Energy Efficient Routing with Directional Antennas in Sensor Networks

Kemal Kılıç

Supervisor: Assoc. Prof. Dr. Tayfun Nesimoğlu
Co-Supervisor: Prof. Dr. Fadi Al-Turjman

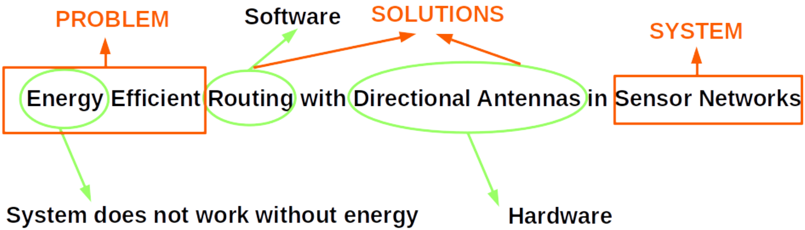
METU - NCC, SEES Program

kemal.kilic@metu.edu.tr

October 16, 2018

Outline

Overview of the Thesis



Premise 1: Sustainable Development needs statistical data analysis.

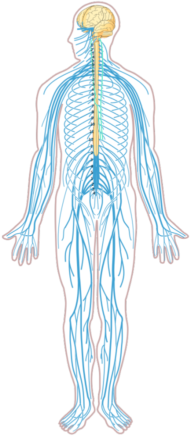
Premise 2: The more the data, the better the analysis and the forecasting.

Premise 3: Sensor Networks are the future for more and accurate data.

Premise 4: Maintenance of Sensor Networks should not be costly.

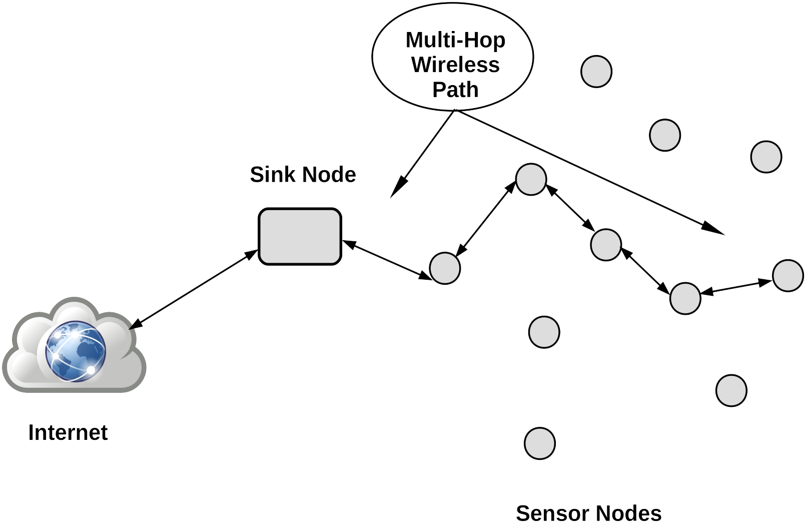
Goal: Making data collection energy efficient by SW and HW solutions.

Analogy: Efficient nervous system vs efficient WSN

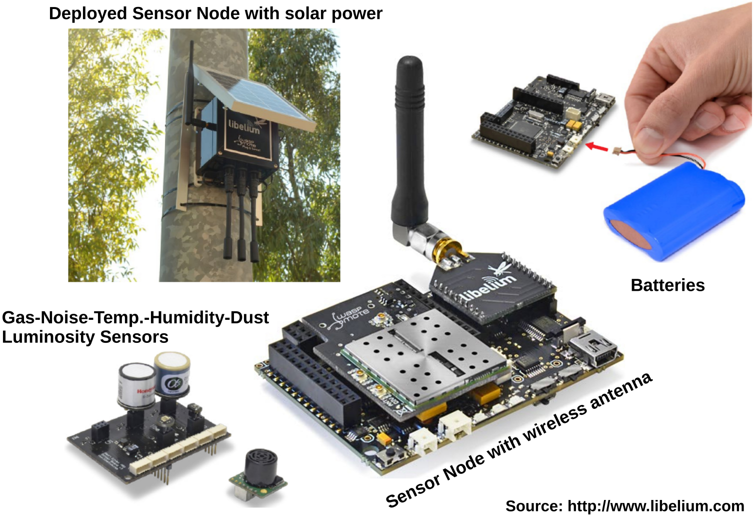


Left: https://upload.wikimedia.org/wikipedia/commons/thumb/5/5a/Nervous_system_diagram_unlabeled.svg/466px-Nervous_system_diagram_unlabeled.svg.png
Right: http://locationlessliving.com/wp-content/uploads/2017/03/5912303770_a60cd8ab88_z.jpg

Today: Typical Wireless Sensor Network - WSN

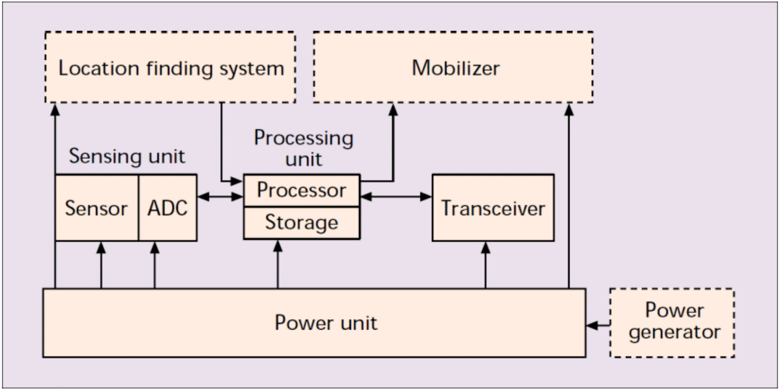


Today: Typical Wireless Sensor Node (“Mote”)



Source: http://www.libelium.com

Today: Components of a Sensor Node[1]



[1] Akyildiz, I. F. et al., "A survey on sensor networks", in IEEE Communications Magazine, vol. 40, no. 8, pp. 102-114, 2002.

Today: Applications

- **Environmental:** Flood Detection, Forest Fire Detection, Air Pollution Monitoring
- **Household:** Water/Energy Metering/Monitoring, Remote Control, Security
- **Health:** Patient Monitoring
- **Industrial:** Monitoring Hazardous Gases, Quality Control
- **Agriculture-Farming:** Green House Control, Animal Tracking

The passion is to create the **"Nervous system of the Earth"!**

Applications cover 3 pillars of the Sustainability:

Economic, social, and environmental

Benefits?

- **Measurements** from sensors can provide **vital statistics** for **Sustainable Development**.
- Referring to the **"management of environmental control systems in large office buildings"**:

"*First-order estimations indicate that such technology could **reduce source energy consumption by two-quadrillion BTUs** (British Thermal Units) in the US alone. This translates to **$55 billion per year, and 35 million metric tons of reduced carbon emissions.***"[2]

[2]Rabaey, J. M. et al., "PicoRadio supports ad hoc ultra-low power wireless networking", in Computer, vol. 33, no. 7, pp. 42-48, 2000.

Near Future: IoT forecasts[3]

- **The current count (2016):**
  - **Gartner: 6.4 billion** (without smartphones, tablets, and computers),
  - **International Data Corporation: 9 billion** (which also excludes those devices),
  - **IHS Markit: 17.6 billion** (with all such devices included).
- **The Future (forecasts/speculations/expectations 2016):**
  - **Ericsson: 28 billion** by 2021
  - **IHS Markit: 30.7 billion** by 2020
  - **Gartner: 20.8 billion** by 2020 (excluding smartphones, tablets, and computers)
  - **IDC: 28.1 billion** (again, not counting those devices)

[3] http://spectrum.ieee.org/tech-talk/telecom/internet/popular-internet-of-things-forecast-of-50-billion-devices-by-2020-is-outdated

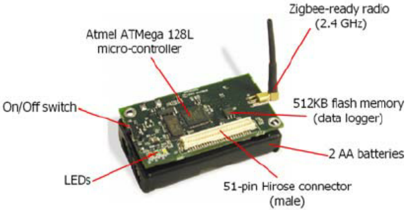
Ultimate Future: Numbers from Network addressing

- IPv4 32-bit, we "had" $2^{32} = 4.3 \times 10^9$ about 4 Billion "Things"
- IPv6 128-bit, we can have about $2^{128} = 3.4 \times 10^{38}$ "Things"
- MAC 48-bit, we can have about $2^{48} = 2.8 \times 10^{14}$ "Things"

Motivation - Energy Issues

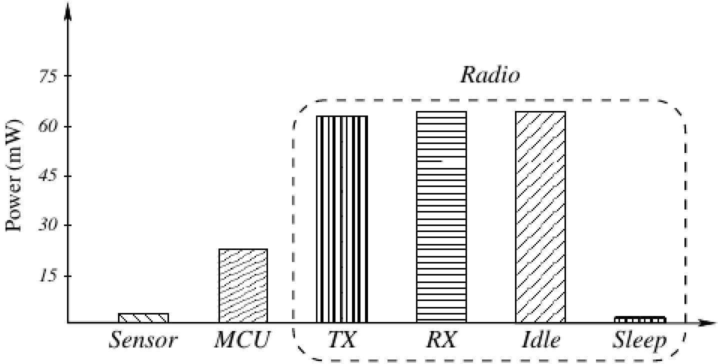
- Sensors are **small** and mostly **batteries** are used.
- Battery = limited energy! Short life!
- Harvesting and wireless charging still "under construction"!
- Energy optimization is necessary! "Keep your sensors alive!"
- **Most energy goes to communication**, not to computation!
- So **energy efficient communication** is crucial!
- Energy-aware SW and Energy-efficient HW.

