SIA: Secure Information Aggregation in Sensor Networks

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(presented by Aleksandr Yampolskiy)

Outline

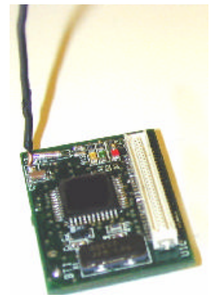
- Motivation
- The model
- Results
  - Median
  - Min/max
  - Counting distinct elements
- Conclusion

What is a sensor network?

- Thousands of sensor nodes
- Sensors collect data and relay information to users
- Many applications
  - battlefield surveillance
  - wildlife monitoring
  - seismic safety
  - tracking NFL players during SuperBowl XXXVIII

What is a sensor network? (cont.)

- Sensors are severely constrained: limited battery power, computation resources, bandwidth.
- **Example:** UC Berkeley mote
  - 4 Mhz Atmel processor
  - 4kB RAM and 128 kB code space
  - 917 MHz RFM radio at 50 kb/s



- Conflict between limited resources and security requirements.

Why do we need aggregation?

Problem:

- Forwarding raw information is too expensive.
- Individual sensors readings are of limited use.
  - May want to know MAX of seismic readings and not the readings themselves.
  - We have a CPU on board. Let's use it!

Why do we need aggregation? (cont.)

Solution:

- Dedicated sensor nodes, called aggregators
- Information is processed in the network and only results are forwarded to the user
- Common aggregation operators: COUNT, MIN/MAX, AVERAGE, SUM, ...

Why this paper?

- Most prior work [DNGS03, EGHK99, IEGH01, MFHH02] study aggregation under the assumption that *every* node is honest.
  - But… what happens if the adversary takes posession of a sensor node or, even worse, an aggregator?

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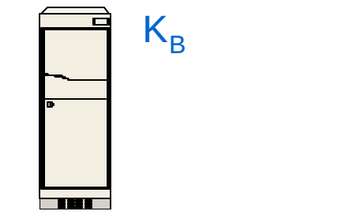
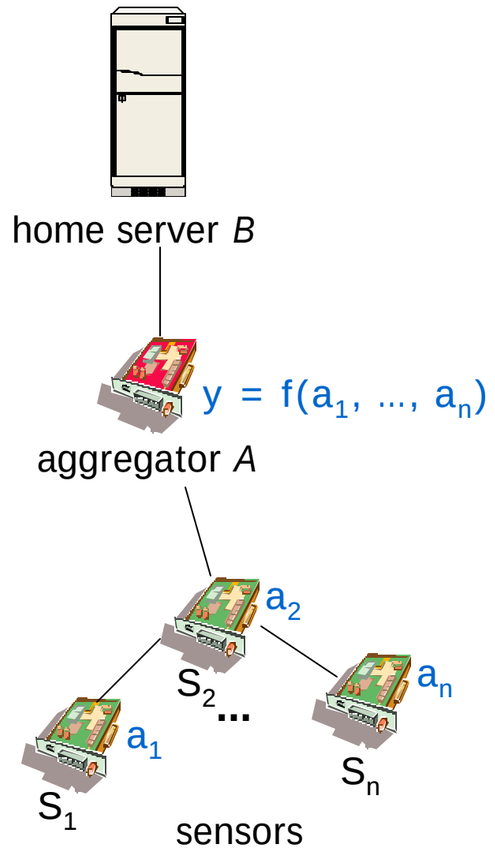
The model

- Sensors S_1,..., S_n
- Single aggregator A
  - resource-enhanced
  - master key K_A
- Home server B
  - master key K_B



