1 Introduction

This lab explores superheterodyne single and dual conversion receiver subsystems for analog and digital modulation. Two VHF (30–300 MHz) FM receivers are considered. The first receiver employs a wideband (about 200 kHz) IF subsystem centered at 10.7 MHz, while the second employs a narrowband (about 10 kHz) IF subsystem centered at 455 kHz. The narrowband FM receiver also utilizes dual conversion, with the first IF at 10.7 MHz and the second IF at 455 kHz. Both receivers have been constructed using readily available radio frequency integrated circuits (RFICs) from NXP semiconductor\(^1\). The receivers are presently in prototype form, constructed on an RF breadboard. In the future the receivers will be fabricated using a custom PCB.

The high sensitivity of these receivers allows the wideband receiver to easily tune in FM broadcast stations and the narrowband receiver to receive the Colorado Springs national weather service (NOAA) station, and lab broadcast frequency shift keyed (FSK) digital modulation.

1.1 Wideband FM Receiver

The block diagram for the wideband receiver is given in Figure 1. The low-noise amplifier (LNA) is not implemented at this time, nor is the front-end bandpass filter (BPF). A short wire (clip lead) will serve as the antenna in the experiment. The receiver requires and external local oscillator (LO). In order to receive VHF signals, in particular FM broadcast which covers 87.5–108 MHz, the output of the Agilent 33250, which will serve as the LO, needs to be frequency doubled. The Agilent 33250 has a maximum frequency of 80 MHz, but with the doubler the effective maximum

\(^1\)http://www.nxp.com/
1.1 Wideband FM Receiver

LO frequency is 160 MHz. With low-side tuning for the LO, this means that carrier frequencies up to \(160 + 10.7 = 170.7\) MHz can be down-converted. The doubler is a passive circuit from Minicircuits\(^2\), which in simple terms acts as a full-wave rectifier, which has a strong second harmonic component.

The mixer output is processed with a multistage IF amplifier, with the 10.7 MHz IF passband shaping formed using ceramic filters. The nominal bandwidth of each filter is 280 kHz. Note from the schematic of Figure 2, the ceramic filters are external to the NXP SA636 RFIC. The final stage is the FM demodulator, which in this design uses a quadrature detector. The theoretical basis of the quadrature detector will be described in a later section.

1.1.1 IF Filters

An RF receiver needs to have high gain in order to process weak signals arriving from a transmitter located many miles away. High gain over a wide bandwidth is hard to manage from a stability standpoint. Sensitive radio receivers also need to be very selective, that is supply high gain over just a relatively narrow band of frequencies. For the case of an FM receiver the needed bandwidth

\(^2\)www.minicircuits.com

Figure 2: Single conversion VHF FM receiver schematic based on the NXP SA636 IF subsystem.
is the bandwidth of the modulated message signal following a Carson’s rule analysis. In the FM broadcast band stations are spaced every 200 kHz at odd 100 kHz spacings, e.g., 101.1 MHz, 99.3 MHz, etc. From Wikipedia\(^3\) the one-sided baseband spectral occupancy is around 100 KHz before being frequency modulated onto the carrier, as shown in Figure 3. The dominant baseband signals are the \(L + R\) and \(L - R\) audio signals. The peak frequency deviation is 75 kHz. If we apply Carson’s rule to just the \(L + R\) signal, which has a nominal bandwidth of 15 Khz, we arrive at a modulated bandwidth of

\[
B_{RF} = 2(D + 1)W = 2 \left( \frac{75}{15} + 1 \right) 15 = 180 \text{ kHz.} \tag{1}
\]

When the \(L - R\) for FM stereo is included along with the other services, e.g. radio data service (RDS) at 57 kHz, the occupied spectrum must still be within a 200 kHz wide footprint.

We desire an IF filter characteristic which passes only the signal/station of interest, rejecting all adjacent signals. A realizable IF filter will transition from passband to stopband over a finite band of frequencies. The ceramic filters employed in the wideband receiver design are wider than needed, being that they have a 3 dB bandwidth of 280 kHz. The filter specifications and plots of the magnitude and group delay response are shown in Figure 4.

