Stateless Linear-path Routing for 3D Nanonetworks

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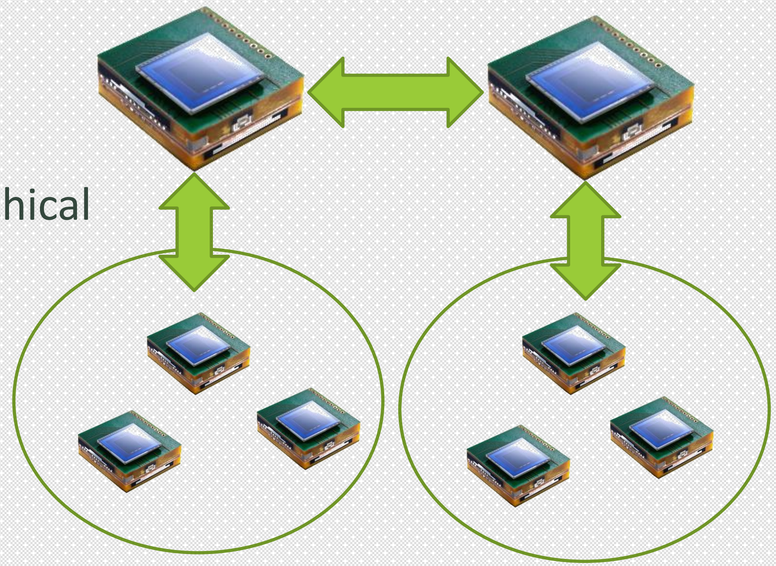
Nano-network classes / **our case**

- A set of minified, wireless comm. – enabled nodes.
- Node components:
  - CPU
  - Actuation/Sensing unit
  - Wireless module (antenna & modem)
  - Power supply (scavenging or WPT)
- Each COMPONENT:
  - A few nanometers
- Final ASSEMBLY:
  - A few μmeters

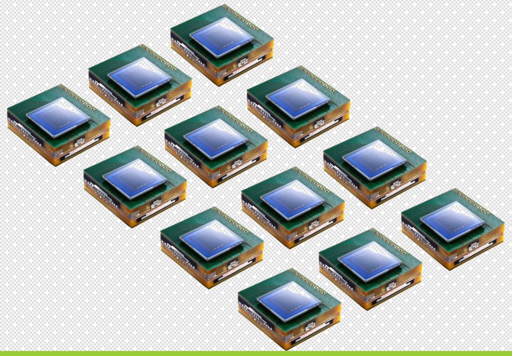
Hierarchical



Other basic categories:

- Mobile/**Static topology**
- Arranged/Random layout
- Small (e.g. 10 nodes) / **large (>10^3)**
- 1-hop / **multi-hop connectivity**

