

Bluetooth Radio Transceiver IC Simulation -- includes GFSK modulated data, FHSS (Frequency Hop Spread Spectrum), Path loss, RF-to-IF conversion, and Quadrature Demodulation Also, the Design of an Analog, LC, 4-pole Gaussian Filter

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Summary

This is a simulation of an IC chip (integrated circuit) that can be used in the unlicensed ISM band as a Bluetooth radio as well as HomeRF and Upbanded DECT. There will be a brief description of the simulation, a review of the RF portion of the Bluetooth specs, a review of GFSK modulation, and then a detailed description of how to design each filter, amplifier, and mixer in SystemView. Several plots will illustrate the operation and trade-offs that can occur in this type of design.

Introduction to the Simulation

The actual RF IC chip for the Bluetooth radio contains one PLL (phase locked loop), a transmitter, and a receiver circuit. All of the filtering is done external to the chip. Additional external items are, an optional LNA (low noise amplifier) for the receiver, and an optional power amplifier (not used here). A Bluetooth radio alternates between transmitting and receiving (duplexes), and the one PLL does double duty. This simulation uses two FM tokens (VCO's) to take the place of the one PLL. A block diagram of the transmitter and receiver is shown in **Figure 1**.

The following two items speed up the simulation:

a. The Bluetooth hop command is specified as having a rate of 1.6 kHz. This simulation uses a hop rate of 16.0 kHz, which is 10 times faster. There is less data per hop.

b. Since an actual PLL is not included in the simulation, the frequency hop command is passed through a Chebyshev lowpass filter to simulate some of the ringing and settling time that a PLL would contribute to establishing a communications link. Instead of the usual 180 us setting time, this simulation uses 18 us, to correspond to the 10 times faster hop rate.

(At the end of this application note, on page 15, the frequencies of this system are rescaled to produce a simulation that runs much faster.)

Table 1 summarizes some of the similarities and differences between an actual Bluetooth system and this simulation.

Another important difference is in this simulation, verses the real world use, is that the transmitter and receiver are tied together by the LO (local oscillator) signal. Normally the task of synchronizing the PN sequence applied to the mixer's LO is done by a combination of the RF chip's PLL and a baseband processor.

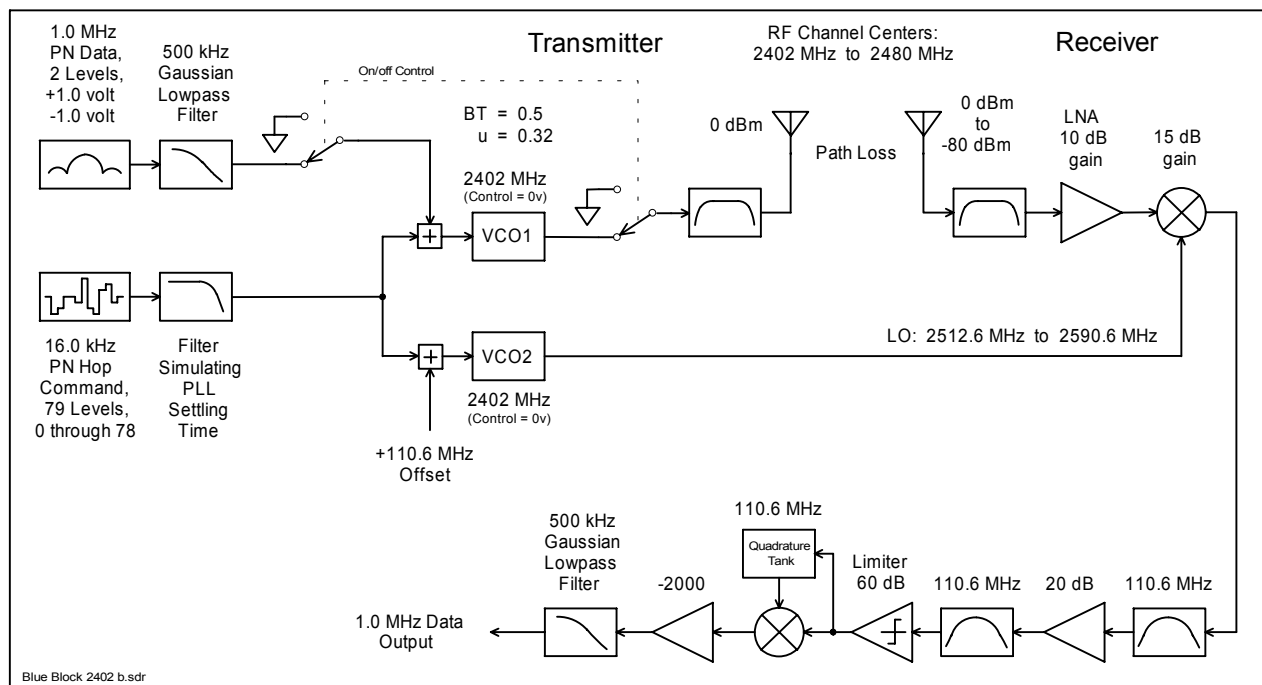


Figure 1. Block diagram of the SystemView Bluetooth simulation. (Note that the hop rate is 10 times faster than normal.)

	Bluetooth Spec. (USA)	Typical Hardware Design	This Simulation
Modulation Format:	GFSK	GFSK	GFSK
GFSK BT:	0.5	0.5	0.5
Modulation data rate (Bits/second):	1.0 e6	1.0 e6	1.0 e6
Modulation index:	0.28 to 0.35	0.28 to 0.35	0.32
Number of channels:	79 (0 - 78)	79 (0 - 78)	79 (0 - 78)
Channel spacing (Hz):	1.0 e6	1.0 e6	1.0 e6
USA ISM RF Band Range (Hz):	2400.0 e6 to 2483.5 e6	2400.0 e6 to 2483.5 e6	2400.0 e6 to 2483.5 e6
Transmitted RF Range -35 dB (Hz):	--	--	2401.0 e6 to 2481.0 e6
Transmitted Bandwidth -35 dB (Hz):	--	--	80.0 e6
Lower guard band (Hz):	--	2.0 e6	2.0 e6
Upper guard band (Hz):	--	3.5 e6	3.5 e6
RF channel center freq. (Hz):	2402.0 e6 to 2480.0 e6	2402.0 e6 to 2480.0 e6	2402.0 e6 to 2480.0 e6
IF center frequency (MHz):	--	110.592, 110.0, 43.0	110.6 e6
Hop rate (hops/sec):	1.6 e3	1.6 e3	16.0 e3
PLL settling time (seconds):	220.0 e-6	180.0 e-6	18.0 e-6
Time Domain Duplex method:	TDD	TDD	--
Duplex Format:	625 usec on and off	625 usec on and off	62.5 usec on and off

Table 1. Bluetooth RF hardware system specification. (-- Not known or not applicable)

Bluetooth RF Standards

A Bluetooth radio system uses the Industrial-Scientific-Medical (ISM) band. In the USA and Europe this RF band ranges from 2.400 GHz to 2.4835 GHz. In Spain, France, and Japan only parts of the ISM band are available (**Table 2**). The ISM band is open to any type of radio system -- cordless telephones, garage door openers, car security, and also random noise generators such as microwave ovens, and sodium vapor street lamps. In this band, microwave ovens are the strongest source of interference.

As seen in **Table 2**, there are 79 RF channels spaced 1.0 MHz apart in the 83.5 MHz bandwidth. In Spain, France, and Japan, a smaller band of 23 RF channels are available. Each of the 79 (or 23) channels is selected by a pseudo-random hopping sequence, using a cyclic code length of $2^{27}-1$. The maximum frequency hopping rate is 1600 hops/s. For a small network (piconet) of Bluetooth devices, this hopping sequence is unique for the net and is determined by the Bluetooth device address of a master device. The Bluetooth clock of the master also determines the phase in the hopping sequence.

The transmitting power is between 1 mW (0.0 dBm) and 100 mW (20 dBm). The low power consumption implies that a Bluetooth unit can operate on the power from a small battery for months. The nominal link range

for 0.0 dBm output power is 10 centimeters to 10 meters, but can be extended to more than 100 meters by increasing the transmit power to 20 dBm.

Four goals or benefits of a Bluetooth device are:

1. Minimal hardware dimensions, low complexity.
2. Low price on Bluetooth components, presently about \$25, hoping to get below \$5 in the future.
3. Low power consumption for Bluetooth connections.
4. A fast frequency-hopping scheme makes Bluetooth robust.

Piconet: Bluetooth devices are connected in a fashion that does not require predefinition or planning, as with a standard network. Two to eight devices can be networked into a piconet. Once connected, each device has equal access to the others. However, one device is defined as master, and the others are slaves. When two piconets overlap and link it becomes a scatternet.

An asynchronous channel can transmit as much as 721 Kb/s in one direction and 57.6 Kb/s in the opposite direction. It is also possible for a connection to support 432.6 Kb/s in both directions if the link is symmetric.

Country	Frequency Band	RF Channel Centers	
USA and most of Europe	2400.0 MHz to 2483.5 MHz	$f = 2402 \text{ MHz} + k \text{ MHz}$	$k = 0, \dots, 78$
Japan	2471.0 MHz to 2497.0 MHz	$f = 2473 \text{ MHz} + k \text{ MHz}$	$k = 0, \dots, 22$
Spain	2445.0 MHz to 2475.0 MHz	$f = 2449 \text{ MHz} + k \text{ MHz}$	$k = 0, \dots, 22$
France	2446.5 MHz to 2483.5 MHz	$f = 2454 \text{ MHz} + k \text{ MHz}$	$k = 0, \dots, 22$

Table 2. Assignments of the 79 or 23 channels of Bluetooth in various countries.

