Energy Harvesting for the Internet-of-Things

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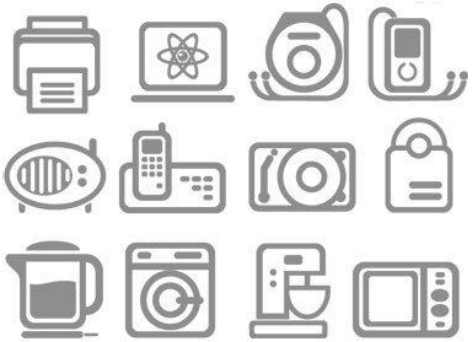
Outline

- Motivation and Challenges of IoT
- Energy Harvesting
- Wireless Energy Transfer
- Ambient RF Energy Harvesting
- Hybrid Techniques
- Ways Forward
  - Multiple Antennas
  - Low Power Receivers
- Review

IoT Motivation

- “Things” have data and the “Cloud” wants data

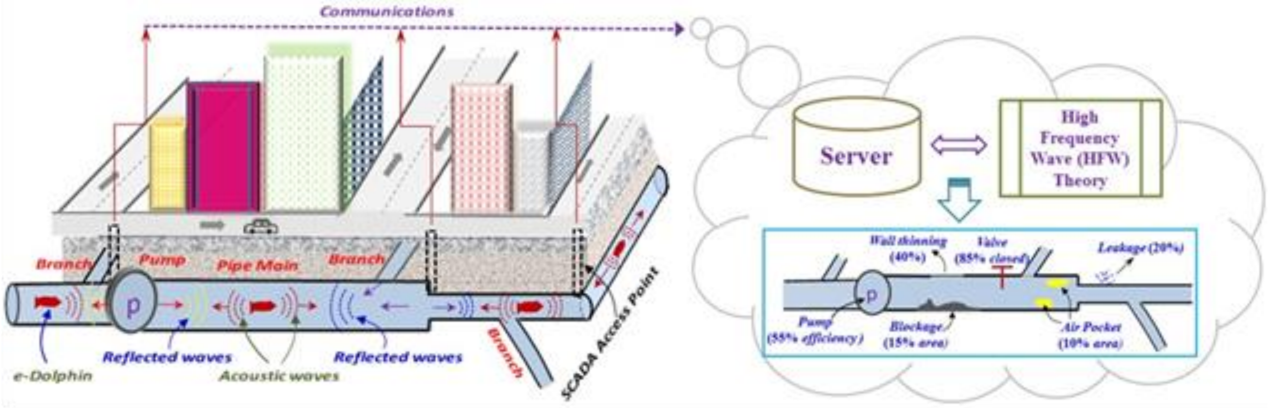


- Connectivity is essential
  infrequent data chunks or packets

- Enhanced services and performance in healthcare, environment, energy, smart city, security…..
- Big Data needs IoT

IoT Challenges

- Unique in that there is no one uniform application
- Home, city, bridges, car, people, health, environment ocean etc
- Each application needs unique tradeoffs
  - Sensors, Channel models, Communication systems, Energy harvesting, Low power



IoT Connectivity Challenges

- Low power challenges
  - Support coin batteries and energy harvesting- 1uA
- Sensors
  - Improved sensor technology required- size, accuracy and type
- Inexpensive
  - There will be billions of these devices
- Diversity
  - Different applications require different solutions and tradeoffs
- Low latency
  - Low delay in making connections and sending data chunks
  - Data rate not as critical- streaming not usually required
- Privacy and Policy
  - Critical policy and social issues to solve

Energy Harvesting

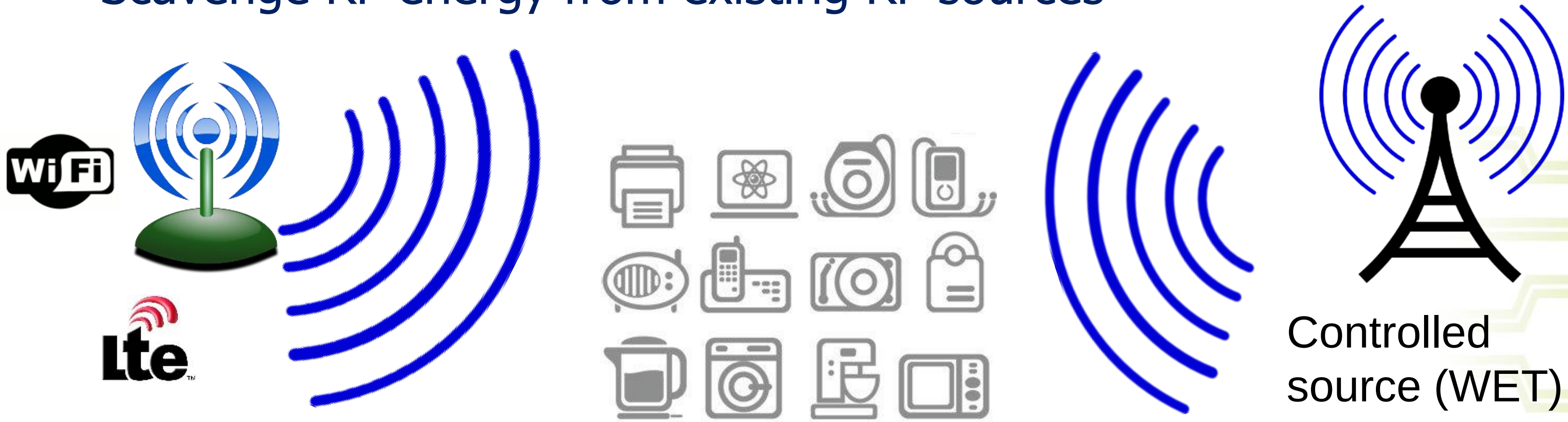
- In this talk we wish to focus on energy harvesting
- If there are to be trillions of IoT devices then it will be impossible to use batteries
- IoT devices will require long lifetimes
- Batteries will need replacement every few years
- Replacing trillions of batteries is time consuming and costly
- Environmentally unsustainable

Energy Harvesting

- Scavenging techniques
  - Solar
  - Wind
  - Thermal
  - Vibration
  - Ambient RF
- Controllable Techniques
  - Wireless Energy Transfer (WET)
  - RFID
    - Limited communication and range
  - Advances in antenna and RF technology allow enhanced approaches

Wireless Energy Harvesting

- Wireless Energy Transfer (WET)
    - RF energy source is controlled
- Ambient RF Energy Harvesting
    - Scavenge RF energy from existing RF sources



- Significant common elements between both techniques

- Bi S, Ho CK and Zhang, R, Wireless Powered Communication: Opportunities and Challenges, IEEE Communications Magazine, April 2015, pp117-125
- Pinuela, M.; Mitcheson, P.D.; Lucyszyn, S., "Ambient RF Energy Harvesting in Urban and Semi-Urban Environments," in Microwave Theory and Techniques, IEEE Transactions on , vol.61, no.7, pp.2715-2726, July 2013

Wireless Energy Transfer (WET)

- Under development for 50 years
- Advantages
  - Continuous and stable energy
  - Combine with communication
  - Wide operating range- Far-field
    - Inductive and magnetic resonance coupling
  - Low production cost and size
  - Multicasting
- Many system results developed but hardware implementation limited
- Minimum RF signal required for EH is around -40dBm
- Compare this to less than -100dBm for communication

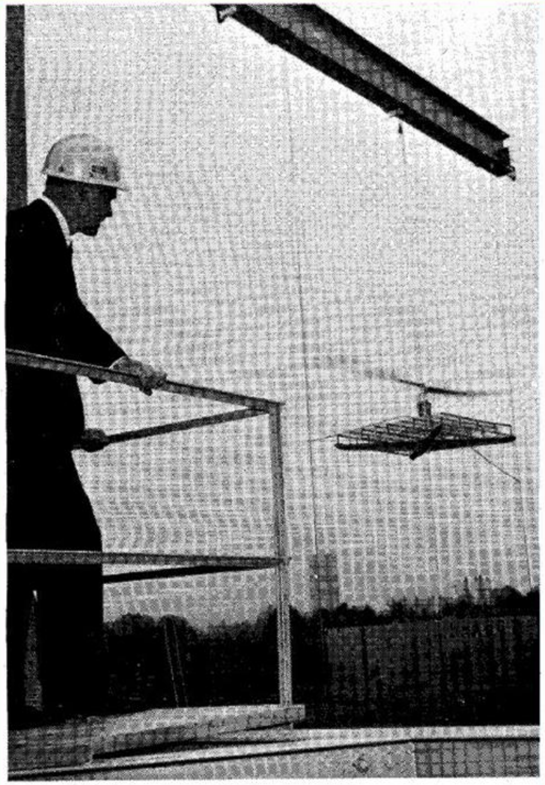
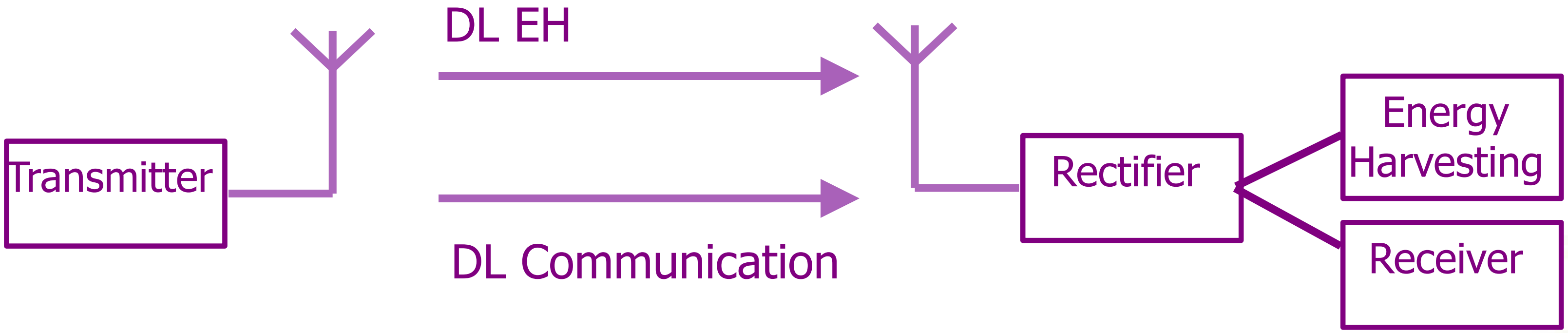


Fig. 5. Microwave-powered helicopter in flight 60 ft above a transmitting antenna. The helicopter was demonstrated to media in October 1964. A 10-h sustained flight was achieved in November of that same year.

