

# *Wireless Communication in Embedded System*

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Material based on

- White papers from [www.radiotronix.com](http://www.radiotronix.com)



# *Networked embedded devices*

- In the past embedded devices were standalone
  - Typically they would interact with human controllers but not with each other
  - But in recent past communication capability among embedded devices have led to a wide plethora of networked embedded devices
  - These devices are having capability of communication – mostly wireless
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# *Components of an embedded wireless link*

- A wireless system can be broken down into several component parts
- Understanding these parts and their interaction with one another is key to mastering the art of embedded wireless design



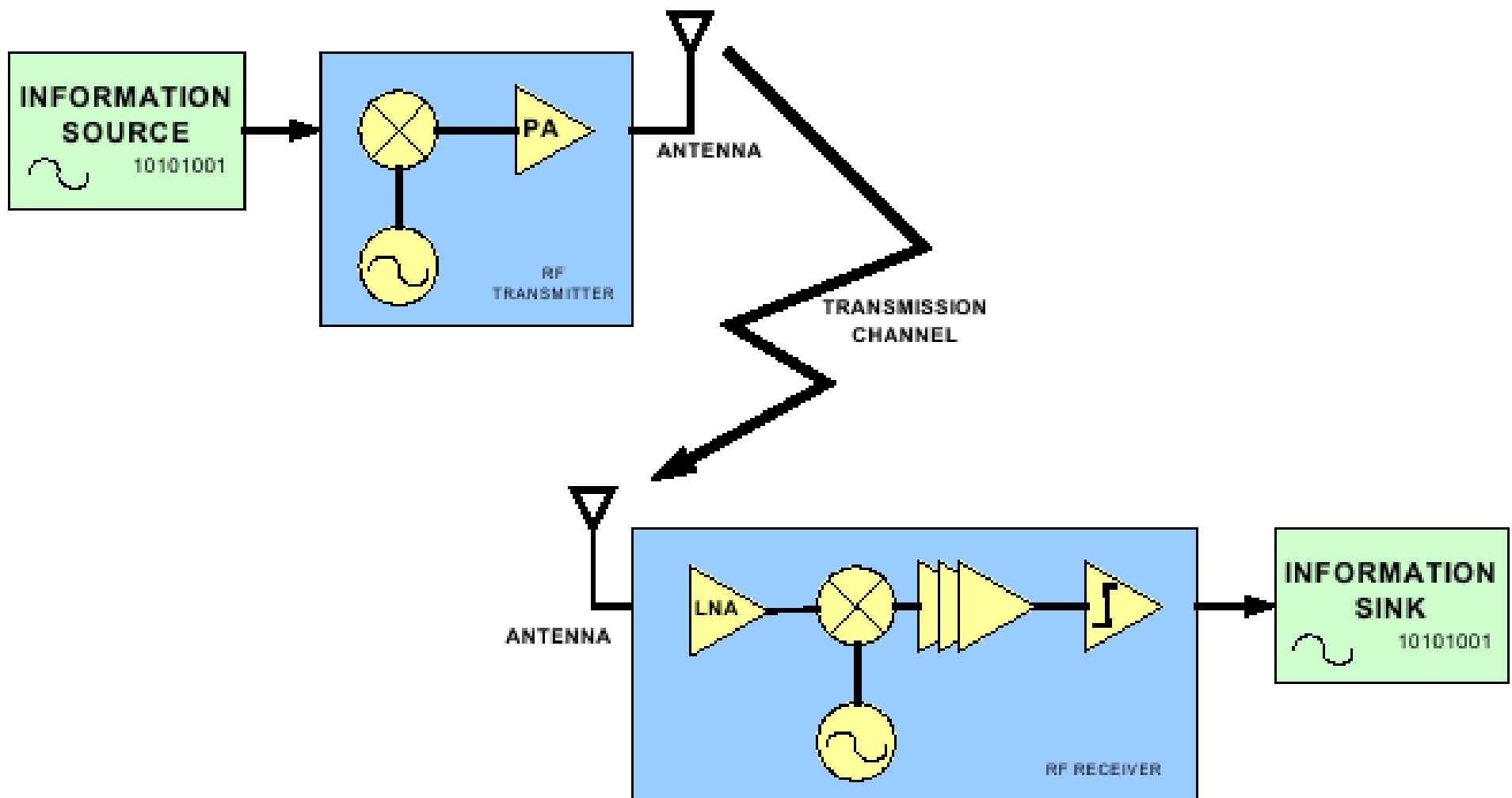


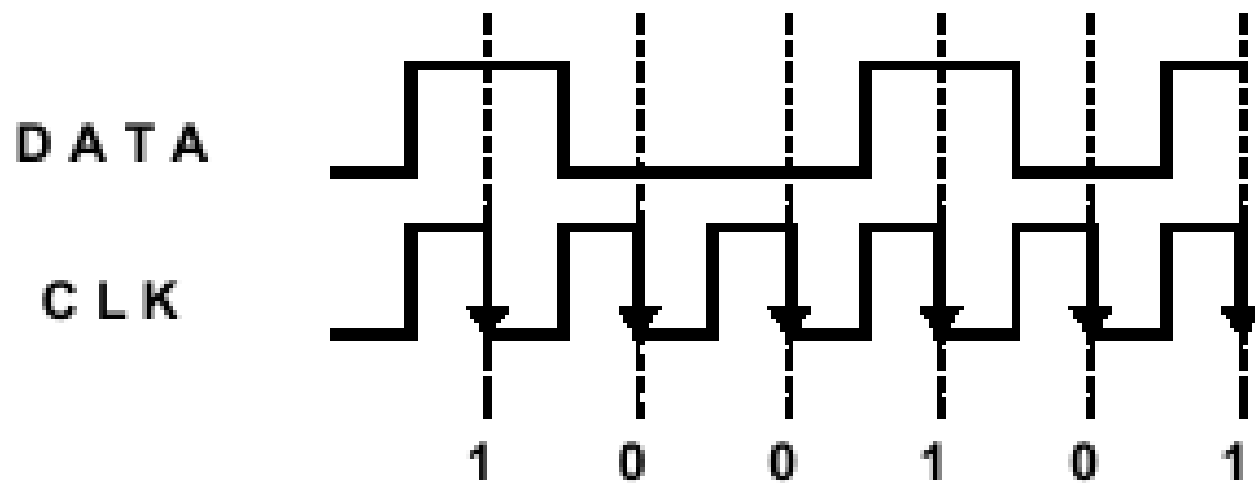
Figure 1: Basic components of wireless link