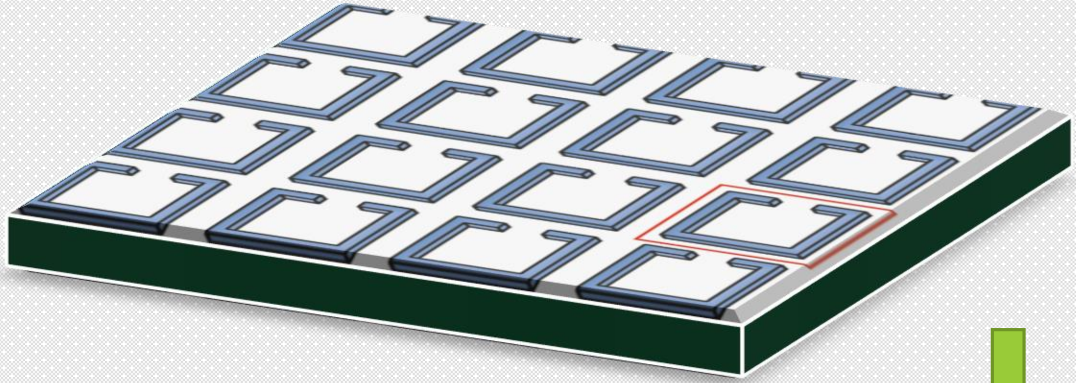
Peer-to-peer



Applications / Our focus

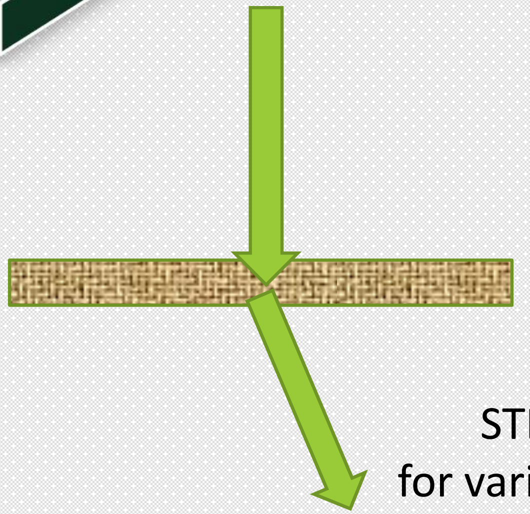
- **Medicine:**
  - Body-area networks. E.g., sensing pH, temperature, bacterial traces within the bloodstream.
  - Key-words: hierarchical, mobility, scavenging, random topology, small network, 1-hop paths.
- **Industrial materials:**
  - Monitor the structural integrity of a structure in real-time.
  - Key-words: P2P, static topology, random/arranged, WPT, large network, multi-hop paths.
- **Active meta-materials:**
  - Control over the EM behavior of an object.
  - Key-words: {{industrial materials}}, arranged topology.

