McGill University

Department. of Electrical and Computer Engineering

Communications systems 304-411A

1 The Super-heterodyne Receiver

1.1 Principle and motivation for the use of the super-heterodyne receiver

The super-heterodyne receiver is a special type of receiver that in addition to demodulating the incoming signal, does carrier-frequency tuning(selection of the desired signal), filtering(separation of the desired signal from interference) and amplification.

Selectivity is a measure of how well a receiver can select a desired station while excluding all others.

By converting the Radio Frequency(RF) signal to a fixed Intermediate Frequency(IF), the super-heterodyne receiver provides improved selectivity. It is much easier, (and much more cost-effective) to implement a band-pass filter with good selectivity at a fixed center frequency, rather than to improve the selectivity of the RF amplifier(which has a variable center frequency).

1.2 AM super-heterodyne Receiver

Let us consider, for example, an AM super-heterodyne receiver, depicted in Fig. 1. The desired signal centered at a carrier frequency f_c,is called the Radio Frequency (RF) signal. With this receiver, any signal within a specified frequency band (Radio Frequency signals) can be selected by the user, by simply changing the frequency of the local oscillator and of the RF filter if necessary. The desired signal, together with unwanted signal at frequencies other than f_c, is received by the antenna, then amplified by the RF amplifier. The amplifier also partially filters out undesired signals. However, its **selectivity** is not sufficient to eliminate the nearby carriers.

In order to improve the selectivity of the receiver, the signal is converted to a fixed Intermediate Frequency (IF) by a mixer, which is cascaded with an IF amplifier, of fixed center frequency f_{IF}, and a narrow bandwidth.

The information signal $s(t)$ is recovered from the IF filter output signal $z(t)$ by using a demodulator and a lowpass filter(if necessary). Note that the design of the demodulator is also simplified by the fact that $z(t)$ is always centered at the IF.

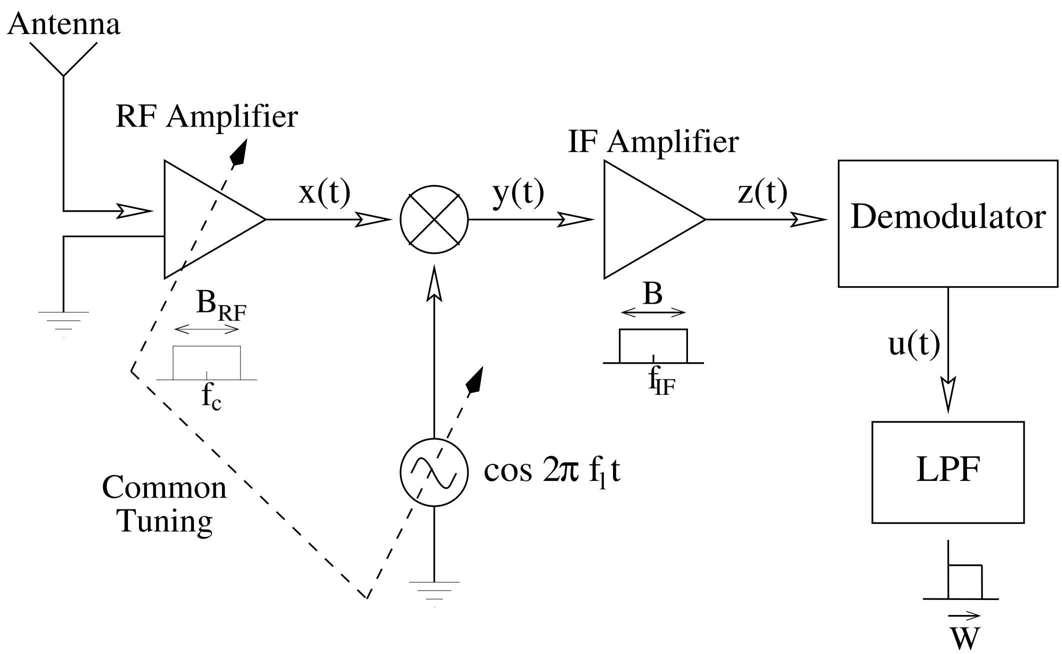

Figure 1: The Super-heterodyne receiver

1.3 The RF amplifier

Let $s(t)$ be the information signal as illustrated in Fig. 2. The AM modulated wave is given

