AN379

ANTENNA DIVERSITY WITH EZRADIOPRO®

1. Purpose

This document describes the concept of antenna diversity, a technique that can be used to recover radio communication in environments of difficult reception. Antenna diversity can greatly improve performance under multi-path fading conditions. This document also provides real-world measurement examples by demonstrating the improvement that can be achieved with the built-in antenna diversity available using the EZRadioPRO® wireless family of RFICs.

While antenna diversity can achieve significant range improvements in wireless communication systems, it is often not implemented due to the added complexity, computation cost, and current consumption that is required to implement the requisite algorithm on the system MCU. EZRadioPRO devices have a built-in antenna diversity algorithm that removes the need for the customer to implement any additional firmware on their system MCU. By incorporating the antenna diversity algorithm into the EZRadioPRO devices directly, customers can achieve the benefits of diversity without the problems of developing and debugging the algorithm themselves, resulting in a more robust solution and a faster time to market.

2. Overview of Antenna Diversity

2.1. Performance Degradation due to Multipath/Fading

Fading is the phenomena often observed when small movements by either a transmitter or a receiver can lead to large differences in link quality. This happens as an antenna moves in and out of the peaks of a signal.

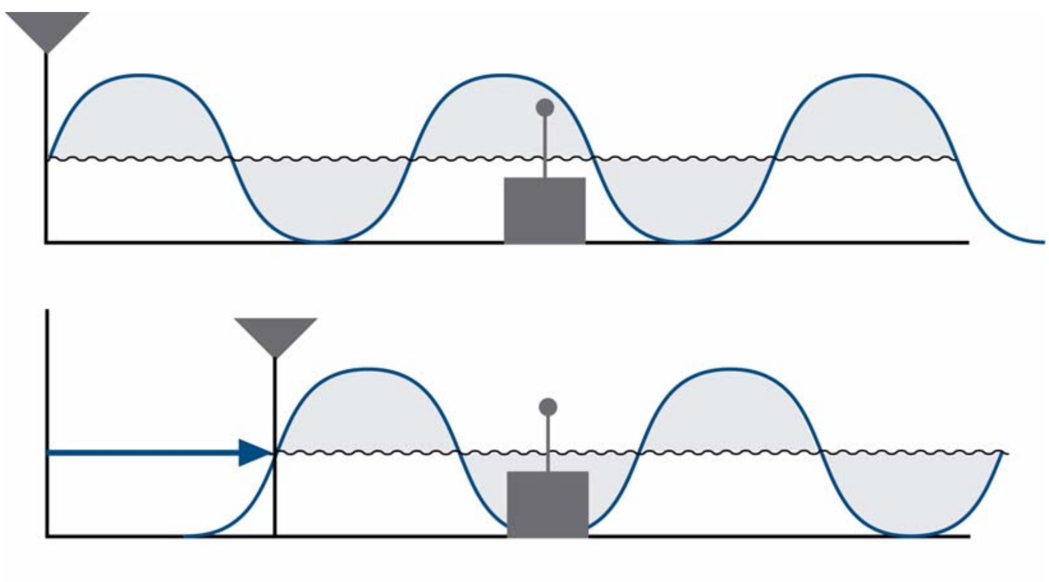

Figure 1. Fading Effects on an Antenna

Multipath expands on this concept. As radio waves are transmitted, they may not be received by the receiver through one signal path, but may come from multiple paths through reflections off other objects such as walls and trees-multipath. The signals received from each of these paths are likely to arrive at slightly different time intervals meaning slight phase shifts may occur. When these signals combine they may result in partial or near-total cancellation-fading.

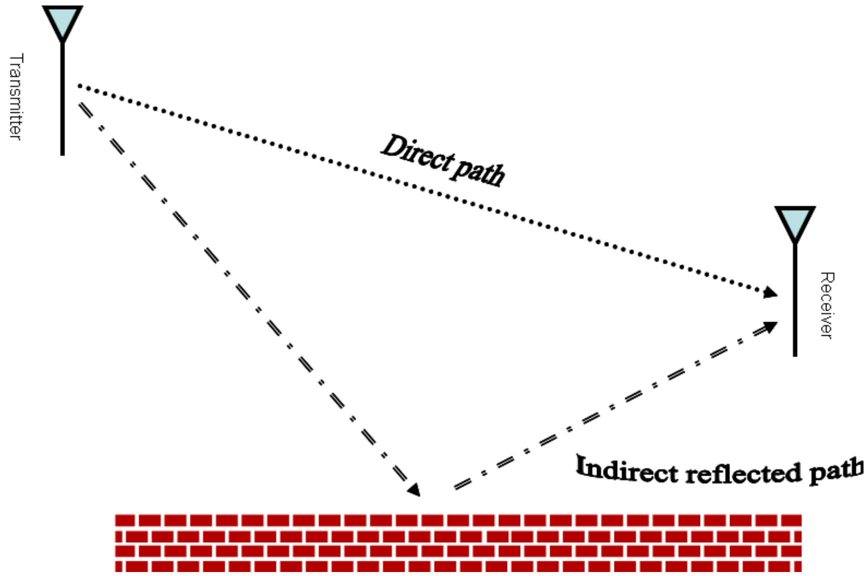

Figure 2. Direct and Indirect RF Pathways

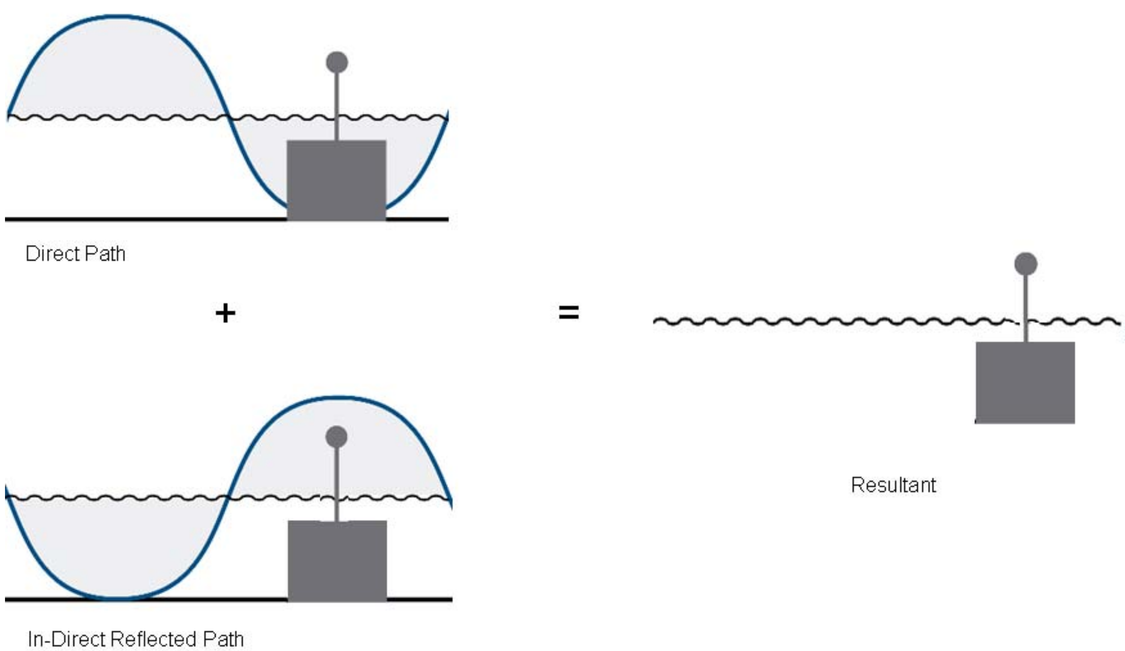

Figure 3. Worst Case RF Fading Effect from Phase Shifts Caused by Multipath

Using a worst case scenario, it can be demonstrated that should two signals arrive at a receiver with equal amplitudes but exactly 180 degrees out of phase, the receiver will not see any data—this would be 100% signal fading. While not typical, it is not overly unusual for a receiver to receive two such signals with exactly 180 degrees of phase shift, especially at higher operating frequencies. However, it is more likely that a multipath environment will give rise to some other value of phase shift, resulting in more moderate signal fades.

2.2. Concept of Antenna Diversity

To mitigate the problem of frequency-selective fading due to multi-path propagation a technique known as antenna diversity can be used. Antenna diversity uses a pair of antennas that are physically separated in location and possibly differ in mounting orientation (i.e., polarization) relative to the radio. Each time the device enters receive (RX) mode, the receive signal strength from each antenna is evaluated. This process is continuously repeated until a valid signal is detected on one of the antennas. The antenna with the strongest received signal strength is then used to receive the remainder of the packet. The same antenna may also be used for transmitting the corresponding transmit (TX) packet. (However, it should be noted that there is no guarantee that the fading characteristics of the return TX path match the fading characteristics of the RX path.)

Under non-multipath conditions, antenna diversity offers no improvement over a single fixed antenna. In a single-path environment, each time the antenna signal strengths are measured the antennas would have the same (maximum) signal strength. Hence the signal strength need only be measured once. However, under real-world conditions the signal strengths observed at the two antennas are generally not equal, due to each antenna receiving a slightly different set of signal paths. Furthermore, these signal paths are generally not static but vary due to people or objects moving in the vicinity which can cause reflections that change the signal strength in a time-varying manner. Under these conditions, the best antenna to choose will vary with time. This requires that the signal strength at each antenna be continually evaluated to determine the optimal antenna at any given instant.

Antenna diversity is thus a technique that is often used to recover signal integrity in non-static multipath environments. Products that implement antenna diversity quite often also have their antennas mounted at 90 degrees from one another for the purpose of countering the effects of polarization/directionality on the radio link.

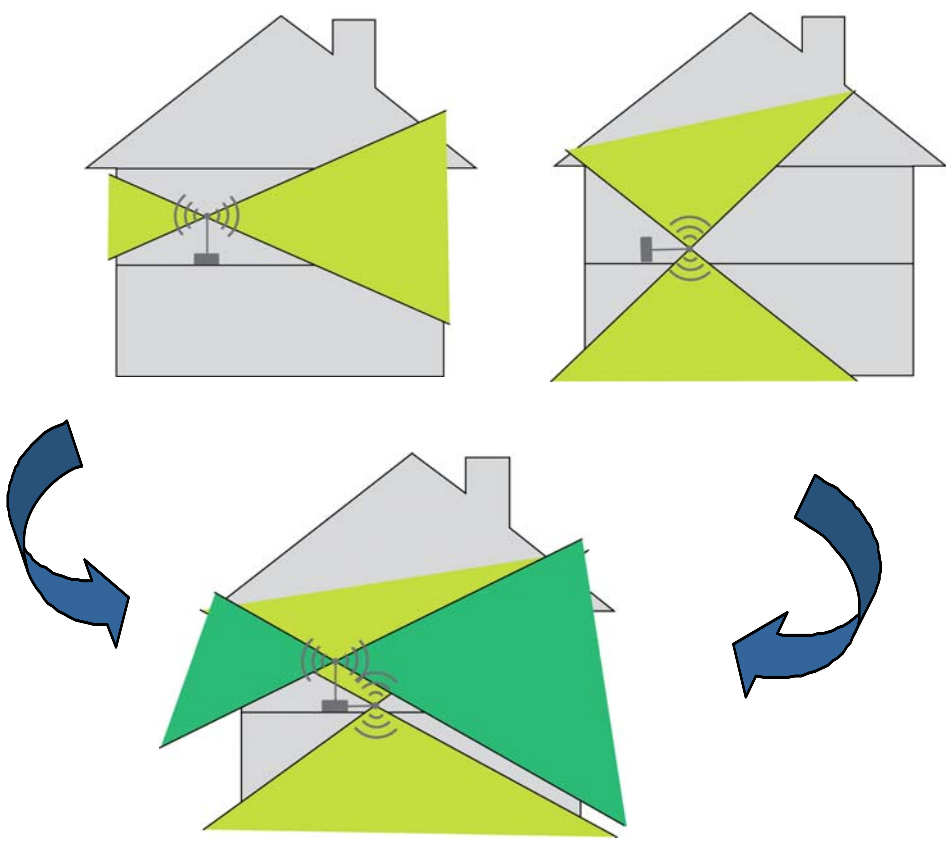

Figure 4. Combating Directionality through the Use of Multiple Antennas

In addition to mounting antennas at 90 degrees relative to one another, antennas in a product that implements antenna diversity have their antennas mounted at a distance of at least 1/4 wavelength apart. This amount of spatial separation improves the probability that at least one antenna is NOT in a deeply faded signal condition.

