Sensor Networks: Energy & Resource Optimization

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CS428 Sensor Networks

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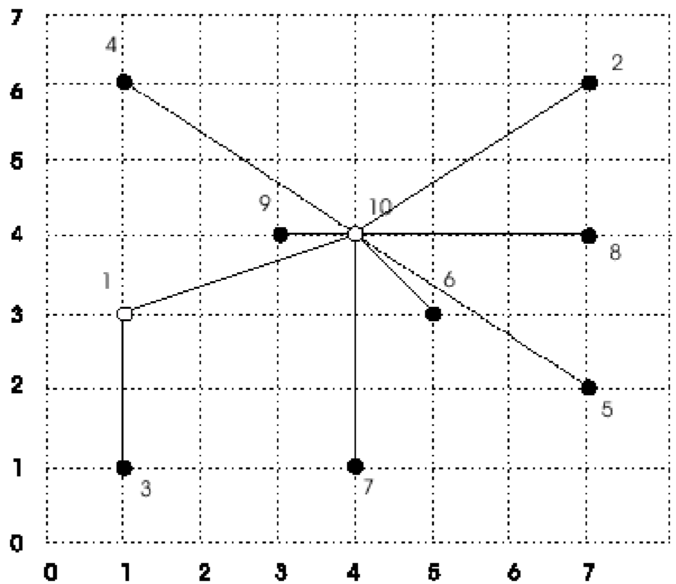
How do we optimize performance?

	Cagalj '02	Brown '01	Doherty '01
Optimization	Routing w/ minimal Energy	Routing w/ maximum Flow Life	Design w/ maximum Functionality
Communication	Source-initiated Broadcast	Source to Destination	Source to Central Receiver Heterogeneous Ad-hoc
Applications/ Scenarios	[Event alert] Update state Maintain route	[point to point communication]	Environment Monitoring Seismic Monitoring Tracking

Mario Calalj, Jean-Pierre Hubaux,

Christian Enz 2002



Minimum-Energy Broadcast in All-Wireless Networks: NP-Completeness and Distribution Issues

Minimum energy model parameters

- Short-range ad hoc wireless
- Battery-operated
- Stationary
- Large bandwidth resources
- No contention issues
- Omnidirectional RF signal

Minimum energy terms

- *Connected:* node *j* falls in the transmission range of node *i*
- *Link cost c_{ij}:* minimum power needed to sustain link (i,j)
- *Variable node power p_i:* power at which node *i* has transmitted.
- Neighbors V_i: node *j* falls in the maximum transmission range of node *i*

Minimum energy complexity

- Minimum energy broadcast tree is hard to solve
  - # possible broadcast trees is *exponential* in the number of nodes.
  - Nodes are allowed to transmit at |P| different power levels
- *Minimum Broadcast Cover* (is there a broadcast tree rooted at r with total cost B or less s.t. all nodes in V are included in the tree?) is NP-complete: provable by the Set Cover problem
- *Geometric MBC* is NP-complete: provable by planar 3-SAT

Minimum energy heuristic routing

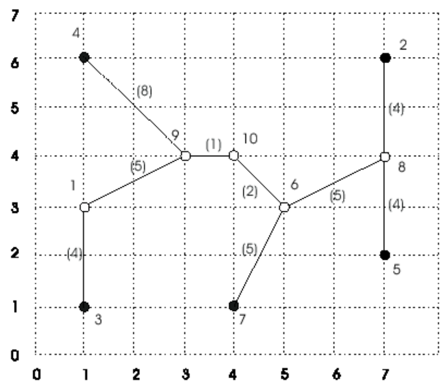


Figure 6: The network example and its MST ($e_{MST} = 23$)

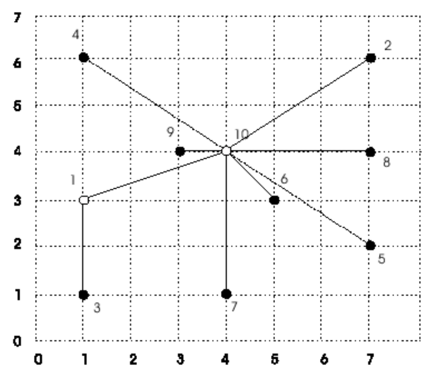


Figure 7: The broadcast-tree obtained by EWMA heuristic ($e_{EWMA} = 17$)

- EWMA: Embedded wireless multicast advantage
  - Start with minimum spanning tree (MST)
  - Calculate total energy
  - Increase source energy to remove other transmitters
  - Calculate change in max energy drop
  - Iterate
- Runtime bounded O(d^4)m^2