1.1.2 Quadrature Demodulator

In analog integrated circuits used for FM radio receivers and the like, an FM demodulator known as a quadrature detector or quadrature discriminator, is quite popular. The schematic for the detector is shown in Figure 5. The input FM signal connects to one port of a multiplier (product device).

\[\text{http://en.wikipedia.org/wiki/FM_broadcasting}\]

Figure 3: One-sided FM broadcast spectrum including the various subcarrier services.
1.1 Wideband FM Receiver

A quadrature signal is formed by passing the input to a capacitor series connected to the other multiplier input and a parallel tank circuit resonant at the input carrier frequency. The quadrature circuit receives a phase shift from the capacitor and additional phase shift from the tank circuit. The phase shift produced by the tank circuit is time varying in proportion to the input frequency deviation. A mathematical model for the circuit begins with the FM input signal

\[ x_c(t) = A_c \cos \left( \omega_c t + \phi(t) \right) \tag{2} \]

The quadrature signal is

\[ x_{\text{quad}}(t) = K_1 A_c \sin \left( \omega_c t + \phi(t) + K_2 \frac{\phi(t)}{dt} \right) \tag{3} \]

Figure 4: Murata SFE10M7 ceramic IF filter specifications: (a) spec table, (b) passband detail, and (c) full band response.
where the constants $K_1$ and $K_2$ are determined by circuit parameters. The multiplier output, assuming a lowpass filter removes the sum terms, is

$$x_{\text{out}}(t) = \frac{1}{2} K_1 A_c^2 \sin \left( K_2 \frac{d\phi(t)}{dt} \right)$$

By proper choice of $K_2$ the argument of the sin function is small, and a small angle approximation yields

$$x_{\text{out}}(t) \approx \frac{1}{2} K_1 K_2 A_c^2 \frac{d\phi(t)}{dt} = \frac{1}{2} K_1 K_2 A_c^2 K_{Dm}(t)$$

1.1.3 Laboratory Exercises

1. The Colorado Springs market has a lot of FM broadcast stations. Several of them are likely familiar to you. Set-up the Agilent 4395A spectrum analyzer with a VHF flex antenna connected to a 50 ohm input, as shown in Figure 6. Set the span to 87.5 to 108 MHz. This will allow you to see the entire FM broadcast spectrum. At this resolution each FM station will appear as a spectral line. Count the number of strong signals you see. For a few stations verify using the marker that the center frequency of each station falls at an odd multiple of 100 kHz and that the minimum spacing between stations is thus 200 kHz. Just from the spectrum analyzer display, and your knowledge of FM stations in the Colorado Springs market, clearly identify one of your favorite stations by setting the marker at the station center frequency.

2. Spectrally zoom into one of the stronger stations and measure the approximate occupied spectral bandwidth. Does it conform to needs of the 200 kHz spacing rule? The spectrum will be changes as the applied modulation, e.g. music or talking changes over time.

3. In the next step you will power up the wideband receiver. You will need to know how to set the LO frequency to receive FM broadcast stations. Develop two formulas for determining the required LO frequency to receive a station using either high-side or low-side LO tuning. Your functions should take as input the desired station frequency, e.g., 99.1 MHz and return the LO frequency. You need to take into account the fact that the LO frequency is doubled, as shown in Figure 1.
1.1 Wideband FM Receiver

Figure 6: Agilent 4395A spectrum analyzer with VHF flex antenna mounted at an input port, to observe the FM broadcast signals present on the 87.5 – 108 MHz band.

4. Finally, on to the receiver hardware. Configure the wideband receiver test set-up according to Figure 7. The photograph of Figure 8 will help you locate the power and signal input and output test points on wideband radio chassis. Use a bench supply for the 3.3v voltage regulator that is on the board. A supply setting of 6v is sufficient. Be careful to not over-voltage the RFIC. The LO signal needs to be connected to the board via a BNC cable. Set the LO level from the Agilent 33250 to about 600 mv pp, but not more than 1 v pp. Be sure to turn the RF output on. As the supply voltage is brought up to 6 v (chip \( v_{cc} \) of 3.3v) you should hear noise coming from the PC speakers. This indicates that the receiver is likely working, but is just not tuned to a station yet.