GFSK Modulation

A Bluetooth radio uses Gaussian Frequency Shift Keying (GFSK). A binary one is represented by a positive frequency deviation, and a binary zero is a negative frequency deviation. In this SystemView example a binary one will be +1.0 volt, and a binary zero is -1.0 volt. This binary bit stream is passed through a Gaussian lowpass filter that has a BTproduct of 0.5. Accordingly, for a binary data rate of 1.0 Mbits/sec the filter's -3.0 dB Bandwidth is 500 kHz.

$$\begin{aligned} \text{Filter's -3 dB cutoff} &= \text{BTproduct} \times \text{Bit rate} \\ &= 0.5 \times 1.0 \text{ e6} \\ &= 0.5 \text{ e6} = 500 \text{ kHz} \end{aligned}$$

The Bluetooth modulation index (μ) must be between 0.28 and 0.35. This SystemView example uses a modulation index of 0.32. The modulation index (μ) is the frequency deviation divided by bit rate. Therefore:

$$\begin{aligned} \text{Frequency deviation} &= \mu \times \text{bit rate} \\ &= 0.32 \times 1.0 \text{ e6} = 0.320 \text{ e6} \\ &= 320 \text{ kHz} \end{aligned}$$

With a frequency deviation of 320 kHz, the RF carrier for a binary 0 will be offset -160 kHz, and a binary 1 will produce a +160 kHz offset.

The symbol timing of the binary bit stream shall be better than ± 20 ppm.

A GFSK modulator is same as FSK modulator, except that before the baseband data pulses (-1, 1) go into the FSK modulator, they are passed through a Gaussian filter to make the pulse smoother to limit the transmitter's spectral bandwidth. With GFSK, the frequency climbs and falls slowly to the two frequency extremes. (With FSK the frequency jumps quickly to the two states.)

Detailed Bluetooth design using SystemView

The Bluetooth simulation in SystemView is shown in **Figure 2**. It is based on a National Semiconductor chip, LMX3162 (Reference 1, 2, and 3). There are two MetaSystems in the transmitter:

Blue_Mod_Tx_2402_b.mta (**Figure 3**) for the Tx

Blue_VCO_Rx_2402_b.mta (**Figure 4**)
for the receiver's LO (local oscillator).

A Gaussian filter is used to condition the TxData before it is applied to the modulator's VCO (FM token). The same Gaussian filter is used at the output of the receiver. A detailed description of this filter is given on pages 8 through 11.

Decimate tokens are used before most of the sinks to speed up the plotting time. 4096 samples in a plot window produce a good high-resolution plot. No decimation is used when the plot is to be a spectrum.

Figure 5 shows the simulation results with a hop between two frequencies. The top plot is an overlay of the hop command and the transmitter on/off command. The middle plot is an overlay of the output of the transmitter's Gaussian filter and the receiver's Gaussian filter. The frequency span of the plot is approximately 2400 MHz to 2480 MHz. The bottom plot shows the two received frequencies after a path loss of 70 dB. In **Figure 6** the number of hops has been increased to 6.3.

Selecting the System Sample Rate

The selection of the sample rate for this system took these items into account:

1. The system being simulated has 79 channels with center frequencies of 2,402 MHz to 2,462 MHz.
2. Because the desired IF frequency is 110.6 MHz, an LO of 2512.6 MHz to 2590.6 MHz is used for the system.
3. The sample rate should be at least 3 to 5 times the highest frequency in an analog system.

$$3 \times 2590.6 \text{ MHz} = 7.7718 \text{ GHz}$$

$$4 \times 2590.6 \text{ MHz} = 10.3624 \text{ GHz}$$

$$5 \times 2590.6 \text{ MHz} = 12.9530 \text{ GHz}$$

4. To get fast and accurate FFT amplitude readings, the number of samples, and sample rate parameters should be set numbers that are "powers of 2", so that the frequency resolution is a "round number".

Given the 4 items above, a sample rate of 10.48576 e9 samples/sec was selected. Using 1,048,576 samples gives a frequency resolution of 10 kHz.

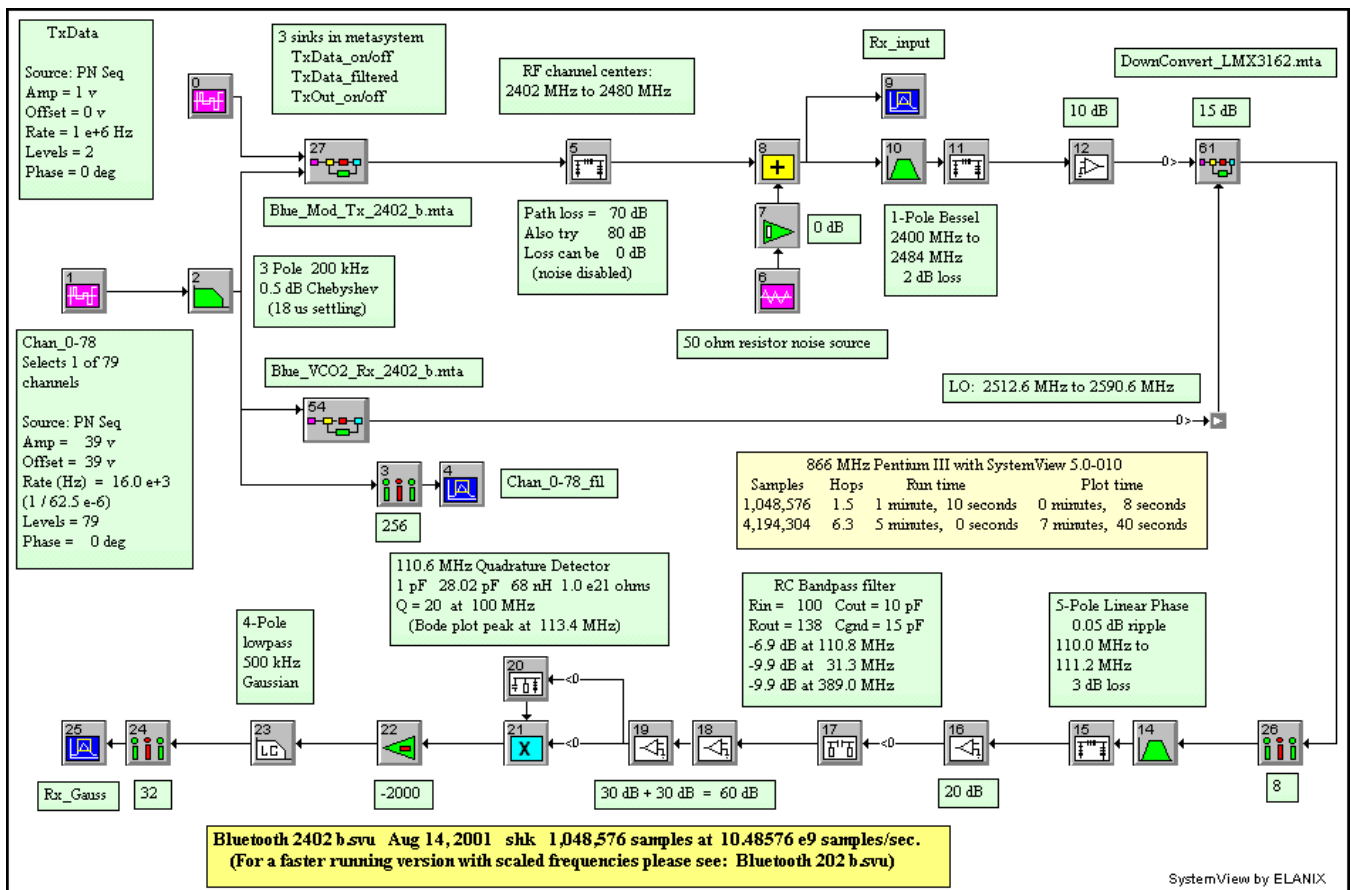


Figure 2. SystemView simulation of an IC chip used for a Bluetooth transmitter and receiver.

Blue_Mod_Tx_2402_b.mta

This MetaSystem (Figure 3) contains the Gaussian filter for the 1.0 bit/sec input data, a channel 0-78 hop command input, summing circuit, Modulator (VCO1), transmitter on/off switch, and output filter. The output of the Gaussian filter is also cycled on and off to make the overlapping plots easier to view.

The TX_Data input goes to a gain-of-2, decimate-by-8, Gaussian filter, and Hold token. These will be detailed in the next section on the Gaussian filter.

On page 3, the modulation index was set to 0.32. This means that the +/-1.0 volt output of the 1.0 MHz PN source, that represents the data, needs to be adjusted in amplitude so it can modulate VCO1 +/-160 kHz away from its current frequency setting. This is done by setting amplifier A1 to a gain as follows:

$$\text{Gain}_{A1} = 160 \text{ e}3 / 110 \text{ e}6 = 1.45454545454545 \text{ e-}3$$

The FM token (VCO1) is given the same modulation gain, 110 MHz/volt, as the VCO in the National Semiconductor chip. (This takes into account the times 2 multiplier in the National chip.)

The channel select, or hop command, is a PN source that varies in amplitude from 0.0 volts to 78.0 volts in

1.0 volt steps. This PN source needs to be adjusted in amplitude so it can shift VCO1's operating frequency from 0.0 MHz to 78.0 MHz away from its frequency setting of 2402.0 MHz. This is done by setting amplifier A2 to a gain as follows:

$$\text{Gain}_{A2} = 1.0 \text{ e}6 / 110 \text{ e}6 = 9.09090909090909 \text{ e-}3$$

The switch following VCO1 is used to cycle the transmitter on and off.

The filter at the output represents the antenna filter, which also is used in the receiver. The MuRata part number for this filter is DFCB22G44LBJAA. The 84 MHz, -3 dB, bandwidth is centered at 2,442 MHz. A 1-pole Bessel filter is a close match to the rolloff properties of the MuRata filter.

Blue_VCO2_Rx_2402_b.mta

This MetaSystem (Figure 4) is similar to the previous MetaSystem, except there is a +110.6 MHz frequency offset at the output so it can drive the receive mixer's LO. Also, there is no data signal in the Blue_VCO2_Rx_2402_b.mta.