# *Information Source*

- In its most fundamental form, information can be considered to be either digital or analog
- Information is communicated digitally by the state (or voltage) of an input at a given time
- The top timing diagram on next slide illustrates an example of digital information



## ORIGINAL DATA



## CORRUPTED DATA

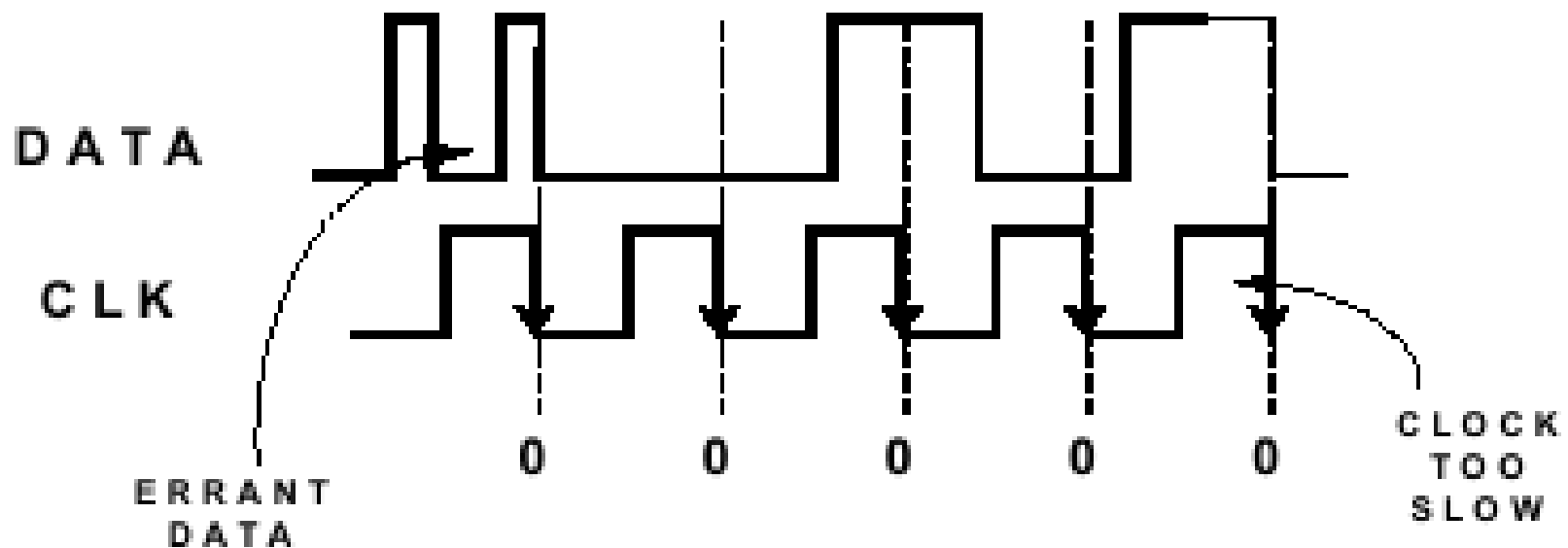


Figure 2: Data corruption through the wireless link

- In this example, the information contained in [data] is valid only when [clock] transitions from high to low
  - Thus, the data to be communicated in this example is 100101, or 0x2b
  - Recovery of this data can only be accomplished if the receiver can reconstruct the timing of [clock] at the receive end
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- Errors are introduced if either the value of [data] is incorrect or if [clock] is not accurate to the point that [data] is in the wrong state when [clock] transitions from high to low
  - The bottom timing diagram in figure 2 illustrates how incorrect data or an out-of-phase clock can cause errors
  - The data received in example is 00000, or 0x00
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- We can see, therefore, that if either the state or timing of the digital information is not accurately reproduced at the receiver, there will be errors in it
  - The quality of a digital receiver is measured by its ability to reproduce the information source data at the receiver and is usually quantified as the minimum input signal required to achieve a particular bit-error-rate
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# Transmitter

- The transmitter converts the digital or analog information present at its input into a signal that allows transmission through the air
- This process involves translating the information from base band (which includes 0 hz) to an RF frequency that allows transmission