Metamaterial Basics

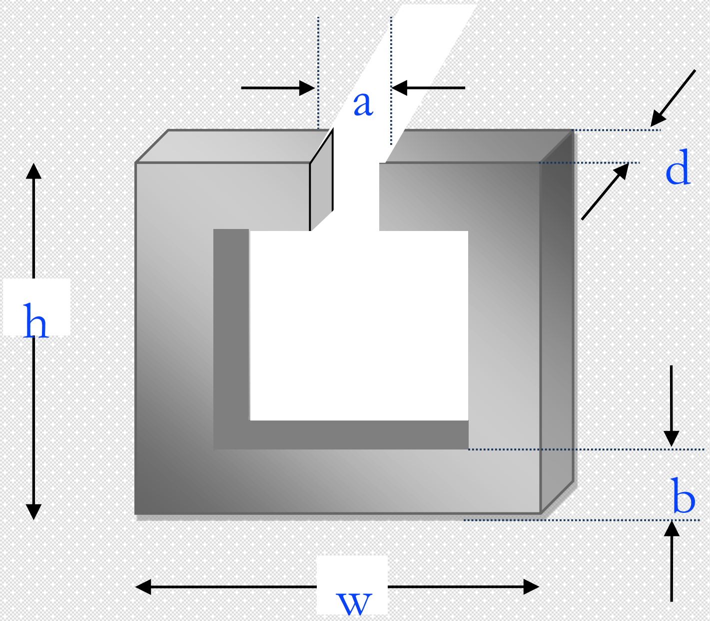


STEER

ABSORB

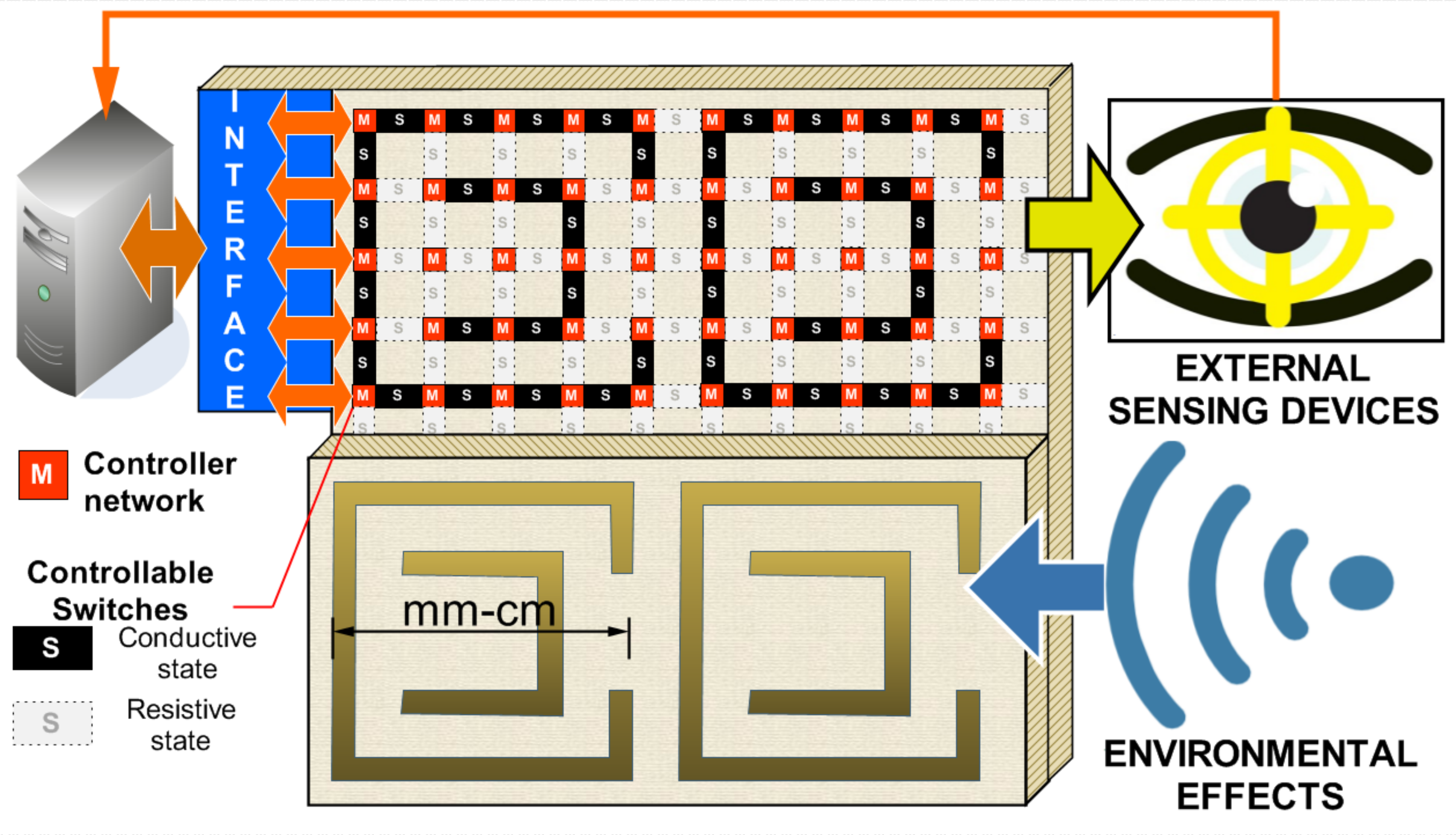


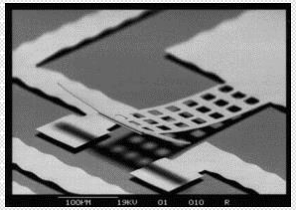
STEER at variable angle,
for variable operating frequency



schematics of the elementary cell.

Active Metamaterials: IoMater

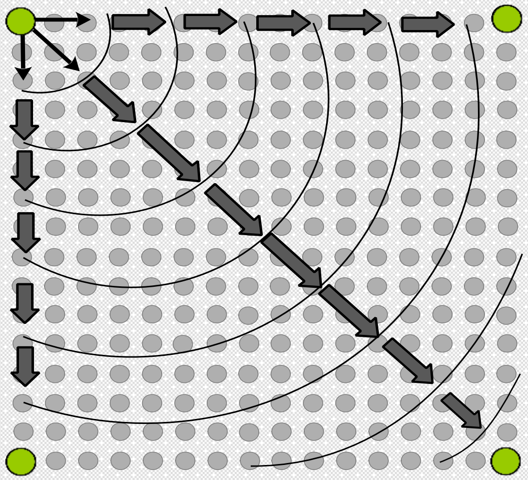




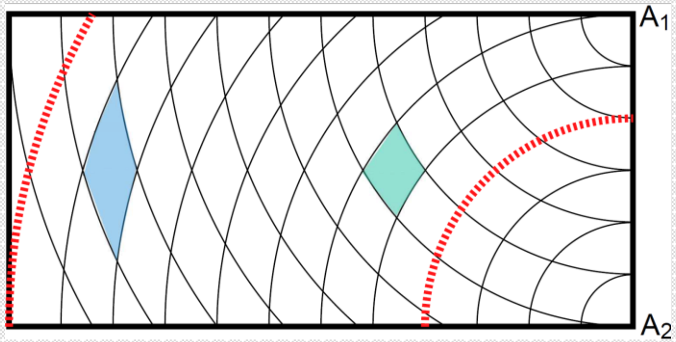
Operational & Networking Assumptions

Topology

- 3D Parallelogram → meta-material
  - Static, grid layout (random studied for completeness)
  - Easily 1000s of nodes
- Nodes identified by **Virtual Coordinates*** (setup).



→8 possible anchors in 3D.