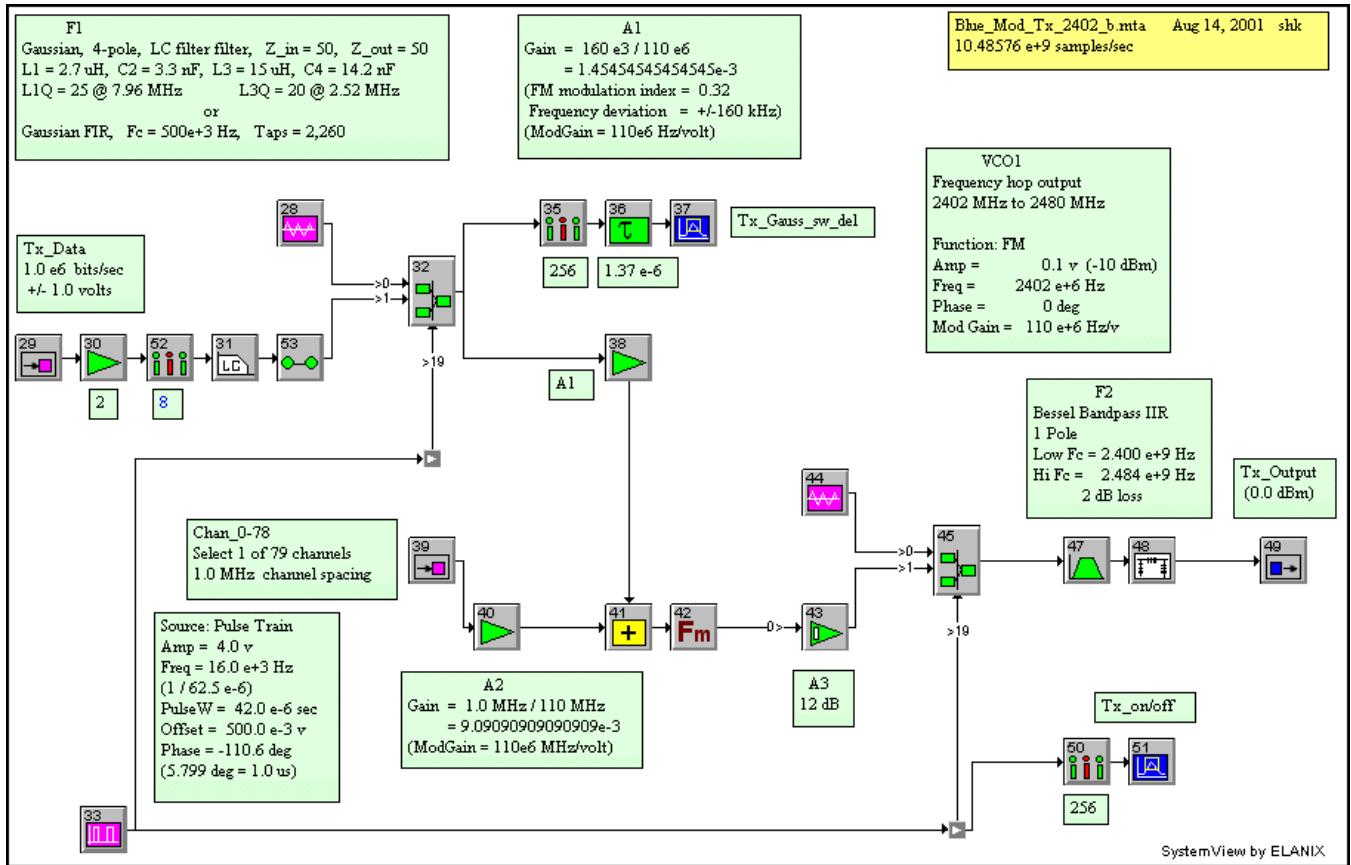


Figure 3. Gaussian filter, switch, summing circuit, VCO1 (FM), switch, and transmitter output filter.

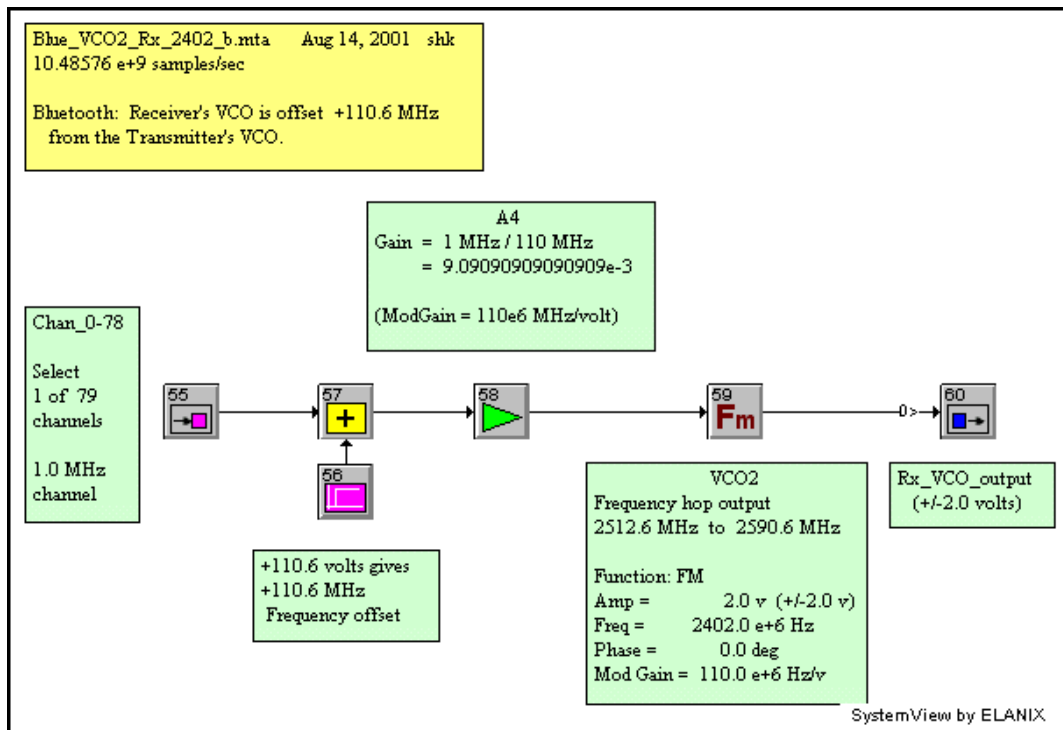


Figure 4. MetaSystem Blue_VCO2_Rx_2402_b.mta for the receiver.

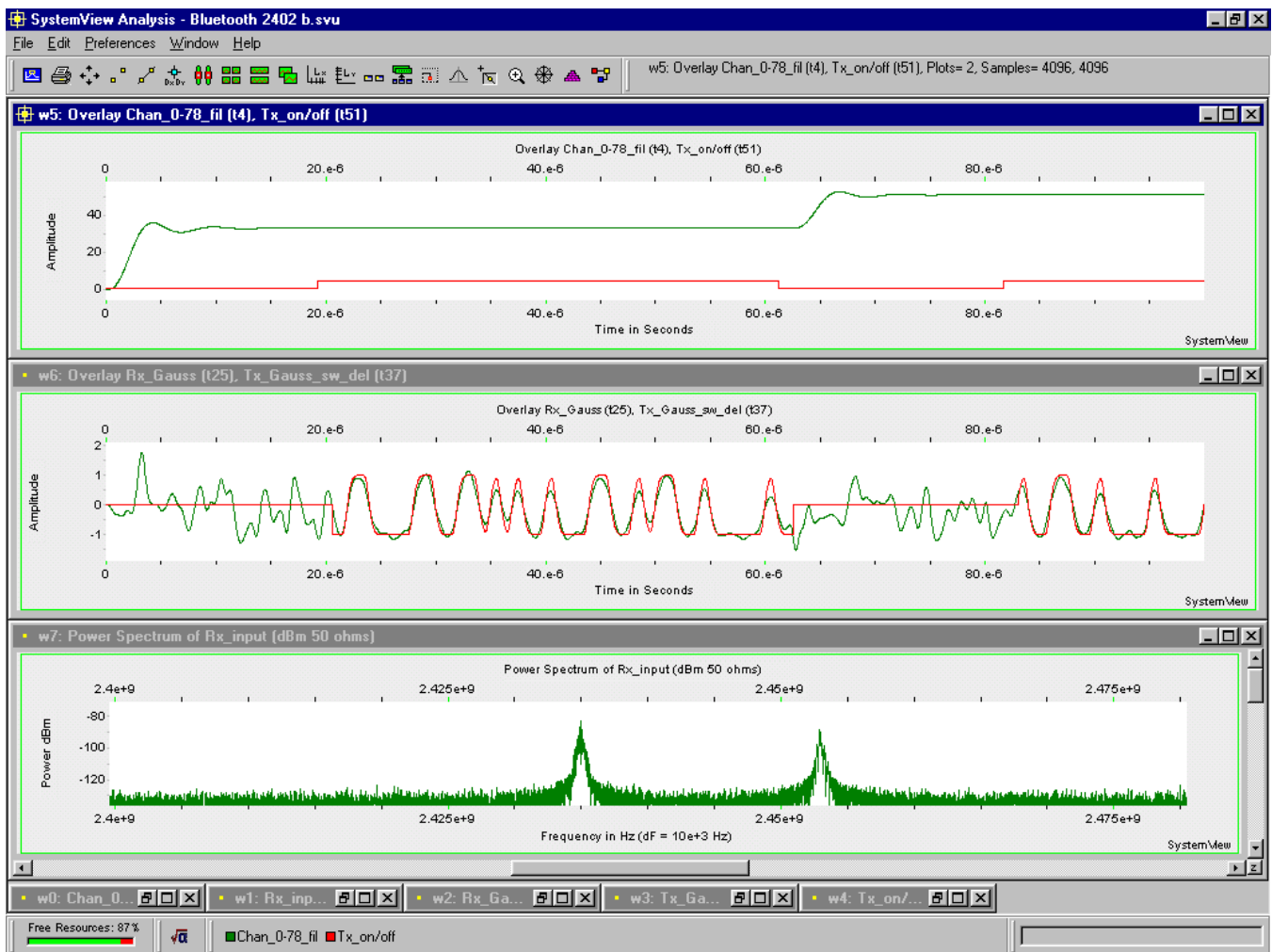


Figure 5. Path loss is 70 dB. (1,048,576 samples, 1.5 hops) (Fix Random Seed is set to 222.)

In the middle: The Tx_Gauss_sw_del (with the straight line) is compared with the Rx_Gauss (with the noise).

At the top: Each of the two channel commands settles in about 14 us, while the Tx cycles off for 18 us increments.

The channels are: 33, (top-left) and 51 (top-right).

At the bottom: The resulting spectrum is two signals, one at 2435 MHz (bottom-left) and the other at 2453 MHz (bottom-right).

(To get MHz, add 2402 to the channel number.)



Figure 6. Path loss is 70 dB. (4,194,304 samples, 6.3 hops) (Fix Random Seed is set to 222.)

In the middle: The Tx_Gauss_sw_del (with the straight line) is compared with the Rx_Gauss (with the noise).

