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Active Cascade Local Oscillator Distribution for Large Arrays

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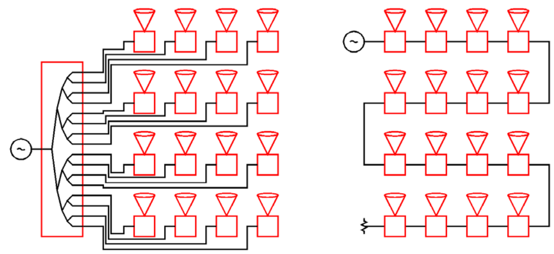
I. Introduction

Of the many challenges engineers face in the attempt to realize cost-effective large-scale focal plane arrays, perhaps none is as deceptively simple as the coherent distribution of the local oscillator to the array elements. The most common method for doing this is shown in Fig. 1a. A single oscillator source is split into equal ratios by a corporate power dividing network, each output then being connected by cables to an independent receiver element. The design of corporate power dividers is well known and straightforward, which may explain its preponderance in existing multi-beam systems.

The relative lossiness of corporate power division when the number of outputs, *N*, is large has led some to develop radial power splitters which transition from one input to *N*-outputs in a single stage. Nevertheless, both of these approaches, along with any others that depend on a localized power dividing network, fail to address the one practical issue which leads to the greatest complexity in large arrays – the mass of cabling between the divider outputs and the individual receiver elements. Somewhat awkward for even modest numbers of elements, the tangled nature of high-frequency, point-to-multipoint cabling becomes virtually intractable in two-dimensional arrays of more than a dozen or so elements.

In one very successful 64-beam receiver called SuperCam built at the University of Arizona, this problem was avoided by injecting the local oscillator into the feedhorns of the array quasi-optically through a Mylar beam splitter [1]. There are a number of reasons, however, why this approach cannot be used in the general case. For one, the optics required can be bulky and complex while unavoidably introducing additional loss. Most significantly, however, the front-ends in the SuperCam instrument use SIS mixers, in which the LO signal is used immediately in the first active component. In lower-frequency front-ends, the mixers will be preceded by cryogenic low-noise amplifiers (LNA), critical to achieving the noise temperature expected of state-of-the-art radio astronomy instrumentation. To require the LNA to remain linear while passing a CW tone powerful enough to drive the subsequent Schottky-diode mixer would put an enormous burden on the amplifier's dynamic range. The constrained design of such an amplifier would almost certainly compromise the sensitivity of the array.



(a) (b)

Fig. 1. Diagram of a) corporate and b) proposed cascade local oscillator distribution.

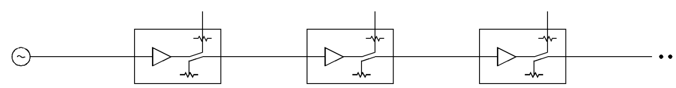


Fig. 2. Diagram of the active cascade LO distribution nodes.

II. Active Cascade Distribution

What is really needed to avoid the complicated cabling of point-to-multipoint distribution in the general case is a distributed, cascade power division scheme as shown in Fig. 1b. Each receiver element is attached to its neighbor by a short (and probably internally integrated) interconnecting transmission line. The first receiver in the chain is fed by a conventional oscillator source. The final element in the chain is capped off by a termination.

It is noteworthy that, unlike most conventional LO distribution schemes which deliver signals to all elements roughly in-phase with each other, the output phase in a cascade chain will tend to rotate across the array. So long as the relative phase delay between elements is stable, this should not cause a problem in most applications.