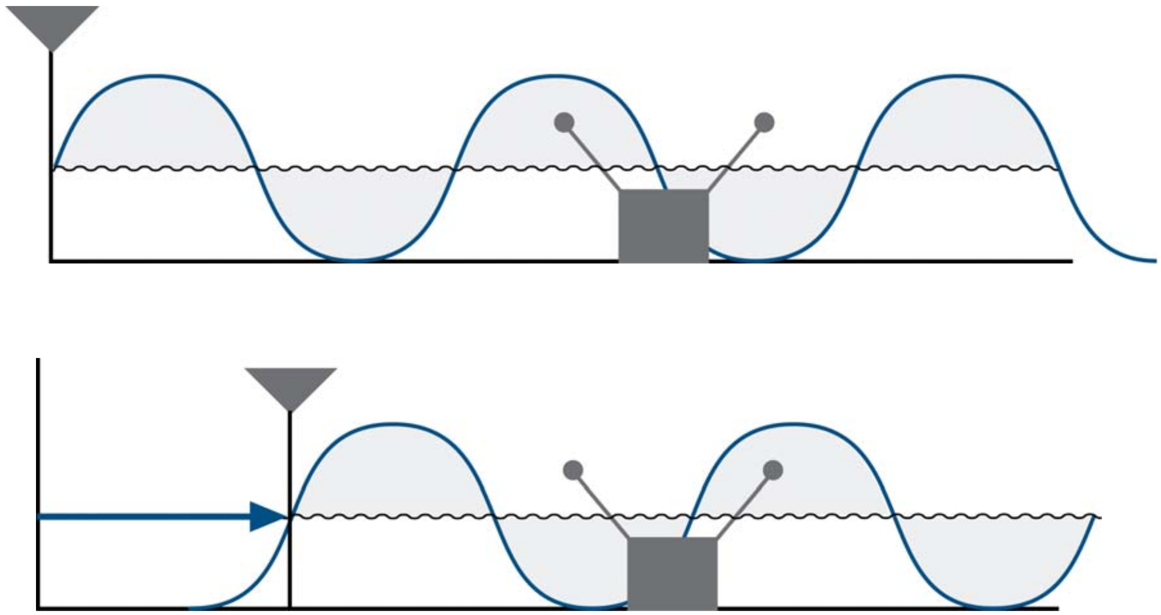

Figure 5. Combating RF Fading with Multiple Antennas

While antenna diversity is useful for recovering signal integrity and retaining link budget in the presence of a multipath environment, many designers opt not to use it as the tradeoffs can be considered quite high in their applications. In most cases, the tradeoff comes from the increased MCU overhead as the MCU has to remain awake for longer periods of time to evaluate the antenna signals. The increased MCU activity usually leads to a greater specification and a more costly MCU; the MCU also has extended “on-times” that result in shorter battery lives. In other cases, the extra space used to implement a two antenna solution or the additional code expertise required restricts the engineers to a single antenna design.

Implementing an effective antenna diversity algorithm in code on an MCU adds a substantial burden to a design. Many antenna diversity systems are optimized to operate in a synchronized manner between the transmitter and the receiver. The MCU on the receiver maintains a timer that allows the receiver to know when to expect to start receiving data from the transmitter. Under these circumstances the MCU can "wake up" at the appropriate time and immediately start evaluating the signal on both antennas. To evaluate the signal, the MCU would switch between each antenna and evaluate the RSSI levels. In implementations where the receiver does not use a timer, the radio must first reliably detect the start of a packet ***before*** evaluating the signal strength of each antenna. This ensures that evaluation of one of the antennas is not accidentally performed on noise (i.e., prior to the arrival of the actual transmit packet). In such a scenario, a deeply-faded antenna may accidentally be selected as the "optimum" choice, simply due to the fact that the non-faded antenna was never evaluated during a time period when the transmit packet was actually being received.

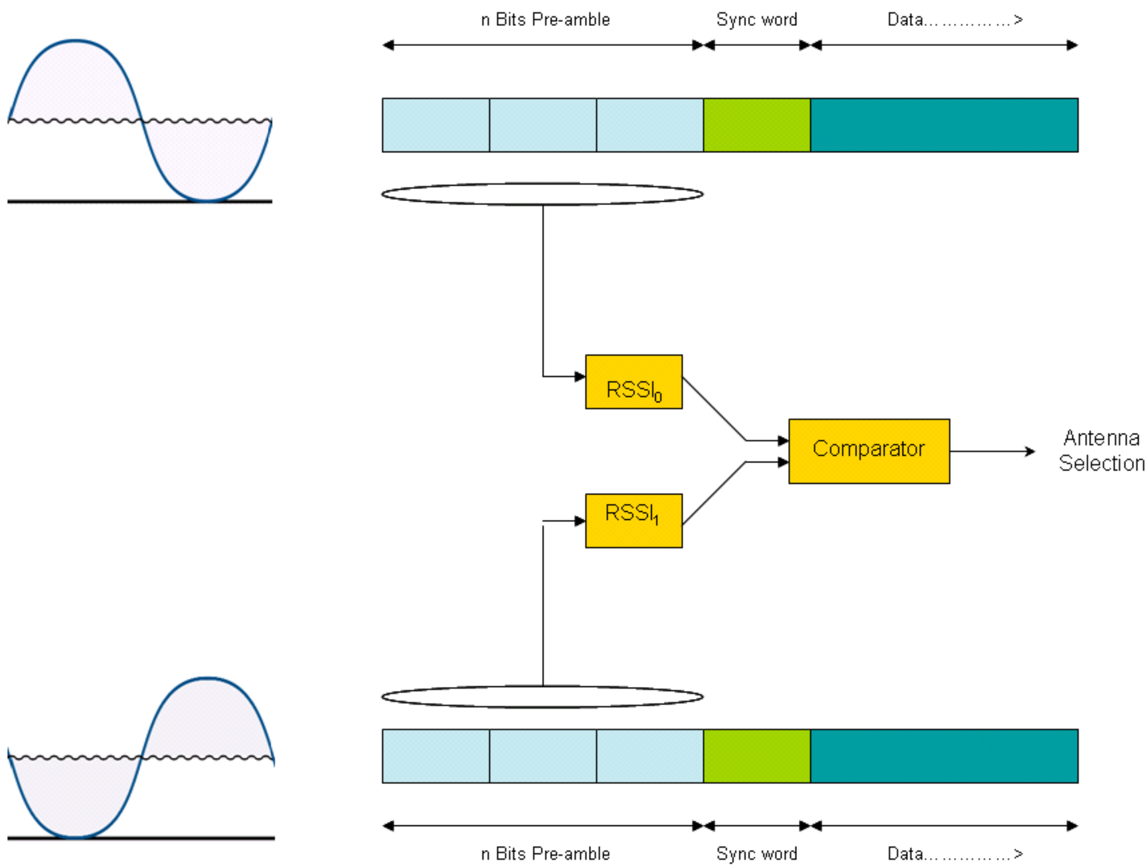

Figure 6. Measuring RSSI Levels to Qualify Antenna Selection

Longer preambles are often used to provide the MCU and its antenna diversity algorithm time to detect and evaluate the signal on each antenna. This helps to ensure that a true preamble is found (i.e., random noise is not mistaken for a preamble), but shorter preambles are preferred as they reduce radio and MCU on-time, and in turn reduce current consumption in both the transmit and receive sides of a radio link. Engineers often try to find a compromise by adjusting their antenna diversity algorithm to reduce preamble lengths. However, this carries the risk of causing other radio related issues, as preamble sequences of some minimal length are usually required to provide fast bit clock recovery.

2.3. Implementation of Antenna Diversity Algorithm

The EZRadioPRO antenna diversity algorithm is designed to select the best antenna based on the RSSI values measured at both antennas. In general, the radio has no prior knowledge as to when a valid packet will arrive, as EZRadioPRO does not necessarily rely on time synchronization between the transmitter and receiver ends of the RF link. This problem is solved by periodically switching antennas until arrival of a valid packet has been confirmed. Periodic toggling between antennas is required because, in a variable environment, the radio also has no prior knowledge as to which antenna will prove to be the "better" antenna when the packet arrives.

EZRadioPRO uses a preamble quality detector to determine signal quality and to confirm arrival of a valid packet. The preamble quality detector is configured by setting the preath[4:0] field in SPI Register 35h. The preath[4:0] field determines the consecutive number of nibbles (1 nibble = 4 bits) of preamble that must be received correctly before the chip issues a PREAMBLE_VALID signal. If a bit error occurs prior to receiving the specified consecutive number of preamble bits, the chip instead issues a PREAMBLE_INVALID signal. When the preamble detector indicates an PREAMBLE_INVALID or a timeout, the next antenna is selected and the receiver again tries to find a valid preamble. The receiver remains in this search loop until a PREAMBLE_VALID signal is observed, indicating arrival of a valid packet. The state diagram of Figure 7 illustrates this process.

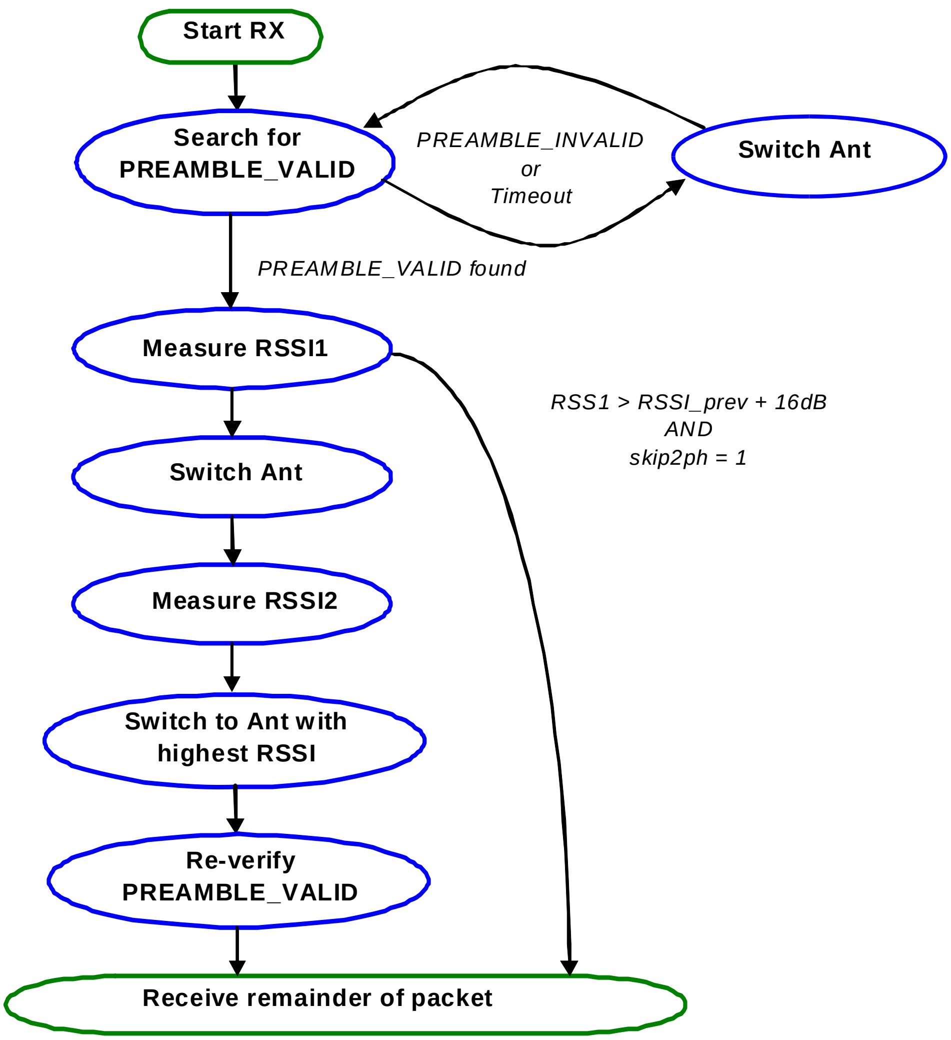

Figure 7. State Diagram of Antenna Diversity Algorithm

If a valid preamble is found, the algorithm proceeds to measuring the RSSI value for that particular antenna. This RSSI value is stored and the receiver then switches to the alternate antenna. The RSSI value on the other antenna is also measured and stored. Based upon the relative values of these two RSSI measurements, a decision is then made to select the optimum antenna (i.e., antenna with the strongest RSSI value) for the remainder of the packet.

The algorithm does ***not*** need to re-verify the PREAMBLE_VALID signal on the alternate antenna; it is sufficient to simply measure the RSSI on the alternate antenna. This is because the purpose of acquiring the PREAMBLE_VALID signal is to simply verify the arrival of a valid packet and to aid in acquiring bit clock recovery timing; this step does not need to be repeated on the alternate antenna. Since RSSI measurements are relatively quick, time is saved and the overall length of the preamble can be made shorter, thus extending the battery life. However, the receiver has no prior knowledge whether the signal level on the alternate antenna is stronger or weaker than on the first antenna. There is a possibility that the signal level on the alternate antenna is so weak (i.e., in such a deep fade) that the signal is below the noise floor of the receiver and cannot be received at all. For this reason, the PREAMBLE_VALID signal is re-verified after the final selection of the optimal antenna. This helps to ensure that false preamble detection does not occur. If PREAMBLE_VALID is not re-verified, the diversity algorithm starts again from the beginning.

During the initial search for a valid packet (i.e., the search for the first PREAMBLE_VALID signal), a timer is maintained to determine when to periodically toggle between antennas. The default value of this timeout period is 16 bit periods, but is configurable by the anwait[2:0] field in SPI Register 1Eh.

As a programmable option, the EZRadioPRO chip can be configured to completely skip the evaluation of the alternate antenna, in the event that the RSSI level measured on the first antenna is deemed sufficiently high. This functionality is controlled by setting the skip2ph bit in SPI Register 30h. It works by comparing the RSSI value of the antenna on which the PREAMBLE_VALID signal is first detected, with the ***previous*** RSSI value of the other antenna. It is evident that this previous RSSI measurement must be taken prior to the arrival of the packet (else PREAMBLE_VALID would be issued earlier), and thus its RSSI value indicates a very weak or no-signal condition. If the current RSSI value on the first antenna which observes a PREAMBLE_VALID signal is greater than 16 dB above the previous RSSI value from the alternate antenna, the signal is deemed sufficiently strong; there is no need to switch to and evaluate the second antenna. If the difference in RSSI value is less than 16 dB, the algorithm proceeds with evaluation of the signal strength on the alternate antenna, as normal. If the skip2ph bit is cleared, the antenna diversity algorithm ***always*** measures the RSSI value on the alternate antenna, regardless of signal strength on the initial antenna.

EZRadioPRO thus offers a best-in-class, low-cost and extremely robust radio link upon which designers can rely.