MicaZ sensor node[4]



[4] **Left:** http://www.diid.unipa.it/networks/wsn/pics/people/big/spk11.jpg
Right: https://www.researchgate.net/profile/Philip_Blythe/publication/228467614/figure/fig1/AS:301982913974274@1449009745525/Figure-1-MPR2400-MICAz-mote.png

Power Consumption: Graphical



A breakdown of the power consumption of a MicaZ sensor node[5]

[5] Akyildiz, I. F. and Vuran, M. C., "Wireless Sensor Networks", John Wiley & Sons, p. 44, 2010.

Power Consumption: Numerical

"*For the Sensoria sensors and Berkeley motes, the ratio of* ***energy consumption for communication and computation is in the range of 1000–10000.***"[6]

[6] Zhao, F. et al., "Collaborative signal and information processing: an information-directed approach", in Proceedings of the IEEE, vol. 91, no. 8, pp. 1199-1209, 2003.

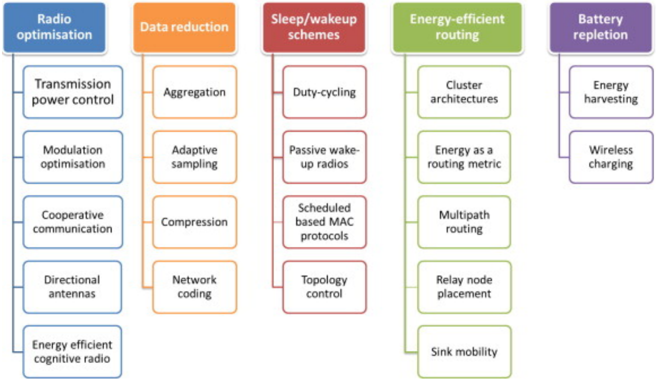
How to optimize Energy consumption in WSN?

- **Caveat 1:** Energy optimization is **"an umbrella term"**!
  - Optimize energy for the **node**
  - Optimize energy for the **overall network**
- **Caveat 2:** Energy optimization and QoS may conflict!
- Basically two solutions: **Software and Hardware optimizations**

We focused on **energy-aware routing** and **energy-efficient antenna**

Especially routing in WNSNs and cheap, high gain patch antenna array

Classification of the optimizations



Classification of energy-efficient mechanisms for WSN[7]

[7] Rault, T., Bouabdallah, A. and Challal, Y., "Energy efficiency in wireless sensor networks: A top-down survey", Computer Networks, vol. 67, no. 4, pp. 104-122, 2014.

Stature of Routing in WNSNs

- **Energy is more critical in WNSNs**
- **WNSNs communication is in THz band**
- **There is no standard routing algorithm for WNSNs yet**
- **WSN methods can not be applied directly to WNSNs**

Nano world is different!

Related Work in Nano Routing

Paper	Contribution Summary
zhou2012	PHY layer and pair-to-pair routing. Not very energy efficient.
yu2015	Channel-aware routing protocol. 1D topology. Energy not considered.
liaskos2015	Minimize hop count. 2D Grid topology. Energy considered. “Anchor” nodes.
liaskos2016	Peer-to-peer routing. 2D Grid topology. Node classification based on past statistics.
tairin2017	Hierarchical AODV. Energy considered.
afsana2018	Channel aware energy conserving protocol. Hybrid clustering of the nanonodes and centralized scheduling.
abuali2018	Offers benchmarking framework for WNSN routing protocols.
lagoon	Minimize hop count. Topology independent. Energy aware protocol.

Proposed Routing Algorithm: LaGOON

- **Goal:** Simple but Energy-aware routing method
- **Idea:** Remembering the "Last GOOd Neighbor" for each packet reception
- Simulations with ns3[8]+ NanoSim[9]package (modified)
- **Routing with omnidirectional antenna**
  - Utilized health-monitoring example of the Nano-Sim, where in-trabody WNSN was considered
  - LaGOON vs Flooding and P2P Random
  - Metric: "CHARGED", "DROP", "FORWARD", "SEND" event counts
- **Routing with directional antenna proposed**

[8] Discrete event-based network simulator: https://www.nsnam.org/

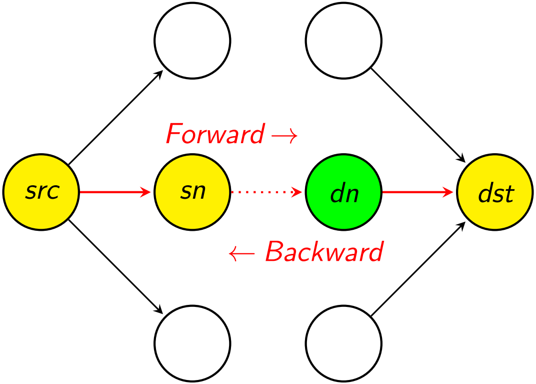
[9] https://telematics.poliba.it/index.php?option=com_content&view=article&id=30&Itemid=204&lang=en

Simulation Parameters

Total 720 Simulations

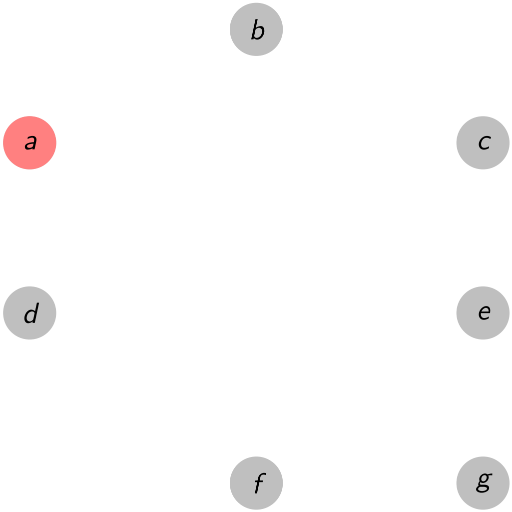
Parameter	Value
Simulation time	7 secs (15 Sims per method)
Packet rate	10 packet per sec
Transmission range	0.005m, 0.01m, 0.015m, 0.02m
Number of gateways	1
Number of routers	10
Number of nodes	50, 100, 200, 300

LaGOON: Important Nodes on the Transmission



sn, *dn* (LaGOON) are src-neighbor and dst-neighbor respectively.

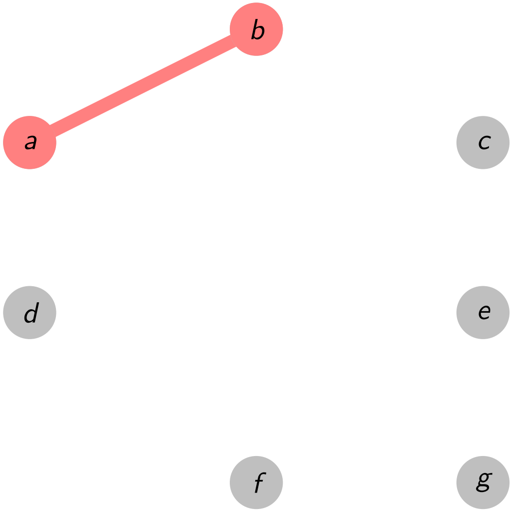
Visual example (Omnidirectional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	-	-
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

Initial collection of entries from "routing tables" of nodes. Empty routing table can lead to flooding or tx to a random neighbor.

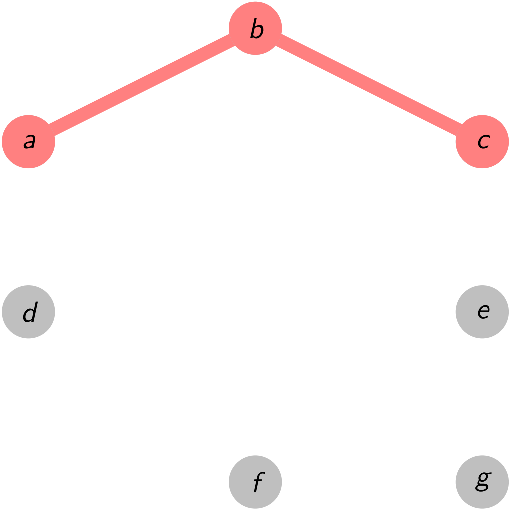
Visual example (Omnidirectional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

"a", having an empty routing table starts to flood. "b" updates entry for reaching "a" via "a" with cost 1, marks "a" as neighbor!

