

# Benefits of Total Integration of Large RF Circuits. Market Requirements in Terms of Cost and Current. Commercial Standards vs. Optimum Solutions

D A Engelién-Lopes

Nordic Semiconductor ASA, Norway

**Abstract.** - This paper details the implementation of a complete radio system for both 2.4GHz and 868/915/433 MHz in a 0.18 micron standard CMOS process. Topics explored include a brief market requirement analysis of standards such as Bluetooth and Zigbee vs. optimally designed devices. Such devices are typically employed in ultra-low cost (< \$1), low-power designs and the governing factors and influences of this shall be discussed. The basic architecture of the Nordic Semiconductor nRF2401 and nRF905 and the ability to implement additional digital functionality of a radio system in the CMOS process is presented. Key system functionality and performance is covered.

## INTRODUCTION

There are several world wide open standards for use in the ISM bands - 433MHz, 868MHz, 915MHz and 2.4GHz. The 2 main open standards currently used for medium data rate transfer are Bluetooth and Zigbee. There are several advantages in adopting an open standard including good connectivity between equipment from different vendors, multiple vendors ensure customers have more choice and a multi-purpose device can be used for many different applications. There are however also several disadvantages; open standards contain a number of negative tradeoffs after years of compromises to set a final standard acceptable for all. A significant increase in competition between manufacturers, where all they can compete on is price, can lead to very low profit margins. Finally, optimum performance is not obtainable for a specific application with an open standard as too many demands are placed on protocol that is often irrelevant for that particular application. Most products consist of a direct link between a company's own products and under these circumstances it is often better to use an application specific circuit which provides optimum performance, but at the cost of interoperability. This paper shows that the nRF2401 and nRF905 designed by Nordic Semiconductor offers two way communications at optimum price and current consumption, while maintaining excellent RF performance. In addition the devices are designed to be very simple to use with minimum BOM (Bill of Materials) cost.

## MARKET REQUIREMENTS

There is an increasing market requirement focus on cost and current consumption while maintaining RF performance. Bluetooth and Zigbee do not meet these requirements as they are designed for interoperability between manufacturers, this leads to an increase in complexity that results in increased cost and higher current consumption.

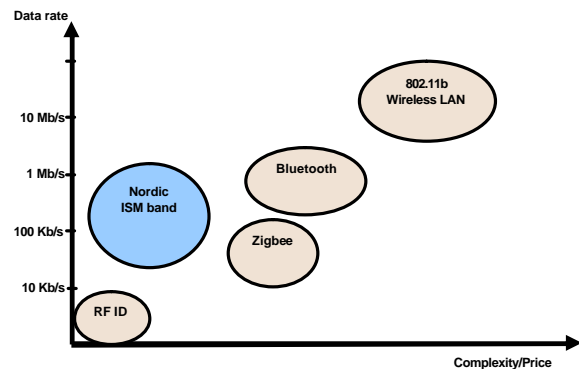


Figure 1: Nordic Semiconductor Price Location

Figure 1 shows a comparison of the data rate and complexity (price) of the nRF2401 and nRF905 with other standards. Due to the fact that these devices are optimised for a specific radio link and do not conform to a standard, the operating complexity and hence price are much lower than compared to a fully integrated Bluetooth or Zigbee circuit. Figure 2 shows how the Nordic Semiconductor circuits perform in relation to power consumption.

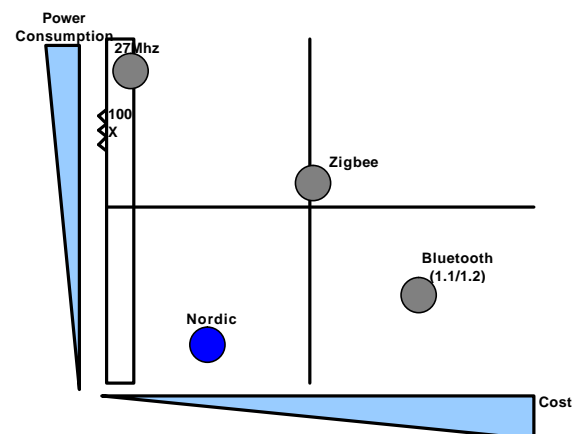


Figure 2: Nordic Semiconductor Power Location

## NRF905 MULTI BAND TRANSCEIVER

The nRF905 [1] is a complete radio system incorporated onto a single piece of silicon. It uses 0.18µm CMOS technology and is designed for the 433MHz, 868MHz and 915MHz radio bands [5]. The three main aims for this product were cost, current consumption and simplicity of use while maintaining good RF performance. The main performance figures are given in TABLE 1.