2.4. Benefits of Antenna Diversity

The antenna diversity algorithm provides the greatest improvement in performance when the operating environment is dynamic in terms of signal strength and fading conditions. These conditions normally occur indoors or in crowded outdoor urban environments where the transmitted signal is reflected off of different objects, arriving at the receiver from multiple paths with different phase shifts and signal attenuation. The summation of the signal from these multiple paths results in a time-varying amplitude for the transmission.

The following examples illustrate some different antenna conditions to demonstrate the benefits of antenna diversity.

2.4.1. Correlated Fade on Both Antennas

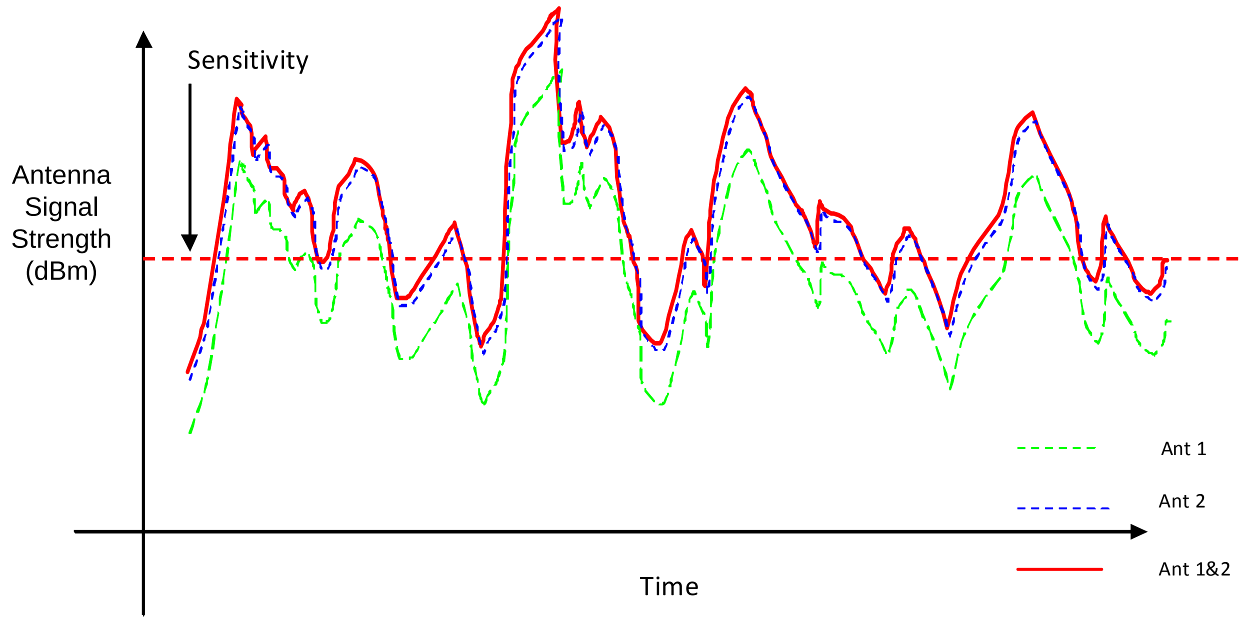

Figure 8. Antenna #1 and Antenna #2 with Correlated Signal Inputs

This example demonstrates a condition where the environment is time-varying, but does not contain any multi-path reflections. The condition demonstrated in Figure 8 could be found in an outdoor open space that is relatively free of any objects that might cause signal reflections; the time-varying nature of the received signal may simply be due to movement of the transmit source. The received signal levels at the two antennas show a consistent fixed gain difference.

Under these conditions, the antenna diversity algorithm will not show improvement in performance compared to the case of statically selecting the optimum antenna (e.g., Antenna #2). In this example, continuously selecting Antenna #2 provides optimal performance because Antenna #2 ***always*** has a stronger signal than Antenna #1. The antenna diversity algorithm will always correctly select Antenna #2, and thus will provide no performance improvement over statically selecting Antenna #2. In other words, if the signal strengths at the two antennas are closely correlated, antenna diversity will not improve the performance when compared to statically selecting the single optimum antenna.

2.4.2. Uncorrelated Fade on both Antennas

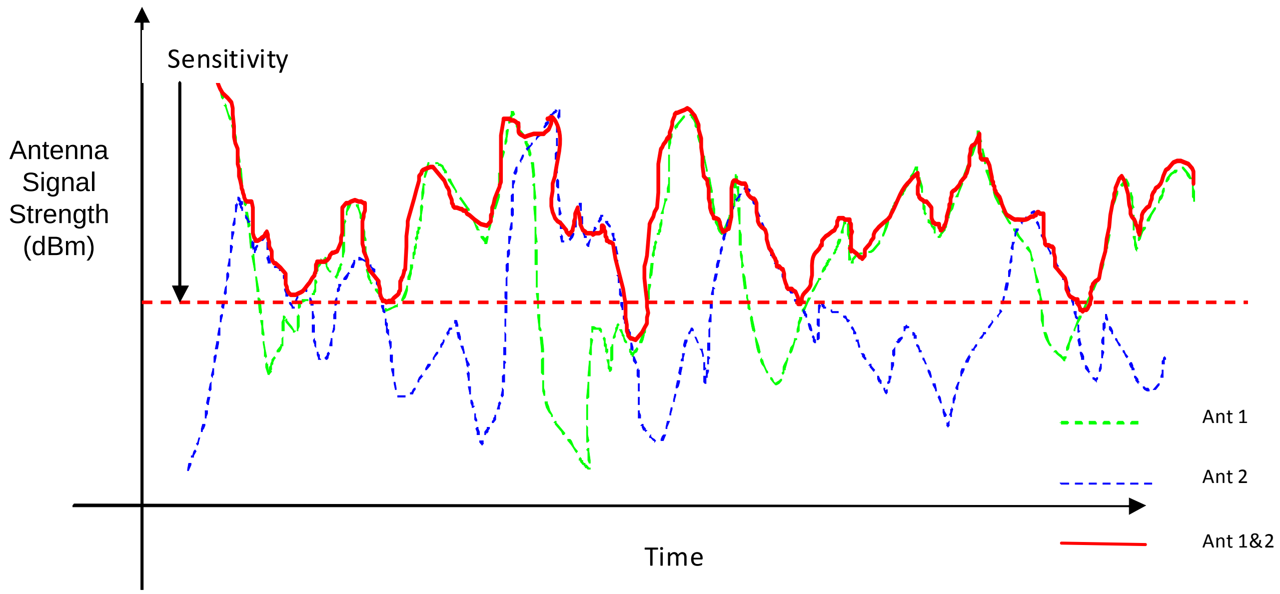

Figure 9. Antenna #1 and Antenna #2 with Uncorrelated Signal Inputs

This example demonstrates a more typical environment where the signal levels received at the two antennas are not identical, due to reflections and movements of people or objects in the environment.

In the above case, Antenna #1 sometimes receives the stronger signal, while at other times Antenna #2 receives the stronger signal. The antenna diversity algorithm will dynamically select the stronger of the two antennas, resulting in improved performance compared to the case of continuously selecting either Antenna #1 or Antenna #2.

These examples illustrate that if the propagation environment does not exhibit multi-path fades (e.g., an outdoor line-of-sight application free of any reflective objects), no improvement in performance will be observed by enabling antenna diversity. However, most applications require the device to operate under more demanding conditions that will be susceptible to multi-path fading; a definite improvement in performance may be obtained by enabling antenna diversity under such conditions.

3. Range Measurement Setup

To illustrate the benefit of antenna diversity, the link range performance of a board can be measured under real-life environmental conditions, with the antenna diversity functionality selectively disabled and enabled to demonstrate the performance improvement. However, this measurement is not a trivial task. Performing both tests (antenna diversity enabled and disabled) on one single board obviously requires the tests to be run at two separate times; the implication is that the two tests may not be subject to exactly the same fading conditions. As an alternative, the two tests could be performed simultaneously using two separate boards, with antenna diversity enabled on one board and disabled on the other. In this test scenario, differences in the receiver sensitivities could skew the results.

An instrument such as a dual-channel fading simulator can be used to create two signals (for the two antennas) that exhibit a repeatable fading profile with certain statistical properties. However, such an instrument may not be available to (or within the budget of) many users. Furthermore, there is no one single propagation model or fading profile that is appropriate for all users.

As a result, Silicon Labs has settled on the following test approach to verify link range and to demonstrate the benefit of antenna diversity:

1. Rather than searching to ***find*** a suitable dynamic multi-path fading environment, such an environment was ***created*** by testing in a typical indoor office with the receivers in continuous physical motion. This was accomplished by placing the receiver board(s) on a rotating platform or turntable. This turntable acted as a "fading simulator". The transmitter remained in a fixed location during the testing.
2. Due to uncontrollable factors (such as the random movement of people inside the building), the fading environment varied over time. Thus it was necessary to average multiple measurements to arrive at a statistical evaluation of the performance.
3. Multiple boards were simultaneously mounted on the rotating platform, with each board configured differently with regards to antenna selection and antenna diversity (e.g., fixed selection of Antenna #1 on Board #1, fixed selection of Antenna #2 on Board #2, antenna diversity enabled on Board #3, and so on). The performance of these boards was ***simultaneously*** measured, with the implication that each board was subjected to (approximately) the same fading conditions.
4. The test was performed for a sufficient period of time to allow reception of 10,000 packets, and the average packet error rate (PER) recorded. This allowed comparison of the performance of a board with fixed antenna selection (e.g., Board #1) with the performance of a board with antenna diversity enabled (e.g., Board #3), during a period of time where all boards are assumed to experience a similar fading environment due to their co-location on the same turntable.
5. Steps 3 and 4 were repeated but with a different selection of antennas or antenna diversity configuration on each board. This allowed averaging the performance across each board to eliminate performance differences between the different boards.

Figure 10. Transmitter Setup

In a normal range measurement test, the physical distance between the transmitter and the receiver would be increased until the performance of the link degraded to some reference threshold level (i.e., a desired packet error rate or PER). The distance between transmitter and receiver would be measured for each test configuration and used as the metric for determining which test configuration provided the optimum performance.

However, in this range measurement the physical distance between the transmitter and the receiver remained fixed. The output power level of the transmitter was adjusted up or down (as necessary) to result in link performance equal to the desired PER. This approach proved useful for conducting measurements inside a building with limited available physical space or range. It also allowed for simple determination of the amount of performance improvement obtained with antenna diversity, in units of dB. That is to say, if the output power level of the transmitter was reduced by 6 dB, and a receiver with antenna diversity enabled exhibited the same PER as a non-diversity board receiving the TX signal at full power, the conclusion would be that antenna diversity provided a link range improvement of 6 dB.

A series of SMA RF attenuators were used on the transmitter for precise control of the TX RF output level. If both antennas received a very strong signal, or if both antennas received very weak signals (below the RX sensitivity threshold), no improvement in performance with antenna diversity enabled could be observed. This is self-evident: if both antennas were "bad" or both antennas were "good” it made no difference which antenna was selected. It was when only one antenna was near the threshold of RX sensitivity that antenna diversity clearly demonstrated its usefulness. A transmitter with "adjustable" output level (via the RF attenuators) proved useful for creating such a test environment.

Figure 11. Measurement Setup with Turntable (artificial fading simulator) and Variac (for controlling the speed of rotation of the turntable)

Figure 11 illustrates how a Variac was used to control the speed of an electric motor which was connected to a platform used as a turntable. By adjusting the speed of the turntable, different fading conditions were realized.

