Directional Wireless Communication Networks

Christopher C. Davis
Department of Electrical and Computer Engineering, University of Maryland

The Maryland Optics Group

IEEE APS Seminar 11-16-2011

Acknowledgments

- Professor Stuart Milner
- John Rzasa
- David Coleman
- Dr. Jaime Llorca
- Dr. Quirino Balzano
- Dr. Shawn Ho
- Dr. Sugianto Trisno (Techno-Sciences)
- Dr. Yohan Shim
- Professor Heba Yuksel (Bogazici University)
- Haijun (Aaron) Zhang, Department of Electronic Engineering, City University of Hong Kong, (now at University of Windsor)
- Bernhard Epple (DLR)
- Hennes Henniger (DLR)

Sponsors

- Air Force Office of Scientific Research
- National Science Foundation
- Techno-Sciences
- Lucent Government Services
- Department of Transportation

Outline

- Directional wireless versus broadcast wireless
- Scalability
- Pointing, Acquisition and Tracking
  – Agile, gimbal-mounted transceivers
  – GPS-based node location
  – Image based node location
- Topology Control
  – Mobility control
- Heterogeneous Hierarchical Wireless Networks (HHWN): Network Cognition and Control
- Molecular Models for HHWN

19th Century FSO Communications

1st Bombay Native Infantry (Grenadiers) (NCOs signaling)

Broadcast Wireless Communications
Challenges

- The RF Spectrum is crowded and regulated
- Bandwidth
  - limited
- Interference
  - A big problem, and getting worse
- Security
  - maybe
- Scalability
  - Kumar's scalability "curse"
    - N nodes
    - End-to-end throughput ~ $1/\sqrt{N}$

P. Gupta, P. R. Kumar, "The capacity of wireless networks",
IEEE Transactions on Information Theory, Vol. 46, No. 2, pp. 388-404l, 2000.

Directional Wireless Communications

- **Opens up new spectral regions**
  - Free Space Optics (Optical Wireless)
  - Ku band and higher
  - Millimeter waves (60GHz, 80GHz)
- **FSO Bandwidths (2007)**
  - Commercially available FSO 155 Mb/s – 2,. Gb/s (1-3 km)
  - 80 Gb/s (FSO) Demonstrated: Air (aerostat) to ground)
  - 40 Gb/s WDM (150 km FSO link, mountain top to ground)
  - 1Tb/s laboratory demonstration (DWDM through the air)
- **Commercially Available Directional RF (Ethernet; IP) (2007)**
  - 1.25 Gb/s (70-80 GHz)
  - 48 Mb/s (up to 40km) (5.8GHz)
  - 400 Mb/s to 40 km (11-38 GHz)
  - 800 Mb/s (11-38 GHz)
- **Physical Layer Security**
- **Scalable**
- **Broadcast wireless is wasteful**
  - Why send your signal to where it is not wanted?
  - Doesn't use spatial diversity efficiently

Scalability Figure of Merit

The beam divergence half angle for an antenna of aperture *D* is

$$\theta_B = \frac{1.22\lambda}{D},$$

So directional links have a smaller beam angle as the antenna size or frequency of the link is increased. FSO links can have much smaller beam angles, typically ranging from 1μrad to 10mrad. The beam angle of an FSO link is

$$\theta_B = \frac{\lambda}{\pi w_0},$$

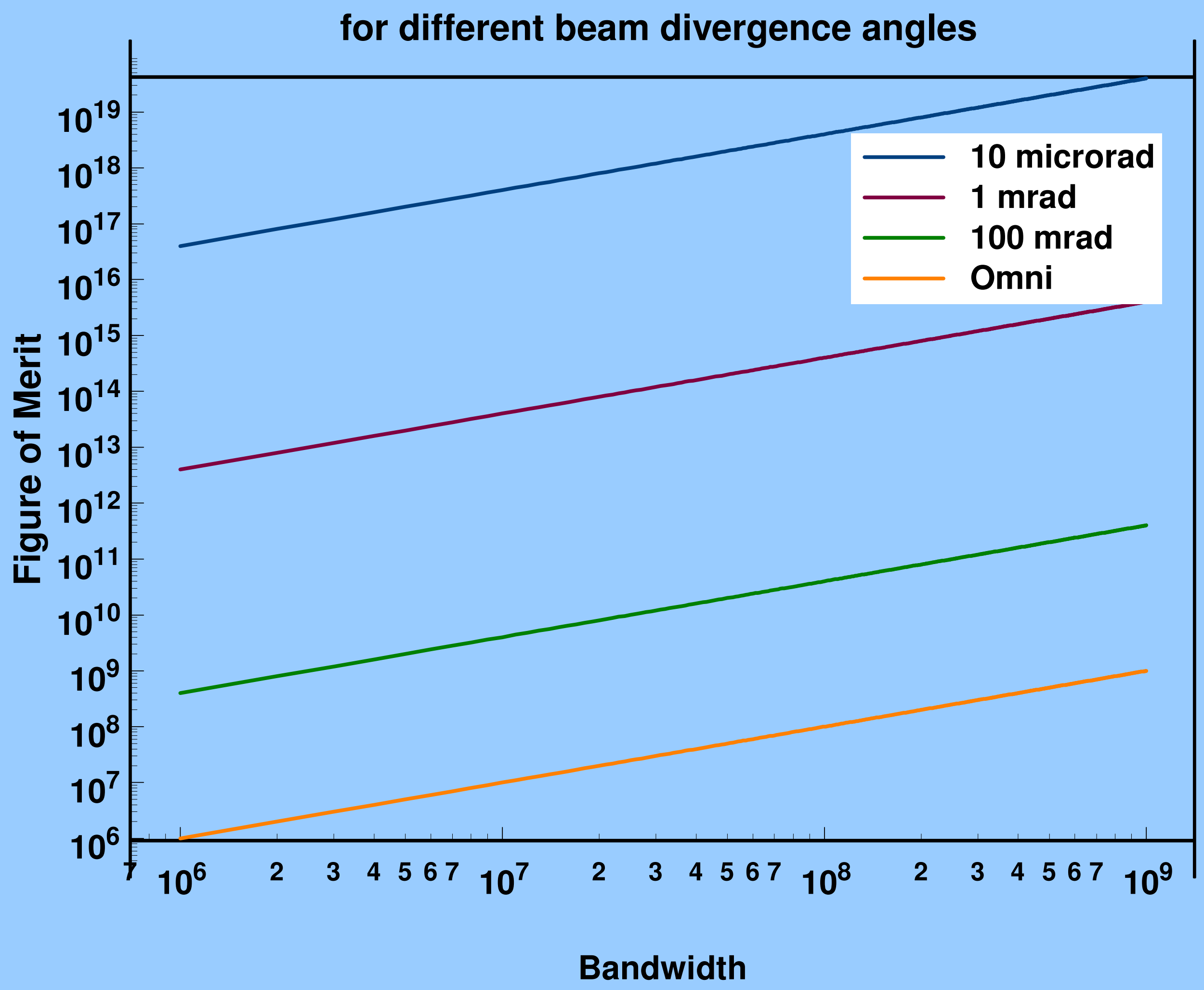
where w_0 is a Gaussian beam radius. Consequently for all directional links we can use an effective beam half angle

$$\theta_B \approx \frac{\lambda}{D},$$

which allows us to write a universal figure of merit for links of half angle θ_B as

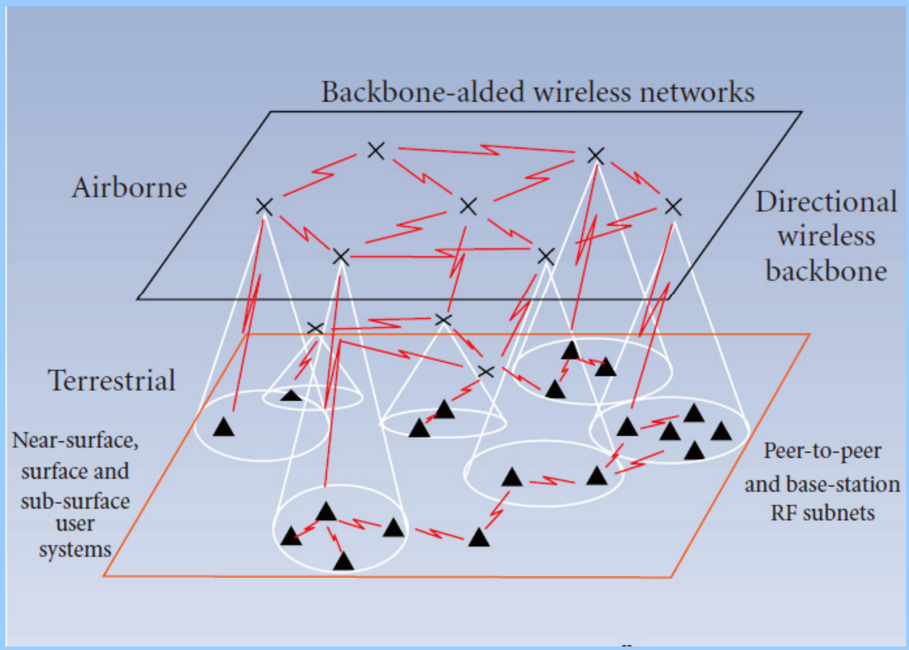
$$F = \frac{2\Delta f}{\left(1-\cos(\lambda / D)\right)V}.$$

SCALABILITY FIGURE OF MERIT FOR DIRECTIONAL LINKS



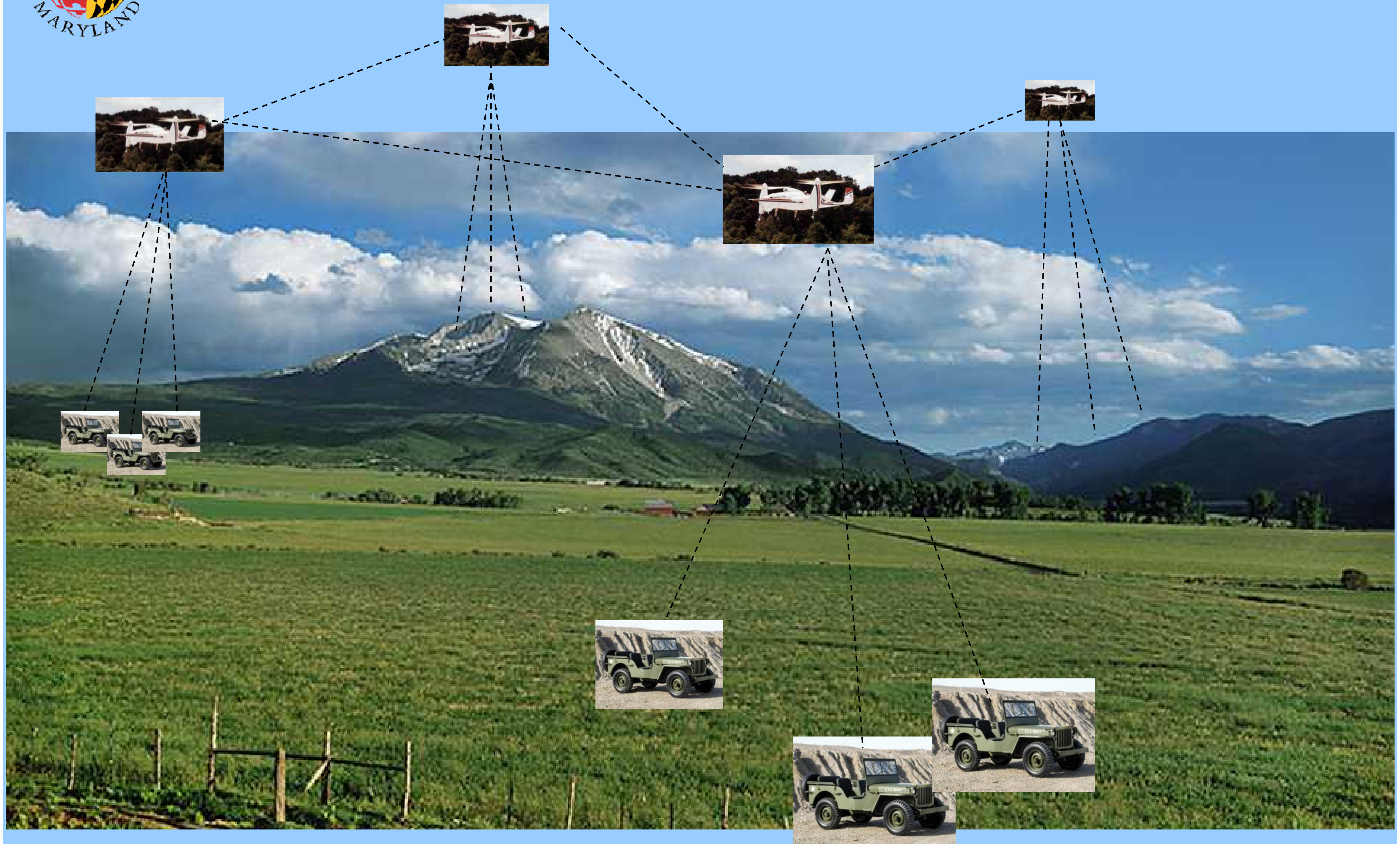
Directional Wireless Backbone Network

- Modeling of directional wireless networks
- Pointing, Acquisition and Tracking
- Answers where and when to point directional wireless transceivers to maximize connectivity
- Physically reconfigure network to maximize connectivity
- Models backbone nodes like atoms in a molecule; each link has a potential energy, can disassociate like a molecule's atoms and break the link to ensure greater connectivity elsewhere
- Use potential energy surface to predict failures



