Noise performance of cryogenic components

Noise is a collective term used to describe unwanted signals produced by communication devices and channels. There are many sources of noise, and hence many noise types: shot noise, Johnson-Nyquist (thermal) noise, flicker noise, burst noise, etc. All noise sources combine to produce a noise floor that sets the minimum signal that can be detected. In cellular communication systems, the thermal (Johnson-Nyquist) noise is the most dominant.

Noise in communication components and systems is measured by its (degrading) effect on the signal-to-noise ratio (SNR). In particular, the noise factor is defined as the ratio of SNR at device (or system) input to the SNR at device (or system) output:

$$F = \frac{SNR_{IN}}{SNR_{OUT}} \tag{1}$$

Noise figure, measured in dB, is related to the noise factor by:

$$NF = 10 \cdot \log(F) \tag{2}$$

Let us consider the degradation of the signal-to-noise ratio of a passive microwave filter, operating at room temperature.

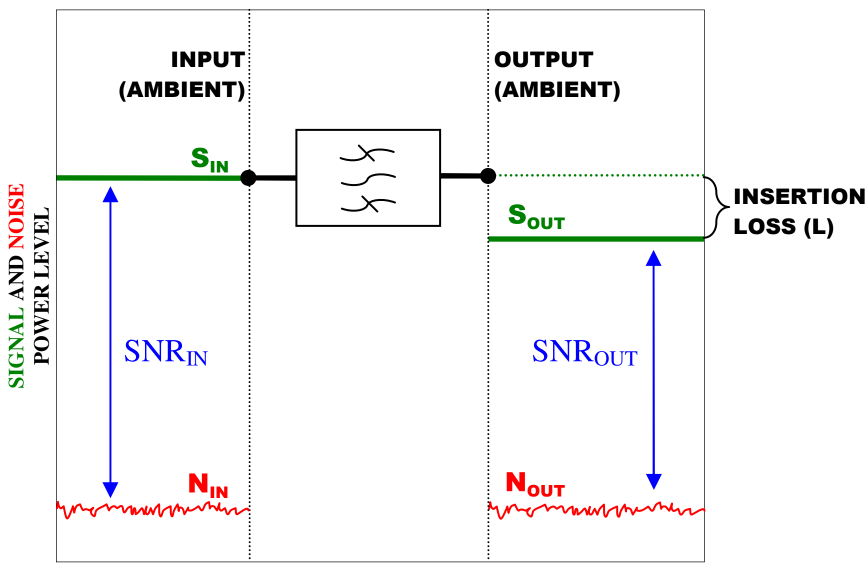

Figure 1: Degradation of the signal-to-noise ratio of a passive microwave filter due to noise.

Figure 1 shows what happens to signal and noise powers as they propagate through the filter. Input signal power (S_{IN}) is attenuated by the filter to give an output power of $S_{OUT} = (1\text{-}L_0)\cdot S_{IN}$.

Noise power at the output (N_{OUT}) consists of the input noise power (N_{IN}) attenuated by the insertion loss of the filter, and the noise power produced by the filter itself: $N_{OUT} = (1\text{-}L_0)\cdot N_{IN} + k\cdot T_0\cdot B\cdot L_0$.

By substituting these values in Eq. (1), we obtain:

$$F_{F,0} = \frac{SNR_{IN}}{SNR_{OUT}} = \frac{\dfrac{S_{IN}}{N_{IN}}}{\dfrac{(1-L_0)\cdot S_{IN}}{(1-L_0)\cdot N_{IN} + k\cdot T_0 \cdot B \cdot L_0}} = \frac{1}{(1-L_0)} = \frac{1}{A_0} \tag{3}$$

Equation (3) simply states that the noise factor of a passive (attenuating) device is equal to the inverse of its attenuation. Equation (2) can be used to translate the noise factor into the noise figure: $NF_{F,0,dB}=10\cdot\log_{10}(F) = 10\cdot\log_{10}(1/A_0) = -10\cdot\log(A_0) = IL_{dB}$. Therefore, the noise figure of a passive device at room temperature is equal to its insertion loss.

Let us now consider the noise figure of an active amplifier, also operating at room temperature, as shown in Fig. 2.

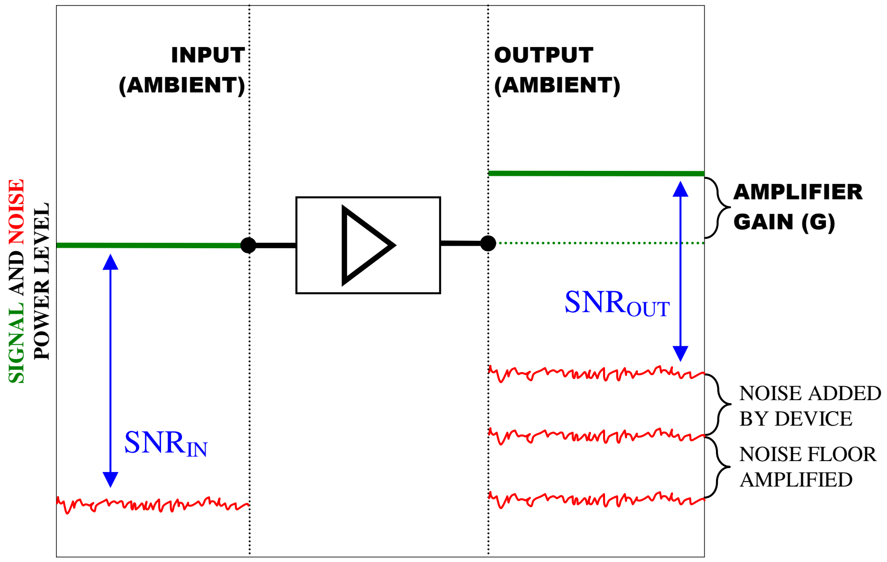

Figure 2: Degradation of the signal-to-noise ratio of an active microwave amplifier due to noise.

Input signal power (S_{IN}) is amplified to produce an output power of $G\cdot S_{IN}$.

Total output noise power consists of the amplified input noise power ($G\cdot N_{IN}$), and the noise power produced by the amplifier itself: $N_{OUT} = G\cdot N_{IN} + N_{LNA,0}$.

Therefore, the noise factor of an amplifier is given as:

$$F_{LNA,0} = \frac{SNR_{IN}}{SNR_{OUT}} = \frac{\dfrac{S_{IN}}{N_{IN}}}{\dfrac{G_{LNA} \cdot S_{IN}}{G_{LNA} \cdot N_{IN} + N_{LNA,0}}} = \frac{\dfrac{1}{1}}{\dfrac{G_{LNA}}{G_{LNA} + \dfrac{N_{LNA,0}}{N_{IN}}}} = \frac{G_{LNA} + \dfrac{N_{LNA,0}}{N_{IN}}}{G_{LNA}} = 1 + \frac{N_{LNA,0}}{G_{LNA} \cdot N_{IN}} \tag{4}$$

Cascading components in a communication link

Apart from knowing the noise figure of individual active and passive components, it is often useful to know the noise performance of their combinations. Let us consider what happens if we cascade two (active) blocks in a communication system, as shown in Figure. 3.

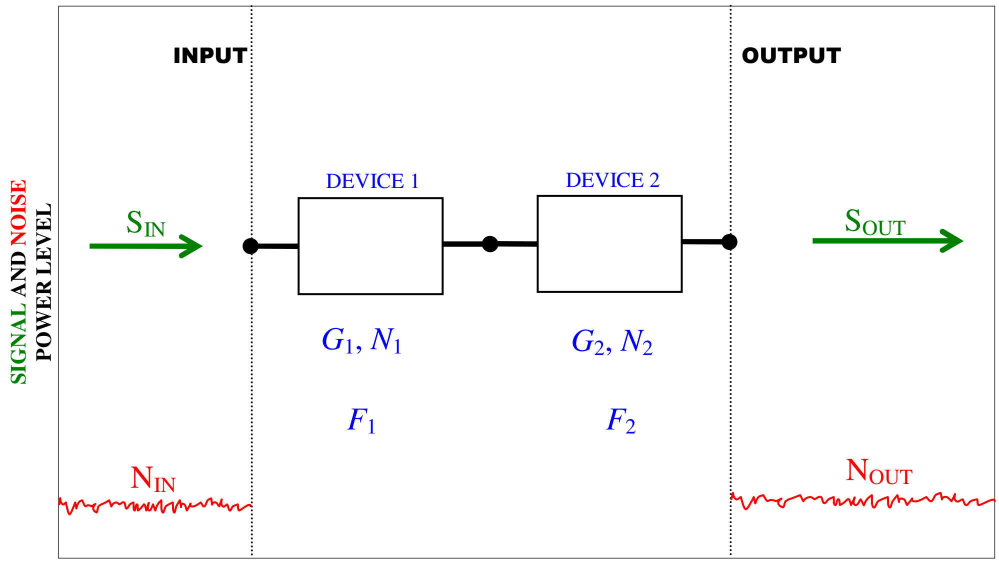

Figure 3: Noise performance of cascaded components.