In order to make the cascade power division work properly, some way must be found to ensure that the power delivered to each receiver element is uniform across the array, despite small but inevitable variations in the components which would normally tend to accumulate into ever larger errors as the number of links is increased. Fortunately, a very simple circuit exists which accomplishes this task, and is shown in Fig. 2. Each node includes a moderate power amplifier, a weak coupler, and a small attenuator pad. The requirement of the amplifier does not incur additional power dissipation than other forms of LO distribution, for some amplification is always required to overcome the losses of

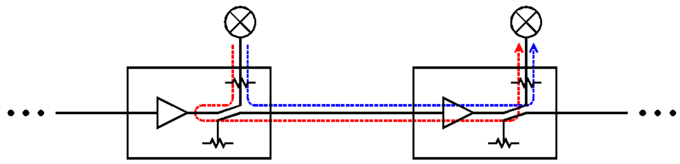


Fig. 3. Two leakage paths which tend to dominate forward isolation.

large divider networks anyway. In this case, we merely absorb those amplifiers into the distribution network where they perform the critical function of power leveling.

It is common practice in the design of downconverters to run the LO buffer amplifiers into compression to de-sensitize the mixer's conversion loss to variations in LO power. The use of the pad introduces a degree of freedom to adjust the power level from the available amplifiers to the optimum point required by the mixer. The coupling value of the coupler is then chosen to be approximately equal to the *compressed* gain of the amplifier plus the loss of the line between adjacent receiver elements, typically around 10-15 dB. It is interesting to note that even at millimeter-wave frequencies, very simple couplers exist which have a small positive slope that can be used to equalize the loss curve of the interconnecting transmission lines [2].

The key is to recognize that the nominal compression of the amplifiers in Fig. 2 makes this distribution chain automatically self-leveling. Consider what happens if the input power to an amplifier is too high. Then, the amplifier will be driven further into compression, reducing its gain and with it the available power going into the next stage. This tends to restore nominal power levels downstream if a particular amplifier has unusually high gain or output power, a coupler has unusually strong coupling, or a cable has unusually low loss.

On the other hand, if the input power is too low, then reduced compression of the amplifier will tend to increase the power available to the next stage. This in turn tends to restore nominal power levels downstream if a particular amplifier has unusually low gain or output power, a coupler has unusually weak coupling, or a cable has unusually high loss.

Isolation between the outputs in the forward direction – that is, from one output to the subsequent one in the cascade chain – may be dominated by leakage along one of two paths, shown in Fig. 3. Note that the coupling of the coupler and the net gain of the amplifier and transmission line are in balance when the distribution chain is in equilibrium. Leakage along the first path, shown with the red dashed curve, is essentially equal to the output return loss of the amplifier plus twice the attenuator value. Leakage along the second path, the blue dashed curve, is essentially equal to the directivity of the coupler plus twice the attenuator value. In practice, the forward isolation will be whichever one is smallest. Isolation in the reverse direction will be greater than this by an amount equal to the directivity of the amplifier (s_{21}/s_{12}).

A subtle risk of this approach is that the sideband- and/or phase noise on the LO signal spectrum will tend to grow from each element to the next, due to cumulative contributions of all the amplifiers. Fortunately, since the coupling loss of the coupler nominally cancels out the gain of its associated amplifier, these contributions are simply additive, not amplified. The impact of sideband noise on the overall receiver noise temperature in the N^{th} position, assuming unbalanced mixers, is

$$\Delta T_{rx} = \frac{(T_S - T_A)G_{PA}A + T_A}{G_{RF}} + N \cdot A\frac{(T_{PA}+T_A)G_{PA} - T_A}{G_{RF}} \tag{1}$$

where T_S is the source noise temperature, T_A is the ambient temperature of the lossy components, G_{PA} is the large-signal power amplifier gain, A is the attenuator value, and G_{RF} is the RF gain preceding the mixer. Neglecting the first term, a constant offset which diminishes in importance for large N, we have

$$\frac{\Delta T_{rx}}{N} \approx A\frac{(T_{PA}+T_A)G_{PA} - T_A}{G_{RF}} \tag{2a}$$

$$= \frac{T_0 P_{mix}}{G_{RF}}\left(\frac{NF \cdot G_{PA} - 1}{P_{1dB}}\right) \tag{2b}$$

where P_{mix} is the LO power delivered to the mixer, P_{1dB} is the 1 dB output compression power of the amplifier, NF is the amplifier's noise figure, and it has been assumed that $T_A=T_0$.