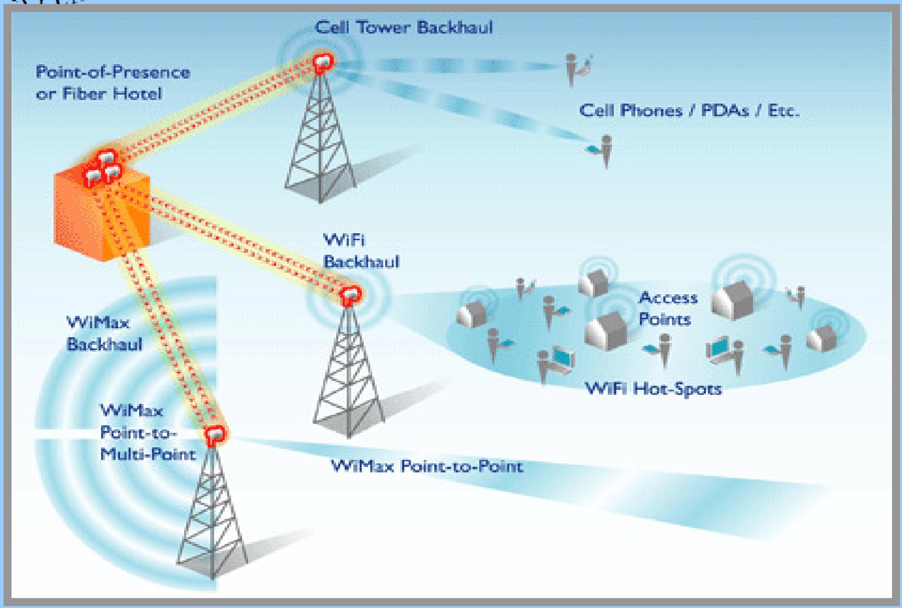
Llorca, J., Milner, S.D., and Davis, C.C., "Molecular System Dynamics for Self-Organization in Heterogeneous Wireless Networks," Eurasip Journal on Wireless Networking (2010)