Brown, W.C.; , "The History of Power Transmission by Radio Waves," Microwave Theory and Techniques, IEEE Transactions on , vol.32, no.9, pp. 1230-1242, Sep 1984

DL EH & DL Communication Systems

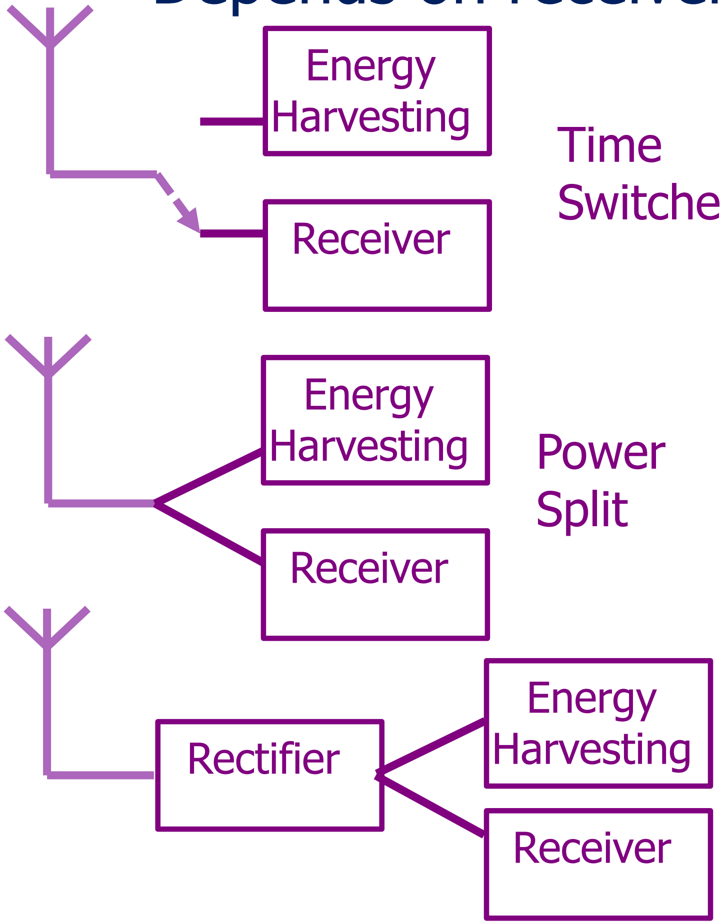
- EH in DL; Communication in DL



- Channel characteristics very important
  - Interference harms only communication
  - As SNR increases logarithmic increase in rate but linear in EH
  - Use communication when SNR poor but EH when SNR good

DL EH & DL Communication Systems

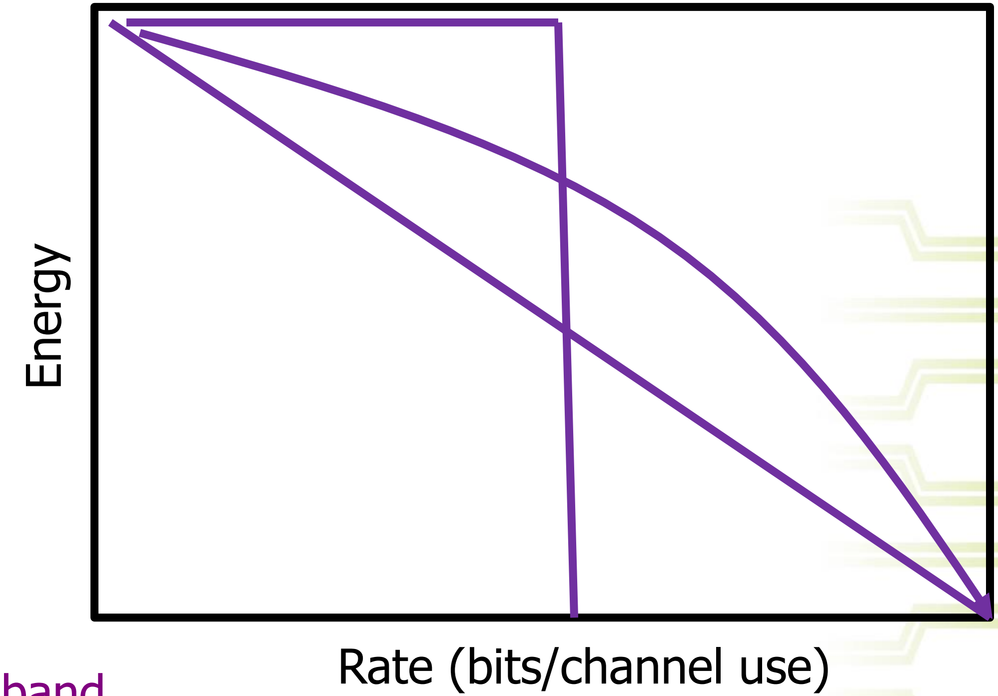
- Rate–Energy Tradeoffs for DL Energy and Communication
- Depends on receiver structure



Time Switched

Power Split

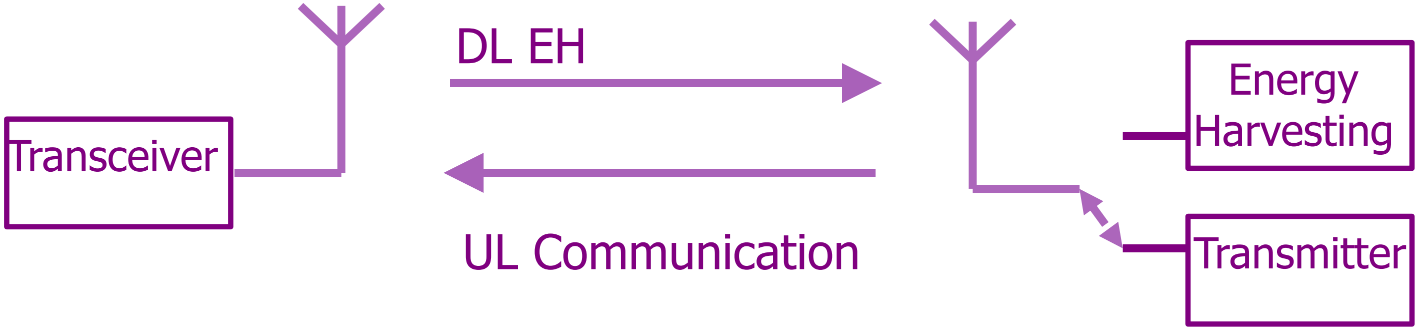
Baseband Energy



- DL only systems may not be the most important for IoT

EH DL Communication UL Results

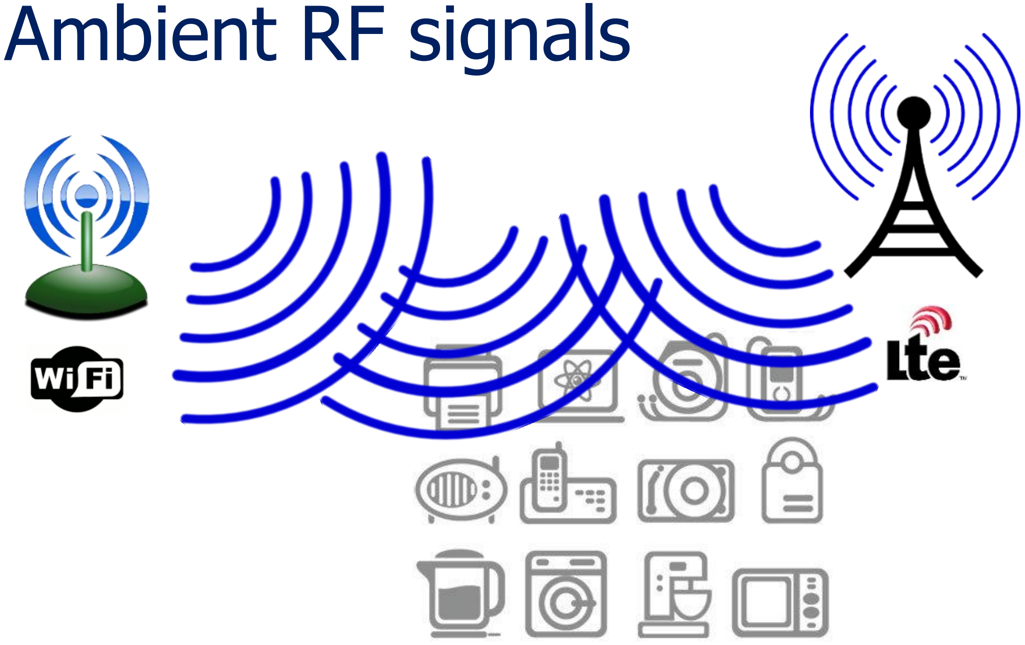
- EH in DL; Communication in UL

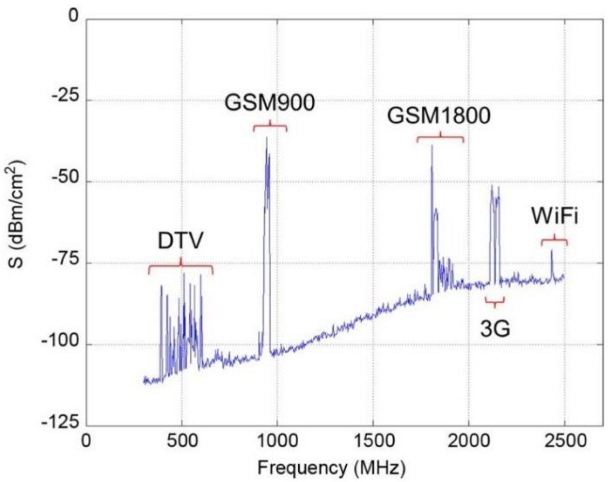


- Essential for IoT
- Two phase harvest then transmit protocol
  - Multicast DL EH
  - Multiple access UL communication
  - Shorter time required for WET when users close
  - Doubly near-far problem for users far away- very low throughputs
  - User cooperation possible but would need DL communication as well

Ambient RF Energy Harvesting

- Ambient RF signals





- Scavenge Ambient RF Energy to power the “Things”
- Harvesting uW is possible
- Pinuela, M.; Mitcheson, P.D.; Lucyszyn, S., "Ambient RF Energy Harvesting in Urban and Semi-Urban Environments," in Microwave Theory and Techniques, IEEE Transactions on , vol.61, no.7, pp.2715-2726, July 2013