Minimum energy heuristic routing

- Distributed EWMA: Embedded wireless multicast advantage
  - Distributed algorithm to form EWMA
  - 2 phases
    - Construct Minimum-weight spanning tree O(|V|log|V|) so each node has information about its two-hop neighbors
    - Final broadcast tree is built up by broadcasting, synchronizing node models. Duration is |F| Tmax long

Minimum energy performance evaluation

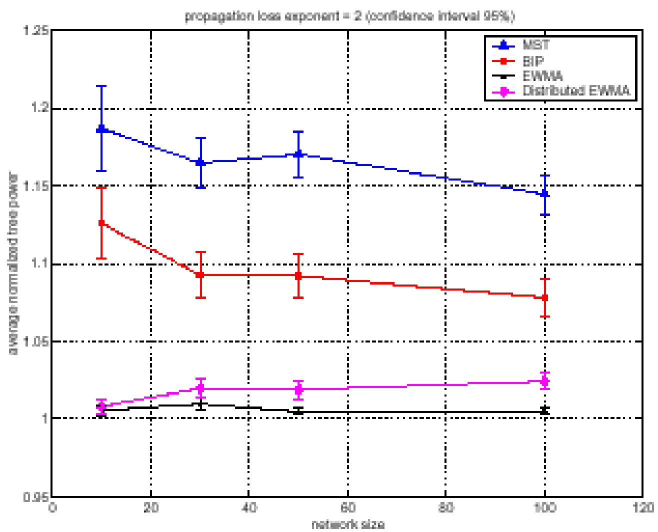


Figure 11: Distributed algorithm - normalized tree power for 100 network instances (confidence interval 95%) and propagation loss exponent $\alpha = 2$

- Performance measured by normalized tree power as a function of network size
- Performs significantly better on average than BIP and MST
- Difference in performance decreases as the propagation loss exponent increases

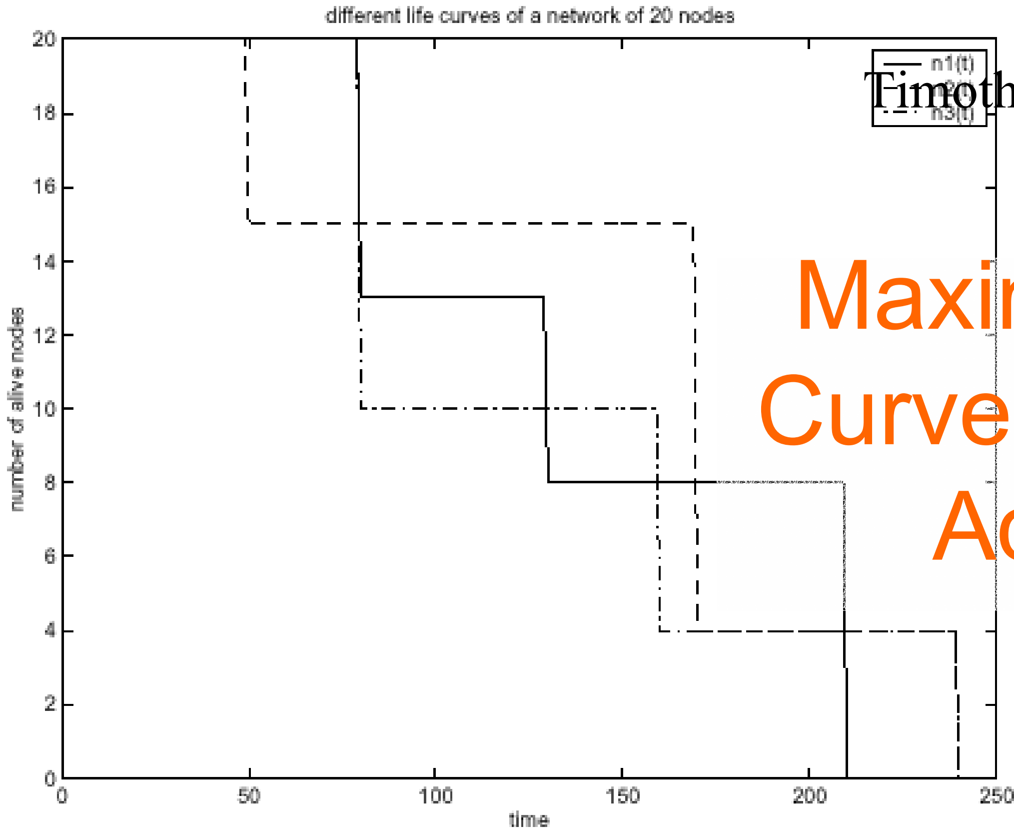
Minimum energy analysis

- Authors address need for additional power consumption reduction mechanisms, minimum-energy multicast and mobility
- Perfectly circular broadcast path is not necessarily realistic
- This solution minimizes overall energy of system but not that of individual nodes.