The input signal power is amplified by both G_1 and G_2:

$$S_{OUT} = S_{IN} \cdot G_1 \cdot G_2$$

The total output noise power consists of the input noise power amplified by G_1 and G_2, of first-device noise power N_1 amplified by G_2, and of the contribution of the second device to the total noise power, N_2:

$$N_{OUT} = N_{IN} \cdot G_1 \cdot G_2 + N_1 \cdot G_2 + N_2$$

By substituting the above in Eq. (1) we obtain:

$$F_{CAS} = \frac{SNR_{IN}}{SNR_{OUT}} = \frac{\frac{S_{IN}}{N_{IN}}}{\frac{S_{OUT}}{N_{OUT}}} = \frac{\frac{S_{IN}}{N_{IN}}}{\frac{S_{IN} \cdot G_1 \cdot G_2}{N_{IN} \cdot G_1 \cdot G_2 + N_1 \cdot G_2 + N_2}} = F_1 + \frac{F_2 - 1}{G_1} \tag{5}$$

By using the same reasoning, it can be shown that the above formula can be extended to a cascade of three, four, or any number of elements:

$$F_{CAS,3} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} \tag{6}$$

It can also be shown that the same cascade formula applies to cascades of passive, active devices, or a mix of both.

Twofold benefit of cryogenic components

Let us now consider the case of a passive microwave filter operating at cryogenic temperature. We will assume that the input to the device is at room temperature, and that we are interested in extracting the output SNR_{OUT} at the cryogenic temperature.

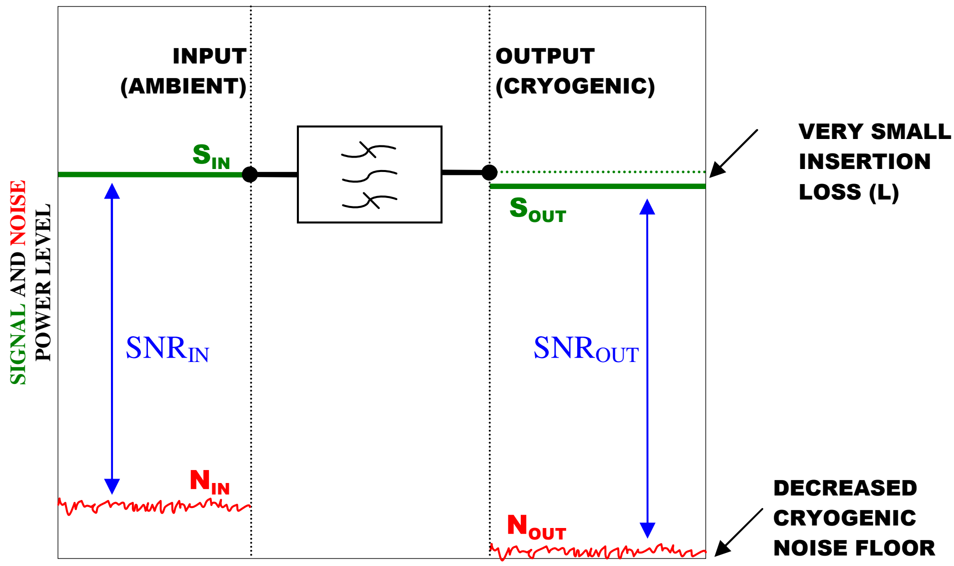

Figure 4: Degradation of the signal-to-noise ratio of a passive microwave filter at cryogenic temperature.

As before, the output signal power is given as: $S_{OUT} = (1\text{-}L_C)\cdot S_{IN}$. Note that the loss a cryogenically cooled filter, L_C, is much smaller than the loss of a conventional filter at ambient, L_0.

The output noise power consists of the input noise power (N_{IN}) attenuated by the insertion loss of the filter, and the noise power produced by the filter itself: $N_{OUT} = (1\text{-}L)\cdot N_{IN} + k\cdot T_C\cdot B\cdot L_C$. Note that the noise produced by the filter itself is not only smaller due to lower temperature, $T_C < T_0$, but it is also smaller due to lower insertion loss, $L_C < L_0$.

Substituting the above in Eq. (1) yields:

$$F_{F,C} = \frac{SNR_{IN}}{SNR_{OUT}} = \frac{\dfrac{S_{IN}}{N_{IN}}}{\dfrac{(1-L_C)\cdot S_{IN}}{(1-L_C)\cdot N_{IN} + k\cdot T_C\cdot B\cdot L_C}} = 1 + \frac{k\cdot T_C\cdot B\cdot L_C}{(1-L_C)\cdot N_{IN}} = 1 + \frac{L_C\cdot T_C}{(1-L_C)\cdot T_0} \tag{7}$$

Equation (7) shows that it is incorrect to assume that the noise figure of a passive device is always equal to its insertion loss (as shown by Eq. (3)). This simple relationship only holds at room temperature. At other temperatures, including cryogenic, it is still possible to relate the insertion loss of the filter to its noise factor, and subsequently the noise figure:

$$F_{F,C} = 1 + \frac{\left(10^{IL/10} - 1\right)\cdot T_C}{T_0} \tag{8}$$

In Eq. (8) IL represents the insertion loss of the cryogenic filter in dB. It is also possible to work out the noise factor of an active microwave amplifier, by using the same reasoning as before. Figure 5 illustrates the situation.

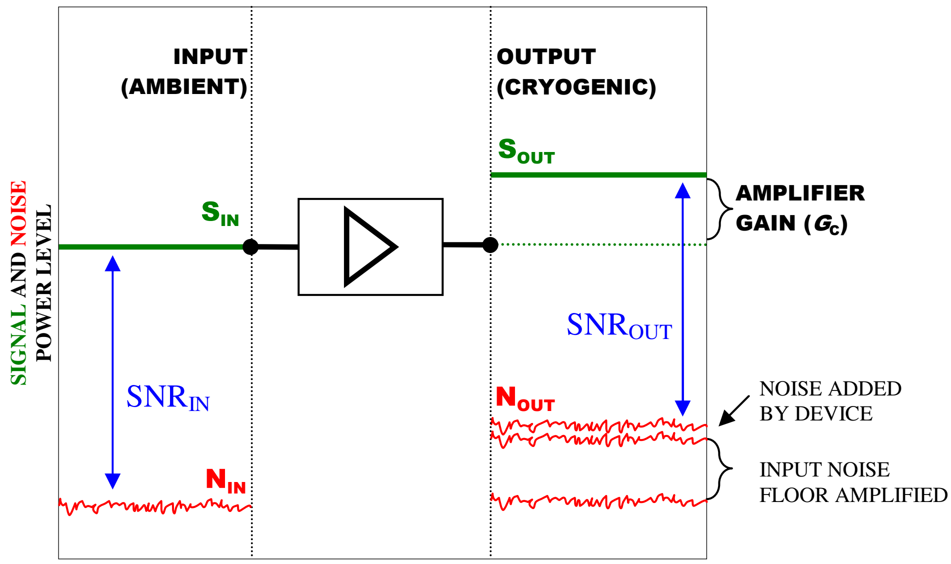

Figure 5: Degradation of the signal-to-noise ratio of an active microwave amplifier at cryogenic temperature.