The terms outside the parentheses in (2) represent parameters of the RF system, while the terms inside the parentheses depend solely on the chosen LO distribution amplifier. Thus, we can observe that the best amplifier, from a noise accumulation standpoint, is one that has minimum noise figure, maximum output power (at the cost of DC power dissipation), and, perhaps surprisingly, minimum gain.

To apply realistic numbers, we take the example of the 7-pixel K-Band Focal Plane Array (KFPA) now undergoing commissioning tests on the Green Bank Telescope [3]. Given the documented receiver gain parameters and a suitably chosen LO distribution amplifier, the evaluation of (2) amounts to about 50 mK per node. However, it is important to realize that this is a conservative estimate that neglects noise suppression due to the compressed mode of the amplifiers. Although difficult to calculate from theory, our experience with the ALMA local oscillators [4] tells us that the effect is quite substantial, and could easily reduce this noise penalty by an order of magnitude.

III. Proof of Concept Test

In order to test the key properties of active cascade local oscillator distribution, a prototype 10-output chain was constructed using surface mount technology for an LO frequency around 1450 MHz. This would be a good match, for example, for phased array feeds now being researched for L-

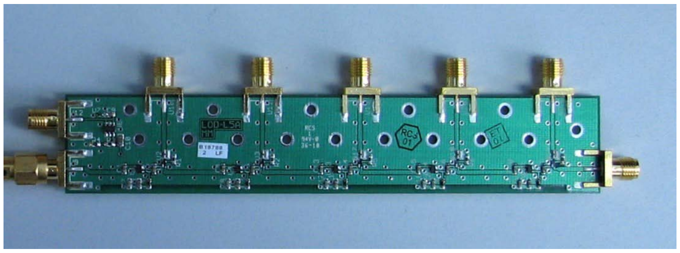


Fig. 4. Photo of a 5-way active cascade LO distribution chain. Two identical boards were cascaded to make the 10-way distribution chain for which all measurements are reported.

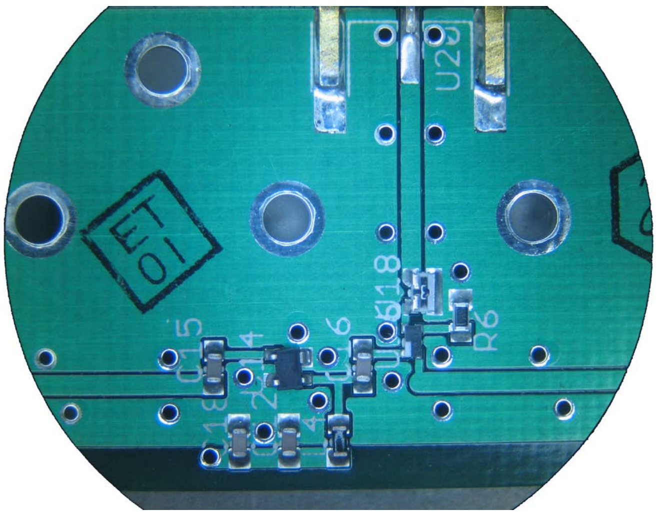


Fig. 5. Close-up of a single distribution node, including the amplifier and associated lumped components for biasing, the coupler with 50 Ω termination, and a 3 dB attenuator.

Band application on large single dishes [5], or in the context of the Square Kilometer Array (SKA). Photographs of the prototype distribution chain are shown in Fig. 4 and Fig. 5. Two boards identical to the one shown were connected in cascade to realize the 10-element distribution chain which is reported in this write-up.