At the top: Each of the 7 channels commands settles in about 14 us, while the Tx cycles off for 18 us increments.

The channels from left to right are: 33, 51, 62, 47, 49, 15, and 62 again).

At the bottom: The resulting spectrum center channels are (in MHz): 2435, 2453, 2464, 2449, 2451, 2417, and 2464 again.
(To get MHz, add 2402 to the channel number.)

Digital Gaussian FIR filter design

The previous section on *GFSK Modulation* indicated that a Gaussian lowpass filter with a -3 dB cutoff at 500 kHz is needed for the modulator. Either an analog LC filter, or a digital Gaussian FIR filter may be used.

A small test system (**Figures 7 and 11**) was created using the same sample rate that is used in the Bluetooth system. To reduce the number of taps needed by the Gaussian filter a decimate-by-8 token precedes the filter. (The same decimation will be necessary to keep the analog Gaussian filter from becoming unstable.)

First, a digital Gaussian FIR filter was setup using the *Linear Sys Filters* token in the *Operators Library* (**Figure 8**). On the right-hand side of **Figure 8**, the *Comm* filter button takes you to the communications filter window (**Figure 9**). Select Gaussian to get **Figure 10**. The recommended number of taps, 1024, is a useable filter, but its output amplitude is low. The amplitude can be checked by using the small test system (**Figures 7, 11, 14 and 15**) or by using the *Bode Plot* button in **Figure 8**. A setting of 2,260 taps produces a filter that has zero loss when a relatively long rectangular pulse is sent through the filter. The relatively large number of taps, 2,260, of two of these FIR filters (in the transmitter and receiver) causes the simulation to take about 4 times as long when compared to two 4-pole lowpass LC analog Gaussian

filters. One way of speeding up the simulation is to use a greater decimation to further reduce the sample rate going into the FIR filter, adjusting the number of taps as necessary, and then let the hold token to bring the output of the FIR filter back up to the system rate. Be aware that the output of the Hold token will also contain alias frequencies. This is not a problem if they are removed by other filters in the system.

Another way of speeding up the simulation, and building the actual hardware, is to use a discrete component LC (inductor/capacitor) lowpass filter. Philips Semiconductor has the following application note, discussing how a 4th-order Gaussian lowpass filter can be used for both pre-modulation and post demodulation filtering:

AN1997

Philips FM/IF systems for GMSK/GFSK receivers, page 6-3, Aug 20, 1997, available on the Internet

The following pages 10 and 11 are devoted to designing and documenting an analog LC 4-pole lowpass Gaussian filter.

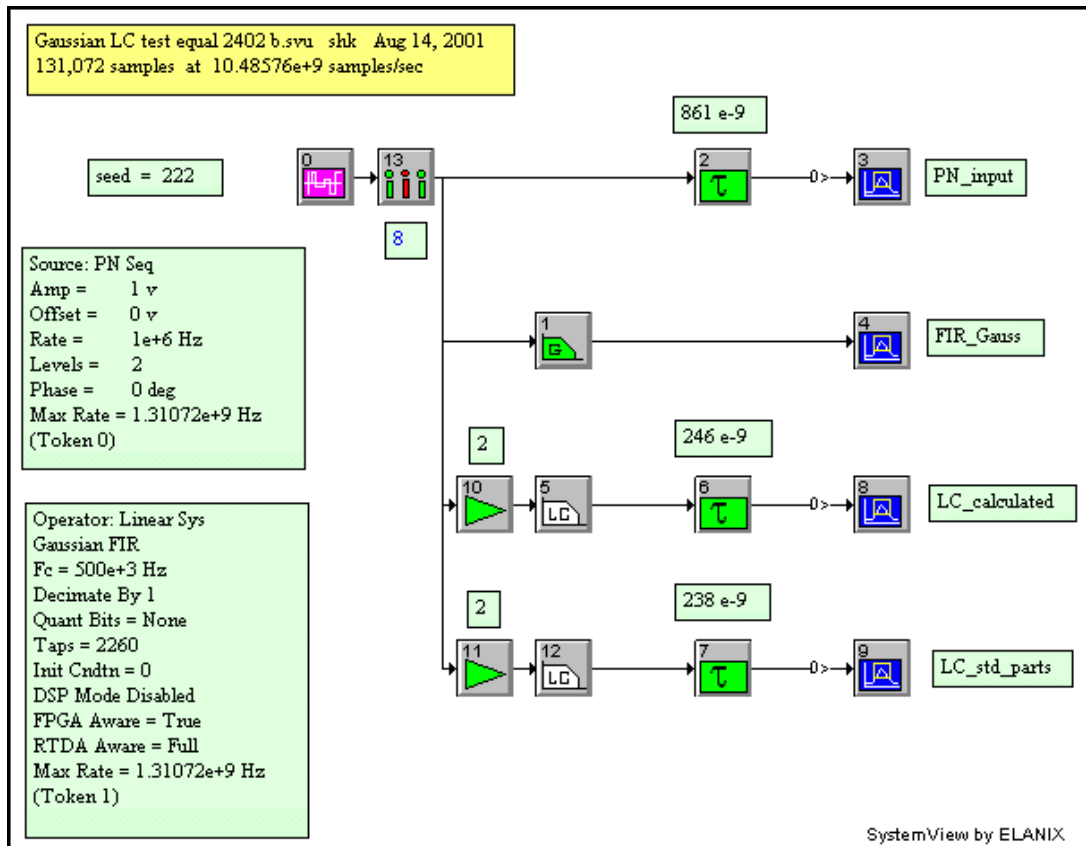


Figure 7. Test system for the Gaussian filter.

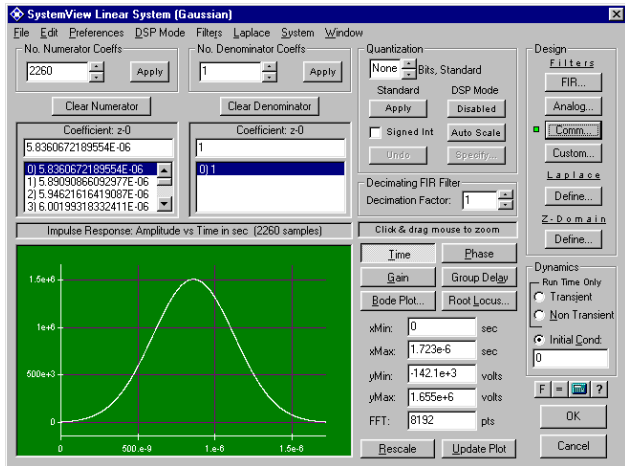


Figure 8. The Gaussian filter token is part of *Linear Sys Filters* in the *Operators Library*.

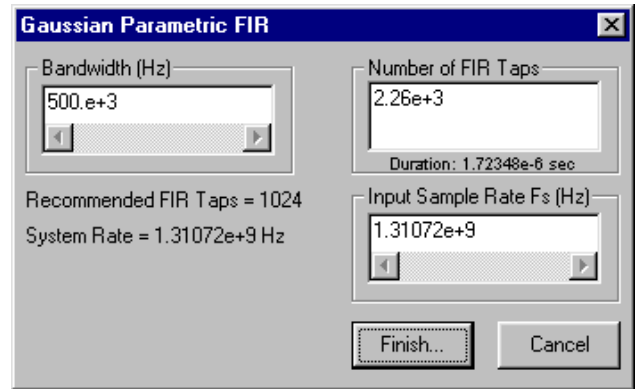


Figure 10. 2,260 taps are used instead of the recommended 1,024 taps.

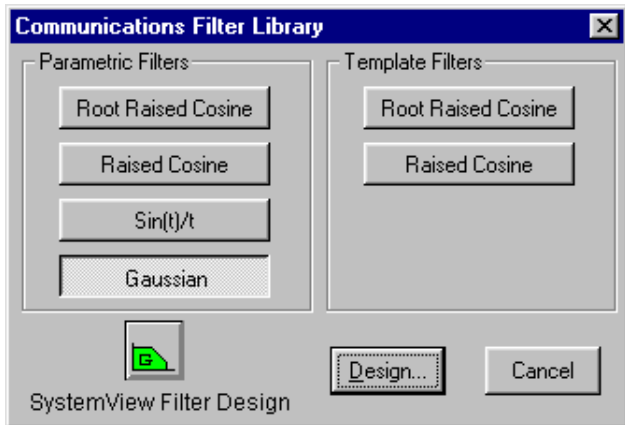


Figure 9. The Gaussian button is selected.

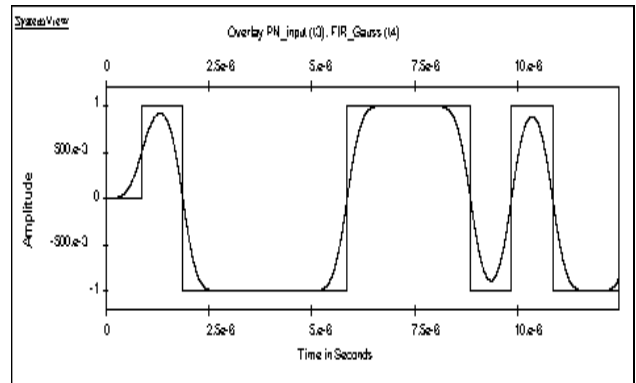


Figure 11. The input and output of a 2,260-tap 500 kHz Gaussian FIR filter.

Analog Gaussian Filter Design -- Equal Termination

The Gaussian filter transmission function has a smooth cutoff and a constant group delay. A 4-element filter can approximate the Gaussian response within 1 dB down to about the 11 dB point, a 6-element filter down to about 18 dB, and 8-elements down to about 26 dB. The design that follows is for a 4-element filter.

Standard component values are used for the analog filter parts. The resulting filter is shown in **Figure 12**. Since the filter has equal termination resistors, its maximum output voltage is 1/2 the input voltage. A gain-of-2 token, preceding the filter, compensates for this loss. A decimate-by-8 token is used to reduce the 10.48576 e9 sample rate to 1.31072 e9 samples/second. This is necessary to keep the LC filter stable. **Figure 13** is a

Bode plot of the LC filter. **Figure 14** shows a step response test system for the analog and digital filters. The 500 kHz, 2,260-tap Gaussian FIR filter, is compared to an analog Gaussian filter using both calculated and standard part values. The results are plotted in **Figure 14**, with the delays adjusted for a best fit considering both zero-crossing and the peaks. **Figure 15** and **Figure 16** show magnified views. Standard part values are used in the transmitter and receiver Gaussian filters. (No difference was seen when both calculated and standard part values were tried in the simulation. A bit error rate (BER) test may show a difference, but it was not performed.)