In the case of a cryogenic amplifier, we have: $S_{OUT} = G_C \cdot S_{IN}$, $N_{OUT} = G_C \cdot N_{IN} + N_{LNA,C}$, and the noise factor is given as

$$F_{LNA,C} = \frac{SNR_{IN}}{SNR_{OUT}} = \frac{\dfrac{S_{IN}}{N_{IN}}}{\dfrac{G_{LNA,C} \cdot S_{IN}}{G_{LNA,C} \cdot N_{IN} + N_{LNA,C}}} = 1 + \frac{N_{LNA,C}}{G_{LNA,C} \cdot N_{IN}} \tag{9}$$

However, a simple rule of thumb can be used to estimate the improvement in the noise figure of an amplifier given its noise figure at ambient

$$NF_C \text{ [dB]} = T_C/T_0 \cdot NF_0 \text{ [dB]} \tag{10}$$

That is, the noise figure at cold (in dB) scales, with respect to the noise figure at ambient (in dB) as the operating temperature. For example, and amplifier with a noise figure of 1.5 dB at $T_0 = 290$ K will have a noise figure of 0.4 dB at 77 K.

In all cases therefore we see that there is a twofold benefit of cryogenic components: increase in signal gain (or decrease in signal loss), and decrease in the contribution to noise by the device itself.

Comparison of cryogenic and conventional devices

In the previous section we assumed that the signal, after passing through a cryogenic filter or amplifier, was detected at cryogenic temperature. Therefore, we calculated the output signal-to-nose ratio at T_C. This will not always be the case in practice. Cryogenic components will be connected to other components that operate at room temperature. Let us consider the case of a cryogenic filter connected to a cable at ambient temperature.

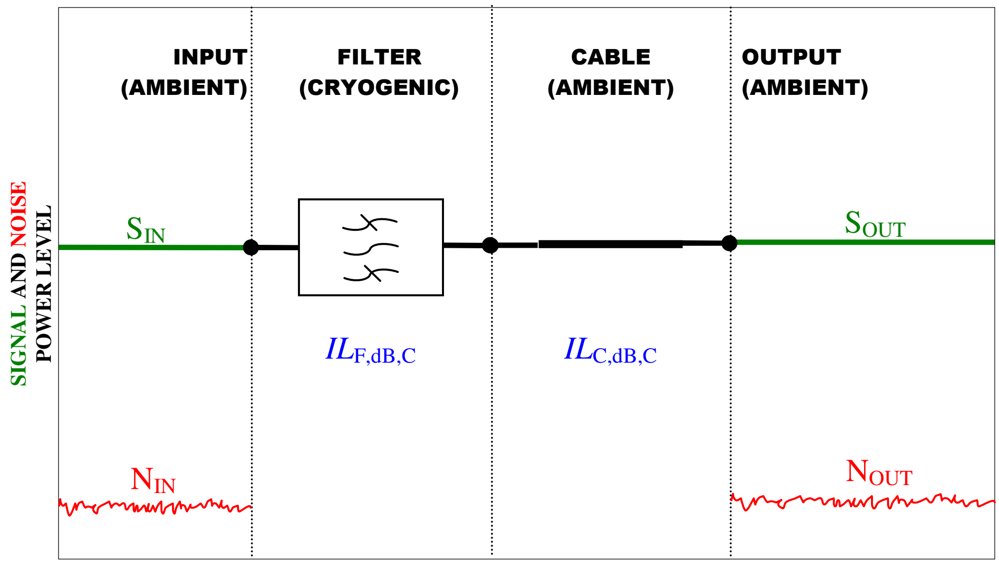

Figure 6: Degradation of the signal-to-noise ratio of an active microwave amplifier at cryogenic temperature.

Given that the insertion loss of the filter (in dB, at cold) is given as $IL_{F,dB,C}$, and the corresponding insertion loss of the cable is given as $IL_{C,dB,C}$, we can use Eq. (8) to calculate the noise factor of the filter, Eq. (3) to calculate the noise factor of the cable, and then Eq. (5) to calculate the total cascaded noise figure.

By using the same reasoning, we can also consider the case where there is also a length of cable present on the input side of the filter. Figure 7 shows the difference in noise figure in all three cases. In the case that a cable is present both at input and at the output, we assumed that their insertion losses were the same.

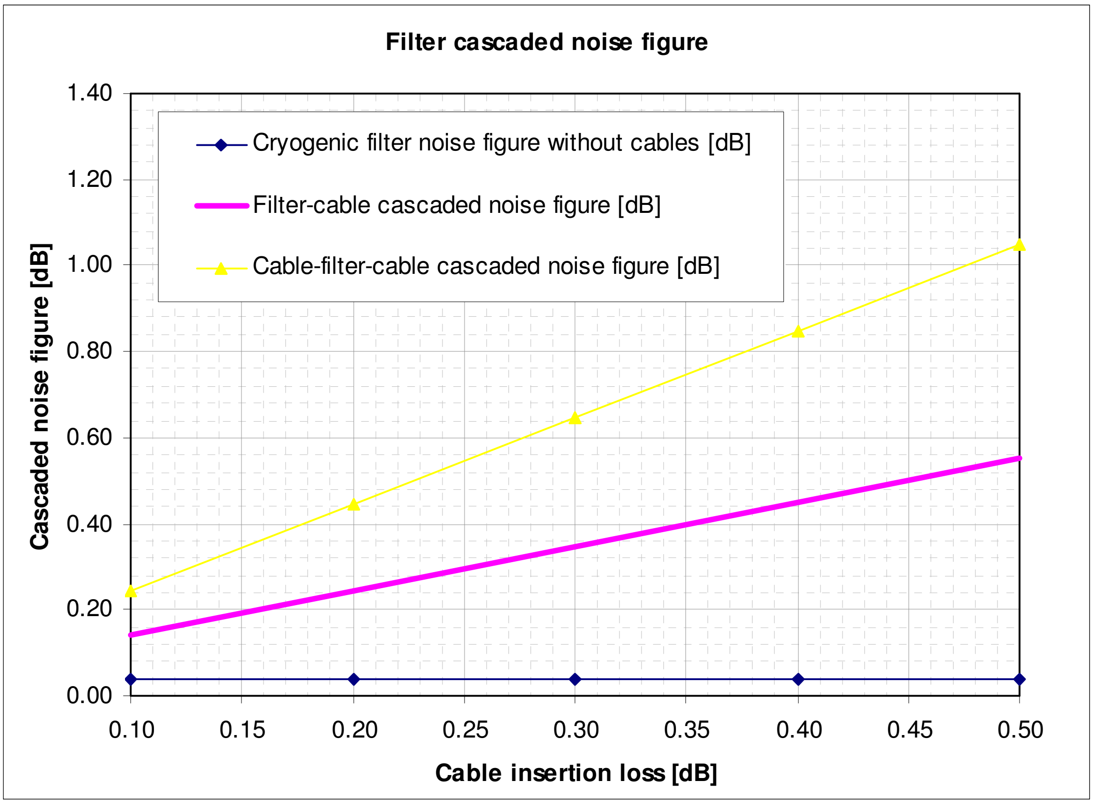

Figure 7: Noise figure of a cryogenic filter compared to cascaded noise figure of the cryogenic filter and input and output cables that might be used to connect it to the "ambient" world.

Figure 7 shows that it is important to keep the connecting cables short in order to minimise the degradation of the cryogenic noise figure. Typical cable insertion loss is in the range of 0.1 – 0.3 dB, depending on the configuration used. The lossiest configuration is when the receive filter is duplexed with a transmit filter (not shown in Fig. 6).

Situation when an amplifier is used after the filter is shown in Fig. 8.