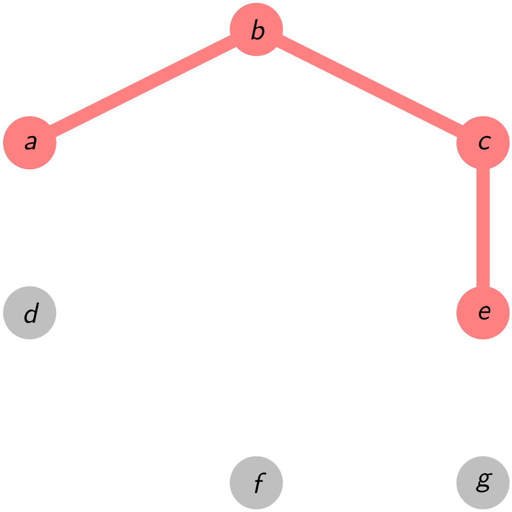
Visual example (Omnidirectional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	-	-
f	-	-
g	-	-

"c" updates entry for reaching "a" via "b" with cost 2, marks "b" as neighbor!

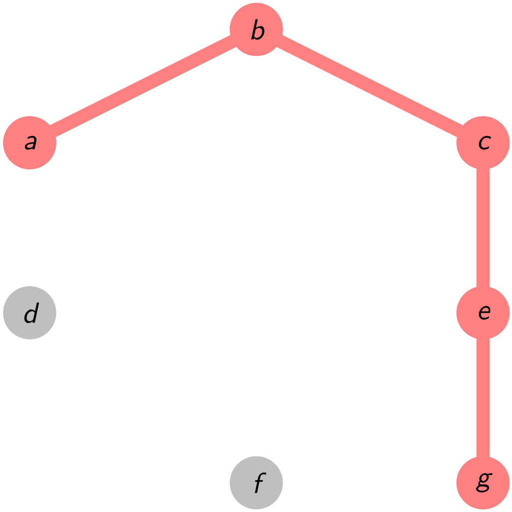
Visual example (Omnidirectional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	c	a-c-3
f	-	-
g	-	-

"e" updates entry for reaching "a" via "c" with cost 3, marks "c" as neighbor!

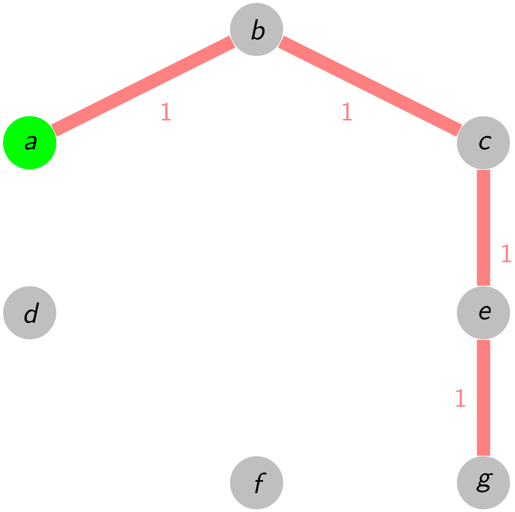
Visual example (Omnidirectional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	c	a-c-3
f	-	-
g	e	a-e-4

"g" updates entry for reaching "a" via "e" with cost 4, marks "e" as neighbor!

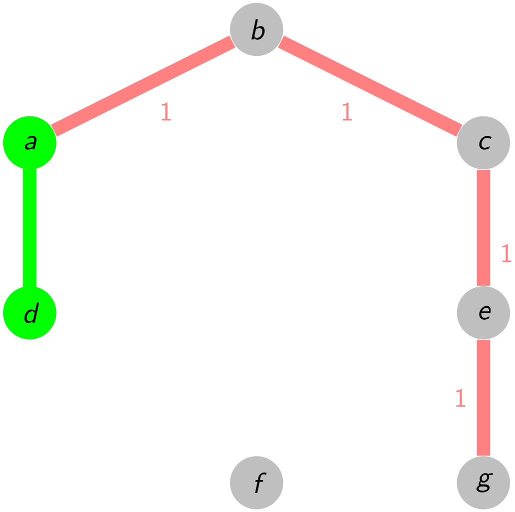
Visual example (Omnidirectional): Path 2 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	c	a-c-3
f	-	-
g	e	a-e-4

"g" remembers that "a" can be reached via "e" with cost 4.

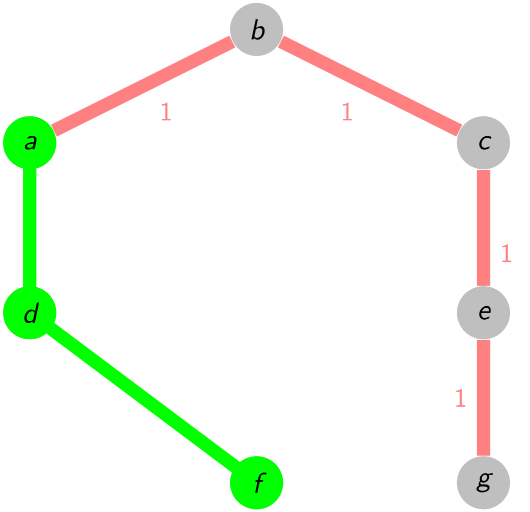
Visual example (Omnidirectional): Path 2 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	a	a-1
e	c	a-c-3
f	-	-
g	e	a-e-4

“d” updates entry for reaching “a” via “a” with cost 1, marks “a” as neighbor!

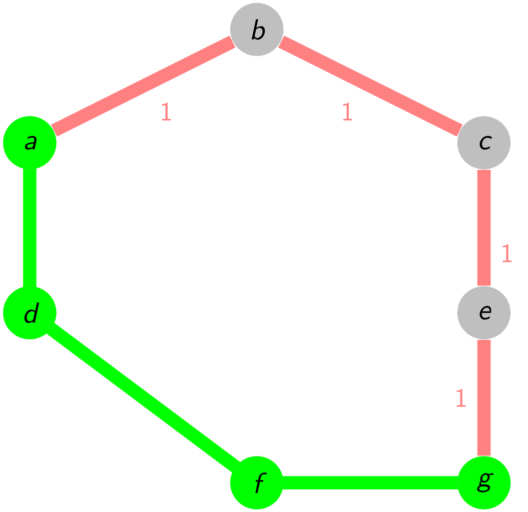
Visual example (Omnidirectional): Path 2 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	a	a-1
e	c	a-c-3
f	d	a-d-2
g	e	a-e-4

"f" updates entry for reaching "a" via "d" with cost 2, marks "d" as neighbor!

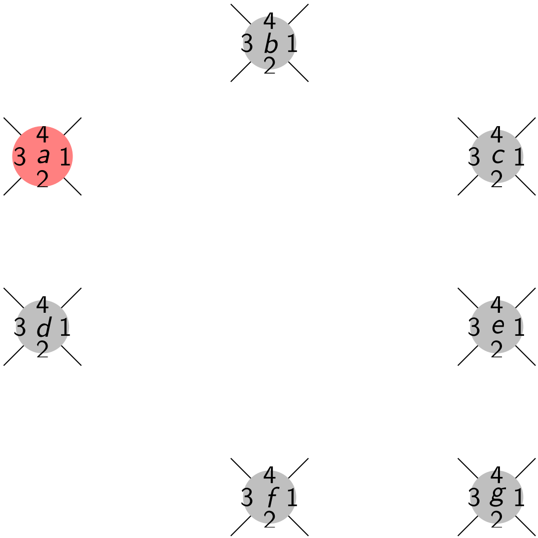
Visual example (Omnidirectional): Path 2 from a to g



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	a	a-1
e	c	a-c-3
f	d	a-d-2
g	e, f	a-f-3

"g" updates entry for reaching "a" via "f" with cost 3, marks "f" as neighbor!

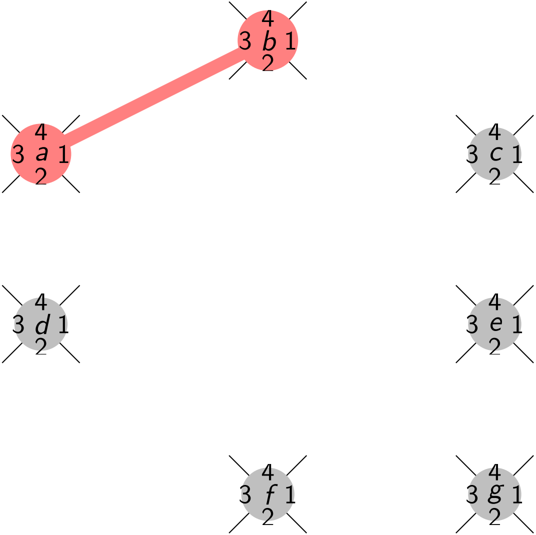
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	-	-
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

Initial collection of entries from "routing tables" of nodes. Empty routing table can lead to flooding or tx to a random neighbor.