4-pole LC, Gaussian filter, from:

Handbook of FILTER SYNTHESIS by Anatol I. Zverev John Wiley & Sons 1967

Page 332, GAUSSIAN RESPONSE, LOW PASS ELEMENT VALUES

The design is for a 4-pole filter.

Since Z input = 50 ohms and Z output = 50 ohms, select: n = 4, Rs = 1.0000

Top Labels:	n	R _s	C ₁	L ₂	C ₃	L ₄
	4	1.0000	0.1772	0.5302	0.9321	2.2450
Bottom Labels:	n	1/R _s	L ₁	C ₂	L ₃	C ₄

Table 3. These values are from the book above, page 332.

Since the input is a voltage source with a 50 ohm impedance, and the output is 50 ohms, use the schematic at the bottom of page 332, and the labels at the bottom the table.

The input impedance is: **z = 50 ohms**

The required -3 dB frequency lowpass cutoff is: **f = 500 kHz**

$$L1 = (0.1772 \times z) / (2 \times \text{PI} \times f) = 2.820 \text{ e-6 Henry, use } 2.7 \text{ uH} \quad (Q = 25 \text{ @ } 7.96 \text{ MHz})$$

(Toko FSLU2520-2R7J)

$$C2 = 0.5302 / (2 \times \text{PI} \times f \times z) = 3.375 \text{ e-9 Farad, use } 3.3 \text{ nF}$$

$$L3 = (0.9321 \times z) / (2 \times \text{PI} \times f) = 14.83 \text{ e-6 Henry, use } 15.0 \text{ uH} \quad (Q = 20 \text{ @ } 2.52 \text{ MHz})$$

(Toko FSLU2520-150J)

$$C4 = 2.2450 / (2 \times \text{PI} \times f \times z) = 14.29 \text{ e-9 Farad, use } 12.0 \text{ nF} + 2.2 \text{ nF} = 14.2 \text{ nF}$$

(The extra 2.2 nF capacitor is not really necessary, but it does make the filter response closer to the ideal.)

Standard values are used for the inductors and capacitors.

The capacitors shown are available as 5% values.

The inductors shown are available as 10% values.

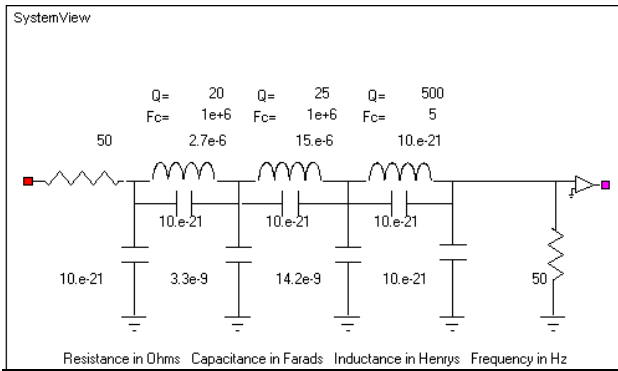


Figure 12. The RF/Analog library, LC circuits, LC-Lpf, parameter entry form filled out as a 4-pole, Gaussian filter, using combinations of standard part values.

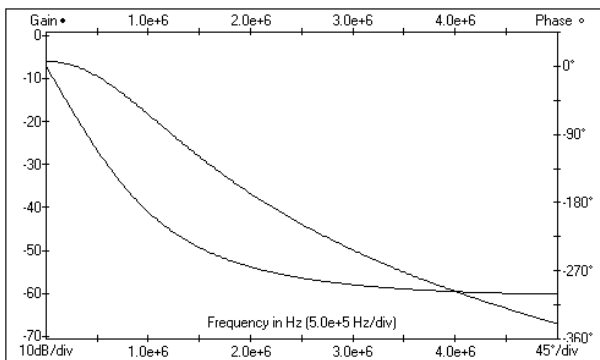


Figure 13. Linear plot of the filter in Figure 11. Because of equal termination, the Gaussian curve is down -6.025 dB at DC, 487 kHz at -9.025 dB, and -9.2 dB at 500 kHz. The phase is linear through the lowpass passband.

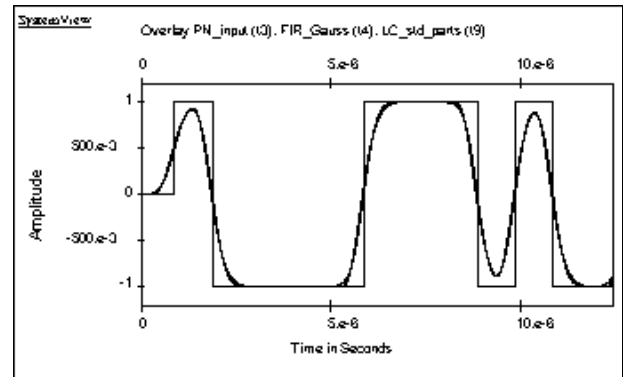


Figure 14. Overlay of PN_input, FIR_Gauss, and LC_std_parts (test system in Figure 12).

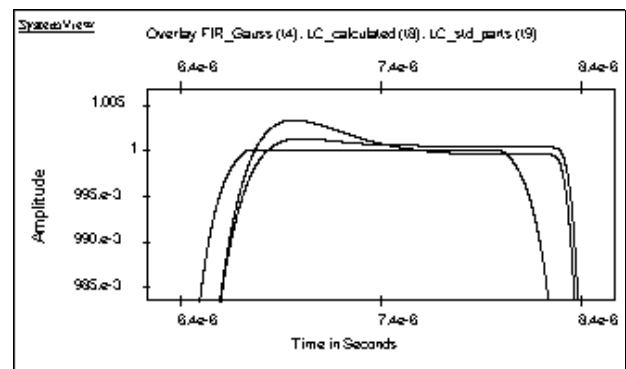


Figure 15. The FIR filter is the symmetrical rounded curve that is flat at 1.0 volts. The smaller overshoot plot is the analog design using calculated part values. The largest overshoot plot is the analog design using standard part values (2 parallel capacitors). (The PN input signal is not shown in this view.)

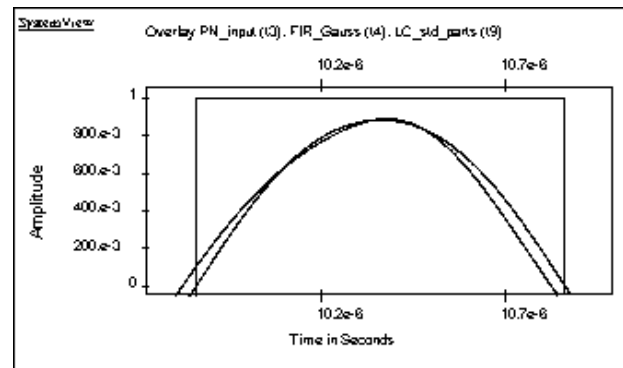


Figure 16. The FIR filter is the curve with the lowest mid amplitude peak, also has symmetrical zero-crossing. The calculated part, and standard part, analog designs are very similar, shown with unsymmetrical zero-crossings. (The rectangular signal, at 1.0 volts, is the PN input signal.)

Bluetooth Receiver -- RF Circuits

The block diagram of the RF receiver, **Figure 1**, is shown as the SystemView simulation in **Figure 2**. An overview the system's gains and losses is shown below:

Tx output at the center of the 84 MHz wide band = 0 dBm

Rx gain (dB): -2
 10
 15
 -3
 20
 30
 30

 100 dB

Path Loss and Antenna Noise at the Receiver's Input

In **Figure 2**, an attenuator token, set to a loss of 70 dB with its noise disabled, is used to simulate the path loss between the transmitter and receiver.

The receiver's input noise is modeled using an adder token with a Thermal noise source token set as follows.

Resistance: 50 ohms
 Temp: 300 deg K

This noise represents a receiver with a front end noise temperature of 300 deg. K (27 deg C or 80.6 deg F) due to the antenna (**Appendix A**). The adder token is also a convenient place to inject interference test signals.

Receiver Input Filter and LNA

The input to the receiver uses the same 1-pole filter and loss as the transmitter's output filter. The Low Noise Amplifier (LNA) is documented in National Semiconductor's app note AN-1162, page 7. The parameters in SystemView are set as shown in **Figure 17**. Notice that the three parameters, Out P1dB, Out IP3, and Out IP2, are in a 10 dB progression. (Please see Appendix C of the SystemView RF manual for more information setting mixer and amplifier parameters when given limited information.)

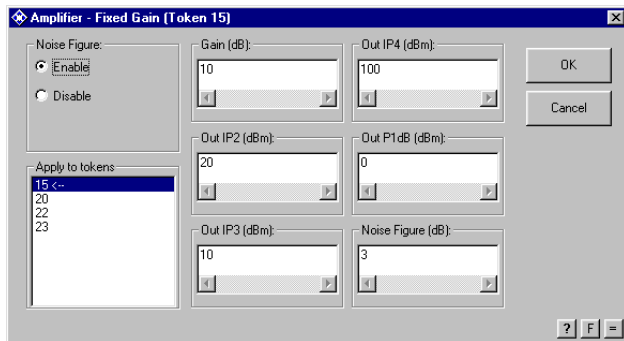


Figure 17. Parameters of the optional LNA.

RF-to-IF Down Converter

Some of the LMX3162 mixer's data sheet parameters are shown in **Figure 3**.

Parameter	Min	Typ	Max	Unit
Gain	13	17	--	dB
In P1dB	--	-20	--	dBm
Out IP3	--	7.5	--	dBm
Noise Figure	--	11.8	16	dB

Table 4. Some mixer datasheet parameters.

The harmonics of the square wave LO of the SystemView active mixer can alias with SystemView's sample rate, causing many unwanted spurs. Normally one can work around these spurs, but with the wide range of frequency hopping in this system it is best not to simulate the LO square wave. Therefore, a special mixer, in a MetaSystem (DownConvert_LMX3162.mta), is used to model the RF-to-IF down converter (**Figure 18**).

