'csense > 0' if
069      }            // end of 'csense == 0' if

070      if ((P3IN & GDO0_Radio1_PIN) > 0) {   // If GDO0 of Radio 1 goes high
                                               // (SYNC detected)
071        syncdetected = 1;
072        break;                              // beak out of 'while' loop (to line 075)
073      }
074    }    // end of first 'while (1)' loop

075    if (syncdetected == 0)                  // if no packet was detected
076      continue;                             // go to end of 'for' loop

077    TBCTL &= ~0x0030;                       // SYNC has been detected - Stop Timer B
078    TBCTL |= TBCLR;                         // Clear Timer B
079    TBCTL |= MC_1;                          // Set mode to UP

080    while (1) {        // loop until either GDO0 drops or Timer B exceeds
                          // SLAVE_RX_TIMEOUT_PER
081      if ((P3IN & GDO0_Radio1_PIN) == 0) {         // If GDO0 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        default:                                   // All other errors
092          other_errors++;
093          break;
094        }  // end of 'switch' statement

095        TBCTL &= ~0x0030;                          // Stop Timer B
096      }    // end of GDO0 dropped 'if'

097      if (TBR > slavetimeout[datarate]) {
098        Strobe_Radio1_Reg(TI_CCxxx0_SIDLE);        // Abort RX
099        Strobe_Radio1_Reg(TI_CCxxx0_SFRX);         // Flush the RX buffer
100        break;                              // beak out of 'while' loop (to line 103)
101      }     // end of timeout 'if'
102    }   // end of second 'while (1)' loop
103  }     // 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).

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.

Line 95: Stop Timer B.

12 Document History

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

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