Notional DoD Scenario

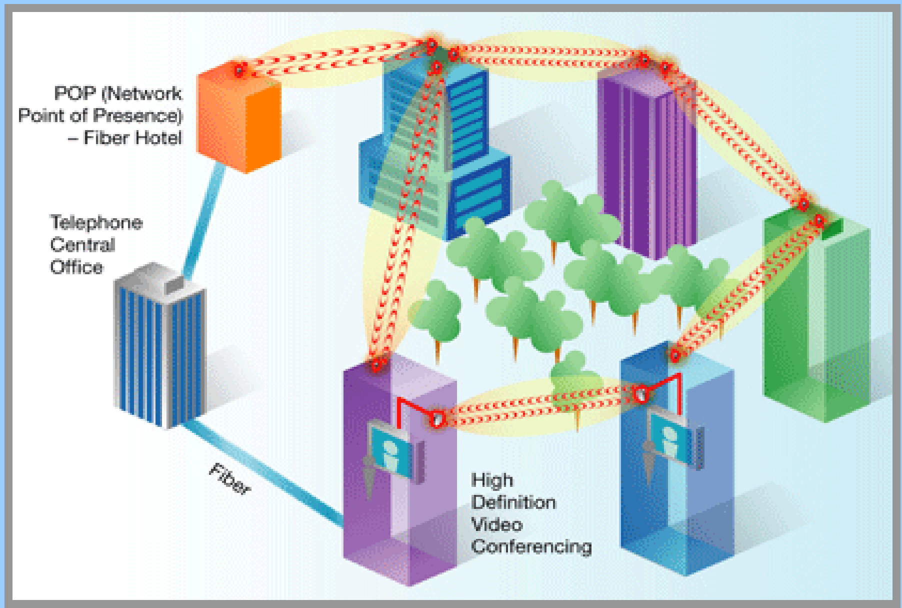


Free Space Optic Infrastructures

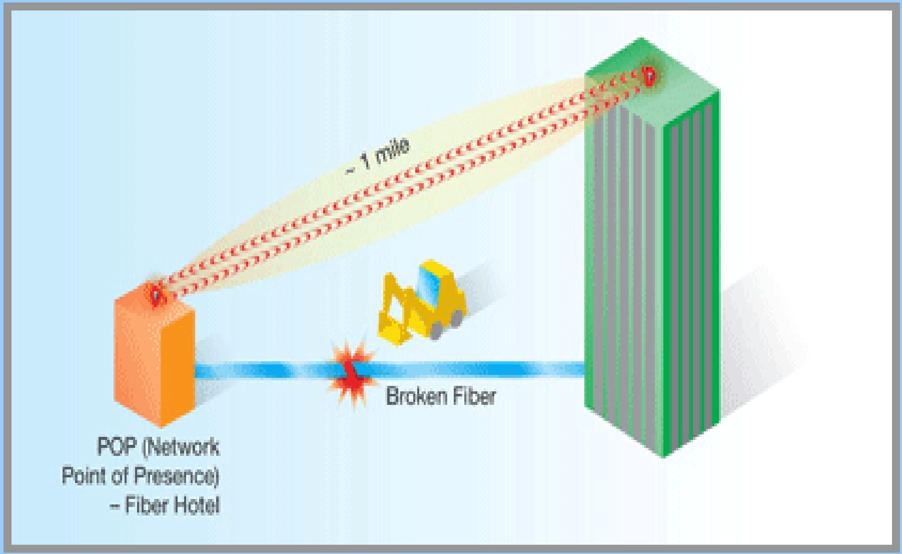
Wireless backhaul



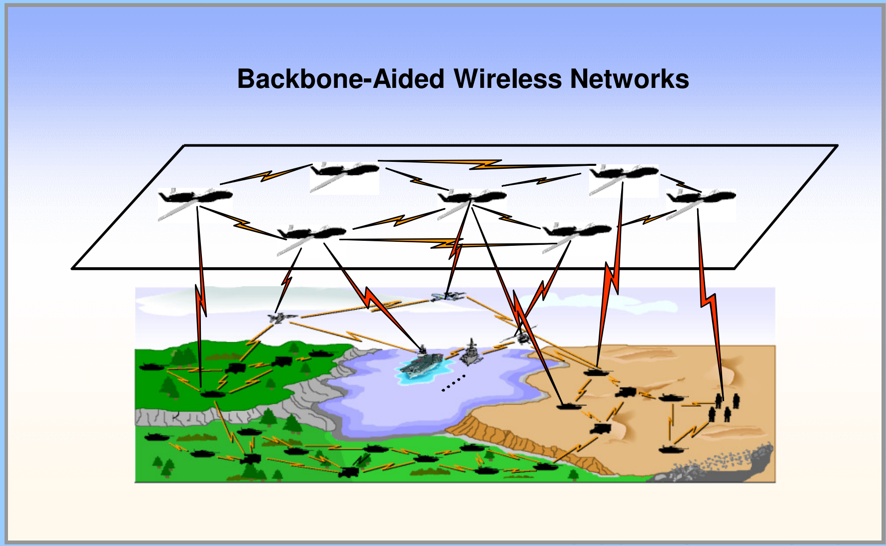
Campus LAN



Disaster recovery

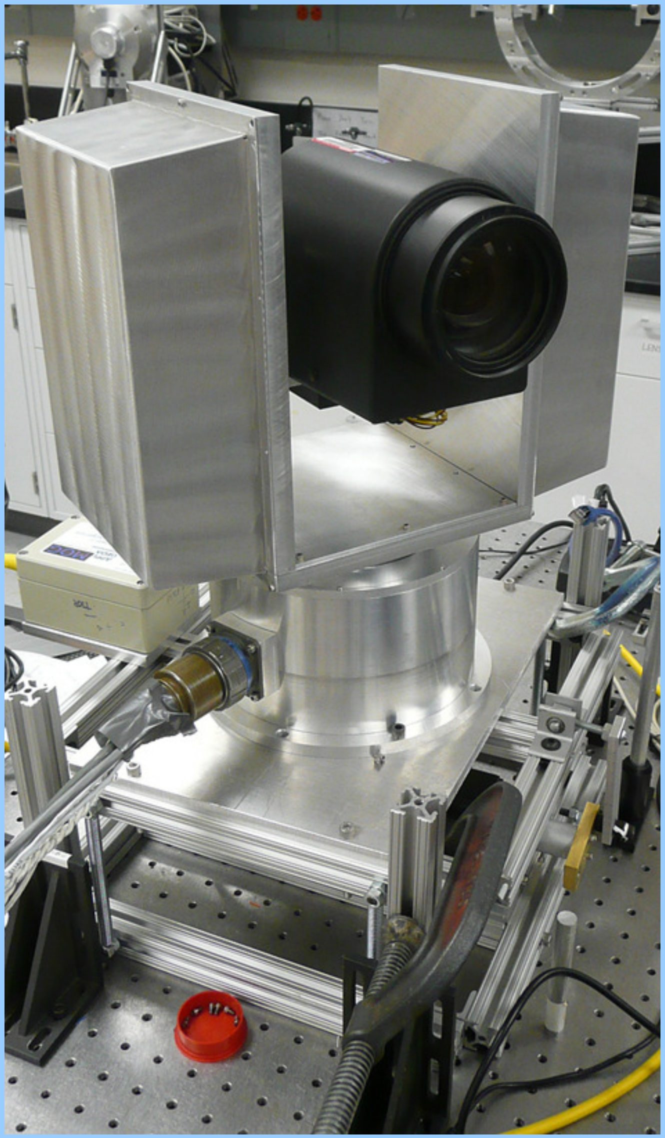


Military/Space applications

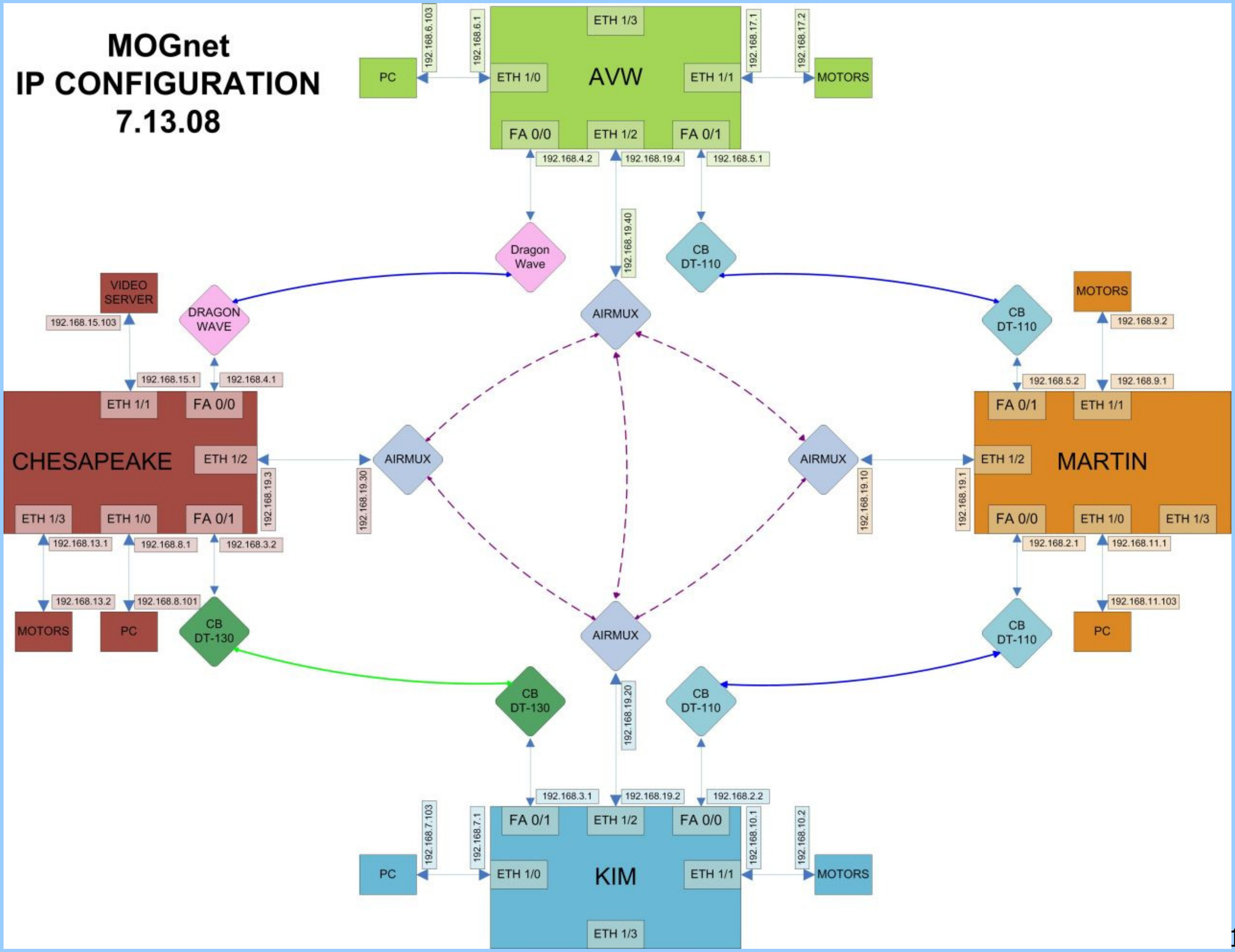


MOG NET

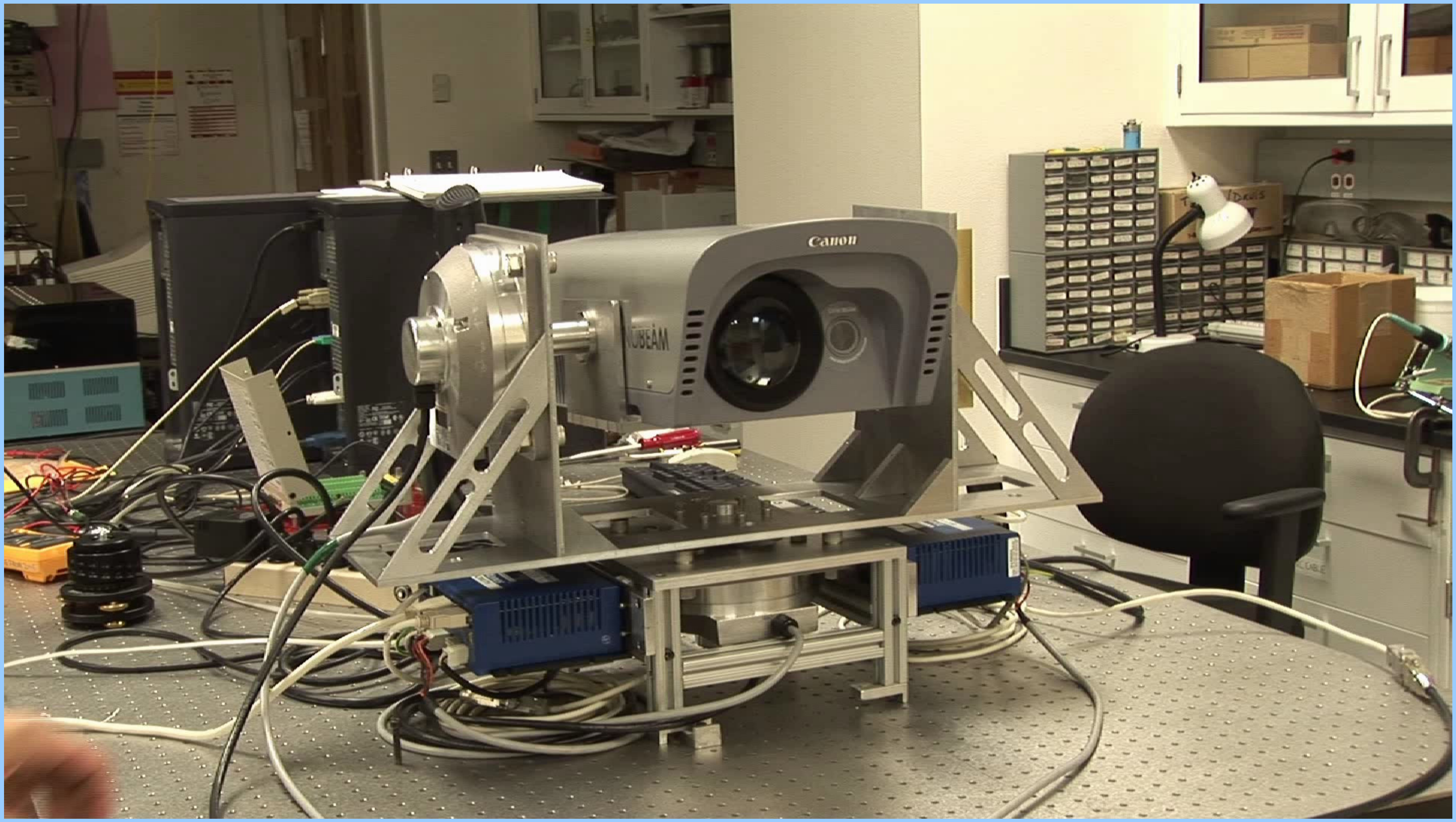
- On the Maryland campus we have a reconfigurable network with four nodes
- FSO (1.25Gb/s)(800 nm) + directional RF (20 Mb/s)(5.8 GHz)
- Each node is gimbal mounted
  - Direct Drive AC Brushless Servo Motors
  - 2 Nm continuous torque,
  - 6 Nm peak torque
  - 200 rpm maximum speed
  - 20 bit absolute serial encoders, 6 µrad per pulse
  - Automatic gain tuning, vibration suppression



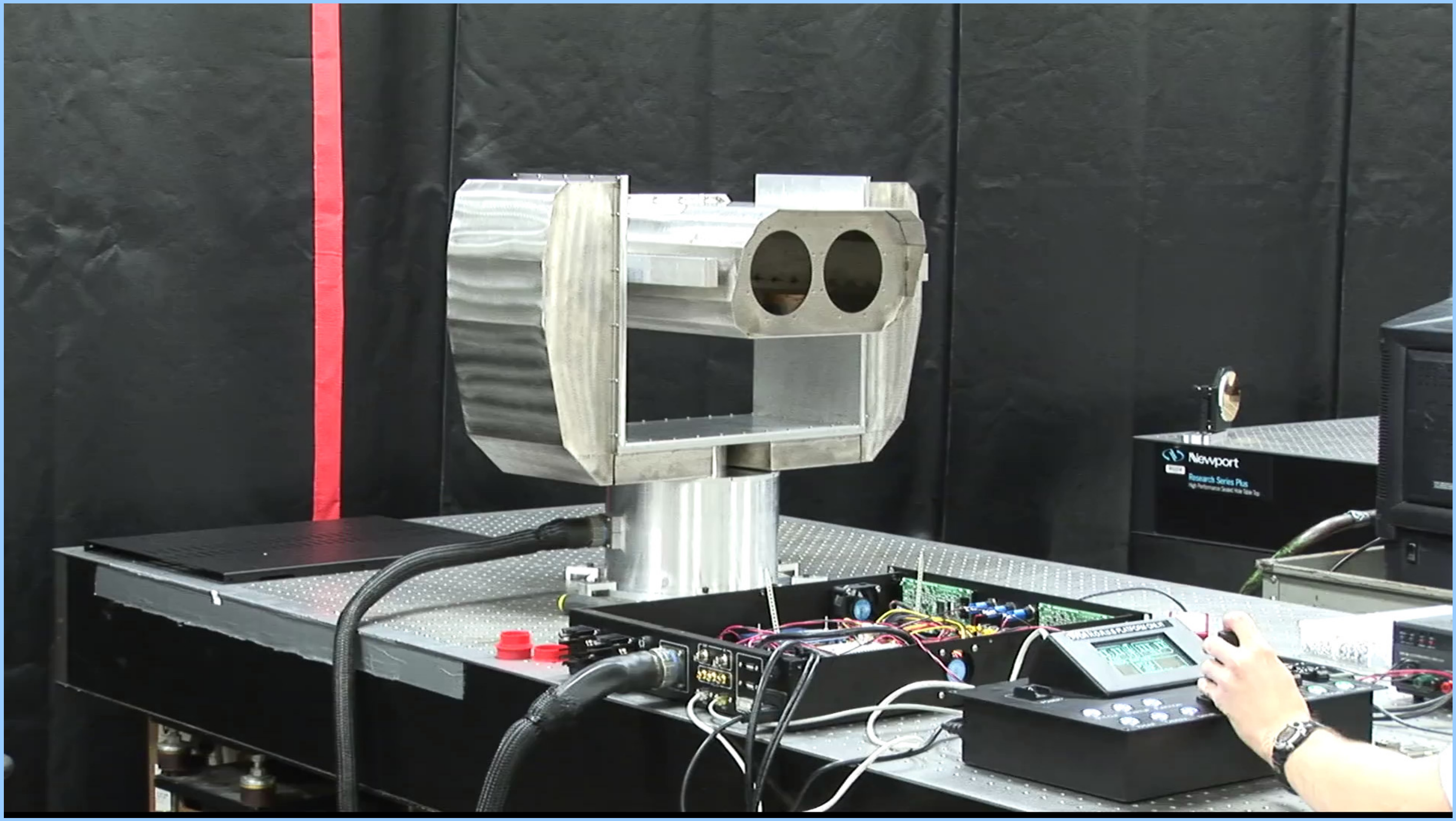
UM Directional Radio Network



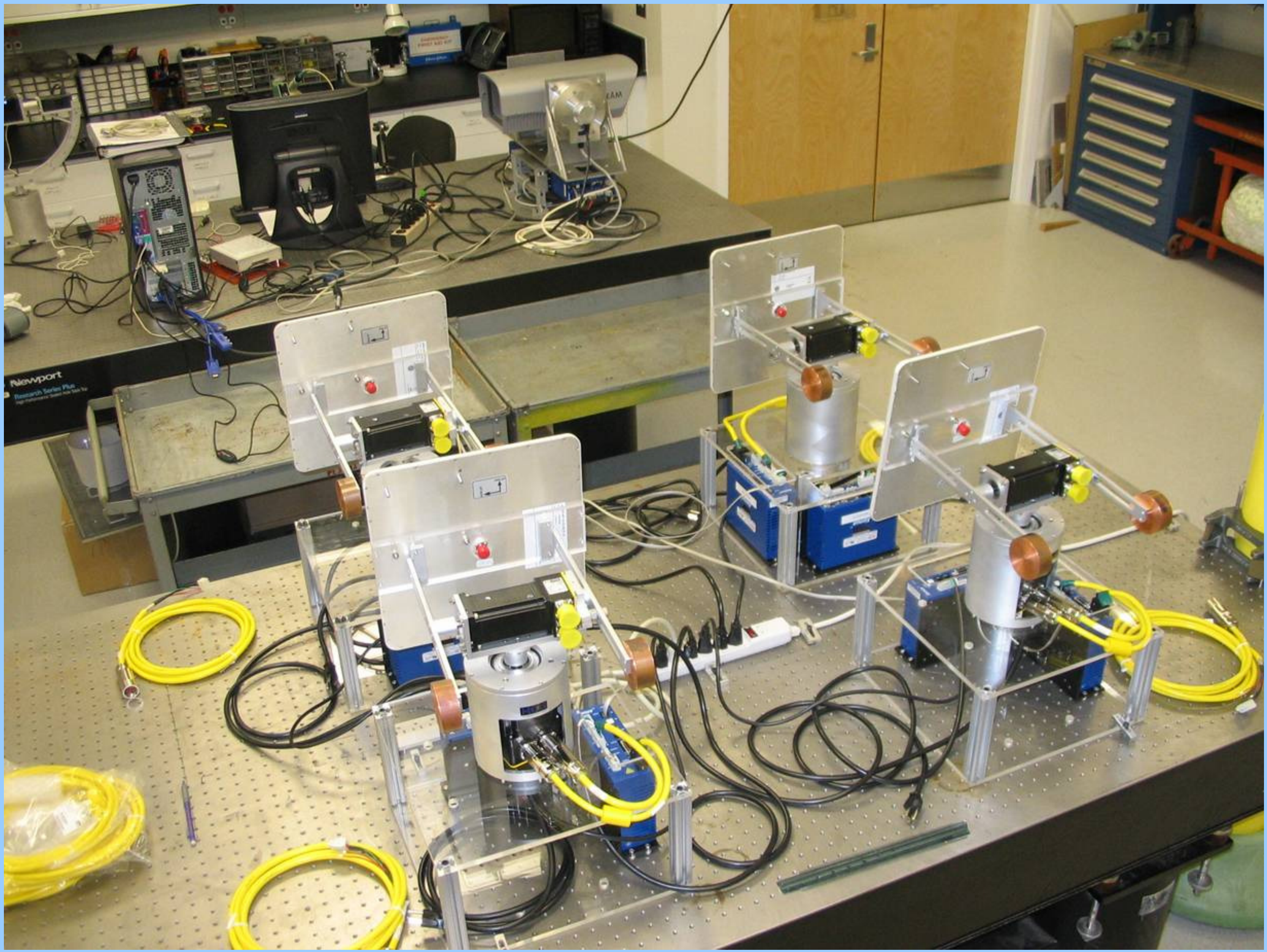
FSO System on Gimbal



Three-Axis Platform

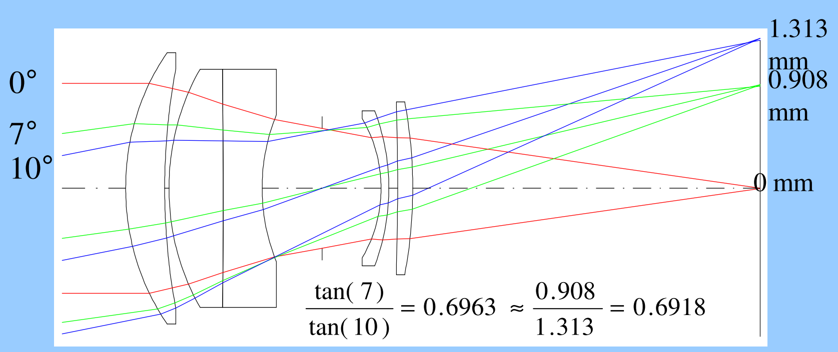


Directional Radios on High Performance Gimbals



The Hard Problems

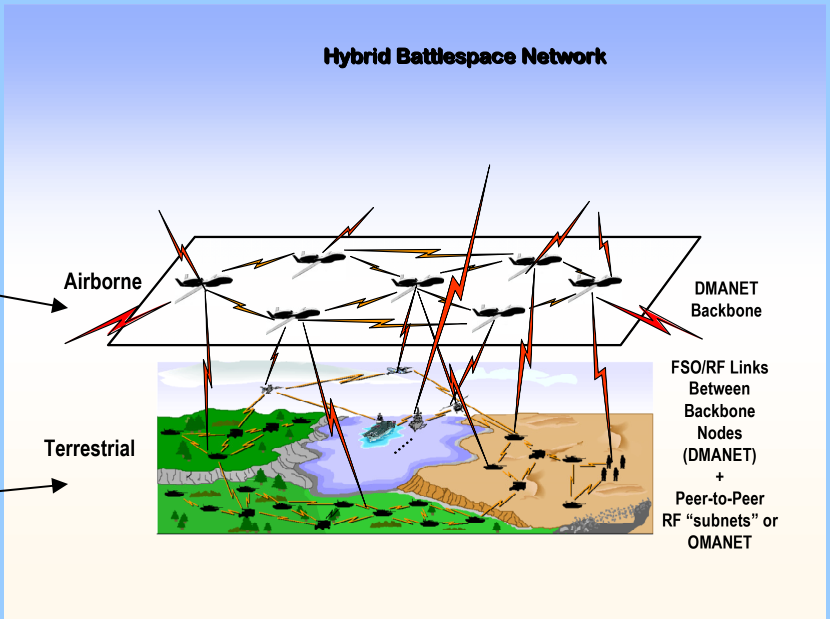
- Provide very high bandwidth (>1 Gb/s) in wireless communication networks
- Node discovery
  - GPS
  - Wireless broadcast of node locations
- Pointing, acquisition, and tracking
  - Inertial sensors for angle determination
  - Microradin pointing accuracy is possible with
    - Real-Time Kinematic (RTK) GPS
    - Tilt sensors
    - 2-axis gimbal
  - Beacon-based pointing
  - Narrow directional beams
  - Phased array antennas
  - Gimbal-mounted antennas
- Ensure physical layer connectivity in hybrid sensor networks
  - Stabilization, Pointing, Acquisition and Tracking in Directional Networks
  - Accurate cost, SNR, attenuation estimate for potential neighbor connectivity assessment in directional FSO/RF networks
  - Assure connectivity and coverage in a morphing, DMANET
- Topology Control. Re-configure the network to recover from failures and degradation: Assure Connectivity and Coverage
  - Select the topology to make this possible
  - How to disseminate topology information to the network
  - How to minimize convergence and packet loss