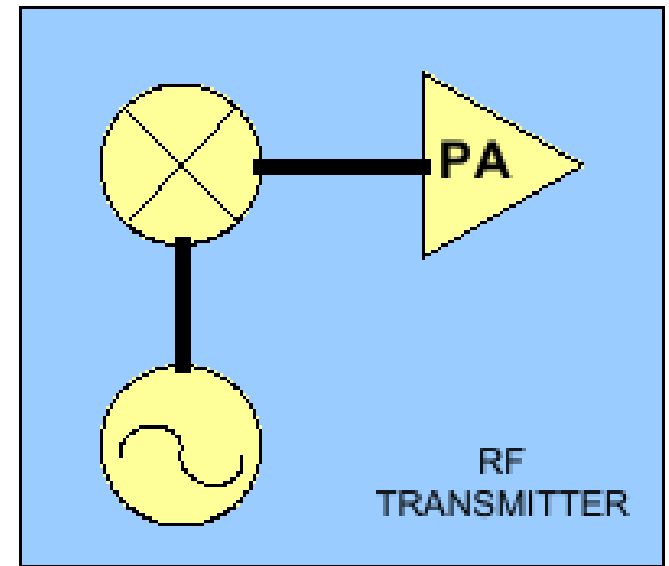
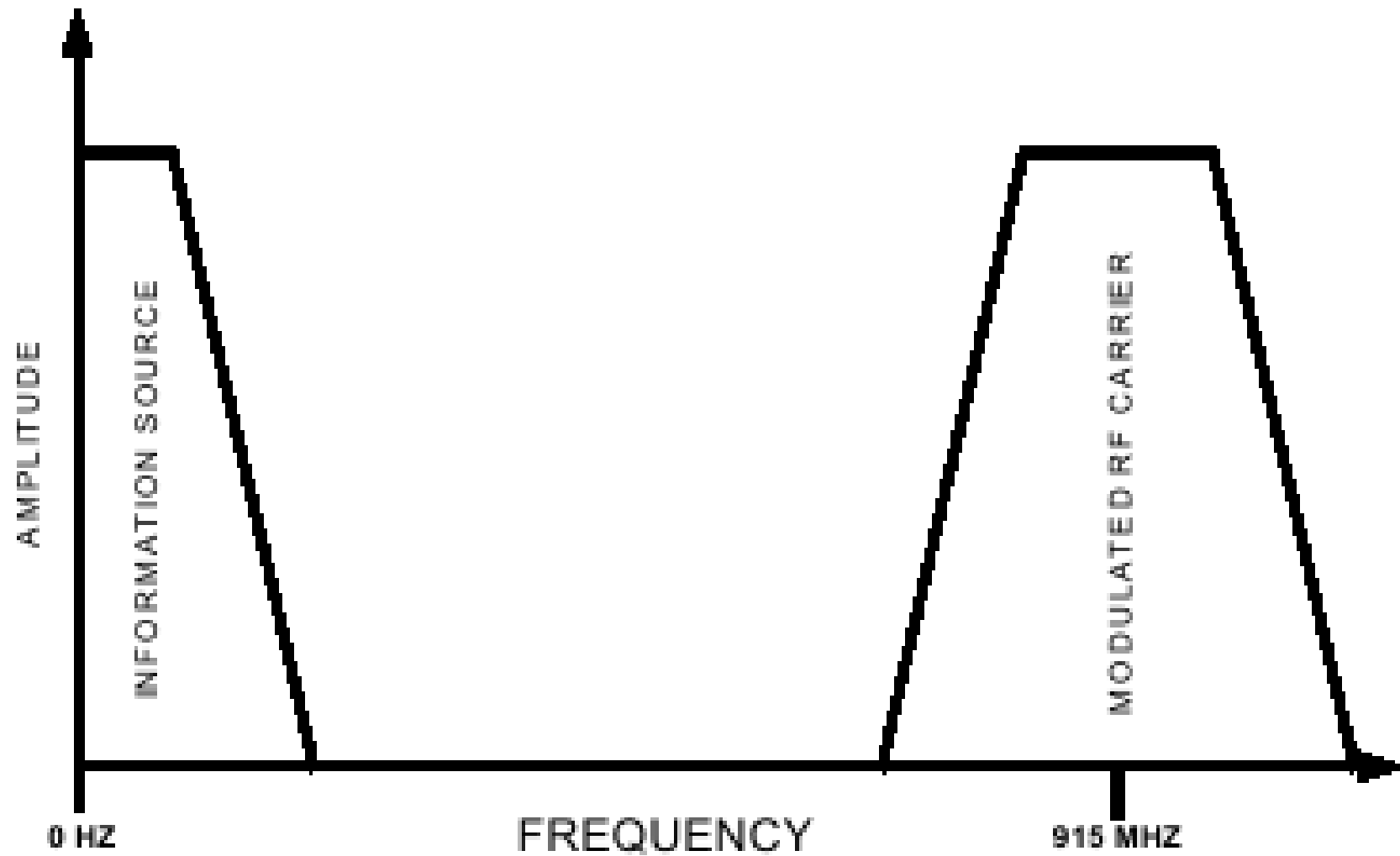