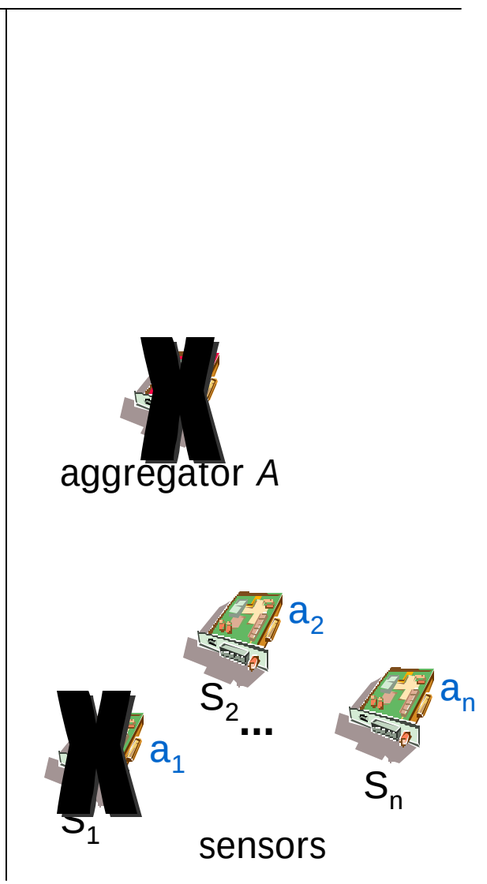
The model (cont.)

- Each sensor S_i has a
  - unique ID_i
  - shared keys $MAC_{K_A}(ID_i)$ and $MAC_{K_B}(ID_i)$
  - sensor measurement $a_i \in \{1, 2, \ldots, m\}$
- Aggregator A computes $y = f(a_1, \ldots, a_n)$



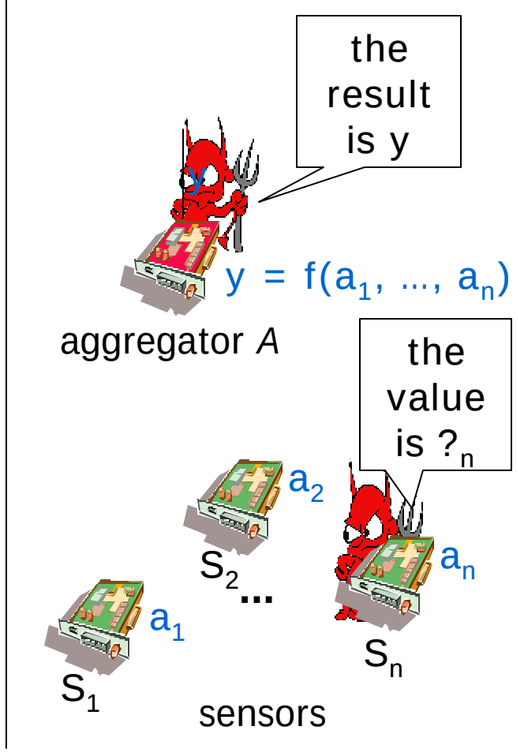
Attack model

- Aggregators or sensors may be compromised
- There are many kinds of attacks.
- **Example:** DDoS attacks, where nodes are too overwhelmed to respond to queries



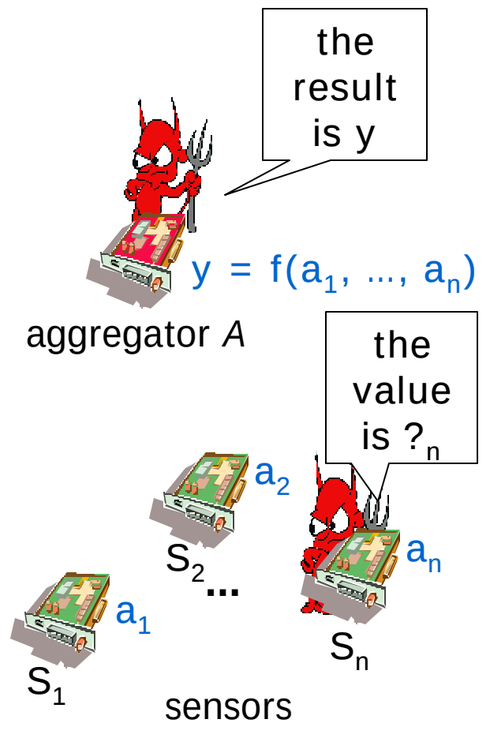
Attack model (cont.)

- The focus is on stealthy attacks.
- They try to cheat the user into accepting false aggregation results which are significantly different from true results.



Attack model (cont.)