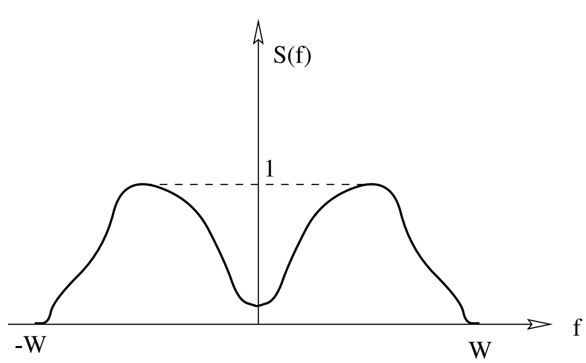

Figure 2: Fourier Transform $S(f)$ of the information signal $s(t)$

by

$$x(t) = A_c(1 + ms(t)) \cos 2\pi f_c t$$

and illustrated in Fig. 3. The RF amplifier is a bandpass filter, with a varying center

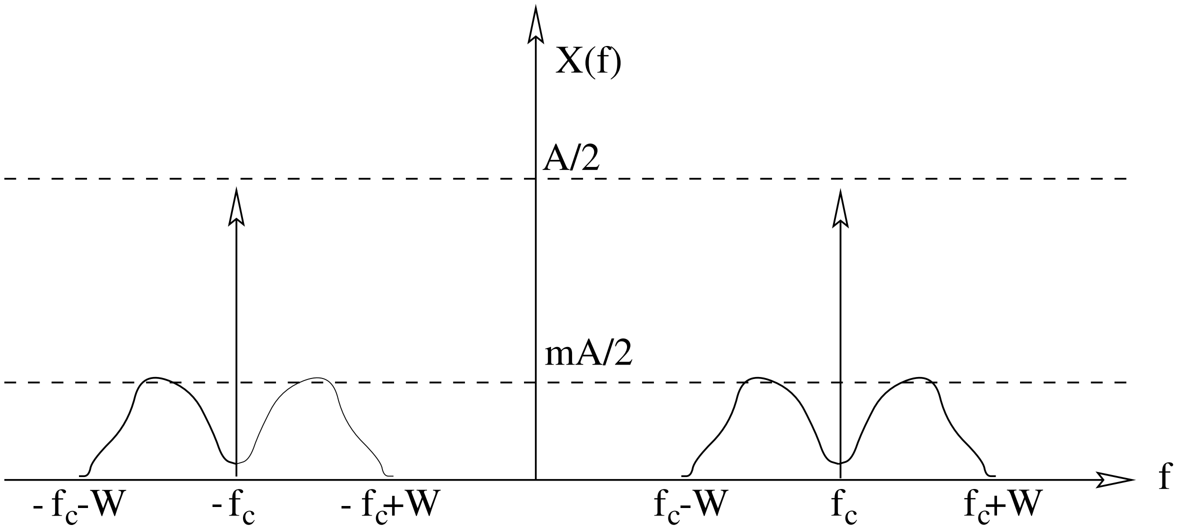

Figure 3: Fourier Transform $X(f)$ of the modulated signal $x(t)$

frequency f_c, and fixed bandwidth B_{RF}. The center frequency is controlled by the choice of the Radio Frequency done by the user of the receiver. The Bandwidth should satisfy

$$B < B_{RF} < 4f_{IF}$$

where B is the bandwidth of the modulated signal. For AM, $B = 2W$, where W is the bandwidth of the message signal $s(t)$. The upper inequality should hold to eliminate the signal at image frequency, $f_{im} = f_c + 2f_{IF}$. This will be explained in detail in the next subsection. The RF spectrum is illustrated in Fig. 4 and the received signal after the RF amplifier is illustrated in Fig. 5.

