A 60 GHz phased array front-end for multi-Gbps wireless applications

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The wireless consumer market is looking for technologies capable of providing multi gigabits per second (Gbps) to satisfy the needs of low-latency high-definition applications such as high-definition video streaming and virtual reality or augmented reality (VR/AR) applications. These requirements have led to next-generation standards such as 5G and extended WiGig (802.11ay), which cover both user and infrastructure equipment.

Multiple Gbps communication speeds require wide bandwidth, which is available at high carrier frequencies in the millimeter wave (i.e., 30-300 GHz) range. For example, IEEE 802.11ay standard defines 6 channels of 2.16 GHz each from 57 GHz to 71 GHz. This gives the potential to go up to 35.4 Gbps coded data rate when four channels are bonded together.

Since transmission loss in air is inversely proportional to the square of the signal frequency, signals at mm-waves are highly attenuated. Therefore, multiple antenna paths are usually required to overcome signal losses. With a high-gain antenna array, the beam becomes too narrow, and electronic beam steering becomes important to establish a communication link. Two key components can be identified when using a large beam-steered antenna array: the transmit-receive (T/R) switch and the phase shifter.

Transmit-receive switch integration

The T/R switch is used to share the large-size antenna array between the transmit and receive modes without degrading the RF performance. The main two specifications of a T/R switch are insertion loss and isolation. As shown in Figure 1, there are three T/R switch types: the series switch, the series-shunt switch and the shunt switch. The series switch usually suffers from a high insertion loss due to Ron and poor isolation due to Coff. The parallel switch in the series-shunt topology improves isolation by grounding the signal but adds to the insertion loss. The shunt topology replaces the series switch with a λ/4 transmission line to provide a high impedance when the signal is grounded. The trade-off among the 3 topologies highly depends on the used technology and frequency of operation. For example, both the series switch and the 50Ω λ/4 TL (~ 600µm long) give an insertion loss of ~ 1.5dB in 28nm bulk-CMOS at 60 GHz.
Another approach for sharing the antenna between the TX and RX can also be used. As shown in Figure 2, the PA and LNA are directly connected together and share the same balun. This requires the LNA design to be of a common-gate type to provide a high impedance when switched off. Another requirement is that both the PA and LNA on-impedances are designed close to each other so that they can share the same matching component (the balun in this case).

An additional feature used in Figure 2 is a DC supply switch. This provides more isolation when the PA or LNA is off as it forces Vds to zero. Moreover, it allows using an NMOS-type LNA, which outperforms its PMOS counterpart. Additionally, the topology uses a third weakly-coupled winding below the balun to couple the input signal in RX mode to the LNA gates and boost its gain, providing...
lower total RX noise figure.

**Phase shifting for electronic beam steering**
The second key component is the phase shifter, which is used to steer the beam in the wanted direction, preferably without losing signal strength and preferably with minimal calibration effort. The main specifications of the phase shifter are its loss, area, linearity, power consumption, phase resolution, and gain difference versus code. RF phase shifting has the potential to be the most power efficient solution. Conventional phase shifters are based on switched delay lines (**Figure 3**), where different delay sections are cascaded to reach a certain phase shift resolution. Therefore, the phase shift resolution is proportional to the number of sections, and similarly, losses. Moreover, the design is usually bulky due to the use of serial passive components.

![Figure 3](image)

**Figure 3** Conventional phase shifter using switched delay cells

Another approach depends on a 90-degree phase splitter, where the outputs are combined after passing by variable-gain amplifiers (VGAs). As shown in **Figure 4**, this can be seen as the vector summation of weighted in-phase (I) and quadrature-phase (Q) amplifiers. The phase splitter can be implemented with a lumped equivalent of a Lange hybrid coupler to occupy a small area. A cascode VGA configuration can ensure better matching with the low-ohmic hybrid. It also allows having equal amplitude values for different phase shift settings by using dummy cells that are switched to the supply to equalize the hybrid load impedance. The example of **Figure 4** uses 5-bit control in the I and Q amplifiers including the sign bit. This results in 360-degree coverage with an average phase shift resolution of 3 degrees, allowing an average beam pointing accuracy of 1 degree. The ideal peak-to-peak amplitude error with this resolution is ±0.4dB, which allows an ideal beam scanning ripple of 0.3dB.
A full 8-way transceiver front-end
Using the T/R switch of Figure 2 and the phase shifter of Figure 4, a 60 GHz phased array wireless module was developed including eight front-ends with antenna patches. Fabricated in TSMC 28nm CMOS technology, the chip (Figure 5) achieves a TX output P1dB of 10dBm and an RX noise figure (NF) of 6.8dB (per path) and consumes 231 mW in RX mode and 508 mW in TX mode. The phase shifter achieves an amplitude error within ±0.8dB and a maximum phase step of 6 degrees over the whole 360-degree phase difference without calibration. The amplitude error and phase step can be adjusted to ±0.35dB and 5 degrees, respectively, after calibration.

The chip is flipped on a 12-layer Megtron 6 PCB for wireless testing using patch antennas placed in a circular shape for similar azimuth and elevation performance (Figure 6). The module uses the uncalibrated phase shifter settings and achieves less than 0.4dB peak-to-peak gain ripple over a 3dB scan angle of ±46 degrees. In this case, the gain and angle errors of a beam directed to a certain angle are a result of the average of the amplitude and phase errors of all phase shifters in the system. A robust active phase shifter enables steering the beam electronically without extensive calibration.
The 60 GHz in-out interface allows integrating the chip with another similar front-end chip (enabling range extension) or a baseband chip. This allows the chip to be useful for both mobile indoor applications such as 5G and WiGig as well as outdoor applications such as small-cell backhaul and fixed wireless access.

**Wireless noise figure measurement and EINF**

The RX noise figure is measured using the wireless module, where all RX path inputs can be excited simultaneously. When measured in a probed setup with only one RX path excited, the Wilkinson combiner becomes lossy, causing lower gain and higher noise figure that does not reflect the true operation of the chip. Instead, the wireless module faces an absorber (Figure 7) and the output noise temperature is measured after being amplified with a waveguide amplifier. The module gain is measured in another setup using a VNA and a horn antenna. This way, the module G/T, a parameter used to represent the noise performance of wireless systems, can be calculated.

Normalizing the inverse of this parameter to the ambient temperature leads to the definition of EINF, which is a new parameter representing the effective isotropic equivalent noise figure and can be seen as the RX counterpart of the EIRP parameter for TX. Using this parameter, the RX noise figure can be extracted after the knowledge of the antenna gain (EINF = NF/Gr), and the link budget equation can be simplified to measurable parameters (SNRout = EIRP/EINF * FSPL / kT0B).
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