Efficient and Scalable Query Routing for Unstructured Peer-to-Peer Networks

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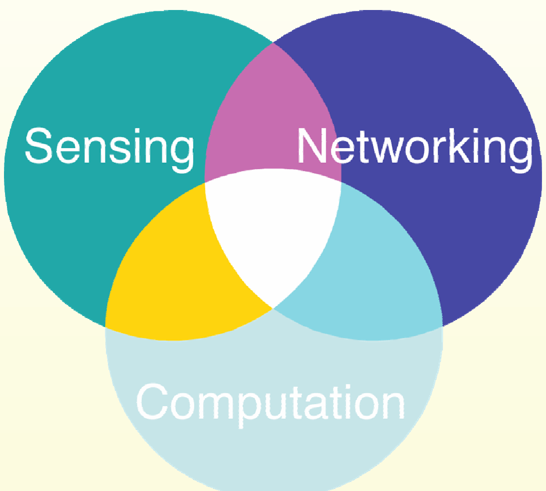
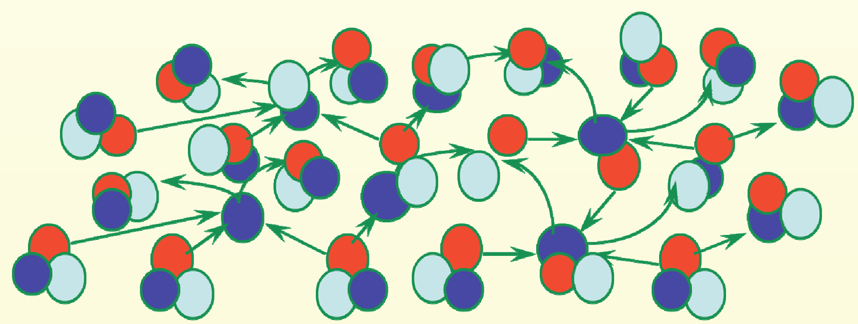




The Problem:

- Searching for content in an unstructured network

Constraints:

- Content and/or structure are highly dynamic
- Any node can originate content (lots of content)
- Limited bandwidth and memory at each node
- No *a priori* knowledge of the environment

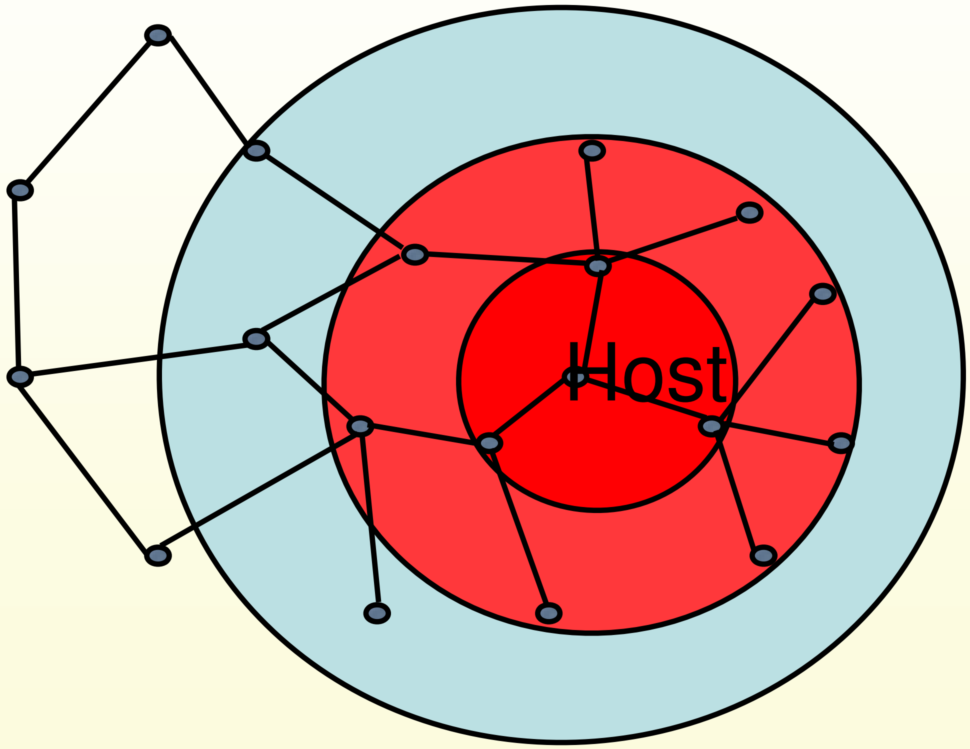
Possible Solutions:

- Flooding
- Random Walk
- Supernodes/Ultrapeers
- One-Hop Replication of Index
- Expanding ring search
- GIA: Optimized Topology Construction, Load Balancing

Problems (trade-offs):

- Speed (low temporal locality in search traffic)
- Scalability (replicating content indices is expensive)