With the amplitude of a sine wave LO set to 2.0 volts (+/-2.0 volts), the multiplier has a single-side-band (SSB) gain of 0.0 dB, allowing the preceding amplifier to set the all of the parameters of the mixer. The LO for the mixer is the output of the Blue_VCO_Rx.mta.

The amplifier's Out_P1dB compression point is based on the mixer's gain and In_P1dB value as follows:

$$\begin{aligned} \text{Out P1dB} &= \text{In P1dB} + \text{GdB} - 1.0 \text{ dB} \\ &= -20.0 + 15.0 - 1.0 = -6.0 \text{ dB} \end{aligned}$$

Notice that the parameters Out IP3, and Out IP2, are in a 10 dB progression. (Again, please see Appendix C of the SystemView RF manual for more information setting mixer and amplifier parameters when given limited information.)

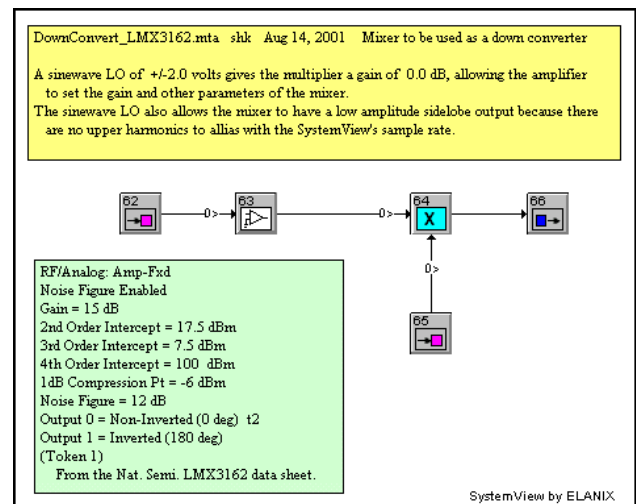


Figure 18. Receiver's RF-to-IF down converter.

Mixer's Output Filter

National Semiconductor's LMX3162 Evaluation Notes, page 8, specifies a SAW filter at the mixer's output that has a 110.6 MHz center frequency and a -3 dB bandwidth of 1.152 MHz, and a -30 dB bandwidth of 3.456 MHz (MuRata SAFU110.6MSA40T). The response of a 5-pole, 0.05 dB, Linear Phase filter is a close match to the attenuation specs of the MuRata filter.

IF Amplifier

Using the LMX3162 data sheet as a guide, the IF amplifier was setup as shown in **Figure 19**.

RC Filter

Between the IF amplifier and limiter, there is a simple RC bandpass filter. The LMX3162 Evaluation Notes, page 8, and 9 specifies this filter as having a loss of 8 dB. In **Figure 20**, only four components are used, two resistors, and two capacitors. No input impedance is specified for the limiter. However, when the output resistor in **Figure 20** is set to 138 ohms, the Bode plot shows the desired band pass properties (**Figure 21**):

Limiter Amplifier

The LMX3162 data sheet indicates that the limiter has a typical RSSI dynamic range of 60 dB. To simulate this range, a pair of amplifiers are used (**Figure 22**), each set to have a gain of 30 dB. Since these amplifiers are intended to operate in the saturated mode, the Out IP2 and Out IP4 parameters are set to 100 dB to remove any effect of saturation causing a DC offset at the amplifier's output. The Out P1dB parameter is set to -4.2 dB, and the Out IP3 parameter is set to +5.3 dB to achieve an output clipping of +/-200 mV. Since the two parameters interact with each other, a trial-and-error method was used to set the two values, keeping them 10 dB apart, and at the same time achieving the +/-200 mV output clipping. The +/-200 mV value is a typical parameter obtained from a different IC (Intersil app note AN9624.6, page 4). The noise figure, not listed on the data sheet, is set to a generous value of 10 dB.

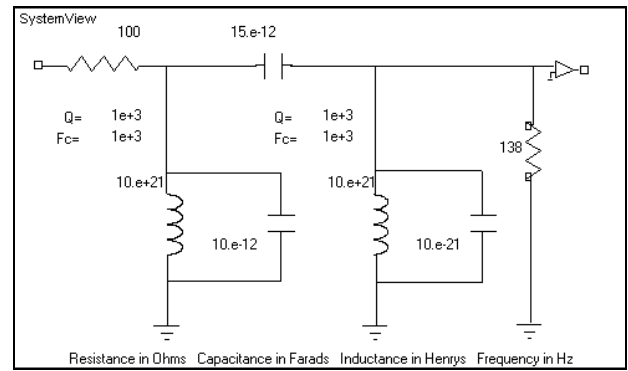


Figure 20. The LC-coupled resonator is used as a RC bandpass filter.

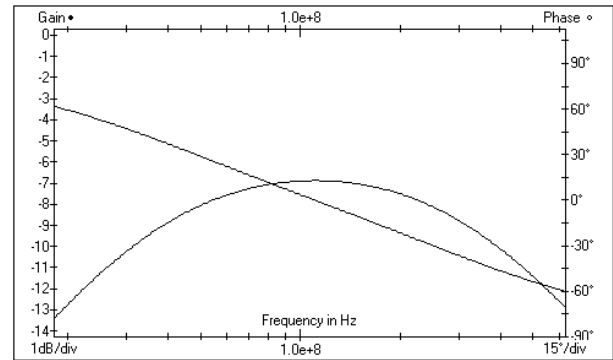


Figure 21. Bode plot of the bandpass filter in **Figure 21**.

Center frequency = 110.8 MHz
 Loss at 110.8 MHz = 6.9 dB
 Loss at 31.3 MHz = 9.9 dB
 Loss at 389.0 MHz = 9.9 dB

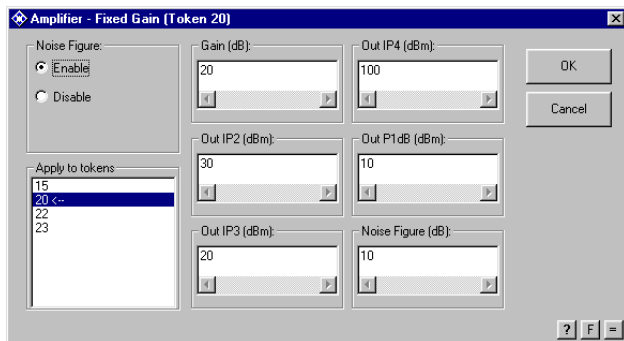


Figure 19. The parameters of the IF amplifier following the SAW filter.

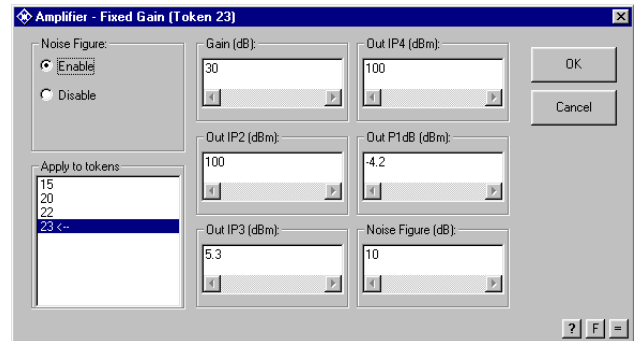


Figure 22. The parameters of each limiter amplifier.

Quadrature Detector

The quadrature detector tank circuit (**Figure 23**) is designed to resonate at 110.6 kHz. The output resistor is set to $1.0 \text{ e}21$ ohms to eliminate it from the circuit. The input capacitor is 1.0 pF, and the 68 nH inductor is given a Q of 20 at 100 MHz (Toko FSLU2520-68NK). With the aid of the Bode plot, the capacitor was initially set to 29.5 e-12 Farads to produce a peak in the gain plot at 110.6 MHz. However, this frequency peak produces a negative offset at the output of the receiver of about -9.5 volts (using a gain of -2000, and the Gaussian filter that has a gain of 0.5). The capacitor was adjusted down to 28.02 e-12 Farads, to null the offset of the quadrature tank circuit. This nulling was done using a path loss of 70 dB. If more loss is used it is difficult to see the null. With the new 28.02 pF capacitor, the peak in the gain plot is at 113.4 MHz. For a sample rate of 10.48576 e9 samples/sec, the Bode plot displays a 113.4 MHz center frequency, while operating as a tank circuit with a 110.6 MHz center frequency (**Figure 24**).

The new 28.02 pF capacitor value is: 5.02% lower.
 The new gain peak frequency is: 2.53% higher.

This difference above is due to a computational phenomenon called frequency warping. This is explained in application note AN119A, *Setting the parameters of the Quadrature Demodulator (RF Library) using the System Bode Plot*.

Notice that the phase plot is quite linear nearby each side of the 110.6 MHz (113.4 MHz) peak. A linear gain token ($g = -2000$) following the multiplier increases the receiver's output amplitude to make it comparable to the transmitter's input. This gain also compensates for the amplitude loss of the equal termination Gaussian filter.

Output Low Pass Filter

The same 500 kHz Gaussian filter used in the transmitter's modulator is used at the output of the receiver's quadrature demodulator. (Mentioned earlier on pages 8, 9, 10, and 11.)

Decimator tokens are used in front of most of the sinks to reduce the computer memory usage, and to reduce the plotting time in the SystemView analysis window.

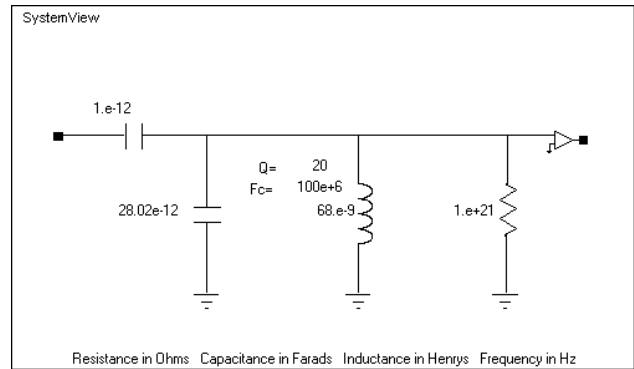


Figure 23. The LC Quadrature Tank design window for the FM demodulator.