In fact, we'd expect the critical relay nodes to exhaust their power first, causing network failure.

Maximum Flow-Life Curve for a Wireless Ad Hoc Network

Timothy Brown, Harold N. Gabow,
Qi Zhang 2001



Maximum flow-life definition

- Flow-life is the maximum period of time for which the network is able to send signals from the source to the destination
- Flow-life is distinct from network life, which is the time to the first node failure; Flow-life assumes that communication continues in a degraded rate.

Maximum flow-life model parameters

- Short-range ad hoc wireless
- Battery-operated
- Stationary
- Large bandwidth resources
- No contention issues
- Point to point

Maximum flow-life terms

- *Hop path* p_k: ordered set of nodes from source s to destination d.
- I_{sd}: set of all indices for paths from s to d.

  $I_{sd}=\{k|s(k)=s$ and $d(k) = d\}$
- *Flow* f_{sd}: long term rate of data transmission from s to d.
- *Routing scheme* r_i: set of flows allocated to all pathes between s and d. $r = \{x_k(r)\}$
- *Energy rate* a_{ik}: rate energy is drawn from node v_i

Maximum flow-life node-life curve

- How many nodes will be alive at time t given routing scheme r? $n(t,r)$
- Maximizing the node-life gives optimum routing scheme.
- Key properties:
  - In the max-node life curve, the exhausted node set for each drop point is unique.
  - There exists a single routing r that achieves the maximum node life curve.
  - In the maximum node life cure, at least one flow is exhausted at each drop point.

Maximum flow-life flow-life curve

- Theorem: A maximum-node life curve routing is also a maximum flow-life curve routing.

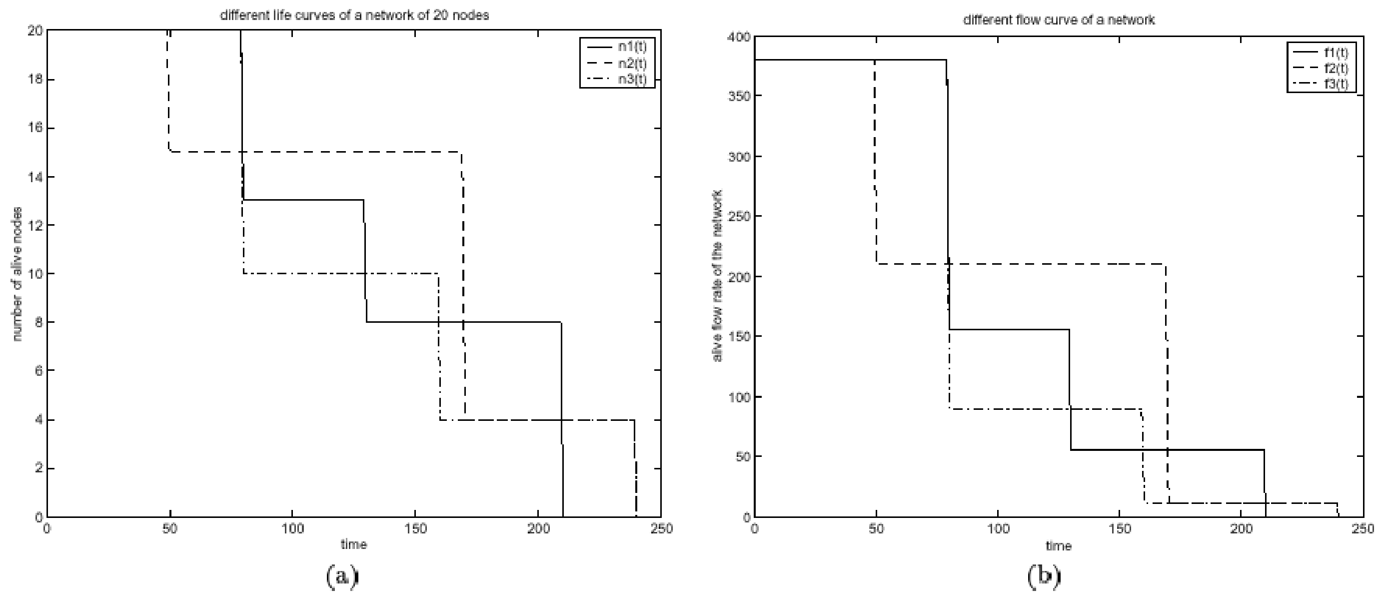


Figure 1: Three node-life curves (a) and flow-life curves (b) in a 20 node network.

