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Wearable Communication Systems and Antennas for Commercial, Sport and Medical Applications

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Chapter 1

Theory of wireless wearable communication systems

The purpose of this chapter is to provide a short introduction to wireless wearable communication systems. Transmitting and receiving information in microwave frequencies is based on the propagation of electromagnetic waves. Wireless wearable communication systems operate in the vicinity of the human body.

1.1 Wireless wearable communication systems: frequency range

The electromagnetic spectrum of wireless wearable communication systems corresponds to electromagnetic waves from the meter to the centimeter wave range to date. However, there are some new designs in the mm wave range. The characteristic feature of this phenomena is the short wavelength involved. The wavelength is of the same order of magnitude as the circuit device used. The propagation time from one point of the circuit to another is comparable with the period of the oscillating voltages and currents in the circuit. Conventional low circuit analysis based on Kirchhoff's and Ohm's laws cannot analyze and describe the variation of fields, voltages and currents along the length of the components. Components with dimensions lower than a tenth of the wavelength are called lumped elements, and components with dimensions higher than a tenth of the wavelength are called distributed elements. Kirchhoff's and Ohm's laws may be applied to lumped elements, but not to distributed elements.

To prevent interference and to provide efficient use of the frequency spectrum, similar services are allocated in frequency bands, see [1–4]. Bands are divided at wavelengths of 10^n m, or frequencies of 3×10^n Hz. Each of these bands has a basic band plan that dictates how it is to be used and shared, to avoid interference and to set a protocol for the compatibility of the transmitters and receivers. In table 1.1 the electromagnetic spectrum and applications of wireless wearable communication

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Table 1.1. Electromagnetic spectrum and applications of wireless wearable communication systems.

Band name	Abbreviation	ITU	Frequency/λ0	Applications
Low frequency	LF	5	30–300 kHz 10 km–1 km	Wearable RFID
Medium frequency	MF	6	300–3000 kHz 1 km–100 m	Wearable RFID
High frequency	HF	7	3–30 MHz 100 m–10 m	Shortwave broadcasts, wearable RFID communications, mobile radio telephony
Very high frequency	VHF	8	30–300 MHz 10 m–1 m	FM, television broadcasts, land mobile communications, weather radio
Ultra-high frequency	UHF	9	300–3000 MHz 1 m–100 mm	Mobile phones, wireless LAN, Bluetooth, ZigBee, GPS and two-way radios such as land mobiles, wireless wearable communication systems
Super high frequency	SHF	10	3–30 GHz 100 mm–10 mm	Wireless LAN, wireless wearable communication systems, DBS

systems are listed. In table 1.2 the International Telecommunication Union (ITU) bands are given. IEEE standard frequency bands for wireless wearable communication systems are listed in table 1.3.

1.2 Free space propagation

The fundamentals of wireless communication systems are presented in several papers and books [5–7].

Flux density at distance R of an isotropic source radiating Pt watts uniformly into free space is given by equation (1.1). At distance R, the area of the spherical shell with the center at the source is $4\pi R^2$.

$$F = \frac{P_t}{4\pi R^2}\ \mathrm{W\ m^{-2}} \tag{1.1}$$

$$G(\theta) = \frac{P(\theta)}{P_0/4\pi} \tag{1.2}$$

$P(\theta)$ is the variation of power with angle.
$G(\theta)$ is the gain at the direction θ.
P_0 is the total power transmitted.
Sphere = 4π solid radians.

Table 1.2. The International Telecommunication Union bands for wireless communication systems.

Band number	Symbols	Frequency range	Wavelength range
4	VLF	3–30 kHz	10–100 km
5	LF	30–300 kHz	1–10 km
6	MF	300–3000 kHz	100–1000 m
7	HF	3–30 MHz	10–100 m
8	VHF	30–300 MHz	1–10 m
9	UHF	300–3000 MHz	10–100 cm
10	SHF	3–30 GHz	1–10 cm

Table 1.3. IEEE standard frequency bands for wireless wearable communication systems.

Symbols	Frequency range
L band	1–2 GHz
S band	2–4 GHz
C band	4–8 GHz

Gain is a usually expressed in **Decibels** (dB). $G\,[\mathrm{dB}] = 10 \log 10\, G$. Gain is realized by focusing power. An isotropic radiator is an antenna that radiates in all directions equally. Effective isotropic radiated power (EIRP) is the amount of power the transmitter would have to produce if it was radiating to all directions equally. The EIRP may vary as a function of direction because of changes in the antenna gain versus angle. We now want to find the power density at the receiver. We know that power is conserved in a lossless medium. The power radiated from a transmitter must pass through a spherical shell on the surface of which is the receiver.

The area of this spherical shell is $4\pi R^2$.

Therefore, the spherical spreading loss is $1/4\pi R^2$.

We can rewrite the power flux density, as given in equation (1.3), now considering the transmit antenna gain:

$$F = \frac{EIRP}{4\pi R^2} = \frac{P_t G_t}{4\pi R^2} \mathrm{Wm}^{-2} \tag{1.3}$$

The power available to a receiving antenna of area A_r is given in equation (1.4):

$$P_r = F \times A_r = \frac{P_t G_t A_r}{4\pi R^2} \tag{1.4}$$

Real antennas have effective flux collecting areas that are less than the physical aperture area. A_e is defined as the antenna's effective aperture area.