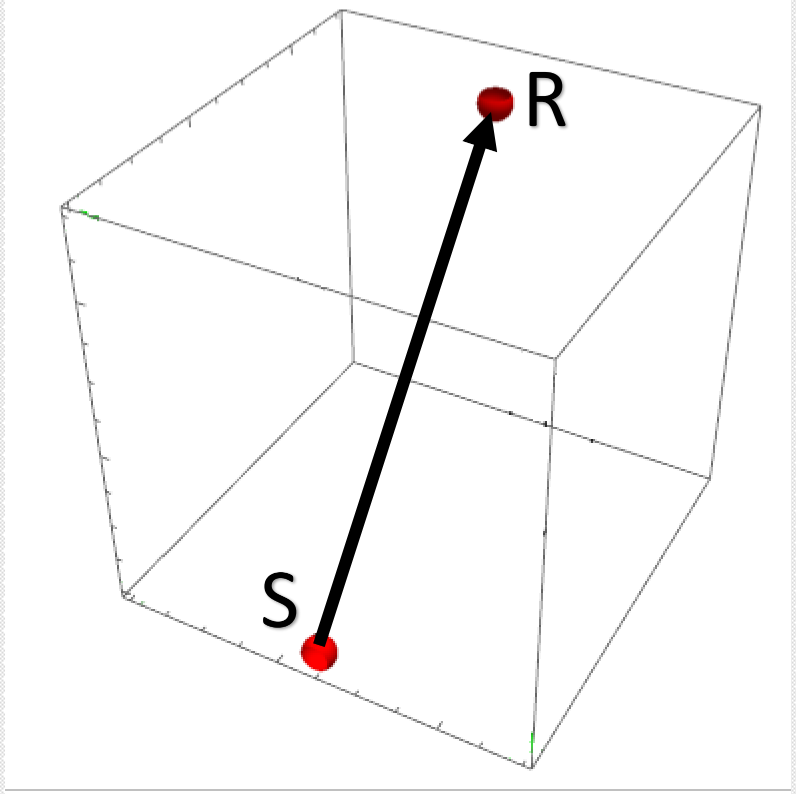


Node architecture

- **Power supply** → WPT
  - (better than scavenging, but not abundant)
- **0.1 THz comm.**
  - High (but tractable) channel losses
  - Short packet duration
- **VERY limited**:
  - CPU (**integer-processing only**)
  - RAM (Bytes)
  - Small Tx radius → **multi-hop**
    - Need for low cross-talk between
      - Meta-material
      - Nano-network

*A. Tsioliaridou et al, 'CORONA: A joint coordinate and routing system for nanonetworks', In NANOCOM'15.

The Goal: Stateless Linear Routing



Stateless routing:

- No forwarding tables at the retransmitters.
- **Why?** Lower memory requirements, smaller cost, less energy.

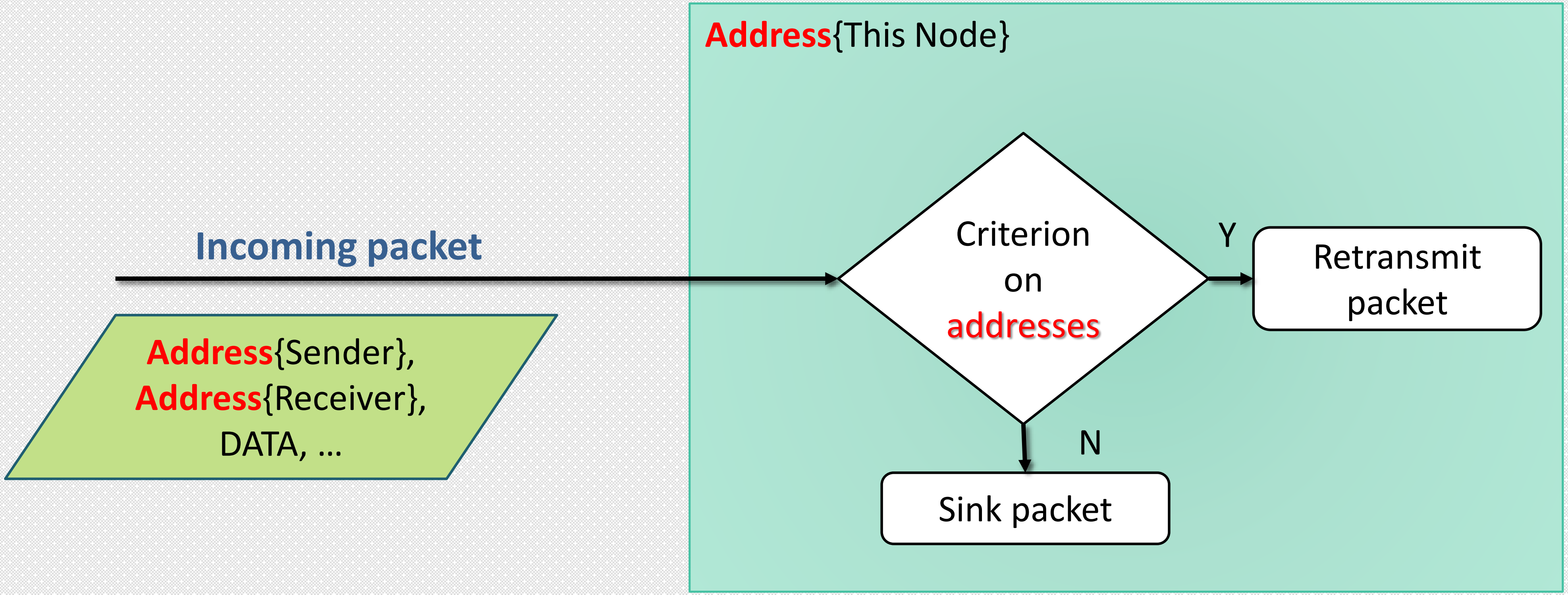
Linear routing:

- I.e., by retransmitters on the line S → R.
- **Why?** Shortest path, minimal retransmitters, energy efficient.

Integer processing capabilities only:

- +,-,<,>,=
- **Why?** Lower complexity, smaller cost, less energy.

A simple routing daemon



Retransmission criterion logic

- **S(x_1,y_1,z_1)** and **R(x_2,y_2,z_2)** define a line segment.
- Check if the **current** node **C(x,y,z)** is on this segment:

$$\begin{cases} a: & (x-x_1)(y_2-y_1)-(y-y_1)(x_2-x_1)=0 \\ b: & (x-x_1)(z_2-z_1)-(z-z_1)(x_2-x_1)=0 \end{cases} \quad , \qquad x \in [x_1, x_2]$$

<u>Two problems:</u>

- Checking equality conformation with integers.
- We have Virtual Coordinates (anchor distances), **NOT** Cartesian.
  - Plus, **FOUR** anchor distances, ($\dot{r}$,$\ddot{r}$, $\dddot{r}$,$\dddot{r}$”) correspond to a triplet (x,y,z).

1. Equality conformation with integers

- Don’t check equality, check for **sign change**.
- I.e., **don’t** check:

$$\begin{cases} a: \quad (x - x_1)(y_2 - y_1) - (y - y_1)(x_2 - x_1) = 0 \\ b: \quad (x - x_1)(z_2 - z_1) - (z - z_1)(x_2 - x_1) = 0 \end{cases}$$

- **Instead**, define:

$$\begin{cases} \Delta^a(x, y) = (x - x_1)(y_2 - y_1) - (y - y_1)(x_2 - x_1) \\ \Delta^b(x, z) = (x - x_1)(z_2 - z_1) - (z - z_1)(x_2 - x_1) \end{cases}$$

and check if (Δ^a AND Δ^b) undergo a sign change in $[x \pm m]$, $[y \pm m]$, $[z \pm m]$

- m controls the “thickness” of the 3D line → great for introducing tunable path redundancy.

2. Working with Virtual Coordinates

- **Solution #1**

Convert VC to Cartesian

- The VC of a node, ($\dot{r}$,$\ddot{r}$, $\dddot{r}$,$\ddddot{r}$) define 4 spheres.
- Have each node find the intersection of the spheres, obtaining (x,y,z).

  - **Requires**:
    - Floating point processing capabilities (extra complexity).
    - Knowledge of the parallelogram space dimensions (extra messaging).