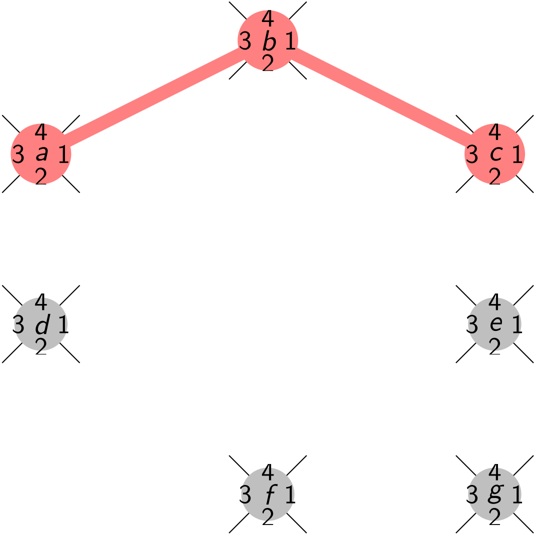
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

“b” updates entry for reaching “a” via “3a” (using antenna 3) with cost 1, marks “a” as neighbor!

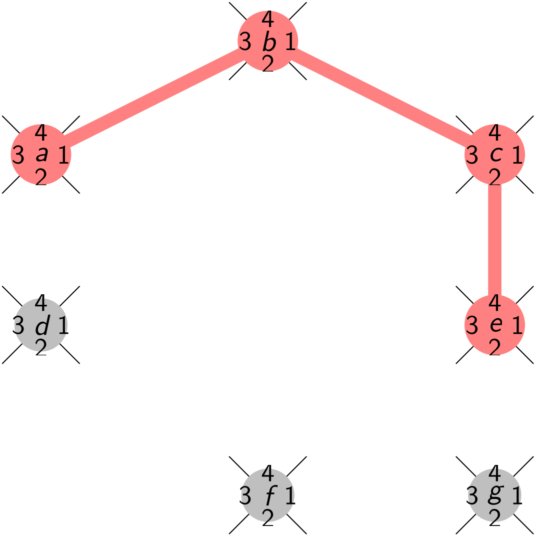
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	-	-
f	-	-
g	-	-

"c" updates entry for reaching "a" via "3b" with cost 2, marks "b" as neighbor!

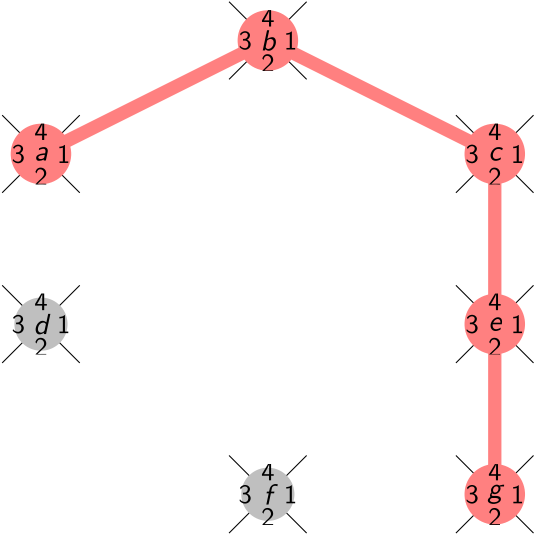
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	c	a-4c-3
f	-	-
g	-	-

"e" updates entry for reaching "a" via "4c" with cost 3, marks "c" as neighbor!

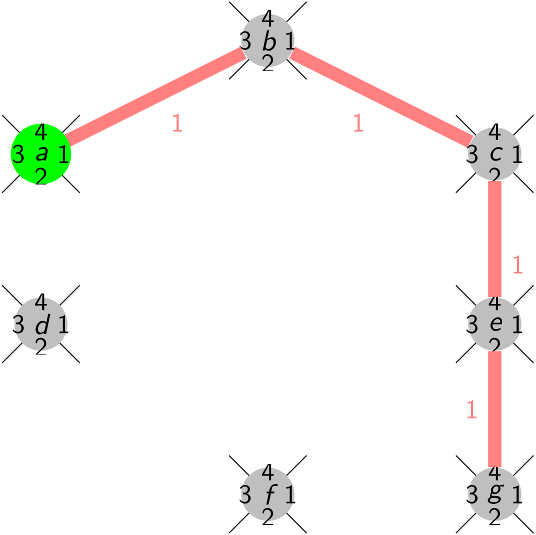
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	c	a-4c-3
f	-	-
g	e	a-4e-4

"g" updates entry for reaching "a" via "4e" with cost 4, marks "e" as neighbor!

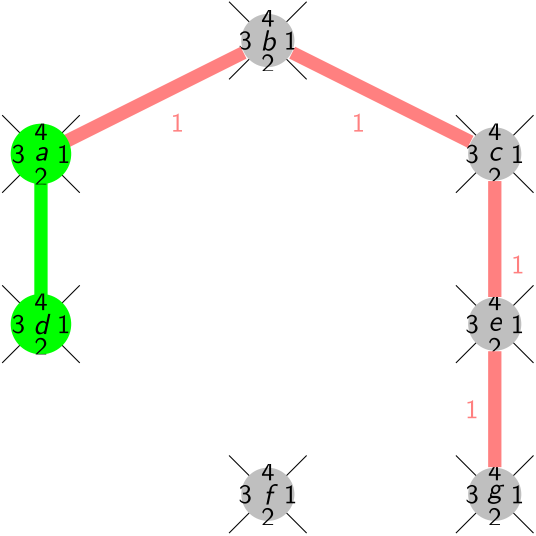
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	c	a-4c-3
f	-	-
g	e	a-4e-4

"g" remembers that "a" can be reached via "3e" with cost 4.

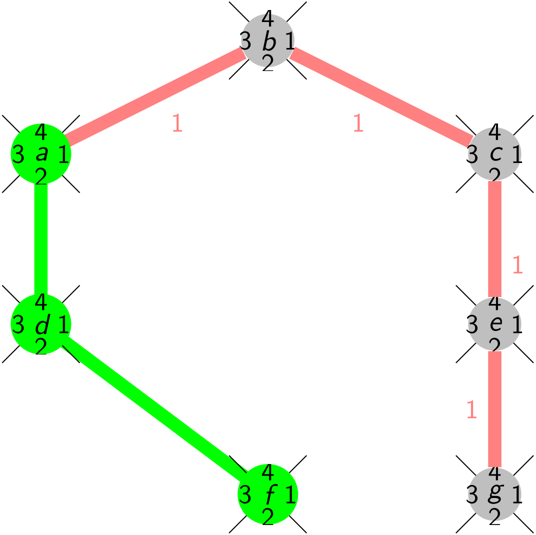
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	a	4a-1
e	c	a-4c-3
f	-	-
g	e	a-4e-4

"d" updates entry for reaching "a" via "4a" with cost 1, marks "a" as neighbor!

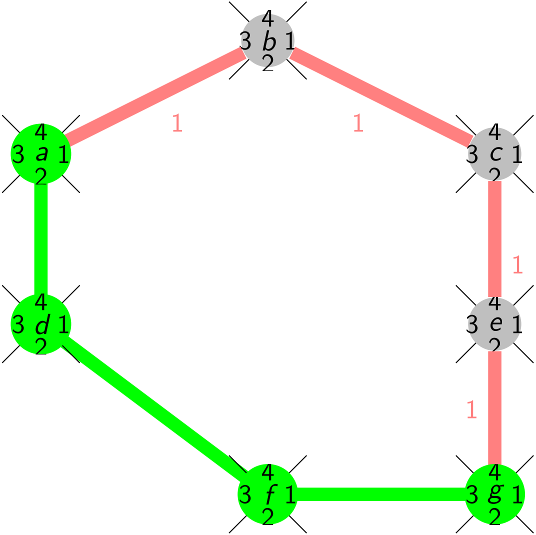
Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	a	4a-1
e	c	a-4c-3
f	d	a-3d-2
g	e	a-4e-4

“f” updates entry for reaching “a” via “3d” with cost 2, marks “d” as neighbor!

Visual example (Directional): Path 1 from a to g



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	a	4a-1
e	c	a-4c-3
f	d	a-3d-2
g	e, f	a-3f-3

“g” updates entry for reaching “a” via “3f” with cost 3, marks “f” as neighbor!

Simulation Results

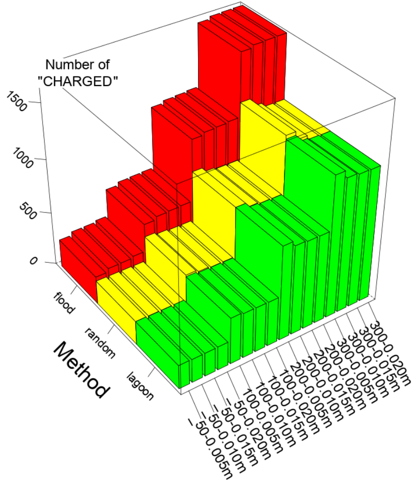
These metrics can not be evaluated in isolation but...