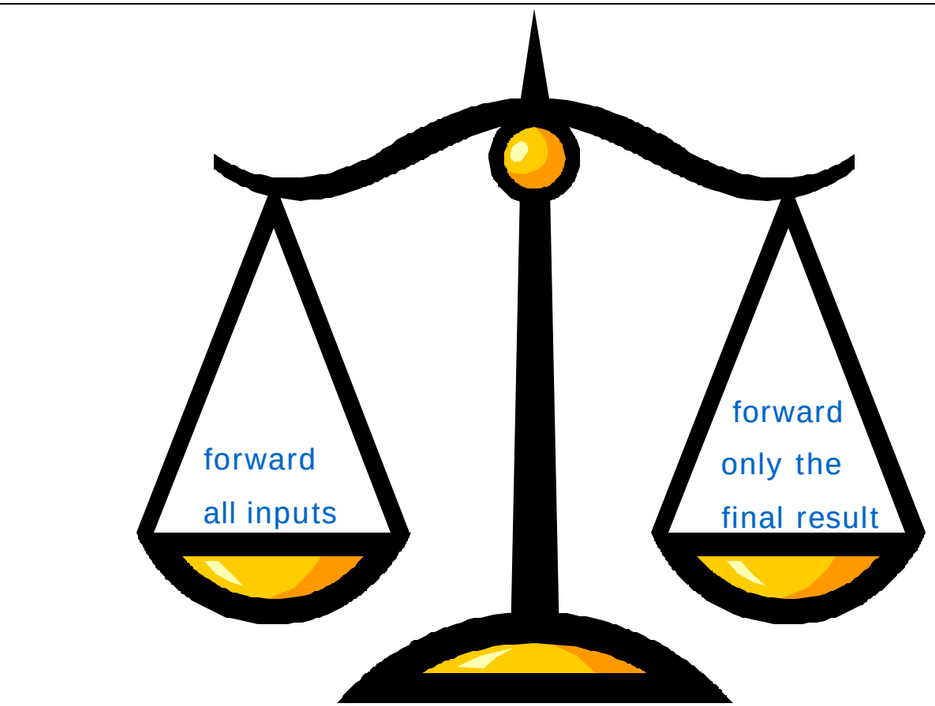
- Suppose aggregator reports y instead of the actual $y = f(a_1, \ldots, a_n)$
- We will look for (ε, δ)-schemes so that if the server accepts y, we have:
  $\Pr[|y - y| \cdot \varepsilon y] \; ¸ \; 1 - \delta$



Some assumptions

- Byzantine fault model [LSP82]
- Polynomially bounded attacker
- Can corrupt a (small) fraction of sensors
- Uncorrupted sensors form a connected component containing an aggregator 
- Home server and aggregator can broadcast to all sensors (e.g., using μTESLA)