Where $A_e = A_{phy} \times \eta$ η = aperture efficiency

Antennas have maximum gain G related to the effective aperture area f as given in equation (1.5). Where: A_e is the effective aperture area.

$$G = Gain = \frac{4\pi A_e}{\lambda^2} \tag{1.5}$$

Aperture antennas (horns and reflectors) have a physical collecting area that can be easily calculated from their dimensions:

$$A_{phy} = \pi r^2 = \pi \frac{D^2}{4} \tag{1.6}$$

Therefore, using equations (1.5) and (1.6) we can obtain a formula for aperture antenna gain as given in equations (1.7) and (1.8).

$$Gain = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi A_{phy}}{\lambda^2} \times \eta \tag{1.7}$$

$$Gain = \left(\frac{\pi D}{\lambda}\right)^2 \times \eta \tag{1.8}$$

$$Gain \cong \eta \left(\frac{75\pi}{\theta_{3dB}}\right)^2 = \eta \frac{(75\pi)^2}{\theta_{3dBH}\theta_{3dBE}} \quad \text{where } \theta_{3dB} \cong \frac{75\lambda}{D} \tag{1.9}$$

θ_{3dB}—The antenna half power beamwidth. Assuming for instance a typical aperture efficiency of 0.55 gives:

$$Gain \cong \frac{30\,000}{(\theta_{3dB})^2} = \frac{30\,000}{\theta_{3dBH}\theta_{3dBE}} \tag{1.10}$$

1.3 Friis transmission formula

The Friis transmission formula is presented in equation (1.11).

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{1.11}$$

Free space loss (L_p) represents propagation loss in free space. Losses due to attenuation in the atmosphere, L_a, should also be accounted for in the transmission equation.

Where, $L_p = (\frac{4\pi R}{\lambda})^2$. The received power may be given as: $P_r = \frac{P_t G_t G_r}{L_p}$.

Losses due to the polarization mismatch, L_{pol}, should also be accounted for. Losses associated with the receiving antenna, L_{ra}, and with the receiver, L_r, cannot be neglected in computation of the transmission budget. Losses associated with the transmitting antenna is written as L_{ta}.

$$P_r = \frac{P_t G_t G_r}{L_p L_a L_{ta} L_{ra} L_{pol} L_o L_r} \tag{1.12}$$

$P_t = P_{out}/L_t$
$EIRP = P_t\ G_t$
Where:
P_t = Transmitting antenna power.
L_t = Loss between the power source and antenna.
$EIRP$ = Effective isotropic radiated power.

$$\begin{aligned} P_r &= \frac{P_t G_t G_r}{L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r} \\ &= \frac{EIRP \times G_r}{L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r} \\ &= \frac{P_{out} G_t G_r}{L_t L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r} \end{aligned} \tag{1.13}$$

Where,

$$G = 10 \log\left(\frac{P_{out}}{P_{in}}\right) \text{dB} \quad \text{Gain in dB.}$$

$$L = 10 \log\left(\frac{P_{in}}{P_{out}}\right) \text{dB Loss in dB.}$$

Gain may be derived as given in equation (1.14).

$$\begin{aligned} &P_{in} = \frac{V_{in}^2}{R_{in}} P_{out} = \frac{V_{out}^2}{R_{out}} \\ &G = 10 \log\left(\frac{P_{out}}{P_{in}}\right) = 10 \log\left(\frac{\frac{V_{out}^2}{R_{out}}}{\frac{V_{in}^2}{R_{in}}}\right) \\ &G = 10 \log\left(\frac{V_{out}^2}{V_{in}^2}\right) + 10 \log\left(\frac{R_{in}}{R_{out}}\right) = 20 \log\left(\frac{V_{out}}{V_{in}}\right) + 10 \log\left(\frac{R_{in}}{R_{out}}\right) \end{aligned} \tag{1.14}$$

Logarithmic relations

Important logarithmic operations are listed in equations (1.15)–(1.18).

$$\begin{aligned} 10\log_{10}(A \times B) &= 10\log_{10}(A) + 10\log_{10}(B) \\ &= A\ \text{dB} + B\ \text{dB} \\ &= (A + B)\ \text{dB} \end{aligned} \tag{1.15}$$

$$\begin{aligned} 10\log_{10}(A/B) &= 10\log_{10}(A) - 10\log_{10}(B) \\ &= A\ \text{dB} - B\ \text{dB} \\ &= (A - B)\ \text{dB} \end{aligned} \tag{1.16}$$

$$\begin{aligned} 10\log_{10}(A^2) &= 2 \times 10\log_{10}(A) \\ &= 20\log_{10}(A) \\ &= 2 \times (A\ \text{in dB}) \end{aligned} \tag{1.17}$$

$$\begin{aligned} 10\log_{10}(\sqrt{A}) &= \frac{10}{2}\log_{10}(A) \\ &= \frac{1}{2} \times (A\ \text{in dB}) \end{aligned} \tag{1.18}$$

Linear ratios versus logarithmic ratios are listed in table 1.4.

The received power P_r in dBm is given in equation (1.19). The received power P_r is commonly referred to as the 'carrier power', C.

$$P_r = EIRP - L_{ta} - L_p - L_a - L_{pol} - L_{ra} - L_{other} + G_r - L_r \tag{1.19}$$

The surface area of a sphere of radius d is $4\pi d^2$, so that the power flow per unit area W (power flux in watts/meter^2) at distance d from a transmitter antenna with input power P_T and antenna gain G_T is given in equation (1.20).

$$W = \frac{P_r G_r}{4\pi d^2} \tag{1.20}$$

The received signal strength depends on the 'size' or aperture of the receiving antenna. If the antenna has an effective area A, then the received signal strength is given in equation (1.21).

$$P_R = P_T G_T (A/(4\pi d^2)) \tag{1.21}$$

Define the receiver antenna gain $G_R = 4\pi A/\lambda^2$.

Where, $\lambda = c/f$

Table 1.4. Linear ratios versus logarithmic ratios.

Linear ratio	dB	Linear ratio	dB
0.001	−30.0	2.000	3.0
0.010	−20.0	3.000	4.8
0.100	−10.0	4.000	6.0
0.200	−7.0	5.000	7.0
0.300	−5.2	6.000	7.8
0.400	−4.0	7.000	8.5
0.500	−3.0	8.000	9.0
0.600	−2.2	9.000	9.5
0.700	−1.5	10.000	10.0
0.800	−1.0	100.000	20.0
0.900	−0.5	1000.000	30.0
1.000	0.0	18.000	12.6

1.4 Link budget examples

$F = 2.4$ GHz => $\lambda = 3 \times 10^8$ m s^{-1}/2.4×10^9 s^{-1} = 12.5 cm.