Figure 3: Basic RF transmitter



0 HZ

FREQUENCY

915 MHZ

- In its simplest form, a transmitter is an oscillator combined with an amplifier
  - The oscillator operates at the transmit frequency
  - The information source will modify one or more of its primary parameters: phase, frequency, or amplitude
  - Thus, the basic modulation techniques are called phase, frequency, and amplitude modulation
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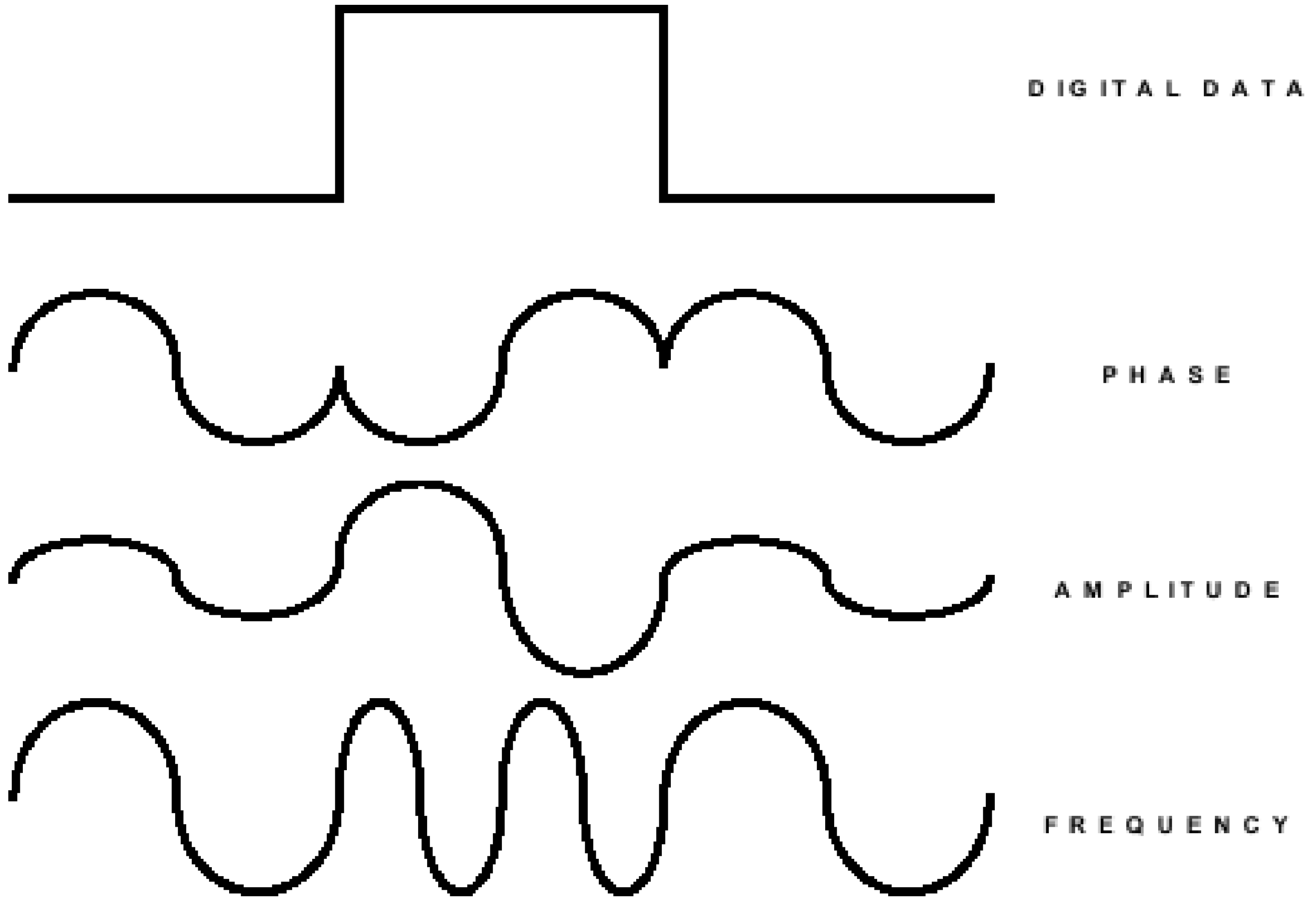


Figure 5: Basic Modulation Forms

# *Transmitter/Receiver Antenna*

- Antennas in a communication system are often the most overlooked component
  - In fact, they are usually the most critical and are directly responsible for poor performance when they are ignored
  - Antennas have the property of reciprocity, meaning that they work equally well for transmission and reception
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# *Transmitter/Receiver Antenna*

- There are many different types of antennas and its difficult to go into details
- However, we will take a basic look at the different types of antennas and make some basic conclusions of antenna selection





- When designing embedded wireless products, the first antenna decision that must be made is whether the antenna will be internal (i.e. PCB trace) or external
  - If product can support an external antenna - preferred choice because an external antenna will always give better performance
  - In many cases, however, the antenna must not extend outside the enclosure, so a PCB trace antenna will be required
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# *Antenna basics – Frequency and impedance*

- An antenna is essentially an impedance transformer that matches the impedance of a transmitter or receiver (which is generally 50 ohms) to the impedance of free space (which is assumed to be 377 ohms)
  - Antennas are designed to have a 50-ohm resistive impedance at the freq of interest
  - Depending on the type of antenna, the bandwidth at which the antenna exhibits this impedance will vary
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# *Antenna basics – Frequency and impedance*

- Ideally, a 1/4 wave whip will exhibit a 77 ohm impedance at center frequency, for a VSWR of 1.54:1
- This assumes a good ground plane and no obstacles in the antenna's field
- If, for example, if we put our hand around the antenna, it will de-tune the antenna, increasing its VSWR, making the antenna less efficient
- Antennas close to human/animal body needs special consideration

# *Transmission channel*

- The transmission channel, in the case of wireless communications, is air
  - Radio waves propagate from the transmit antenna to the receive antenna through air, bouncing off of obstacles along the way
  - The difference between the signal strength at the transmit antenna and the signal strength at the receive antenna is called **path loss**
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# *Transmission channel*

- The path loss is affected by a number of factors including obstacles in the path, antenna height, air moisture, and many others
  - The difference between transmit power and receiver sensitivity is called **link budget**:
    - XBee module has +0 dBm transmit power and -92dBm receiver sensitivity, yielding a +92dB link budget
    - XBeePro module has +20 dBm transmit power and -100dBm receiver sensitivity, yielding a +120dB link budget
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- If the link budget is greater than the path loss, the transmitter will be able to successfully communicate information to the receiver
  - If the link budget is less than the path loss, the transmitter will not be able to successfully communicate information to the receiver
  - Since path loss is variable and dependent on many uncontrollable and unpredictable variables, it is virtually impossible to predict range performance for a given wireless link
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- For this reason, link budget is a much better figure of merit to us to compare different wireless solutions for a given application
  - Generally speaking, the radio with the best link budget will give the best range performance in any given environment
  - There are other factors that can affect multipath performance and interference rejection in a real world setting
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# Receiver