Parameter	Typical
<b>GENERAL</b>	
Voltage Supply	1.9 – 3.6V
Data Rate (Manchester Encoded, GFSK)	50kbps
Operating temperature	-40 to 85C
Standby Current	20µA
Power Down Current	2.5µA
<b>RECEIVER</b>	
Sensitivity	-100dBm
Current Consumption RX Mode	13mA
<b>TRANSMITTER</b>	
Maximum Output Power	10dBm
Power Control	20dB
Current Consumption @ Max Power	28mA
Current Consumption @ Min Power	9mA
<b>COST</b>	
nRF905	\$2.10
Crystal	\$0.15
Passive Components	\$0.05
<b>TOTAL COST</b>	<b>\$2.30</b>

TABLE 1: General Performance for nRF905

### Digital Functionality

The digital functionality in the nRF905 provides the protocol for a complete radio system. The packet that is transmitted is constructed in four parts which are; pre-amble (10 bits), address (1 byte to 4 bytes), payload (1 byte to 32 bytes) and CRC (1 or 2 bytes) see Figure 3. The pre-amble is added automatically by the transmitter and stripped by the receiver; the same is true for the address and CRC.

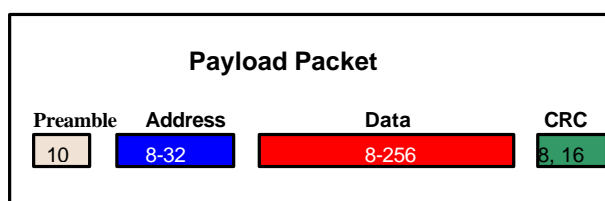


Figure 3: Internal Packet Construction

The address and the payload is set up by the user via a standard SPI (Serial to Parallel Interface) and kept in internal registers. When the packet is to be transmitted, a single external pin must be switched to the positive supply rail (Vdd) to enable the radio. The radio is automatically powered up; the packet is constructed internally and then transmitted. As soon as the packet has been sent the device enters a low current consumption mode. When a device receives a packet, it checks that the address and CRC is correct. It then strips the packet of pre-amble, address, CRC and places the data into a register ready to be clocked out of the device via the SPI interface. An external pin is set high to indicate that a valid packet has been received. The packet sits in the data register ready to be clocked out by a micro-controller. Since so much of the basic packet construction is handled internally on the nRF905, a very cheap micro-controller can be used to drive the device. The total result is an ultra low cost radio solution that provides excellent RF performance for a fraction of the current consumption used for devices that follow standards such as Zigbee and Bluetooth.

### Physical Characteristics of the nRF905

The nRF905 is produced in a 32 pin QFN green package. The external component count is minimal as seen in Figure 4. The critical components are a crystal with two tuning capacitors and a single reference resistor to set the internal current. If a 50 ohm match is required, then a low cost passive balun can be implemented. Decoupling capacitors on the supply rails are recommended for optimal RF performance but if cost is the most important factor, then these too can be removed to save cost. All internal power supplies are from internal regulators which provide excellent immunity to noise. An optional external clock can be activated to drive the clock of a micro-processor; the aim again is to save cost by reducing the number of crystals needed for a complete application to just one.