At 933 MHz => $\lambda = 32$ cm.

Receiver signal strength: $P_R = P_T\, G_T\, G_R\, (\lambda/4\pi d)^2$.

P_R (dBm) = P_T (dBm) + G_T (dBi) + G_R (dBi) + 10 $\log_{10}((\lambda/4\pi)^2) - 10 \log_{10}(d^2)$.

For $F = 2.4$ GHz => 10 $\log_{10}((\lambda/4\pi)^2) = -40$ dB.

For $F = 933$ MHz => 10 $\log_{10}((\lambda/4\pi)^2) = -32$ dB.

Mobile phone downlink

$\lambda = 12.5$ cm,

$f = 2.4$ GHz,

P_R (dBm) = $(P_T\, G_T\, G_R\, L)$ (dBm) − 40 dB + 10 $\log_{10}(1/d^2)$,

$P_R - (P_T + G_T + G_R + L) - 40$ dB = 10 $\log_{10}(1/d^2)$,

or $155 - 40 = 10 \log_{10}(1/d^2) =$

or $(155 - 40)/20 = \log_{10}(1/d)$

$d = 10^{((155\ -\ 40)/20)} = 562$ km.

Mobile phone uplink

$d = 10^{((153\ -\ 40)/20)} = 446$ km.

For standard 802.11

- $P_R - P_T = -113.2$ dBm,
- 6 Mbps:
  - $d = 10^{(113.2\ -\ 40)/20} = 4500$ m.
  - $d = 10^{(113.2\ -\ 40\ -\ 3)/20} = 3235$ m with 3 dB gain margin.
  - $d = 10^{(113.2\ -\ 40\ -\ 3\ -\ 9)/20} = 1148$ m with 3 dB gain margin and neglecting antenna gains.

- 54 Mbps needs −85 dBm:
  - $d = 10^{(99.2 - 40)/20} = 912$ m.
  - $d = 10^{(99.2 - 40 - 3)/20} = 646$ m with 3 dB gain margin.
  - $d = 10^{(99.2 - 40 - 3 - 9)/20} = 230$ m with 3 dB gain margin and neglecting antenna gains.

Signal strength

- Measure signal strength in
  - dBW = 10 log (power in watts)
  - dBm = 10 log (power in mW)
- 802.11 can legally transmit at 30 dBm.
- Most 802.11 PCMCIA cards transmit at 10–20 dBm.
- Mobile phone base station: 20 W, but 60 users, so 0.3 W/user, but antenna has gain = 18 dBi.
- Mobile phone handset: 21 dBm.

1.5 Noise

Noise limits a system's ability to process weak signals.

The system dynamic range is defined as the system's capability to detect weak signals in the presence of large-amplitude signals.

Noise sources

1. Random noise in resistors and transistors.
2. Mixer noise.
3. Undesired cross-coupling noise from other transmitters and equipment.
4. Power supply noise.
5. Thermal noise present in all electronics and transmission media due to thermal agitation of electrons.

Thermal noise = $kTB(W)$

Where k is Boltzmann's constant = 1.38×10^{-23}.

Where T is temperature in Kelvin (C + 273).

b is bandwidth.

Examples

For temperature = 293 °C, => −203 dB, −173 dBm Hz^{-1}.

For temperature = 293 °C and 22 MHz => −130 dB, −100 dBm.

Random noise

- External noise.
- Atmospheric noise.
- Interstellar noise.

Receiver (internal)

- Thermal noise.
- Flicker noise (low frequency).
- Shot noise.

SNR is defined as the signal-to-noise ratio. The SNR varies with frequency. SNR = signal power/noise power, SNR is given in equation (1.22).

$$SNR = \frac{S(f)}{N(f)} = \frac{\text{average} - \text{signal} - \text{power}}{\text{average} - \text{noise} - \text{power}} \tag{1.22}$$

- SNR (dB) = 10 log10(signal power/noise power)
  Noise factor, F, is a measure of the degradation of SNR due to the noise added as we process the signal. F is given in equations (1.23) and (1.24).

$$F = \frac{\text{available} - \text{output} - \text{noise} - \text{power}}{\text{available} - \text{output} - \text{noise} - \text{due} - \text{to} - \text{source}} \tag{1.23}$$

Noise figure = NF = 10 log(F).
A **multistage noise figure** is given by equation (1.24):

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}} \tag{1.24}$$

Signal strength is the transmitted power multiplied by a gain minus losses.

Loss sources

- Distance between the transmitter and the receiver.
- The signal passes through rain or fog at high frequencies.
- The signal passes through an object.
- Part of the signal is reflected from an object.
- Signal interferes, multi-path fading.
- An object not directly in the way impairs the transmission.

The received signal must have a strength that is larger than the receiver's sensitivity.

A SNR of 20 dB or larger would be good.

Sensitivity is defined as the minimum detectable input signal level for a given output SNR, also called the noise floor.

1.6 Communication systems: link budget

A link budget determines if the received signal is larger than the receiver's sensitivity.

A link budget analysis determines if there is enough power at the receiver to recover the information. The link budget must account for effective transmission power, and take into account the following parameters. The transmitting channel power budget is presented in table 1.5.

Table 1.5. Transmitting channel power budget for wireless wearable communication systems.

Component	Gain (dB)/Loss (dB)	Power (dBm)	Remarks
Input power		−10	
Transmitter gain	40		
Power amplifier output power		30	
Filter loss	1	29	
Line loss	1	28	
Matching loss	1	27	
Radiated power		27	

Table 1.6. Receiving channel power budget for wireless wearable communication systems.