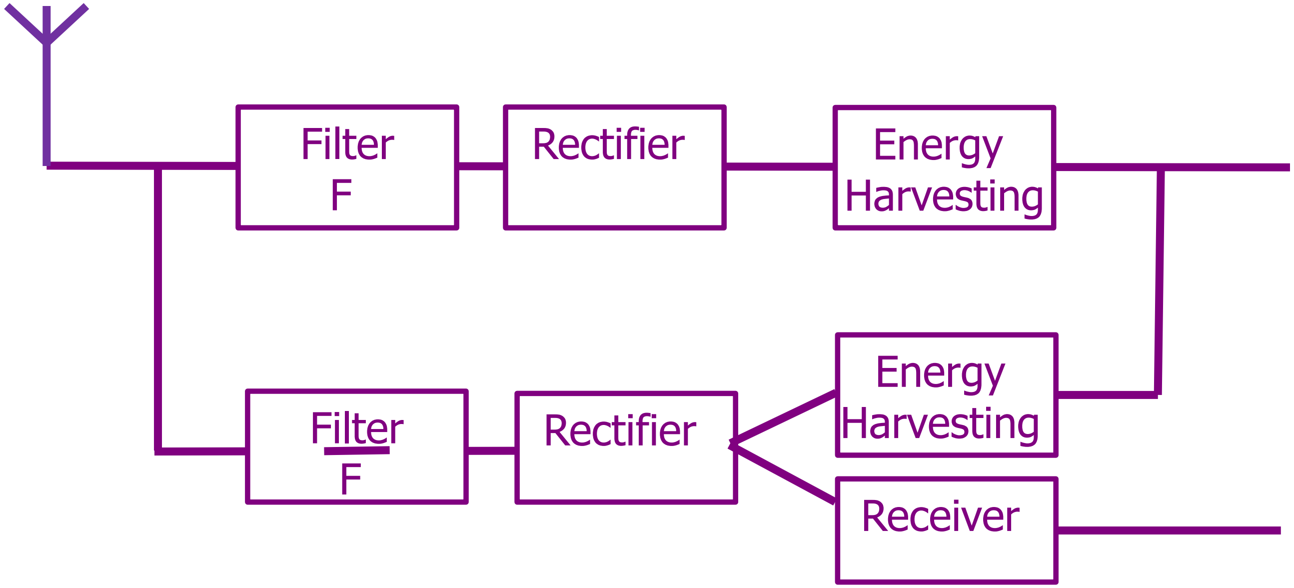
Ambient RF Energy Harvesting

- 270 London underground stations surveyed
- DTV, GSM 900, 1800 and 3G (1900GHz)
- BS more important ambient sources than MS
- Efficiency and impedance varies with EH power
- 50% of stations suitable for ambient EH
- GSM 900 and 1800 most useful
- 40% efficiency at -25dBm
- Competitive compared to thermal and vibration EH in terms of power per volume of hardware

- Pinuela, M.; Mitcheson, P.D.; Lucyszyn, S., "Ambient RF Energy Harvesting in Urban and Semi-Urban Environments," in Microwave Theory and Techniques, IEEE Transactions on , vol.61, no.7, pp.2715-2726, July 2013

Hybrid WET and Ambient RF EH

- WET and Ambient RF EH are independent approaches and can be combined together



- Filters necessary in non-hybrid form too in order to support communication

Hybrid WET and Ambient RF EH

- If no communication in DL then receiver structure can be very straightforward- both WET and ambient RF can be harvested together

- Power splitting or power switching are also possible options if DL communication required

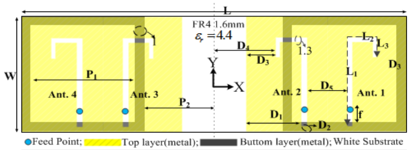
Ways Forward

- More Effective Energy Harvesting
  - Use multiple antennas
  - Baseband energy combining
- Low Power receivers
  - Non-coherent Energy Detectors
  - Baseband energy detection combining

- Soltani, S.; Murch, R.D., "A Compact Planar Printed MIMO Antenna Design," *in Antennas and Propagation, IEEE Transactions on* , vol.63, no.3, pp.1140-1149, March 2015
- S. Shen and R. D. Murch, "Impedance Matching for Compact Multiple Antenna Systems in Random RF Fields," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 2, pp. 820-825, Feb. 2016.
- R. K. Mallik and R. D. Murch, "Noncoherent Reception of Multi-Level ASK in Rayleigh Fading with Receive Diversity," in *IEEE Transactions on Communications*, vol. 62, no. 1, pp. 135-143, January 2014.
- R. Mallik; R. Murch; S. Dash; S. K. Mohammed, "Optimal Multi-Level ASK with Noncoherent Diversity Reception in Uncorrelated Non-Identical and Correlated Rayleigh Fading," in *IEEE Transactions on Communications* , to appear 2016

Compact Multiple Antennas

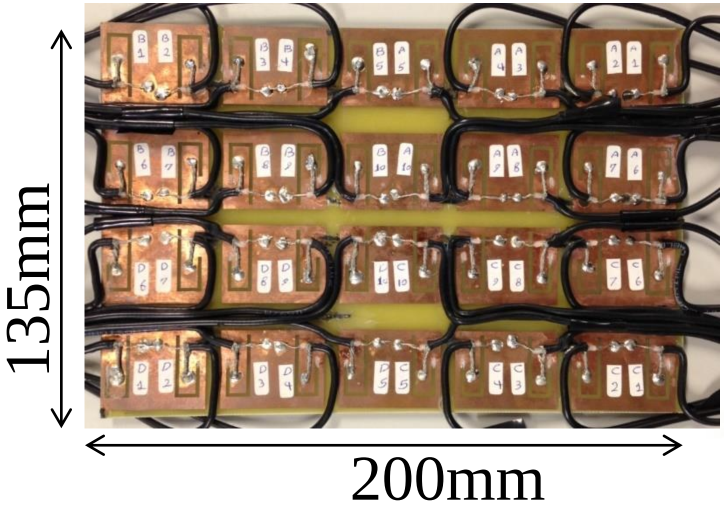
- Canonical 40 port planar design

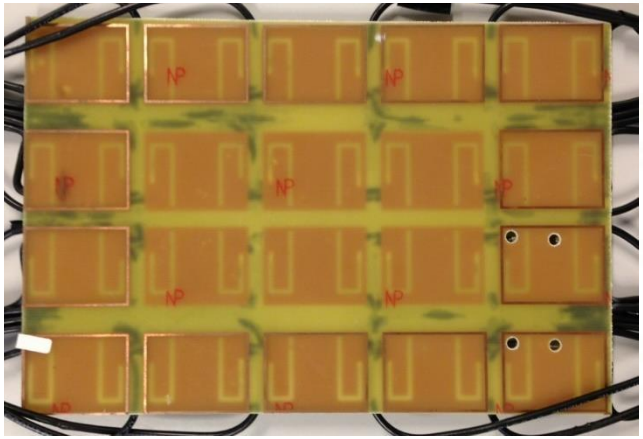


W	27.4	L	80	L_1	21.7	L_2	8.3	L_3	13
D_1	9	D_2	1.6	D_3	2	D_4	6	D_5	8
P_1	30	P_2	8	f	3		Unit(mm)		

- Antenna densities of 22 antennas per square wavelength
- Greater than 10dB isolation between ports

- *Soltani, S.; Murch, R.D., "A Compact Planar Printed MIMO Antenna Design," in Antennas and Propagation, IEEE Transactions on , vol.63, no.3, pp.1140-1149, March 2015*

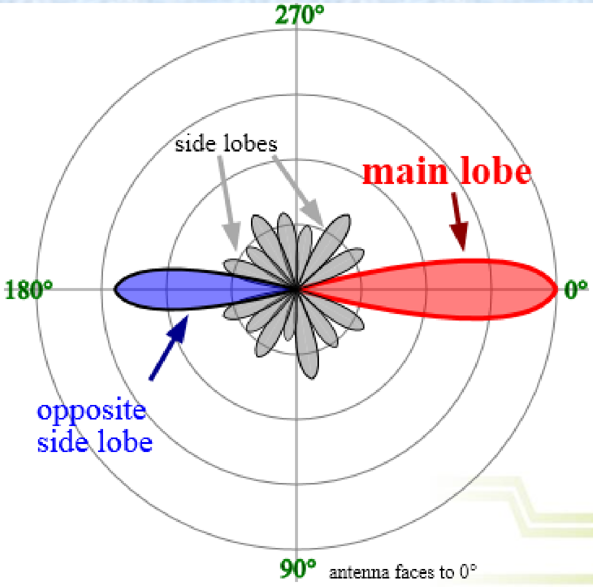




40 antennas at 2.6GHz

Antenna Directivity

- In order to collect all the power beamed to it the antenna must be very directive
- For example an array of antennas
- However this is not true for rectennas
- In an array of rectennas the outputs are all combined at baseband so there is no phasing
- Therefore we can get high gain over a broad angle
- Critical for use in many applications



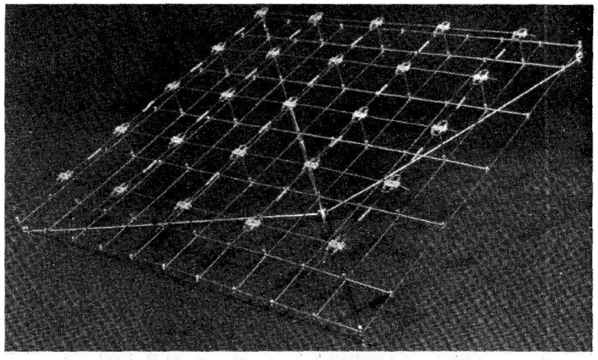
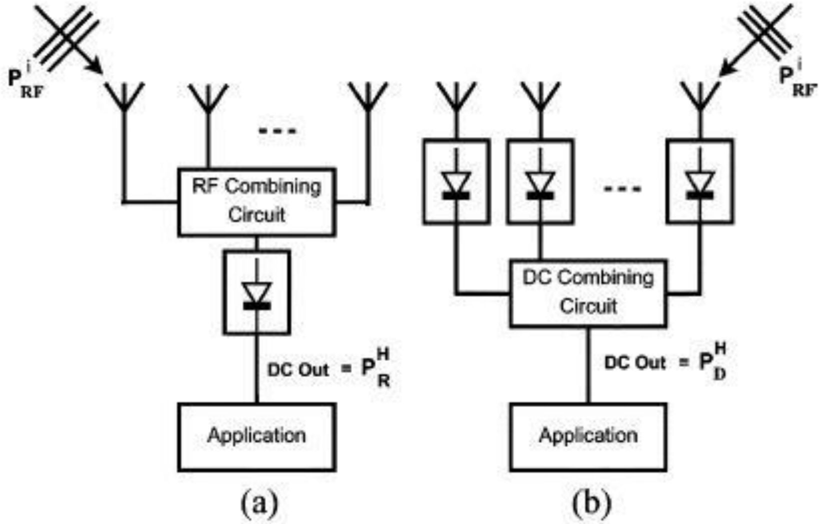


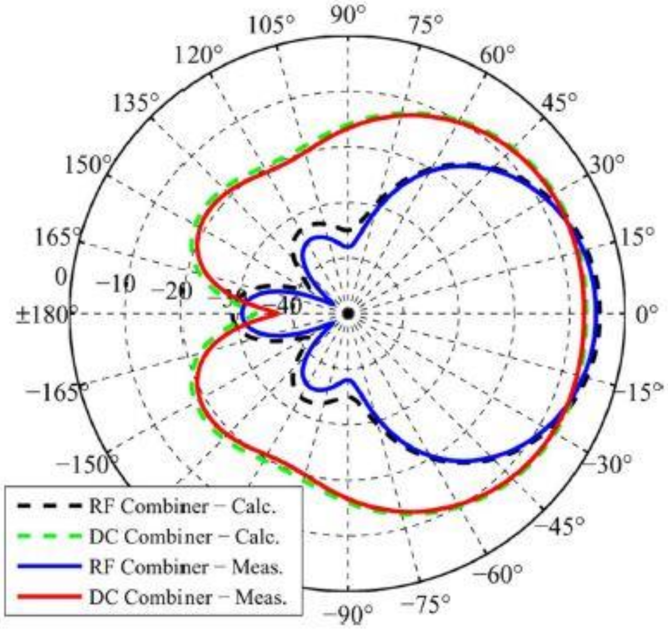
Fig. 6. Greatly improved rectenna made in 1968 from improved diodes (HPA 2900). The 0.3-m^2 structure weighed 20 g and delivered 20 W of dc output for a power to mass ratio improvement of 10 over rectenna shown in Fig. 3.