HOW to CIRCUMVENT THE SCALABILITY CURSE

Directional Mobile Ad Hoc Network (DMANET)

Omni-Directional Mobile Ad Hoc Network (OMANET)



•**<u>Higher Tier (DMANET):</u>** High Capacity Backbone with Directional Transmission Free Space Optical/RF (up to Gb/s)

- *Scalable*

•**<u>Lower Tier (OMANET):</u>** Low Capacity Networks with Omni-Directional Transmission RF (2-10 Mbps)

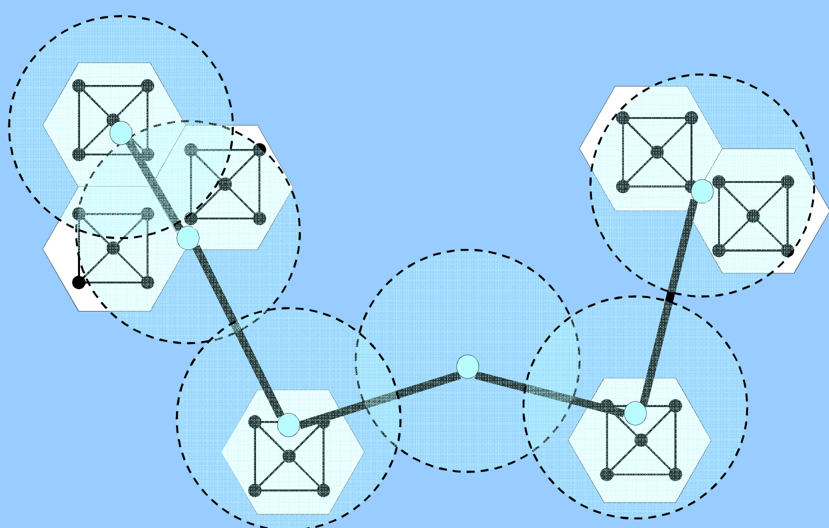
- *Capacity Limited*
- *Non-scalable (vanishing throughput)*

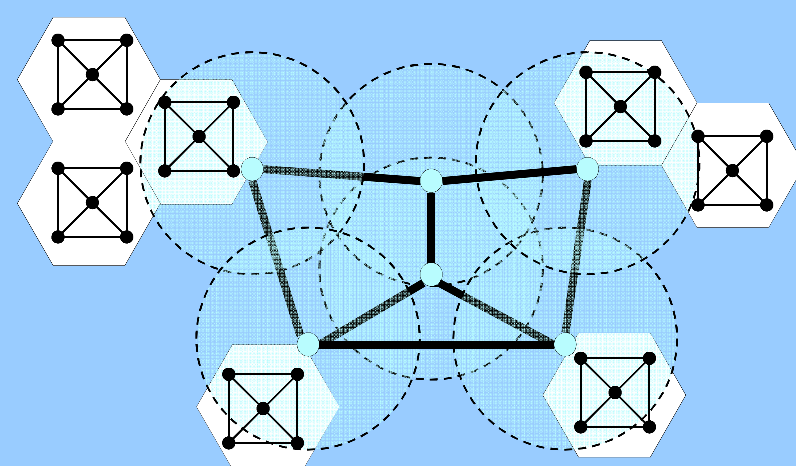
WIRELESS NETWORKS ARE MORE COMPLICATED THAN WIRELESS LINKS

Structured or Infrastructureless? Base-station oriented or ad-hoc?

Competing Objectives:

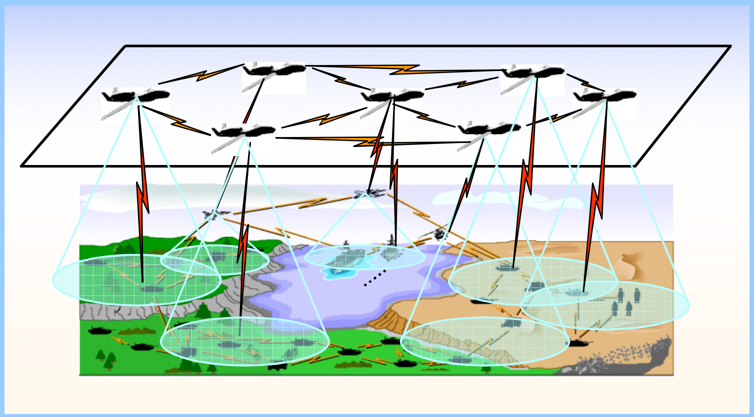
- Network Coverage
  - Backbone nodes spread over to clusters
  - Backbone topology stretches
  - Low backbone connectivity
- Backbone connectivity
  - Nodes come closer together
  - Backbone topology contracts
  - Low network coverage





Challenge: Backbone Robustness

- DWB networks must assure highly available broadband connectivity in a **dynamic** wireless environment
  - Node mobility
  - Node addition/deletion
  - Atmospheric turbulence
  - Atmospheric obscuration



- **Need Topology control**
  - Autonomous network capability to dynamically reconfigure its physical topology
  - Topology reconfiguration (TR)
    - Dynamic redirection of directional wireless links
  - Mobility Control (MC):
    - Dynamic reposition of backbone nodes

TOPOLOGY CONTROL FOR WIRELESS NETWORK INFRASTRUCTURE WITH ASSURED CONNECTIVITY AND COVERAGE

- Topology is tightly coupled with the overall behavior of the network
- Topology is directly related to stability, robustness and fragility of the overall dynamics.
- Change in topology, due to random and/or coordinated mobility, is a factor in the coupling between topology and the overall dynamics.
- Directional wireless networks allow scalable adjustment of topologies to provide responsive connectivity and capacity, but need to be matched by ability to manage and control topologies effectively.

DIRECTIONAL, HIGH CAPACITY, BACKBONE NETWORK MODEL

- **Communication channels:**
  - High data-rate directional channel (FSO/RF):
    - Up to Gb/s data traffic
    - Degree limitation: number of directional transceivers
  - Low data-rate omni-directional control channel:
    - control traffic (ID, location, link cost)

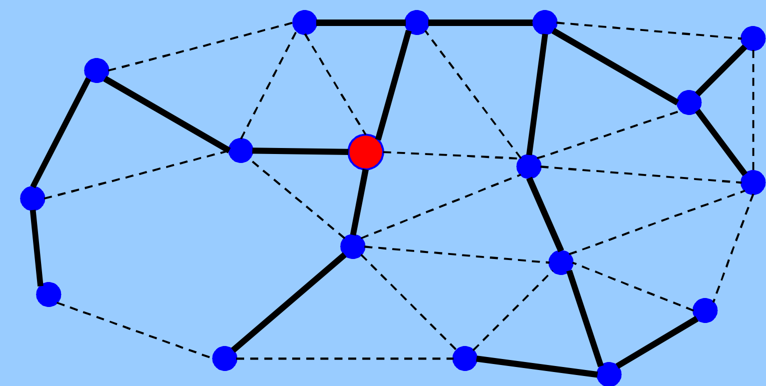
- **Graph model:**
  - <u>Potential</u> connectivity graph:

    $G = (V, E)$ *V:* set of backbone nodes

    E: set of potential directional links
  - <u>Actual</u> connectivity graph:

    $T = (V, E_T)$ *V:* set of backbone nodes

    $E_T \subseteq E$: set of active directional links
  - *k(v):* potential node degree (= number of neighbors)
  - *d(v):* actual node degree (=number of directional links)



***G*: – –** ***T*: —** **DTCN:** ●

● Designated Topology Control Node (DTCN)

PHYSICAL LAYER COSTS
GOAL: INTRODUCE LINK DEGRADATION CRITERIA

Based on BER, determine
# of links degraded,
Minimize packets dropped

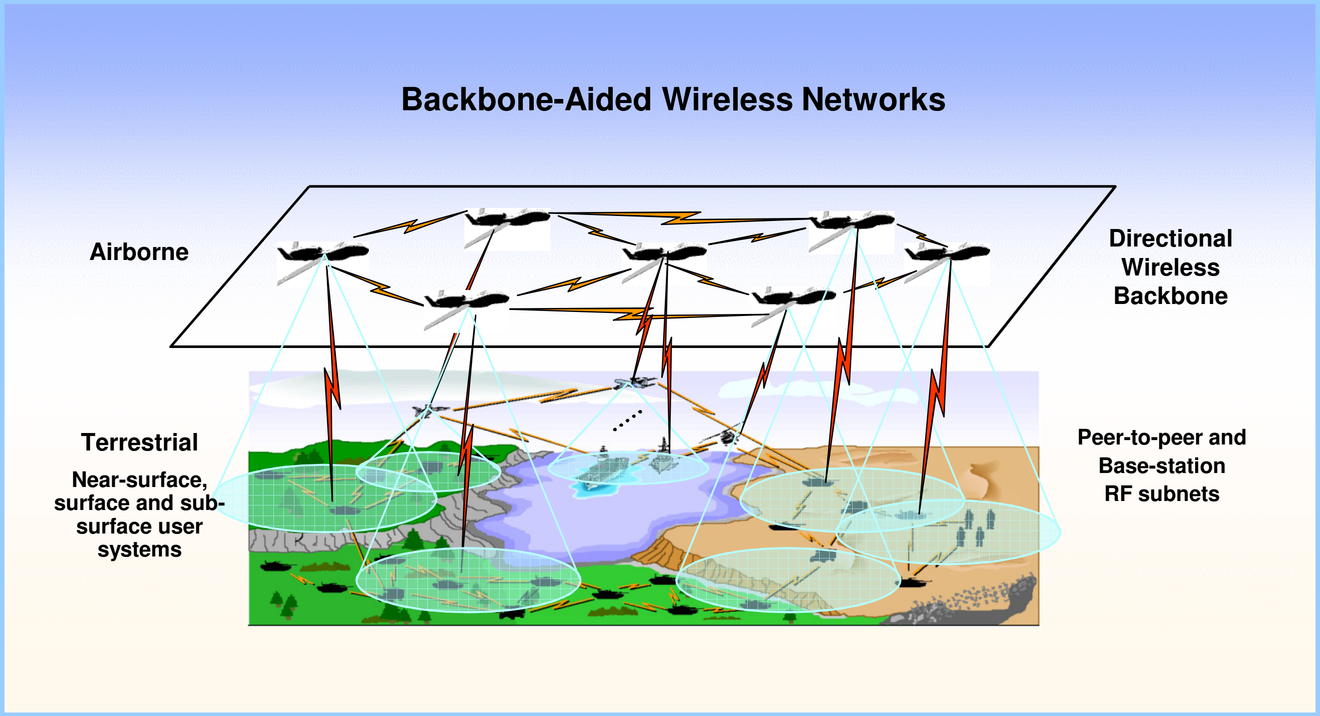
+

Reconfiguration Cost
Minimization (SA)

- Change in link states makes current topology suboptimal
- New topology has to be calculated to minimize the number of packets dropped during the transient state of the network
  - Metric – packets dropped during the transient state of the network
  - Reconfiguration Metric – Packet drops due to reconfiguration.

Hierarchical Wireless Networks: **Network** Cognition and Control

– Increasing need for network architectures that **integrate and unify communication technologies** to overcome their limitations
– A **Two Tiered Network Architecture**



Two Tiers with Complementary Requirements and Capabilities. Cognitive Networks Unify the Two

Higher tier

- Base station, infrastructure
- High Capacity Directional RF/FSO
- Directional transmission
  - Large transmission distance
  - LPI/LPD
  - Large aggregated throughput
  - Unlimited scalability
  - PAT
- Relatively stable topology
  - Limited number of nodes
  - High, assured connectivity
  - Low reconfiguration rate
- Network cognition and control
  - Topology reconfiguration
  - Mobility management

Lower Tier

- Ad-hoc nature
- Low Capacity RF
- Omni-directional transmission
  - Smaller distance
  - High interference
  - Limited throughput capacity ($1/\sqrt{n}$)
  - Non-scalable
  - User-free PAT
- Ad-hoc topology
  - Large number of nodes organized in clusters
  - Lower, ad hoc connectivity
  - High reconfiguration rate
- Radio cognition and control
  - Power control
  - Cognitive radios

The integrated two tier architecture drastically improves the overall scalability and performance over a single flat network

SELF-ORGANIZATION OF HIERARCHICAL, HETEROGENEOUS, WIRELESS NETWORKS (HHWN)

- Assure highly available end-to-end broadband connectivity in HHWN environments
  - Node mobility
  - Node addition/deletion
  - Channel attenuation
  - Blockage due to changing terrain
  - Network congestion
  - Jammers

- Self-organizing backbone (base stations) through topology control
  - **Topology reconfiguration**
    - Dynamic redirection of directional wireless links
    - Pointing, Acquisition and Tracking
  - **Mobility Management**
    - Dynamic reposition of backbone nodes

TWO TIERS WITH COMPLEMENTARY CAPABILITIES

Higher tier

- Base station, infrastructure
- High Capacity Directional RF/FSO
- Directional transmission
- Large transmission distance
- LPI/LPD
  - Large aggregated throughput
  - Unlimited scalability
  - PAT
- Relatively stable topology
  - Limited number of nodes
  - High, assured connectivity
  - Low reconfiguration rate
- Network cognition and control
  - Topology reconfiguration
  - Mobility management

Lower Tier

- Ad-hoc nature
- Low Capacity RF
- Omni-directional transmission
  - Smaller distance
  - High interference
  - Limited throughput capacity
  - Non-scalable
- Ad-hoc topology
  - Large number of nodes organized in clusters
  - Lower, ad hoc connectivity
  - High reconfiguration rate
- Radio cognition and control
  - Power control
  - Cognitive radios

The integrated two tier architecture drastically improves the overall scalability and performance over a single flat network