Component	Gain (dB)/Loss (dB)	Power (dBm)	Remarks
Input power		−20	
Receiver gain	23		
Line losses	1	−21	
Filter loss	1	−22	
Matching loss	1	−23	
LNA amplifier output power		0	

Transmitter

- Transmission power.
- Antenna gain.
- Losses in cables and connectors.

Path losses

- Attenuation.
- Ground reflection.
- Fading (self-interference).

Receiver

- Receiver sensitivity.
- Losses in cable and connectors.

The receiving channel power budget is listed in table 1.6. A transmitter block diagram for wireless wearable communication systems is shown in figure 1.1. A receiver block diagram is shown in figure 1.2.

1.7 Path loss

Path loss is a reduction in the signal's power, which is a direct result of the distance between the transmitter and the receiver in the communication path.

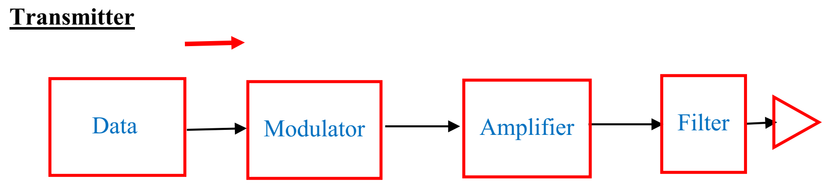


Figure 1.1. Transmitter block diagram for wireless wearable communication systems.

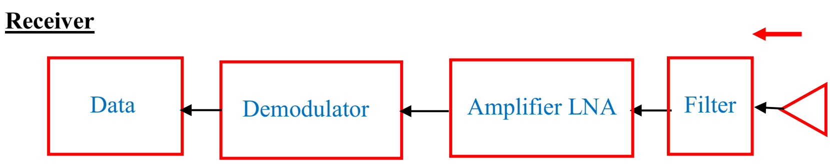


Figure 1.2. Receiver block diagram for wireless wearable communication systems.

There are many models used in the industry today to estimate the path loss and the most common are the free space and Hata models. Each model has its own requirements that need to be met in order to be utilized correctly. The free space path loss is the reference point that other models use.

Free space path loss

Free space path loss (dB) = $20\log_{10}f + 20\log_{10}d - 147.56$

Where F is the frequency in Hz, d is the distance in meters.

The free space model typically underestimates the path loss experienced for mobile communications, and predicts point-to-point fixed path loss.

Hata model

The Hata model is used extensively in cellular communications. The basic model is for urban areas, with extensions for suburbs and rural areas.

The Hata model is valid for these ranges only:

- Distance 1–20 km.
- Base height 30–200 m.
- Mobile height 1–10 m.
- 150 MHz to 1500 MHz.

The Hata formula for urban areas is:

$L_H = 69.55 + 26.16\log_{10}f_c - 13.82\log_{10}h_b - \mathrm{env}(h_m) + (44.9 - 6.55\log_{10}h_b)\log_{10}R$

- h_b is the base station antenna's height in meters.
- h_m is the mobile antenna's height also measured in meters.
- R is the distance from the cell site to the mobile in km.
- f_c is the transmitting frequency in MHz.
- $\mathrm{env}(h_m)$ is an adjustment factor for the type of environment and the height of the mobile. $\mathrm{env}(h_m) = 0$ for urban environments with a mobile height of 1.5 m.

1.8 Receiver sensitivity

Sensitivity describes the weakest signal power level that the receiver is able to detect and decode. Sensitivity is determined by the lowest SNR at which the signal can be recovered. Different modulation and coding schemes have different minimum SNRs. Sensitivity is determined by adding the required SNR to the noise present at the receiver.

Noise sources

- Thermal noise.
- Noise introduced by the receiver's amplifier.

Thermal noise = $N = kTB$ (watts)

- $k = 1.3803 \times 10^{-23}$ J K^{-1}.
- T = temperature in Kelvin.
- B = receiver's bandwidth.

N (dBm) = $10 \log_{10}(kTB) + 30$
Thermal noise is usually very small for reasonable bandwidths.

Basic receiver's sensitivity calculation

Sensitivity (W) = $kTB\ NF$ (linear) minimum SNR required (linear)
Sensitivity (dBm) = $10 \log_{10}(kTB\ 1000) + NF$(dB) + minimum SNR required (dB)
Sensitivity (dBm) = $10 \log_{10}(kTB) + 30 + NF$(dB) + minimum SNR required (dB)

Sensitivity decreases in communication systems when:

- the bandwidth increases,
- the temperature increases,
- the amplifier introduces more noise,
- there are losses in space, rain and snow.

1.9 Receivers: definitions and features

Figure 1.3 presents a basic receiver block diagram.

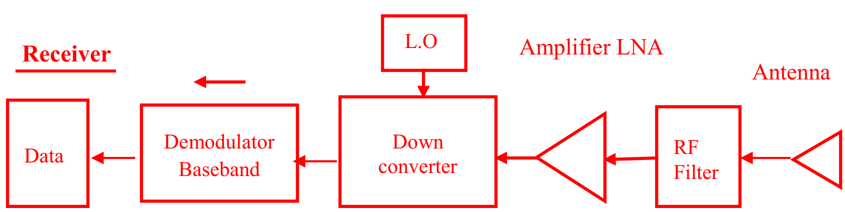


Figure 1.3. Basic receiver block diagram for wearable communication systems.

Receivers: definitions

RF, IF and LO frequencies

When a receiver uses a mixer we refer to the input frequency as the RF frequency. The system must provide a signal to mix down the RF, this is called the local oscillator. The resulting lower frequency is called the intermediate frequency (IF), because it is somewhere between the RF frequency and the base band frequency.

Base band frequency

The base band is the frequency at which the information you want to process is located.

Pre-selector filter

A pre-selector filter is used to keep undesired radiation from saturating a receiver. For example, we don't want a cell phone to pick up air-traffic control radar.