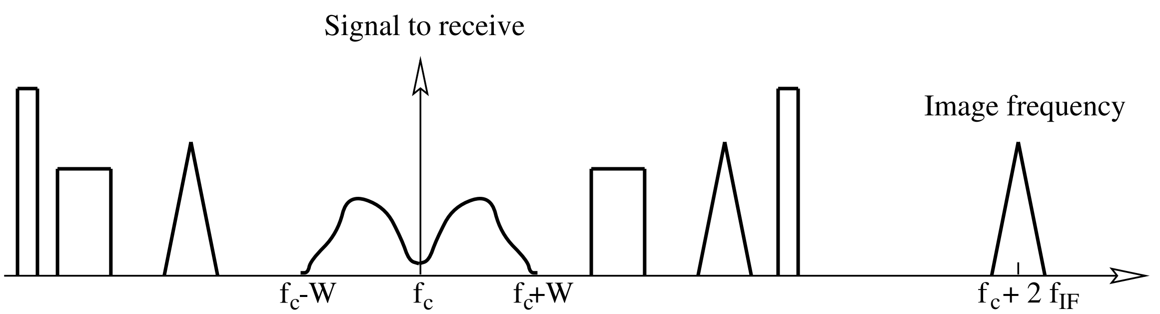

Figure 4: RF spectrum

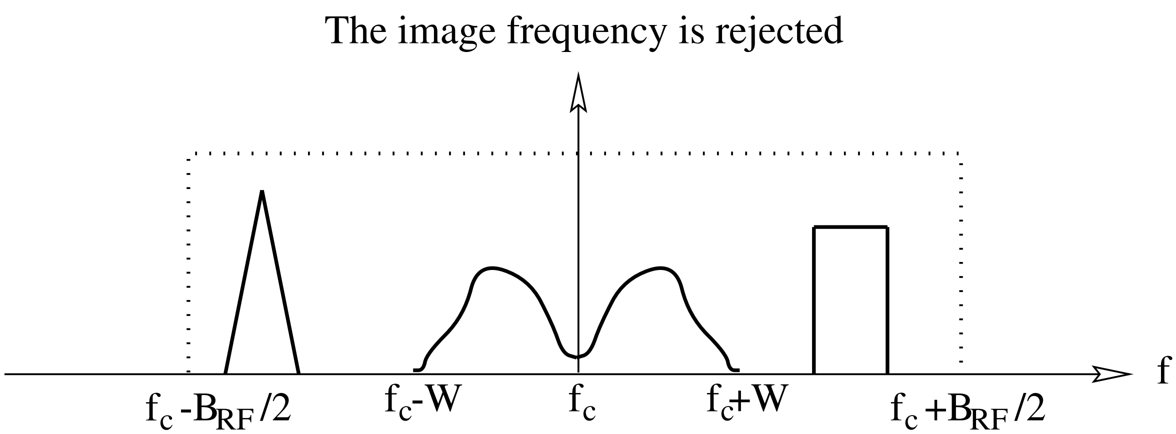

Figure 5: Output of RF amplifier

1.4 The mixer

The output of the mixer is given by

$$\begin{aligned} y(t) &= x(t)\cos 2\pi f_l t \\ &= A_c(1+ms(t))\cos 2\pi f_c t \cos 2\pi f_l t \\ &= \frac{A_c}{2}(1+ms(t))\Big[\cos 2\pi(f_c+f_l)t + \cos 2\pi(f_l-f_c)t\Big] \end{aligned}$$

Most of the super-heterodyne receivers use High-Side Injection(HSI) of the oscillator, i.e. $f_l = f_c + f_{IF}$(for Low-Side Injection(LSI), $f_l = f_c - f_{IF}$). As the receiver is tuned to the frequency of another incoming signal, the frequency of the local oscillator is also automatically changed so as to satisfy $f_l = f_c + f_{IF}$(for HSI). Hence the output of the mixer for HSI is given by

$$y(t) = \frac{A_c}{2}(1+ms(t))\Big[\cos 2\pi f_{IF}t + \cos 2\pi(2f_c+f_{IF})t\Big] + \text{possibly other signals}$$

and illustrated in Fig. 6.

