Tradeoffs in Millimeter-wave Beam-steering Technologies

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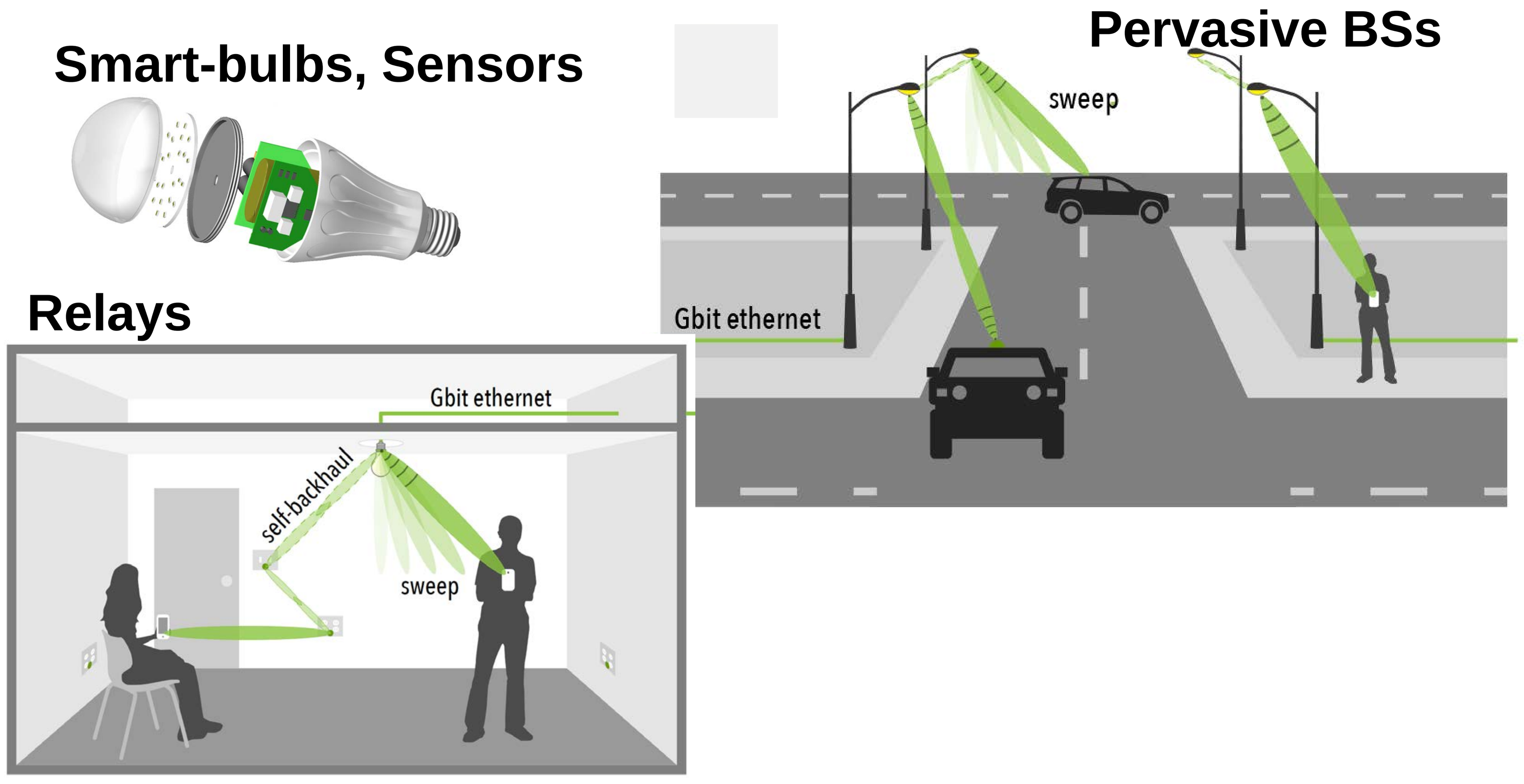
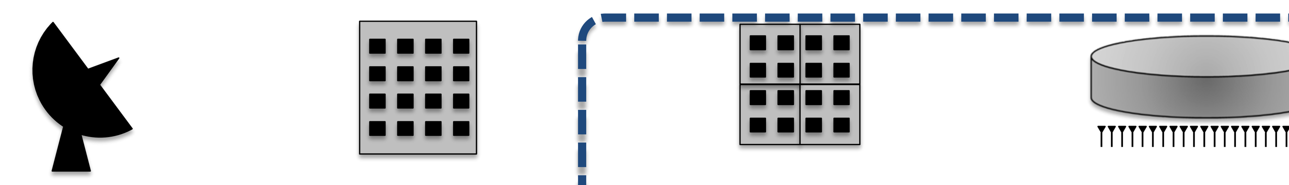
MMW Beam-steering