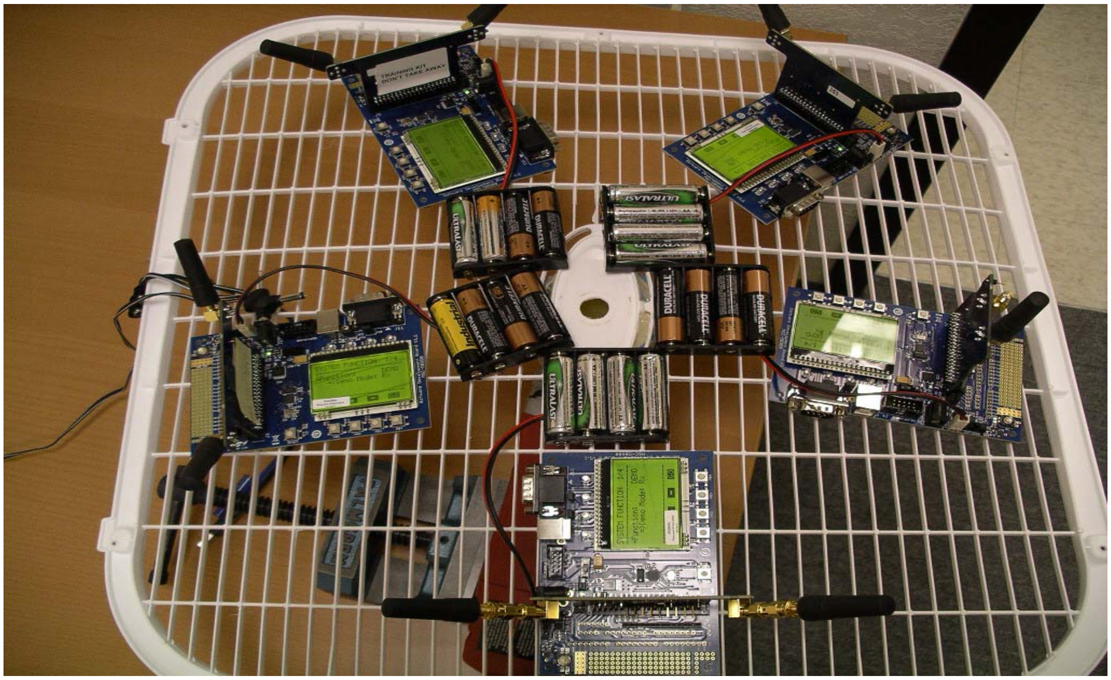

Figure 12. Arrangement of RF Test Boards on the Turntable

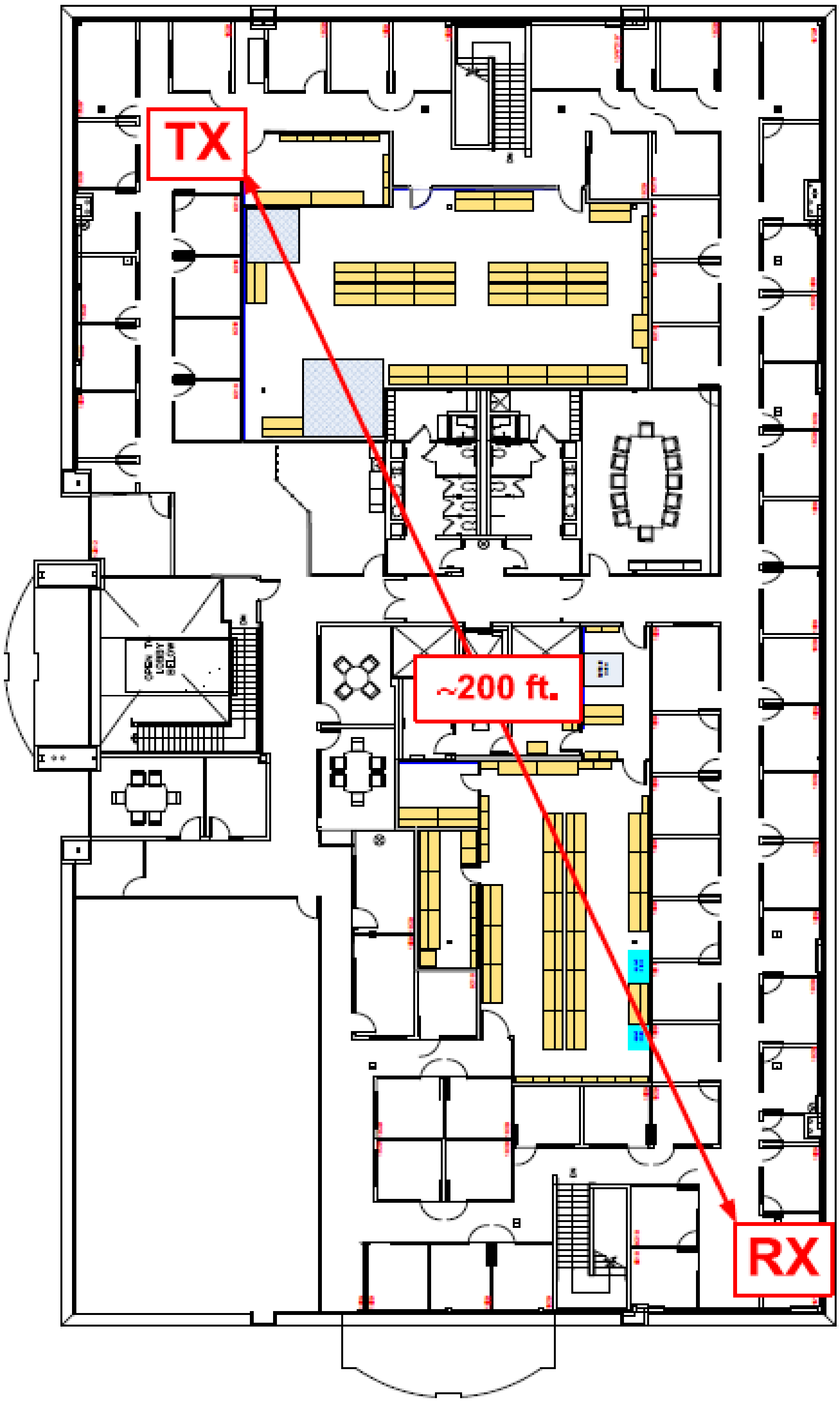

Figure 13. Plan View of the Indoor Office Environment for the Test, TX and RX Locations Demonstrated

4. Range Measurement Results

4.1. How the Results are Presented and Formatted

Measurements were conducted with the transmitter at a fixed location and the receivers mounted on a rotating turntable located a fixed distance away from the transmitter. Each measurement cycle consisted of four different runs, with each run consisting of 10,000 received packets. Multiple boards (five boards) were mounted simultaneously on the turntable. The antenna selection or the antenna diversity functionality on the boards were configured differently for each run as shown in the example table below:

Attenuation at	Antenna Configurations				
TX=x dB	**Brd#1**	**Brd#2**	**Brd#3**	**Brd#4**	**Brd#5**
Run 1	Fxd Ant1	Ant Div	Ant Div	Fxd Ant2	Non-Div
Run 2	Ant Div	Ant Div	Fxd Ant2	Fxd Ant1	Non-Div
Run 3	Ant Div	Fxd Ant2	Fxd Ant1	Ant Div	Non-Div
Run 4	Fxd Ant2	Fxd Ant1	Ant Div	Ant Div	Non-Div

Note: The runs (rows) compare antenna diversity performance with measurements taken at the same time. The boards (columns) compare antenna diversity performance with measurements taken on the same board.

This table is interpreted as follows: For the first run, Board #1 was set to fixed selection of Antenna #1 (i.e., no antenna diversity), Board #2 was set to enable antenna diversity, Board #3 was also set to enable antenna diversity, Board #4 was set to fixed selection of Antenna #2, and Board #5 was a non-diversity card and thus was inherently set to fixed selection of its single antenna. For the second run, the antenna configurations were modified to a different combination of settings, interpreted in a similar fashion.

For each run (i.e., horizontal line in the table) the average PER was calculated across those boards with antenna diversity enabled, and also the average PER was calculated across those boards with fixed antenna selection (i.e., non-diversity mode). This allows comparison of the average PER between diversity and non-diversity boards with measurements taken essentially at the same point in time.

For each board (i.e., vertical column in the table) the average PER was calculated across the runs with the board in antenna diversity mode, and also the average PER was calculated across the runs with the board in non-diversity mode. This again allows comparison of the average PER between diversity and non-diversity modes of operation on the same board.

4.2. Interpreting the Results

For each table, the important numbers to compare are the average PER values for each run (horizontal line) and each board (vertical column). In all cases, it may be observed that the PER in antenna diversity mode is less than in non-diversity mode. This difference indicates that antenna diversity provides a consistent improvement in performance.

In order to quantify the improvement in performance from antenna diversity, multiple measurements with different transmit power levels were taken. The goal of these measurements was to quantify how much additional power at the transmitter was required to achieve the same PER in a system with antenna diversity disabled, compared to a system with antenna diversity enabled. For example, demonstrating that it would take an additional 6 dB of TX output power to achieve the same PER results for a receiver with diversity disabled compared to a receiver with diversity enabled would clearly indicate the benefit of antenna diversity was equal to 6 dB.

To quantify this level of improvement, a series of tests were performed with reduced transmit power. In this reduced power condition, the difference in PER between non-diversity and diversity operation was recorded. For example there may be an average PER of 15% in non-diversity mode and 4% PER in diversity mode.

The transmit power level was then increased and the measurements repeated. The increase in transmit power level resulted in stronger received signal levels, thus reducing the average PER values for both diversity and non-diversity modes. The transmit power level was further increased until the PER in non-diversity mode dropped to the value of PER in diversity mode previously recorded with reduced transmit power level.

Note: The difference in transmit power level (in dB) required to achieve the same PER in non-diversity mode versus diversity mode is defined as the performance improvement obtained by enabling antenna diversity.

Using this test setup, results for GFSK modulation with different data rates, deviation levels, and with AFC enabled are presented.

4.3. Measurement Results for 10 kbps Data Rate, 40 kHz Deviation

Measured results for the case of 10 kbps data rate with ±40 kHz deviation (GFSK, AFC enabled) are presented in this section. The transmitter was initially set to a power level that was recorded as the reference TX power level. The average PER across all runs using antenna diversity was 7.84%, compared with an average PER of 14.93% across all non-diversity runs.

Reference TX Power Level	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	14.08%	7.16%	8.53%		14.78%	**14.43%**	**7.85%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	8.69%	7.10%	16.90%		16.60%	**16.75%**	**7.90%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	7.17%	17.22%	7.99%		19.98%	**15.06%**	**7.17%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	18.64%	7.73%	8.38%		22.34%	**16.24%**	**8.38%**
Board Avg of Non-Diversity Runs	**16.36%**	**12.48%**	**12.45%**	**(N/A)**	**18.43%**		
Board Avg of Diversity Runs	**7.93%**	**7.13%**	**8.46%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**14.93%**						
Total Board Avg of Diversity Runs	**7.84%**						

The TX output power was next increased in an attempt to reduce the non-diversity PER to (approximately) 7.84%. In this next test, the power level of the transmitter was increased by 2 dB and the measurements repeated. Note that the non-diversity PER measurement decreased to 11.3% which is still above the PER target of 7.84%.

Reference TX Power Level + 2 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	9.48%	4.54%	5.47%		11.32%	**10.40%**	**5.01%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	5.28%	4.74%	12.58%		11.50%	**12.04%**	**5.01%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	6.47%	10.80%	10.90%		12.70%	**11.47%**	**6.47%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	11.80%	10.90%	6.50%		12.40%	**11.70%**	**6.50%**
Board Avg of Non-Diversity Runs	**10.64%**	**10.85%**	**11.74%**	**(N/A)**	**11.98%**		
Board Avg of Diversity Runs	**5.88%**	**4.64%**	**5.99%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**11.30%**						
Total Board Avg of Diversity Runs	**5.50%**						

The TX power level was further increased by an additional 3 dB (5 dB above the reference TX power level) and the measurements repeated. In this test case the non-diversity PER measurement dropped to 9.01%, still slightly above the PER target of 7.84% from the initial antenna diversity test condition.

Reference TX Power Level + 5 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	7.33%	4.44%	4.73%		10.48%	**8.91%**	**4.59%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	4.45%	4.25%	10.82%		11.22%	**11.02%**	**4.35%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	3.74%	9.78%	6.77%		12.15%	**9.57%**	**3.74%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	9.60%	5.65%	4.70%		10.45%	**8.57%**	**4.70%**
Board Avg of Non-Diversity Runs	**8.47%**	**7.72%**	**8.80%**	**(N/A)**	**11.08%**		
Board Avg of Diversity Runs	**4.10%**	**4.35%**	**4.72%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**9.01%**						
Total Board Avg of Diversity Runs	**4.39%**						

The TX power level was further increased by an additional 3 dB (8 dB above the reference TX power level) and the measurements repeated. In this test case the non-diversity PER measurement dropped to 1.73%, which is now below the PER target of 7.84% from the initial antenna diversity test condition. Thus slightly more than a 5 dB increase in TX output power, but less than an 8 dB increase in TX output power, was required to achieve the same level of performance with antenna diversity disabled, compared with antenna diversity enabled.

Reference TX Power Level + 8 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	1.04%	0.62%	0.67%		2.66%	**1.85%**	**0.65%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	0.98%	0.67%	1.70%		2.15%	**1.93%**	**0.83%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	0.88%	1.88%	1.36%		2.80%	**2.01%**	**0.88%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	2.19%	0.64%	0.88%		2.42%	**1.75%**	**0.88%**
Board Avg of Non-Diversity Runs	**1.62%**	**1.26%**	**1.53%**	**(N/A)**	**2.51%**		
Board Avg of Diversity Runs	**0.93%**	**0.65%**	**0.78%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**1.73%**						
Total Board Avg of Diversity Runs	**0.78%**						

Antenna diversity consistently demonstrated improved performance when compared with non-diversity mode. This observation held true for measurements averaged over time on the same board, as well as for measurements averaged over several different boards.

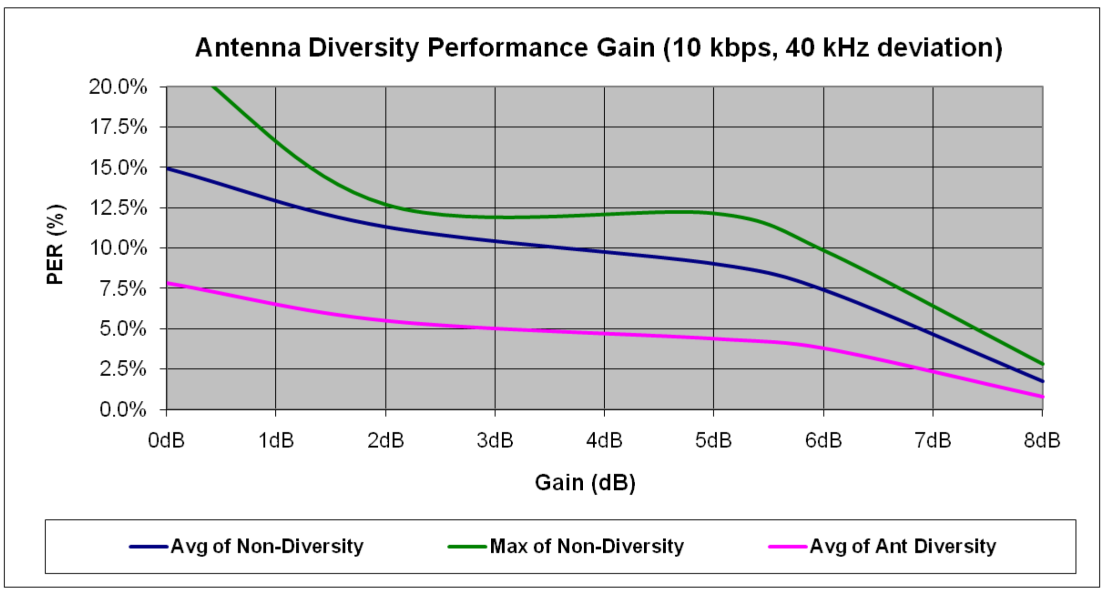

Figure 14. Antenna Diversity Performance Gain (Data Rate = 10 kbps)

The performance improvement provided by enabling antenna diversity may be more clearly estimated by plotting these measured PER values versus the change in TX output power level, as shown in Figure 14. This graph compares the PER between antenna-diversity and non-diversity modes at different TX output power levels. To achieve the same PER in non-diversity mode versus diversity mode, an additional ~5.8 dB of output power (on average) was required. In the worst case an additional ~6.5 dB increase was required.