- The number of **“CHARGED”** events. To see the **“energy efficiency”**. More efficient protocol should have less battery recharges.
- The number of **“DROP”** events. To see the **“reliability”**. More reliable protocol should drop less packets.
- The number of **“SEND”** events. To see the **“transmission efficiency”**. More efficient protocol should send more packets.
- The number of **“FORWARD”** events. To see the **“transmission efficiency”**. More efficient protocol should forward less.

Results: Energy Efficiency

Number of "CHARGED" events

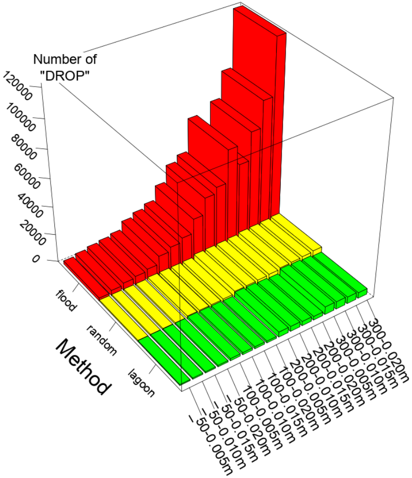
TX Range	Method	Number of Nano Nodes			
		50	**100**	**200**	**300**
0.005	**lagoon**	222	434	878	1306
	random	222	449	878	1339
	flood	261	567	1172	1775
0.01	**lagoon**	219	422	831	1238
	random	221	431	836	1263
	flood	293	595	1194	1797
0.015	**lagoon**	219	420	822	1226
	random	220	422	824	1224
	flood	295	600	1200	1801
0.02	**lagoon**	220	418	820	1222
	random	218	421	822	1223
	flood	310	604	1209	1803



Results: Reliability

Number of "DROP" events

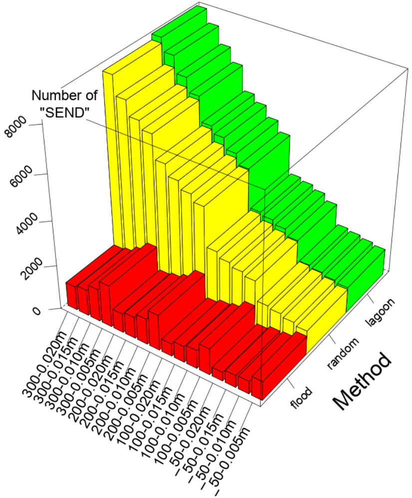
TX Range	Method	Number of Nano Nodes 50	100	200	300
0.005	lagoon	701	1548	3642	5614
	random	858	2052	4250	6364
	flood	2295	8199	30347	56101
0.01	lagoon	863	1516	3577	5382
	random	1001	2158	4460	6671
	flood	3961	14029	42136	75739
0.015	lagoon	860	1461	3079	4839
	random	1115	2274	4764	7142
	flood	5516	17051	46482	94080
0.02	lagoon	1013	1297	2626	4072
	random	1159	2478	5256	7812
	flood	6645	20145	69524	132895



Results: Transmission Efficiency

Number of “SEND” events

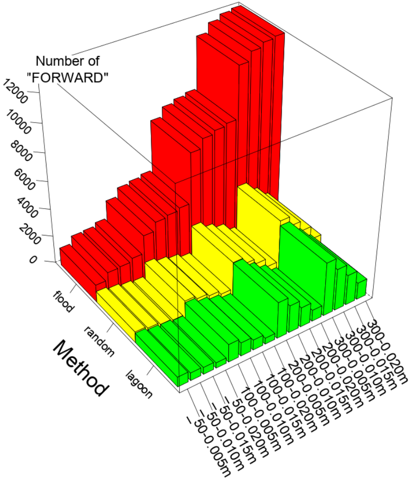
TX Range	Method	50	100	200	300
		Number of Nano Nodes			
0.005	**lagoon**	1183	2371	4684	6997
	random	1102	2323	4634	6831
	flood	867	1192	1610	1894
0.01	**lagoon**	1280	2666	5147	7598
	random	1230	2479	4951	7181
	flood	582	834	1167	1469
0.015	**lagoon**	1384	2847	5624	8319
	random	1357	2649	5294	7821
	flood	548	731	976	1182
0.02	**lagoon**	1472	2972	5930	8883
	random	1449	2885	5787	8643
	flood	404	569	870	1084



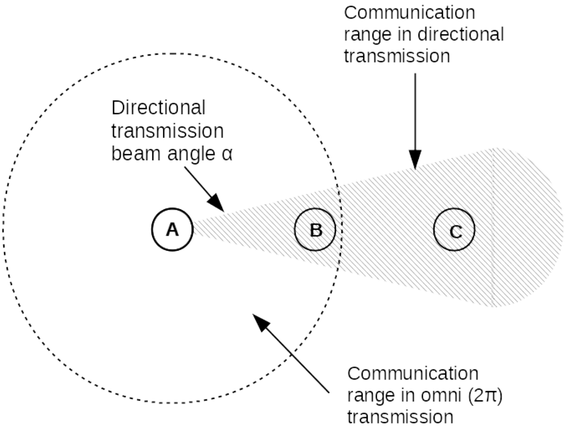
Results: Transmission Efficiency

Number of “FORWARD” events

TX Range	Method	Number of Nano Nodes			
		50	**100**	**200**	**300**
0.005	**lagoon**	716	1291	2628	3871
	random	807	1416	2666	4210
	flood	1284	3408	7928	12590
0.01	**lagoon**	560	971	1980	3017
	random	662	1178	2192	3514
	flood	1825	4033	8591	13217
0.015	**lagoon**	504	737	1419	2184
	random	511	988	1819	2778
	flood	1877	4181	8833	13530
0.02	**lagoon**	388	439	818	1222
	random	414	702	1210	1802
	flood	2117	4355	9012	13661



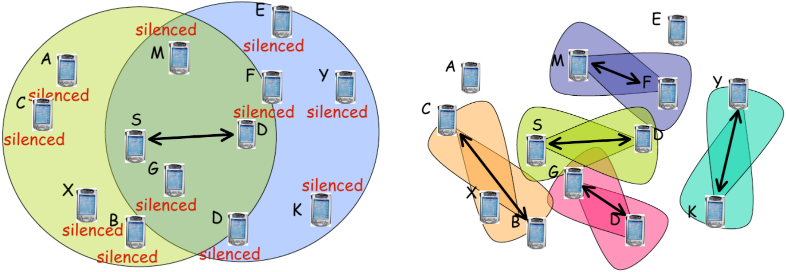
Omnidirectional vs Directional Antennas



Transmission coverage of the omnidirectional and the directional antennas[10]

[10] Corderio, C. M. and Agrawal, D. P. editors., "Ad Hoc & Sensor Networks Theory And Applications", World Scientific, p. 308, 2006.

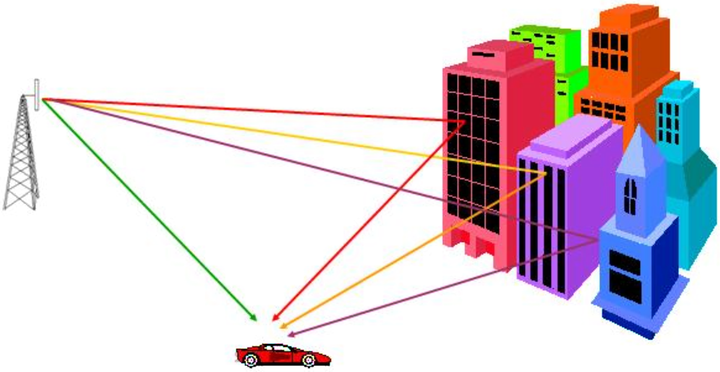
Omnidirectional vs Directional Antennas



Comparison of omnidirectional and directional antennas in communication[11]

[11]Choudhury, R. R., http://synrg.csl.illinois.edu/ppts/cisco-talk.pdf

Omnidirectional vs Directional Antennas



"Multipath Fading" in omnidirectional antenna[12]

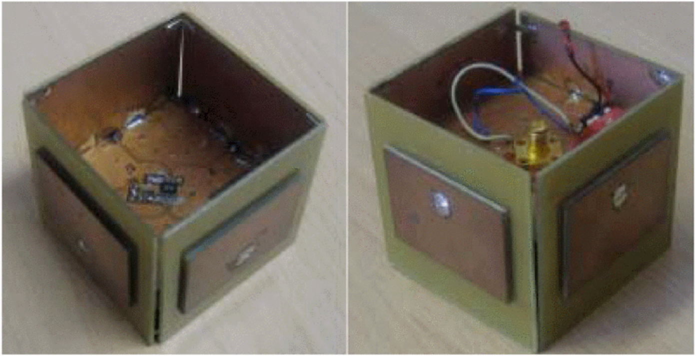
[12] http://www.teletopix.org/wp-content/uploads/2013/01/MUltipath-effect.jpg

Omnidirectional vs Directional Antennas[13]

Characteristics	Omnidirectional	Directional
Spatial reuse	Low	High
Network connectivity	Low	High
Interference	Omni	Directional
Coverage range	Low	High
Cost and complexity	Low	High

[13] Corderio, C. M. and Agrawal, D. P. editors., "Ad Hoc & Sensor Networks Theory And Applications", World Scientific, p. 307, 2006.