2. Working with Virtual Coordinates

- **Solution #2**

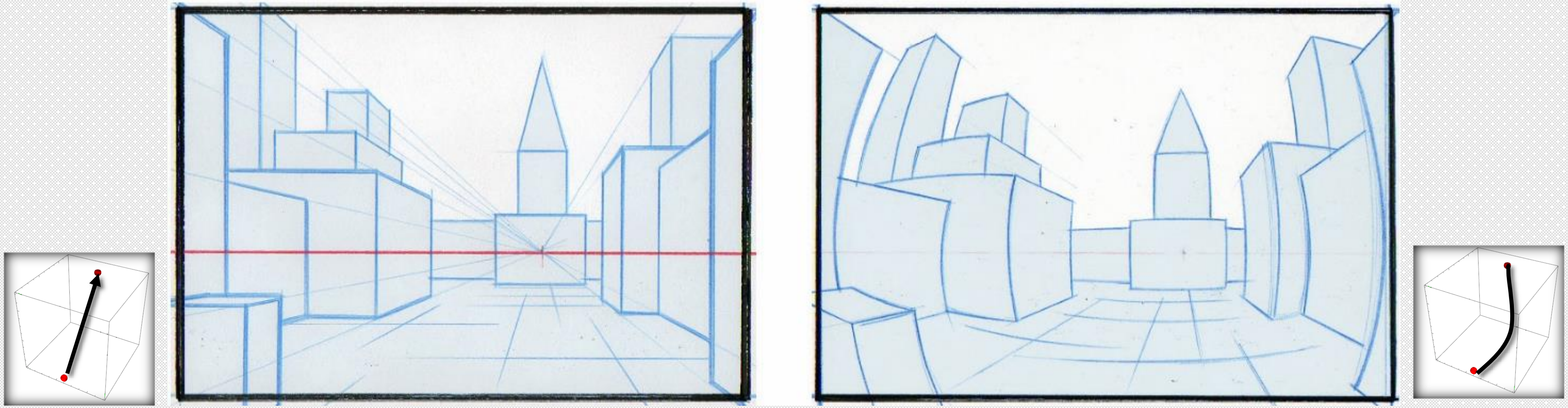
Map VC to Cartesian, then use the mentioned equations normally.

$$\begin{pmatrix} \dot{r} \\ \ddot{r} \\ \dddot{r} \\ \dddot{r}' \end{pmatrix} \rightarrow \begin{pmatrix} x \\ y \\ z \\ null \end{pmatrix}$$

- How about $\dddot{r}'$?
  - **Not needed!** We can work with just three carefully selected anchors only (once, at setup, for all nodes)!
    - Proof in the paper.
  - This also reduces the setup overhead (-1 anchor beacon, -1 packet address field).

- Mapping side-effect: **Curvilinearity**

Curvilinearity

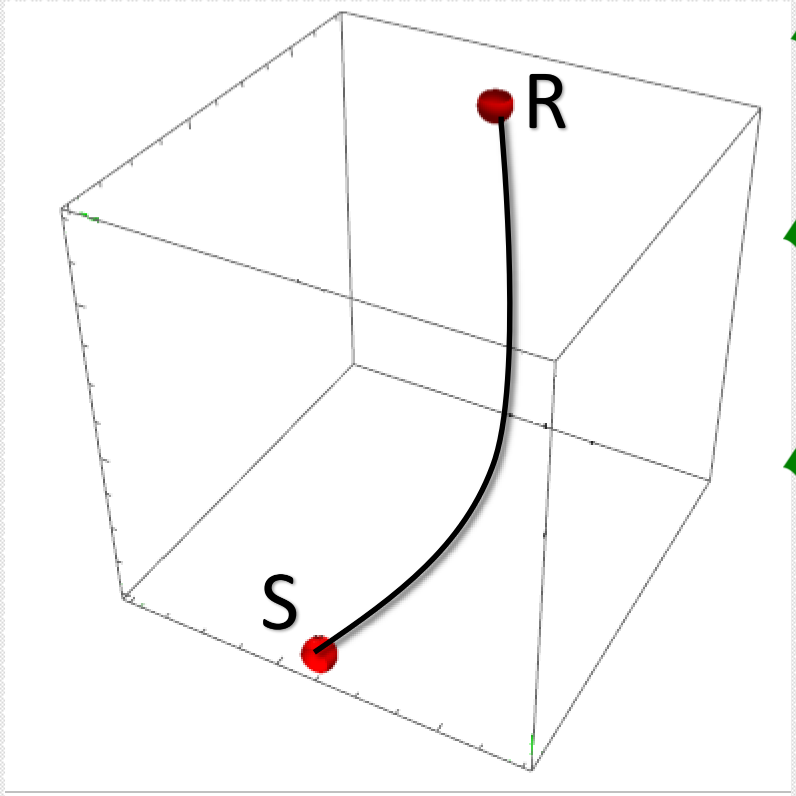


- Straight paths get “bent” a bit. (We can live with that, given the gain in complexity).

WORK EXTENSION POINT: Select the anchor triplet (a.k.a. “viewport”) that bends the given path less.

- **Catch:** The VC address resolution degrades with distance.

The result: Stateless Linear Routing



Stateless routing:

- No forwarding tables at the retransmitters.