Tradeoff



security

$a_1, \ldots, a_n$

efficiency

$y = f(a_1, \ldots, a_n)$

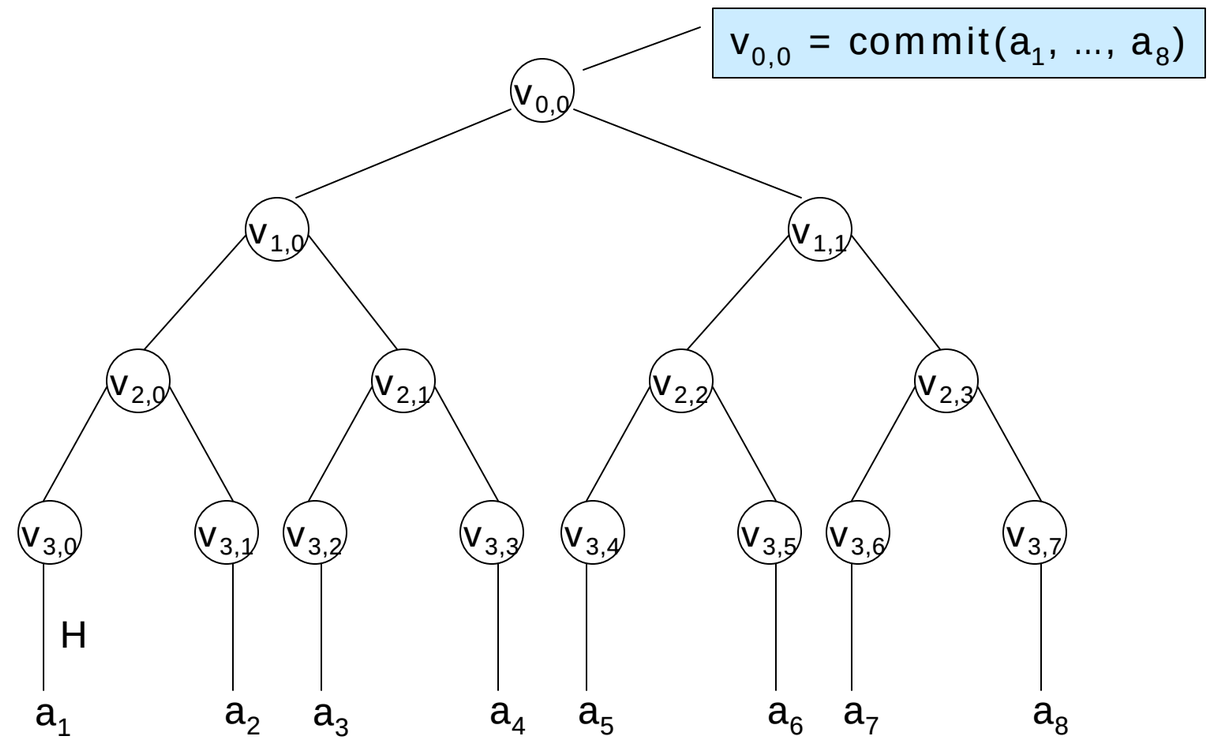
General approach

- Three phases: aggregate, commit, prove
  1. Aggregator collects data from sensors and locally computes aggregation: $y = f(a_1, \ldots, a_n)$
  2. Aggregator commits to the collected data: $c = commit(a_1, \ldots, a_n)$.
  3. Aggregator sends y and to the home server and engages in an IP:
     1. Home server checks that committed data is a good representation of true data values.
     2. Home server checks if the aggregator is cheating: Is ? close to y?

General approach (cont.)

- Merkle hash tree [Merkle80] is used to commit to measurements $a_1, \ldots, a_n$
- Basic idea:
  - Put data $a_1, \ldots, a_n$ at the leaves.
  - Each node contains a hash of its children: $v_{i,j} = H(v_{i+1,2j} \mid\mid v_{i+1,2j+1})$.
  - Root node $v_{0,0}$ is the commitment.

General approach (cont.)



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Computing the median

- **Goal:** Securely compute the median of a_1, …, a_n (if a_i are not distinct, use (a_i, ID_i) pairs).
- Median is the middle of distribution. For example, the median of 3, 5, 11, 4, 7 is 5.
- n' corrupted nodes can cause aggregated median to deviate by at most n' positions from true value.

Computing the median (cont.)

- **Naïve approach 1**: send *all* measurements to the home server.
  - Too inefficient.
- **Naïve approach 2**: send sample of *l* measurements to the server.
  - Use sample's median as an approximation to the true median.

Computing the median (cont.)

Thm: The median of a uniform sample of *l* out of *n* elements yields an element whose position in the sorted sequence $a_1, \ldots, a_n$ is within εn of $n/2$ with probability $\geq 1 - (2/e^{2l\varepsilon^2})$.

Proof idea:

- Can bound $\Pr[|X_l - n/2| > \varepsilon n]$ using Hoeffding bound.
- Sample size $\Omega(1/\varepsilon^2)$ is needed [BKS01].

Digression: spot-checkers

- Program P computes function *f* on input x [EKK+99].
- Ascertain that program output P(x) is reasonably correct in o(|x| + |f(x)|) time.
- ε-spot-checker for sorting: ? (1/ε) running time.

```
procedure Sort-Check-II(A, ε):
repeat O(1/ε) times
    choose i2_r [1, n]
    perform binary search as
if to determine if a_i is in A
    if not found
        return FAIL
return PASS
```

Computing the median (cont.)

- **Better approach:**
  1. *A* commits to a sorted sequence $\vec{a} = sort(a_1, \ldots, a_n)$ using a Merkle tree
  2. When *B* obtains an alleged a_{med}, he first verifies that $\vec{a}$ is sorted using `Sort-Check-II`.
  3. Then *B* uses `MedianCheck` to check that that a_{med} is close to the true median.

Computing the median (cont.)

```
procedure MedianCheck(n, a_med, ε):
request a_{n/2}
if a_{n/2} ? a_med then
      return REJECT
for i = 1…(1/ε) do
      pick j 2_r {1…n}\{n/2}
      request a_j
      if j < n/2 and a_j > a_med then
            return REJECT
      if j > n/2 and a_j < a_med then
            return REJECT
return ACCEPT
```

Computing the median (cont.)