POTENTIAL ENERGY FUNCTION FOR HHWNs

$$U = \underbrace{\sum_{i=1}^{N}\sum_{j=1}^{N} b_{ij}\, u(\mathbf{R_i}, \mathbf{R_j})}_{F} + \underbrace{\sum_{k=1}^{M} u(\mathbf{R_{h(k)}}, \mathbf{r_k})}_{G}$$

$$b_{ij} = \begin{cases} 1 & \text{if } (i,j) \in T \\ 0 & \text{o.w.} \end{cases}$$

F: backbone connectivity cost

G: network coverage cost

N: number of backbone nodes

M: number of terminal nodes

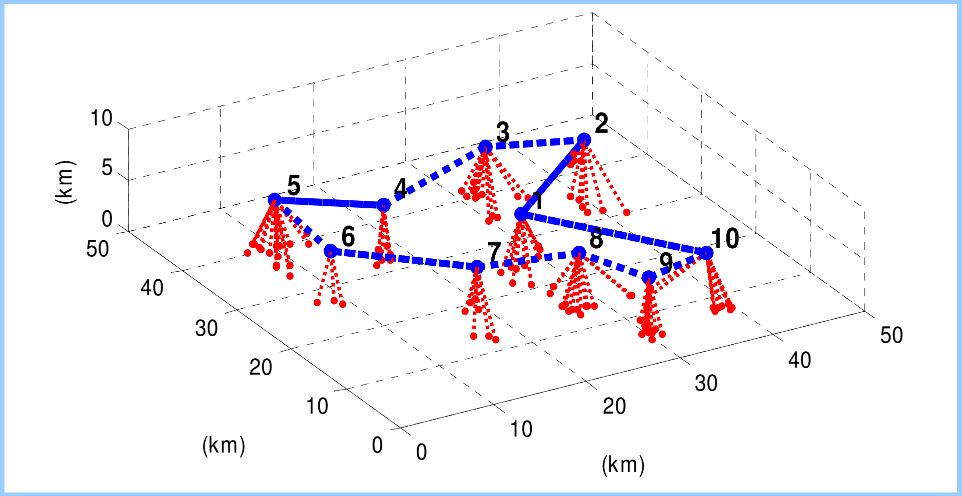
T: backbone topology

R_i: location of backbone node i

r_k: location of terminal node k

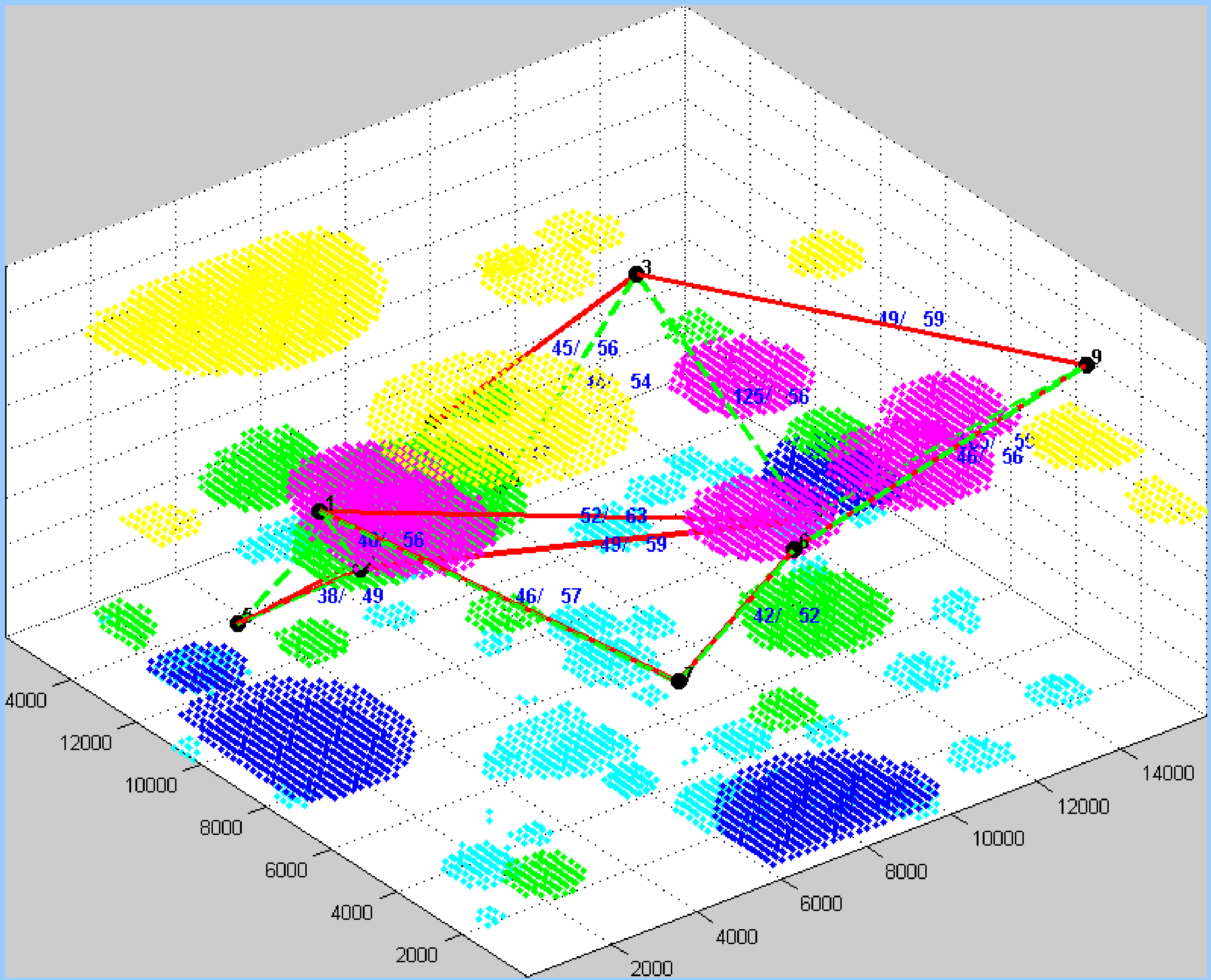
u_{ij}: potential energy stored at wireless link (i,j)

$h(k)$: backbone node assigned to terminal node k

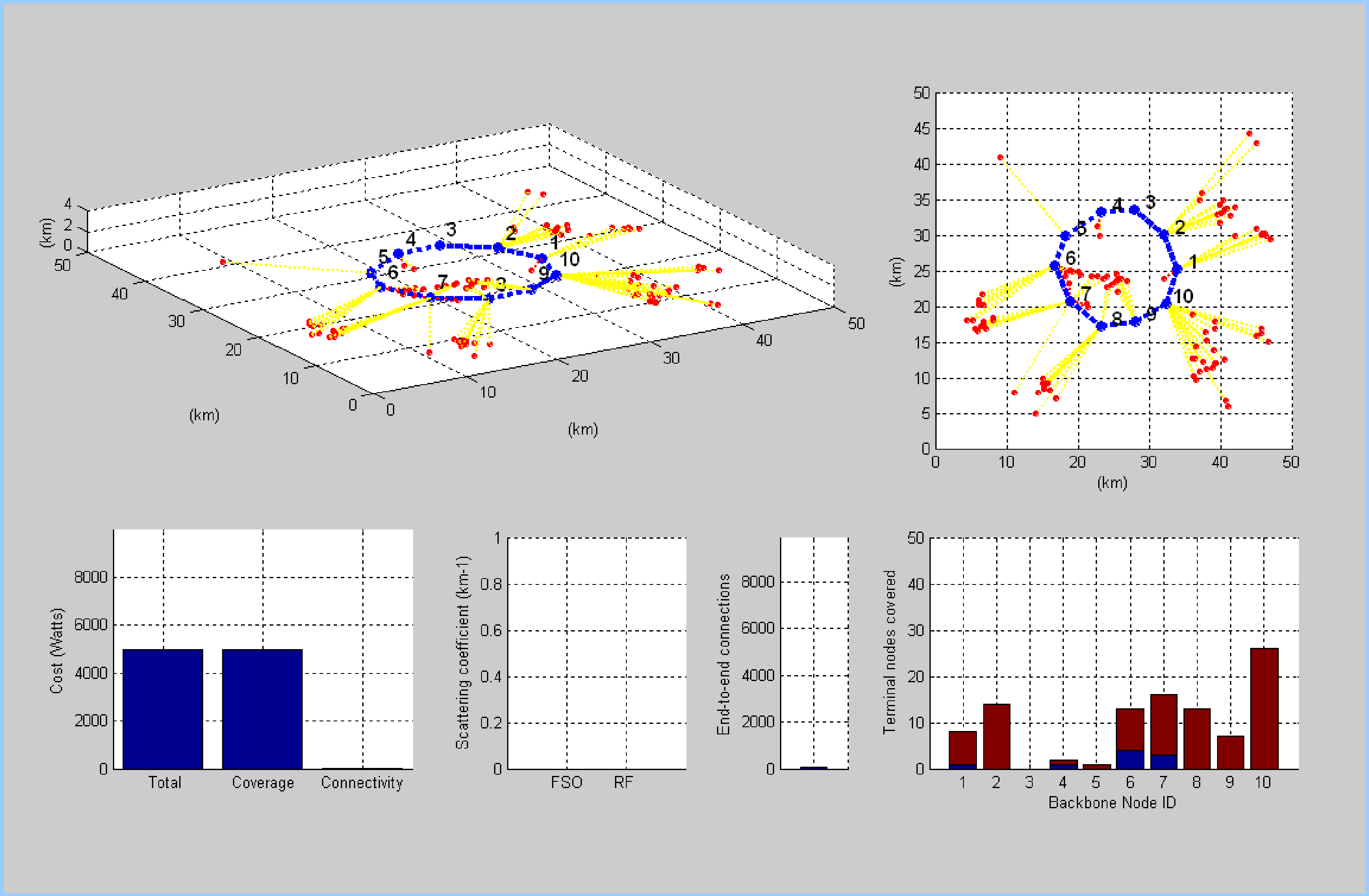


Blue – backbone nodes, Red – terminal nodes

FSO + RF Simulation with Clouds



Mobility Control



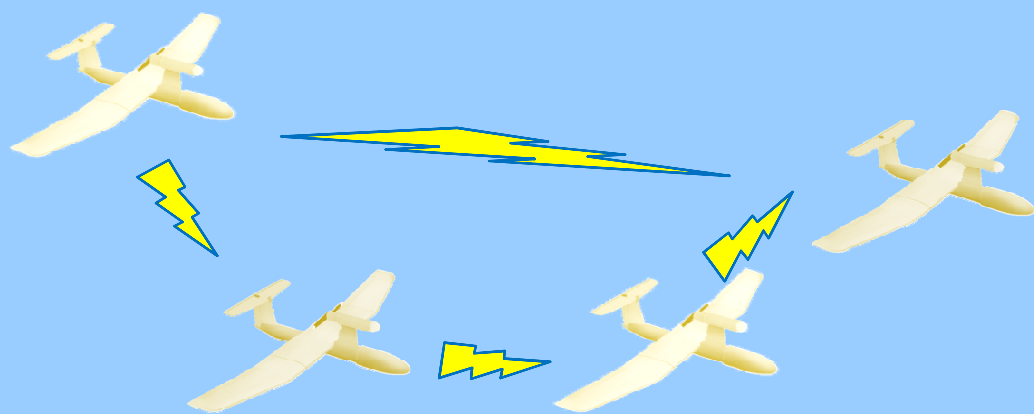
CHARACTERIZATION, CONTROL AND PREDICTION IN HETEROGENEOUS AND DYNAMIC NETWORKS

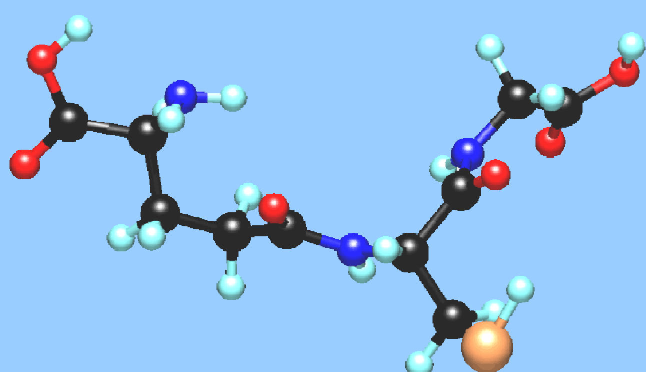
- Characterization
- Control
- **PREDICTION**
  - Objective**:** predict link degradation or failure
  - Methodology
    - Investigate network **reconfiguration strategies analogous to rearrangements in molecular systems**.
  - Prediction leads to **self-diagnosing** capabilities
  - What can we learn from *molecular systems*?

MOLECULAR ANALOGY

- By modeling the **network as a giant molecule** we can learn how nature adapts to external forces and constraints within a connected structure.

