Connectivity and Security in Directional Sensor Networks

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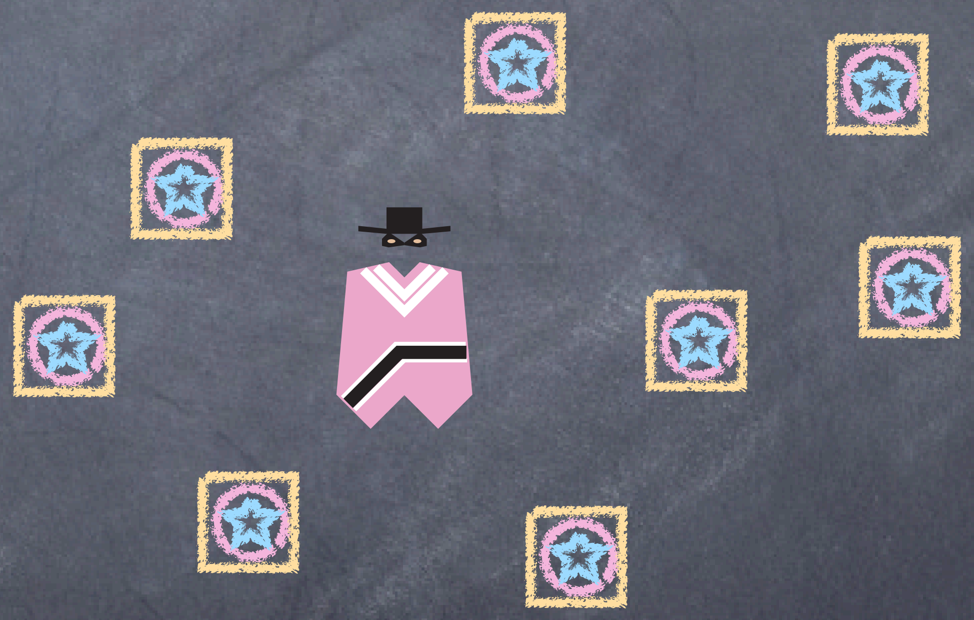
Multimedia Sensor Systems

- densely distributed, ad hoc, collaborative, autonomous, resource-constrained
- diverse specialized sensing
- sensors are multimodal



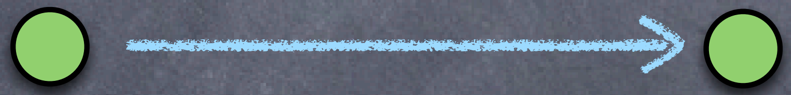
focus: subset of data is visual

Multimedia Sensor Systems

- Applications
  - healthcare monitoring
  - disaster exploration
  - unmanned vehicle control ...
- Need widespread adoption
  - societal trust

