Compressed Neighbor Discovery for Wireless Ad Hoc Networks

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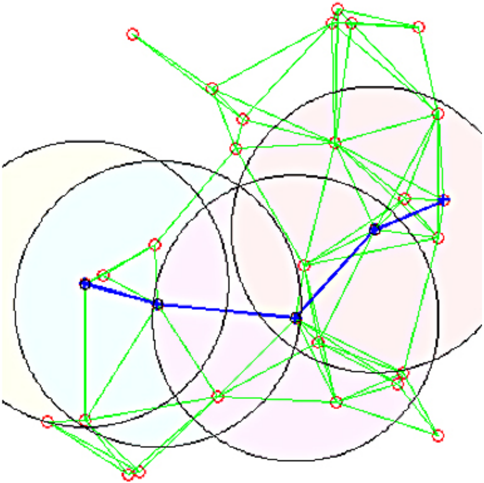
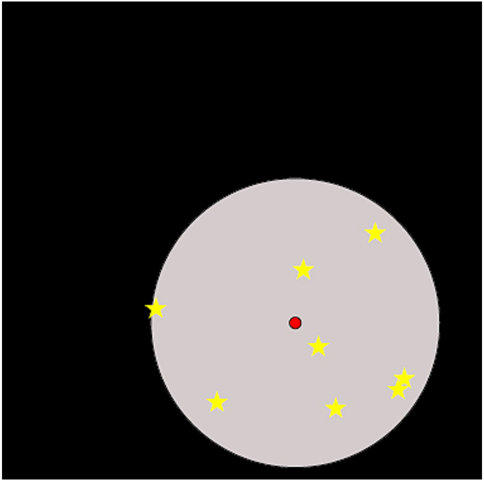
Neighbor Discovery is Fundamental to a Reliable Ad Hoc Network



How to Discover Neighbors?

- Query node emits a beacon.
- Neighbors illuminated.
- Synchronized response.



State of the Art

- Repeated and randomly-delayed announcements of identity.
  - the "birthday" scheme [McGlynn & Borbash '01] [Borbash, Ephremides & McGlynn '07]
  - the directional antenna neighbor discovery [Vasudevan *et al* '05] [Zhang '05]
- TND Protocol (IETF MANET Workgroup)
  Periodic HELLO massages with jitter.

Self Network Interface Address				
n	TYPE	HSEQ	Pri	n
Neighbor Interface Address (1)				
...				
Neighbor Interface Address (n)				

- A large amount of OVERHEAD.

The Neighbor Discovery Problem

- Many network interfaces, but only a few around query node.
- Response synchronized by beacon.
- $\mathbf{S}_n$: response (signature) of node n.
- Measurement via multiaccess channel (U_n: channel gain):

$$\mathbf{Y} = \sum_{n=1}^{N} \sqrt{\gamma}\mathbf{S}_n U_n B_n + \mathbf{W} = \underline{\mathbf{S}}\mathbf{U}\mathbf{B} + \mathbf{W}.$$

- Equivalent to inferring about a neighborhood vector:

Node addresses:	1	2	3	4	...	n	...	99999
Neighborhood $\mathbf{B}^\top$:	0	1	0	0	...	1	...	0

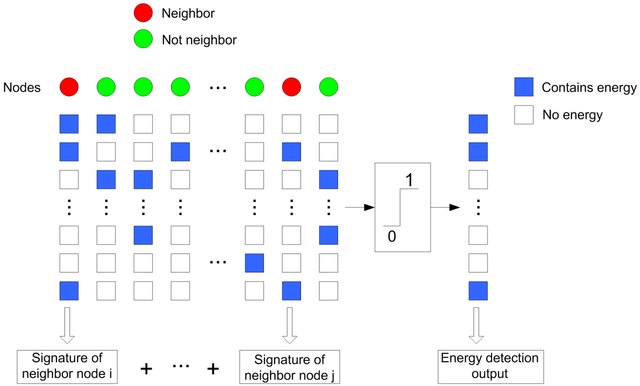
Goal of Neighbor Discovery

The goal of neighbor discovery is to detect one's neighborhood vector based on (noisy) measurements of the superposition of the signatures,
ideally using as few measurements as possible.

Insight from *compressed sensing*: Suppose $\mathbf{x} \in \mathbb{R}^N$ is unknown; we measure linear functions of $\mathbf{x}$ and then reconstruct. If $\mathbf{x}$ is sparse, then the number of measurements can be dramatically smaller than the size N. [Candès and Tao '07]

A Practical Scheme Based on Group Testing

- Binary signatures.
- Noncoherent energy detection via thresholding.
- Reconstruction by elimination.
- Group testing literature [Dorfman '43] ... [Berger-Levenshtein '02].