Multi-antenna Energy Harvesting

- Multi-antenna combining



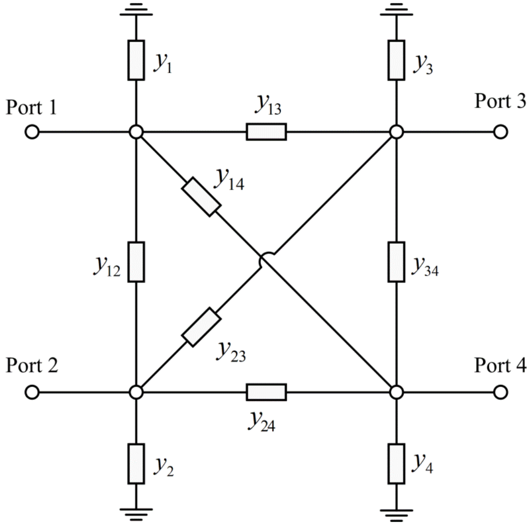
(a) (b)

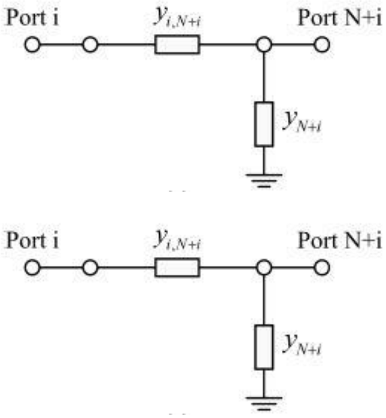


- RF Olgun, U.; Chi-Chih Chen; Volakis, J.L., "Investigation of Rectenna Array Configurations for Enhanced RF Power Harvesting," in Antennas and Wireless Propagation Letters, IEEE , vol.10, no., pp.262-265, 201

Lossless Matching Networks

- Matching needed to achieve maximum power transfer from multiple antennas into the energy harvesting and receiver circuits

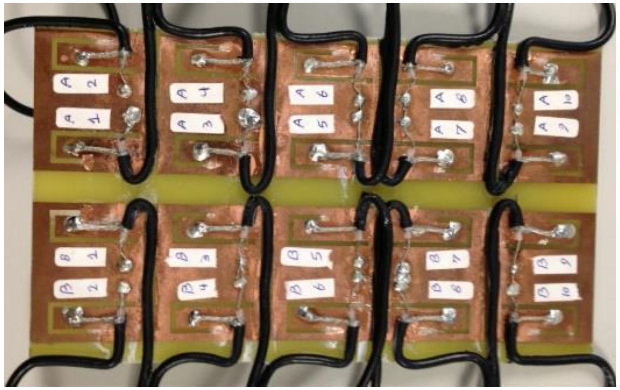


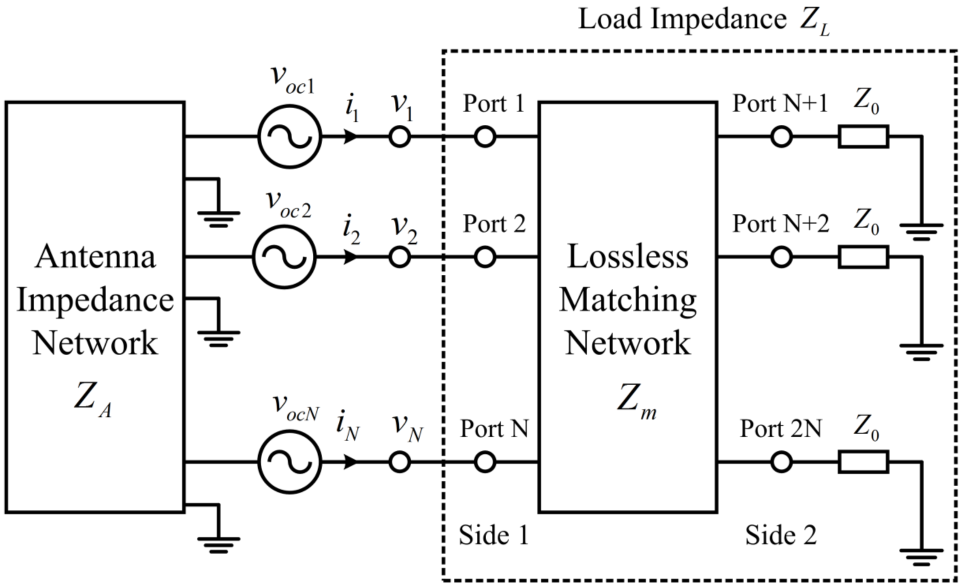


- MCM ($2N^2$ +N)
- Low bandwidth
- High Complexity
- Maximum harvest

- SPM (2N)
- Widely used
- Low complexity
- Good Bandwidth
- Reduced harvest

Equivalent Network of Multi-antenna System in Random RF Field

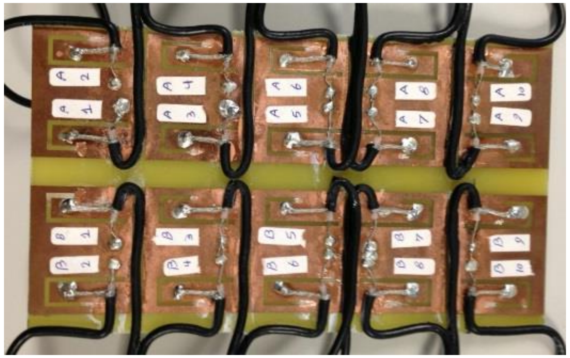




- Z_A: the antenna impedance matrix
- Z_L: the load impedance matrix
- Z_m: the impedance matrix of the lossless matching network
- Z_0: the standard load impedances

Ambient RF- Random RF Field

- N-element antenna in random RF Field $\bar{E}_{inc}(\Omega, f)$



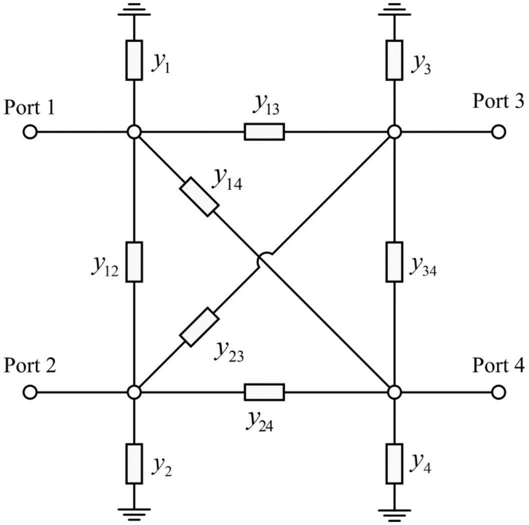
- $\bar{E}_{inc}(\Omega, f)$ is assumed to be a zero-mean complex Gaussian stochastic process with angular correlation given by

$$E[\bar{E}_{inc}(\Omega, f)\bar{E}_{inc}(\Omega', f)^H] = \bar{\bar{S}}(\Omega, f)\delta(\Omega - \Omega')$$

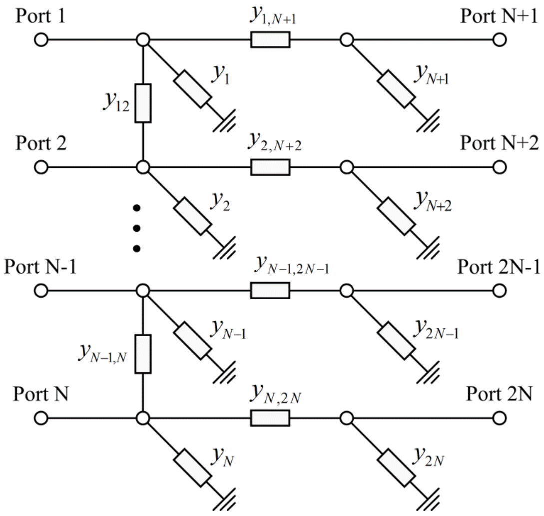
$\bar{\bar{S}}(\Omega, f) = E[\bar{E}_{inc}(\Omega, f)\bar{E}_{inc}(\Omega, f)^H]$ is the power angular spectrum (PAS)

Impedance Matching Contributions

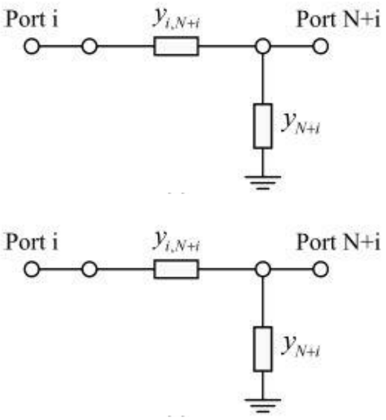
- Illustrative 4-port network examples



- MCM ($2N^2 + N$)
- Simplify to SOM
- SOM ($N^2 + 2N$)



- New technique
- MLM ($3N$)
- Solutions



- SPM ($2N$)
- Improved Solutions

- *Shen and Murch, Impedance Matching for Compact Multiple Antenna Systems in Random RF Fields, IEEE Transactions on Antennas and Propagation, February 2016*

Numerical Results

- To provide a platform for the comparison of multiple antennas and impedance matching, we select the linear N-element antenna array with length L and consider two array configurations.
  1) The first is the uniform linear antenna array with adjacent spacings all equal so that $d_{ij} = L/(N-1)$;
  2) The second is the linear antenna array with geometric ratio spacing so that adjacent antenna spacing satisfy $d_{i,i+1} = q d_{i-1,i}$

- For fixed length L, the larger N may not guarantee increase in total power due to mutual coupling and spatial correlation.