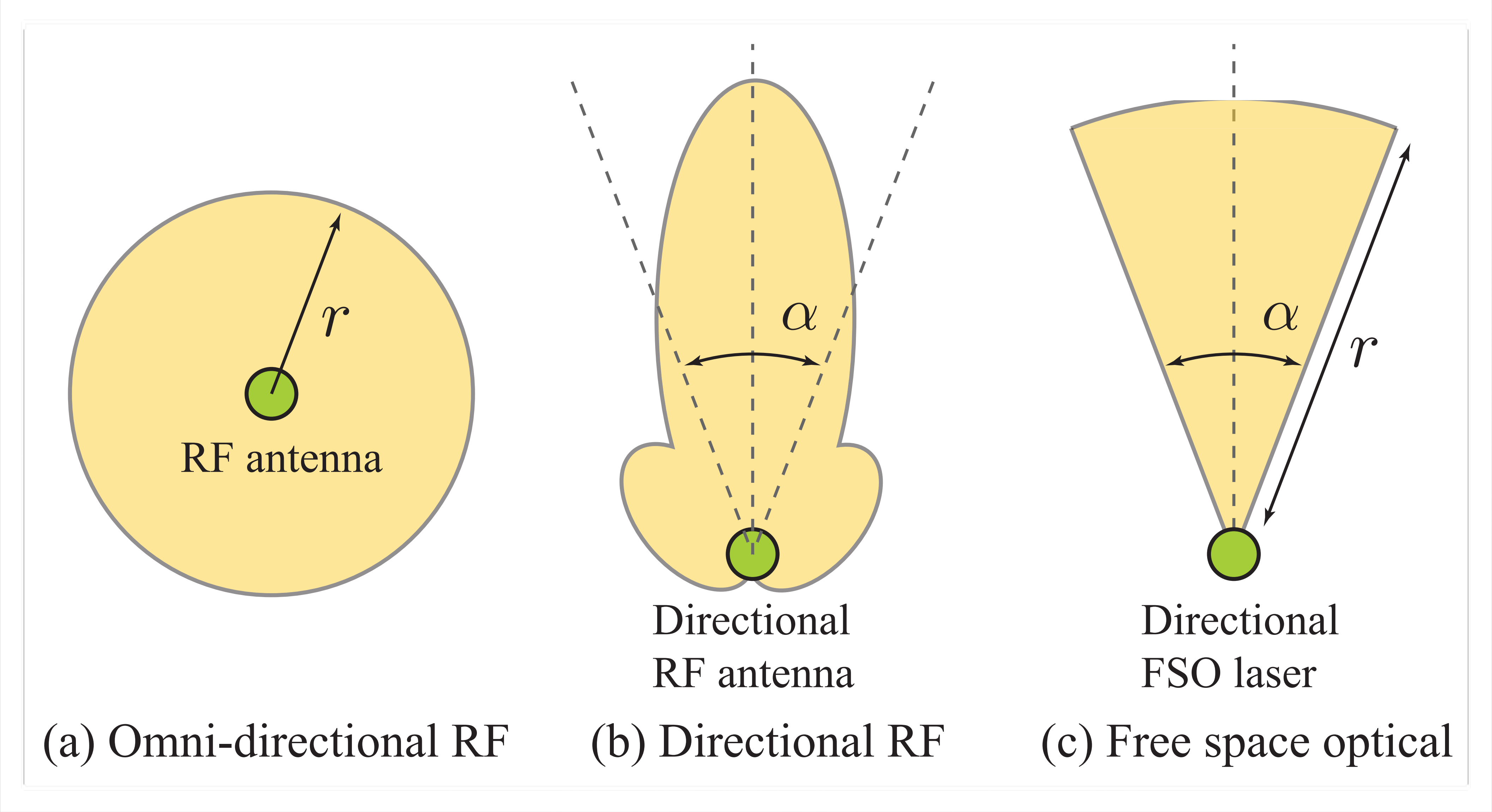
Multimedia Sensor Systems

- Significant technical challenges
  - communications bandwidth
  - security and privacy



Physical layer perspective:
directional communications

Directional Communications



(a) Omni-directional RF (b) Directional RF (c) Free space optical

Directional Communications

- Transceiver configurations:

trans-recv

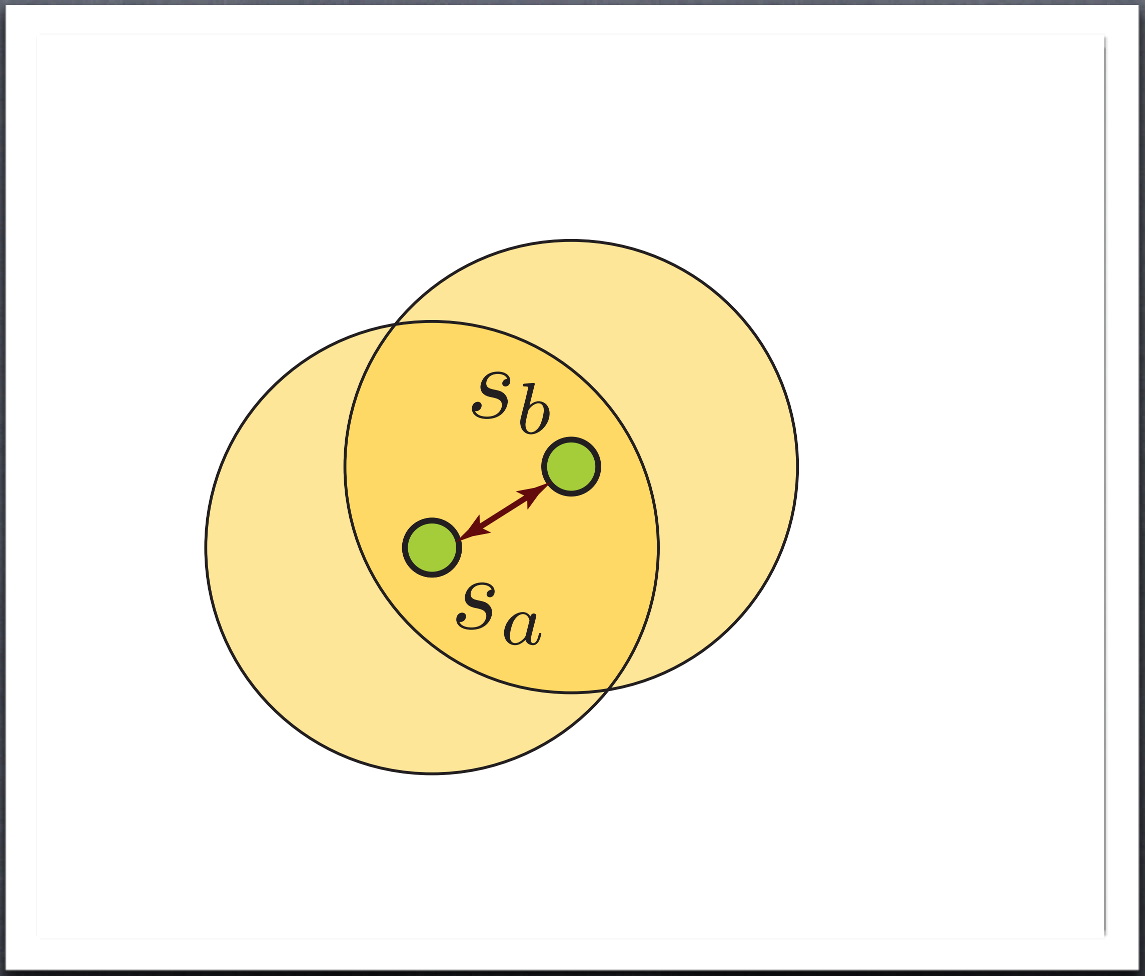
omni-omni

direc-omni

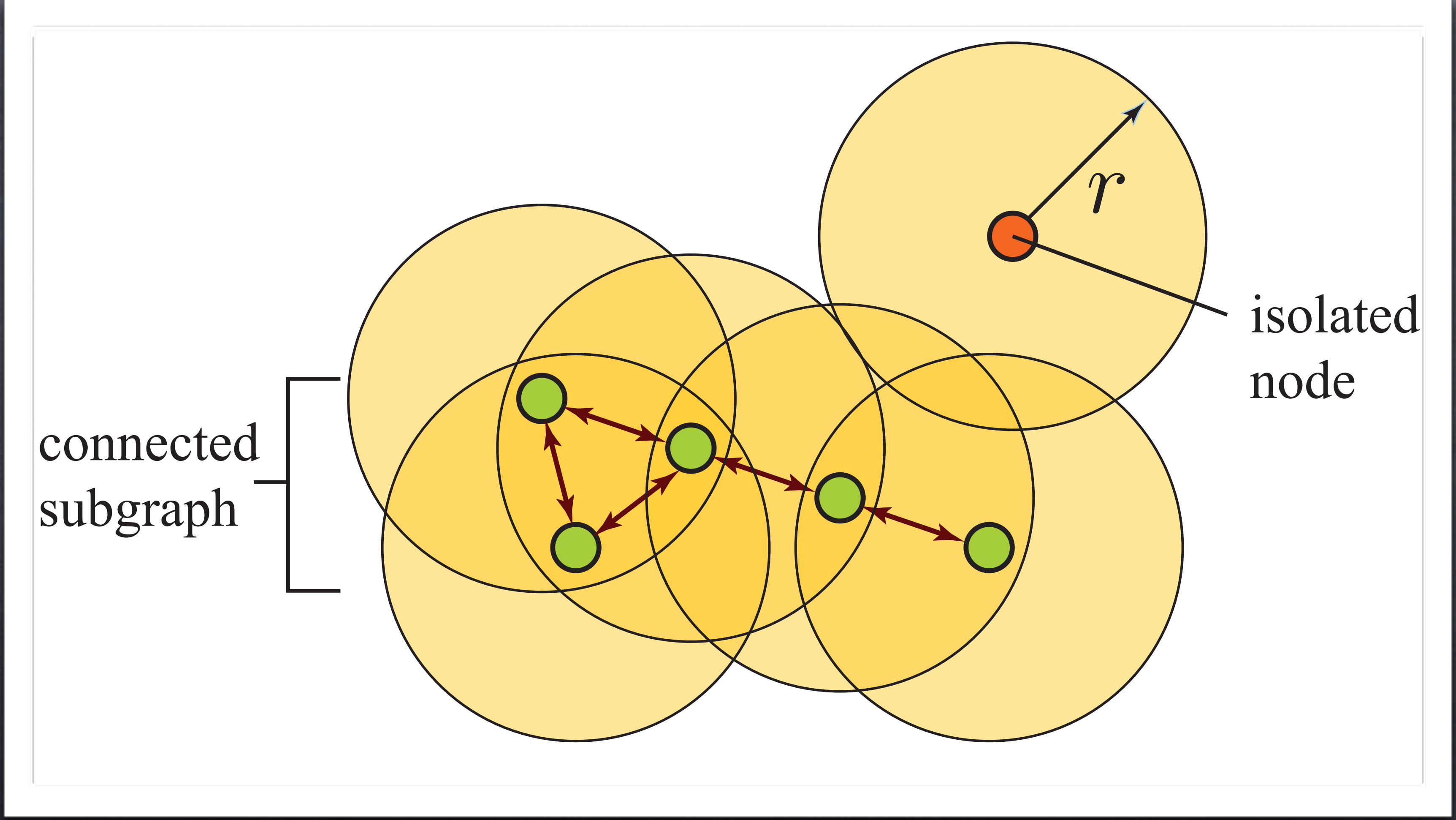
direc-direc