Maximum flow-life computation algorithm

- Calculates the timing and nodes at each drop point within $O(N^2(M+N)^4 \log N)$
- Variables:
  - t_{sd}: time messages cease being sent from s to d
  - ϕ_k:the total flow that the routing sends through path p_k.
- Maximum routing satisfies these constraints

(1) $\sum_{k \in I_{sd}} \phi_k = f_{sd} t_{sd}$ for all s, d with $f_{sd} \in F$

(2) $\sum_{k \in I_F} a_{ik} \phi_k \leq E_i$ for all nodes v_i

Maximum flow-life performance evaluation

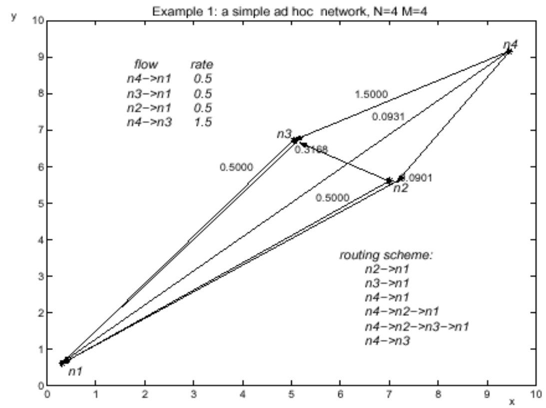


Figure 2: Node placement and flows in a four node network where the labels are the traffic carried on each path under the maximum flow-life curve routing.

i	τ_i	S_i^n	S_i^f	$\sum f_{kl}$
0	0	$\{v_1, v_2, v_3, v_4\}$	$\{f_{41}, f_{31}, f_{21}, f_{43}\}$	3.0
1	3.410	$\{v_1\}$	$\emptyset$	0

Table 1: Drop points and surviving nodes with maximum flow-life curve routing (Ex. 1).

i	t_i	S_i^n	S_i^f	$\sum f_{kl}$
0	0	$\{v_1, v_2, v_3, v_4\}$	$\{f_{41}, f_{31}, f_{21}, f_{43}\}$	3.0
1	1.857	$\{v_1, v_2, v_4\}$	$\{f_{41}, f_{21}\}$	1.0
2	3.878	$\{v_1, v_4\}$	$\{f_{41}\}$	0.5
3	4.562	$\{v_1\}$	$\emptyset$	0

Table 2: Drop points and surviving nodes with minimum total power routing (Ex. 1).

Two simulated node networks

- 4 nodes, 4 flows: maximum flow-life curve keeps network connected 80% longer than minimum total power routing

Maximum flow-life performance evaluation

- 12 nodes with 20 flows: maximum flow-life curve routing maintains all flows twice as long as minimum total power routing.

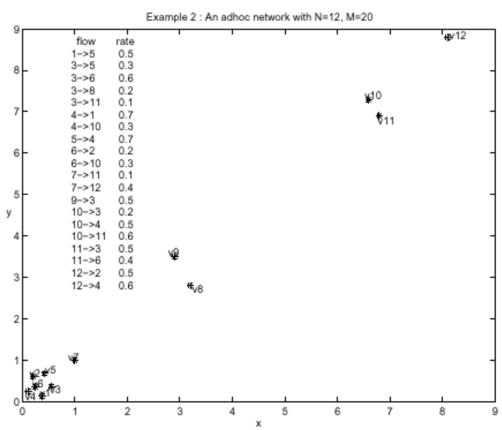


Figure 3: Node placement and flows in a 12 node network.

i	t_i	S_i^n	S_i^f	$\sum f_{kl}$
0	0	$\{v_1, \ldots, v_{12}\}$	$F = \{f_{ij}\}$	8.2
1	11.01	$\{v_1, \ldots, v_9\}$	$\{f_{15}, f_{35}, f_{36}, f_{38}, f_{41}, f_{54}, f_{62}, f_{93}\}$	3.7
2	260.4	$\emptyset$	$\emptyset$	0.0

Table 3: Drop points and surviving flows with the maximum flow-life curve routing (Ex. 2).