The self-leveling property was tested by driving the input of the chain with a synthesizer and measuring each output with a power meter. The power delivered to each output port over a wide range of input powers is shown in Fig. 6. The input power was varied from +2 to +13 dBm, leading to a much smaller variance in the output power delivered to the first output port which rapidly diminishes for subsequent ports. The equilibrium output power is also demonstrated to be tunable using the amplifier drain voltage. Small fluctuations in the compressed power performance of the amplifiers is evident, particularly at output #5 where the amplifier is the weakest of the lot, and output #7 which is the strongest. Nevertheless, the total variation across the output array remains within 1 dB of the nominal value, and tends to converge rather than diverge at the far end.

Isolation was tested with a network analyzer connected to two adjacent outputs near the middle of the array. A plot of the forward isolation with the LO pump both off and on is shown

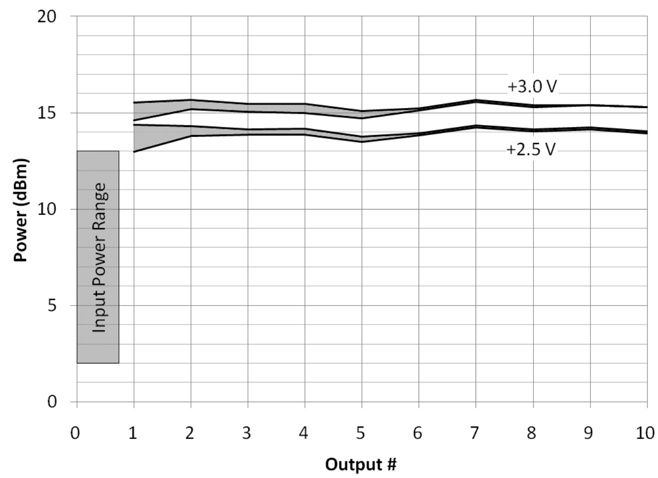


Fig. 6. Measured output power versus port number for the 10-way distribution chain for LO amplifier drain voltages of 2.5V and 3.0V as indicated.

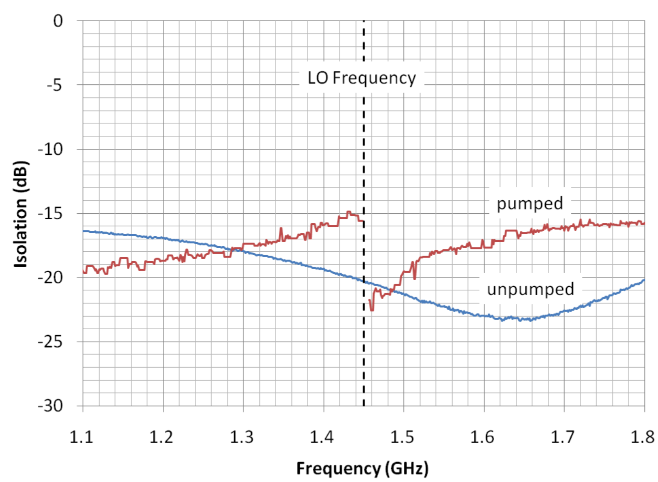


Fig. 7. Measured forward isolation versus frequency with and without the LO pump present. The pumped data was smoothed to take out strong spurious artifacts introduced by interference from the LO drive getting into the network analyzer. Reverse isolation (not shown) was better than 50 dB.

in Fig. 7. The presence of the LO pump introduced spurious tones on the spectrum analyzer which were removed by smoothing. The overall isolation level of about 15-20 dB is consistent with the output return loss of the amplifier. Reverse isolation (not shown) was better than 50 dB across the band.

Should greater isolation be required, a modified version of the distribution node is certainly possible and is shown in Fig. 8. The addition of a buffer amplifier after the coupler unquestionably increases the part count, but the effect on the DC efficiency could be made very small, as the distribution amplifier in front of the coupler may now operate at a very low bias level.