5G systems will depend upon the additional power density provided by high-gain millimeter-wave antennas. Such high gain equates to narrow beams and is thus subject to blockage effects. It is anticipated that 5G MMW networks will be blockage limited, not path-loss limited. As such a network will require **pervasive beam-steering base-stations** and could benefit from **relays**. It also requires beam-steering at UEs, and even on simple sensors. The need for so many beam-steering devices, as well as the burden of beam-steering on all devices from base-stations down to sensors motivates a close examination of power-efficient, low-cost, simple, and scalable-complexity beam-steering methods.



Candidate Technologies



	Dish	Full-digital Array	Hybrid Array	GRIN Lens
Architecture	Aperture	Discrete array	Array of Subarrays	Switch-feed and lens
Power draw	Passive	Active	Active/Passive	Passive
Gain	High gain	High gain	High gain	High gain
Power out	High	High (n xcvrs)	Medium (p xcvrs)	Medium (p xcvrs)
Beams	# of feeds	*n* beams/xcvrs	*p* beams/xcvrs	*p* beams/xcvrs
Angular res.	Pointing	~0°	~0°	Adjacent partial beams (reduced gain)
Bandwidth limit	Flexible feed	Fixed xcvr; spacing	Flexible xcvr; spacing	Flexible xcvr
Interference	Sidelobe I/F	Null steering	Null steering	Angular filtering
Form-factor	Large (3D)	2.5D (for xcvrs)	Flat array	Flattened
Complexity	Steering	*n* xcvrs	Phase shifters	Feed switch matrix
Computation	Low	Medium	High	Low

Complexity Scaling

The nature of millimeter-wave propagation necessitates high gain (narrow-beams) which means that any millimeter-wave application, regardless of complexity, will require a beam-steering aperture. This can place an incommensurate burden on low-power and low-cost platforms such as IoT sensors.

Phased arrays and hybrid arrays must be realized in the same manner regardless of the application: a base-station, a mobile handset, and a simple IoT sensor would all require the same number of phase shifters (though the number of transceiver chains (w/ DAC/ADC) could be reduced to one).

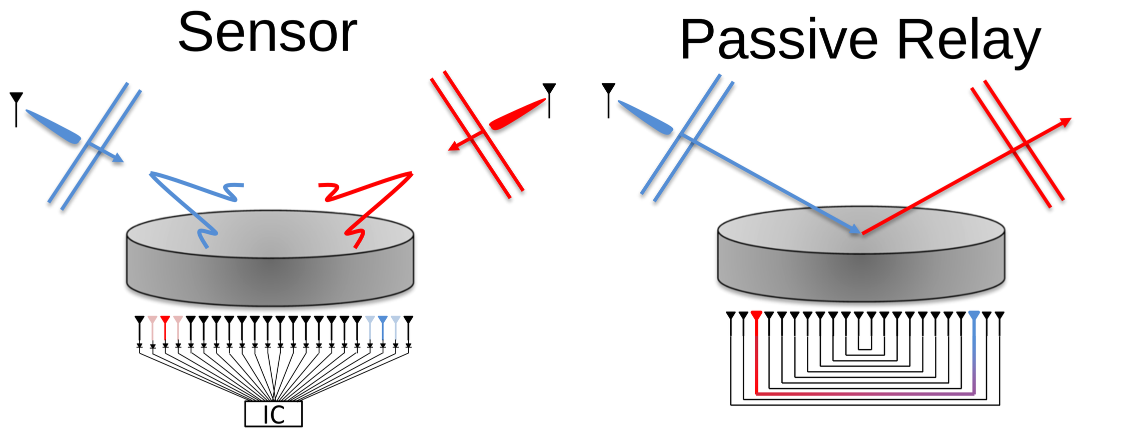
Because lenses provide angular selectivity passively and inherently, reduced application requirements also relax requirements on back-end electronics. Consider the hardware required for various devices:

Base-station: lens plus full switch matrix (e.g,. 4 or more transceivers)

UE: lens plus simplified (two transceiver) switch matrix

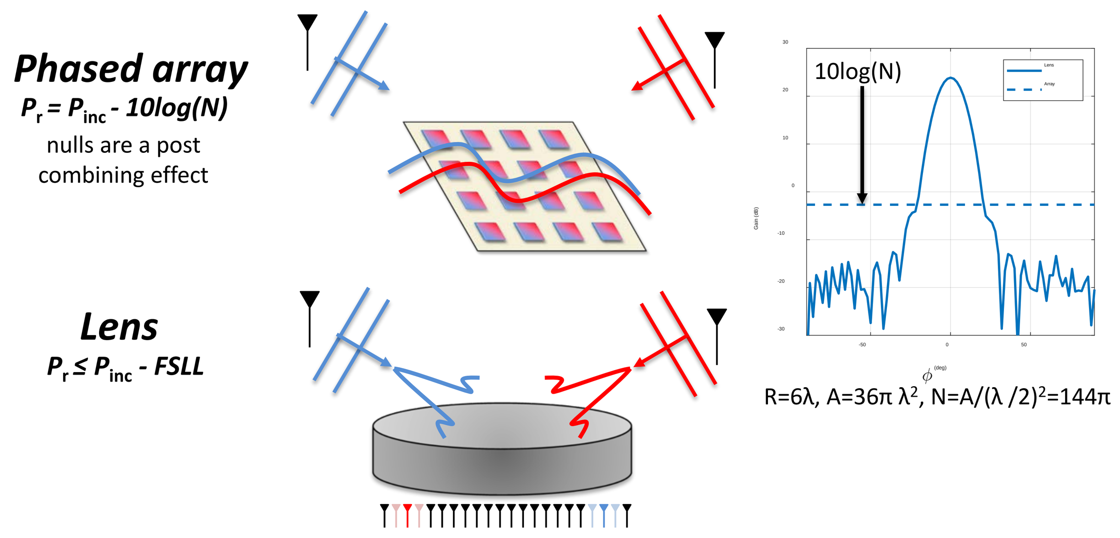
IoT sensor: lens plus diode-based energy detectors and DC wiring