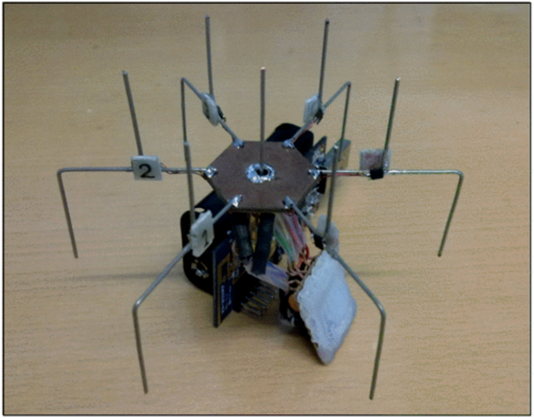
Related Work



2.4 GHz, 8.3 dBi (gain) Four-beam patch antenna (FBPA) having dimensions of 56mm x 56mm and thickness of 2.4mm with 2xFR4[14]

[14] Giorgetti, G. et al., "Exploiting Low-Cost Directional Antennas in 2.4 GHz IEEE 802.15.4 Wireless Sensor Networks", in European Conference on Wireless Technologies, pp. 217–220, 2007.

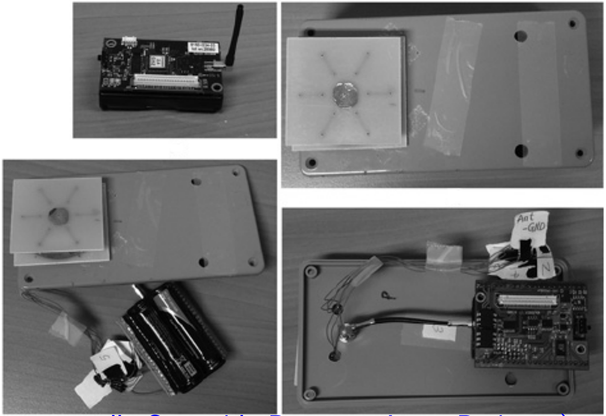
Related Work



2.4 GHz, 7 dB (gain) SPIDA antenna with TMote Sky mote[15]

[15]Mottola, L. et al., "Electronically-switched directional antennas for wireless sensor networks: A full-stack evaluation", in IEEE International Conference on Sensing, Communications and Networking (SECON), pp. 176–184, 2013.

Related Work

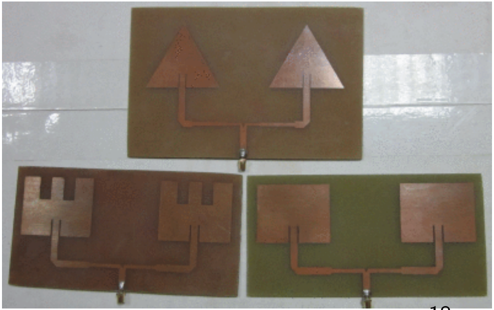


ESPAR[16](Electronically Steerable Parasitic Array Radiator) smart antenna with MicaZ sensor node[17]

[16] Electronically Steerable Parasitic Array Radiator. 2.4GHz and provides 4dBi gain with S11 around -35dB [liu2012]

[17] Loh, T. et al., "Assessment of the adaptive routing performance of a Wireless Sensor Network using smart antennas". IET Wireless Sensor Systems, 4(4):196–205, 2014.

Related Work

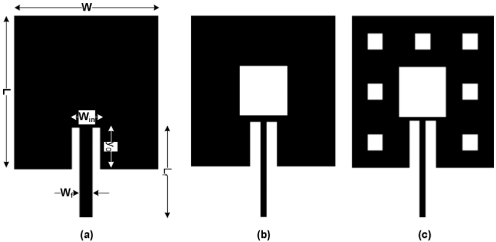


Microstrip patch antenna arrays[18]

Type	Return loss (dB)	Gain (dB)	Area (L x W mm^2)
Rectangular	-24.46	2.648	113.5 X 57.91
Triangular	-25.83	2.017	117.55 X 76.63
E-shaped	-30.43	2.48	113.5 X 57.91

[18] Nagaraju, S. et al., "Performance analysis of rectangular, triangular and E-shaped microstrip patch antenna arrays for wireless sensor networks", in Int. Conf. on Computer and Comm. Tech. (ICCCT), pp. 211–215, 2014.

Related Work



Sierpinski Carpet Fractal patch, 2.45GHz, FR4 with $\epsilon r = 4.7$[19]

Characteristic	Base case	Iter1(31%)	Iter2(32%)
Return Loss (dB)	29.08	28.42	24.28
Impedance BW (%)	70MHz	60MHz	60MHz
Bandwidth (%)	2.86	2.45	2.45
Gain (dB)	3.73	2.77	2.64
VSWR	1.07	1.08	1.13

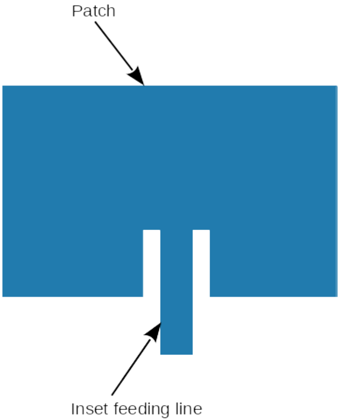
[19] Shrestha, S. et al., "Design of modified Sierpinski fractal based miniaturized patch antenna", in Int. Conf. on Information Networking (ICOIN), pp. 274–279, 2013.

Advantages and Disadvantages of the Microstrip Patches[20]

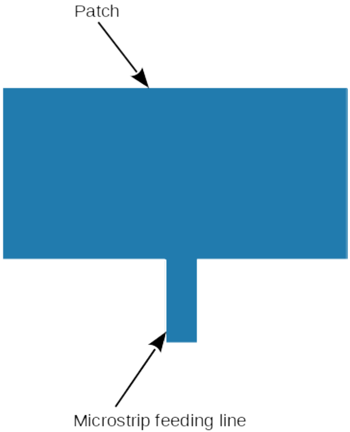
Advantages	Disadvantages
Thin profile	Low efficiency
Light weight	Small bandwidth
Simple to manufacture	Extraneous radiation from feeds, junctions and surface waves
Can be made conformal	Tolerance problems
Low cost	Require quality substrate and good temperature tolerance
Can be integrated with circuits	High-performance arrays require complex feed systems
Simple arrays readily created	Polarization purity difficult to achieve

[20] James, J. R. and Hall, P. S., "Handbook of microstrip antennas, Volume 1", IEE electromagnetic waves series. Peter Peregrinus on behalf of the Institution of Electrical Engineers, p. 6, 1989.

Feeding Lines for Patch Antennas



(a) The patch antenna with the inset fed line.



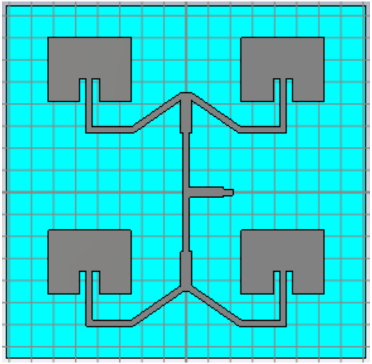
(b) The patch antenna with the microstrip fed line.

Inset Feeding Line[21]

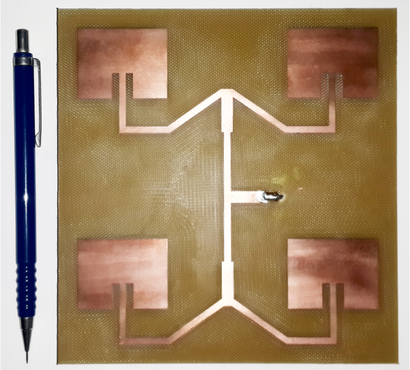
- The **highest directivity** (more convenient for long distance communication)
- The spurious radiation from the feed line makes inset fed antennas **worst in reflection loss** (compared to aperture coupled and co-axial fed antennas)

[21] Chakravarthy, S. S. et al., "Comparative study on different feeding techniques of rectangular patch antenna", in 13th Int. Conf. on Wireless and Optical Communications Networks (WOCN), pp. 1–6, 2016.

Proposed Directional Antenna[22]



(a) Schematic drawing of the directional antenna designed.



(b) Photo of the directional antenna designed.