Description	Molecular System	Wireless Network
Nodes	Atoms	Hosts/users
Connections	Bonds	Links
Topology control	Rearrangements (distributed)	Reconfiguration (centralized)
Objective	Energy minimization & structure stability	

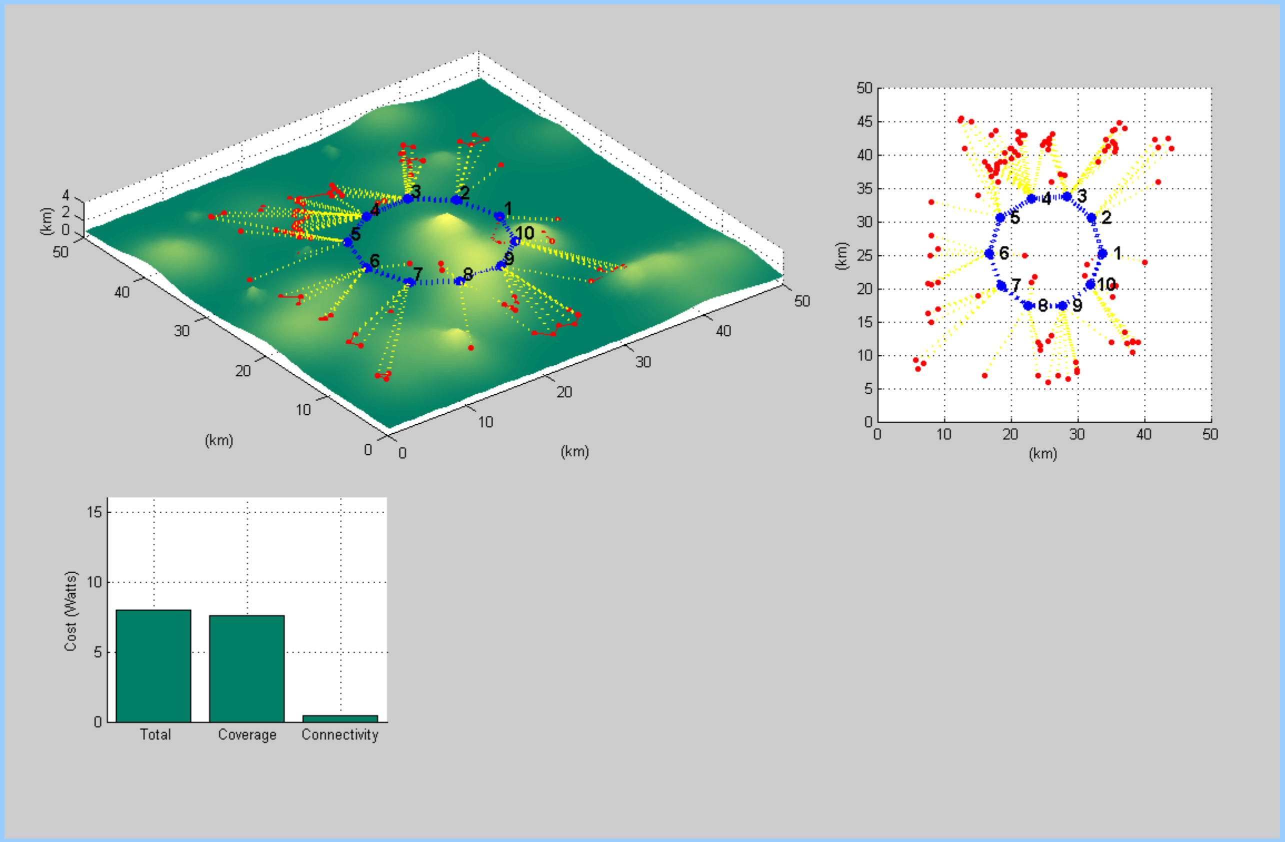




An example network in action… similar to molecular rearrangements?

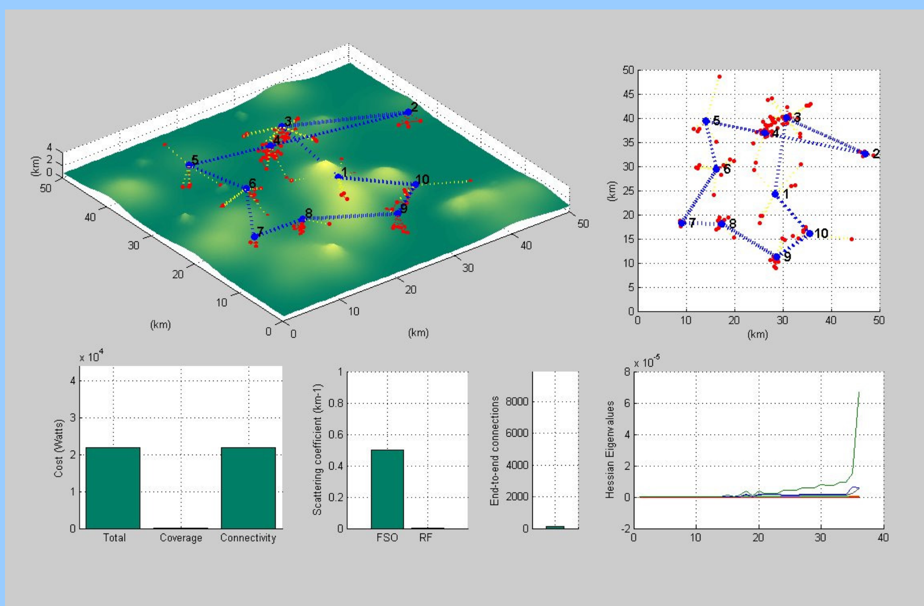
HHWN = Hierarchical Heterogeneous Wireless Networks

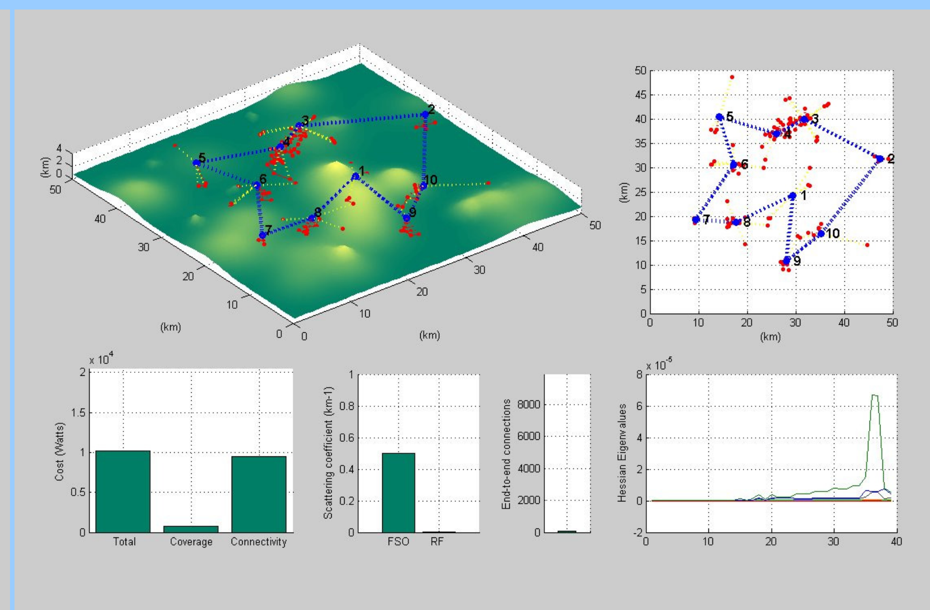
- 10 backbone nodes using FSO links (BLUE)
- 100 terminal nodes using omni RF links (RED)
- YELLOW is used to show inactive links due to excessive cost (distance, power, BER, etc)
- FORCE acting on backbone nodes shown in GREEN in 2D plot
- Evolution of Eigenvalues of the network Hessian shown in right-bottom plot



Can we track the network structure as a function of its energy?

- The **PES of our networks** will provide similar insight into network topology reconfigurations.
- **Link dynamics** (as a function of node movement) will be illustrated.
    - Attempting to predict topology reconfigurations **("buffer time")**



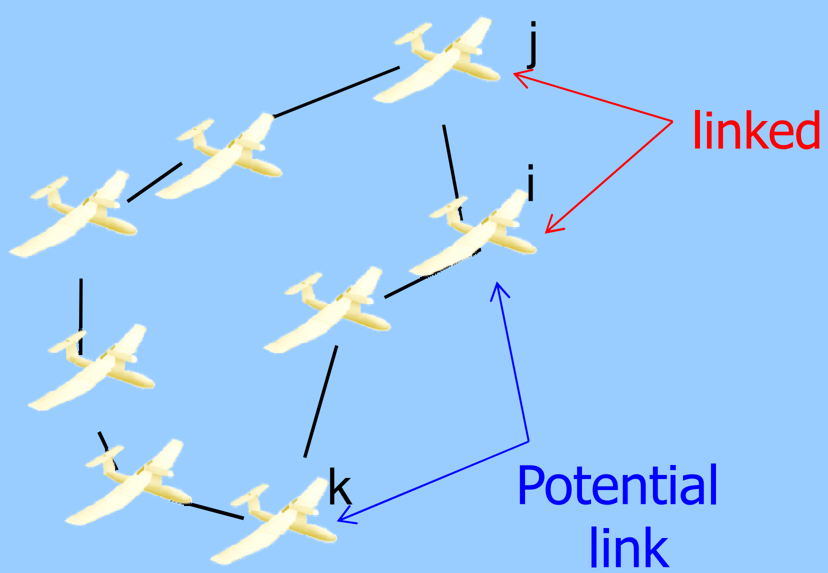


Before Reconfiguration
(Eigenvalue increases)

After Reconfiguration
(Eigenvalue decreases)

MODELING NETWORK DYNAMICS

- The "total energy" is derived from pair-wise interactions between nodes
- A connection between two nodes can be a **link** or a **potential link**;
  - We model each case differently similar to the molecular system;



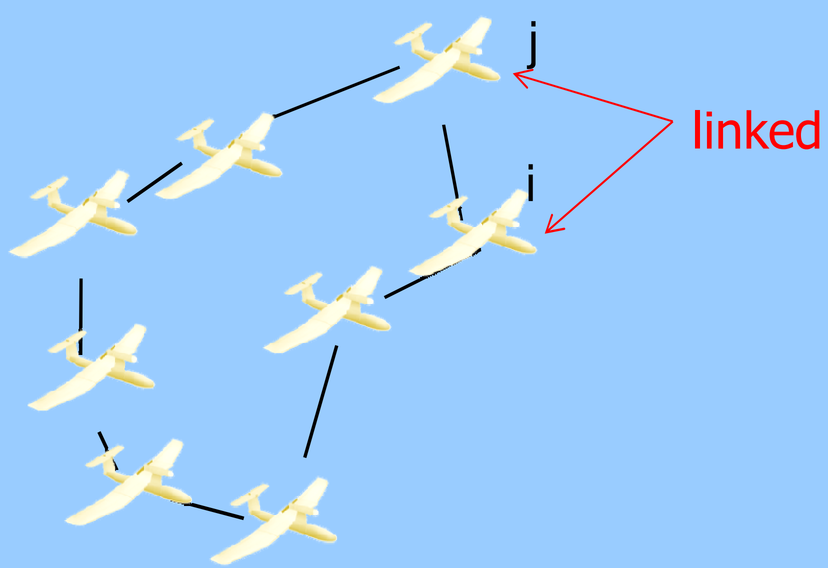
$$u_{total} = \sum_{\forall \, links \, (i,j)} u_{ij} + \sum_{\forall \, P.L \, (i,k)} u_{ik}$$

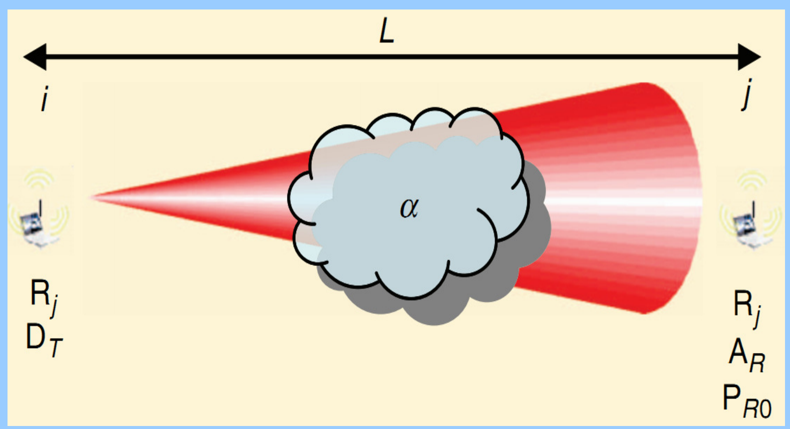
- u_{ij} = current communication links
- u_{ik} = potential connections

MODELING NETWORK DYNAMICS
"Understanding links"

- The "total energy" is derived from pair-wise interactions between nodes
- A connection between two nodes can be a **link** or a potential link;
  - A link is shared between neighbors; a node can at most 2 links;
  - The cost of a link is determined by the bit-error rate, distance, obscuration, etc;
  - Increasing/decreasing of cost is similar to "stretching/retracting the link".

$$u_{link} = \sum_{i}\sum_{j\neq i} b_{ij}\left(P_{RO}^{j}\frac{4\pi}{D_T^i A_R^j}\right) L_{ij} e^{a_{ij}L_{ij}}$$

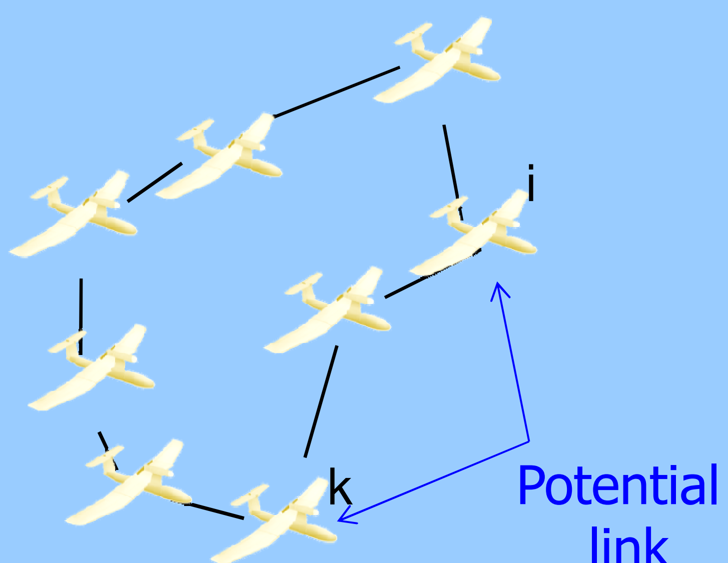


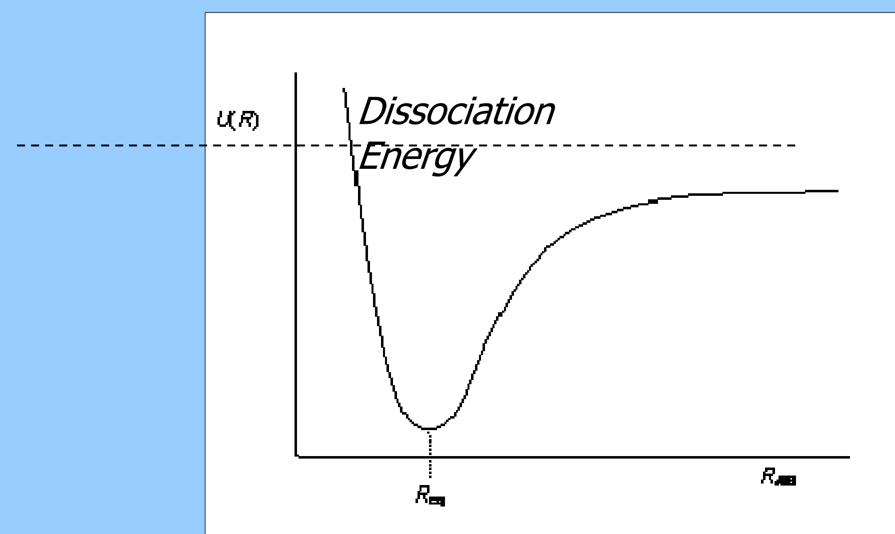


MODELING NETWORK DYNAMICS
"Understanding potential links"