Numerical Experiment Settings

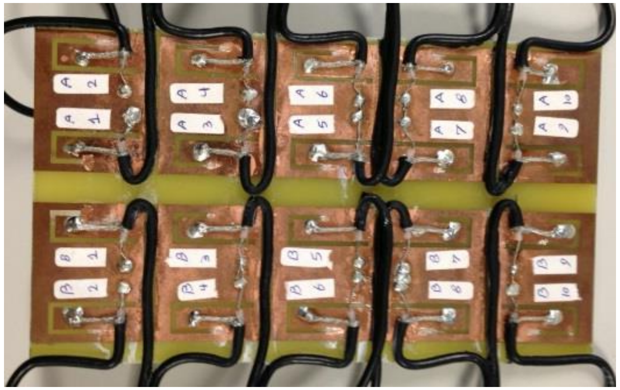
- Total length of linear array: one wavelength λ
- Ideal half-wavelength dipole array: closed form for mutual impedance
- 2D uniform power angular spectrum: the open-circuit voltage correlation can be found by Jakes Model
- Assuming equal expected power:

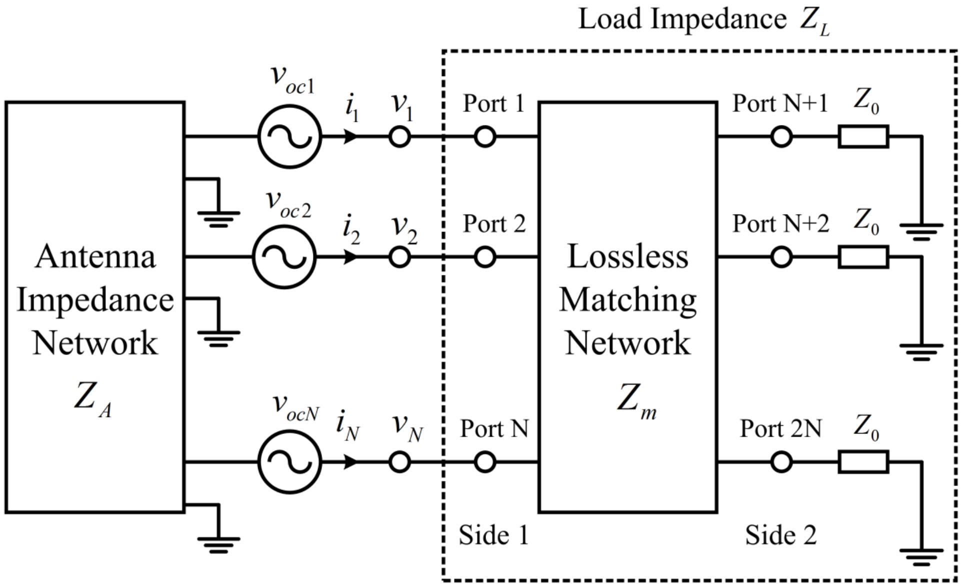
$$E[|v_{\mathrm{oc}1}|^2] = E[|v_{\mathrm{oc}2}|^2] = \cdots = E[|v_{\mathrm{oc}N}|^2]$$

- Power Normalization: normalize the total expected received power by the expected power received by a single antenna in isolation with self-conjugate matched load.

$$\tilde{P} = \frac{4R_1 E[P]}{E[|v_{\mathrm{oc}1}|^2]}$$

Equivalent Network of Multi-antenna System in Random RF Field

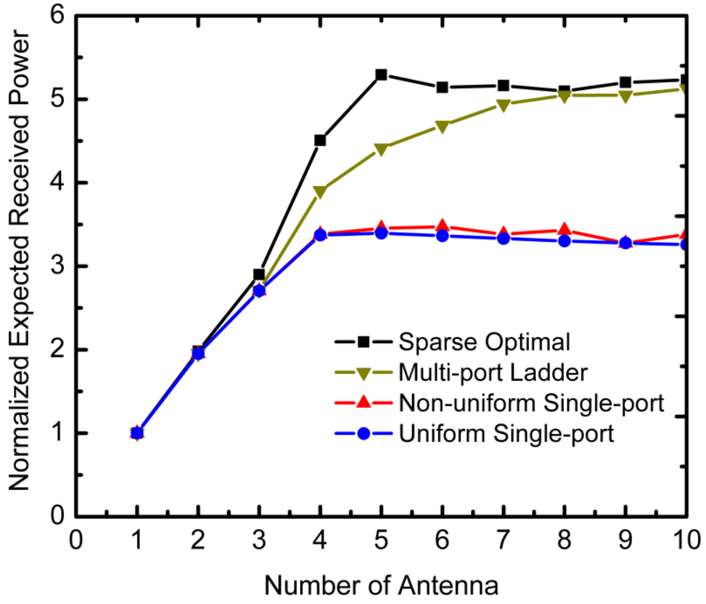




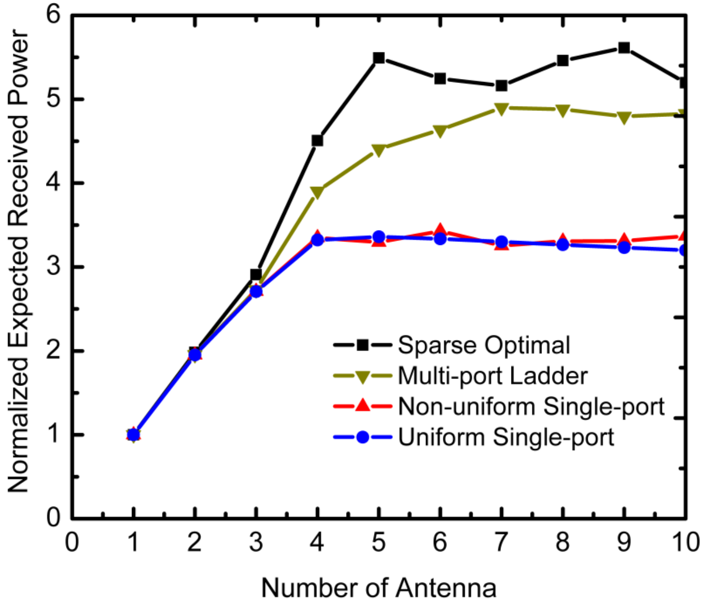
- Z_A: the antenna impedance matrix
- Z_L: the load impedance matrix
- Z_m: the impedance matrix of the lossless matching network
- Z_0: the standard load impedances

Numerical Result

uniform array



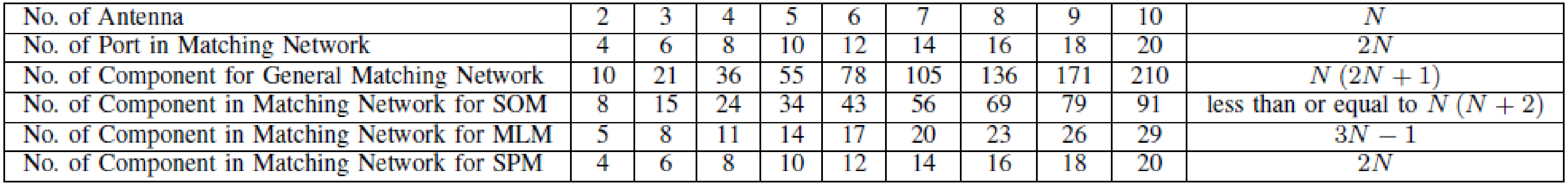
Array with Geometric Ratio Spacing



- SOM has the optimal performance and MLM is next best with sub-optimal performance
- When the number of antennas becomes larger, the performance gap between MLM and SPM becomes larger.
- Non-uniform SPM is slightly better than uniform SPM when the number of antennas is larger.

Numerical Result

- The number of LC components is



No. of Antenna	2	3	4	5	6	7	8	9	10	N
No. of Port in Matching Network	4	6	8	10	12	14	16	18	20	$2N$
No. of Component for General Matching Network	10	21	36	55	78	105	136	171	210	$N(2N+1)$
No. of Component in Matching Network for SOM	8	15	24	34	43	56	69	79	91	less than or equal to $N(N+2)$
No. of Component in Matching Network for MLM	5	8	11	14	17	20	23	26	29	$3N-1$
No. of Component in Matching Network for SPM	4	6	8	10	12	14	16	18	20	$2N$

- Compared to the number of components for general matching, SOM has less than half the components for large N.
- The matching network for MLM has only a few more components than for SPM, but its power performance is better than SPM.

Bandwidth Analysis

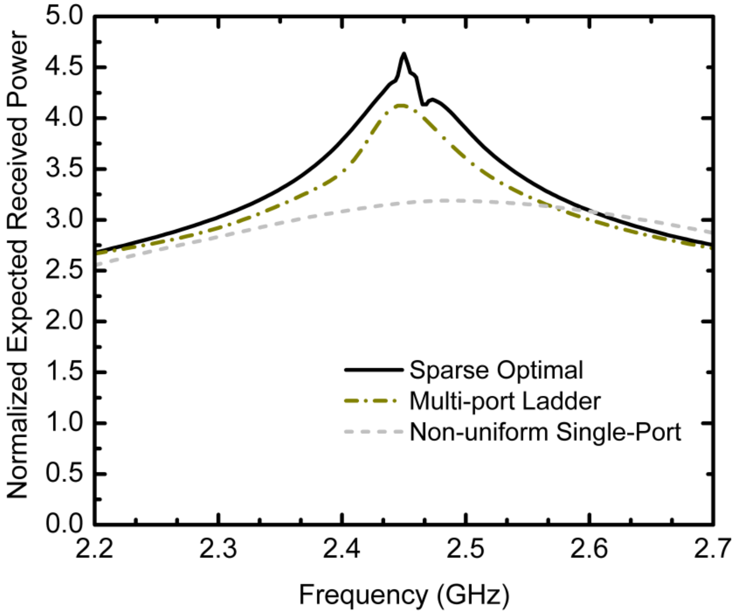
- Previous work suggests the bandwidth performance of MCM is narrow and SPM is large
- We also investigate the bandwidth performance of SOM and MLM to compare with SPM.
- In the formulation of expected received power, there are three frequency-dependent terms: $Z_L(f)$, $Z_A(f)$ and $C(f)$

$$E[P] = Tr(R_L(Z_L + Z_A)^{-1}C(Z_L + Z_A)^{-H})$$

- We use lumped LC element to build the matching network so $Z_L(f)$ can be found and the $Z_A(f)$ can be found by HFSS.