Amplitude and phase matching versus tracking

In a multi-channel receiver (more than one receiver) it is important for the channels to match and track each other over frequency. Amplitude and phase *matching* means that the relative magnitude and phase of signals that pass through the two paths must be almost equal.

Tunable bandwidth versus instantaneous bandwidth

Instantaneous bandwidth is what we get with a receiver when we keep the LO at a fixed frequency, and sweep the input frequency to measure the response. The resulting bandwidth is a function of the frequency responses of everything in the chain. The instantaneous bandwidth has a direct effect on the minimum detectable signal. Tunable bandwidth implies that we change the frequency of the LO to track the RF frequency. The bandwidth in this case is only a function of the pre-selector filter, the LNA and the mixer. A tunable bandwidth is often many times greater than an instantaneous bandwidth.

Gain

The gain of a receiver is the ratio of the input signal power to the output signal power.

Noise figure

The noise figure of a receiver is a measure of how much the receiver degrades the ratio of the signal-to-noise of the incoming signal. It is related to the minimum detectable signal. If the LO signal has a high AM and/or FM noise, it could degrade the receiver noise figure because, far from the carrier, the AM and FM noise originate from the thermal noise. Remember that the effect of LO AM noise is reduced by the balance of the balanced mixer.

1 dB compression point
The 1 dB compression point is the power level where the gain of the receiver is reduced by one dB due to compression.

Linearity
A receiver operates linearly if a one dB increase in input signal power results in a one dB increase in IF output signal strength.

Dynamic range
The dynamic range of a receiver is a measurement of the minimum detectable signal to the maximum signal that will start to compress the receiver.

Signal-to-noise ratio (S/N) SNR
The SNR is a measure of how far a signal is above the noise floor.

Noise factor, noise figure and noise temperature

- The noise factor is a measure of how the signal-to-noise ratio is degraded by a device:
  - F = noise factor = $(S_{in}/N_{in})/(S_{out}/N_{out})$
  - S_{in} is the signal level at the input,
  - N_{in} is the noise level at the input,
  - S_{out} is the signal level at the output,
  - N_{out} is the noise level at the output.
- The noise factor of a device is specified with noise from a noise source at room temperature ($N_{in} = KT$), where K is Boltzmann's constant and T is approximately room temperature in Kelvin. KT is somewhere around -174 dBm Hz^{-1}. Noise figure is the noise factor, expressed in decibels:
  - NF (decibels) = noise figure = 10 log (F).
  - T = noise temperature = 290 ($F - 1$).
  - 1 dB NF is about 75 Kelvin, and 3 dB is 288 Kelvin.

The noise factor contributions of each stage in a four stage system is given in equation (1.25).

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} \tag{1.25}$$

1.10 Types of radars

In mono-static radars: the transmitting and receiving antennas are co-located. Most radars are mono-static.

Bi-static radar: Bi-static radars means that the transmitting and receiving antennas are not co-located.

Doppler radar is used to measure the velocity of a target, due to its Doppler shift. Police radar is a classic example of Doppler radar.

FMCW radar: Frequency modulated/continuous wave implies that the radar signal is 'chirped', or its frequency is varied in time. By varying the frequency in this manner, you can gather both range and velocity information.

Synthetic aperture radar (SAR): SAR uses a moving platform to 'scan' the radar in one or two dimensions. Satellite radar images are mostly done using SAR.

1.11 Transmitters: definitions and features

Figure 1.4 presents a basic transmitter block diagram.

Amplifiers
Class A—The amplifier is biased at close to half of its saturated current. The output conducts during all 360 degrees of phase of the input signal sine wave. Class A does not give maximum efficiency, but provides the best linearity. Drain efficiencies of 50% are possible in class A.

Class B—The power amplifier is biased at a point where it draws nearly zero DC current; for a FET, this means that it is biased at pinch-off. During one half of the input signal sine wave it conducts, but not during the other half. A class B amplifier can be very efficient, with theoretical efficiency of 80%–85%. However, we give up six dB of gain when we move from class A to class B.

Class C—Class C occurs when the device is biased so that the output conducts for even less than 180 degrees of the input signal. The output power and gain decrease.

Power density—This is a measure of power divided by the transistor's size. In the case of FETs it is expressed in watts/mm. GaN transistors have more than 10 W mm^{-1} power density.

Saturated output power—PSAT is the output power where the P_{in}/P_{out} curve slope goes to zero.

Load pull—The process of varying the impedance seen by the *output* of an active device to other than 50 ohms in order to measure performance parameters, in the

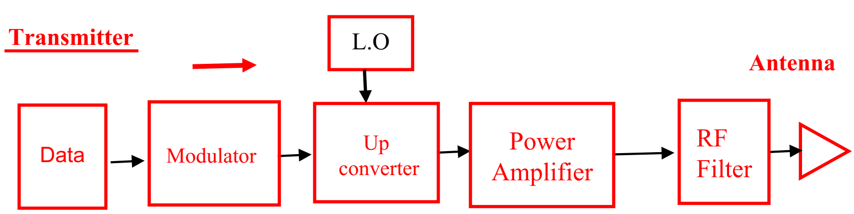


Figure 1.4. Basic transmitter block diagram for wearable communication systems.

simplest case, gain. In the case of a power device, a load pull power bench is used to evaluate large signal parameters such as compression characteristics, saturated power, efficiency and linearity as the output load is varied across the Smith chart.

Harmonic load pull—The process of varying the impedance at the output of a device, with separate control of the impedances at F0, 2F0, 3F0, etc.

Source pull—The process of varying the impedance seen by the input of an active device to other than 50 ohms in order to measure the performance parameters. In the case of a low noise device, source pull is used in a noise parameter extraction setup to evaluate how the SNR (noise figure) varies with the source impedance.

Amplifiers: temperature considerations

In the case of a FET amplifier, the gain drops and the noise figure increases.