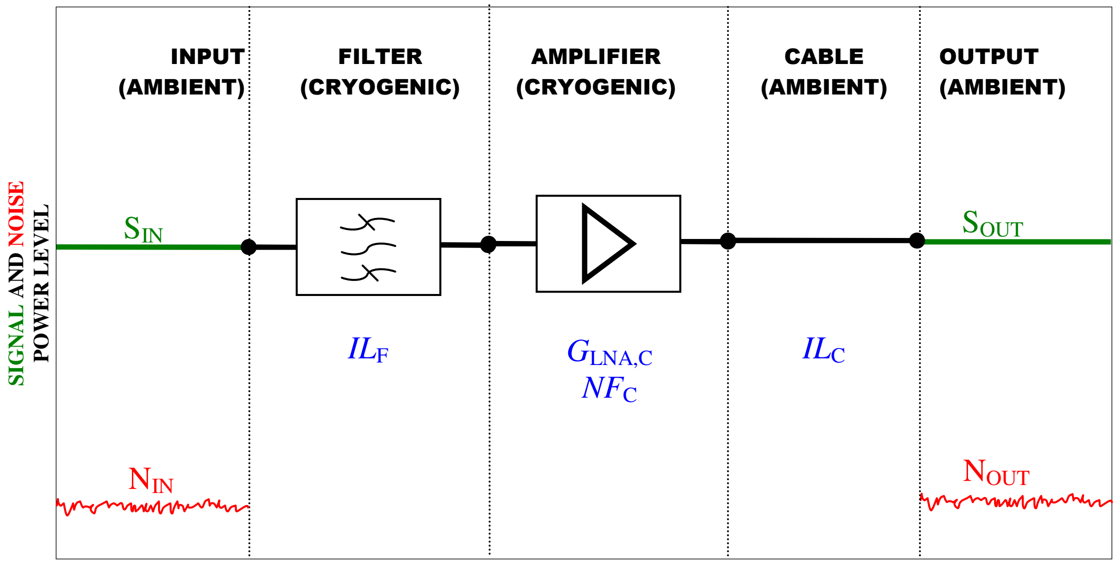

Figure 8: Degradation of the signal-to-noise ratio of an active microwave amplifier at cryogenic temperature.

Given that the insertion loss of the filter and cables is known, as well as the noise factor and gain of the amplifier, we can use Eq. (8) to calculate the noise factor of the filter, Eq. (3) to calculate the noise factor of the cable, and then Eq. (5) to calculate the total cascaded noise figure.

Figure 9 shows the degradation of the cryogenic filter-amplifier noise figure due to connecting cables present at input and output. As in the case of Fig. 7, the actual cable loss depends on the configuration used.

Even with significant input and output cable loss, Fig. 7 and Fig. 9 show that the total cascaded noise figure is (well) below 1 dB. Conventional filter-amplifier systems, especially at higher operating temperatures (55° C) typically exhibit noise figures of above 1.5 dB.

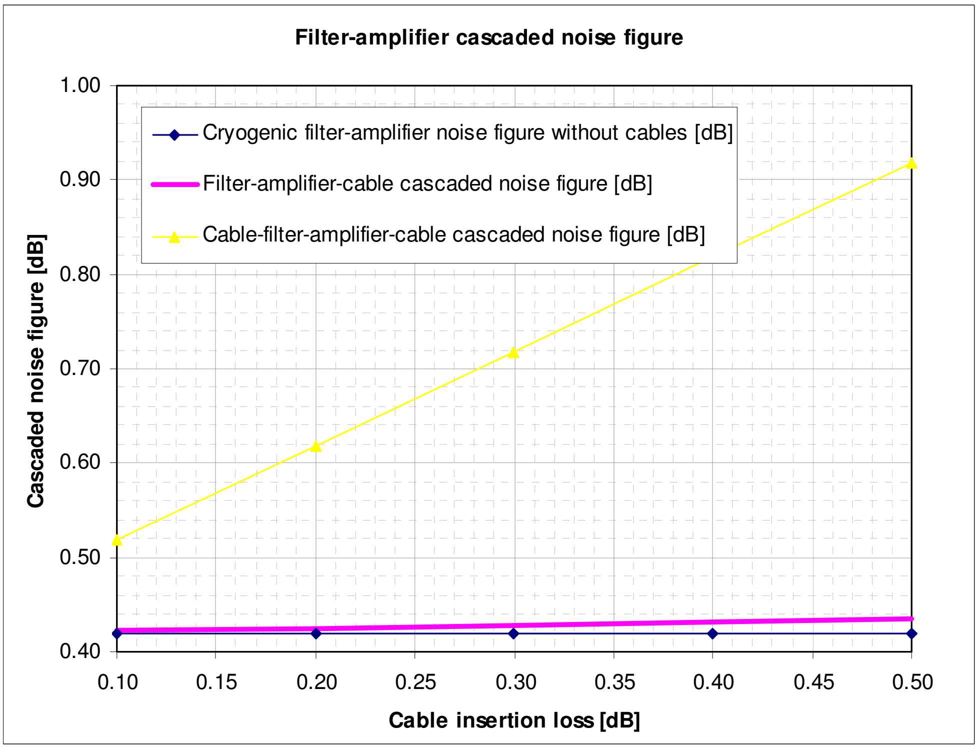

Figure 9: Noise figure of a cryogenic filter-amplifier combination compared to cascaded noise figure with input and output cables.

System benefits

The previous section showed noise figure improvements due to using cryogenic filters and amplifiers. However, it is also important to consider the effect they have on the performance of a cellular system. A simplified model of a CDMA (code-division multiple-access) base station is shown below.

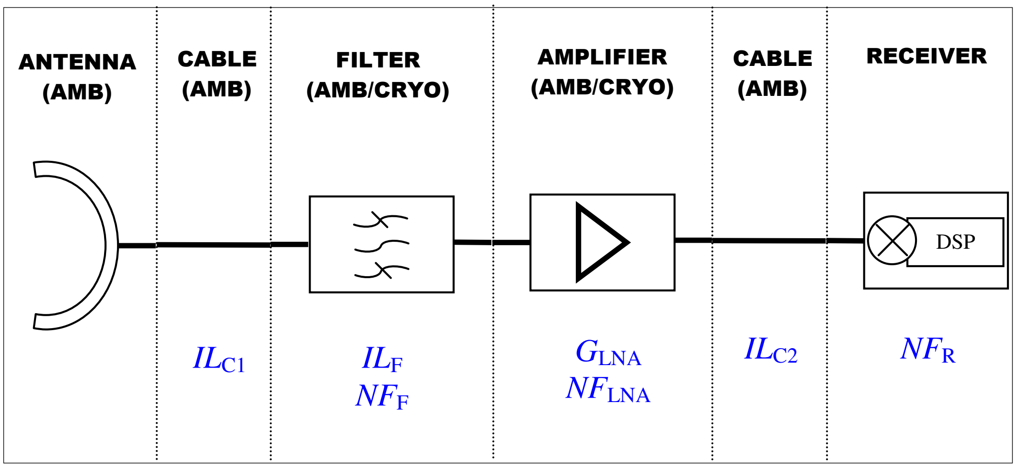

Figure 10: Schematic diagram of a CDMA base station.

The signal-to-interference-and-noise ratio (SINR) at the output of the analog portion of the receiver (before the block labelled "RECEIVER" in Fig. 10) is given as [1]

$$SINR = \frac{S_{IN}}{R \cdot F \cdot N}$$

Where S_{IN} is the input signal power and $R \cdot F \cdot N = I + F \cdot N$ is the total power received. Quantity I is the co-channel interference power due to transmissions of mobiles in the same cell and in the other cells, $N = k \cdot B \cdot T$ is the thermal noise, F is the noise figure of the base station, and B is the spread-spectrum bandwidth.

The reverse-link noise rise, R, is an important parameter in a CDMA system, and is defined as the rise of the interference level above the thermal noise level [2] due to the traffic load. R is a good indicator of whether or not the base station is heavily loaded on the reverse link.

Let us consider three practical scenarios: (i) there is only cable present between the antenna and the receiver in Fig. 9, (ii) there is a conventional filter-amplifier combination, operating at room temperature, and (iii) there is a cryogenic filter-amplifier combination. The SINR in the three situations is denoted as: $SINR_{\text{CABLE,AMB}}$, $SINR_{\text{FIL-AMP,AMB}}$, $SINR_{\text{FIL-AMP,CRYO}}$.