5. Adjust the LO, using your formula, to tune in and demodulate one or more of the FM broadcast stations you earlier identified on the spectrum analyzer.

Figure 7: Wideband FM receiver test set-up.
1.2 Narrowband Receiver

The block diagram for the narrowband receiver is given in Figure 9. The low-noise amplifier (LNA) is not implemented at this time, but a tank circuit is located at the input to provide some bandpass filtering. A short wire (clip lead) will serve as the antenna in the experiment. This receiver also requires and external local oscillator (LO). In order to receive VHF signals, in particular narrowband FM broadcasts, such as the national weather service\(^4\), which has carrier frequencies near 162.4 MHz, the output of the Agilent 33250, which will serve as the LO, again needs to be frequency doubled. Other VHF band services using narrowband FM include police and fire departments and Ham radio operators near 146.94 MHz.

The narrowband receiver utilizes a dual conversion superheterodyne approach. The first mixer output is processed with a single stage IF filter centered at 10.7 MHz. The 10.7 MHz IF signal then enters a second mixer with a fixed LO of 11.155 MHz. The difference frequency is at 455 KHz. The 455 kHz difference frequency is processed with a multistage IF amplifier, with the 455kHz IF passband shaping formed using ceramic filters. The nominal bandwidth of each filter is 10 kHz.

\(^4\)http://www.nws.noaa.gov/nwr/nwrbro.htm
1.2 Narrowband Receiver

Figure 9: Narrowband dual conversion FM receiver block diagram.

Note from the schematic of Figure 10, the ceramic filters 10.7 MHz and 455 kHz, are external to the NXP SA602 and SA606 RFICs. The final stage is the FM demodulator, which in this design is again a quadrature detector.

1.2.1 IF Filters

For the case of the narrowband FM receiver the signal bandwidth is much narrower than in the wideband case (10 kHz versus 200 kHz). The NOAA stations are spaced by 25 kHz from 162.400 – 162.550 MHz. The NOAA weather stations in Colorado are listed in Table 1.

The 10.7 MHz first-conversion IF filter is the same 280 kHz bandwidth SFU 10.7, as used in the wideband design. For the second IF, the ceramic filters have a 6 dB bandwidth of 10 kHz. The filter specifications and plots of the magnitude and group delay response are shown in Figure 11.

1.2.2 Laboratory Exercises

1. In the Colorado Springs area the NOAA station easiest to receive is WXM56 from Colorado Springs. Looking at Table 1, we see that this station has its transmitting antenna on Cheyenne Mountain. The transmission power is small, only 100 W, compared with broadcast FM which is over 1000 W. Using the VHF flex antenna, as shown in Figure 6, try to find WXM56 on the spectrum analyzer. You have to reduce the attenuation on the analyzer front-end to zero dB, to find the signal.

2. In the next step you will power up the narrowband receiver. You will need to know how to set the LO frequency to receive narrowband FM signals, like NOAA stations. Develop two formulas for determining the required LO frequency to receive a station using either high-side or low-side LO tuning. Your functions should take as input the desired station
Figure 10: Dual conversion VHF FM receiver schematic based on the NXP SA605 IF subsystem plus the NXP SA602 mixer.

frequency, e.g., 162.475 MHz and return the LO frequency. You need to take into account the fact that the LO frequency is doubled and the receiver is dual-conversion, as shown in Figure 9. Given that the Agilent 33250 only tunes to 80 MHz, which formula will you be using in practice?