The gain drop is around —0.006 dB/stage/degrees Centigrade.

The noise figure of an LNA increases by +0.006 dB/degrees Centigrade. In an LNA, the first stage will dominate the temperature effect.

Power amplifiers

Power amplifiers are used to boost a small signal to a large signal.

Solid state amplifiers and tube amplifiers are usually employed as power amplifiers.

The output power capabilities of power amplifiers are listed in table 1.7.

1.12 Satellite communication transceiver

This section presents an example of a satellite communication transceiver. This section describes the design, performance and fabrication of a compact and low-cost MIC RF-head for satellite communication applications. Surface mount MIC technology is employed to fabricate the RF-head.

1.12.1 Introduction

The mobile telecommunications industry is currently growing [8–15]. Moreover, the great public demand for cellular and cordless telephones has stimulated a wide interest in new mobile services such as portable satellite communication terminals.

Table 1.7. Power amplifiers' output power capabilities.

Frequency band	Solid state	Tube type
L band through C band	200 W (LDMOS) GaN	
X band	50 W (GaN HEMT device)	3000 W (TWT)
Ka band	6 W (GaAs PHEMT device)	1000 W (klystron)
Q band	4 W (GaAs PHEMT device)	

For example, the Inmarsat-M system provides digital communications between the public switched terrestrial networks and mobile users.

Communication links to and from mobile installations are established via an Inmarsat geostationary satellite and the associated ground station.

The RF-head includes the receiving and transmitting channels, RF controller, synthesizers, modem and a DC supply unit. The RF-head size is 30 × 20 × 2.5 cm and weighs 1 kg. The transmitting channel may be operated in high power mode to transmit 10 W or in low power mode to transmit 4 W. The transmitted power level is controlled by an automatic leveling control unit to ensure low power consumption over all the frequency and temperature range. The RF-head vent is set to 'on' and 'off' automatically by the RF controller. The gain of the receiving channel is 76 dB and is temperature-compensated by using a temperature sensor and a voltage-controlled attenuator. Surface mounted technology is employed to fabricate the RF-head.

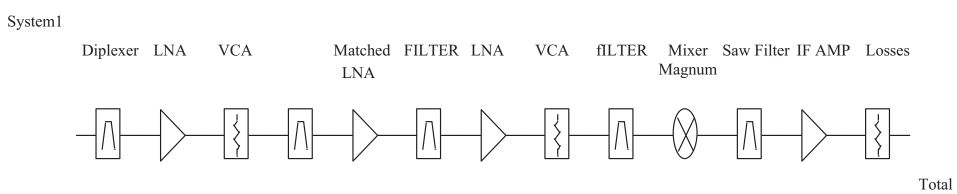
1.12.2 Description of the receiving channel

A block diagram of the receiving channel is shown in figure 1.5.

The receiving channel consists of low noise amplifiers, filters, active mixer, saw filter, temperature sensor, voltage-controlled attenuator and IF amplifiers.

The low noise amplifier has 10 dB gain and 0.9 dB noise figure for frequencies ranging from 1.525–1.559 GHz. The total gain of the receiving channel is 76 dB.

The low noise amplifier employs a $1.8 (GaAS) Fet. The receiving channel, noise figure and power budget calculation are given in table 1.8. The channel gain is temperature-compensated by connecting the output port of a temperature sensor to



	Diplexer	LNA	VCA		Matched LNA	FILTER	LNA	VCA	fILTER	Mixer Magnum	Saw Filter	IF AMP	Losses	Total
Gain (dB)	-1.00	20.00	-3.50	-2.00	14.00	-2.00	10.00	-3.50	-2.00	15.00	-8.00	42.50	-2.50	76.33*
NF (dB)	1.00	0.95	3.50	2.00	1.45	2.00	0.90	3.50	2.00	20.00	8.00	2.50	2.50	2.35
IP1dB (dBm)	20.00	-2.00	20.00	20.00	4.00	20.00	7.00	20.00	20.00	8.00	20.00	10.00	20.00	-59.50
NF+ (dB)	0.71	0.86	0.04	0.04	0.04	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	

Input Pwr (dBm)	-60.00	System Temp (K)	290.00
Modulation: FM			

System BW (MHz)	0.03	MDS (dBm)	-126.86	Input IP3 (dBm)	N/A
S/N (dB, Actual)	66.18	S/N (dB, Req'd)	6.00	Output IP3 (dBm)	N/A
Srce Temp (K)	290.00	Sens. Loss (dB)	0.00	OIM3 (dBm)	N/A
Te Eff. (K)	208.30	Sensitivity (dBm)	-120.86	ORR3 (dB)	N/A
SFDR3 (dB)	N/A	G/T (dB/K)	-16.97	IRR3 (dB)	N/A

Figure 1.5. Block diagram and gain budget of the receiving channel.

Table 1.8. Noise figure and gain calculation.

Component	Noise figure (dB)	Gain (dB)	P_{out} (dBm)
Diplexer	1	−1	−131
LNA	0.95	20	−111
VCA	3.5	−3.5	−114.5
Filter	2	−2	−116.5
Matched LNA unit	1.45	14	−102.5
Filter	2	−2	−104.5
LNA	0.9	10	−94.5
VCA	3.5	−3.5	−98
Filter	2	−2	−100
Mixer	20	15	−85
Saw filter	8	−8	−93
IF amplifiers	2.5	42.5	−50.5
Transmission line losses	2.5	−2.5	−53
Total	2.35	77	−53

the reference voltage port of a voltage-controlled attenuator. The variation of the sensor output voltage as a function of temperature varies the attenuation level of the attenuator. Gain stability as a function of temperature is less than 1 dB. The receiving channel noise figure is less than 2.2 dB, including 1 dB diplexer losses. The receiving channel rejects out-of-band signals with a power level lower than −20 dBm.