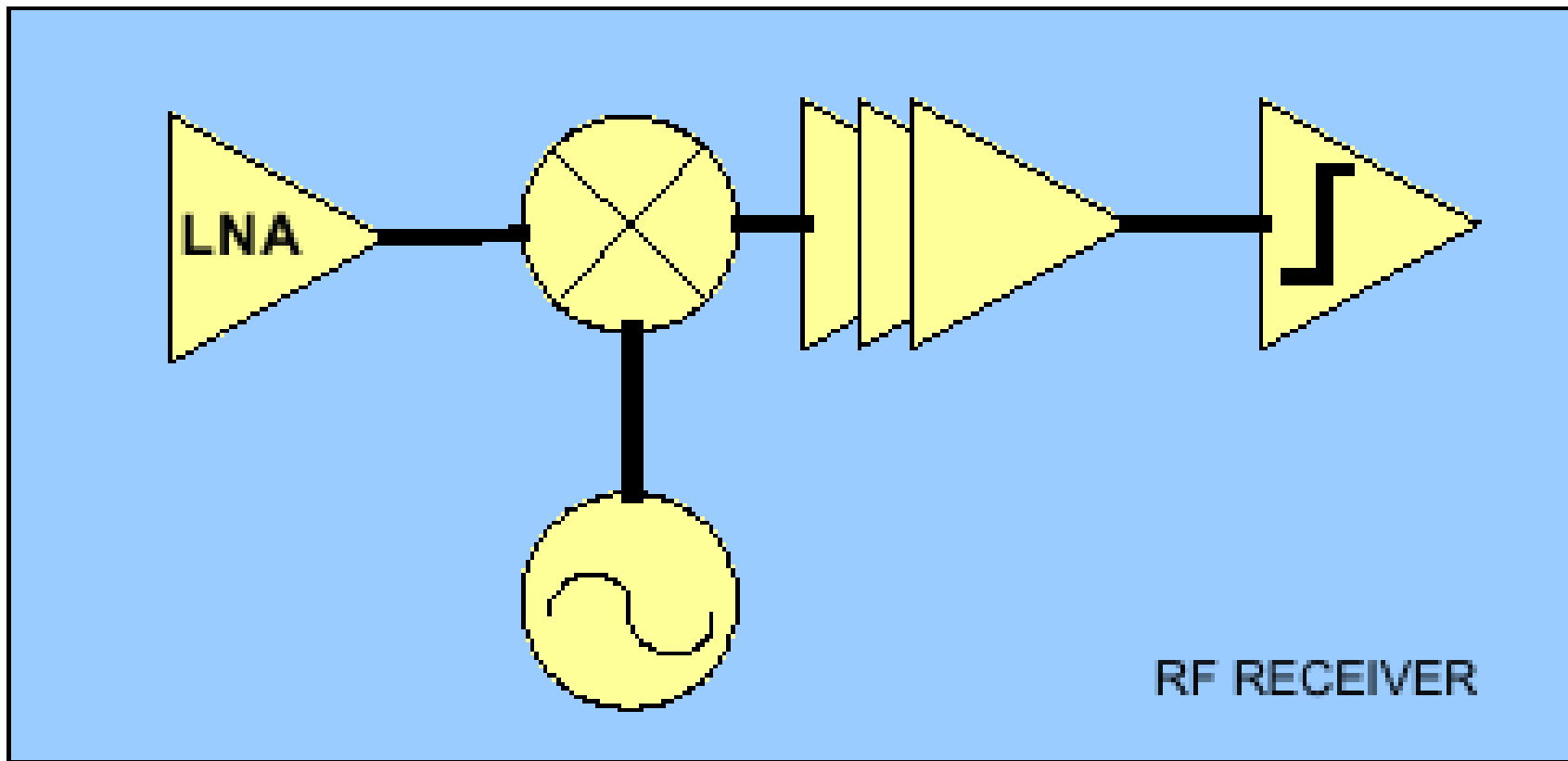


Figure 6 Basic RF receiver



- The receiver's job is the opposite of the transmitter's
  - It receives a modulated RF signal and recreates the base band information present at the transmitter's input
  - The structure and components of a receiver vary depending on the type of modulation used
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- Most embedded wireless solutions today use three types of modulation: ASK, FSK and DSSS(PSK)
- ASK stands for amplitude shift keying and is the digital version of amplitude modulation
- OOK is special forms of ASK whereby the carrier is completely suppressed when a zero is being transmitted
- Common receiver architectures for ASK/OOK modulation are super-regenerative and super-heterodyne

- Generally speaking, super-regenerative receivers have a wider bandwidth, and therefore more susceptible to interference
  - Super-heterodyne receivers are more expensive (about 200% or more), but have much better performance regarding sensitivity and off-channel interference rejection
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- FSK stands for frequency shift keying and is the digital version of frequency modulation
  - Common receiver architectures for FSK are:
    - Zero-IF (or homodyne) and
    - Super-heterodyne
  - Zero-IF is newer technology, and is the technique employed in most of the high-performance single chip transceivers today
  - Super-heterodyne usually required external filters, which are expensive and bulky
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- Performance is similar between the two, but Zero-IF implementations are generally less expensive and have a lower component count