Linear routing:

- Yes, but *not shortest*.
- **Bonus: tunable path redundancy (line thickness, *m*).**

Integer processing capabilities only:

- +,-,<,>,=

Evaluation

System setup

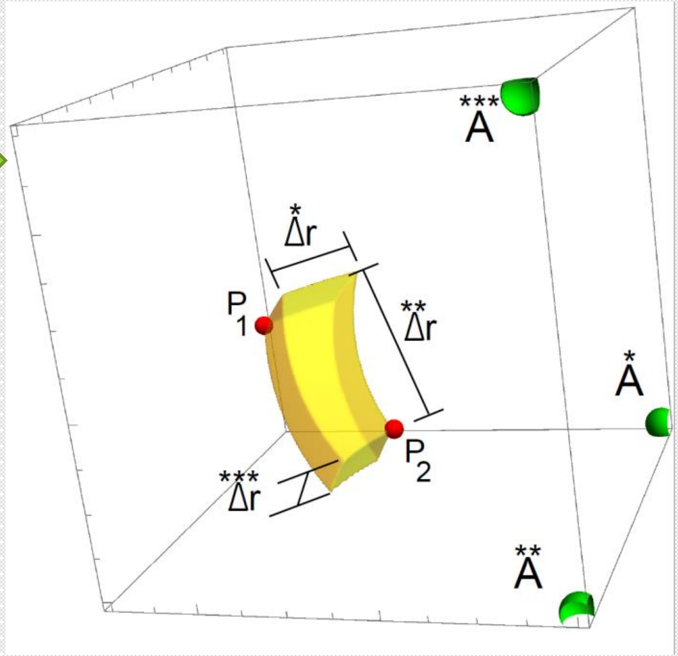
- Space dimension setup:

- 5.000 identical nodes.
- Layouts:
  - Grid (17x17x17)
  - Random placement.

We study:

- **End-to-end packet delivery.**
  - Parallel delivery attempts
- **Energy efficiency.**
  - Retransmissions imposed on nodes.

- Compared schemes:
  - **Stateless Linear Routing** (line thickness m: 1,3,5)
  - **CORONA** (retransmitters defined by volume)



Measurements in a progressively failing network (1-pair comm.)

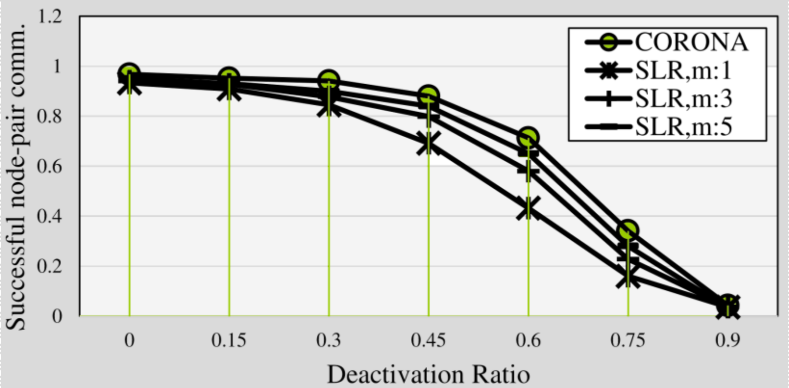


Fig 4. SLR tunability effects on the node-pair communication ratio.

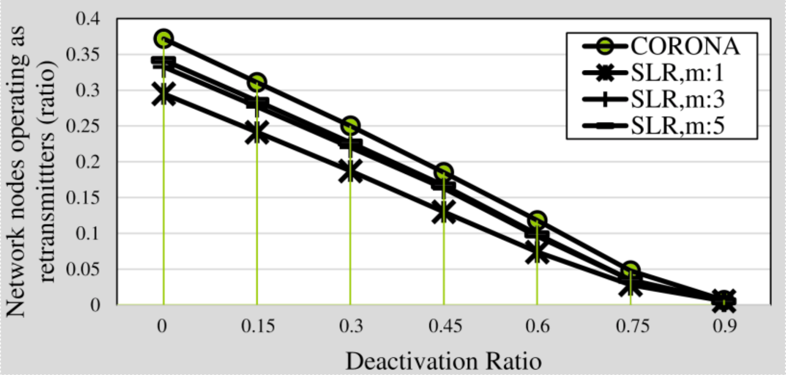


Fig 5 . SLR tunability effects on the average, network-wide ratio of retransmitters serving each communicating pair.