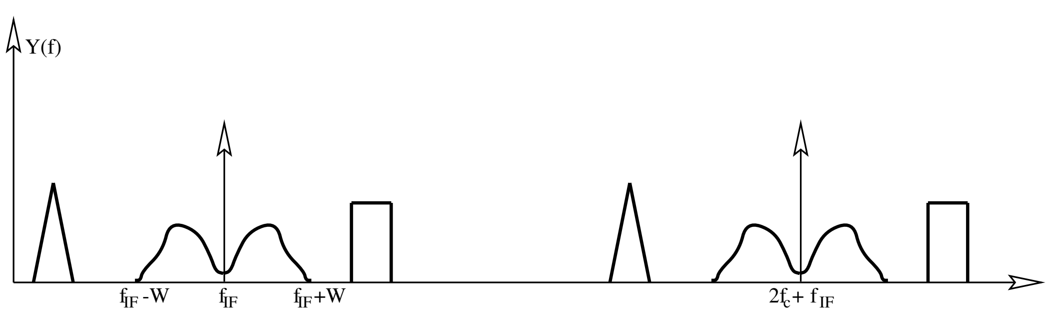

Figure 6: Fourier transform Y(f): Output of the mixer

Image response

Another signal at $f_{im} = f_c + 2f_{IF}$, called the image response, can be down converted to the IF if the RF bandpass filter does not have a good image response. Assume that the RF amplifier is not narrow enough and that there is another signal at f_{im}, then the output of the RF amplifier is given by

$$x(t) = A_{c1}(1 + m_1 s_1(t)) \cos 2\pi f_c t + A_{c2}(1 + m_2 s_2(t)) \cos 2\pi(f_c + 2f_{IF})t$$

The output of the mixer is given by(assuming HSI)

$$\begin{aligned}
y(t) &= x(t) \cos 2\pi f_l t \\
&= \frac{A_{c1}}{2}(1 + m_1 s_1(t)) \Big[\cos 2\pi(f_c + f_l)t + \cos 2\pi(f_l - f_c)t\Big] \\
&\quad + \frac{A_{c2}}{2}(1 + m_2 s_2(t)) \Big[\cos 2\pi(f_c + 2f_{IF} + f_l)t + \cos 2\pi(f_l - f_c - 2f_{IF})t\Big] \\
&= \left\{\frac{A_{c1}}{2}(1 + m_1 s_1(t)) + \frac{A_{c2}}{2}(1 + m_2 s_2(t))\right\} \cos 2\pi f_{IF} t \\
&\quad + \frac{A_{c1}}{2}(1 + m_1 s_1(t)) \cos 2\pi(2f_c + f_{IF})t + \frac{A_{c2}}{2}(1 + m_2 s_2(t)) \cos 2\pi(2f_c + 3f_{IF} + f_l)t
\end{aligned}$$

We can see that the signal at the image frequency gets superimposed with the desired signal at f_c. To avoid this problem, the RF bandpass amplifier should be narrow enough to reject the image response(i.e. $f_c + \frac{B_{RF}}{2} < f_c + 2f_{IF}$).

1.5 The IF amplifier

The IF amplifier provides most of the required gain and selectivity. Its bandwidth is equal to B. The output signal of this filter is

$$z(t) = \frac{A_c}{2}(1 + ms(t)) \cos 2\pi f_{IF} t$$

and illustrated in Fig. 7.

1.6 The Demodulator

At the output of the IF filter, the desired signal $z(t)$ is centered at f_{IF}. Theoretically, the output of the demodulator is

$$u(t) = \frac{A_c}{2}(1 + ms(t))$$

If the demodulator is an envelope detector, the amount of ripples is usually not negligible and can be removed by low-pass filtering when necessary.

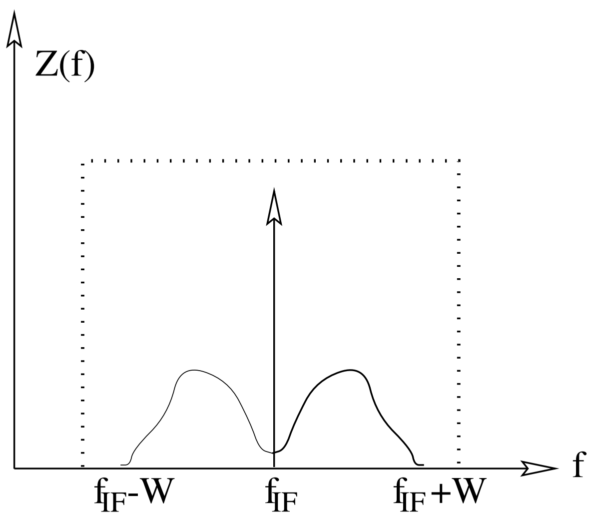

Figure 7: Fourier transform Z(f): Output of the IF amplifier