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# *Direct Sequence Spread Spectrum*

- DSSS stands for direct sequence spread spectrum and is a special form of phase modulation
  - A random sequence of ones and zeros, called a chipping sequence, operates at a multiple, usually ten or higher, of the rate of the data to be transmitted
  - Until recently, low-cost DSSS single chip transceivers did not exist, so this was not a modulation scheme of choice
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- However, the new 802.15.4 standard is changing that and several manufacturers including XEMICS, Chipcon, FreeScale, and others either have 802.15.4 chips now or are planning them in the near future
  - XBee/XBeePro are DSSS
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# *Information sink*

- The information sink is simply the device that receives the information from the receiver
  - In a properly designed embedded wireless system, the information sink should not be able to differentiate whether the information is being received directly from the information source or indirectly via a wireless communication system
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# *Information sink*

- However, in a wireless link, the transmission channel is more prone to errors than in a wired link, so the information sink must have the ability to identify and recover from corrupt data

# *Error detection and correction*

- There are many ways that the data generated at the receiver can be corrupted in the transmission channel
  - Therefore, it is important that the wireless link be able to detect and recover from the errors resulting from the corruption
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- The easiest way to check for bit errors is to append a checksum onto the outgoing packet
  - This is basically a sum of all of the bytes transmitted
  - The sum is truncated, generally to 16 bits, and then transmitted
  - While this technique is simple, it is not very reliable for a wireless link because of the bursting nature of bit errors in a transmission channel
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- For that reason, most wireless links use a 16-bit CRC (cyclic redundancy check), which is very good at detecting bit errors
  - It is more complicated to calculate, however it is a far more desirable solution
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# *Recovery of data*

- One way link – add additional information with the data so that on the receiving end data can be recovered in case of errors – e.g FEC (also useful in case of real time constraints)
  - Two way link – One can do acknowledge and retransmit to assure correct data is transmitted – e.g. Assured Delivery
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# *Forward Error Correction (FEC)*

- FEC - Essentially send redundant bits in the data stream so that when errors occur, the original data can be recovered
  - Consider a very basic example where the data is simply duplicated, i.e. three copies are sent of each byte
  - At the receiver, each bit of the three copies is compared. If an errant bit was received, it will disagree with the other two bits, but we can still recover the original bit
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Transmitter:

Receiver:

Original byte :

0b10101010

Received bytes:

0b10101011

FEC encoded:

0b10101010

0b10101010

0b10101010

0b10101010

0b10101010

=====

Recovered byte

0b10101010

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- This simple FEC technique is very basic and, truthfully, not very good
- If bit zero of two of the three bytes were corrupted, the recovered data would be wrong
- There are much better solutions such as using interleaving and more sophisticated FEC coding
- For example, a common solution is to combine a Trellis coder (interleaving) with a Reed-Solomon coder (FEC) to achieve excellent performance



- FEC is complicated and does require processor resources, but it is much more bandwidth efficient than assured delivery, introduces less delay into the transmit channel, and only requires a one-way link to work
  - That is why it is used in satellite communications and CD players
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# *Assured Delivery*

- Another technique that is used to recover from corrupted data is called assured delivery
  - With assured delivery, the transmitter waits for the receiver to acknowledge that the data was properly received
  - If the acknowledgement is not received in a certain period of time, the transmitter will send the data packet again
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# Successful packet transmission

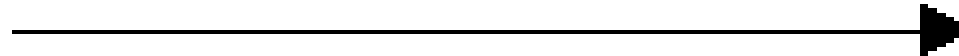
Transmitter

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Receiver

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Send Packet

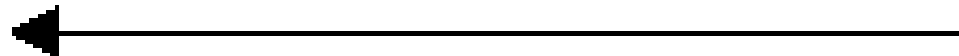


Receive Packet

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Check Packet

Receive ACK



Send ACK



# Unsuccessful packet transmission

Transmitter

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Receiver

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Send Packet



Receive Packet

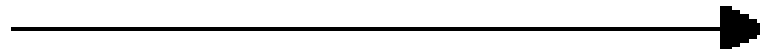
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Check Packet

Bad Packet

TX Timeout

Send Packet Again



Receive Packet

...

Check Packet

Receive ACK



Transmit ACK



- This technique is simpler to implement, but it does have limitations and drawbacks:
    - First, it requires a transceiver on each end, so it doesn't work for one-way links. One-way links have to use some form of FEC.
    - Second, it requires a lot more overhead. A portion of the available bandwidth is now used for acknowledgements and retries.
    - Third, it requires that the wireless link operate as a network with each node having a globally unique address
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- For point-to-point links this doesn't matter.
  - But for point-to-multipoint and multipoint-to-multipoint links, it does
  - The net result is that protocol must have link-layer functionality that handles the end-to-end addressing
    - Lastly, it introduces a significant delay to the transmission channel
  - For applications, such as sports timing, where the delay must be short and fixed, FEC is the appropriate solution
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# *Performance of the wireless link*

- Examine the factors that can reduce link performance:
  - free space path loss,
  - multipath fading, and
  - interference