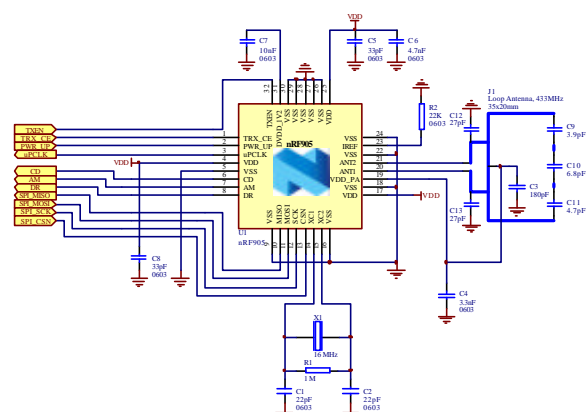


Figure 4: External Components with Loop Antenna

## RF Implementation of nRF905

The nRF905 consists of a fully integrated PLL, receiver chain and transmitter chain. All RF components such as VCO, LNA, PA and mixers are included on the silicon. No external components are needed for tuning of the VCO or loop filter. By full integration large savings are achievable by customers both in design time but also in external component count.

The receiver architecture is a single conversion superheterodyne with image rejection via an internal poly phase filter. The VCO lies 1MHz above the wanted frequency and the image 2MHz above. An internal IF filter provides excellent blocking which meets the ETSI EN 300 220 blocking standard for Class 2 receivers [5].

The transmitter functions by direct modulation of the VCO. An internal digital circuit Manchester encodes the data packet to maintain a zero average DC point on the VCO. Modulation of the VCO may not be the most advanced method of modulation implementation, but it is by far the optimal method for lowest current consumption. The power amplifier is a dual stage Class A amplifier with internal current regulation. Four available output powers are available ranging from +10dBm to -10dBm.

The PLL is run at 1.8GHz and is divided to obtain the correct frequencies for the receiver and transmitter. Start up times and PLL switching times are in the order of 650µs from standby mode. The VCO incorporates an automatic calibration routine that selects the right frequency of operation. Internal inductors are used for the VCO which allows excellent control of frequency operation and phase noise. Channel resolution is 200kHz at 868MHz and 915MHz and 100kHz at 433MHz.

The crystal oscillator which is used to provide the reference for the entire circuit may be run using a 4MHz, 8MHz, 12MHz, 16MHz or 20MHz crystal. No extreme tolerance high cost crystals are needed, a simple 30ppm crystal is more than adequate to provide a stable reference for the device. An optional output clock is also available to drive a micro-controller, this may be set to 0.5MHz, 1MHz, 2MHz or 4MHz depending on the micro-controller requirements.

RF parameters such as frequency and output power are programmable and are contained in a stand alone RF configuration register. The devices own address and the address that is to be transmitted is also contained in this register. Programming is byte based via the SPI interface.

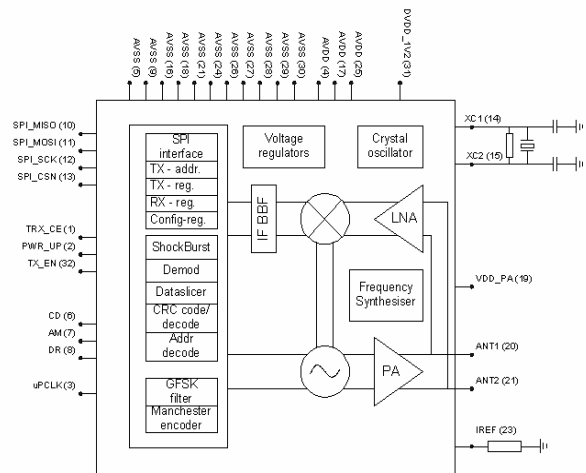


Figure 5: Internal Architecture

**Typical Transmitter Operation.** When the application MCU has data for a remote node, the address of the receiving node (TX-address) and payload data (TX-payload) are clocked into nRF905 via the SPI interface. The address only needs to be clocked into the device once; it is held in the RF configuration register and is used every time a payload is sent. A separate payload register is used for the payload. The application protocol or MCU sets the speed of the interface. The MCU sets TRX\_CE and TX\_EN high (two external pins on the device see Figure 4), this activates a nRF905 ShockBurst™ transmission. The radio is automatically powered up. The data packet is completed with preamble and address is added to the payload, CRC is calculated and also added. The data packet is transmitted using a real data rate of 50kbps, this is then Manchester encoded. After the data has been sent the device automatically enters standby mode.