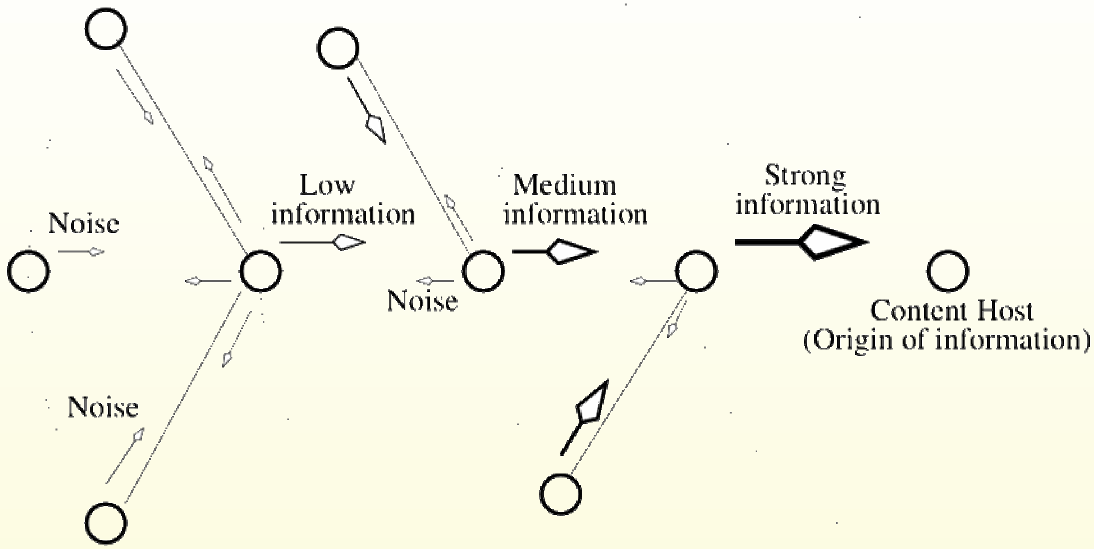
Scalable Query Routing (SQR)



Scalable Query Routing (SQR)

- Maintain probabilistic “routing tables”
- High information about close neighbors
- Information intensity “decays” with distance
- A data-structure at each node to achieve this
- Queries perform a “partially guided” random walk

Scalable Query Routing (SQR)



Information about content on a host
decays exponentially with distance

Bloom Filter

Given a set $S = \{x_1, x_2, x_3, \ldots x_n\}$ on a universe U, want to answer queries of the form:

$$\text{does } z \in S$$

- Bloom filter answers in "constant" time
- Small amount of space.
- But with some probability of being wrong.

Bloom Filter

Array of *m* bits all set to 0 initially

B	0	0	0	0	0	0	0	0	0	0	0	0

When inserting an element *x*, set B[$h_i(x)$] = 1 for *i* =1 to *k*

B	0	1	0	0	0	0	1	0	0	1	0	0

To check if *y* is in *S*, check *B* at $h_i(y)$. All *k* values must be 1

B	0	1	0	0	1	0	1	0	0	1	1	1

May have false positives; all *k* values are 1, but *y* is not in *S*

B	0	1	0	0	1	0	1	0	0	1	1	1

Bloom Filter

Under the assumption:

- Good (pseudo-random) hash functions

Can bound the probability of a false positive and optimize the number *k* of hash functions to minimize this probability.

Given *n* objects and a Bloom filter of size *m*:

$$p = \Pr[\text{cell is empty}] = (1 - 1/m)^{kn} \approx e^{-kn/m}$$

$$f = \Pr[\text{false pos}] = (1 - p)^{k} \approx (1 - e^{-kn/m})^{k}$$

k that minimizes $f = (\ln 2)m/n$

Exponentially Decaying Bloom Filter (EDBF)

Array of *m* bits. Also uses *k* hash functions.
Insertion is identical to BF.

Testing for membership, returns the number of bits set to 1

$$\theta(x) = |\{i | A[h_i(x)] = 1, i = 1, 2, ..., k\}|$$

When EDBF is used in the probabilistic query routing in SQR, $\theta(x)/k$ roughly represents the probability of finding *x* along a particular link

Exponentially Decaying Bloom Filter (EDBF)

- Nodes advertise their EDBF to their neighbors
- Each node keeps separate copies of EDBF received from each of its neighbors
- When advertising to downstream neighbors nodes take the union of local EDBF with EDBFs of the neighbors resetting bits in these with probability (1/*d*)
- Because of the decay, for any object *x*, $\theta(x) = k$ for a node one hop away, k/d two hops away, $k/(d^n)$ n hops away

Exponentially Decaying Bloom Filter (EDBF)

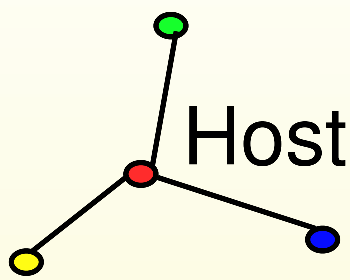
Constructing and updating EDBF:

```
Create Local EDBF (given local content X):
      // Populate local EDBF A.
 1. ∀x ∈ X
 2.      Set bits A[h_1(x)], ..., A[h_k(x)] to 1;

Create Update (for neighbor j):
    // Copy all the bits from the local EDBF A into
    // the update U_j.
 1. U_j ← A;
    // Decay the information received from all neighbors
    // other than j by a factor of d, and add the
    // surviving bits to U_j.
 2. ∀i ∈ neighbor_list, i ≠ j
 3.      ∀r ∈ {1, ··· , m}
 4.           if(A_i[r] == 1)
 5.                with probability 1/d, U_j[r] ← 1;
 6. Return U_j;
```

Fig. 2. Algorithms for creating updates in SQR.