i	t_i	S_i^n	S_i^f	$\sum f_{kl}$
0	0	$\{v_1, \ldots, v_{12}\}$	$F = \{f_{ij}\}$	8.2
1	5.149	$\{v_1, \ldots, v_{10}, v_{12}\}$	$\{f_{15}, f_{35}, f_{36}, f_{38}, f_{41}, f_{4,10}, f_{54}, f_{62}, f_{6,10}, f_{7,12}, f_{93}, f_{10,3}, f_{10,4}, f_{12,2}, f_{12,4}\}$	6.5
2	12.07	$\{v_1, \ldots, v_8, v_{12}\}$	$\{f_{15}, f_{35}, f_{36}, f_{38}, f_{41}, f_{54}, f_{62}, f_{7,12}, f_{12,2}, f_{12,4}\}$	4.7
1	14.51	$\{v_1, \ldots, v_8\}$	$\{f_{15}, f_{35}, f_{36}, f_{38}, f_{41}, f_{54}, f_{62}\}$	3.2
3	949.2	$\{v_1, \ldots, v_4, v_6, v_8\}$	$\{f_{36}, f_{38}, f_{41}, f_{62}\}$	1.7
4	1211	$\{v_1, v_2, v_4, v_6, v_8\}$	$\{f_{41}, f_{62}\}$	1.7
5	13,200	$\{v_1, v_2, v_6, v_8\}$	$\{f_{62}\}$	0.2
6	46,130	$\{v_1, v_2, v_8\}$	$\emptyset$	0.0

Table 4: Drop points and surviving flows with the minimum total power routing (Ex. 2).

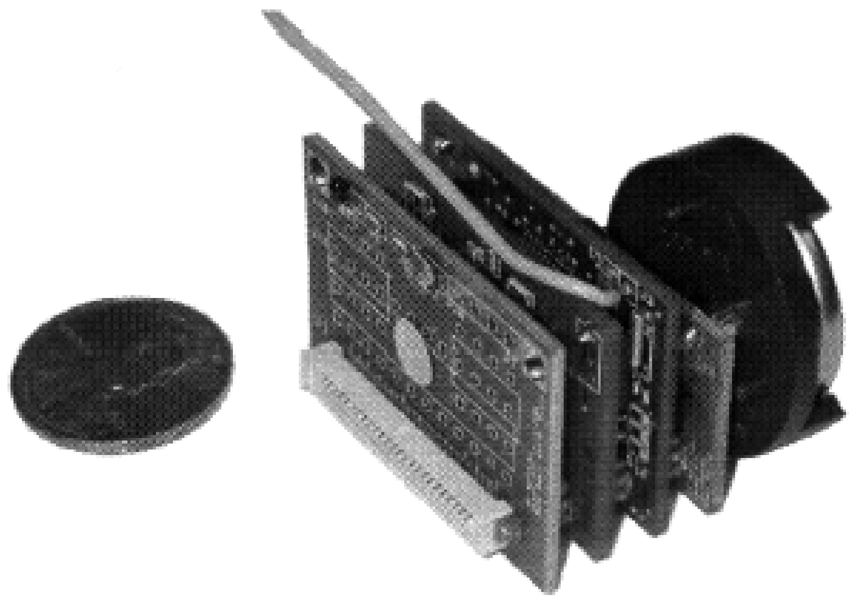
Maximum flow-life analysis

- Even without direct comparison, can see the appeal of this method over that of minimum energy!
- Authors note the need for making system distributed, choosing routes, mobility, congestion.
- Also, how might these simulated analyses compare to real-world implementation?

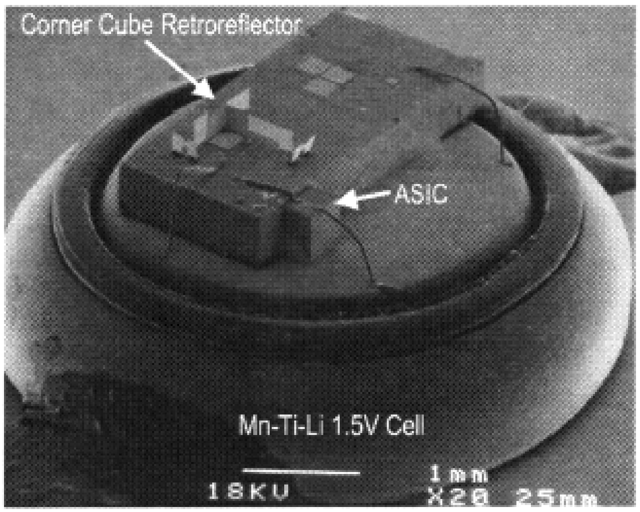
L Doherty, BA Warneke, BE Boser,

KSJ Pister 2001

Energy and Performance Considerations for Smart Dust



Smart dust characteristics



- Short-range peer to peer
- RF communication/optical
- Battery-operated/Solar-powered
- Stationary
- Cubic mm in size
- Situated in the physical world