Receiving channel specifications

Frequency range: 1525–1559 MHz.
Local oscillator frequency: 1355–1389 MHz.
IF frequency: 170 MHz.
Channel 1 dB bandwidth: 50 KHz.
Noise figure: 3 dB.
Input signals: 105–135 dBm.
Output signals: 30–60 dBm.
Receiving sensitivity: $C/N = 41$ dB Hz^{-1} for −130 dBm input signal.

1.12.3 Receiving channel: design and fabrication

A major parameter in the receiving channel design was to achieve a very low target price in the manufacturing of hundreds of units. The components were selected to meet the electrical requirements for a given low target price assigned to each component. The low production cost of the RF-head is achieved by using SMT technology. Trimming is not required in the fabrication procedure of the receiving channel. The gain and noise figure values of the receiving channel are measured in each RF-head. Around 300 receiving channels have been manufactured to date.

1.12.4 Description of the transmitting channel

A block diagram of the transmitting channel is shown in figure 1.6. The transmitting channel consists of low power amplifiers, pass band filters, voltage-controlled attenuator, active mixer, medium power and high power amplifiers, high power isolator, coupler, power detector and DC supply unit.

The power budget of the transmitting channel is given in table 1.9.

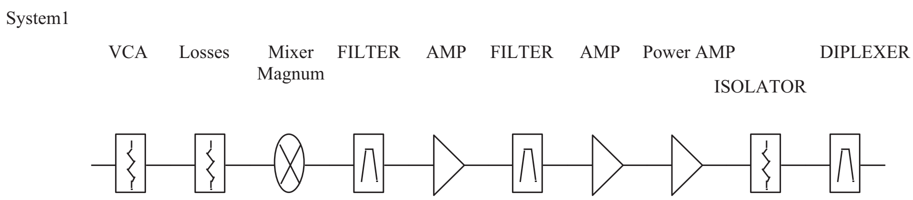
Five stages of power amplifiers amplify the input signal from 0 dBm to 40 dBm. The fifth stage is a 10 W power amplifier with high efficiency. The amplifier may transmit 10 W in high power mode or 4 W in low power mode. The DC bias voltage of the power amplifier is automatically controlled by the RF controller to set the power amplifier to the required mode and power level. A −30 dB coupler and a power detector are used to measure the output power level. The measured power level is transferred via an A/D converter to the RF controller to monitor the output power level of the transmitting channel by varying the attenuation of the voltage-controlled attenuator. This feature ensures low DC power consumption and high efficiency of the RF-head. The RF controller sets the transmitting channel to ON and OFF. A temperature sensor is used to measure the RF-head temperature. The RF controller sets the RF-head vent to ON and OFF according to the measured RF-head temperature.

1.12.4.1 Transmitting channel specifications

Frequency range: 1626.5–1660.5 MHz.

I.F frequency range: 99.5–133.5 MHz.

LO frequency: 1760 MHz.



	VCA	Losses	Mixer Magnum	FILTER	AMP	FILTER	AMP	Power AMP	ISOLATOR	DIPLEXER	Total
Gain (dB)	-4.00	-0.50	2.00	-2.00	20.50	-2.00	16.00	11.50	-0.50	-1.00	40.00
NF (dB)	4.00	0.50	2.00	2.00	3.00	2.00	3.00	5.00	0.50	1.00	9.23
IP1dB (dBm)	20.00	20.00	10.00	20.00	10.00	20.00	10.00	20.00	20.00	20.00	-21.67
NF+ (dB)	0.87	0.16	0.95	0.58	1.77	0.01	0.02	0.00	0.00	0.00	

Input Pwr (dBm)	-60.00	System Temp (K)	290.00
Modulation: FM			

System BW (MHz)	0.03	MDS (dBm)	-119.98	Input IP3 (dBm)	N/A
S/N (dB, Actual)	59.98	S/N (dB, Req'd)	6.00	Output IP3 (dBm)	N/A
Srce Temp (K)	290.00	Sens. Loss (dB)	0.00	OIM3 (dBm)	N/A
Te Eff. (K)	2136.86	Sensitivity (dBm)	-113.98	ORR3 (dB)	N/A
SFDR3 (dB)	N/A	G/T (dB/K)	-23.85	IRR3 (dB)	N/A

Figure 1.6. Block diagram and gain budget of the transmitting channel.

Table 1.9. Transmitting channel power budget.

Component	Gain/Loss (dB)	P_{out} (dBm)
Input	0	0
VCA	−4	−4
Tr. line loss	−0.5	−4.5
Mixer	2	−2.5
Filter	−2	−4.5
Low power amplifiers	20.5	16
Filter	−2	14
Medium power amplifier	16	30
Power amplifier	11.5	41.5
Isolator	−0.5	41
Diplexer	−1	40
Total	40.0	40

Input power: 0 dBm.
Output power (high mode): 38–40 dBm.
Output power (low mode): 34–36 dBm.
Power consumption: 42 W.

1.12.4.2 Diplexer specifications

A very compact and lightweight diplexer connects the receiving and transmitting channels to the antenna. The diplexer's simple structure and easy manufacturability ensures lower costs in production than similar diplexers.

Transmitting filter

Pass band frequency range: 1626.5–1660.5 MHz.
Pass band insertion loss: 0.7 dB.
Pass band VSWR < 1.3:1.
Rejection > 54 dB at 1525–1559 MHz.

Receiving filter

Pass band frequency range: 1525–1559 MHz.
Pass band insertion loss < 1.3 dB.
Pass band VSWR <1.3:1.
Rejection > 65 dB at 1626.5–1660.5 MHz.
Size: 86 × 36 × 25 mm.