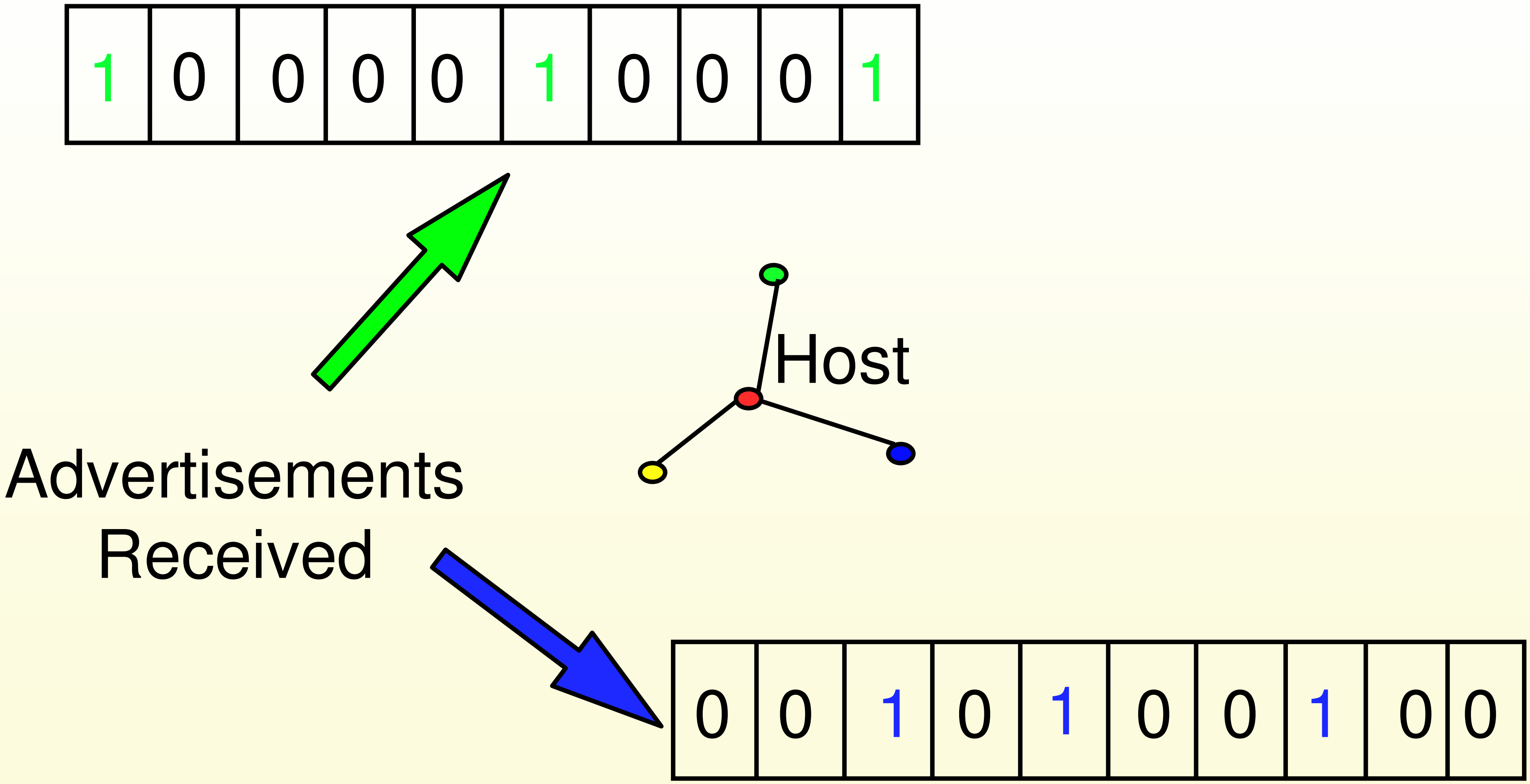
Using EDBF for Routing



Local EDBF

0	1	0	0	1	0	0	1	0	0

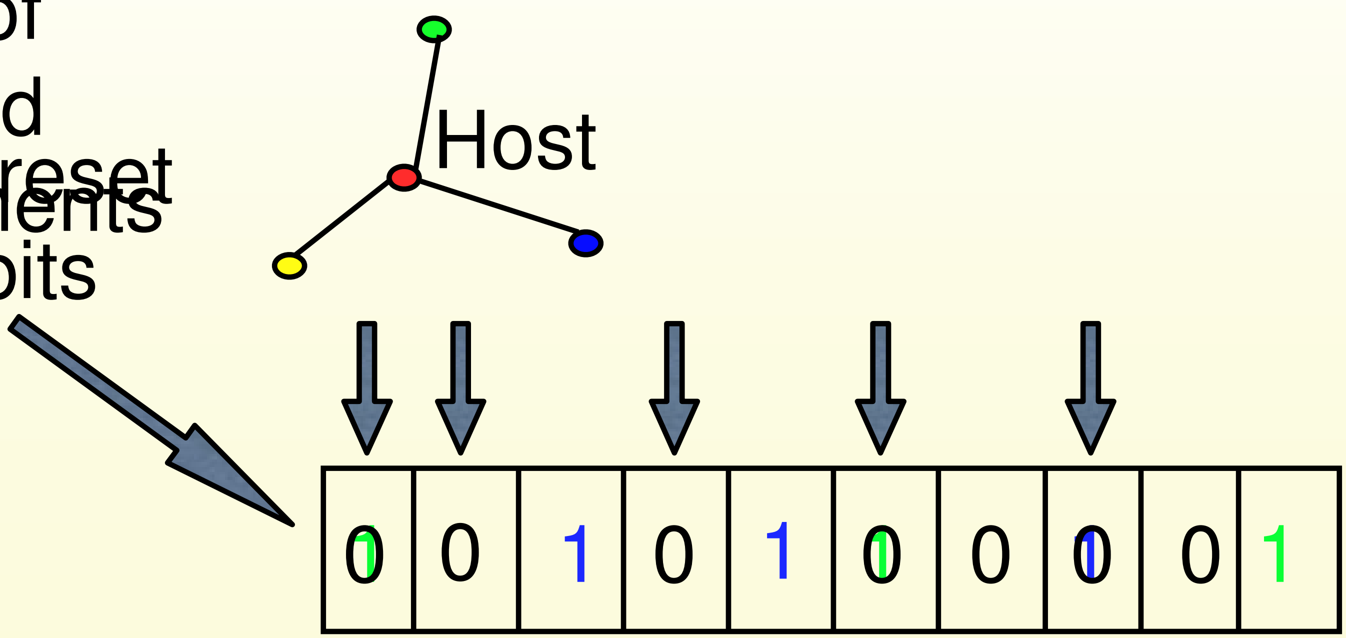
Using EDBF for Routing



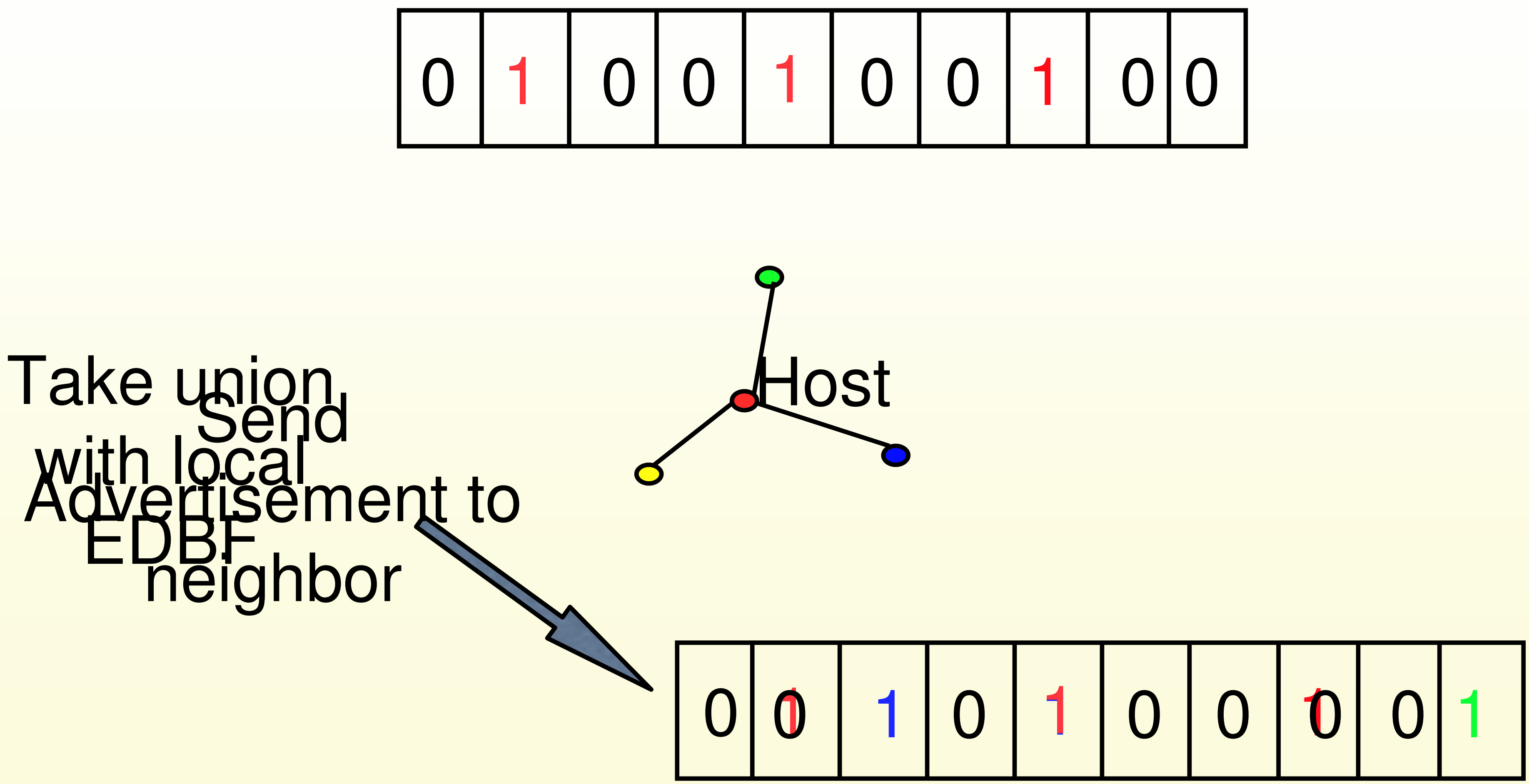
Using EDBF for Routing

Union of received advertisements

Randomly reset half the bits



Using EDBF for Routing



Exponentially Decaying Bloom Filter (EDBF)

Query routing:

- If the query is satisfied locally, it is answered
- If the query has previously been seen, it is forwarded to a random neighbor
- Otherwise the query is forwarded to the neighbor advertising the highest value $\theta(x)$, the total number of bits set to 1 in locations indexed by $h_j(x), j \in 1...k$

Exponentially Decaying Bloom Filter (EDBF)

Query routing:

`Forward Query (given query` Y`):`

// Forward previously seen queries to neighbor i, .
// chosen randomly from `neighbor_list`.