**Typical Receiver Operation.** ShockBurst™ RX is selected by setting TRX\_CE high and TX\_EN low. After 650us nRF905 is monitoring the air for incoming communication. When the nRF905 senses a carrier at the receiving frequency, Carrier Detect (CD) pin (external pin on the device see Figure 4) is set high. When a valid address is received, the Address Match (AM) pin (external pin on the device see Figure 4) is set high. When a valid packet has been received (correct CRC found), nRF905 removes the preamble, address and CRC bits, and the Data Ready (DR) pin (external pin on the device see Figure 4) is set high. The MCU sets the TRX\_CE low to enter standby mode (low current mode). The MCU can clock out the payload data at a suitable rate via the SPI interface. When all payload data is retrieved, nRF905 sets Data Ready (DR) and Address Match (AM) low again. The chip is now ready for entering ShockBurst™ RX, ShockBurst™ TX or power down mode.

## NRF2401 2.4GHz TRANSCEIVER

The nRF2401 [2] is a complete radio system incorporated onto a single piece of silicon. It uses 0.18µm CMOS technology and is designed for the 2.4GHz to 2.5GHz radio band. The three main aims for this product were the same as for the nRF905 i.e. cost, current consumption and simplicity of use, while maintaining good RF performance. The main performance figures are given in TABLE 2.

Parameter	Typical
<b>GENERAL</b>	
Voltage Supply	1.9V – 3.6V
Data Rate (GFSK)	0.25/1Mbps
Operating temperature	-40 to 85C
Standby Current	20µA
Power Down Current	2.5µA
<b>RECEIVER</b>	
Sensitivity	-85dBm
Current Consumption RX Mode	19mA
<b>TRANSMITTER</b>	
Maximum Output Power	0dBm
Power Control	20dB
Current Consumption @ Max Power	13mA
Current Consumption @ Min Power	8.8mA
<b>COST</b>	
nRF2401	\$1.40
Crystal	\$0.15
Passive Components	\$0.05
<b>TOTAL COST</b>	<b>\$1.60</b>

TABLE 2: General Performance for nRF2401

### General Functionality

The digital functionality in the nRF2401 is very similar to nRF905, the same shock burst protocol is used and a similar packet is constructed i.e. pre-amble, address, payload and CRC. The main difference apart from the frequency of operation is the data rate. The nRF2401 transmits and receives at data rates of up to 1Mbps.

The nRF2401 is produced in a 24 pin QFN green package. The external component count is very similar to nRF905, see Figure 6. Like the nRF905 all power supplies are via internal regulators which produce very high resistance to external noise.

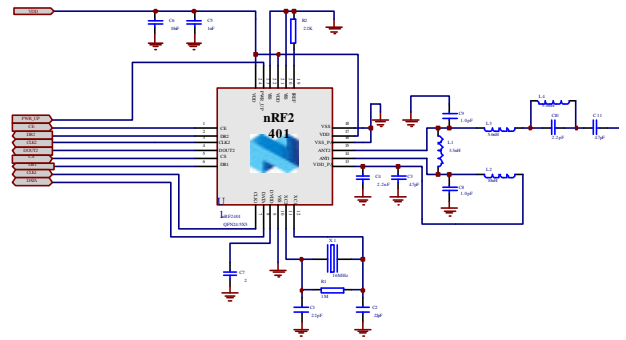


Figure 6: External Components with 50 ohm Balun

### RF Implementation of nRF2401

The nRF2401 is similar in architecture to the nRF905. It consists of two fully integrated PLLs, receiver chain and transmitter chain. All RF components such as VCOs, LNA, PA and mixers are included on the silicon. No external components are needed for tuning of the VCO or loop filter.