1.12.5 Transmitting channel fabrication

A photo of the RF-head prototype for an Inmarsat-M ground terminal is shown in figure 1.7. A major parameter in the transmitting channel design was to achieve a low target price in the fabrication of hundreds of units. The components were selected to meet the target price given to each component and the electrical

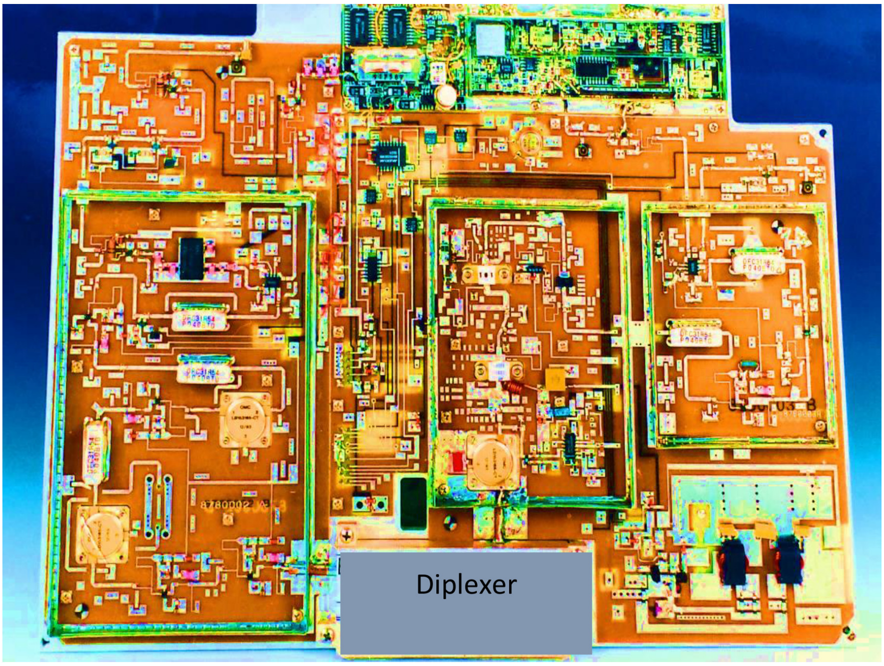


Figure 1.7. RF-head prototype for an Inmarsat-M ground terminal.

requirements. Low production cost is achieved by using SMT technology to manufacture the transmitting channel. A quick trimming procedure is required in the fabrication of the transmitting channel to achieve the required output power and efficiency. The output power and spurious level of the transmitting channel are tested in the fabrication procedure of each RF-head. Around 300 transmitting channels have been manufactured during the first production cycle.

A photo of the RF-head modules for an Inmarsat-M ground terminal is shown in figure 1.8. The RF-head is separated into five sections. Receiving and transmitting channels, diplexer, synthesizers, RF controller and a DC supply unit. A metallic fence and cover separate the transmitting and receiving channels.

1.12.6 RF controller

The RF controller is based on an 87c51 microcontroller. The RF controller communicates with the system controller via a full duplex serial bus. The communication is based on message transfer. The RF controller sets the transmitting channel to 'on' and 'off' by controlling the DC voltage switching unit. The RF controller monitors the output power level of the transmitting channel by varying the attenuation of the voltage-controlled attenuator in the transmitting channel. The RF controller sets the transmitting channel to burst or scpc modes with high or low power levels, and produces the clock data and enables signals for the Rx and Tx synthesizers.

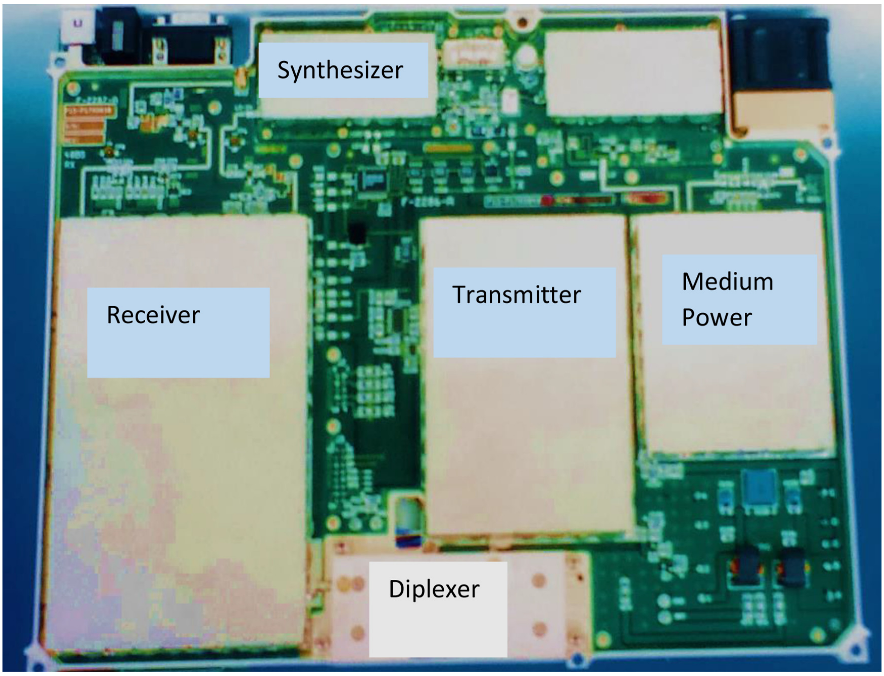


Figure 1.8. RF-head modules for an Inmarsat-M ground terminal.

1.12.7 Conclusions

A compact and low-cost RF-head for Inmarsat-M applications is presented in this section. The RF-head is part of a portable satellite communication ground terminal, 'Cary-phone', which supplies phone and fax services to customers.

The RF controller automatically monitors the output power level to ensure low DC power consumption. A dc-to-dc converter supplies a controlled DC bias voltage to the power amplifier to a high power level mode, 10 W or 4 W.

The receiving channel noise figure is less than 2.2 dB. The total gain of the receiving channel is 76 dB with a gain stability of 1 dB as a function of temperature.

The RF-head size is 30 × 20 × 2.5 cm and weighs less than 1 kg.

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