Smart dust parameters

- Sensor performance, *power* and cost.
- How much energy is available to the sensor nodes?
- What functionality can a sensor node achieve within this energy budget?
- Integrate power ramifications of power source, computation, sensing and communication for sensor networks.

Smart dust energy sources

- Lithium energy cell: $2J/mm^3$
- Solar:
  - 0.3 mW/mm2 full sunlight
  - 0.3 mW/mm2 bright indoor illumination
- Parasitic vibration
  - ~10mW/g of converter mass (much less useful)

Smart dust energy of circuitry

Table 3
Energy Consumption of Various Processor Instructions

Instruction	Basic Processor (Calculated)	Basic Processor (Simulated)	ARM8 [3]	Description
MOVI	0.047	0.38	4.3	Move immediate value into a register
MOV	0.047	0.59	5.1	Move from register to register
ADD	0.068	0.79	4.6	Add two registers and store in a third
LW	0.053	0.44	4.6	Load from memory location specified by one register into a second register
SW	0.047	0.46	4.6	Store from a register to the memory location specified by a second register
MUL			31.9	Multiply two registers and store in a third
B - fail	0.041	0.51	4.8	Conditional branch not taken
B - pass	0.047	0.60	4.8	Conditional branch taken
JMP	0.047	0.43	4.8	Unconditional jump

Note. Energy consumption is based on (a)calculations from the component consumption values, (b) the simulated consumption of a full processor using a standard cell library, and (c) simulations of an ARM8 core. Energy consumption of the SRAM is not included. Values are given in pJ per datapath bit.

- Could be beneficial to reduce #, types of operations to lower energy use
- Selection of devices, operating voltage, register widths,bus lengths, & RAM may affect power profile.
- 1 pJ/instruction

Smart dust sensor interfaces

- Not size dependant.
- Increased operating speed, resolution dramatically affect power dissipation.
- For thermal noise limited circuit:

$$E = \frac{NV_{DD}}{(\Delta V)^2} \frac{1}{F_{Amp}}$$

  » N: accuracy in bits, Vdd: supply voltage, DV: resolution of the system, F:design multiplier

- Typical sensors (10 bit):
  - Temperature 4nJ/sample
  - Accelerometer 2uJ/sample for milliG resolution
- A/D conversion 10-bit conversion ~4nJ

Smart dust low power RF communication

- Limited by thermal noise, min. signal power must be:

$$P_{r,min} = kTB \cdot N_f \cdot SNR_{min}$$

- In typical operation, min. receiver power is:

$$P_r = \frac{P_t G_{ant}}{16\pi^2 (d/\lambda)^n}$$

shere n=2 in freespace, and n=2-7 at ground level with an average of 4

- Fundamental ground-to-ground communication limit at 1kbps over 100m is 1µJ/bit, 100nJ/bit short range

Smart dust optical communication

- Over 0-50m range requires ~20pJ/bit (vs 100nJ/bit using RF on gound)
- Over 1-10kM 10nJ/bit required(vs 50uJ/bin)
- However, requires line of sight and orienting of optical beam

Smart dust scenarios

	Building Monitoring	Seismic Profiling	Tracking Scenario
Communication	Source to central receiver (single hop) Radio	Source to central receiver (single hop) Radio	Ad hoc wireless nodes
Energy requirement/ Life	300mJ/day Battery:1week/mm^3 Solar: indefinite w/900mm^2 array	10mJ/day Battery: 2 days/mm^3 with wakeup	10mA from 3V lithium. 2 days/battery Solar: 0.15W/day
Other issues	Sampling period maps nearly linearly to battery life	Low duty cycle necessitates self-awakening or beacon	Suggest heterogeneous modes of operation

Smart dust analysis

- Sensor networks are possible (but have a definite lower bound on power consumption!)
- High density is necessary to overcome distance attenuation
- Computation significantly less expensive than communication or sensing

(100 million instructions ⇔ 100 bits ⇔ 50 samples)

- Distributed sensing, but most scenarios avoid doing real networking (no listening?)