4.4. Measurement Results for 40 kbps Data Rate, 20 kHz Deviation

The procedure described in "4.3. Measurement Results for 10 kbps Data Rate, 40 kHz Deviation" on page 15 was repeated at 40 kbps data rate and ±20 kHz deviation. The results obtained are given in the tables below.

Reference TX Power Level	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	9.76%	5.80%	6.86%		12.75%	**11.26%**	**6.33%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	9.24%	6.94%	36.95%		12.50%	**24.73%**	**8.09%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	8.97%	25.97%	8.30%		9.29%	**14.52%**	**8.97%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	22.24%	11.88%	5.99%		10.53%	**14.88%**	**5.99%**
Board Avg of Non-Diversity Runs	**16.00%**	**18.93%**	**22.63%**	**(N/A)**	**11.27%**		
Board Avg of Diversity Runs	**9.11%**	**6.37%**	**6.43%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**17.20%**						
Total Board Avg of Diversity Runs	**7.30%**						

Reference TX Power Level + 2 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	7.11%	4.30%	5.04%		7.57%	**7.34%**	**4.67%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	5.02%	4.97%	20.77%		5.85%	**13.31%**	**5.00%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	4.76%	20.46%	10.61%		8.53%	**13.20%**	**4.76%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	18.12%	3.01%	4.28%		9.47%	**10.20%**	**4.28%**
Board Avg of Non-Diversity Runs	**12.62%**	**11.74%**	**15.69%**	**(N/A)**	**7.86%**		
Board Avg of Diversity Runs	**4.89%**	**4.64%**	**4.66%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**11.97%**						
Total Board Avg of Diversity Runs	**4.73%**						

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Reference TX Power Level + 5 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	3.92%	3.13%	3.52%		6.12%	**5.02%**	**3.33%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	2.63%	2.77%	17.41%		5.83%	**11.62%**	**2.70%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	2.69%	11.60%	5.01%		5.58%	**7.40%**	**2.69%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	12.52%	1.97%	3.25%		7.47%	**7.32%**	**3.25%**
Board Avg of Non-Diversity Runs	**8.22%**	**6.79%**	**11.21%**	**(N/A)**	**6.25%**		
Board Avg of Diversity Runs	**2.66%**	**2.95%**	**3.39%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**8.12%**						
Total Board Avg of Diversity Runs	**3.00%**						

Reference TX Power Level + 8 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	1.09%	0.66%	0.89%		0.81%	**0.95%**	**0.78%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	0.34%	0.51%	3.10%		0.88%	**1.99%**	**0.43%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	0.65%	3.84%	1.30%		1.11%	**2.08%**	**0.65%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	2.60%	0.77%	0.63%		0.64%	**1.34%**	**0.63%**
Board Avg of Non-Diversity Runs	**1.85%**	**2.31%**	**2.20%**	**(N/A)**	**0.86%**		
Board Avg of Diversity Runs	**0.50%**	**0.59%**	**0.76%**	**(N/A)**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**1.80%**						
Total Board Avg of Diversity Runs	**0.61%**						

It can be estimated from these measurements that enabling antenna diversity provides approximately 5.9 dB improvement over the non-diversity mode of operation.

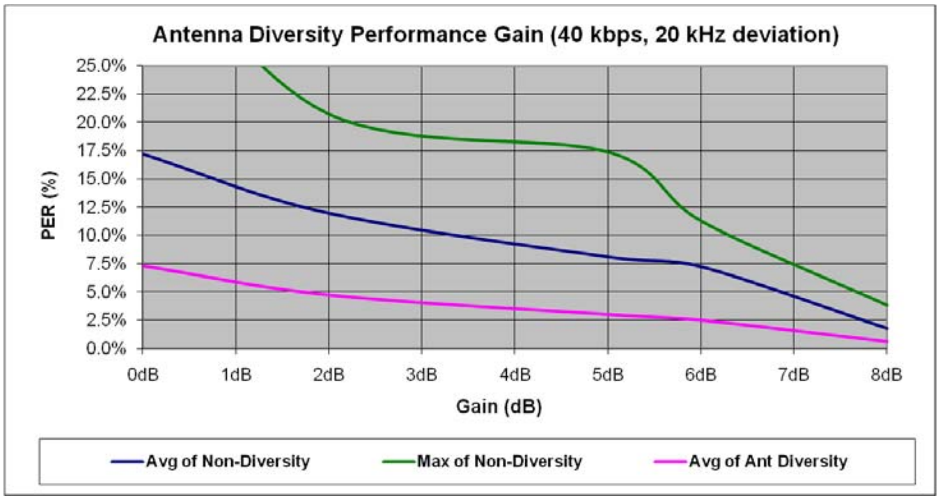

Figure 15. Antenna Diversity Performance Gain (Data Rate = 40 kbps)

4.5. Measurement Results for 100 kbps Data Rate, 50 kHz Deviation

The procedure described in "4.3. Measurement Results for 10 kbps Data Rate, 40 kHz Deviation" on page 15 was repeated at 100 kbps data rate and ±50 kHz deviation. The results obtained are given in the tables below.

Reference TX Power Level	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	8.72%	7.08%	6.70%	18.16%	9.01%	**11.96%**	**6.89%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	6.91%	5.56%	15.90%	9.73%	4.21%	**9.95%**	**6.24%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	5.23%	22.55%	10.30%	5.85%	9.19%	**14.01%**	**5.54%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	20.40%	8.81%	8.29%	4.79%	7.60%	**12.27%**	**6.54%**
Board Avg of Non-Diversity Runs	**14.56%**	**15.68%**	**13.10%**	**13.95%**	**7.50%**		
Board Avg of Diversity Runs	**6.07%**	**6.32%**	**7.50%**	**5.32%**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**12.96%**						
Total Board Avg of Diversity Runs	**6.30%**						

Reference TX Power Level + 2 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	2.12%	2.63%	3.66%	14.25%	4.58%	**6.98%**	**3.15%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	3.56%	5.79%	10.56%	3.17%	5.22%	**6.32%**	**4.68%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	3.71%	14.26%	6.32%	2.94%	6.77%	**9.12%**	**3.33%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	11.51%	4.03%	3.77%	4.00%	6.54%	**7.36%**	**3.89%**
Board Avg of Non-Diversity Runs	**6.82%**	**9.15%**	**8.44%**	**8.71%**	**5.78%**		
Board Avg of Diversity Runs	**3.64%**	**4.21%**	**3.72%**	**3.47%**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**7.78%**						
Total Board Avg of Diversity Runs	**3.76%**						

Reference TX Power Level + 5 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	2.19%	2.84%	2.73%	10.49%	5.59%	**6.09%**	**2.79%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	3.06%	2.04%	7.97%	7.28%	4.46%	**6.57%**	**2.55%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	2.98%	6.09%	4.21%	2.36%	4.36%	**4.89%**	**2.67%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	11.27%	4.69%	2.56%	2.40%	4.33%	**6.76%**	**2.48%**
Board Avg of Non-Diversity Runs	**6.73%**	**5.39%**	**6.09%**	**8.89%**	**4.69%**		
Board Avg of Diversity Runs	**3.02%**	**2.44%**	**2.65%**	**2.38%**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**6.36%**						
Total Board Avg of Diversity Runs	**2.62%**						

Reference TX Power Level + 8 dB	RX Brd#1	RX Brd#2	RX Brd#3	RX Brd#4	RX Brd#5	Time Avg of Non-Div Boards	Time Avg of Div Boards
Ant. Mode selection for Run #1	Fxd 1	AntDiv	AntDiv	Fxd 2	NonDiv		
Run #1: PER over 10K Packets	0.73%	0.87%	0.70%	2.26%	1.24%	**1.41%**	**0.79%**
Ant. Mode selection for Run #2	AntDiv	AntDiv	Fxd 2	Fxd 1	NonDiv		
Run #2: PER over 10K Packets	0.89%	0.86%	2.34%	0.80%	0.78%	**1.31%**	**0.88%**
Ant. Mode selection for Run #3	AntDiv	Fxd 2	Fxd 1	AntDiv	NonDiv		
Run #3: PER over 10K Packets	0.86%	1.29%	1.44%	0.68%	1.88%	**1.54%**	**0.77%**
Ant. Mode selection for Run #4	Fxd 2	Fxd 1	AntDiv	AntDiv	NonDiv		
Run #4: PER over 10K Packets	2.30%	1.89%	0.64%	0.61%	1.36%	**1.85%**	**0.63%**
Board Avg of Non-Diversity Runs	**1.52%**	**1.59%**	**1.89%**	**1.53%**	**1.32%**		
Board Avg of Diversity Runs	**0.88%**	**0.87%**	**0.67%**	**0.65%**	**(N/A)**		
Total Board Avg of Non-Diversity Runs	**1.57%**						
Total Board Avg of Diversity Runs	**0.76%**						

It can be estimated from these measurements that enabling antenna diversity in this environment provides approximately 5.4 dB improvement over the non-diversity mode of operation.

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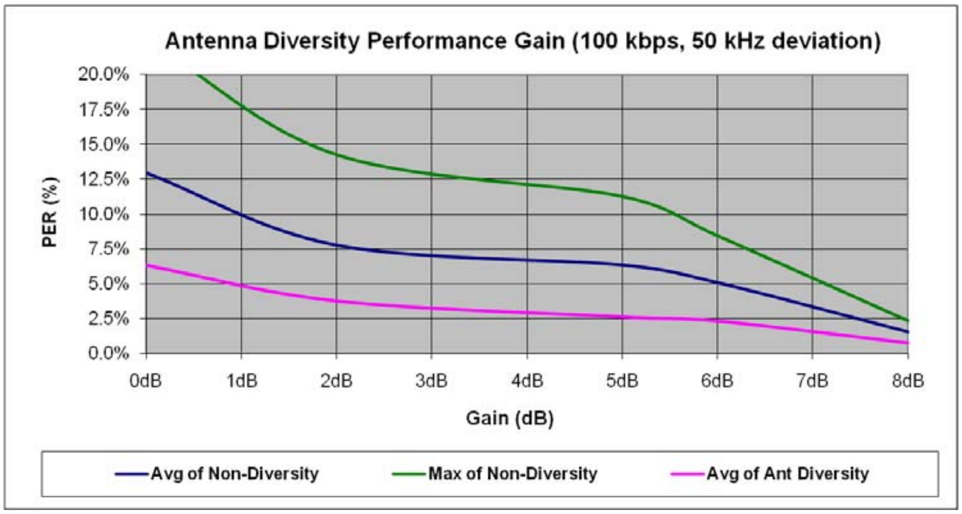

Figure 16. Antenna Diversity Performance Gain (Data Rate = 100 kbps)

5. Verification on Lab Test Bench

The measurement results presented in the previous section clearly demonstrate the benefit of antenna diversity, when operated in a real-world dynamic multi-path fading environment. However, it is also useful for the user to be able to create a simple test setup in a lab environment, using commonly-available test equipment, RF test cards, development kits, and Wireless Development Suite (WDS) software. This test setup may be used to visually inspect the various waveforms associated with proper operation of the antenna diversity algorithm such as the antenna diversity switch control signals, PREAMBLE_VALID, RXDATA, etc. The purpose of such a test setup is not to quantify the ***amount*** of performance improvement provided by antenna diversity, but instead is to provide the user with visual confirmation that the antenna diversity algorithm is functional (i.e., the strongest antenna is reliably selected).

5.1. Lab Test Setup and WDS Script

A typical lab test setup for verification of antenna diversity is shown in Figure 17. An arbitrary waveform generator (ArbGen) is programmed to provide one complete packet of TXDATA (including Preamble, Sync word, and Payload) that is connected to the External FM Modulation input of the signal generator. The RF output of the signal generator is split into two paths by a power splitter. A fixed RF attenuator (e.g., 6 dB) is installed in one path, while an adjustable RF attenuator is installed in the other path. In this fashion, the relative signal level of the two paths may be adjusted over both a positive and negative range. These two signal paths are connected to the two antenna inputs of the antenna diversity RF test card. It should be clearly understood that this test setup does not provide signals that vary in a dynamic (i.e., time-varying) fashion; the relative amplitude of the two signals remains fixed until the user adjusts the setting of the RF attenuator(s).