Output harmonics were also measured for several of the outputs using a spectrum analyzer. Although each amplifier in the chain is nominally subjected to the same level of

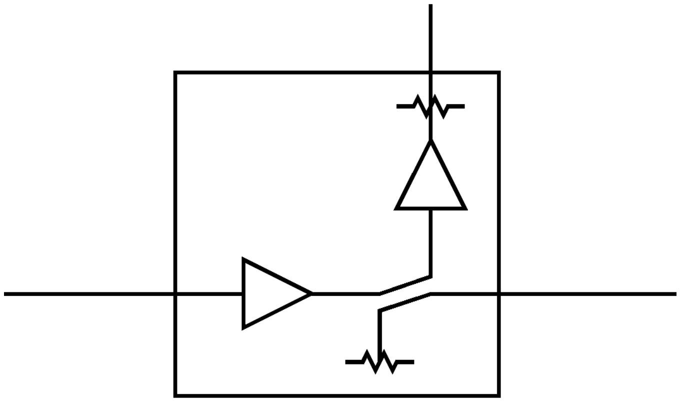


Fig. 8. Alternate distribution node with buffer amplifier for improved isolation. The distribution amplifier (preceding the coupler) may operate at a substantially reduced bias and power level.

compression, the latter amplifiers receive additional harmonics at their input, so the exact harmonic content should not be expected to be the same for all outputs. The harmonic levels as measured are shown in Table 1.

Although phase noise was measured for completeness using the spectrum analyzer, no difference between the 1st and 10th output spectra could be detected. It was not expected that the test setup would have the sensitivity necessary to see the spectral growth resulting from the 10 cascaded distribution nodes. A more meaningful test would require testing the LO with a receiver of comparable noise temperature and gain to that used in the final application, keeping in mind that balanced mixers would also tend to reduce the impact of LO sideband noise on receiver performance.

IV. Potential for Integration

A natural side-effect of reducing the topological complexity of LO distribution is that the distributor network itself is now easier to integrate within the rest of the (warm) receiver electronics. A common proposed methodology is to integrate linear arrays of receivers, or rows, and then stack multiple rows together to form a two-dimensional array.

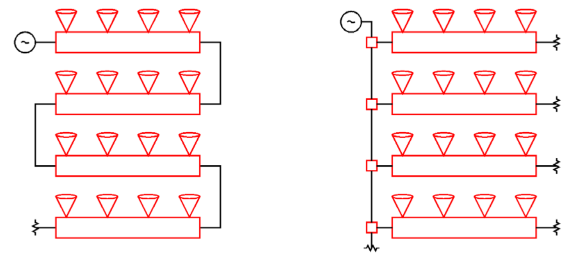
The amplifiers and couplers which comprise the distribution nodes can easily be built into these arrays, leaving each row with a single LO input and output. The rows may then be daisy-chained together, as in Fig. 9a, or fed by another level of active cascade LO distribution, as in Fig. 9b. The latter approach has the advantage that the longest chain of distribution nodes is shorter by a factor of $\frac{1}{2}\sqrt{N}$, potentially alleviating problems associated with sideband noise or harmonic growth.

V. Conclusion

A viable approach for cascaded local oscillator distribution has been proposed and tested in the lab. This neatly avoids the practical complexity of point-to-multipoint cabling, which is a common logistical problem for two-dimensional receiver arrays. The distribution network is straightforward to design, easy to implement, efficient, robust to process variation, and integrates well with linearly-grouped receivers.

TABLE 1: OUTPUT SIGNAL HARMONIC CONTENT

Harmonic	Output Port # 1	4	7	10
fundamental	0 dBc	0 dBc	0 dBc	0 dBc
2nd	-30 dBc	-33 dBc	-24 dBc	-17 dBc
3rd	-20 dBc	-20 dBc	-18 dBc	-23 dBc
4th	-33 dBc	-35 dBc	-53 dBc	-26 dBc
5th	-39 dBc	-36 dBc	-38 dBc	-48 dBc
6th	-49 dBc	-43 dBc	-41 dBc	-48 dBc



(a) (b)

Fig. 9. Illustration of row-by-row integration incorporating a) daisy-chain, or b) nested cascade LO distribution.

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