In CDMA, power control adjusts the mobile transmit power so that a constant SINR is maintained, i.e. the mobile transmit power is adjusted so that $SINR_{\text{CABLE,AMB}} = SINR_{\text{FIL-AMP,AMB}} = SINR_{\text{FIL-AMP,CRYO}}$. The reverse-link sensitivity improvement by going from $SINR_X$ to $SINR_Y$, Q, is defined as:

$$Q = \frac{SINR_X}{SINR_Y}$$

If we assume that, in two situations ($SINR_X$ and $SINR_Y$), $S_{IN,X} = S_{IN,Y}$ (same input signal power), and $N_X = N_Y$ (same ambient noise), we see that the sensitivity improvement becomes

$$Q = \frac{R_X}{R_Y} \cdot \frac{F_X}{F_Y}$$

Furthermore, if we assume that $R_X = R_Y$ (no loading), we see that the reverse-link sensitivity improvement in a CDMA system is directly related to the improvement in the noise figure of the receiver.

By using the results of previous sections, we can now compare two sensitivity improvements: one by going from cable-only situation to a conventional filter-amplifier situation, and another one by going from cable-only situation to a cryogenic filter-amplifier combination. Results are shown in Fig. 11 below. Cable-only antenna-receiver connection is shown in Fig. 12.

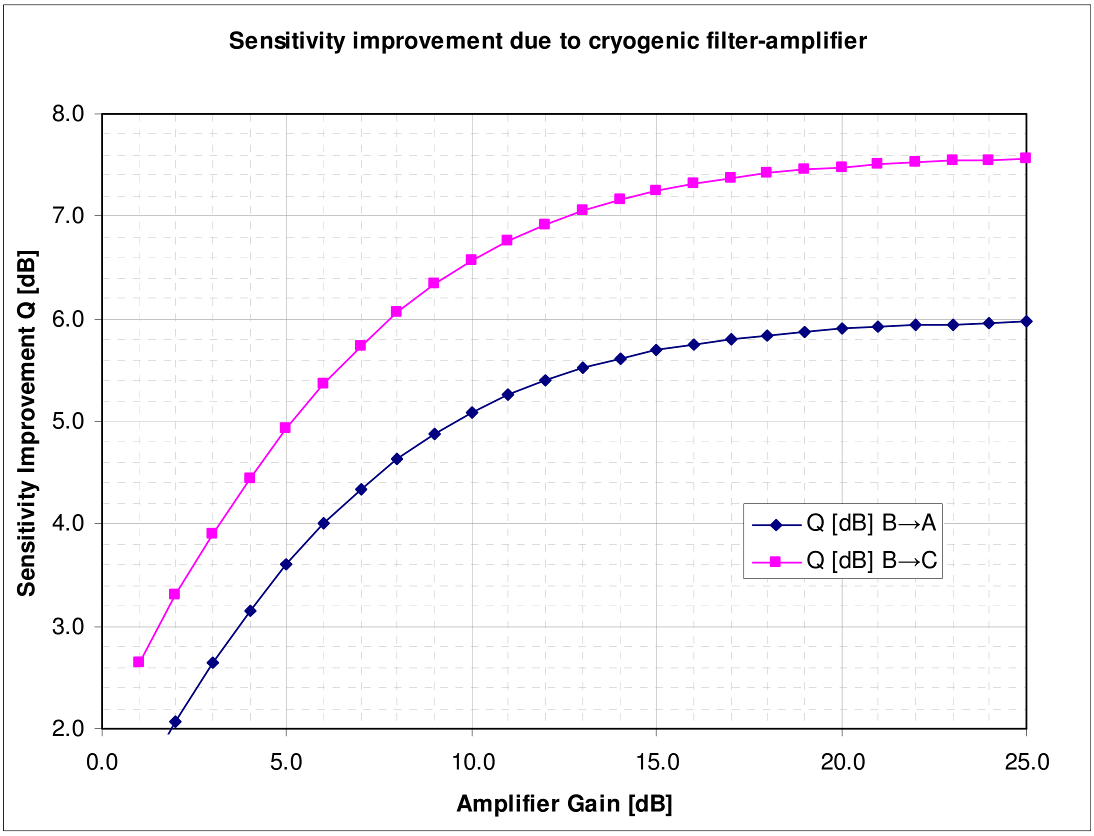

Figure 11: Sensitivity improvement (Q), as a function of amplifier gain, obtained in two situations: (i) obtained by replacing a cable-only antenna-receiver connection by a conventional filter-amplifier combination, and (ii) obtained by replacing the cable-only antenna-receiver connection with a cryogenic filter amplifier.

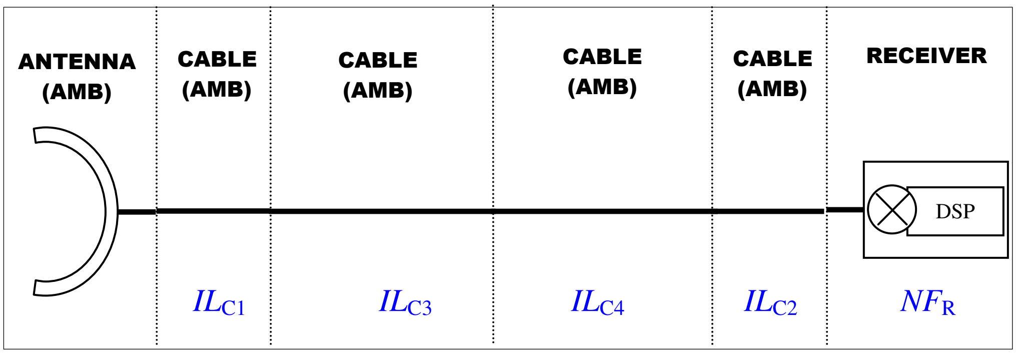

Figure 12: Diagram with of a cable-only base station.

Parameters used in Fig. 11 are as follows:

- Cable-only insertion loss: $IL_{C1} + IL_{C2} + IL_{C3} + IL_{C4} = 2.3$ dB. This is as per measured value presented in [1].
- Receiver noise figure: $NF_R = 6$ dB. This is also as per measured value for a real base-station presented in [1].
- Conventional filter-amplifier noise figure = 1.8 dB.

- Cryogenic filter-amplifier noise figure = 0.8 dB.
- Effective antenna temperature = 290 K.

In the case of a conventional filter-amplifier we did not include any cable loss before and after; it was assumed that the conventional filter-amplifier is connected directly between the antenna and the receiver. This is a conservative assumption.

We have assumed that there was a cable before and after cryogenic filter-amplifier, with insertion loss of 0.1 dB. This is to allow for referencing the noise figure to ambient temperature (where it is ultimately measured, in accordance with discussion in *Comparison of cryogenic and conventional devices* above).

Measured results that support the values used in Fig. 11 are discussed below.

Measured results

We have built and tested a cryogenic filter-amplifier, in the form of tower-mounted amplifier (TMA) with cryogenic receive filter, cryogenic low-noise amplifier, and conventional transmit filter. TMA Schematic diagram is shown in Fig. 13 below.

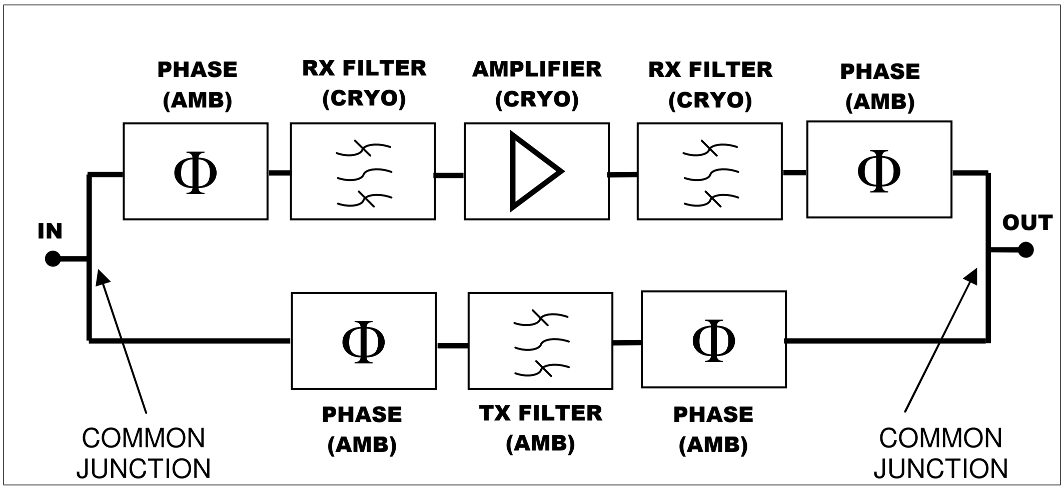

Figure 13: Schematic diagram of a cryogenic TMA. Receive and Transmit channels are duplexed together, at input and output, with phase harness (phase-shifting cables). Common junctions are connected by short cables to the input and output connector.