3. Finally, on to the receiver hardware. Configure the narrowband receiver test set-up according to Figure 12, but don’t connect the LO just yet. The photograph of Figure 13 will help you locate the power and signal input and output test points on wideband radio chassis. Use a bench supply for about 8v (6v following the voltage regulator. As the supply voltage is brought up to 8v (6v internally) you should hear noise coming from the PC speakers. This
1.2 Narrowband Receiver

Table 1: NOAA stations throughout Colorado.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Transmitter Name</th>
<th>Call Sign</th>
<th>Frequency</th>
<th>Power</th>
<th>WFO</th>
</tr>
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<tr>
<td>Denver</td>
<td>Glendale</td>
<td>KEG76</td>
<td>162.550</td>
<td>300</td>
<td>Boulder, CO</td>
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<tr>
<td>Canon City</td>
<td>Canon City</td>
<td>KJY81</td>
<td>162.500</td>
<td>300</td>
<td>Pueblo, CO</td>
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<tr>
<td>Arton</td>
<td>Arton</td>
<td>KJY84</td>
<td>162.450</td>
<td>300</td>
<td>Boulder, CO</td>
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<tr>
<td>Fort Morgan</td>
<td>Fort Morgan</td>
<td>KWN40</td>
<td>162.525</td>
<td>300</td>
<td>Boulder, CO</td>
</tr>
<tr>
<td>Durango</td>
<td>Durango</td>
<td>KWN54</td>
<td>162.425</td>
<td>300</td>
<td>Grand Junction, CO</td>
</tr>
<tr>
<td>Steamboat Springs</td>
<td>Walton Peak</td>
<td>KWN56</td>
<td>162.525</td>
<td>300</td>
<td>Grand Junction, CO</td>
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<tr>
<td>Lamar</td>
<td>Prowers County</td>
<td>KWN60</td>
<td>162.525</td>
<td>1000</td>
<td>Pueblo, CO</td>
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<td>Montrose</td>
<td>Buckhorn Lakes</td>
<td>KX90</td>
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<td>300</td>
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<td>Colorado Springs</td>
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<td>Wray</td>
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<td>Black Hollow</td>
<td>WXM92</td>
<td>162.450</td>
<td>300</td>
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indicates that the receiver is likely working, but is just not tuned to a station yet.

4. Before connecting the LO to the frequency doubler you will test that the receiver functions
1.2 Narrowband Receiver

Figure 11: Murata CFU 455D2 ceramic IF filter specifications: (a) spec table, (b) passband detail of a similar design, and (c) full band response of a similar design.

properly from the second mixer input to the demodulated output. Move the blue jumper from the default position (as in the photo of Figure 8) so a 10.7 MHz signal can be directly applied to the 10.7 MHz IF input, below the blue jumper. The BNC input is located on the lower left side of the board. Configure the Agilent 33250 to produce a narrowband FM signal with $f_c = 10.7$ MHz and a deviation of about 2 KHz. Set the output to about 100 mv pp. Just bringing the BNC cable lead end close to the 10.7 MHz IF input should quiet the noise PC speakers and you should hear the modulation tone. The high sensitivity is due to the very high gain of the second IF amplifier chain. This verifies that the back-end of the receiver is working properly.

5. Now connect the LO (Agilent 33250) to the board via a BNC cable. Set the LO level from the Agilent 33250 to about 600 mv pp, but not more than 1 v pp. Be sure to turn the RF
output on. Place a clip-lead on one of the two receiver input test points in the lower left of Figure 13. Reconnect the jumper between the first-mixer output and the 10.7 MHz IF input. You can do this by carefully springing the wires together, no need to twist or solder, etc. You lab instructor will help you.

6. Adjust the LO, located about in using the one valid formula, to tune in and demodulate NOAA station WX56. The overall sound quality of this signal will be poorer than the broadcast FM stations you hear from the wideband receiver. The signal is also rather weak, so you may have to position antenna carefully to get good signal strength.

7. To actually see the superheterodyne principle in action in this dual-conversion receiver, place a probe from a high impedance input on the spectrum analyzer to the first and then the second mixer tests found on the upper left side of the PCB photo of Figure 13. Center the spectrum analyzer on 455 kHz with a span of about 50 kHz. As you tune the LO you should see the spectra of the WX56 station, originally at 162.475 MHz, translated down to 455 kHz.