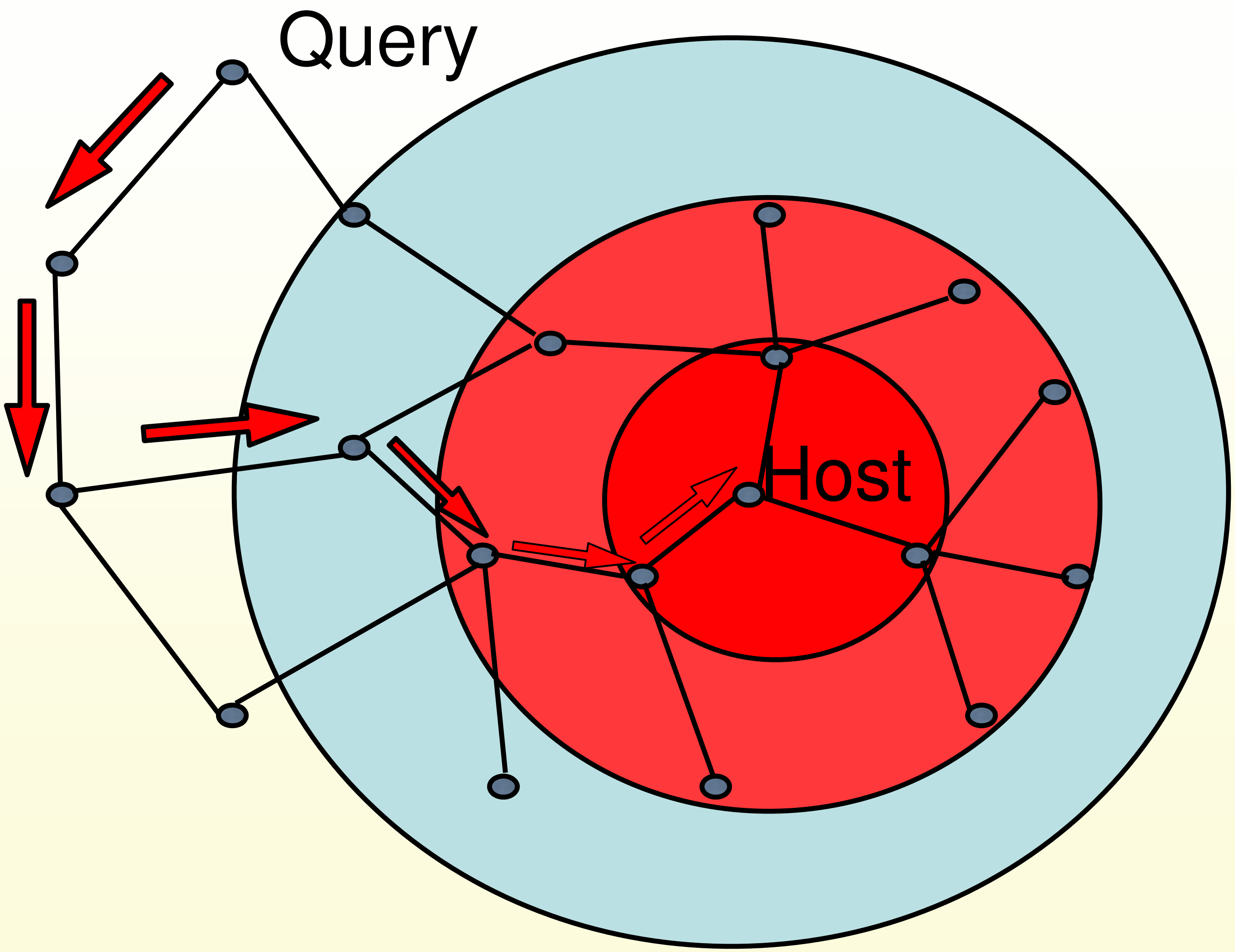
1. if(`Seen Query(`Y`))`
2. `Deliver Query(`Y`,`i`);`
3. else
   //Forward previously unseen queries to the neighbor
   // with the maximum information about this query.
4. $\Theta \leftarrow$ `Lookup (`Y`);`
5. Pick i such that $\theta_i = max(\Theta)$;
6. `Deliver Query(`Y`,`i`);`

`Lookup (given query` Y`):`

1. $\forall i \in$ `neighbor_list`
2. $\forall q \in \{1, \cdots, k\}$
3. $\theta_i += A_i[h_q(y)]$;
4. `Return` Θ; /* $\Theta = \{\theta_i\}$ */

Fig. 3. Algorithms for forwarding queries in SQR.