Evaluation scenario

- A random percentage of nodes is deactivated, emulating failing nodes (deactivation ratio).
- We select randomly 100 sender/receiver pairs. each requiring the exchange of a single, unique packet.
- Each run is repeated 100 times, randomizing the node failures anew

Observations

- SLR: Uses less retransmitters, good delivery rate.
- As SLR line thickness (path redundancy) increases,
  - → nearer to CORONA, still less retransm.

Measurements with multiple pairs in parallel

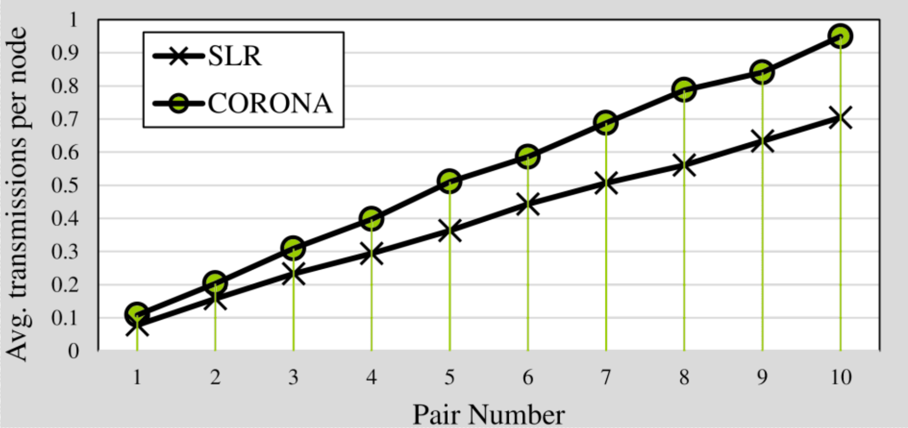


Fig 5. Resilience against parallel communications for the proposed SLR and the CORONA

Evaluation scenario

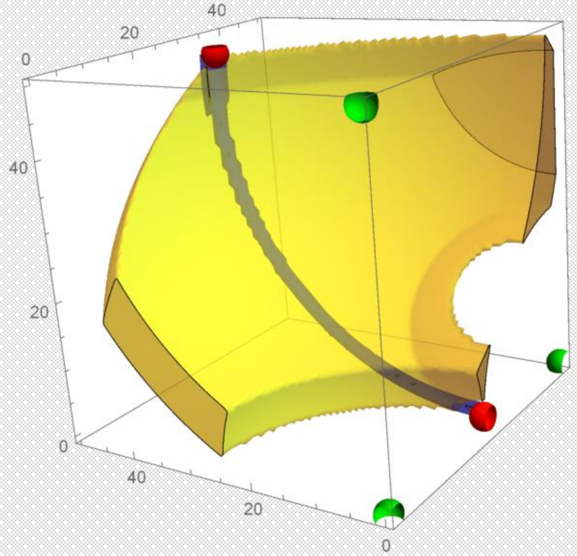
- **x-axis:** node pairs attempting communication in parallel.
- **y-axis:** retransmissions imposed per node.

Observations

- CORONA yields overlapping volumes → More retransmissions per node.
- SLR performs better (lines are less likely to overlap).

NanoCom 2016

Results in denser networks



Comparison of **CORONA (yellow area)** and the novel **SLR (dark curve)** routing behavior for a given communicating node pair in a high-resolution space.

Preceding results

- Just 17 x 17 x 17 nodes
  - Low space "resolution" → small profit margin
  - Runtime restrictions.

A high resolution use case

- 800 x 800 x 800 nodes (50x50x50 cm).
  - SLR gets exponentially better than CORONA.

Conclusion

Multi-hop nano-networks have interesting applications (combo with metamaterials).

- Low **manufacturing cost** per node → an additional restriction (e.g., int-processing only).
- **Stateless**, **Linear** Routing → an effective solution for:
  - node addressing,
  - packet routing with tunable path redundancy

- **Key-enabler:** Curvilinear coordinates.
- **Extension:** Which “viewport” “curves” less?

Thanks!

- More works, 1-page reviews and resources at:

  - http://users.ics.forth.gr/cliaskos

- Also related:

Design and Development of Software Defined Metamaterials for Nanonetworks.
Liaskos C., Tsioliaridou A., Pitsillides A., Akyildiz I. F., Kantartzis N., Lalas A., Dimitropoulos X., Ioannidis S., Kafesaki M., Soukoulis C.
IEEE Circuits and Systems Magazine, 2015.

CORONA: A Coordinate and Routing system for Nanonetworks.
Tsioliaridou A., Liaskos C., Ioannidis S., Pitsillides A.
In ACM NANOCOM'15.