- The "total energy" is derived from pair-wise interactions between nodes
- A connection between two nodes can be a link or a **potential link**;
  - A potential link is a product of separation only since other metric are unmeasured;
  - Similarly, modeled as a Morse potential;
  - Pair-wise computation between all unconnected nodes;
    - Saturation energy eases computational complexity for nodes beyond specific distance

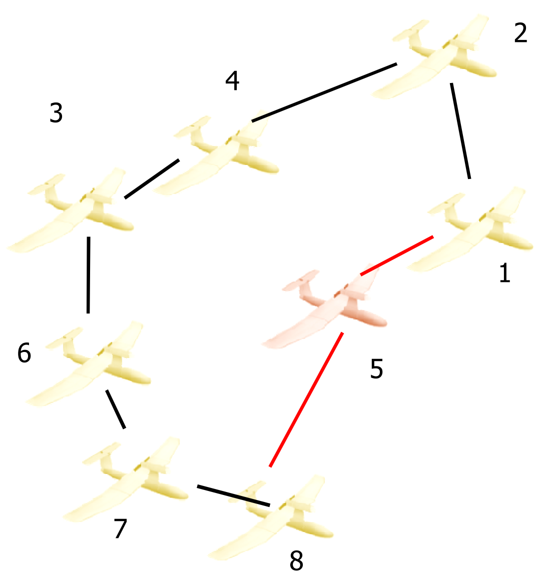
$$u_{potential\_links} = \sum_i D_i \left(1 - e^{-B_{ik}\|\mathbf{R}_k - \mathbf{R}_i\|}\right)^2$$

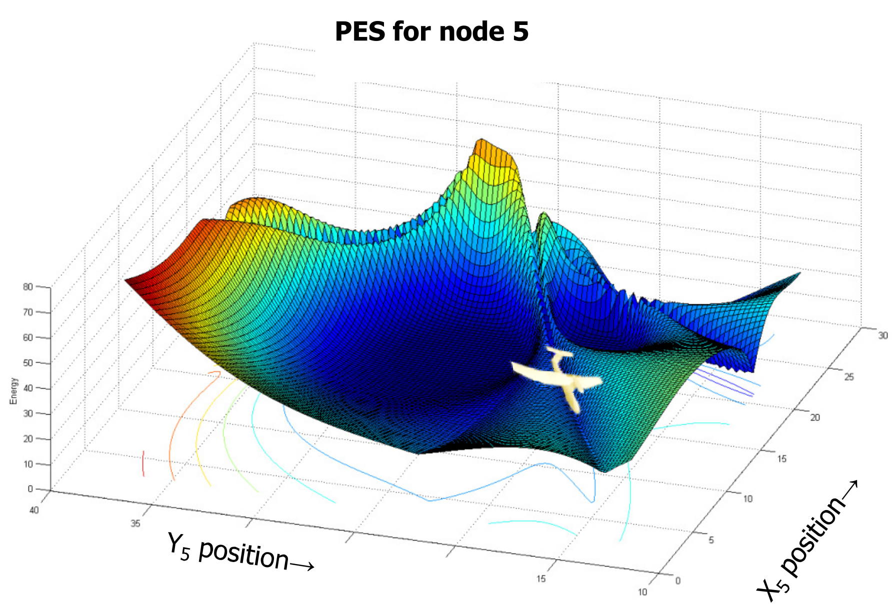




MODELING NETWORK DYNAMICS
“Isolation around a specific node”

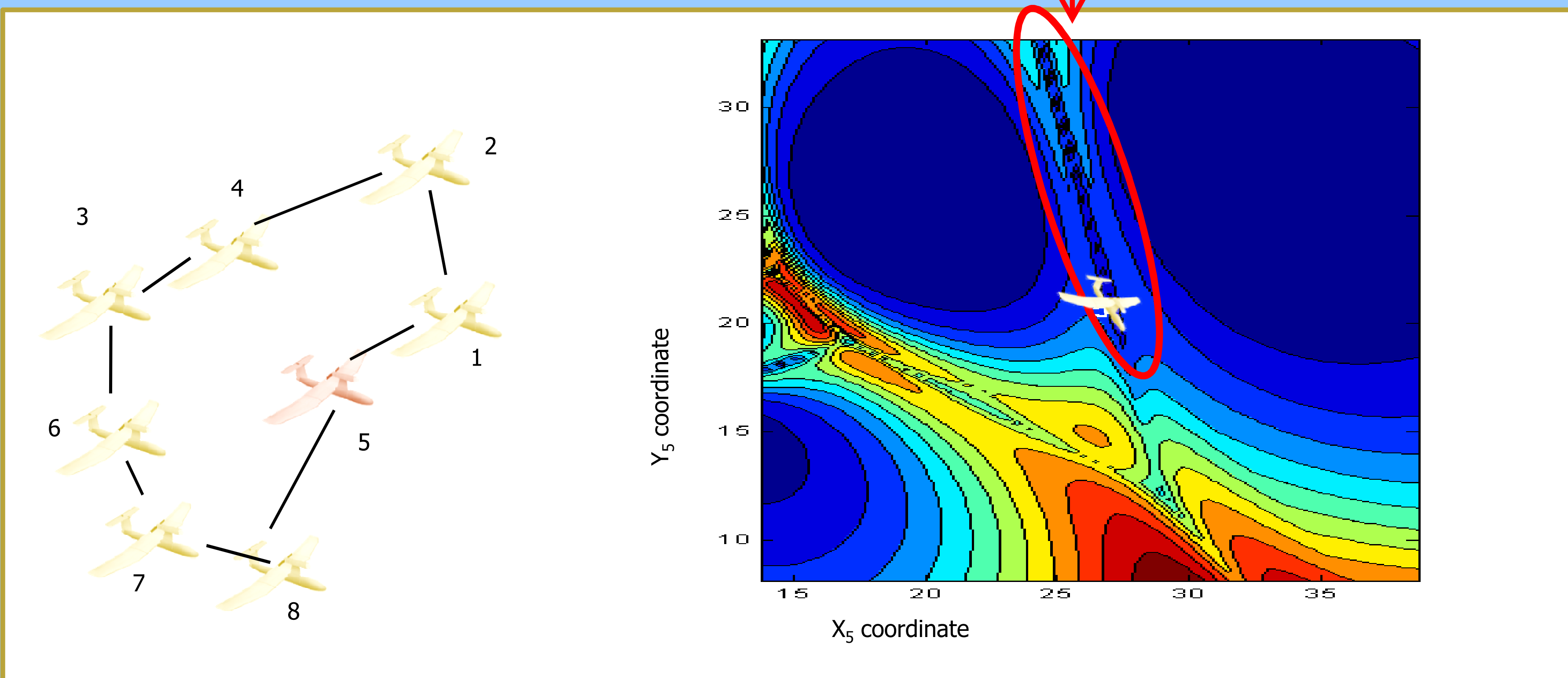
- For example, we show the links around node 5 (highlighted) to be <u>stretched and obscured</u> similar to the previous molecular simulations.
- The system energy will **increase** and **decrease** as a consequence.
- The transition points will indicate possible network reconfigurations.
- Red = high energy; Blue = low energy





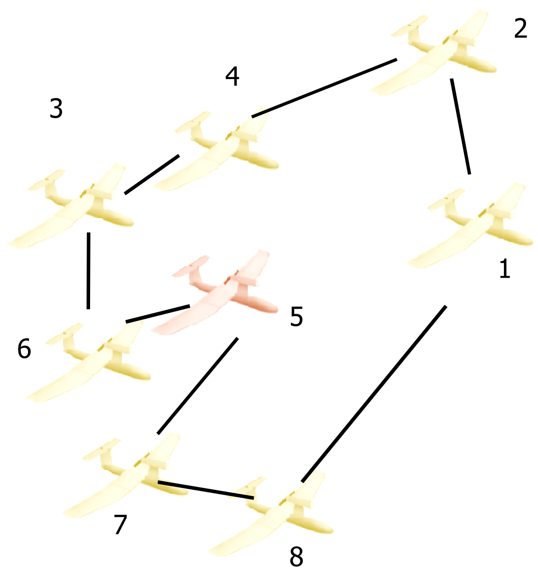
APPLYING MOLECULAR DYNAMICS TO NETWORKS cont'd

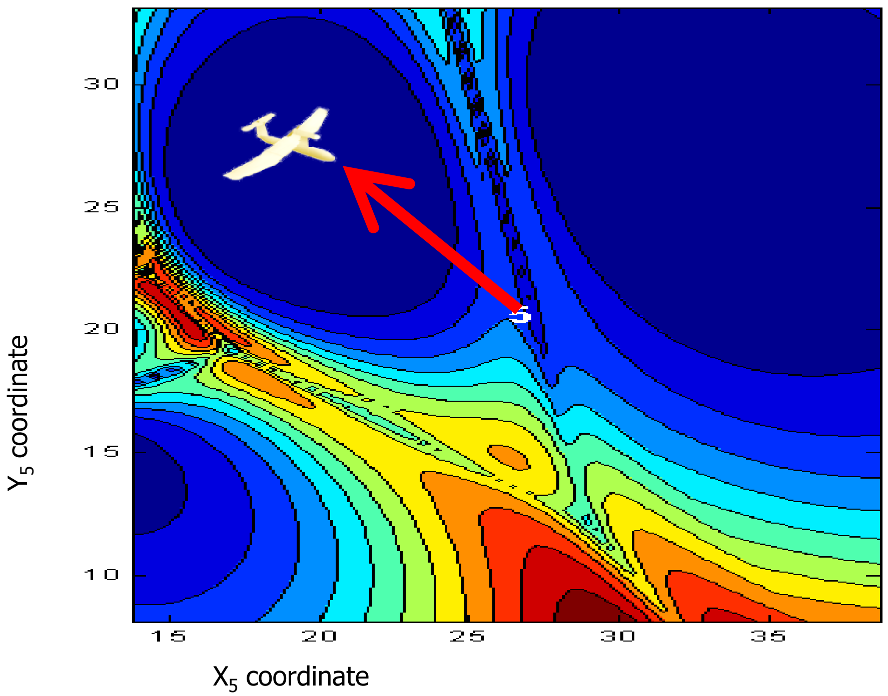
- **Minimum valley**
  - System requires minimum energy to maintain connections (i.e. node 5 can move within this valley or region without increasing its link costs significantly).



APPLYING MOLECULAR DYNAMICS TO NETWORKS cont'd

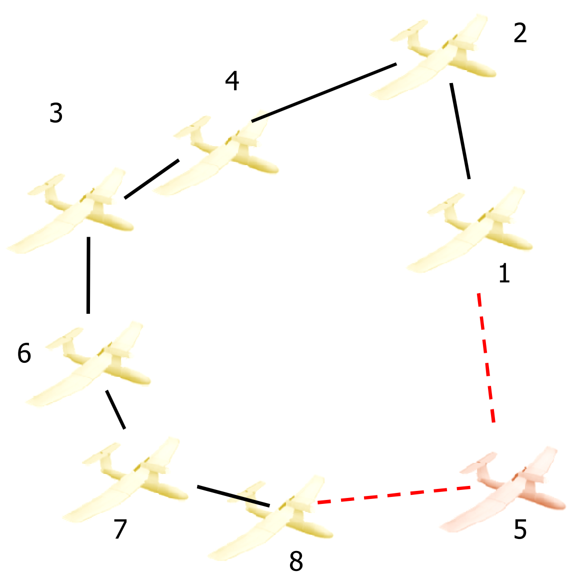
- **Minimum energy wells**
  - The bonds are sub-optimal → bonds are broken
  - New bonds are formed from **potential neighbor** set.
- Similar network structures exist for top right/bottom left minimum wells.