Inset-fed 2-by-2 rectangular patch array with corporate feed.

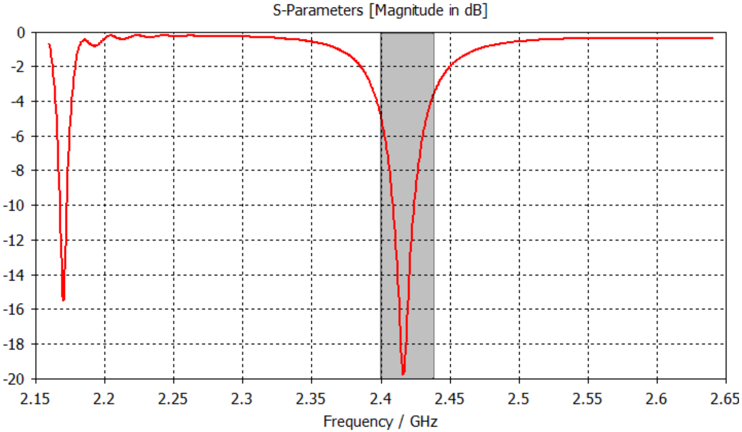
[22] AntennaMagus (`http://www.antennamagus.com/`) software package is used for the design (version 2017).

Properties of the Proposed Antenna

Property	Value
Size (X × Y)	124.9mm × 131.0mm
Substrate	FR4 with $\epsilon r = 4.35$ and thickness $= 1.5$mm
S11 (Measured)	Max -11dB in 2.40GHz - 2.48GHz[23]
Gain (Simulated)	12.74dB (CST 2017)

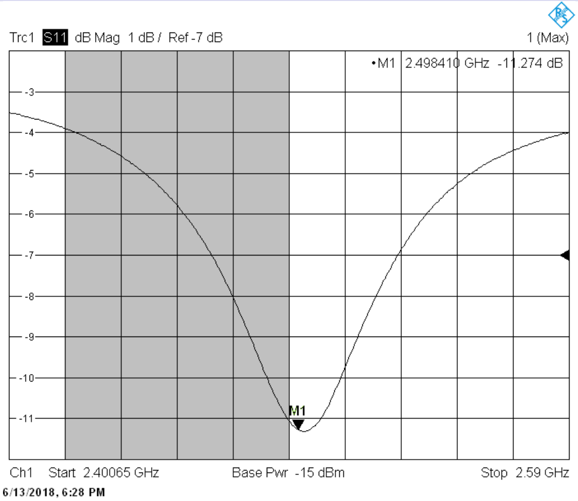
[23] Standard operating frequency for the IEEE 802.11 and the IEEE 802.15.4

Simulated S11 of the Proposed Antenna



S11 plot from the CST simulation.

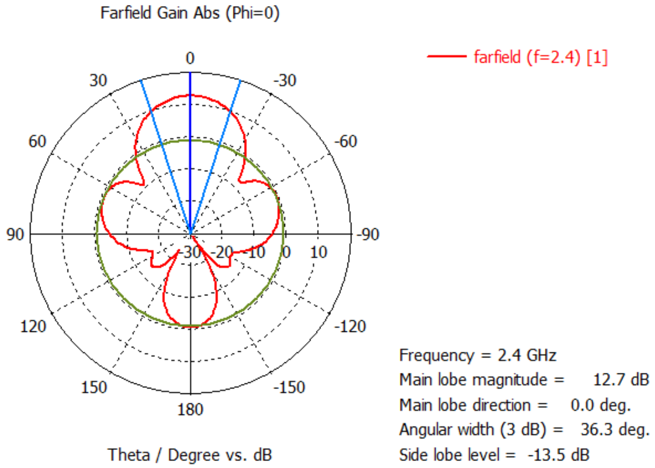
Measured S11 of the Proposed Antenna



Measured[24] S11 plot.

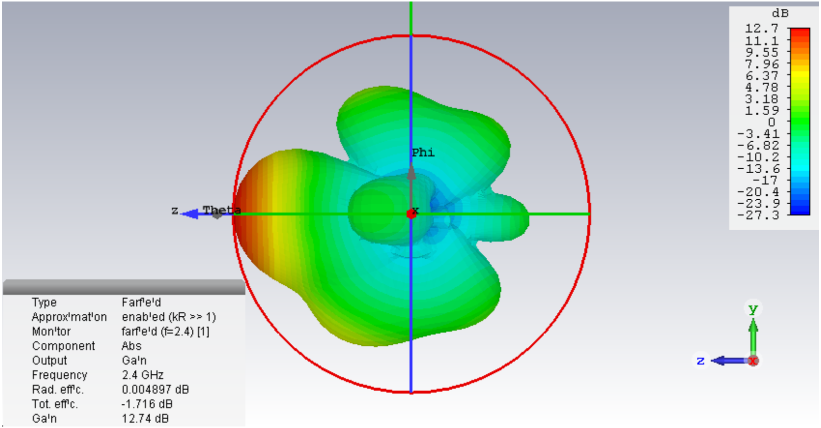
[24] Measured with Rohde&Schwarz® ZVB8 Vector Network Analyzer 2 ports, 8 GHz.

Gain of the Proposed Antenna 2.4GHz



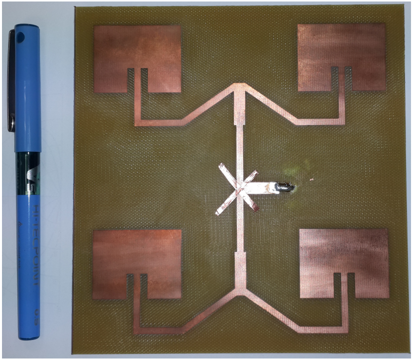
2D Far field plot from the CST simulation.

Gain of the Proposed Antenna 2.4GHz



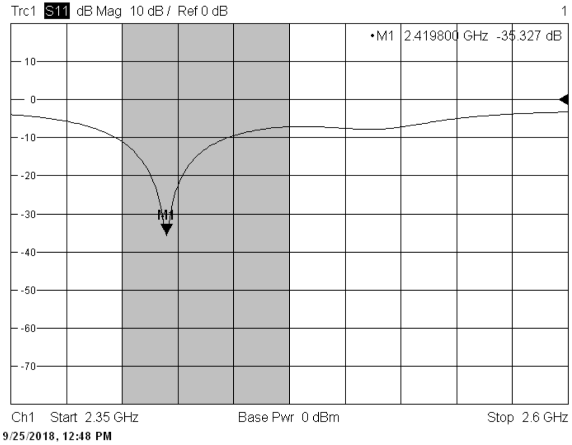
3D Far field plot from the CST simulation.

"Tuned" Antenna



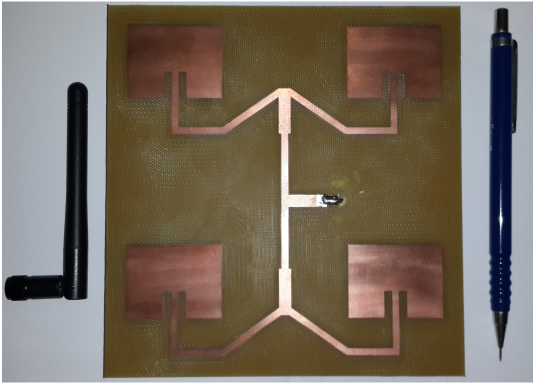
Designed antenna after tuning.

S11 of the "Tuned" Antenna



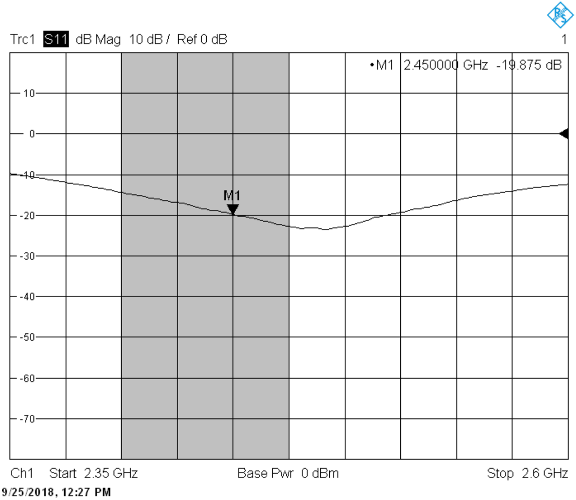
Measured S11 plot for the tuned antenna, about -35dB.

Data Rate Benchmark



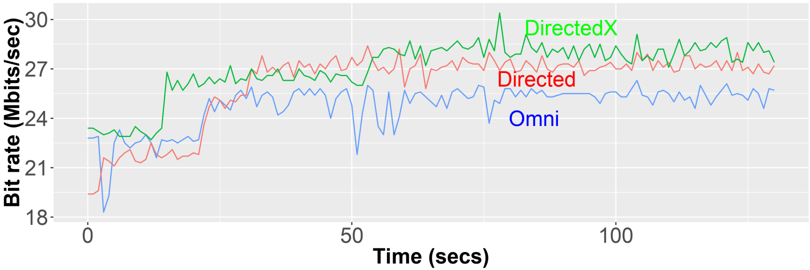
Omnidirectional (left) and directional antennas (right) used in benchmarking.