Measured RF performance of this unit is shown in Fig. 14 below.

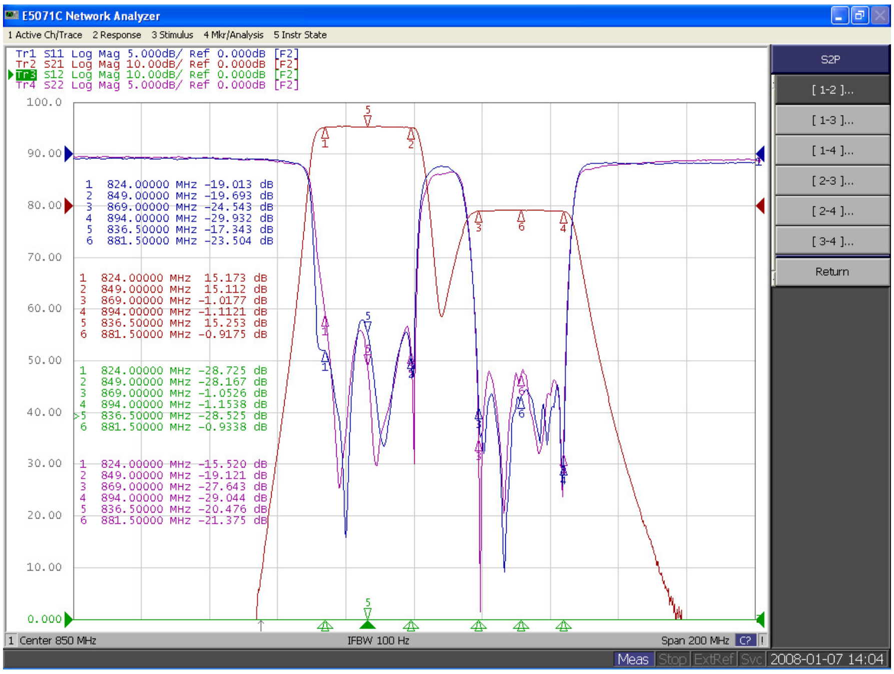

Figure 14: Measured performance of the cryogenic TMA.

Table 1 summarises the most important RF performance specifications of the cryogenic TMA.

Rx Channel				
	Passband	824-849	MHz	
	Return Loss	15	dB	min
	Gain Midband	15	dB	min
	Gain Variation	0.25	dB	max
	Gr. Delay Abs	130	ns	max
	Gr. Delay Var.	45	ns	max
	Gr. Delay Var. for any 5 MHz	35	ns	max
Tx Channel				
	Passband	869-894	MHz	
	Return Loss	22	dB	min
	Ins. Loss Midband	0.92	dB	max
	Ins. Loss Variation	0.2	dB	max
	Gr. Delay Abs	80	ns	max
	Gr. Delay Var.	27	ns	max
	Gr. Delay. Var. for any 5 MHz	21	ns	max

Table 1: Summary of cryogenic TMA RF performance

For comparison, Figure 15 below shows the performance of a commercially-available conventional TMA.

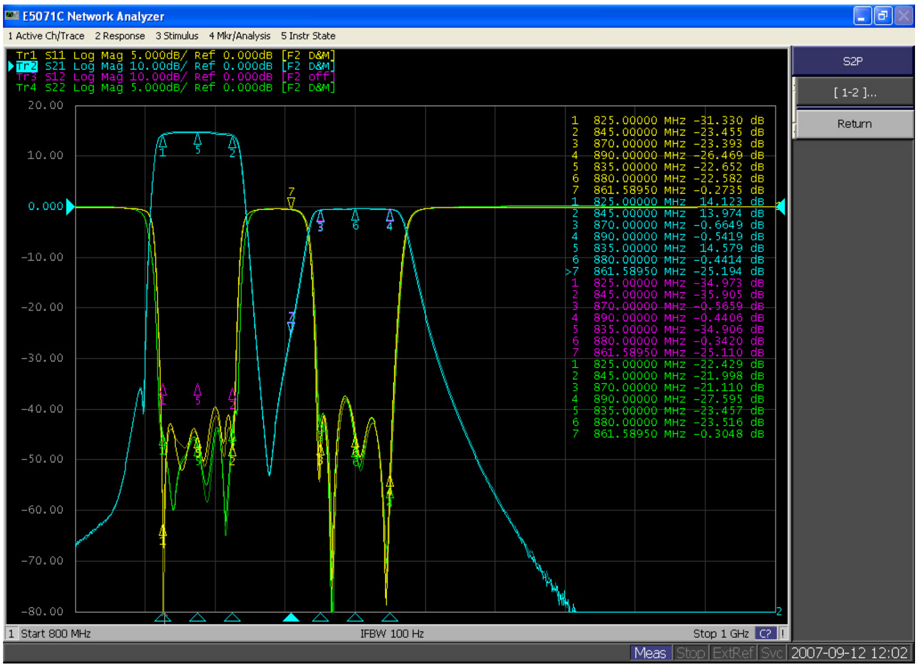

Figure 15: Measured performance of a conventional TMA.

Figure 15 shows the measured performance of a conventional, commercially available TMA. Note that the Rx frequency band in this particular TMA was 5 MHz narrower than the Rx band of the cryogenic TMA (825 – 845 MHz). The Rx channel of the conventional TMA is somewhat better than that of the cryogenic TMA Rx channel return loss. However, the gain and gain flatness performance of the cryogenic TMA is considerably better than in the case of the conventional TMA. Performance of the Tx channel in both cases is comparable. This comparison is only applicable to the specific instances of conventional and cryogenic TMAs considered here, when extrapolating to other cases it should be used as a guide only.

The most significant benefit that the cryogenic TMA offers over a conventional TMA is in the noise figure performance.

Figure 16 below shows the measure noise performance, in terms of the noise figure, of a conventional TMA (with RF performance shown in Fig. 15). Note that the noise performance was measured at different temperatures, since a conventional TMA is not operating in a controlled environment.

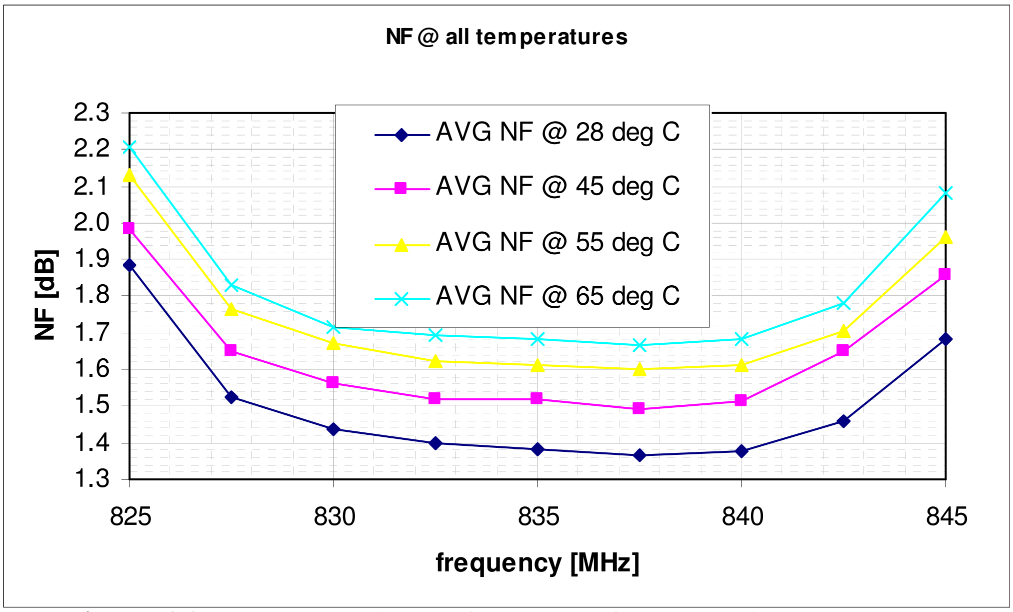

Figure 16: Measured noise performance of a conventional TMA.