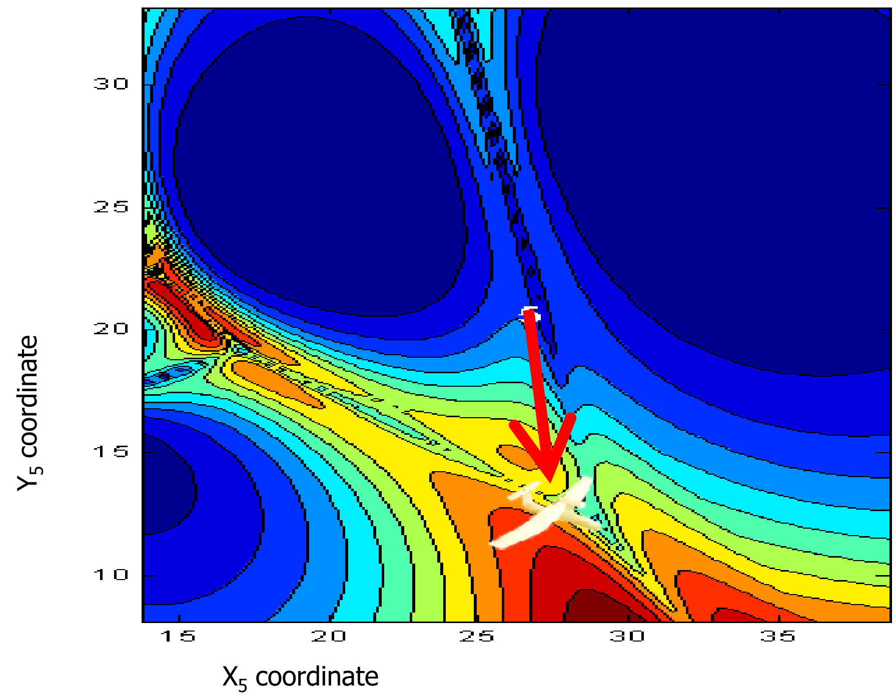




APPLYING MOLECULAR DYNAMICS TO NETWORKS cont'd

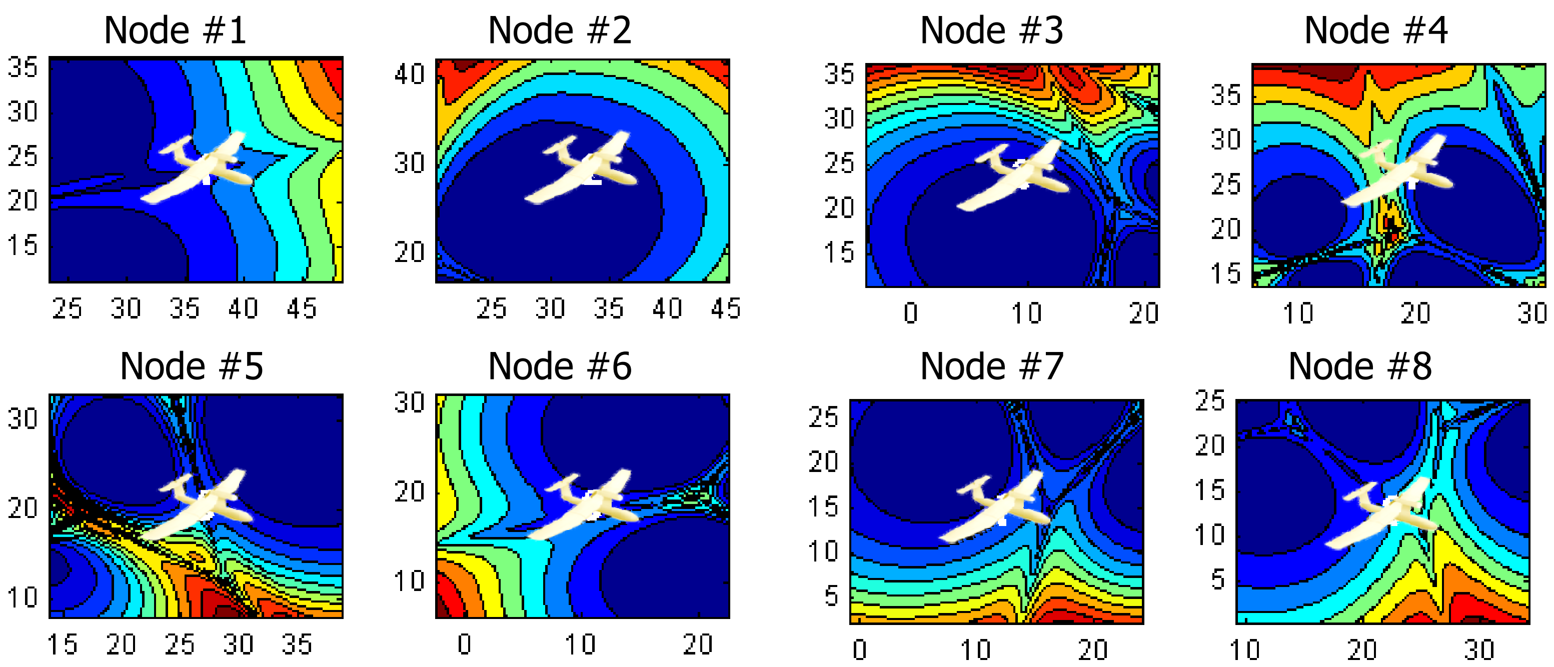
- **Maximum energy peaks**
  - Node 5 is moving to an unstable region with no minimum present and therefore will only have a negative impact on the system





ADDITIONAL INFORMATION OBTAINED FROM THE NETWORK PES

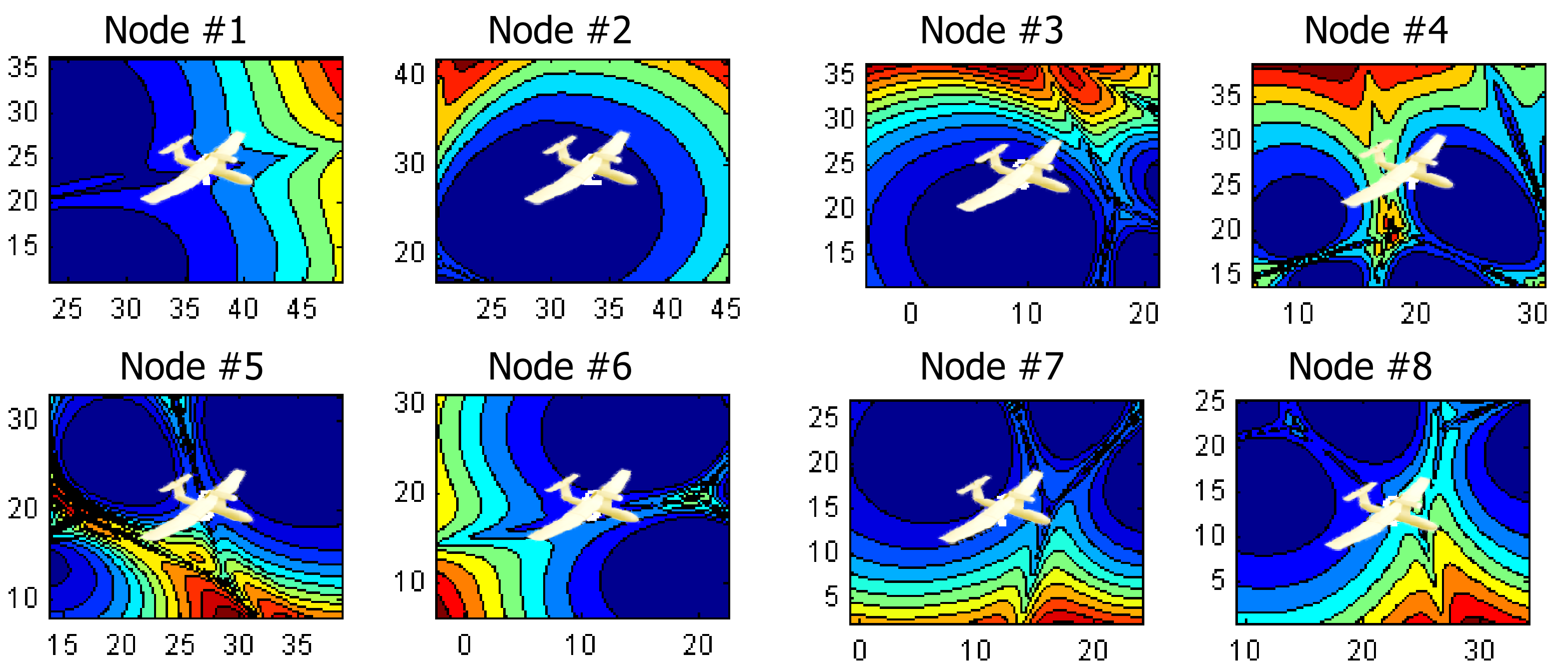
- Furthermore, the PES identifies **proximate regions** within the environment to permit intelligent decisions regarding resource allocation, the realignment of directional technologies, and the reduction of latency



All (x,y)-axes are absolute positions of nodes in environment space

ADDITIONAL INFORMATION OBTAINED FROM THE NETWORK PES

- Furthermore, the PES identifies **proximate regions** within the environment to permit intelligent decisions regarding resource allocation, the realignment of directional technologies, and the reduction of latency



All (x,y)-axes are absolute positions of nodes in environment space

Why networks reconfigure? How often?

- A network can have multiple objectives
  - Bit-error rate (aggregate > 10^{-9})
  - Obscuration (avoid clouds between nodes)
  - Transmit power (reduce power requirements)
  - Distance (reduce tracking difficulties)
- In our simulation, we curetnly focus on distance (L) but it does not limit our results.

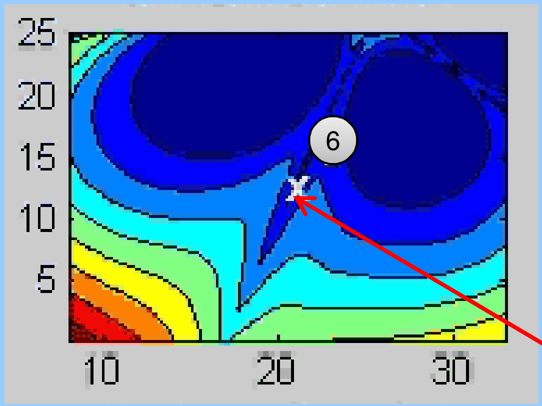
$$P_{RX} = P_{TX} e^{-\alpha L} \frac{2A}{\pi\theta^2 L^2}$$

A is the area of the receiver aperture
P_T denotes the transmitter power
θ is the beam divergence half angle
L is the link distance
α is the obscuration in the link path

- A **threshold** is established to indicate the network is not achieving specific objectives and a reconfiguration (new topology) needs to be computed.
- This is the first step towards the identification of network degradation.

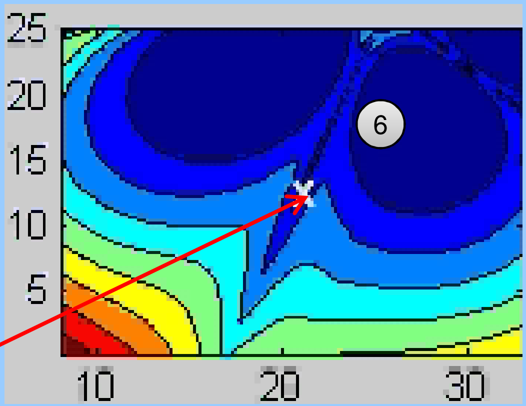
Reconfiguration aide in achieving objectives
SIMULATION SETUP

- Environments were generated in MATLAB.
- Five 40-minute simulations
  - 8 mobile base stations
  - Altitude = 2 km with constant obscuration
  - Different threshold objectives



Time = 15 minutes

Starting position



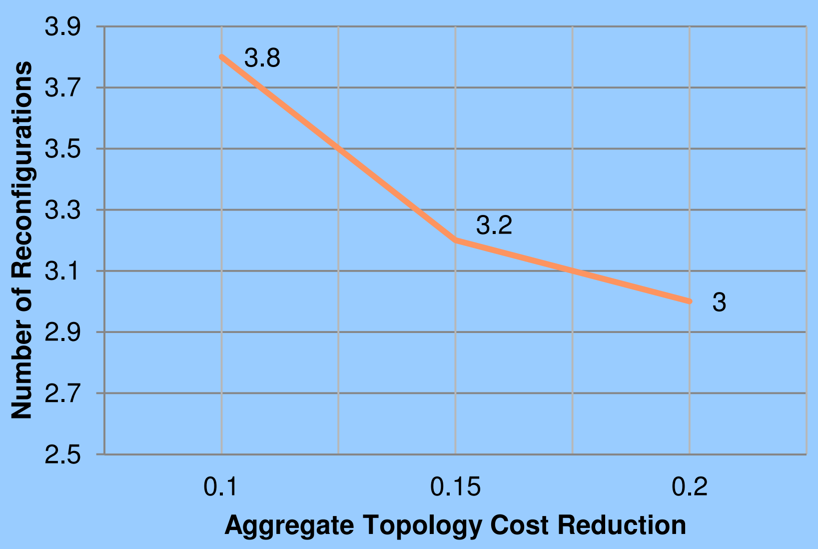
Time = 18 minutes

Buffer time = (Time of reconfigure) – (Time node crosses energy barrier)
Buffer Time = 18 minutes – 15 minutes = **3 minutes**

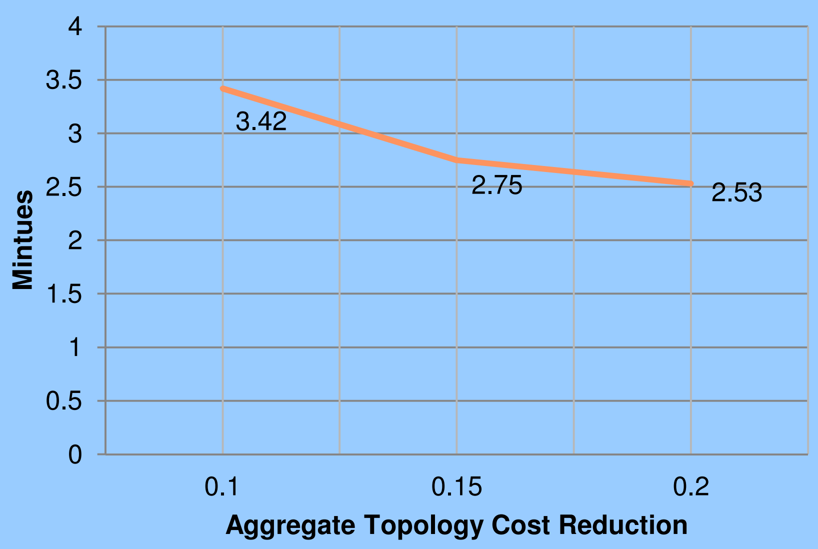
THE NETWORK BECOMES SELF-DIAGNOSING
(How did we do?)

- Node movement along energy surface provides a *buffer time* on the order of **<u>minutes</u>**.
- *Buffer time* = (Time of reconfigure) – (Time node crosses energy barrier)
- Shows <u>self-diagnosing</u> capability

Average Number of Reconfigurations
across varying cost reduction requirements



Average Buffer Time Prior to Reconfiguration
across varying cost reduction requirements



SUMMARY

- **Potential energy surfaces** yield an efficient metric to characterize robustness in complex communication networks
  - Energy functions from different fields being investigated
- Force-driven control algorithms shown to be efficient, **scalable** and **self-organized** (first-order dynamics)
  - Joint coverage-connectivity optimization
- Potential energy surfaces provide **self-diagnosing** capabilities to networks
  (second order dynamics)
  - Promising approach to predict global network health
    - Track network dynamics in the same manner as molecular rearrangements

THANK YOU