8. In this section you explore digital modulation transmission using the Rhode & Schwarz SMIQ vector signal generator using a VHF flex antenna. The receiver will be the narrowband FM radio. The SMIQ will be used to generate frequency-shift keyed (FSK) modulation with $f_c = 163$ MHz a data rate of 5 kbps with a 1 – 4 KHz peak deviation. A PN test sequence will be configured on the SMIQ as the data source. The demodulated output will be confirmed by observing the data pattern on the scope. Your lab instructor will help you configure the SMIQ.

1.3 Appendix A: Data Sheet Highlights
Figure 13: Dual conversion VHF FM receiver based on the NXP SA602 and SA605.
Low voltage high performance mixer FM IF system with high-speed RSSI

SA636

**DESCRIPTION**

The SA636 is a low-voltage high performance monolithic FM IF system with high-speed RSSI incorporating a mixer/oscillator, two limiting intermediate frequency amplifiers, quadrature detector, logarithmic received signal strength indicator (RSSI), voltage regulator, wideband data output and fast RSSI op amps. The SA636 is available in 20-lead SSOP (shrink small outline package).

The SA636 was designed for high bandwidth portable communication applications and will function down to 2.7 V. The RF section is similar to the famous SA605. The data output has a minimum bandwidth of 600 kHz. This is designed to demodulate wideband data. The RSSI output is amplified. The RSSI output has access to the feedback pin. This enables the designer to adjust the level of the outputs or add filtering.

SA636 incorporates a power-down mode which powers down the device when Pin 8 is LOW. Power down logic levels are CMOS and TTL compatible with high input impedance.

**FEATURES**

- Wideband data output (600 kHz min.)
- Fast RSSI rise and fall times
- Low power consumption: 6.5 mA typ. at 3 V
- Mixer input to >500 MHz
- Mixer conversion power gain of 11 dB at 240 MHz
- Mixer noise figure of 12 dB at 240 MHz
- XTL oscillator effective to 150 MHz (L.C. oscillator to 1 GHz local oscillator can be injected)
- 92 dB of IF Amp/Limiter gain
- 25 MHz limiter small signal bandwidth
- Temperature compensated logarithmic Received Signal Strength Indicator (RSSI) with a dynamic range in excess of 90 dB
- RSSI output internal op amp
- Internal op amps with rail-to-rail outputs
- Low external component count; suitable for crystal/ceramic/LC filters
- Excellent sensitivity: 0.54 µV into 50 Ω matching network for 12 dB SINAD (Signal to Noise and Distortion ratio) for 1 kHz tone with RF at 240 MHz and IF at 10.7 MHz
- ESD hardened
- 10.7 MHz filter matching (330 Ω)
- Power-down mode (I \(_{CC}\) = 200 µA)

**APPLICATIONS**

- DECT (Digital European Cordless Telephone)
- Digital cordless telephones
- Digital cellular telephones
- Portable high performance communications receivers
- Single conversion VHF/UHF receivers
- FSK and ASK data receivers
- Wireless LANs

**PIN CONFIGURATION**

![Image of pin configuration]

**ORDERING INFORMATION**

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<th>DWG #</th>
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<td>SA636DK</td>
<td>SOT266–1</td>
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Figure 14: A portion (first page) of the NXP SA636 data sheet.
Double-balanced mixer and oscillator SA602A

DESCRIPTION
The SA602A is a low-power VHF monolithic double-balanced mixer with input amplifier, on-board oscillator, and voltage regulator. It is intended for high performance, low power communication systems. The guaranteed parameters of the SA602A make this device particularly well suited for cellular radio applications. The mixer is a "Gilbert cell" multiplier configuration which typically provides 18dB of gain at 45MHz. The oscillator will operate to 200MHz. It can be configured as a crystal oscillator, a tuned tank oscillator, or a buffer for an external LO. For higher frequencies the LO input may be externally driven. The noise figure at 45MHz is typically less than 5dB. The gain, intercept performance, low-power and noise characteristics make the SA602A a superior choice for high-performance battery operated equipment. It is available in an 8-lead dual in-line plastic package and an 8-lead SO (surface-mount miniature package).