The receiver architecture is a double conversion superheterodyne with image rejection via an internal poly phase filter at the second IF. The first IF frequency is at 350MHz and the second is at 3MHz. The device incorporates two receive channels so both the wanted 3MHz channel and an image with a frequency offset resulting in a 5MHz channel can be used independently. Two independent receiver chains allow multiple channel operation. Internal IF filters provide excellent blocking rejection. With the addition of an easily realisable frequency agility algorithm, excellent resistance to multiple possible blockers such as Bluetooth, Zigbee and WLAN is achievable. The device has been operated within a mouse while in the presence of two Bluetooth devices, one 2.4GHz frequency hopping cordless telephone and one WLAN operating on the same computer without noticeable delay in the operation of the mouse.

The transmitter functions by direct modulation of the VCO. When the packet is ready to be sent, the PLL is opened and the VCO is directly modulated at 1Mbps. The power amplifier is a dual stage class AB amplifier with internal voltage regulation. Four available output powers are available ranging from 0dBm to -20dBm. With the transmitters low peak current consumption, (see TABLE 2) the resulting average current consumption for the transmitter is approximately 30nJ/bit. This includes start up time and all energy needed to transmit one packet of data with pre-amble/address/payload and CRC.

The PLL is run at 2.45GHz with a 1MHz channel resolution. Start up times is in the order of 200µs from standby mode. The VCO incorporates an automatic calibration routine that selects the right frequency of operation. Internal inductors are used for the VCOs which allows excellent control of frequency operation and phase noise. All RF parameters are programmable and are contained in a stand alone RF configuration register. Programming is via a 3 wire SPI.

**Transmitter Typical Operation.** The external MCU interfaces with the following pins: CE (Chip Enable), CLK1 and DATA. When the application MCU has data to send the CE pin is set high. This activates nRF2401 on-board data processing. The address of the receiving node (RX address) and payload data is clocked into the nRF2401. The application protocol or MCU sets the speed. The MCU sets the CE pin low; this activates a nRF2401 ShockBurst™ transmission. The RF front end is powered up, the RF packet is completed (preamble added, CRC calculated) and the data is transmitted at high speed (250 kbps or 1 Mbps configured by user), finally the device returns to stand-by mode when finished.

**Receiver Typical Operation.** The MCU interface pins: CE, DR1 (Data Ready 1), CLK1 and DATA (one RX channel receive mode). To activate RX, the CE pin is set high, after 200µs settling the device is monitoring the air for incoming communication. When a valid packet has been received (correct address and CRC found), nRF2401 removes the preamble, address and CRC bits. It then notifies (interrupts) the MCU by setting the DR1 pin high. The data is available for the MCU to clock out. When all of the payload data is retrieved the device sets DR1 low again and is ready for a new incoming data packet.

## CONCLUSIONS

There exists a very large market for optimized circuits that do not conform to an open standard such as Bluetooth or Zigbee. Cost, complexity and current consumption can all be significantly decreased when not complying with an open standard. For companies whose products communicate solely with its own products an open standard can be overly expensive and complicated, it is therefore often better to use a specialized circuit.

Integration of the entire RF circuitry not only minimizes external cost but also greatly increases ease of use for the final customer; this greatly reduces

the time to manufacture. With a fully integrated RF circuit it is relatively easy to add digital functionality such as internal protocols which include pre-amble, address and CRC. By incorporating these protocol functions as part of the device a very low cost MCU can be used hence further reducing the total solution cost.

Further digital functionality can be incorporated by including an onboard micro-controller and ADC. Nordic Semiconductor has already implemented this with products nRF24E1 [4] and nRF9E5 [3]. These products include the RF cores discussed in this paper, ie nRF905 and nRF2401 but also include an 8051 MCU and 10 bit ADC in a single chip solution. The additional cost to the customer is approximately 25 cents.

## REFERENCES

1. Nordic Semiconductor. nRF905 Datasheet
2. Nordic Semiconductor. nRF2401 Datasheet
3. Nordic Semiconductor. nRF9E5 Datasheet
4. Nordic Semiconductor. nRF24E1 Datasheet
5. ETSI EN 300 220-1. V1.3.1. 2001. Electromagnetic compatibility and radio matters. Short range device. Radio equipment to be used in the 25MHz to 1000MHz frequency range with power levels ranging up to 500mW. Part 1.