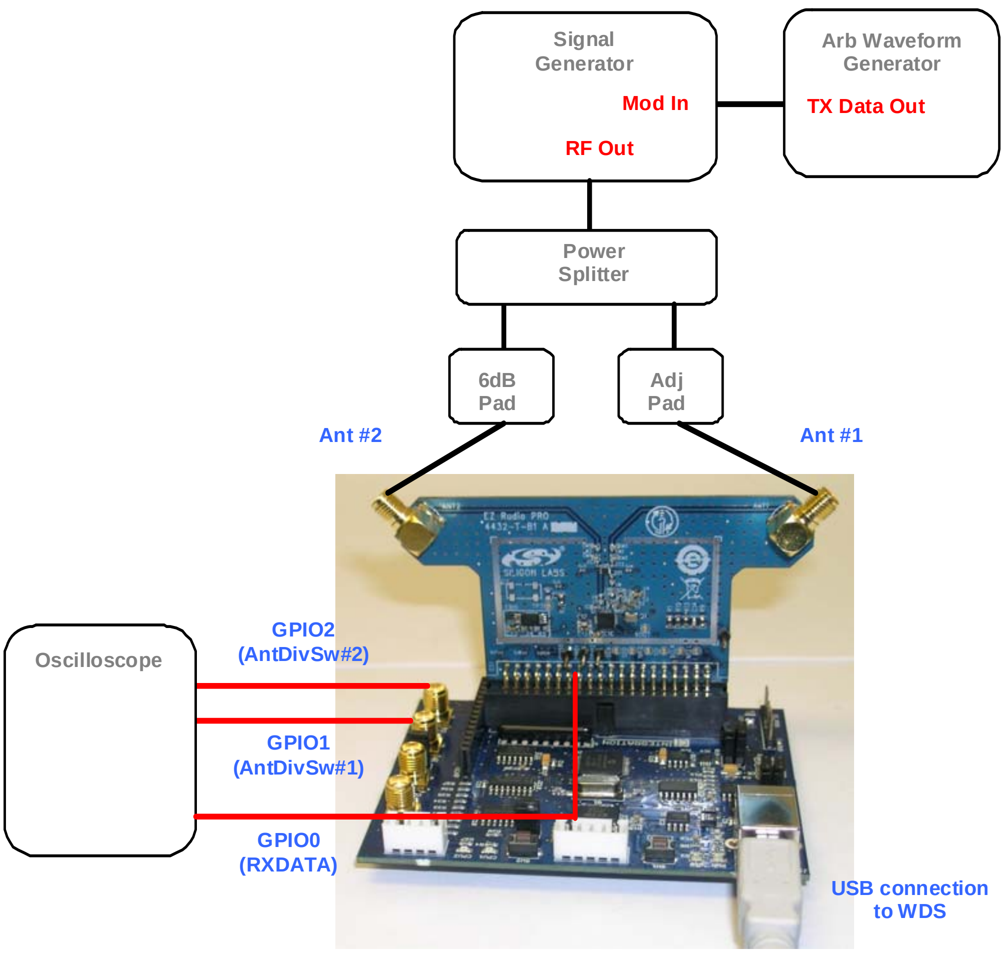

Figure 17. Lab Test Setup for Antenna Diversity

The Antenna Diversity RF Test Cards (e.g., 4432-T-B1-A-xxx or DKDB0) available from Silicon Labs require the mapping of two GPIO pins on the RFIC as control lines for the antenna diversity switch. These RF test cards are hard-wired to use GPIO1 and GPIO2 as the control lines for the antenna diversity switch, and thus are not available for any other function. This means that only GPIO0 remains available for output of signals such as RXDATA, PREAMBLE_VALID, etc. The user ***must*** ensure that, when operating with RF test cards available from Silicon Labs, the GPIO1 and GPIO2 signals are not accidentally re-defined for any purpose other than control of the antenna diversity switch.

An RX script appropriate for demonstrating the operation of antenna diversity is shown in detail below. This script may be executed from within WDS to place the RF test card into receive mode at a center channel frequency of 913.0 MHz. The RX modem parameters are optimized to receive a GFSK-modulated signal at a data rate of 40 kbps with 20 kHz peak deviation. The RX Packet parameters are configured to expect a packet structure with a 64-bit Preamble, a 2-byte Sync word with a value of 2DD4h, no Header, a 4-byte Payload, and no CRC checksum. The RX modem parameters used in this script are obtained directly from the EZRadioPRO Register Calculator worksheet. This script is appropriate for use with only 443x-T-B1-A-xxx or DKDB0 Antenna Diversity RF Test Cards; all other EZRadioPRO RF Test Cards are not recommended for use with this script.

Script Name: Rx_913.0MHz_PacketFIFO_GFSK_40kbps_20kDev_AntDiv.txt

```
#BATCHNAME RX 913.0 MHz Packet FIFO 40kbps w/AntDiv
# Revision Date:  1/20/2010
# This script is appropriate for use with EZRadioPRO:
#  443x-T-B1-A-x (or DKDB0) Split Antenna Diversity RF Test Card
#  Do NOT use with 443x-T-B1-B-x (or DKDB1) Split TX/RX RF Test Card
#  Do NOT use with 443x-T-B1-C-x (or DKDB2) Single Antenna RF Test Card
#  Do NOT use with 443x-T-B1-D-x Direct Tie RF Test Card
# Set SDN Pin 20 = LOW
L6
# Set VDD:  1.8V=V54, 2.4V=V7E, 3.0V=V98, 3.3V=VA1, 3.6V=VA9
VA1
# Apply Software Reset
S2 8780
# Adjust Crystal for zero freq error (User may need to modify this value)
S2 8971
### Set Desired Receive Frequency = 913.0 MHz ###
S2 F575
S2 F6A2
S2 F780
# Select TR Data Clock out via GPIO, FIFO Mode GFSK.
S2 F163
### Set RX Packet Parameters ###
# Enable automatic RX Packet Handling, Disable CRC
S2 B080
# Set Preamble Length = 16 nibbles (64 bits)
S2 B410
```

```
# Set Preamble Detection Threshold = 6 nibbles (24 bits)
S2 B530
# Set Fixed packet length, SYNC Word = 2 Bytes:  Sync Word 3 & 2
S2 B30A
# Set SYNC word = 2DD4h
S2 B62D
S2 B7D4
# Set TX-RX Packet Length = 4 bytes
S2 BE04
### Set RX Modem Parameters (from Excel Register Calculator) ###
# 40KBPS data rate, 20kHz dev, Mod Index=1, XtalTol=1/1, BW=83.2kHz
S2 9C02
S2 A064
S2 A101
S2 A247
S2 A3AE
S2 A405
S2 A521
S2 9D40
S2 AA1E
S2 E960
### Configure GPIOs ###
# Set GPIO0 = RXDATA output (with increased GPIO drive)
S2 8B94
# Set GPIO1 = AntDivSw #1
#   (GPIO1 is conveniently hard-wired to SMA connector on Load Board)
S2 8C17
# Set GPIO2 = AntDivSw #2
#   (GPIO2 is conveniently hard-wired to SMA connector on Load Board)
S2 8D18
# AntDiv Mode Enabled
S2 8880
### Turn Receiver ON ###
S2 8704
# Note that this script will receive one packet and automatically
# drop out of RX Mode.  Further packets may be received by
# simply re-entering RX mode (S2 8704) for each packet.
```

In the event that the user desires to receive an additional packet, it is not necessary to re-send the entire script shown above. This example script must be run once (to configure the RFIC for RX Packet FIFO Mode); subsequent packets may be received by simply turning the receiver on with the following one-line script:

```
### Turn Receiver ON ###

S2 8704
```

The user will need to create an RF test signal with the appropriate packet data structure. Possible methods of generation include the following:

- Manually programming an ArbGen or BER Analyzer with the required data packet structure, and using that to modulate a lab signal generator
- Using another Si443x RF Test Card in TX Packet FIFO mode as the test signal source

5.2. AntDiv Switch Control Signals to Demonstrate Antenna Selection

The example script above is not intended for purposes of BER measurement; instead, this script allows the user to configure the GPIO0 pin to output other interesting signals related to antenna diversity functionality and the reception of the packet, such as RXDATA, PREAMBLE_VALID, or the SYNC_OK signal. Figure 18 illustrates the reception of the RXDATA signal, overlaid with the antenna diversity switch control signals (AntDivSw #1 & #2).

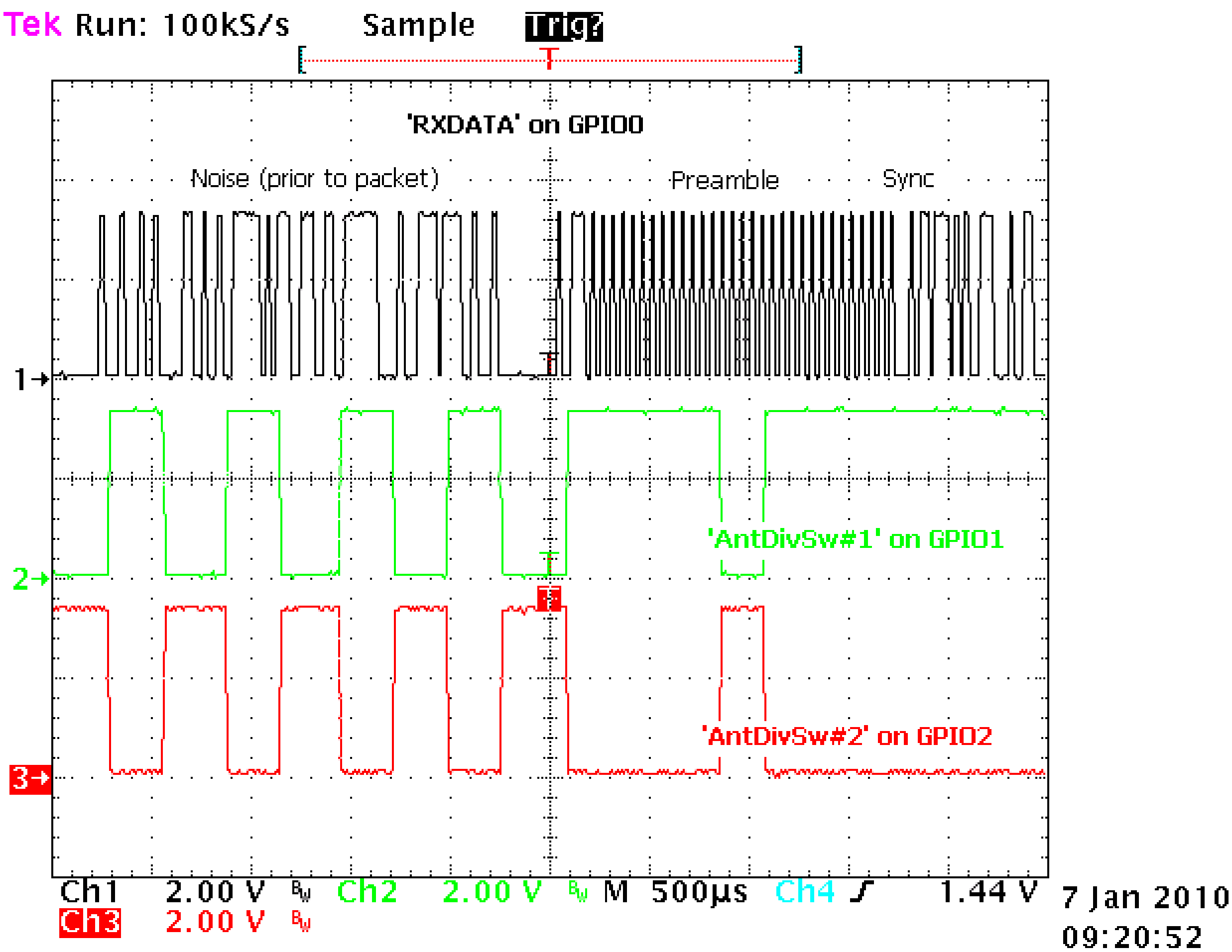

Figure 18. RXDATA and Antenna Diversity Control Signals in Diversity Mode

The traces in Figure 18 clearly demonstrate the periodic toggling between selection of antennas in the time period prior to the arrival of the transmit packet. After arrival of the transmit packet, the antenna diversity algorithm dwells on one antenna for a sufficient period of time to allow detection of the preamble and evaluation of RSSI, followed by switching to the alternate antenna for quick evaluation of the RSSI value on the other antenna. The antenna selection is then switched back to re-select the first antenna, as the RF attenuators had been configured to provide a stronger signal to Antenna #1 than to Antenna #2 (in this example).

The user should clearly understand that unless the system is designed for time synchronization between the transmitter and receiver, the receiver generally has no prior knowledge of when the transmit packet will arrive. Thus the state of the AntDivSw #1 & #2 control signals (and thus the state of antenna selection) is arbitrary at the instant the packet arrives, due to the periodic toggling between antennas. Figure 18 illustrates a case where the stronger antenna was arbitrarily selected at the arrival time of the packet; while the alternate antenna was subsequently evaluated for signal strength, the final decision was to switch back to the original (stronger) antenna for the remainder of the packet. However, there is an equal probability that the weaker antenna may be arbitrarily selected at the arrival time of the packet. In such a case, the algorithm proceeds to evaluate the signal strength of the alternate antenna, and remains on the alternate antenna for the remainder of the packet due to its greater signal strength. This is illustrated in Figure 19.