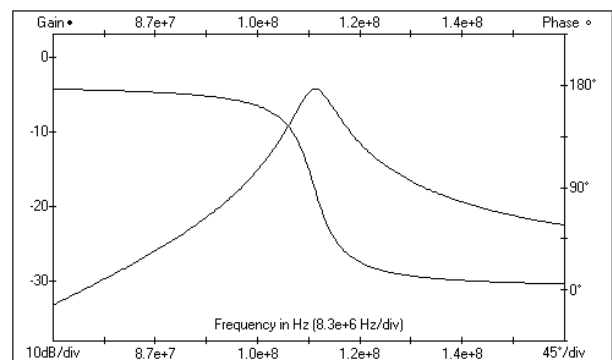


Figure 24. The Bode plot for the LC-Quad tank circuit displays a 115.0 MHz center frequency, while operating as a tank circuit with a 110.6 MHz center frequency .

Speeding Up the Simulation

The previous Bluetooth simulation can run much faster if the 2402 MHz carrier is reduced to 202 MHz. In deed, it is usually easier to start a simulation with a reduced frequency range, and when it is working fine then rescale the frequency plan to match the desired project. Of course, a few filters and decimators will change also. Here is a list of 13 changes and the relevant figures for the changes to produce a simulation that runs faster.

1. New Block diagram (**Figure 25**).
2. New system window (**Figure 26**).

Inside the new system window (**Figure 26**):

3. Old sample rate: 10.48576 e9 samples/second
New sample rate: 1.31072 e9 samples/second
(8 times lower rate)
4. Change the receiver's input bandpass filter:
199.5 e6 to 283.5 e6 MHz
5. Change the Decimate-by-256 before the Chan_0-78_fil sink to Decimate-by-64.
6. Remove the Decimate-by-8 token before the receiver's 110.6 MHz bandpass filter.

Inside Blue_Mod_Tx_202_b.mta (**Figure 27**):

7. Remove the Decimate-by-8 before the Gaussian filter.
8. Remove the Hold token after the Gaussian filter.
9. Change the FM token (VCO1) frequency from 2402 e6 to 202 e6.
10. Change the filter (F2) to: 199.5 e6 to 283.5 e6
11. Change the Decimate-by-256 before the Tx_Gauss_sw_del sink to Decimate-by-64.
12. Change the Decimate-by-256 before the Tx_on/off sink to Decimate-by-32.

Inside Blue_VCO2_Rx_202_b.mta (**Figure 28**):

13. Change the FM token (VCO2) frequency from 2402 e6 to 202 e6.

The results of the fast simulation may be seen in **Figure 29**. The new test system for the Gaussian filter is shown in **Figure 30**.

The time to run the full Tx/Rx simulation on a 866 MHz Pentium III using Windows 98, and SystemView 5.0-010 is summarized below in **Tables 5** and **6**. The APG times do not include the 7 second compile time (approximate). None of the numbers include the various plotting times.

System samples	SystemView 5.0-010	APG
1,048,576	70.0 seconds	22.8 seconds
4,194,304	300.0 seconds	90.7 seconds

Table 5. Run times for the 2402 MHz simulation.

System samples	SystemView 5.0-010	APG
131,072	10.0 seconds	4.1 seconds
2,097,152	160.0 seconds	58.8 seconds

Table 6. Run times for the 202 MHz simulation.

References

1. "LMX3162 Single Chip Radio Transceiver", PRELIMINARY, March 2000, www.national.com
2. "Using the LMX3162 for 2.4 GHz ISM Band", AN-1162, January 2000, www.national.com
3. "LMX3162 Evaluation Notes", 4/6/99 Rev. B, www.national.com
4. Ulrich L. Rohde and T. T. N. Bucher, "COMMUNICATIONS RECEIVERS Principles and Design", McGraw-Hill, 1988, pages 95-102.
5. Jerry Iseli, "A BASIC TUTORIAL ON NOISE FIGURE", RF Proceedings, 1987, pages 201-206.
6. Harold Goldberg, "Some Notes on Noise Figures", Proceedings of the IRE, October 1948, page 1209.

More Information

For more information on SystemView simulation software please contact:

ELANIX, Inc.
5655 Lindero Canyon Road, Suite 721
Westlake Village CA 91362.
Tel: (818) 597-1414
Fax: (818) 597-1427

Or visit our web home page (www.elanix.com) to download an evaluation version of the software that can run this simulation as well as other user-entered designs.

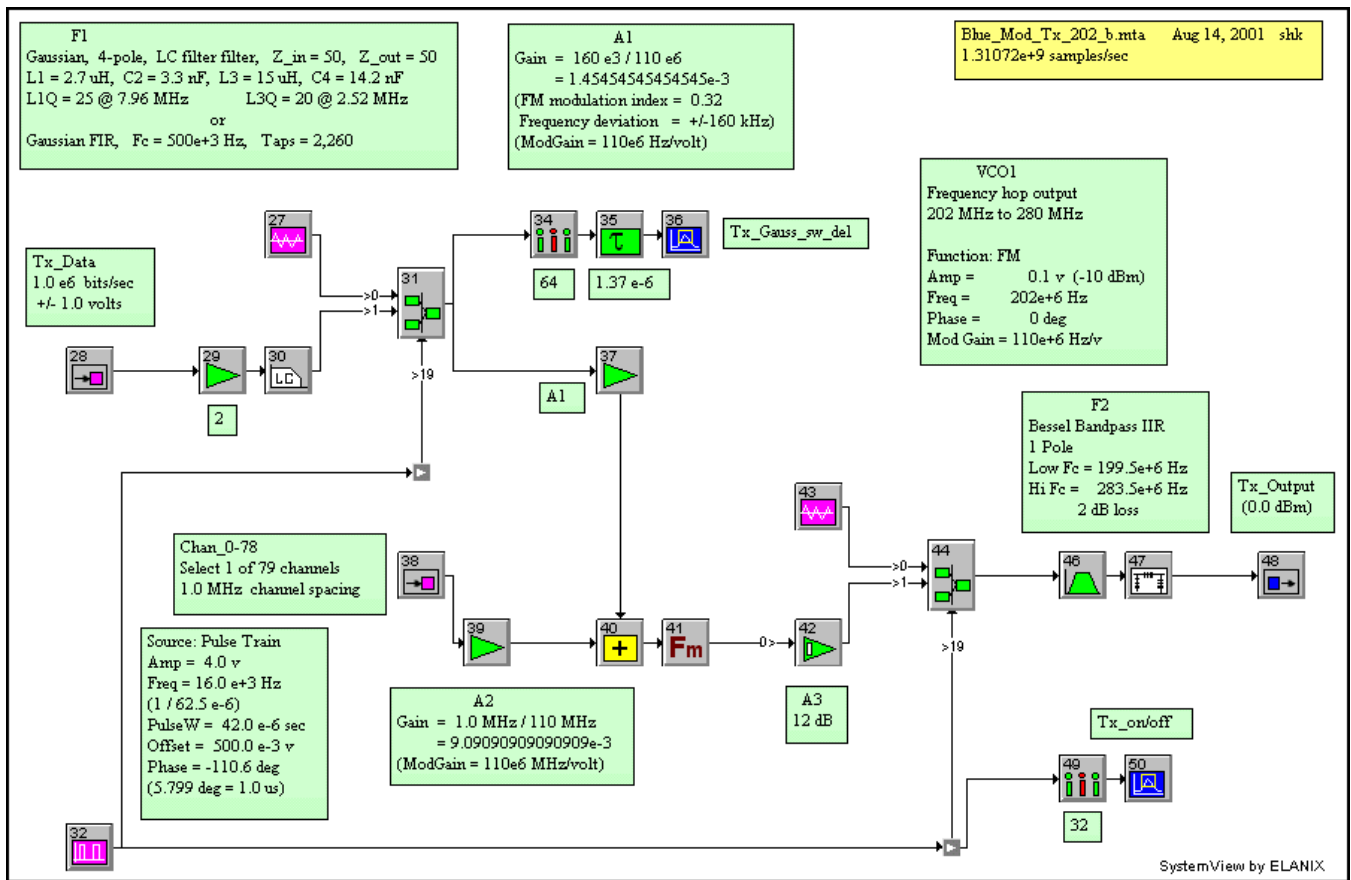


Figure 27. Gaussian filter, switch, summing circuit, VCO (FM), switch, and transmitter output filter, fast version.

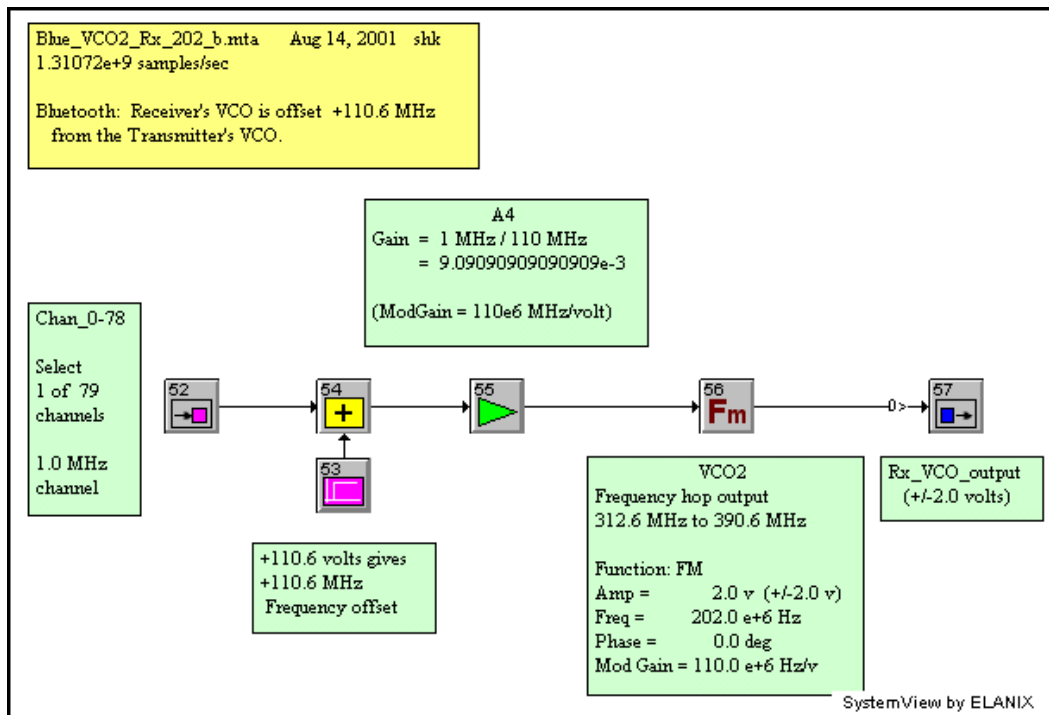


Figure 28. MetaSystem Blue_VCO2_Rx_202_b.mta for the fast receiver.