FEATURES
- Low current consumption: 2.4mA typical
- Excellent noise figure: <4.7dB typical at 45MHz
- High operating frequency
- Excellent gain, intercept and sensitivity
- Low external parts count; suitable for crystal/ceramic filters
- SA602A meets cellular radio specifications

ORDERING INFORMATION

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<td>-40 to +85°C</td>
<td>SA602AD</td>
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ABSOLUTE MAXIMUM RATINGS

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<td>9</td>
<td>V</td>
</tr>
<tr>
<td>TSTG</td>
<td>Storage temperature range</td>
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<td>°C</td>
</tr>
<tr>
<td>TA</td>
<td>Operating ambient temperature range</td>
<td>-40 to +85°C</td>
<td>°C</td>
</tr>
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<td>θJA</td>
<td>Thermal impedance</td>
<td>D package</td>
<td>90</td>
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<td></td>
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<td>N package</td>
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Philips Semiconductors

High performance low power mixer FM IF system

SA605

DESCRIPTION
The SA605 is a high performance monolithic low-power FM IF system incorporating a mixer/oscillator, two limiting intermediate frequency amplifiers, quadrature detector, muting, logarithmic received signal strength indicator (RSSI), and voltage regulator. The SA605 combines the functions of Signetics’ SA602 and SA604A, but features a higher mixer input intercept point, higher IF bandwidth (25MHz) and temperature compensated RSSI and limiters permitting higher performance application. The SA605 is available in 20-lead dual-in-line plastic, 20-lead SOL (surface-mounted miniature package) and 20-lead SSOP (shrink small outline package).

The SA605 and SA615 are functionally the same device types. The difference between the two devices lies in the guaranteed specifications. The SA615 has a higher $I_{CC}$, lower input third order intercept point, lower conversion mixer gain, lower limiter gain, lower AM rejection, lower SINAD, higher THD, and higher RSSI error than the SA605. Both the SA605 and SA615 devices will meet the EIA specifications for AMPS and TACS cellular radio applications.

For additional technical information please refer to application notes AN1994, 1995 and 1996, which include example application diagrams, a complete overview of the product, and artwork for reference.

APPLICATIONS
- Cellular radio FM IF
- High performance communications receivers
- Single conversion VHF/UHF receivers
- SCA receivers
- RF level meter
- Spectrum analyzer
- Instrumentation
- FSK and ASK data receivers
- Log amps
- Wideband low current amplification

FEATURES
- Low power consumption: 5.7mA typical at 6V
- Mixer input to >500MHz
- Mixer conversion power gain of 13dB at 45MHz
- Mixer noise figure of 4.6dB at 45MHz
- XTAL oscillator effective to 150MHz (L.C. oscillator to 1GHz local oscillator can be injected)
- 102dB of IF Amp/Limiter gain
- 25MHz limiter small signal bandwidth
- Temperature compensated logarithmic Received Signal Strength Indicator (RSSI) with a dynamic range in excess of 90dB
- Two audio outputs - muted and unmuted
- Low external component count; suitable for crystal/ceramic/LC filters
- Excellent sensitivity: 0.22µV into 50Ω matching network for 12dB SINAD (Signal to Noise and Distortion ratio) for 1kHz tone with RF at 45MHz and IF at 455kHz
- SA605 meets cellular radio specifications
- ESD hardened

ORDERING INFORMATION

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>TEMPERATURE RANGE</th>
<th>ORDER CODE</th>
<th>DWG #</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-Pin Plastic Dual In-Line Package (DIP)</td>
<td>–40 to +85°C</td>
<td>SA605N</td>
<td>SOT146-1</td>
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<tr>
<td>20-Pin Plastic Small Outline Large (SOL) package</td>
<td>–40 to +85°C</td>
<td>SA605D</td>
<td>SOT163-1</td>
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<tr>
<td>20-Pin Plastic Shrink Small Outline Package (SSOP)</td>
<td>–40 to +85°C</td>
<td>SA605DK</td>
<td>SOT266-1</td>
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</tbody>
</table>

Figure 16: A portion (first page) of the NXP SA605 data sheet.