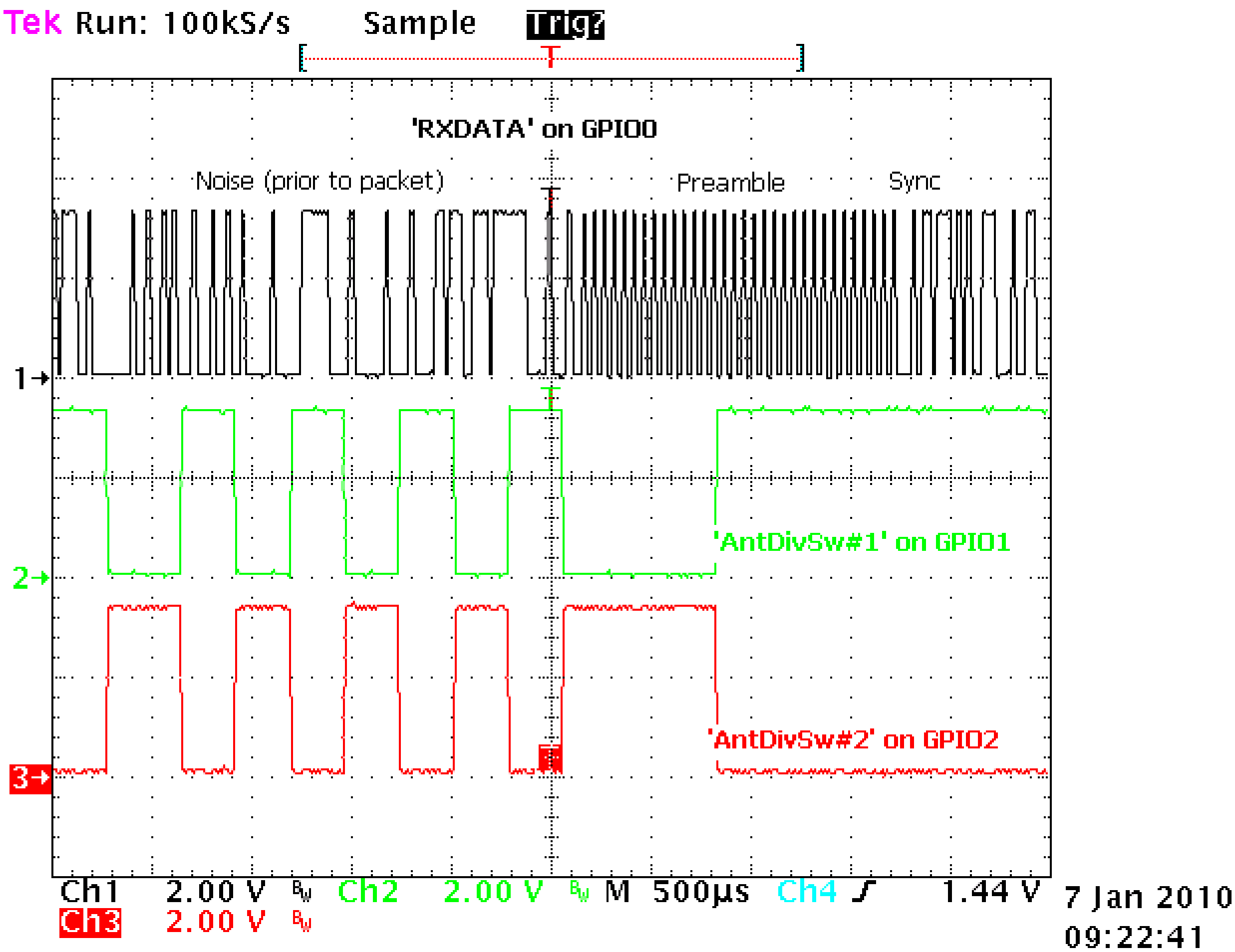

Figure 19. RXDATA and Antenna Diversity Control Signals in Diversity Mode (Alternate Timing)

The important point to be gained from these two plots is that, regardless of the initial state of antenna selection at the arrival of the packet, the stronger antenna was always reliably selected by the algorithm. In this example, the RF attenuator(s) were adjusted to provide a 6 dB stronger signal on Antenna #1 than on Antenna #2, and thus Antenna #1 was always selected.

Figure 20 demonstrates the case where the RF attenuators are adjusted such that the signal on Antenna #1 is 6 dB weaker than on Antenna #2. The result is that the final state of the AntDivSw #1 & #2 control signals now switch to indicate that Antenna #2 is selected to receive the remainder of the packet.

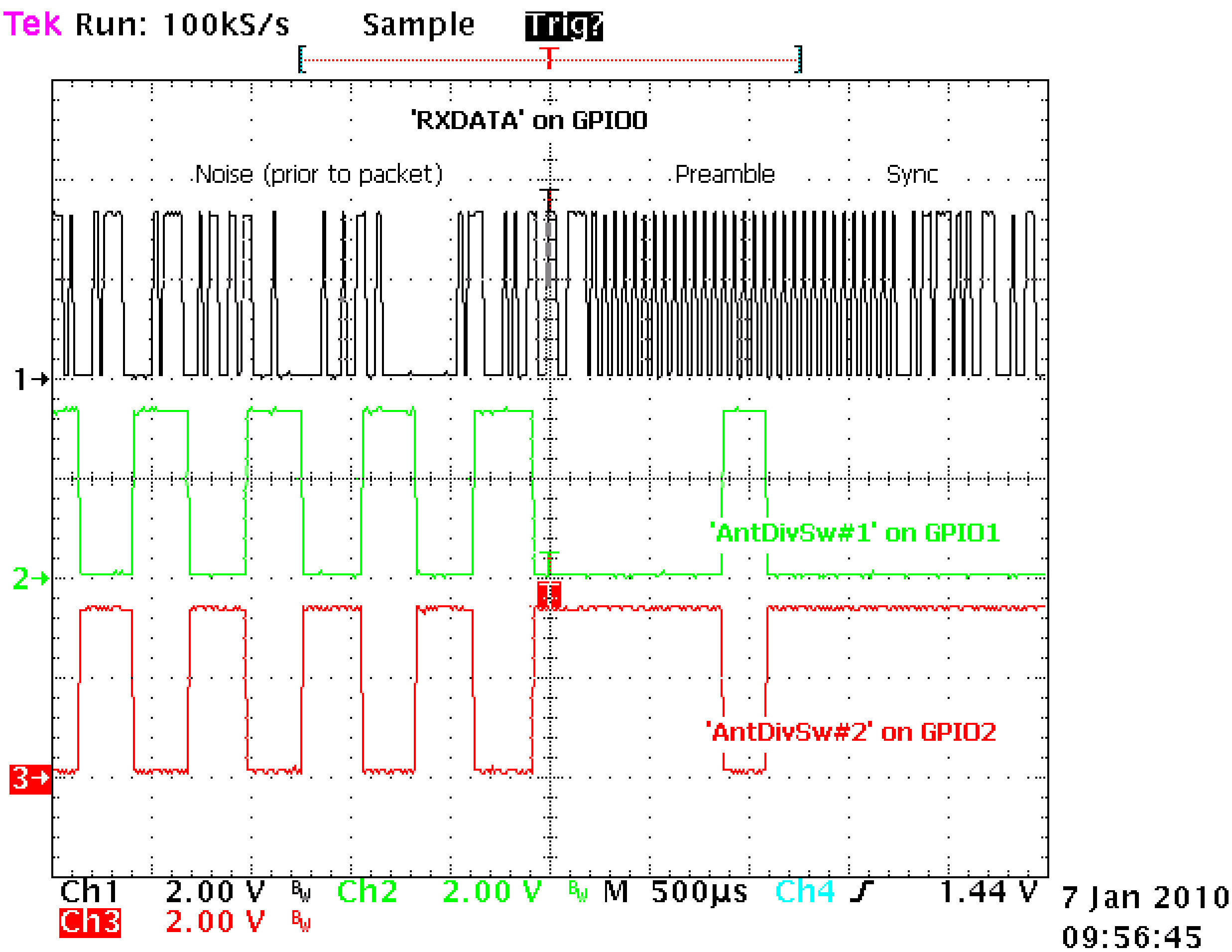

Figure 20. RXDATA and Antenna Diversity Control Signals in Diversity Mode (Alternate RF Levels)

It is self-evident that if equal signal levels are applied to both antenna inputs, the antenna diversity algorithm has no basis for selecting one antenna over the other. Under such conditions, the algorithm should select one or the other antenna as the "optimal" antenna with roughly equal probability. The window of uncertainty in the RSSI measurement and antenna signal strength evaluation process is only about 2 dB wide; at relative signal levels exceeding this value, the antenna selection is essentially error-free.

5.3. PREAMBLE_VALID in Antenna Diversity Mode

Signals other than RXDATA may be output on the GPIO0 pin. Specifically, it is informative to view the PREAMBLE_VALID signal during antenna diversity operation. The following script variation may be used to configure the chip to output PREAMBLE_VALID on the GPIO0 pin.

```
# Set GPIO0 = PREAMBLE_VALID

S2 8B19
```

As illustrated in the algorithm state diagram of Figure 7, the algorithm toggles antenna selection until arrival of the packet, as indicated by detection of a valid preamble (i.e., demodulation of the consecutive number of 1010 bits specified by the preath[4:0] field in SPI Register 35h). At this point in time, the chip issues a PREAMBLE_VALID signal, as illustrated in Figure 21. The algorithm evaluates the RSSI level on that selected antenna and then switches to the alternate antenna. The RSSI level is evaluated on the alternate antenna, but the preamble quality is not re-evaluated at this time. After switching back to (or remaining on) the stronger of the two antennas, the PREAMBLE_VALID signal is re-verified to confirm proper acquisition of bit timing. The PREAMBLE_VALID signal remains high until the Sync word is detected and the SYNC_OK signal goes active (not shown in Figure 21). (Note that in this example, the RF attenuators have been re-configured to again provide a 6 dB stronger signal at Antenna #1.)

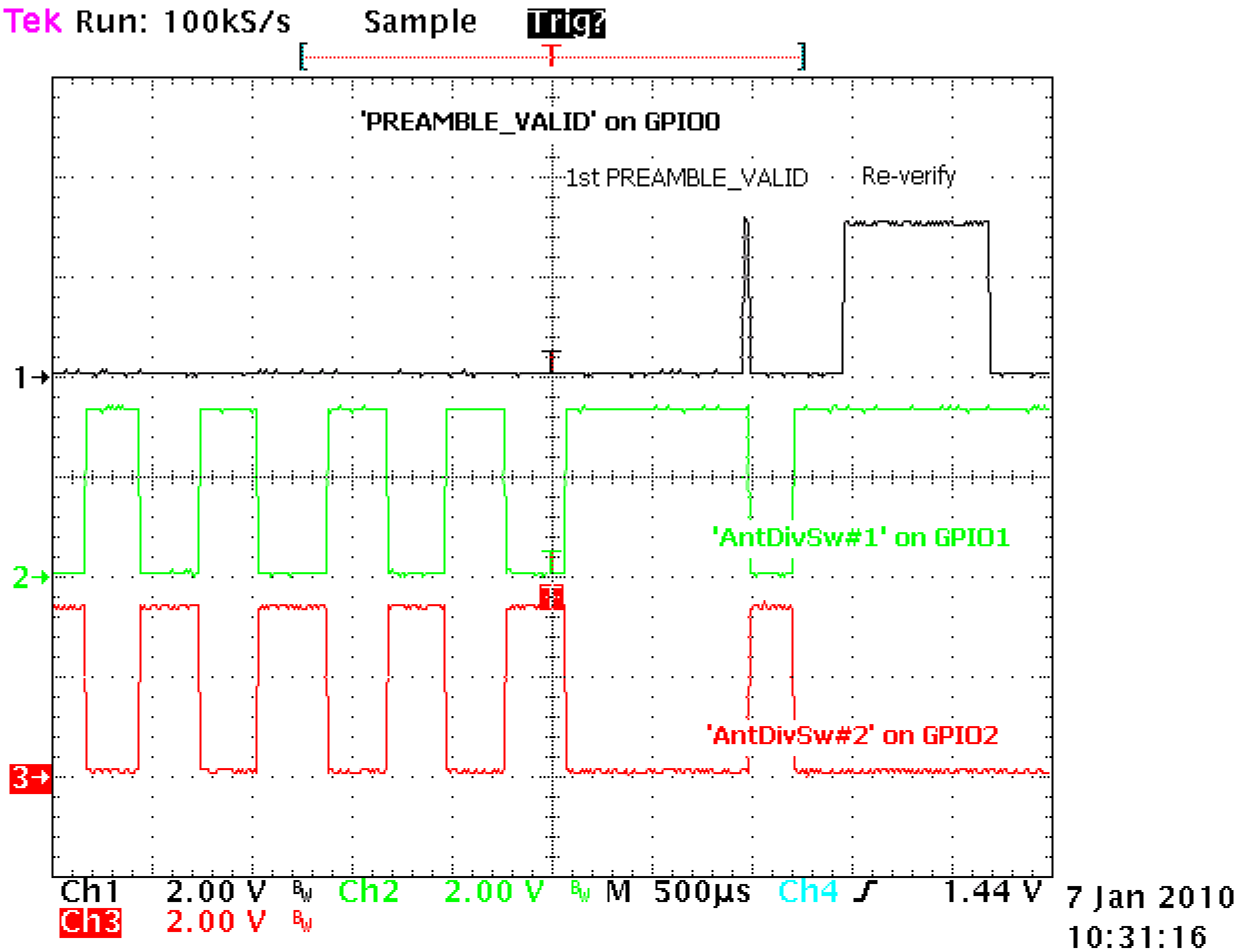

Figure 21. PREAMBLE_VALID in Diversity Mode

5.4. Faster Evaluation by Skipping Alternate Antenna Evaluation

As discussed in "2.3. Implementation of Antenna Diversity Algorithm" on page 6, under certain conditions the RSSI evaluation on the alternate antenna may be skipped, thus reducing the overall amount of time required to complete the antenna selection process. This may be advantageous in systems which desire to scan a large number of channels in the shortest possible amount of time. This functionality is enabled by setting the skip2ph bit in SPI Register 30h. The following script variation may be used to configure the chip to demonstrate this mode of operation.

```
# Enable automatic RX Packet Handling, set 'skip2ph' bit, Disable CRC
S2 B090
```

In this mode, the RSSI value for the antenna that first obtained a PREAMBLE_VALID indication (RSSI1 in Figure 22) is compared with the previous RSSI value, obtained on the alternate antenna. As no PREAMBLE_VALID signal was previously obtained on this alternate antenna, it is self-evident that the RSSI_prev value must reflect measurement of noise, prior to the arrival of the packet. Thus the difference in RSSI value between the current RSSI measurement and the previous RSSI measurement is indicative of how far the desired signal is above the noise floor of the receiver. If this difference in RSSI level exceeds a certain threshold (i.e., the desired signal is above the noise floor by a sufficient amount), the signal on that antenna is deemed strong enough to receive without bit errors, and thus there is no need to also evaluate the signal strength on the alternate antenna. That is to say, if zero bit errors may be obtained on one antenna, there is no point in switching to (or even evaluating) an alternate antenna that may potentially provide a stronger signal.

