Arrays for Wireless Power Transfer and Harvesting

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Outline

• Motivation for amplifier and rectifier arrays for WPT
• Example far-field rectifier arrays:
  – Narrowband 10-GHz array for powering aircraft health-monitoring acoustic tomographic system
  – Narrowband 2-GHz array for harvesting power from a base-station with load power management
  – Narrowband 10-GHz ground-based array for harvesting power from a satellite
  – Broadband 2-18GHz array for harvesting very low power levels
  – Broadband 2-5GHz wearable array for harvesting
• High-power far-field WPT link requirements
Far-field Rectifier Arrays: Link Budget

Transmitted power
Needs to be determined

Received DC power – Given by requirement

DC power IN

Feed

\[ P_T = P_{Te} N_T \eta_{PAE} \eta_c \]

Combining efficiency \( \eta_c \)
TX aperture and gain \( A_T \) \( G_T \)
Total TX power \( P_T \)

\( G_e, P_{Te} \)

DC power OUT

dc collection circuit

\( \eta_{dc} \)

\( N_R \)

RX aperture \( A_R \)
Total RX power \( P_R \)

\( P_{rect} \)

Range, \( R \)
Propagation loss \( \sim 1/R^2 \)

PAE of transmitter element
RF combining efficiency

Received power per element
Rectification efficiency
DC combining efficiency

\( \eta_{rect} \)
Motivation for Rectenna Arrays: Harvesting

- Scalable wireless harvesting
- In an array, each antenna element has its own rectenna and incident phase is not relevant since the DC is combined
- DC combining can be reconfigurable
Example 1:

10-GHz Rectenna Array for Aircraft Health Monitoring

- piezoelectric sensors detect defects before they pose risk
- large area inspection for defects
- batteries introduce malfunction – eliminate using powering through rectenna array

Conformal rectenna array size: 15 cm x 15 cm
- Required power: 100mW with +15V and -15V dc
- Controlled Parameters: 10GHz, linearly polarized; range ~ 1 m; power density = 10mW/cm²
Example 1: 10GHz 36-element patch rectenna array

Power from a single element ~5mW at 52% max conversion efficiency; need at least 20 elements

- Array etched on 0.254-mm thick Rogers Duroid 5880 with a relative dielectric constant of 2.2

Example 1

Antenna array measurements

Maximal efficiencies:
- N=16, \( \eta = 44\% \)
- N=19, \( \eta = 44\% \)
- N=25, \( \eta = 39\% \)

• ± 15V required: use commercial inverter chip
• Maxim ICL7662 inverter, transient startup current \( \sim 40 \text{ mA} \)
  – 1-mF capacitor stores enough energy to compensate for the initial 200-mW requirement
Example 2:  
2-GHz Harvesting Array for Base-Station Monitoring

Example 2: Harvesting from a base-station

Emulator circuit models rectenna element
Example 2: array

The image shows a diagram of a wireless power transfer system, including a ground plane side view and a cross-sectional view. The diagram illustrates the arrangement of components such as S1, S2, R1,1, R1,2, R1,3, R1,4, and R, connected in an array configuration.

The text mentions that a converter significantly improves the harvested power relative to a direct-connect system.
Example 3:  
10-GHz Array for Harvesting Power from a Satellite

Space-to-Earth WPT enables on-tap energy access in remote locations

- Incident power density varies up to 3 orders of magnitude for a given satellite orbit
- Efficient RF-dc energy conversion required at very low incident power density
- Most work done at 2.5 and 5.8GHz down to 1 µW/cm²; very few results in X band for lower power densities

Scalable approach:

Unit cell:
- 2x2 patch elements with sequential feed network
- 9.9dB gain at 10GHz
- Return loss >10dB, 1GHz bandwidth

Example 3

- Improved output power from array over 30° beamwidth across power density range
- Up to 20% conversion efficiency for array, 15% for unit cell
- Optimal dc load decreases from 3 kΩ to 750 Ω as power density increases
- All testing performed with CW excitation
- Up to 10pp efficiency variation measured across multiple boards (array)

Specifications for power-combined array:
- Power density: 0.1-100 μW/cm²
- Frequency: 10 GHz, Polarization: LHCP

Circuit diagram

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Example 4: Broadband Multi-octave Harvesting Array

- Measured broadband frequency response for various incident power levels related to the power density.
- Shaded area – range of rectified power levels from ambient RF background signal present in the building.
Example 4: Harmonics and patterns

Example 4: Multitone harvesting

Example 5: Broadband 2-5GHz Wearable Harvesting Array

Multimode rectenna array printed on cotton

Simulated source-pull results showing contours of constant rectified power (in $\mu$W) at 2 and 5 GHz with an input power and dc load of 100 $\mu$W and 2 k$\Omega$, respectively.

Region of optimum impedance to present to the diode for peak dc output power, showing the trend in frequency ($f$) and load ($R_L$). $f$ is swept from 2 to 5 GHz while $R_L$ goes from 500 to 3000$\Omega$ and the input RF power is 100$\mu$W.
Example 5: simulations

Simulated driving point impedance, 2-5GHz

Simulated 4x4 radiation patterns with 1mm air gap between shirt and skin
Example 5: Measurements

Vertical polarization

Horizontal polarization

Vertical polarization

Horizontal polarization

2 kohm
2.9GHz
Example 5: some realistic parameters

Body curvature

Diode behavior before and after hand washing

High-Power Far-Field WPT

- Diodes limited for high-power rectification: use transistors
- Use the same device for PTX and PTX: time-reversal duality
Time-reversal duality: works for any PA mode

\[ v_{PA}(t) = v_{R}(t) \text{ and } i_{PA}(t) = -i_{R}(t) \]

- Example: Class-F PA
- Special nonlinear model – includes 3rd quadrant of I-V curve
- Time domain waveforms at the intrinsic drains

Example PA and PR

\[ f = 2.14 \text{GHz} \]

High-Power GaN Self-Synchronous Rectifier

Vgs=-4.4V, Zg=230+j10Ω, Max 85% with Vdc=30V and Pin=10W
X-band GaN MMIC PA and PR

- Peak PAE = 67.87%
- Peak $\eta_{DE} = 78.36$
- $P_{in} = 26.42$ dBm
- $P_{out} = 35.16$ dBm

$V_G = -4.0$ V, $V_{DD} = 20$ V, $f_0 = 10.1$ GHz

- Single-stage PA, one $10 \times 100 \, \mu m$ FET
- Class-B in pinch-off
- Optimized for PAE
- $3.8 \, mm \times 2.3 \, mm$

\[ \eta_R = 64.40\% \]
\[ V_G = -4.7 \, V \]
\[ R_D = 100 \, \Omega \]
\[ Z_g = 8.45 + j24.5 \, \Omega \]

Conclusion

• Several examples of narrowband and broadband harvesting arrays shown
• High-power far-field WPT link array requirements discussed
• Examples of power amplifier – power rectifier duality for high-power WPT arrays