Passive relay: lens, feeds, and loop-back routing



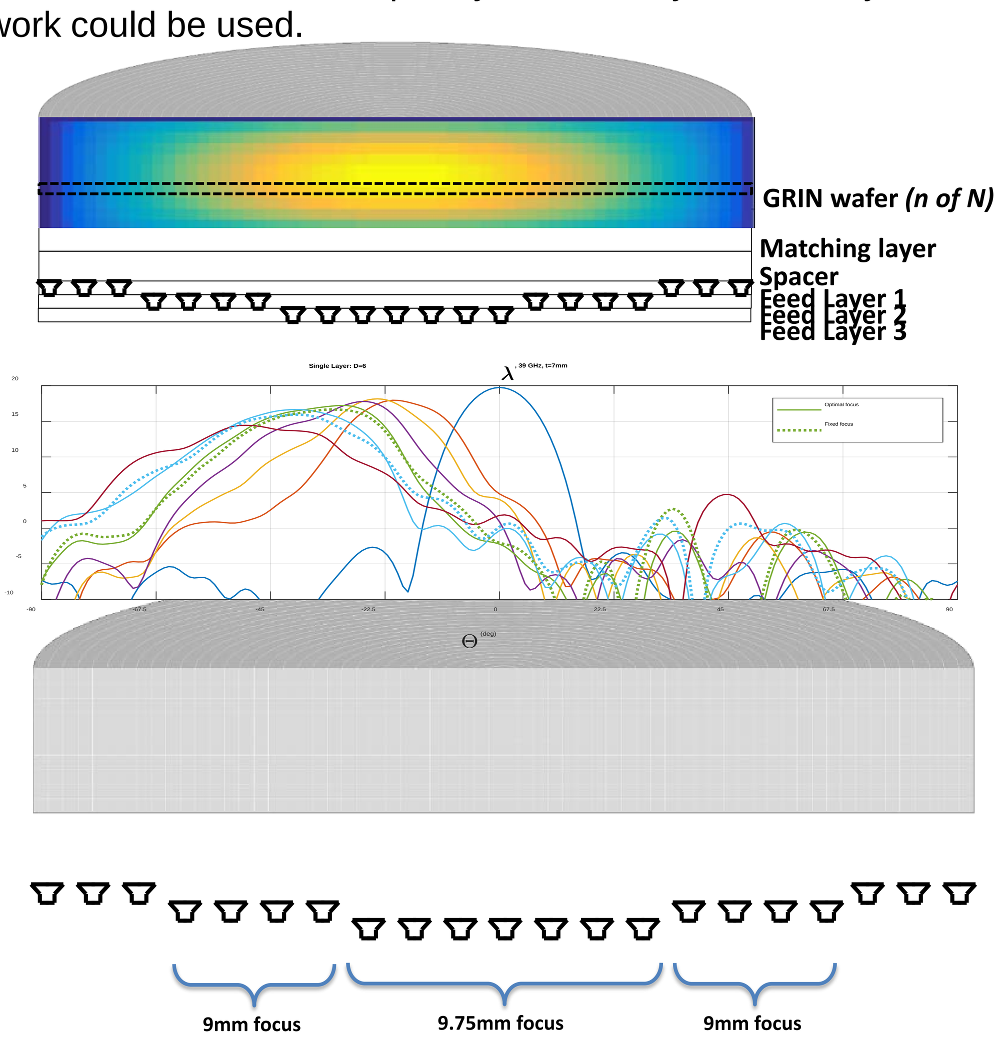
Isolation

- Multi-user antennas must provide angular isolation of UEs
- Phased arrays distribute incident power over N receivers
- Hybrid arrays phase for isolation but require linear phase shifters
- Lenses isolate receivers in angle-space based on the radiation pattern using a completely passive material



Feed Networks

The advantages of lenses come with some new challenges. The optimal focal point of a lens antenna varies across the base of the lens. Transformation optics could be used to flatten the focal points at the cost of further complexity. Alternately, a multilayer feed network could be used.

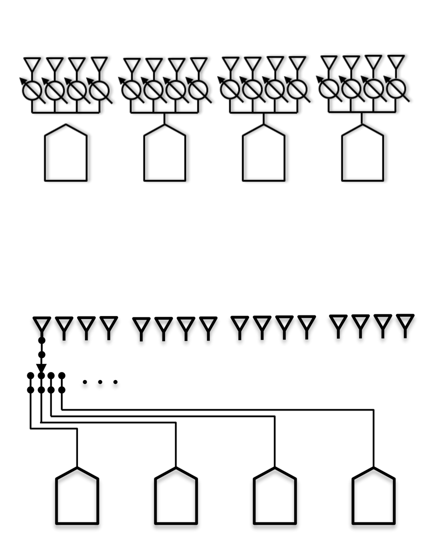


Feed network electronics consume power, contribute loss, add complexity, and increase the physical volume required for the antenna. A hybrid array uses **phase shifts** and bias at each element while a lens uses a **switch** matrix with multiple switches at each element.

Power and loss: GeTe switches consume zero static power but multiple switches in series are lossy (1-3 dB) attenuation. Phase shifters dissipate power all the time.

Complexity: Switch matrix becomes increasingly complex for multi-user (multi-xcvr) apertures.

Form-factor: A full-digital phased array with N transceivers will require significant space behind the array. Hybrid arrays can be realized with planar technology. Lenses must be flattened (e.g., with transformation optics) and even then, the feed must be extended.

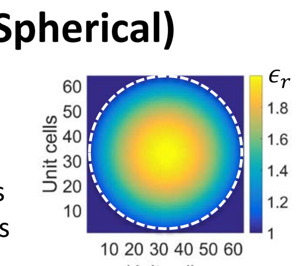


Design and Fabrication

I: Original lens (Spherical)

- Application prescribes performance (gain, side-lobes, etc.)
- Spherical Luneberg lens has desirable properties
- Permittivity gradient:

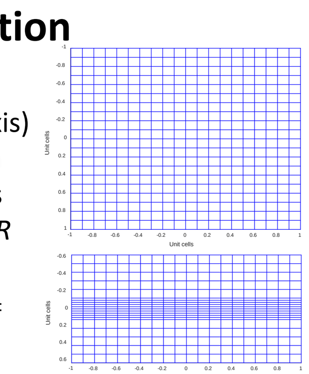
$$\epsilon_r = 2 - \left(\frac{r}{R}\right)^2 \begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix}$$



II: Transformation

- Desire flat lens
- Define vertical (y-axis) spatial compression where lens height is compressed from *2R* to *2δ*:

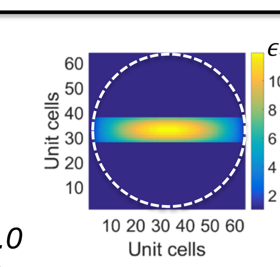
$$x' = x$$
$$y' = \frac{\delta y}{\sqrt{R^2 - x^2}}$$
$$z' = z$$



III: T.O.

- Transformation Optics (T.O.) converts spatial compression into new permittivity gradient
- Spherical lens ε_{rmax}=2.0
- Flat lens ε_{rmax}=2/δ=12

$$\epsilon'_{rxx} = \epsilon'_{rzz} = -\sqrt{R^2 - x^2}\,\frac{\frac{x^2+y^2}{R^2} - 2}{\delta}$$
$$\epsilon'_{ryy} = 1$$



IV: Full-wave EM

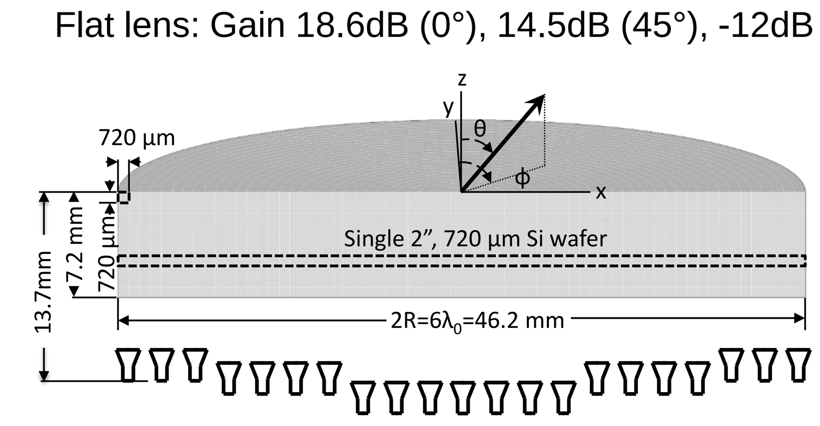
- Matlab T.O. algorithm defines compressed permittivity profile
- Python automats HFSS to create 3D model
- HFSS solves full-wave EM lens

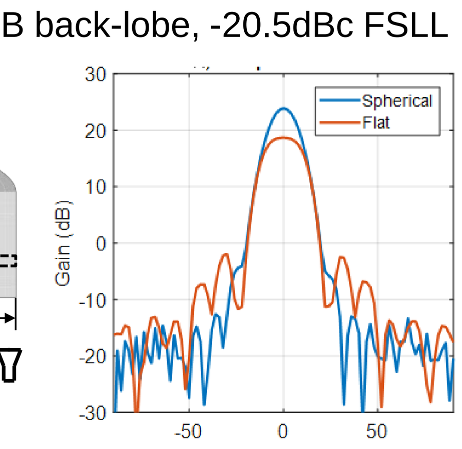
Flattened Luneberg Lens: 39 GHz (D=6λ, t=7.2mm, focus = 6.5mm)

Unit cell: 720um x 720um, Permittivity gradient: 11.8 to 1.25

Spherical lens: Gain 24dB, -28dBc FSLL

Flat lens: Gain 18.6dB (0°), 14.5dB (45°), -12dB back-lobe, -20.5dBc FSLL





GRIN medium: perforated dielectrics with Bosch D-RIE

Using contiguous polygons we can achieve maximum fill-factors and thus maximum permittivity contrast--ranging from (1.25 – 11.8)±0.15 in silicon.

$$\epsilon_{eff} = \frac{2\alpha(1-\epsilon_r)+1+2\epsilon_r}{\alpha(\epsilon_r-1)+1+2\epsilon_r}$$