Figure 17 shows the measured performance of a cryogenic TMA.

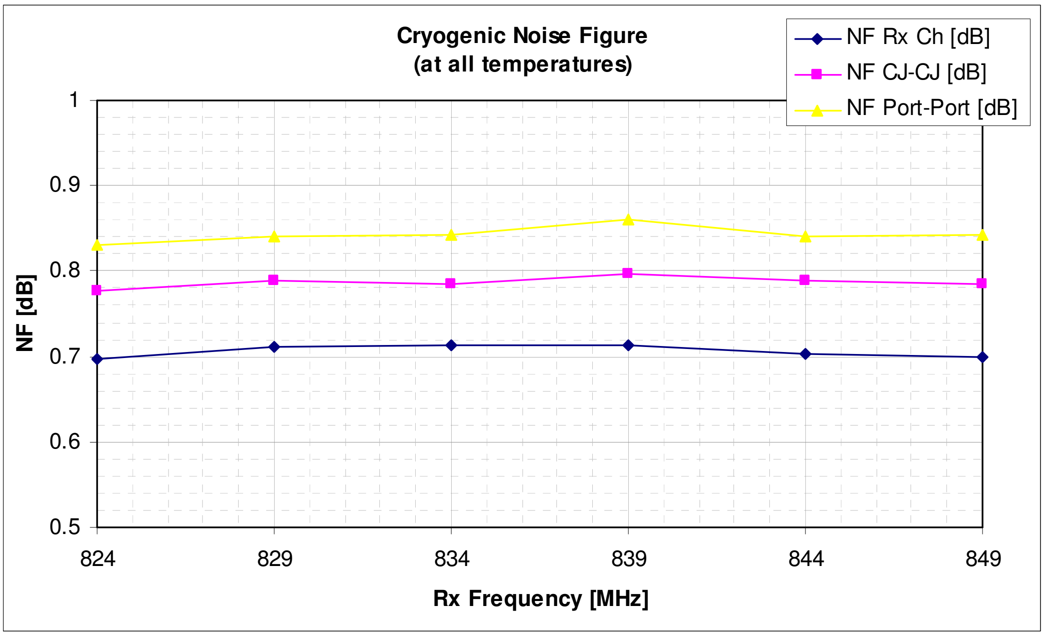

Figure 17: Measured noise performance of a cryogenic TMA.

With measured noise performance of a cryogenic TMA it is important to notice that it applies to all temperatures, due to controlled environment. Also, do to very high Q of the cryogenic filter and a flat gain response of the cryogenic amplifier, it is effectively the same across the entire passband.

As discussed in section *Comparison of cryogenic and conventional devices*, adding room-temperature connecting cables (such as the phase harness, or the external port-common junction cable) degrades the noise performance of cryogenic devices. This is shown in Fig. 17 and Fig. 18, where three sets of noise figure measurements are shown. The first set shows the noise figure of the Rx channel only, without duplexing cables. This measurement is taken between points just outside the cryogenic chamber. The second set of measurements shows a slight degradation in noise performance between the input and output common junctions, after duplexing. The third set of measurements shows the noise performance of the entire unit from the input to the output connector.

Figure 18 compares the noise performance of the two TMAs.

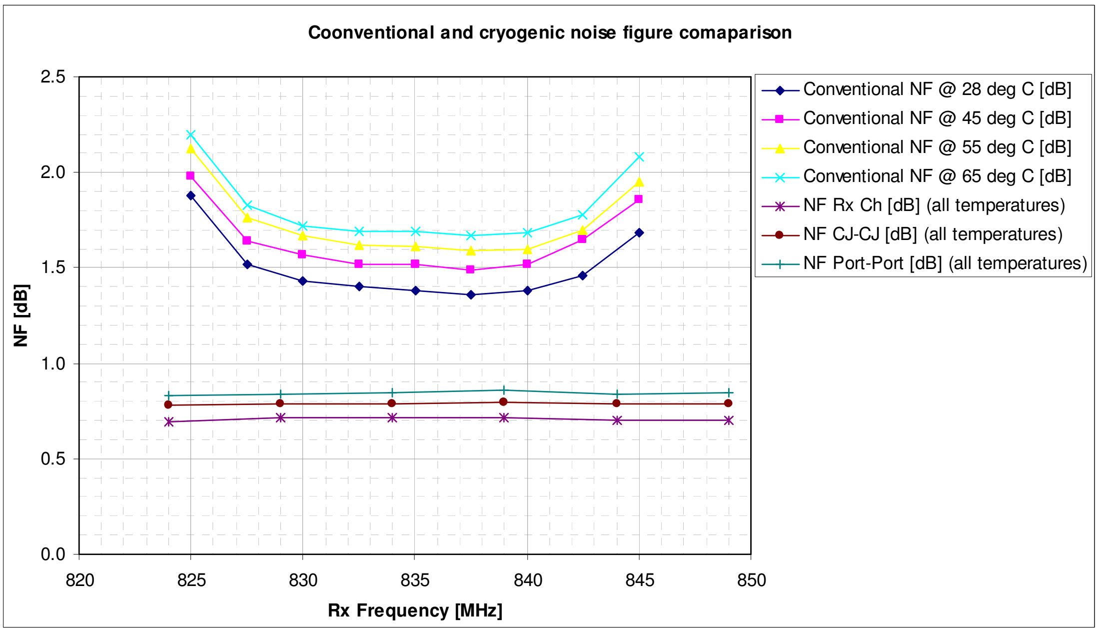

Figure 18: Comparison of conventional and cryogenic TMA noise figure performance.

Noise temperature and the effect of the antenna

The effective noise temperature is the source temperature of a two-port network that will result in the same output noise power, when connected to a noise-free network, as that of the actual network connected to a noise-free source. This is illustrated in Fig. 19 below.

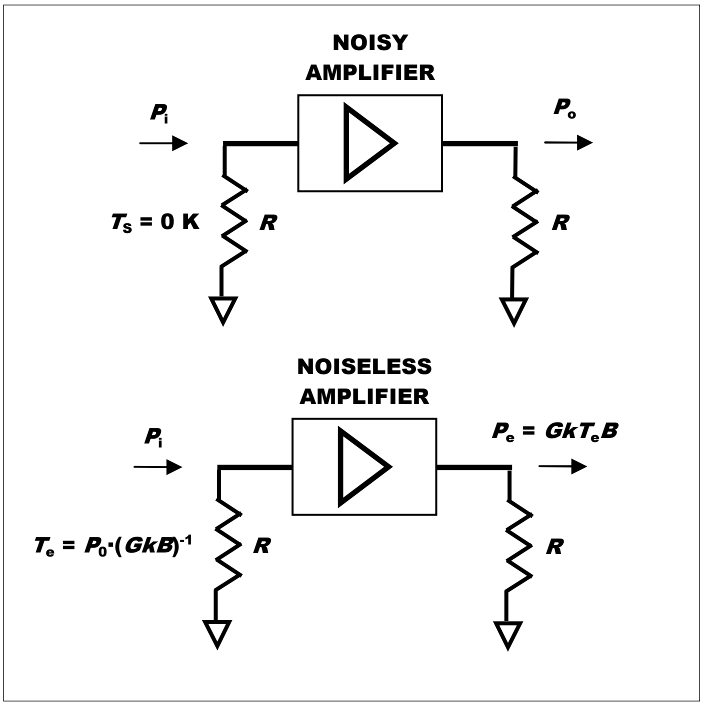

Figure 19: Effective noise temperature.

Using the concept of the effective temperature enables one to effectively model any noisy device as a noise resistor at certain effective (not physical) temperature. The equivalent noise temperature is directly related to the noise factor (and hence the noise figure) by $T_e = (F - 1) \cdot T_0$, where T_0 is the ambient (reference) temperature. The concept of the effective noise temperature has found a particular use in quantifying the noise performance of antennas.