Query Routing

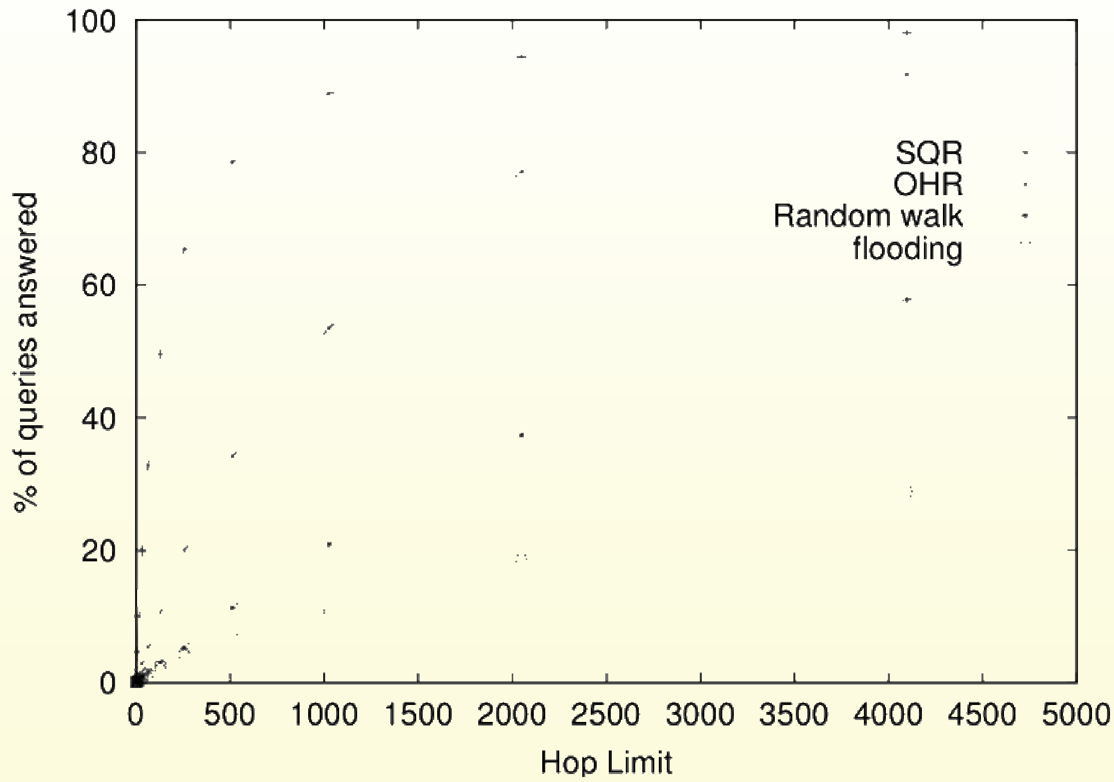


Exponentially Decaying Bloom Filter (EDBF)

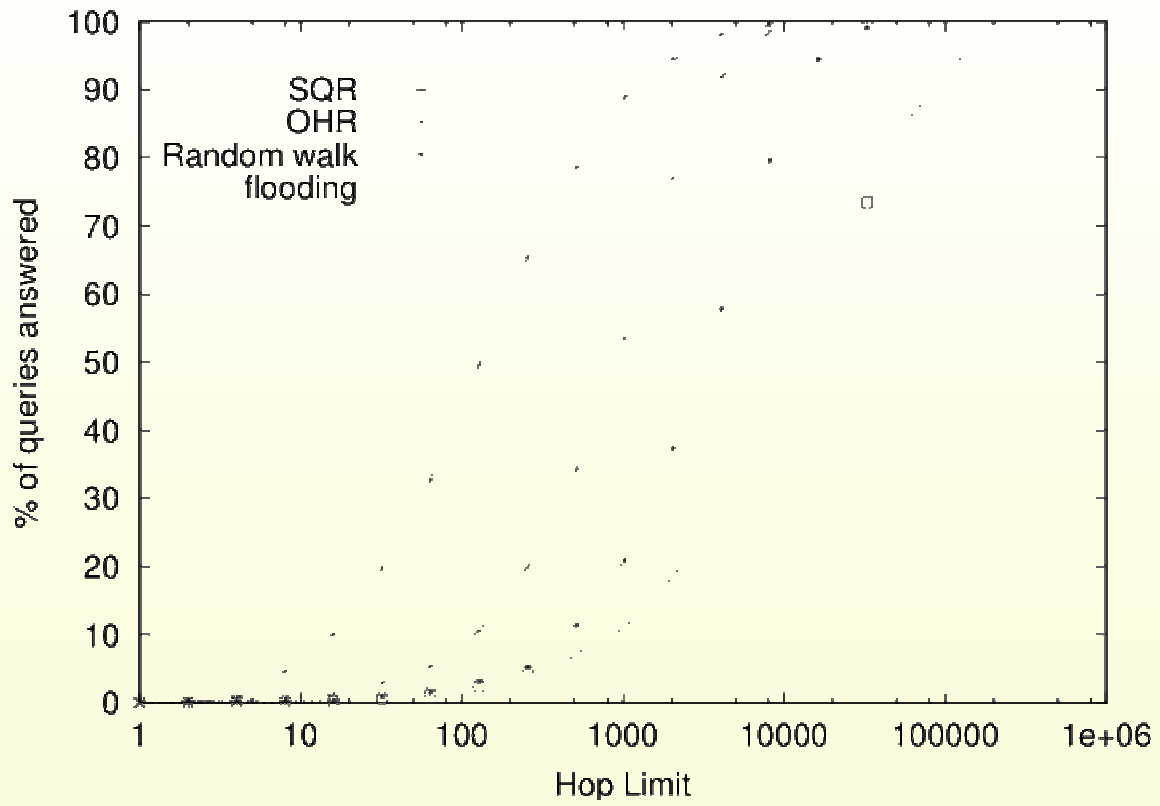
Optimizations:

- Use delta encoding for updates
- Use arithmetic coding for data compression
  - increasing the size of the array while reducing the number of hash functions slightly can improve the efficiency of BF

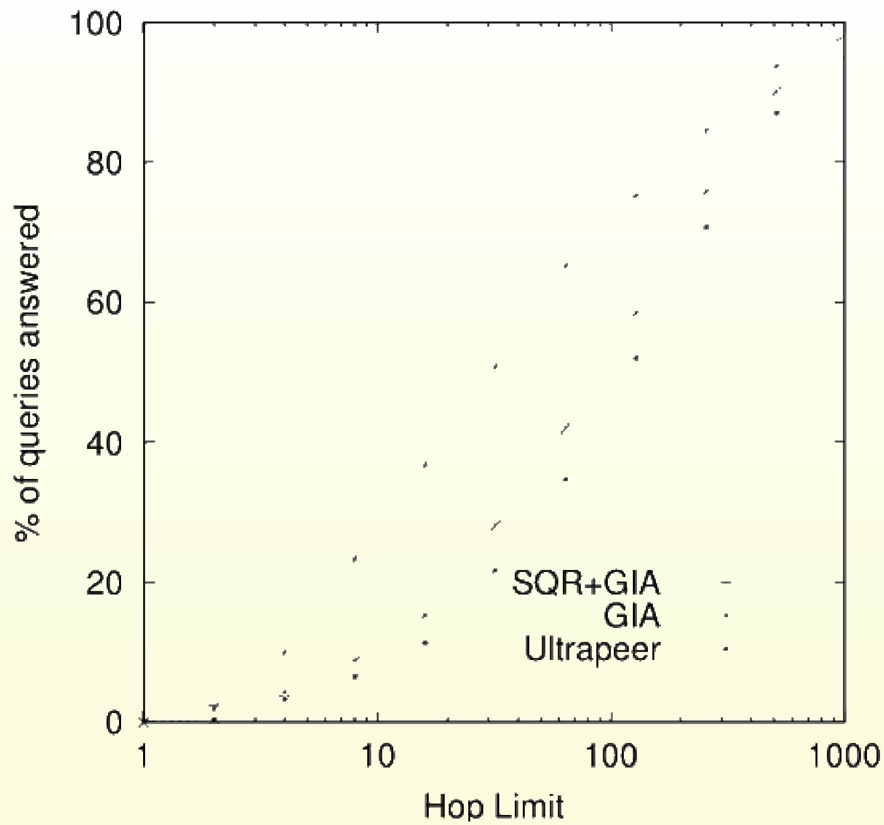
SQR Performance: Flat Topologies



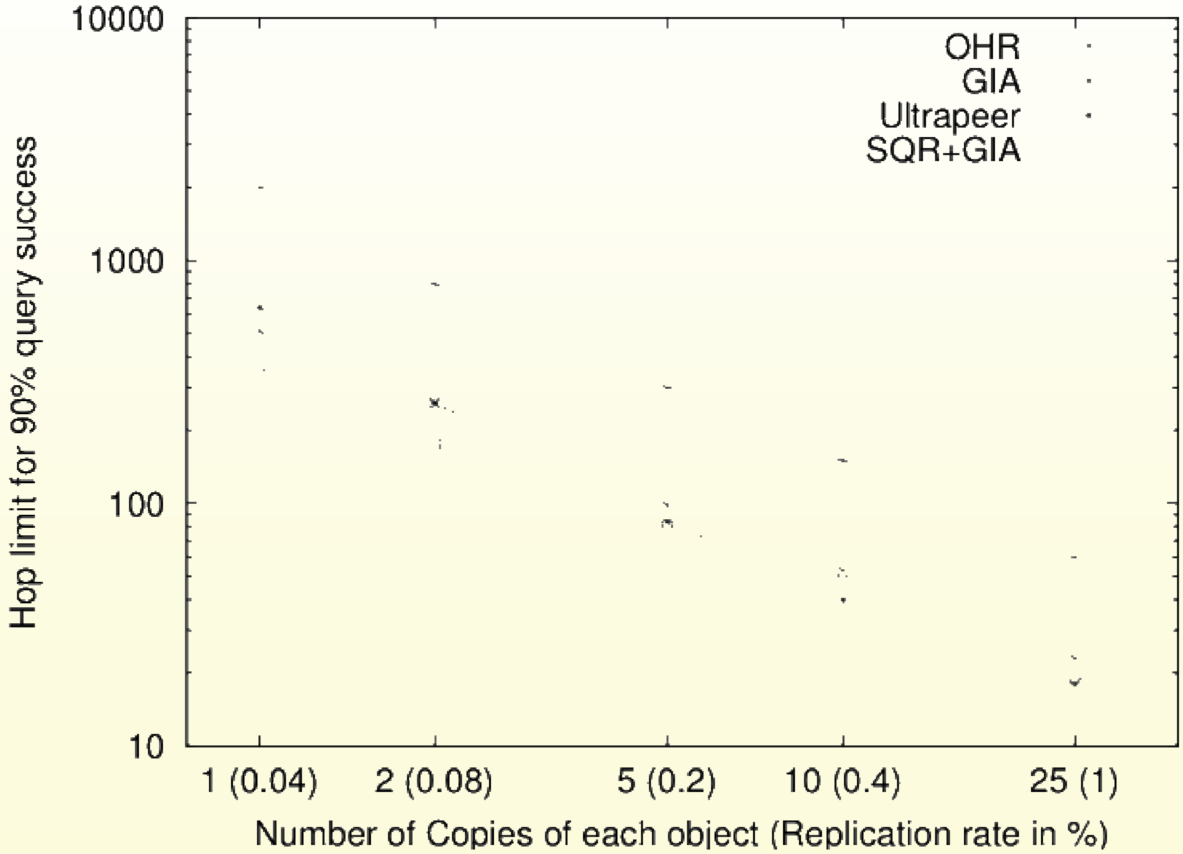
SQR Performance: Flat Topologies



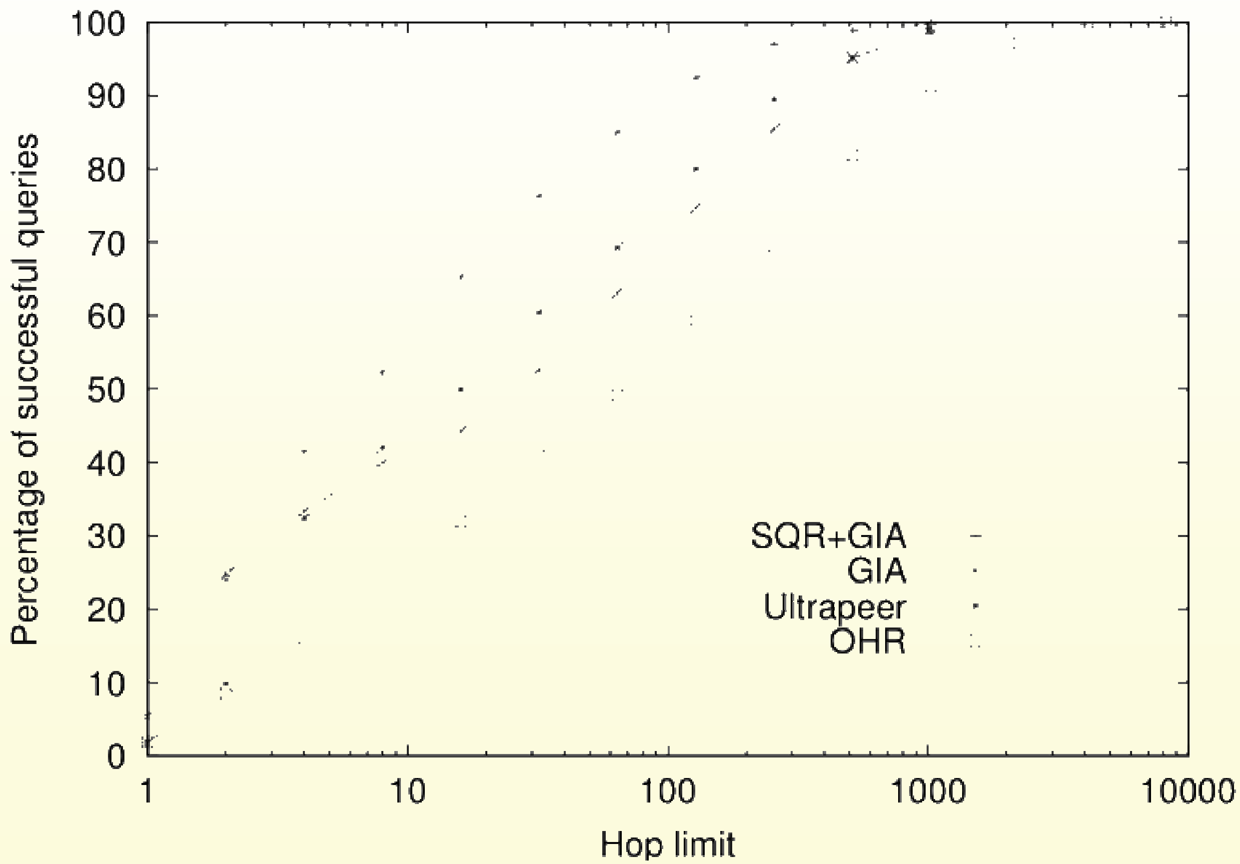
SQR Performance: Hierarchical Topologies



SQR Performance: Impact of Replication



SQR Performance: Impact of Replication with Zipf distribution



Conclusions:

• Highly compressed information about content in the neighborhood cab speed up the routing

• Exponential decay of information with distance ensures scalability of the approach

• Probabilistic routing information can be “reliable” and efficient

Problems:

- Deleting content is unsupported in Bloom filters (could be done in EDBF due to probabilistic nature)

- In a large sensor network, random walks may be highly inefficient

- Hashing may be too time/energy expensive for simple nodes

Thank You