Thm: MedianCheck(n, a_{med}, ε) requests $1/\varepsilon$ elements a_i, runs in time $O(t¢1/\varepsilon)$ and satisfies:

1. if $a_{med} = a_{n/2}$, then the result is "ACCEPT"
2. if a_{med} is not in the sequence or its position p satisfies $|p - n/2| > \varepsilon n$, then with probability > ½ the result is "REJECT".

Computing the median (cont.)

Proof:

(1) Trivial.

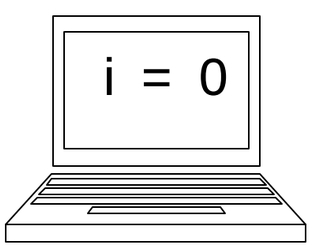
(2) Notice that if $|p - n/2| > \varepsilon n$, then there are $\geq \varepsilon n$ values of j, which yield reject. Hence, with probability $\leq (1 - \varepsilon)^{1/\varepsilon} \leq 1/e$ for-loop completes without rejection. QED.

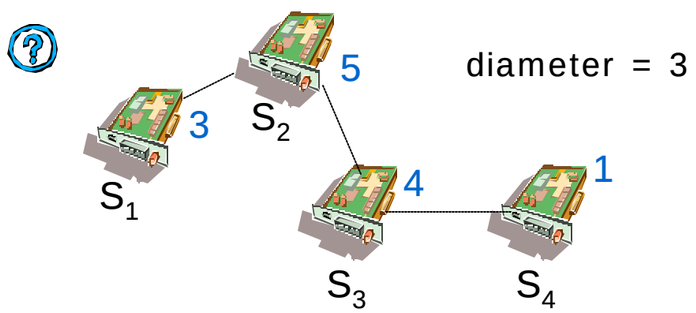
Computing min/max

- **Goal:** Securely compute min(a_1, …, a_n), where a_i 2 [m].
- Corrupted sensor can always claim his measurement to be 1 and disrupt the calculations
- Assume that sensors don't lie about their values

Computing min/max (cont.)

- First construct a spanning tree so that the root holds the minimum element.

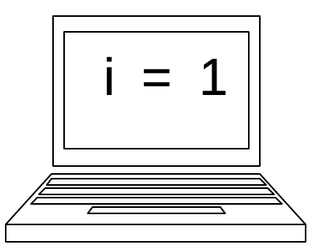


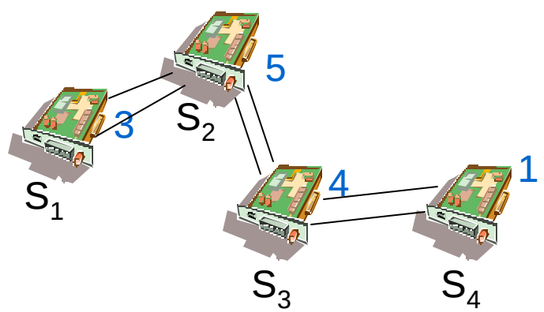


	p_i	V_i	id_i
S_1	S_1	3	id_1
S_2	S_2	5	id_2
S_3	S_3	4	id_3
S_4	S_4	1	id_4

Computing min/max (cont.)

- First construct a spanning tree so that the root holds the minimum element.

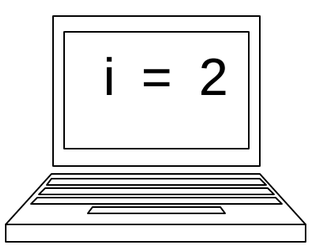


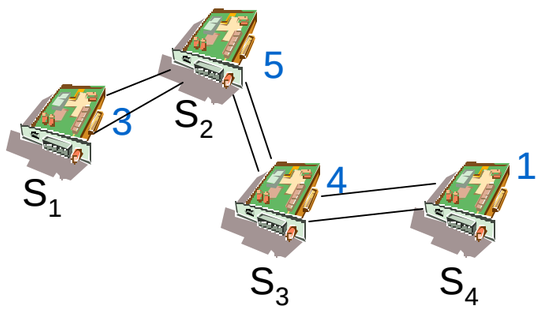


	p_i	V_i	id_i
S_1	S_1	3	id_1
S_2	S_1	3	id_1
S_3	S_4	1	id_4
S_4	S_4	1	id_4

Computing min/max (cont.)