Data Rate Benchmark



Measured S11 plot of the omnidirectional antenna used in benchmarking.

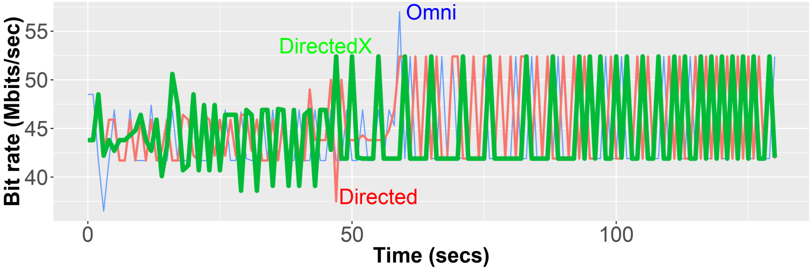
Reception Benchmark



Antenna reception benchmark results. “DirectedX” is the tuned version.

Type	Min	Max	AVG	STD
Omni	18.3	26.3	24.73	1.35
Directed	19.4	28.4	26.06	2.24
DirectedX	22.7	30.4	27.04	1.66

Transmission Benchmark



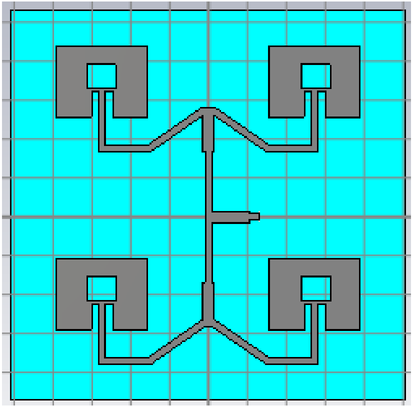
Antenna transmission benchmark results. "DirectedX" is the tuned version.

Type	Min	Max	AVG	STD
Omni	36.5	57	44.82	4.44
Directed	37.5	52.4	45.72	4.45
DirectedX	38.6	52.4	44.75	4.31

Statistical Analysis of the Observations

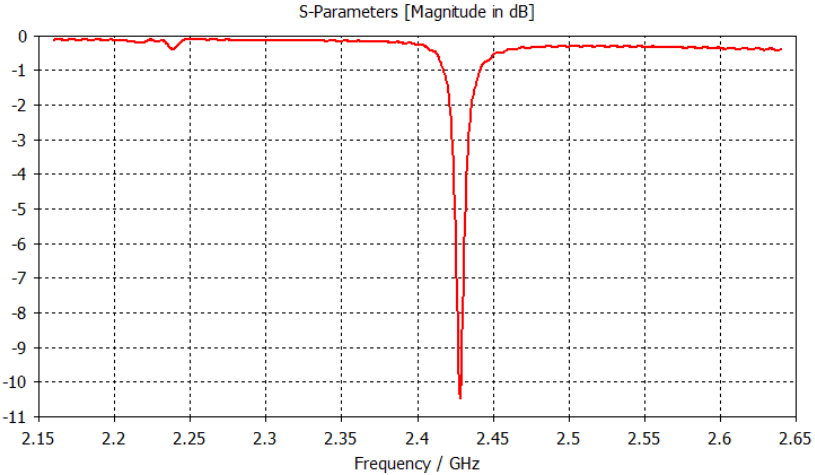
Group	Test	Tested property	Result
RX	Welch Two Sample t-test	Means are same?	No
	Two-sample Kolmogorov-Smirnov	Distributions are same?	No
TX	Welch Two Sample t-test	Means are same?	Yes
	Two-sample Kolmogorov-Smirnov	Distributions are same?	Only Directed and DirectedX

Size Reduction: Sierpinski Fractal



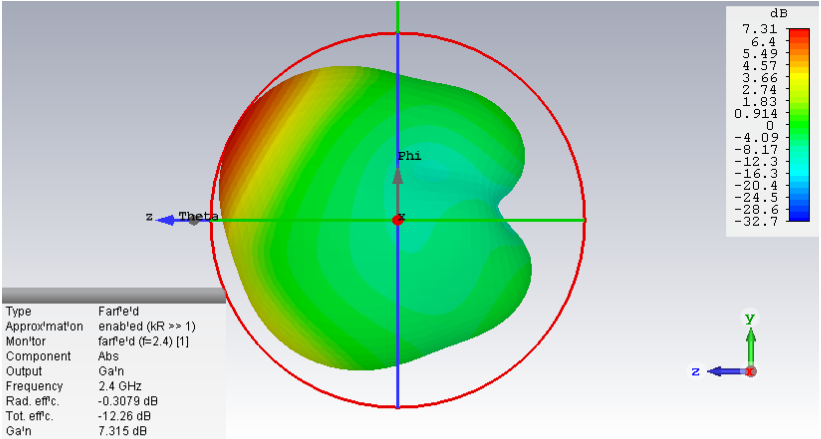
62.5% size reduction: From(X×Y) 124.9mm×131.0mm to 78.06mm×81.88mm

Size Reduction: S11



S11 plot from the simulation for the first iteration fractal version. -10dB

Size Reduction: Gain



3D gain plot for 2.4GHz for the first iteration fractal version. 7.32dB

SW Energy Optimization for SN

- LaGOON: Proposed simple and energy-aware routing protocol for WNSNs and for WSNs.
- Omnidirectional and directional versions are presented.
- Simulations results show that LaGOON is better than flooding and point-to-point random.

HW Energy Optimization for SN

- "Inset-fed 2-by-2 rectangular patch array with corporate feed".
- Design principles: Simple to produce, cost effective, energy saving, and directional.
- 124.9mm $\times$ 131.0mm, FR4 substrate, 12.74dB gain (about 3dB per patch?), about -10dB (measured) return loss.
- Fractal size reduction: 62.5%. But gain drops to 7.32dB, S11 (simulated) -10dB.

Failures

- Platforms like Onion-Omega2+ and Particle-Photon was suitable: External antenna interface
- Actual SW and HW integration was not carried out: Proprietary firmware stuff!
- Energy consumption comparison was not possible: FCC rules, power to antenna can not be changed.
- Range comparison: Need sensitive equipment.
- WSN and WNSNs simulators currently do not support "directional antenna" models.

Future work

- Experiments with research based WSN platform in which power to antenna can be adjusted.
- Directional implementation of LaGOON.
- Increasing robustness of LaGOON with enhancements for node failure, mobility involving far distance, etc...

Thank You!

References I

[abuali2018] N. Abuali et al.
Performance Evaluation of Routing Protocols in Electromagnetic Nanonetworks.
IEEE Access, 6:35908–35914, 2018.
http://dx.doi.org/10.1109/ACCESS.2018.2845305.

[afsana2018] F. Afsana et al.
An Energy Conserving Routing Scheme for Wireless Body Sensor Nanonetwork Communication.
IEEE Access, 6:9186–9200, 2018.
http://dx.doi.org/10.1109/ACCESS.2018.2789437.

[liaskos2015] A. Tsioliaridou et al.
CORONA: A Coordinate and Routing System for Nanonetworks.
In *Proc. of the 2^{nd} Annual Int. Conf. on Nanoscale Computing and Comm.*, NANOCOM' 15, pages 1–6, 2015.
https://doi.org/10.1145/2800795.2800809.

References II

[liaskos2016] C. Liaskos et al.
A deployable routing system for nanonetworks.
In *IEEE Int. Conf. on Comm. (ICC) 2016*, pages 1–6, 2016.
https://doi.org/10.1109/ICC.2016.7511151.

[liu2012] H. Liu et al.
Electrically Small and Low Cost Smart Antenna for Wireless Communication.
IEEE Transactions on Antennas and Propagation, 60(3):1540–1549, 2012.
http://dx.doi.org/10.1109/TAP.2011.2180300.

[tairin2017] S. Tairin et al.
Network-level performance enhancement in wireless nanosensor networks through multi-layer modifications.
In *2017 International Conference on Networking, Systems and Security (NSysS)*, pages 75–83, 2017.
http://dx.doi.org/10.1109/NSysS.2017.7885805.

References III

[yu2015] Y. Hang et al.
Forwarding Schemes for EM-based Wireless Nanosensor Networks in the Terahertz Band.
In *Proc. of the 2nd Annual Int. Conf. on Nanoscale Computing and Comm.*, pages 1–6, 2015.
https://doi.org/10.1145/2800795.2800799.

[zhou2012] R. Zhou et al.
Buddy Routing: A Routing Paradigm for NanoNets Based on Physical Layer Network Coding.
In *2012 21st Int. Conf. on Computer Comm. and Networks (ICCCN)*, pages 1–7, 2012.
https://doi.org/10.1109/ICCCN.2012.6289272.