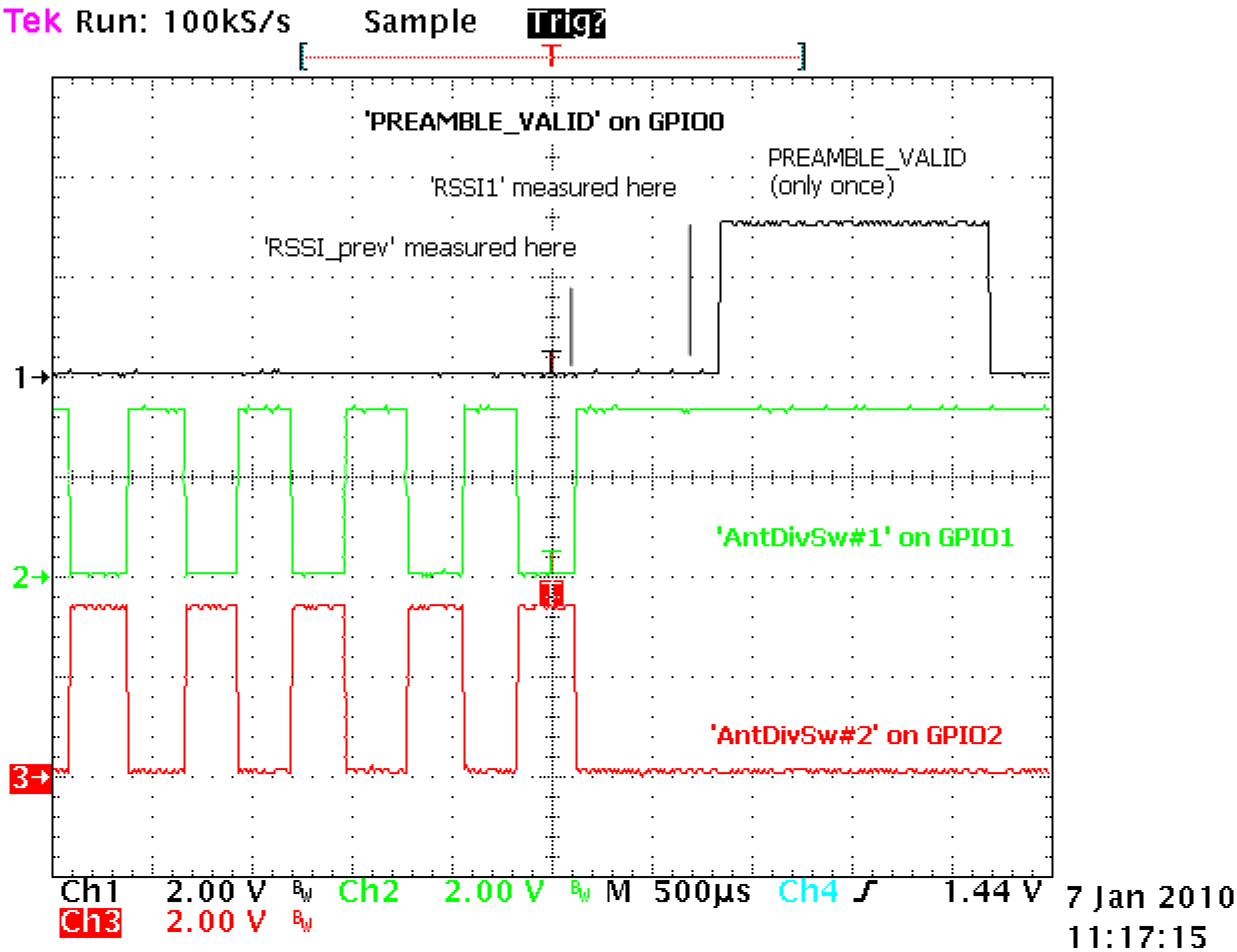

Figure 22. Skipping Alternate Antenna Evaluation

Figure 22 illustrates this mode of operation. For this test scenario, the RF attenuators were set so that the signal level on the alternate antenna was greatly reduced and below the noise floor of the receiver. The PREAMBLE_VALID signal is developed on the stronger antenna; however, no attempt is now made to switch to the alternate antenna, as the RSSI value of the current antenna (RSSI1) is judged to be sufficiently above the previous RSSI value (RSSI_prev). Thus only one PREAMBLE_VALID signal is issued.

The signal threshold that must be exceeded in order to skip evaluation of the alternate antenna is controlled by the skip2phth bit in SPI Register 21h, and is 16 dB for the default value of skip2phth = 0. Setting skip2phth = 1 results in a threshold value of 11 dB.

5.5. Antenna Diversity and AGC

The antenna diversity algorithm is designed to operate in the presence of signals with significantly different amplitudes on each antenna. As the algorithm rapidly switches between antennas, the signal level in the RX chain thus also changes rapidly, and may potentially require action by the automatic gain control (AGC) circuitry of the RFIC.

This is usually not of concern. Loss of link range due to multi-path fading conditions generally occurs at signal levels just above end-of-range sensitivity. For such weak signals, the AGC circuitry of the RFIC will cause the receiver to remain at maximum gain for either antenna, and no AGC gain switching will occur. This is illustrated in

Figure 23, where the following script variation is used to output the down-converted IF signal (from PGA I-Channel output) to GPIO0 and display it on a spectrum analyzer configured for zero-span mode (i.e., power-vs.-time display).

```
# Set GPIO0 = Analog Test Bus (p), PGA I-Channel Output
S2 8B0D
S2 D003
```

In this test scenario the RF attenuators are again set to provide a 6 dB stronger signal at Antenna #1 than at Antenna #2; however, the signal level at both antennas is chosen to be relatively weak, such that the gain of the receiver remains at maximum for both antennas and no AGC action occurs. The evaluation periods of both antennas are clearly visible in this plot.

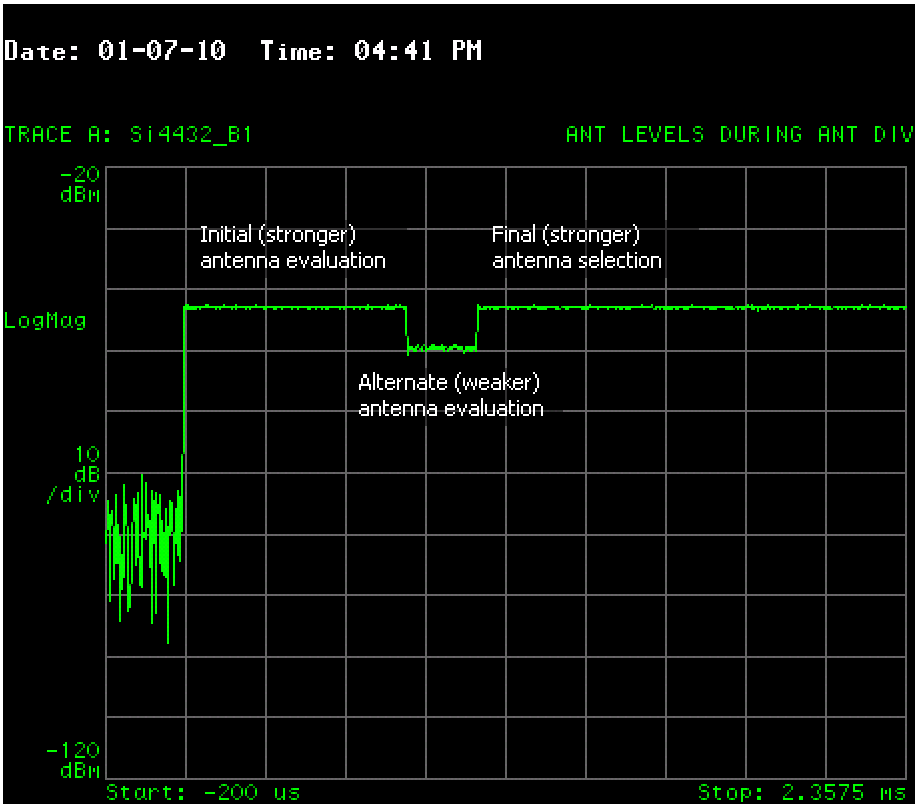

Figure 23. Signal Levels in RX Chain During Antenna Switching (below AGC)

However, even for signals that are sufficiently strong to require gain adjustment by the AGC circuitry, this is still not an issue. The AGC circuitry is capable of rapidly adjusting the receiver gain to handle the abrupt signal level changes that may result from switching antennas. This is illustrated in Figure 24, where the same 6 dB relative amplitude difference exists between the two antennas, but the absolute amplitude level has been increased to the point where AGC action results in the receiver chain. During evaluation of the weaker antenna (6 dB signal reduction at the alternate antenna input), the AGC circuitry increases the receiver gain to result in (nearly) the same signal level at the PGA output. In a similar fashion, the receiver gain is reduced upon final selection of the stronger antenna, again resulting in essentially a constant level at the PGA output.

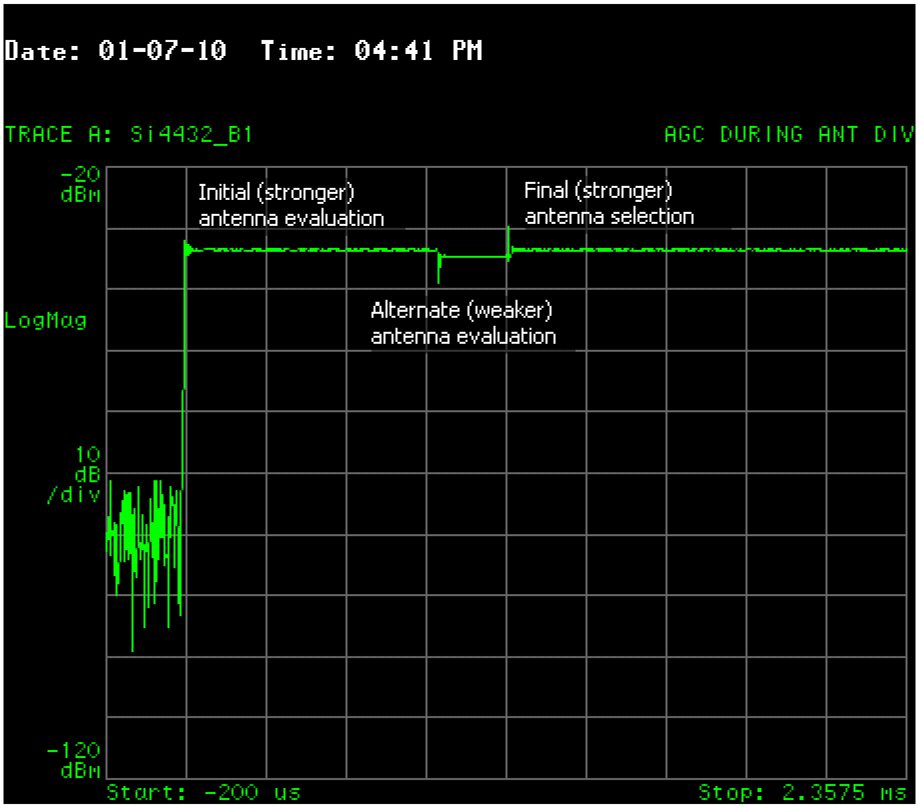

Figure 24. Signal Levels in RX Chain During Antenna Switching (with AGC)

If desired, the user can disable AGC gain increases during evaluation of a weaker antenna by clearing the sgin bit in SPI Register 69h; gain reductions, if required by an increase in signal strength, remain enabled at all times.

5.6. Antenna Diversity RSSI Value Registers

As the antenna diversity state diagram of Figure 7 illustrates, two separate RSSI measurement are performed; these measured RSSI values are stored and compared in order to determine the optimal antenna. These two antenna diversity RSSI values are stored in SPI Registers 28h and 29h.

The primary purpose of these two registers is for internal temporary storage of the two RSSI values to support the decision-making process of the algorithm. The RSSI values in these two registers may be read by the user over the SPI bus; however, the process is not straight-forward. The values held in these registers are cleared at the successful completion of a receive packet (i.e., PACKET_VALID signal), in preparation for reception of the next packet. As a result, these values cannot be read after the packet has completed; a READ to these registers at such a time will return all zeroes.

Under normal circumstances, the user should not require knowledge of these antenna diversity RSSI values. However, if the user absolutely desires to read these values, there are two options:

- Quickly read the contents of the two registers over the SPI bus, during the reception of the packet.
- Ensure that the packet does not issue a PACKET_VALID signal, thus remaining in RX mode and allowing the user time to read the two registers.

6. Conclusion

The Silicon Labs Antenna Diversity RF Test Card (443x-T-B1-A-x, or DKDB0) operated in a dynamic multi-path fading environment with the antenna diversity algorithm enabled provides nearly 6 dB improvement in link performance, when compared with operation with antenna diversity disabled (i.e., fixed antenna selection). It is possible that this amount of link range improvement can be increased further, as the small physical dimensions of the RF Test Cards (i.e., small spatial separation between antennas) may currently be limiting the performance. Boards with greater spatial separation between antennas, or with larger ground plane, might add to this improvement even more.

Antenna diversity provides the greatest benefit when signal conditions are near end-of-range sensitivity levels. In this scenario, antenna diversity will provide a robust link while operation with antenna diversity disabled may provide no-link performance. Under stronger signal conditions, selection of either antenna provides good link performance; in this scenario, antenna diversity performance is as good as non-antenna diversity performance.

A lab test setup and WDS script may be used to verify the functionality of the antenna diversity algorithm.

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