Let us consider the simplified model of a CDMA base station once again. The model is shown in Fig. 20, where the filter, amplifier, and all cable losses have been incorporated into one block, labelled "TMA".

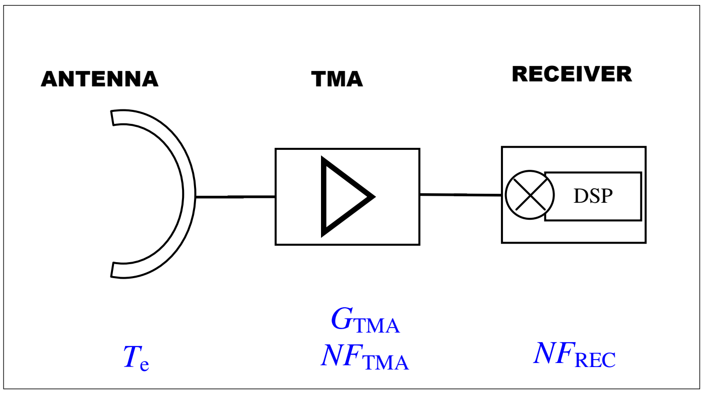

Figure 20: Simplified block diagram of a CDMA base station.

If the effective noise temperature of the antenna (T_e) is larger than the ambient temperature (T_0), due to various sources of noise, the sensitivity improvement is given as

$$Q = \frac{R_X}{R_Y} \cdot \frac{1 + (F_X - 1) \cdot \left(\frac{T_0}{T_A} \right)}{1 + (F_Y - 1) \cdot \left(\frac{T_0}{T_A} \right)}$$

where F_X and F_Y are as before, i.e. noise figures (without the antenna) of the cable-only base station, and TMA-enhanced base station. Assuming, as before, that R_X/R_Y = 1, Fig. 21 below shows the expected sensitivity improvement as a function of different effective antenna temperatures.

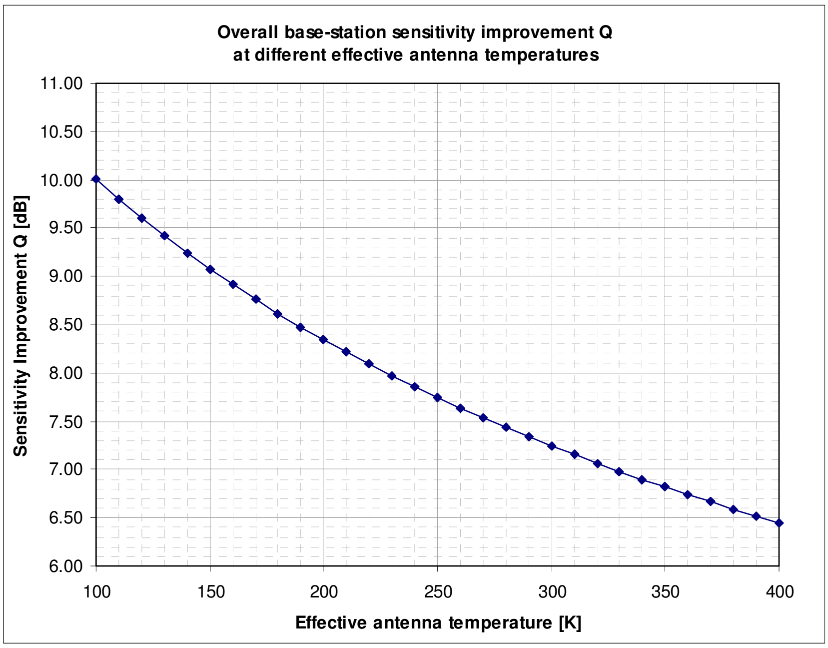

Figure 21: Overall sensitivity improvement
as a function of the effective antenna temperature.

From Fig. 21 it is clear that larger sensitivity improvements can be obtained with lower effective antenna temperatures. In suburban environments, it is not unusual to have lower effective antenna noise temperatures than the $T_A = T_0 = 290$ K value that we have been using. If, in a suburban environment, we have $T_A = T_0 = 150$ K, the resulting sensitivity improvement is shown in Fig. 22 below.

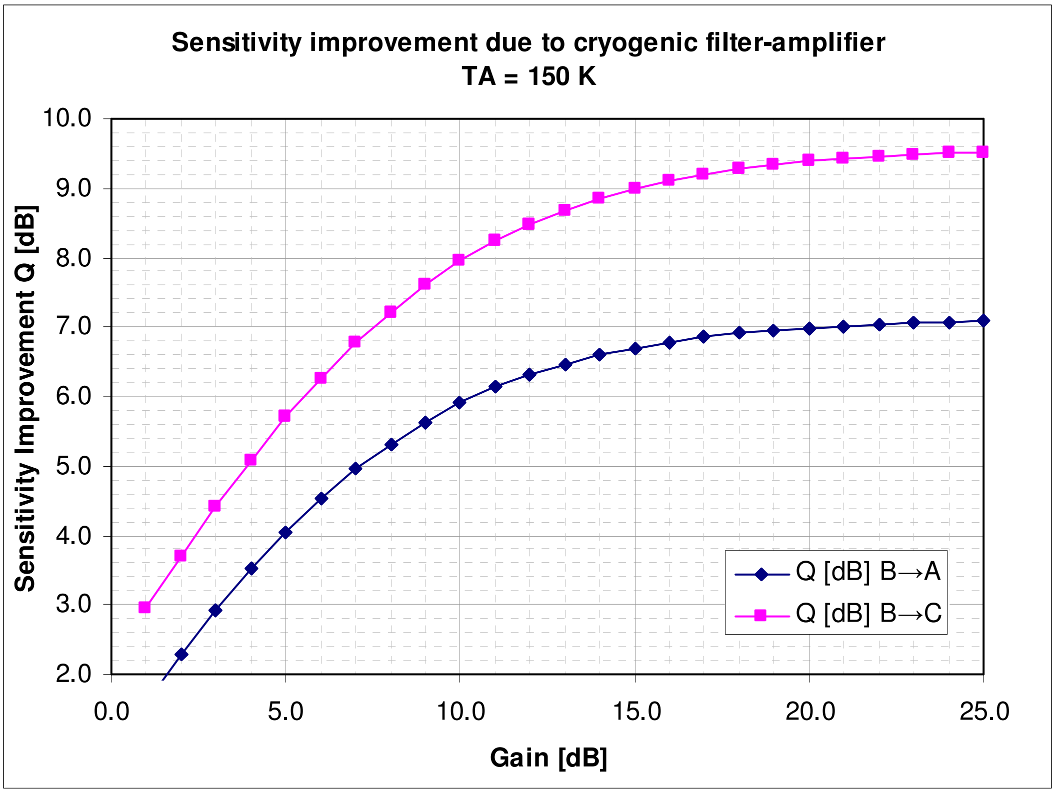

Figure 22: Sensitivity improvement (Q), as a function of amplifier gain, obtained in two situations: (i) obtained by replacing a cable-only antenna-receiver connection (baseline, B) by a conventional (ambient, A) filter-amplifier combination, and (ii) obtained by replacing the cable-only (baseline, B) antenna-receiver connection with a cryogenic filter amplifier (cryogenic, C). In this case, a rural/suburban value for the effective antenna temperature of T_A = 150 K was used.

Figure 22 shows that a cryogenic TMA not only provides a greater absolute sensitivity improvement (with G = 15 dB, Q = 9 dB, whereas from Fig. 11 with G = 15 dB, Q = 7.2 dB), but it also provides a greater improvement relative to a conventional TMA (with G = 15 dB, the improvement is 2.3 dB, whereas from Fig. 11 with G = 15 dB, 1.5 dB).

References

[1] S. C. Yang, J. Payne, and M. I. Salkola, "The Effect of Higher Receiver Sensitivity on the Coverage of a Spread Spectrum CDMA System," *IEEE Microwave and Wireless Components Letters* vol. 15, no. 5, pp. 372 – 374, May 2005.

Version information

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