The Rayleigh Fading Case

Proposition

N nodes in total, on average c neighbors (c a constant);
U_n: Rayleigh fading $\sim \mathcal{CN}(0,1)$;
$\underline{S}$: $M \times N$ measurement matrix, i.i.d Bernoulli(q);
γ: signal-to-noise ratio;
T : threshold for energy detection;
the average $\sharp$ of neighborhood errors can be upper bounded as:

$$\mathcal{E} \leq \frac{cMqT^2}{\gamma} + N \exp\left(-Mq\Phi(T) + c\left(e^{Mq^2\Phi(T)} - 1\right)\right),$$

where

$$\Phi(T) = 1 - \exp(-T^2).$$

Design Approach I

Design (Minimum Signature Length)

Given a neighborhood error requirement $\mathcal{N}_e$, to ensure $\mathcal{E} \leq \mathcal{N}_e$, choose M and T as the minimum and minimizer of the following optimization problem:

$$\min_t \quad \frac{\mathcal{N}_e^2 \gamma^2 \Phi(t)}{4c^2 t^4} \left[\log \left(1 + \frac{1}{c} \left(\frac{\mathcal{N}_e \gamma \Phi(t)}{2ct^2} - \log \left(\frac{2N}{\mathcal{N}_e} \right) \right) \right) \right]^{-1}$$

$$s.t. \quad \frac{\Phi(t)}{t^2} > \frac{2c}{\mathcal{N}_e \gamma} \log \left(\frac{2N}{\mathcal{N}_e} \right), \quad t \geq 0,$$

and choose q as

$$q = \frac{\mathcal{N}_e \gamma}{2cT^2 M},$$

when

$$\gamma > \frac{2c}{\mathcal{N}_e} \log \left(\frac{2N}{\mathcal{N}_e} \right).$$

System Design Examples Based on Approach I

Table: System Design Examples of the Minimum Signature Length Approach

N	c	$\mathcal{N}_e$	SNR γ (dB)	M	q	T
10 K	6	0.01	45	1263	0.026	0.889
1 million	6	0.01	45	3958	0.017	0.619
2^{32}	6	0.01	47	4252	0.018	0.734

Design Approach II

Design (Minimum SNR)

For a given neighborhood error upper bound $\mathcal{N}_e$ and a maximum signature length constraint L, choose M, q and T as the minimizers of the following optimization problem:

$$\begin{aligned}
\min_{\{M,q,T\}} \quad & MqT^2 \\
s.t. \quad & N \exp\left(-Mq\Phi(T) + c\left(e^{Mq^2\Phi(T)} - 1\right)\right) \leq \frac{\mathcal{N}_e}{2}, \\
& 0 < M \leq L, \\
& 0 < q < 1, \quad T \geq 0.
\end{aligned}$$

System Design Examples Based on Approach II

Table: System Design Examples of the Minimum SNR Approach

N	c	$\mathcal{N}_e$	SNR γ (dB)	M	q	T	L
10 K	6	0.01	45	1263	0.026	0.889	1263
10 K	6	0.01	44	2526	0.020	0.646	2526
1 million	6	0.01	45	3958	0.017	0.619	3958
1 million	6	0.01	44	7916	0.013	0.482	7916
2^{32}	6	0.01	47	4252	0.018	0.734	4252
2^{32}	6	0.01	46	8504	0.014	0.551	8504

Numerical Results

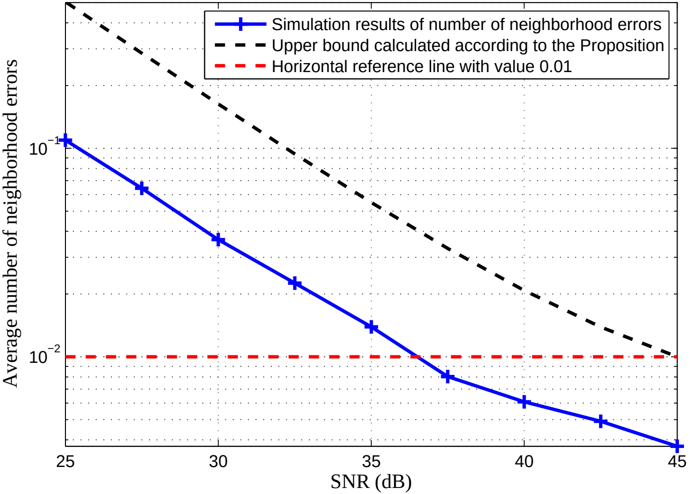


Figure: $N = 10000$, $C = 6$, $M = 1263$, $q = 0.026$ and $T = 0.889$.

Comparison: Compressed Neighbor Discovery v.s. Random Access

10,000 nodes, average neighborhood size 6.

- Metric: average $\sharp$ of neighborhood errors.
- Compressed neighbor discovery:
  1263 measurements (bits), $\sharp$ of neighborhood errors < 0.01.
- Birthday algorithm [McGlynn and Borbash '01]:
  - Identification of each node takes $\lceil \log_2 10,000 \rceil = 14$ bits.
  - To achieve an error rate of 0.01, at least 143 contention periods are required.
  - $143 \times 14 = 2002$ bits.
  - Not yet counting error control and synchronization overhead.
- Compressed neighbor discovery saves 40%.

Comparison: Mark-into IEEE 802.11g Standard

10,000 nodes, average neighborhood size 6. Using specifications in IEEE 802.11g standards.

- Birthday algorithm:
  - One contention period takes $850\mu s$, counting error-control and synchronization redundancy.
  - $850\mu s \times 143 = 122ms$.
- Compressed neighbor discovery:
  - A chip time takes about $40\mu s$ (including symbol duration, transmitter ramp period and propagation delay).
  - $1263 \times 40\mu s = 51ms$.
- Compressed neighbor discovery saves 60%.

Conclusion

- Practical noncoherent energy detection.
- Significantly reduced overhead.
- Similar result even with half-duplex constraint.
- Results can be generalized to fading processes other than Rayleigh.