Bandwidth Analysis

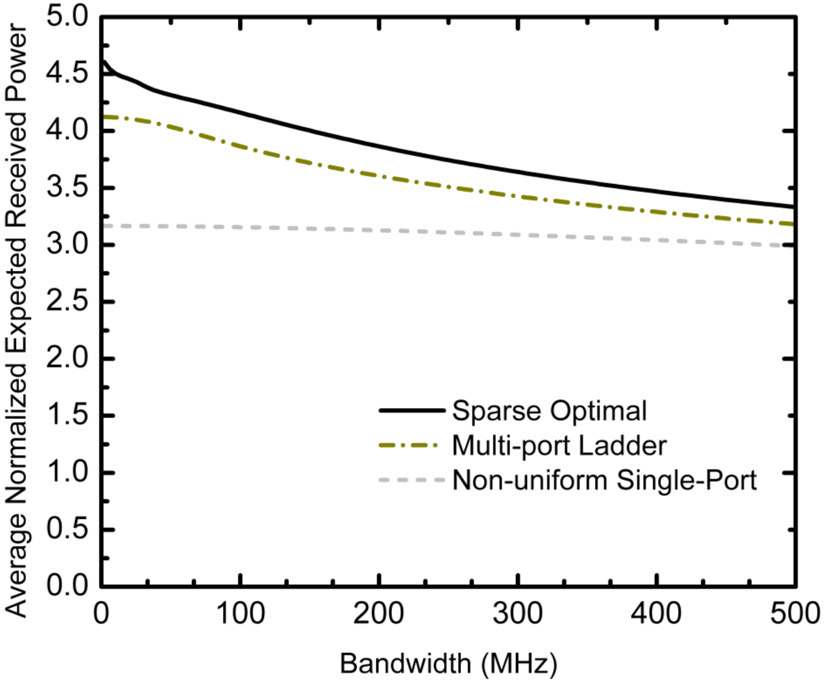
- We simulate the harvesting of energy from a WiFi signal with frequency band from 2.4GHz to 2.5GHz for a 6 element dipole array (antennas uniformly placed in one-wavelength).



- At the central frequency, SOM has the maximum normalized expected power at 4.636 and those of MLM and non-uniform SPM are 4.123 and 3.166 respectively, amounting to 88.9% and 68.3% of that of SOM.

Bandwidth Analysis

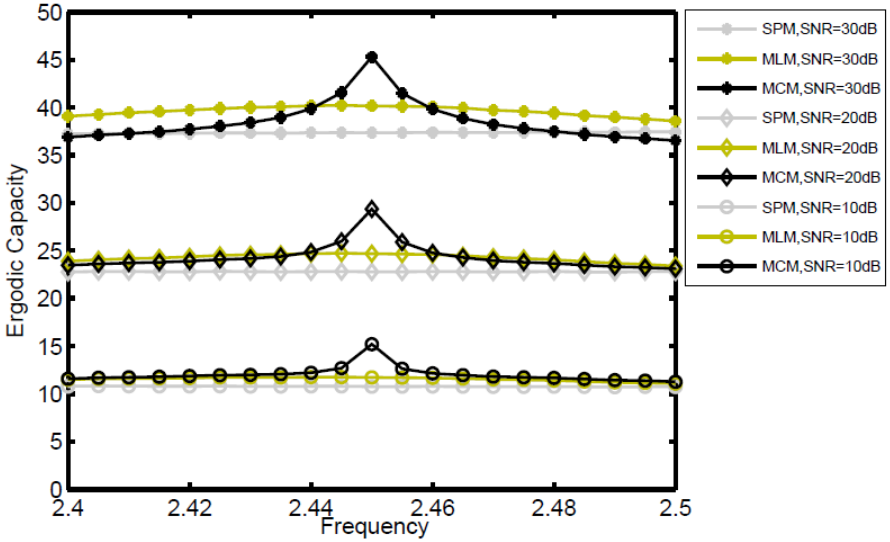
- The average normalized expected power $P_a(\Delta f)$ over the bandwidth Δf.



- For a WiFi frequency band (2.4GHz-2.5GHz), the average power harvested by SOM, MLM and non-uniform SPM is 4.161, 3.866 and 3.156 respectively. This amounts to 92% and 75% for MLM and SPM compared to SOM.
- Build MLM impedance for WET but it will perform as good as SPM at all f

Wireless Communications

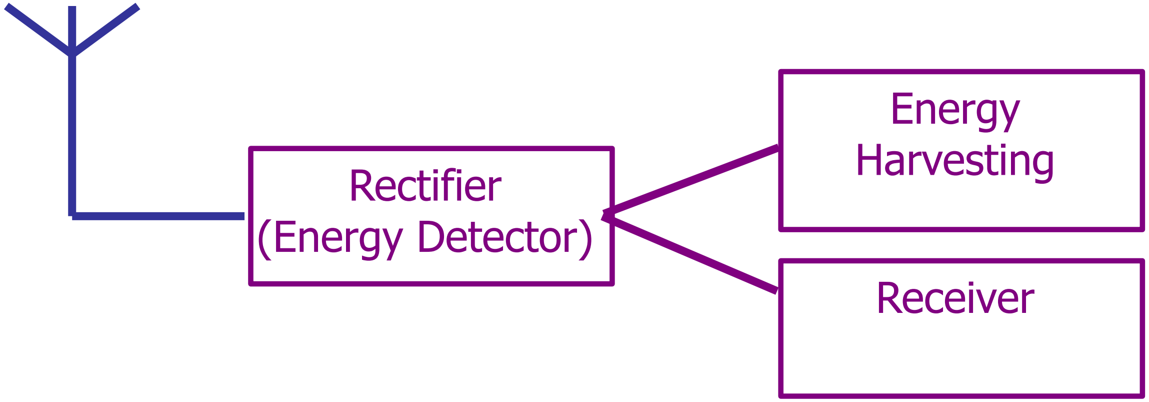
- MLM can increase the Ergodic capacity by around 8% compared to SPM over the whole band for different SNR.



- MCM is optimal around 2.45GHz but when the frequency deviates from 2.45GHz MLM can increase the ergodic capacity by up to 5.3% compared with MCM.
- In conclusion, MLM is better than SPM for both narrow and broad bands and better than MCM for broad bands.

Low Power Receiver

- Non-Coherent Energy Detector Receiver
  - Simplified synchronization
  - Simple front end
  - Good rate-energy tradeoff
  - Can use previous ladder matching network
  - High gain broad-beam



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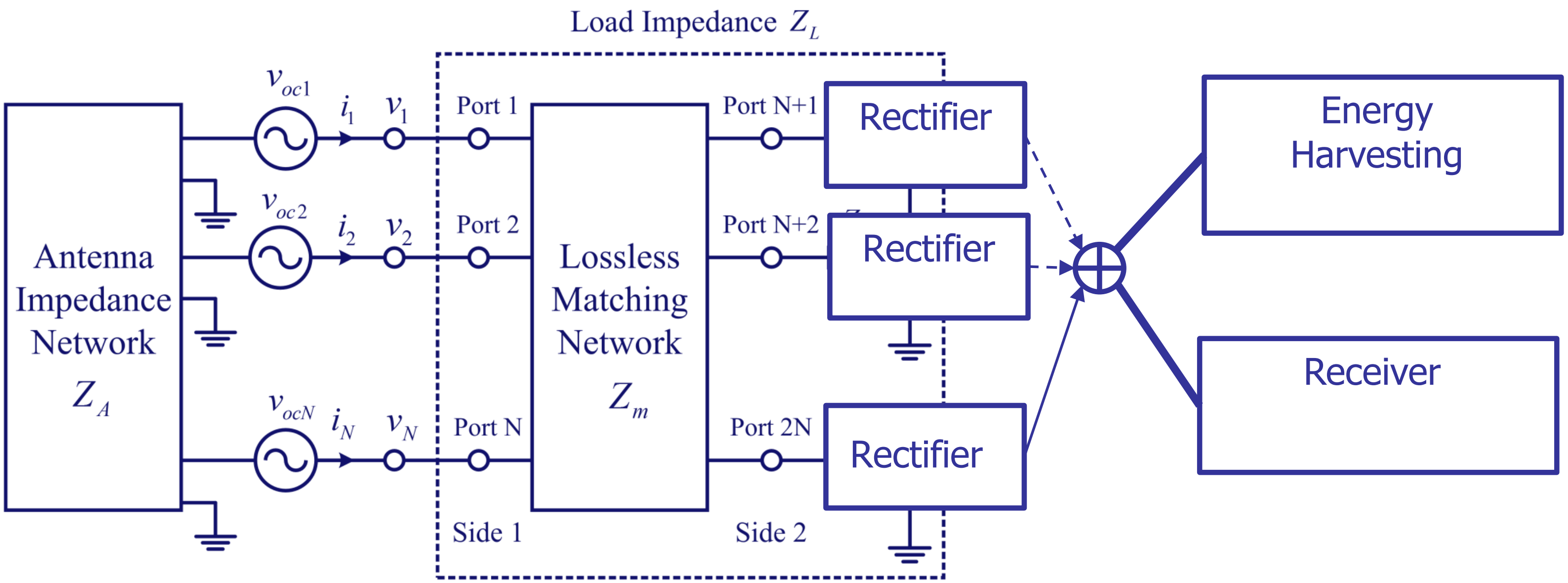
Overall Receiver Structure



- The received energy of each branch is summed to form $\mathbf{r}^H\mathbf{r}$

Problem Statement

- Given the receiver structure is fixed what can we optimize?
- We can optimize the transmit power levels to minimize BER?
- Since we do not know the channel at the receiver side (non-coherent) the optimum ASK signal levels are no longer uniformly distributed for Rayleigh Fading channels
- Turns out they are optimum if distributed in geometric progression with common ratio

System Model

- Assuming N receive branches the received signal can be written as

$$\mathbf{r} = \mathbf{h}s + \mathbf{n}$$

- where h is N x 1 random complex fading gain and n the AWGN vector
- Assume *s* is from the constellation

$$\mathcal{S} = \left\{\sqrt{E_{s_1}}, \ldots, \sqrt{E_{s_L}}\right\}$$

- Average energy is

$$E_{s,av} = \frac{1}{L}\sum_{i=1}^{L} E_{s_i}$$

System Model

- The channel is Rayleigh fading so **h** is complex Gaussian independent of the AWGN noise
- Average SNR per branch of the ith signal is therefore

$$\Gamma_i = \frac{E_{s_i}\sigma_h^2}{\sigma_n^2}, \quad i = 1, \ldots, L,$$

$$\Gamma_{av} = \frac{E_{s,av}\sigma_h^2}{\sigma_n^2} = \frac{1}{L}\sum_{i=1}^{L}\Gamma_i$$

System Model

- Overall decision statistic is also zero-mean Gaussian

$$\mathbf{r}|_s \sim \mathcal{CN}\left(\mathbf{0}_N\,,\ \left(|s|^2\sigma_h^2 + \sigma_n^2\right)\mathbf{I}_N\right)$$

- Because we have no channel information the phase of the signal is completely lost in the transmission process
- The magnitude of the received signal is also scaled randomly by a Rayleigh distribution