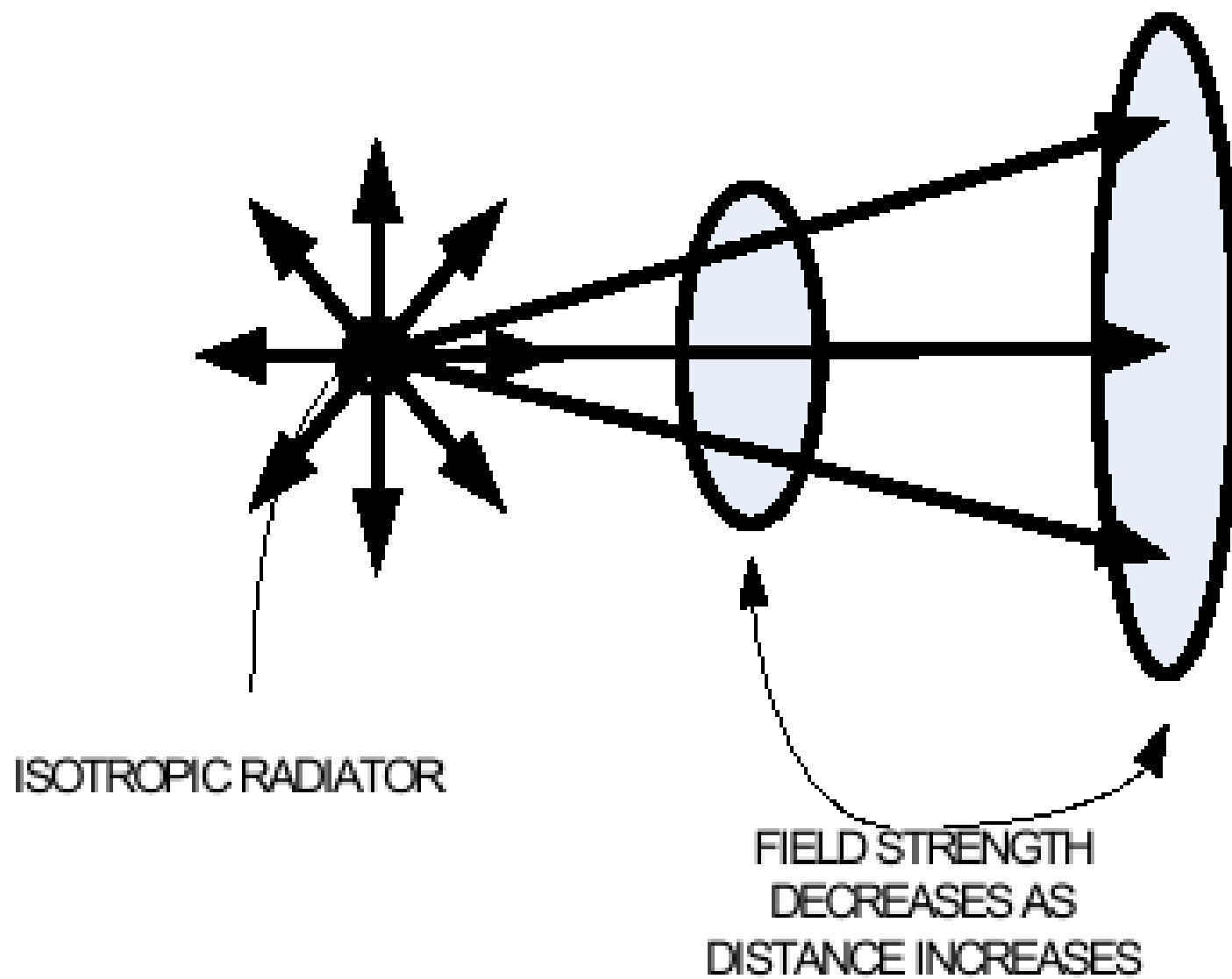
# *Basic free space path loss model*

- For the purposes of this discussion, we will assume that free space means that there are no obstacles to alter or interfere with the propagation of the RF signal from the transmit antenna to the receive antenna

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**Figure 1: Isotropic radiation**

- Using this law, we find that the RF signal is reduced by a factor of four every time the distance is doubled
- We can convert that to dB:  
 $10 * \text{LOG}(4) = 6.02\text{dB}.$

**Equation 1: Inverse square law**

$$P_{RF} \propto \frac{1}{d^2}$$

# *Rule of thumb #1*

- In free space, the received signal is reduced by 6dB every time we double the distance.
- Using the information, we can construct a free space path loss model:

Equation 2: Free space path loss

$$L_p \text{ (dB)} = 20 * \text{LOG} ( f ) + 20 * \text{LOG} ( d ) - 27.6$$

Where: d is distance in m

f is frequency in MHz

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# *Receive Power*

Equation 3: Receive power

$$P_r = P_t - L_p + G_t + G_r$$

Where:

$P_r$  = signal power at the receiver

$P_t$  = Transmitter output power

$L_p$  = path loss calculated in equation 2

$G_t$  = transmit antenna gain

$G_r$  = receive antenna gain

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# Example 1

- A transmitter with an output power of +0dBm is located 500 meters from a receiver operating at 915Mhz. Both antennas are 3dBi dipole antennas. Calculate the receive power.
  - Using equation 2, we calculate the path loss:  
$$L_p = 20 * \text{LOG}(915) + 20 * \text{LOG}(.5) - 27.6$$
$$L_p = 85.61 \text{dB}$$
  - Using equation 3, we can calculate the receive power:
    - $P_r = 0 - 85.61 + 3 + 3$
    - $P_r = -79.61 \text{ dBm}$
- 
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- From this example, it appears that a wireless link with a link budget of 85dB would work at 500 meters
  - In practice it NEVER, EVER HAPPENS
  - In fact, the actual range expected from such a system in an outdoor application is usually 1/4 to 1/8 of that prediction
  - In other words, it would actually require 97dB to 103 dB link budget to work at 500 meters, which is more in line with real-world results
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- Some component and module manufacturers use this model to predict their operating range, but you can be sure you will never see it in the real world
  - Why? The answer is found in multipath fading and interference
  - The real world is full of obstacles that absorb, reflect, and scatter RF energy, including the earth itself
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- In addition to multipath fading, the ISM band radios are also subject to interference from other unlicensed radios, raising the noise floor in the transmission channel
  - If the noise floor is high enough, it can limit receiver sensitivity, reducing the effective link budget and decreasing the overall range performance
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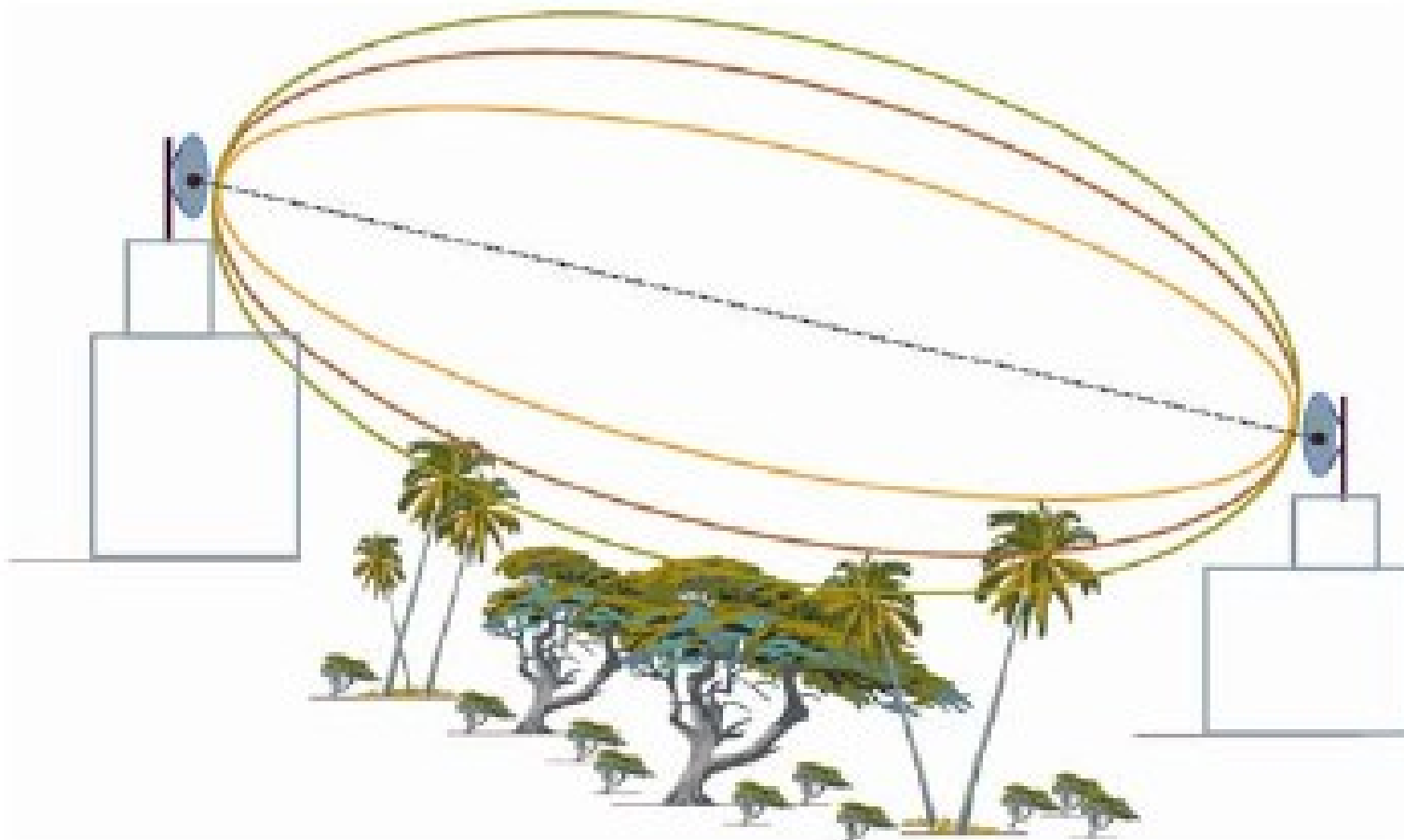


# *Line of Sight*

- Since there are no obstacles in a free space channel, it is assumed that the transmitting antenna and the receiving antenna can “see” each other
- However, in the real world, we have the curvature of the earth, buildings, foliage, and automobiles that obstruct the transmitter’s view of the receiver
- When, in the real world, the transmitter can “see” the receiver, we say that the channel is “line of sight”. The meaning is obvious

- When RF energy comes into contact with an obstacle, one of three things can happen.
  - It can be reflected, it can be scattered, or it can be absorbed.
  - Depending on the surface, more than one of these can happen. When a signal is reflected or scattered, it has the possibility of reaching the receiving antenna by another path (also called the reflected path)
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**Figure 3. Physical Obstructions overcome by antenna height**



Ref : [www.maxstream.net](http://www.maxstream.net)

**Table 1. Fresnel Zone Diameters**

<b>Range Distance</b>	<b>Required Fresnel Zone Diameter (900 MHz Radios)</b>	<b>Required Fresnel Zone Diameter (2.4 GHz Radios)</b>
1000 ft. (300 m)	16 ft. (7 m)	11 ft. (5.4 m)
1 Mile (1.6 km)	32 ft. (12 m)	21 ft. (8.4 m)
5 Miles (8 km)	68 ft. (23 m)	43 ft. (15.2 m)
10 Miles (16 km)	95 ft. (31 m)	59 ft. (20.2 m)

In order to have ground clearance, the combined antenna height should be equal to the diameter of the Fresnel zone.