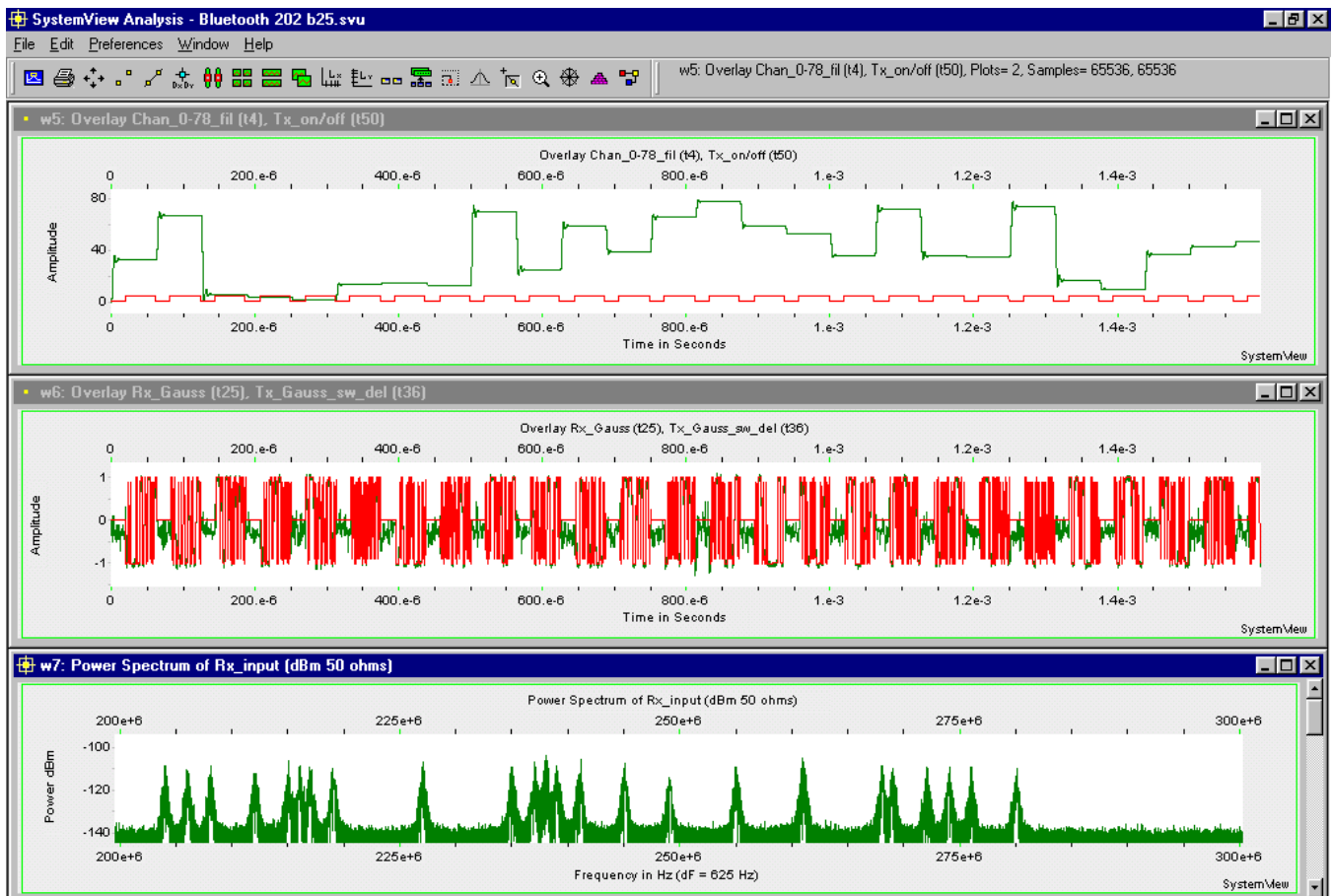


Figure 29. Path loss is 70 dB. (2,097,152 samples, 25.6 hops) (Fix Random Seed is set to 222.)

In the middle: The Tx_Gauss_sw_del (with the straight line) is compared with the Rx_Gauss (with the noise).

At the top: Each of the 26 channels commands settles in about 14 to 17 us, while the Tx cycles off for 18 us increments.

The channels from left to right are: 33, 67, 6, 4, 2, 14, 15, 13, 70, 25,
59, 39, 66, 78, 59, 53, 36, 72, 36, 35,
74, 17, 10, 37, 43, 47

At the bottom: The resulting spectrum center channels span the range from 204 MHz to 280 MHz.
(To get MHz, add 202 to the channel number.)

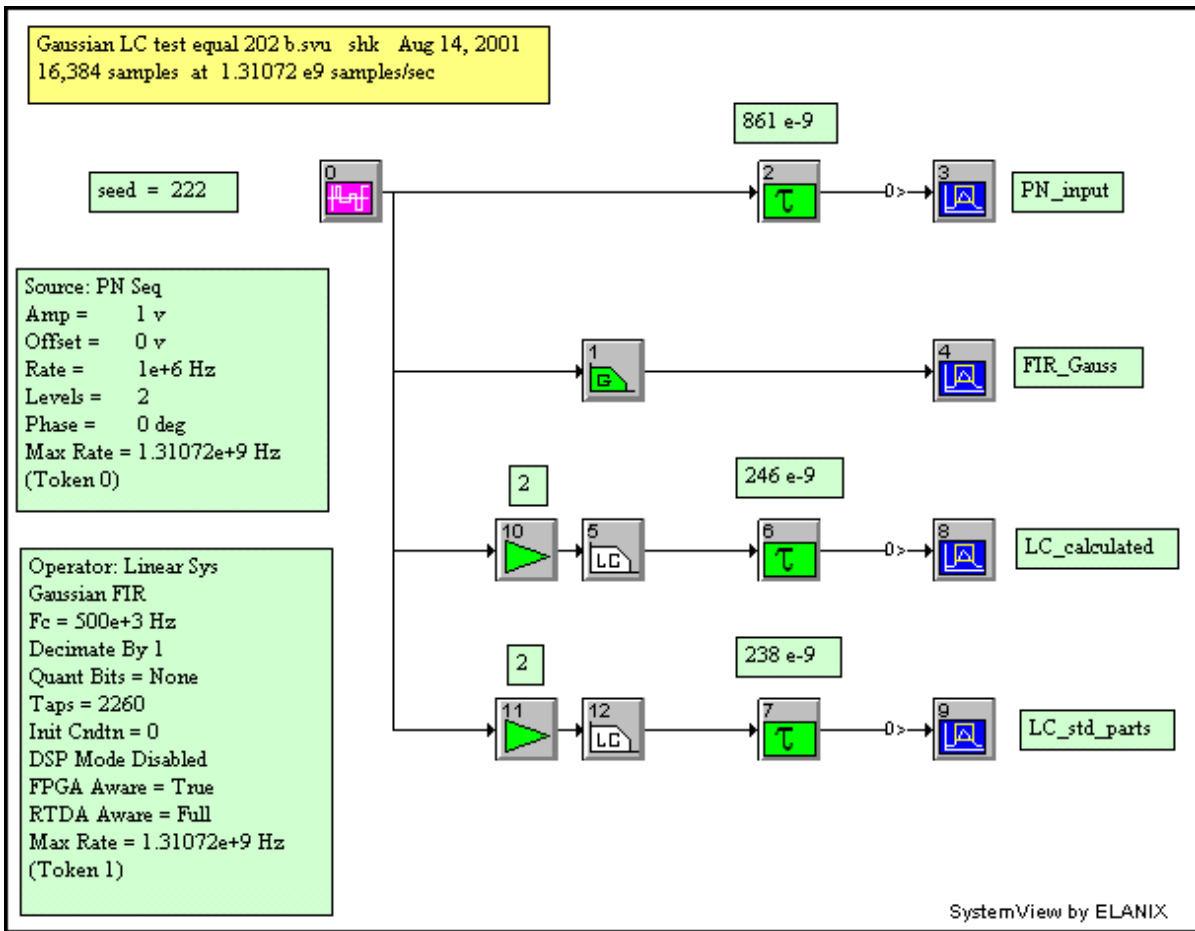


Figure 30. Test system for the Gaussian filter in the fast simulation.

Appendix A

Simulating the noise due to a virtual 50 ohm source resistor (antenna) at a receiver's input connector. (Ref. 4) Referring to **Figure 31**, the current in the receiver's input circuit is:

$$I = \frac{E}{2R}$$

where: E is the noise voltage of the noiseless source resistor. Therefore, the input noise power is:

$$P_{noise} = I^2 \times R = \frac{E^2}{(2R)^2} \times R = \frac{E^2}{4R}$$

Since the thermal noise due to a resistor is given by (Ref. 5 and 6):

$$V^2 = 4kTBR \quad \text{where:}$$

- k = Boltzman's constant, 1.38×10^{-23} J/deg K
- T = Temperature, deg K
- R = Resistance, ohms
- B = Bandwidth, Hz

substituting:

$$P_{noise} = \frac{4kTBR}{4R} = kTB \text{ watts}$$

SystemView automatically takes care of the bandwidth when using the Gaussian noise source token.

Using a T of 300 (27 deg C or 80.6 F) we get:

$$P_{noise-sv} = kT = 1.38 \text{ e-}23 \times 300 = 4.14 \text{ e-}21 \text{ watts/Hz}$$

This value may be used with the Gaussian Noise source token, with the density in 50 ohms feature enabled.

Another way of generating this noise is by using a Thermal noise source token with it's parameters set as follows (32-bit version of SystemView):

Resistance: 50 ohms
Temp: 300 deg K

Notice that the actual value of the resistors (50 ohms) never entered into the equations.

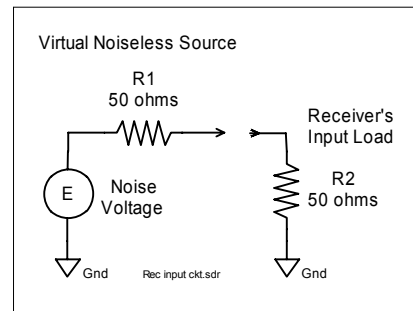


Figure 31. Receiver's input circuit.