System Model

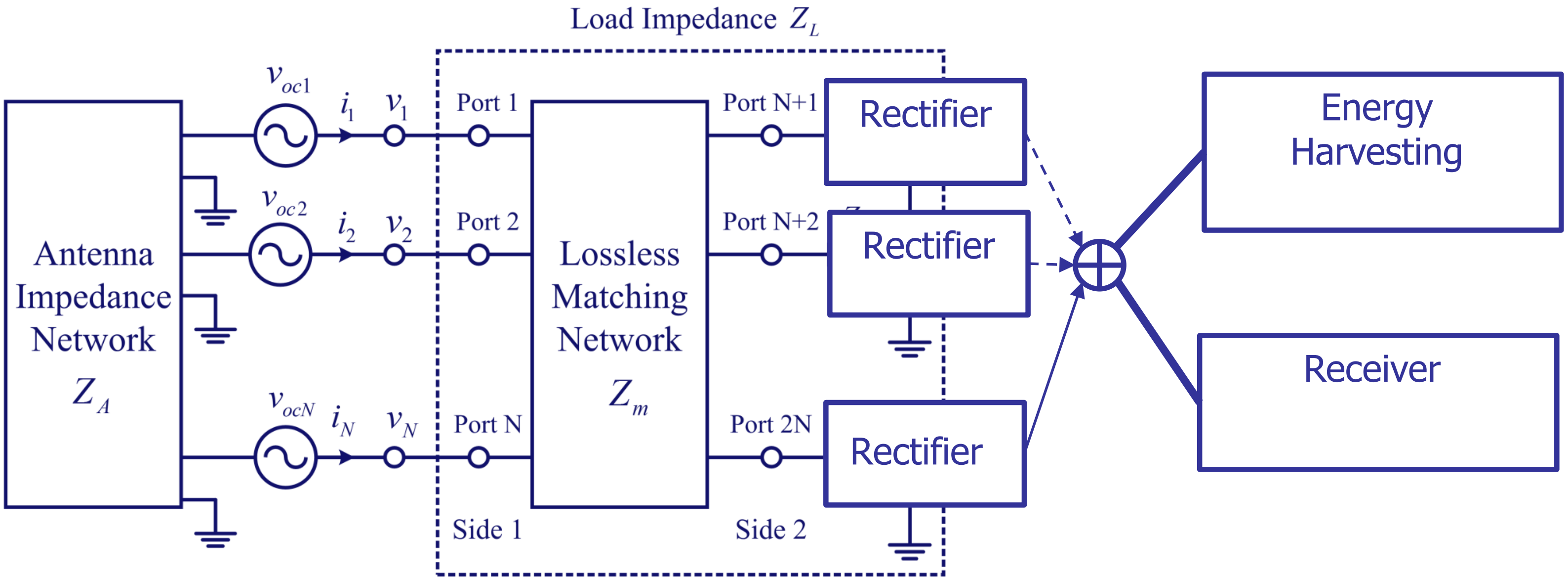
- The decision rule is

$$\hat{s} = \arg\max_{s \in \mathcal{S}} \ \ln\left\{ f(\mathbf{r} | \, s) \right\}$$

$$\hat{s} = \arg\min_{s \in \mathcal{S}} \ \frac{1}{\left(|s|^2\sigma_h^2 + \sigma_n^2\right)} \mathbf{r}^H \mathbf{r} + N \ln\left(|s|^2\sigma_h^2 + \sigma_n^2\right)$$

- The $\mathbf{r}^H\mathbf{r}$ is the key term and in essence represents the energy of the received signal

Overall Receiver Structure

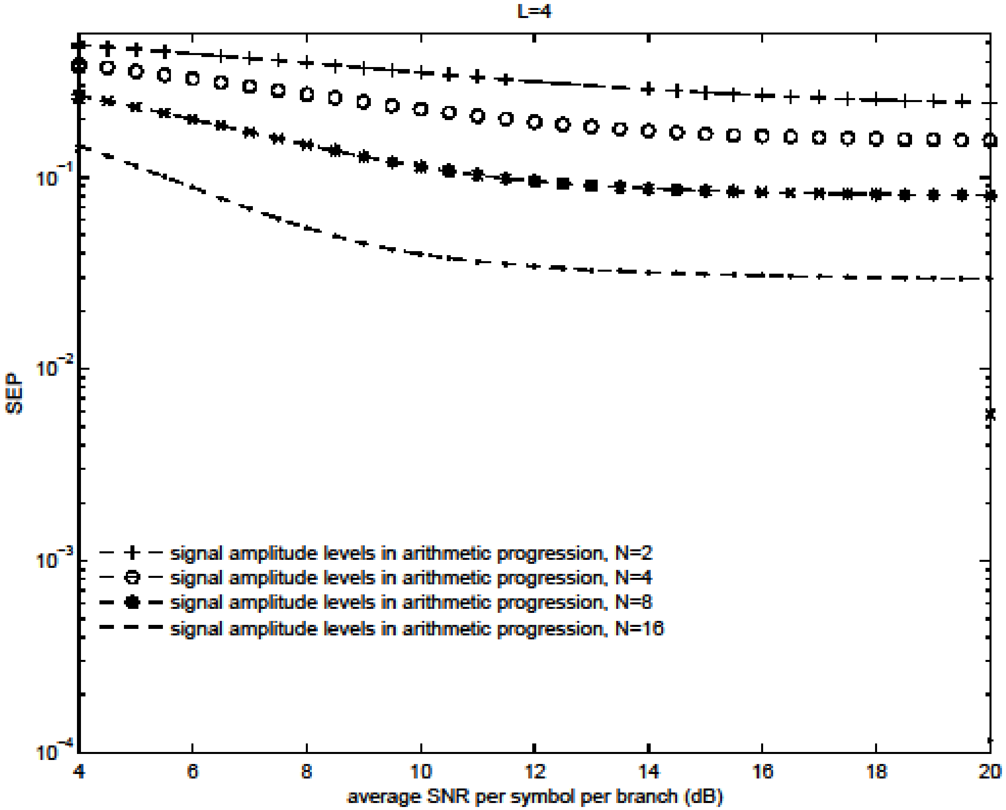


- The received energy of each branch is summed to form $\mathbf{r}^H\mathbf{r}$

Numerical Results

- We can find an analytical expression for Pe
- L=4 and varying numbers of branches N

- Uniformly spaced symbols
- Saturation at high SNR caused by random magnitude scaling of channel



Optimization of Symbol Levels

- Can we overcome the saturation effect by using transmit symbol levels different from uniform?
- Formulate as an optimization problem with constraints on total average power as follows:

$$\min_{\substack{E_{s_1},\ldots,E_{s_L}\\ \sum_{i=1}^{L} E_{s_i}=E_{s,\,tot}\\ 0\leq E_{s_1}<\cdots<E_{s_L}}} \qquad P_e$$

Optimization of Symbol Levels

- Can solve approximately for high average SNR per branch

$$\begin{aligned}
\sqrt{E_{s_1,\,asymp}} &= 0\,, \\
\sqrt{E_{s_i,\,asymp}} &= \frac{\sigma_n}{\sigma_h}\sqrt{L^{(i-1)/(L-1)}\Gamma_{av}^{(i-1)/(L-1)}} \\
& \quad i = 2, \ldots, L,
\end{aligned}$$

- Implies signal levels follow geometric progression with a common ratio of

$$(\sigma_n/\sigma_h)\sqrt{L^{1/(L-1)}\Gamma_{av}^{1/(L-1)}}$$

Probability of Error and Diversity

- Pe

$$P_e \approx \frac{(L-1)\left(\frac{N}{(L-1)}\left(\ln\Gamma_{av} + \ln L\right)\right)^{N-1}}{(N-1)!\, L^{1+N/(L-1)}\, \Gamma_{av}^{N/(L-1)}}$$

- We can also determine the diversity easily

$$\begin{aligned} -\left.\frac{\ln P_e}{\ln\Gamma_{av}}\right|_{\Gamma_{av}\gg 1} &\approx \frac{N}{(L-1)} - (N-1)\frac{\ln\left(\ln\Gamma_{av}\right)}{\ln\Gamma_{av}} \\ &\approx \frac{N}{(L-1)}, \end{aligned}$$

Numerical Results

- Baseline comparison is to uniformly spaced ASK

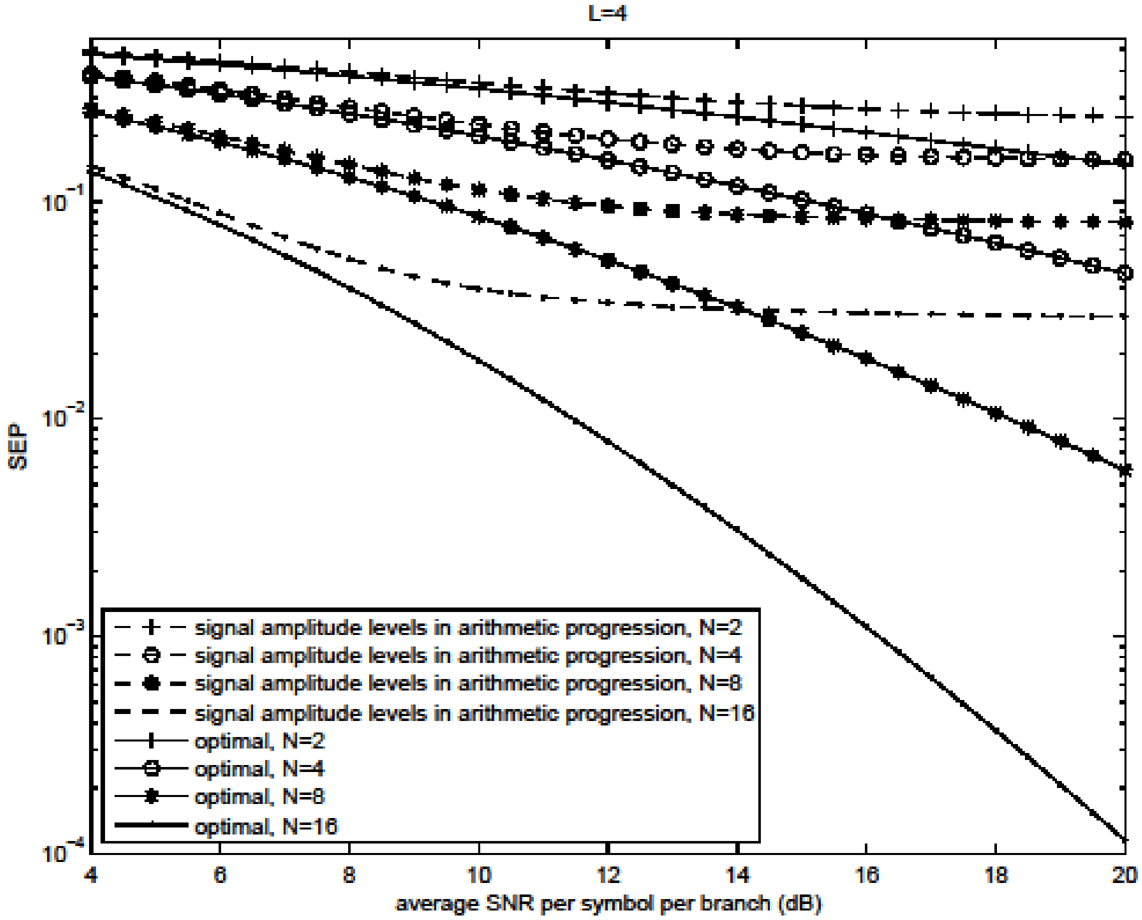
$$\Gamma_i = \frac{(i-1)^2\delta^2\sigma_h^2}{\sigma_n^2}, \quad i = 1, \ldots, L,$$