- First construct a spanning tree so that the root holds the minimum element.

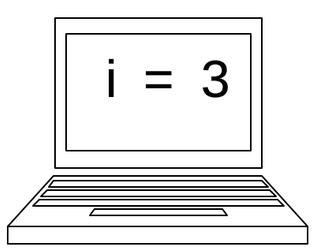


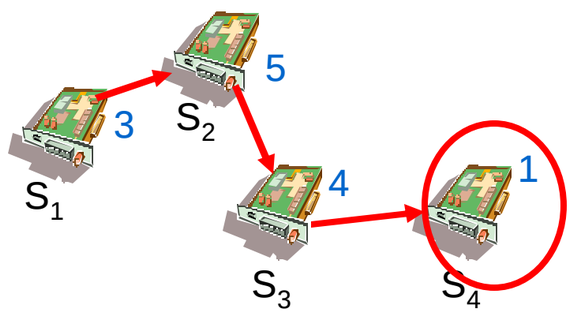


	p_i	V_i	id_i
S_1	S_1	3	id_1
S_2	S_3	1	id_4
S_3	S_4	1	id_4
S_4	S_4	1	id_4

Computing min/max (cont.)

- First construct a spanning tree so that the root holds the minimum element.





	p_i	V_i	id_i
S_1	S_2	1	id_4
S_2	S_3	1	id_4
S_3	S_4	1	id_4
S_4	S_4	1	id_4

Computing min/max (cont.)

Algorithm:

- First construct a spanning tree so that the root holds the minimum element.
- Aggregator *A* commits the tree and reports the root of the tree to the server.
- Home server *B* randomly picks a node in the list and traverses the path from the node to the root. If unsuccessful, *B* rejects.

Thm: If no more than ε fraction of sensors are corrupted, and diameter is *d*, home server requests $O(d/\varepsilon)$ and rejects invalid minimum with probability ¸ $1 - \varepsilon$.

Counting distinct elements

- **Goal:** Given a_1, …, a_n, how many distinct measurements (denoted μ) are there?
- For example, (1, 3, 5, 7, 3, 3) has 4 distinct measurements.
- n’ corrupted sensors can alter the result by at most n’

Counting distinct elements (cont.)

- **Basic idea:** use [FM83] algorithm for counting distinct elements in a data stream $a_1, \ldots, a_n$:
  - Pick a random hash function h: [m] ! [0…1].
  - Keep the value $v = \min_{i=1}^{n} h(a_i)$.
  - Let $\mu' = 1/v$. Then $\mu/c \cdot \mu' \cdot c\mu$ for all $c > 2$ [AMS96].

Counting distinct elements (cont.)

- Can adapt the data-stream algorithm to compute the minimum:

procedure CountDistinct

1. Home station **chooses** $h2_r$ **H** and through aggregator announces **h** to each sensor.
2. Each sensor S_i computes $h(a_i)$.
3. Run **FindMin** algorithm to compute $v = \min_{i=1}^{n} h(a_i)$.
4. **return** $1/v$.

Counting distinct elements (cont.)

- Protocol to count distinct elements can be used to:
  - Compute the size of the network.

    -Run it on the set of sensor identifiers $\{ID_1, \ldots, ID_n\}$.
  - Compute the average of $a_1, \ldots, a_n$ [EKR99].

    -Run it on $\Psi = \{(i, j) \mid 1 \cdot i \cdot n, 1 \cdot j \cdot a_i\}$. Then $avg = |\Psi|/n = (\sum_{i=1}^{n} a_i)/n$.

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Conclusion **if I were article's author**

- Information aggregation when sensors and aggregator are malicious can be *hard*
- Proposed aggregate-commit-prove framework
- Gave concrete sublinear protocols for
  - median
  - min/max
  - counting
  - average

My conclusion

- The article studies an interesting problem of SIA
- Aggregate-commit-framework is useful, yet gives no general cookbook recipe for constructing protocols
- Some assumptions are unrealistic:
  - single aggregator
  - knowledge of topology of the sensor network: diameter *d*, number of nodes *n*, connected components
- It would be interesting to try to lift some of these assumptions and consider classes of general aggregation operators.