- Relating to average SNR we can find the spacing as

$$\delta = \frac{\sigma_n}{\sigma_h}\sqrt{\frac{6\Gamma_{av}}{(L-1)(2L-1)}}\,.$$

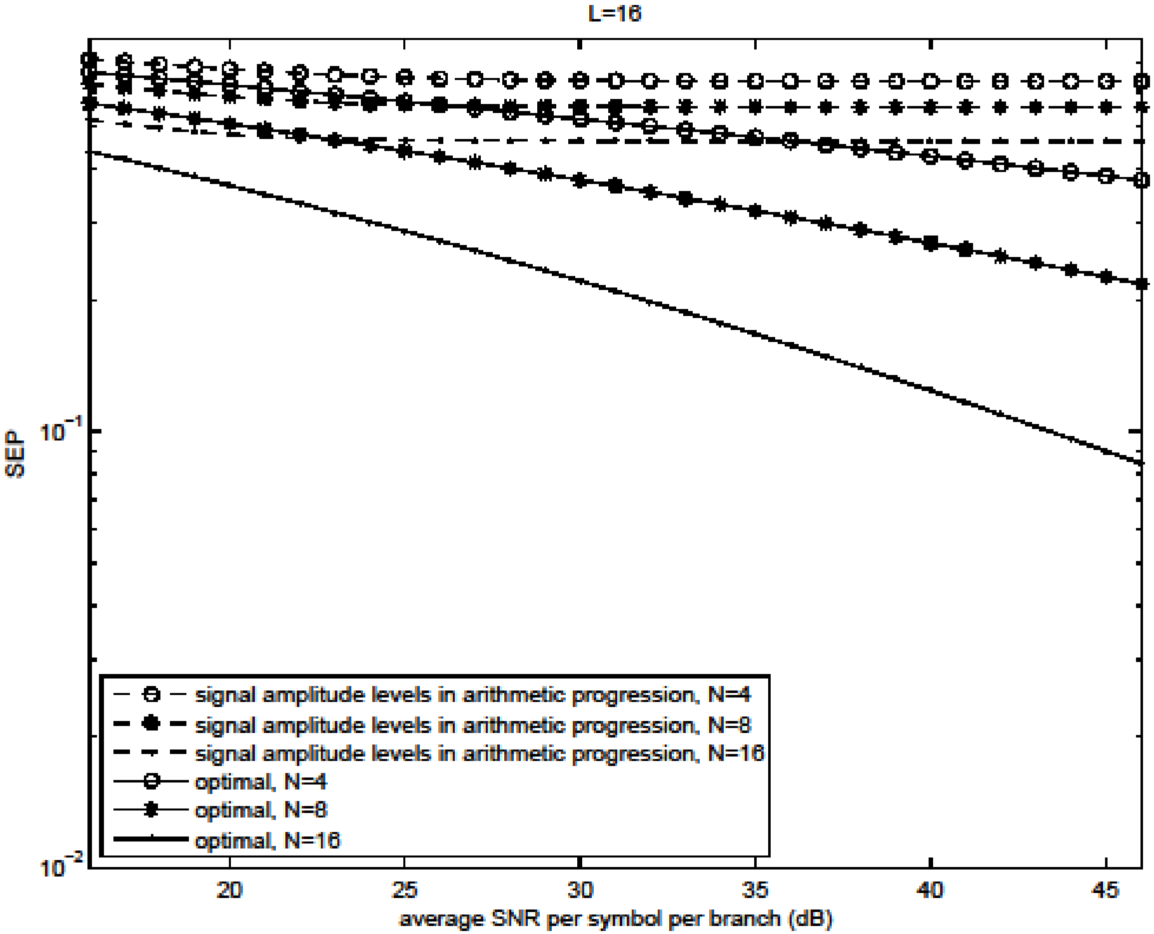
Numerical Results

- L=4 and varying numbers of branches N



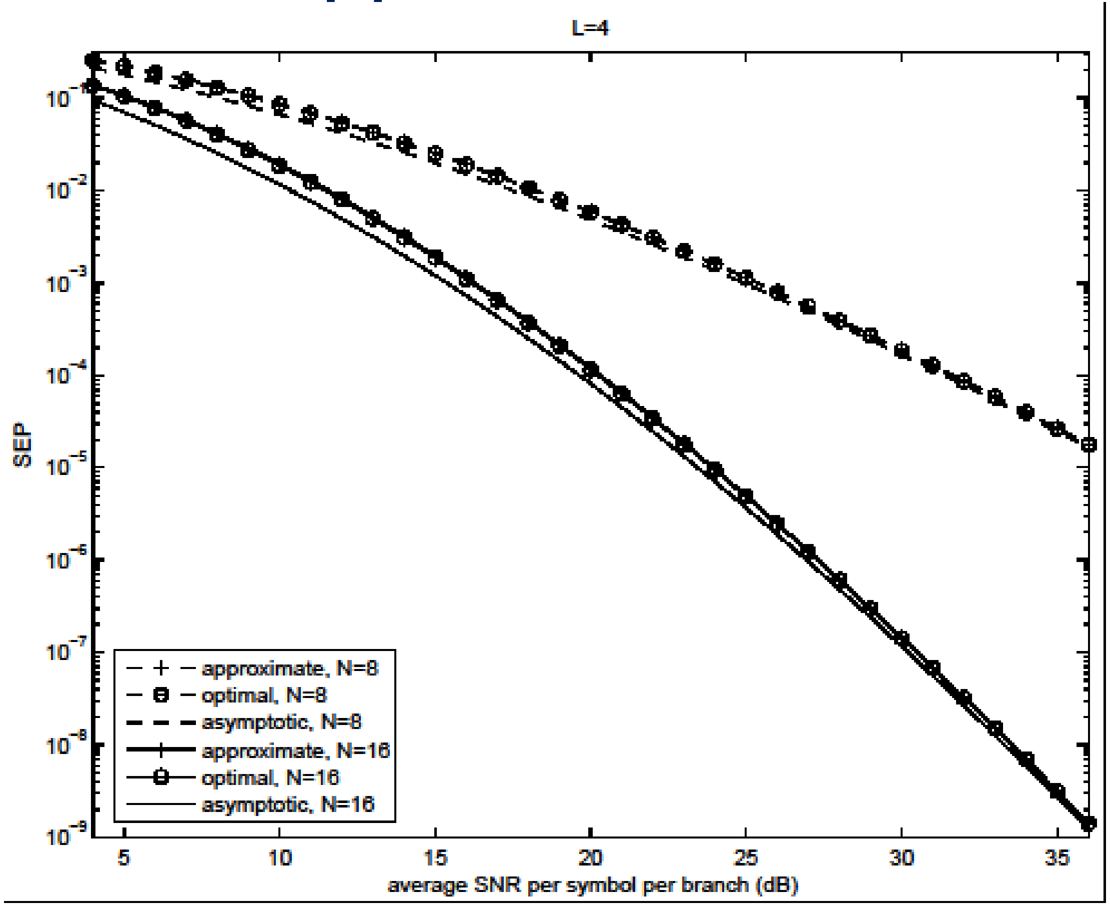
Numerical Results

- L=8 and varying numbers of branches N



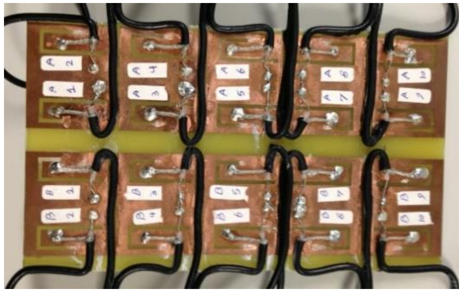
Numerical Results

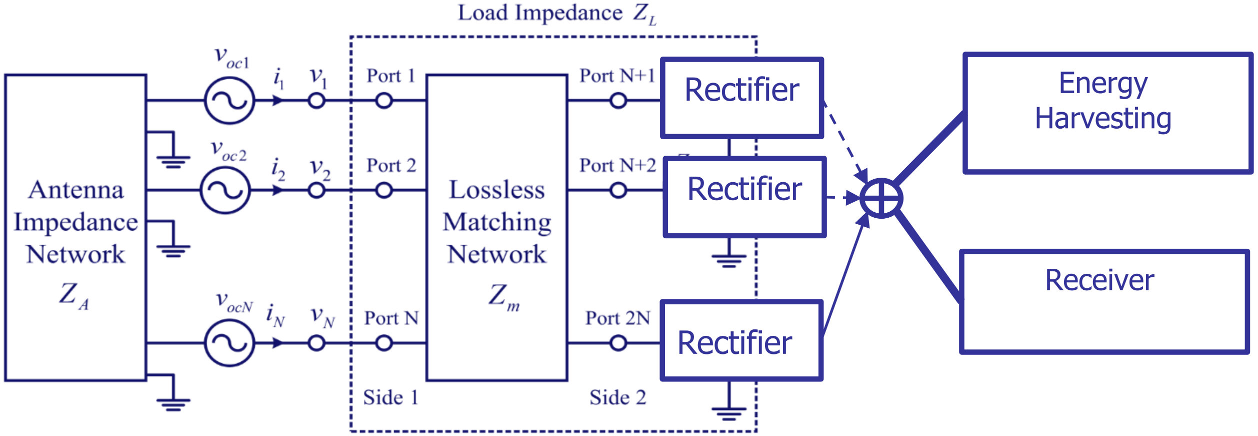
- L=4 and comparisons with geometric progression approximation



What’s next: Implementation?

- Many results but not many implementations





Summary

- Energy Harvesting is very important in IoT devices
- Provides devices with long life
- Ambient RF EH competitive with other scavenging techniques in terms of power and volume
- WET could be used together with ambient RF EH
- Multiple antennas give useful energy gains
- Noncoherent receivers can be low power and useful
- Need further developments
  - Results required for hybrid systems
  - Exploit multiple antennas at AP
  - UL communication critical for IoT
  - Low power transmitters and receivers
  - Hardware implementations