omni-direc

Omnidirectional Communications



RANDOM GEOMETRIC GRAPH (RGG) MODEL

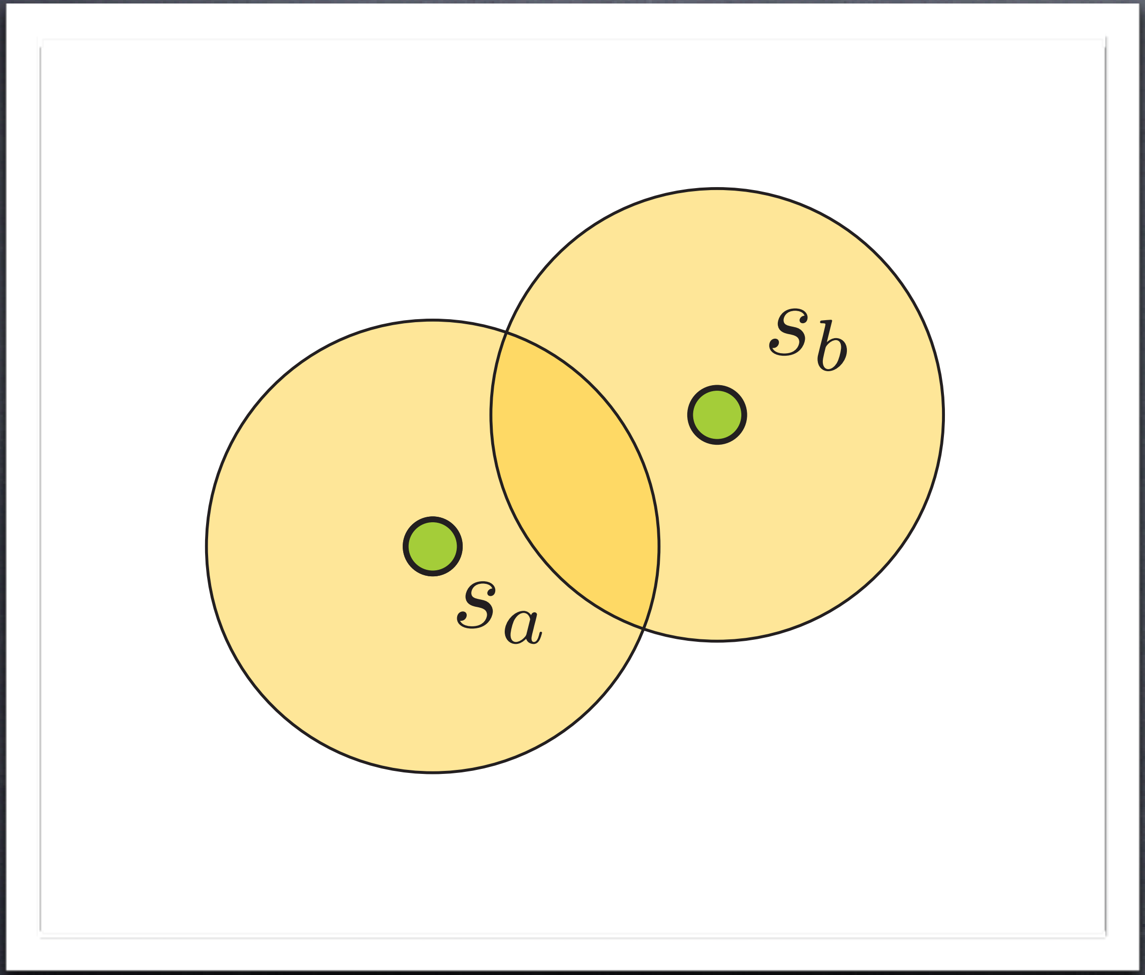


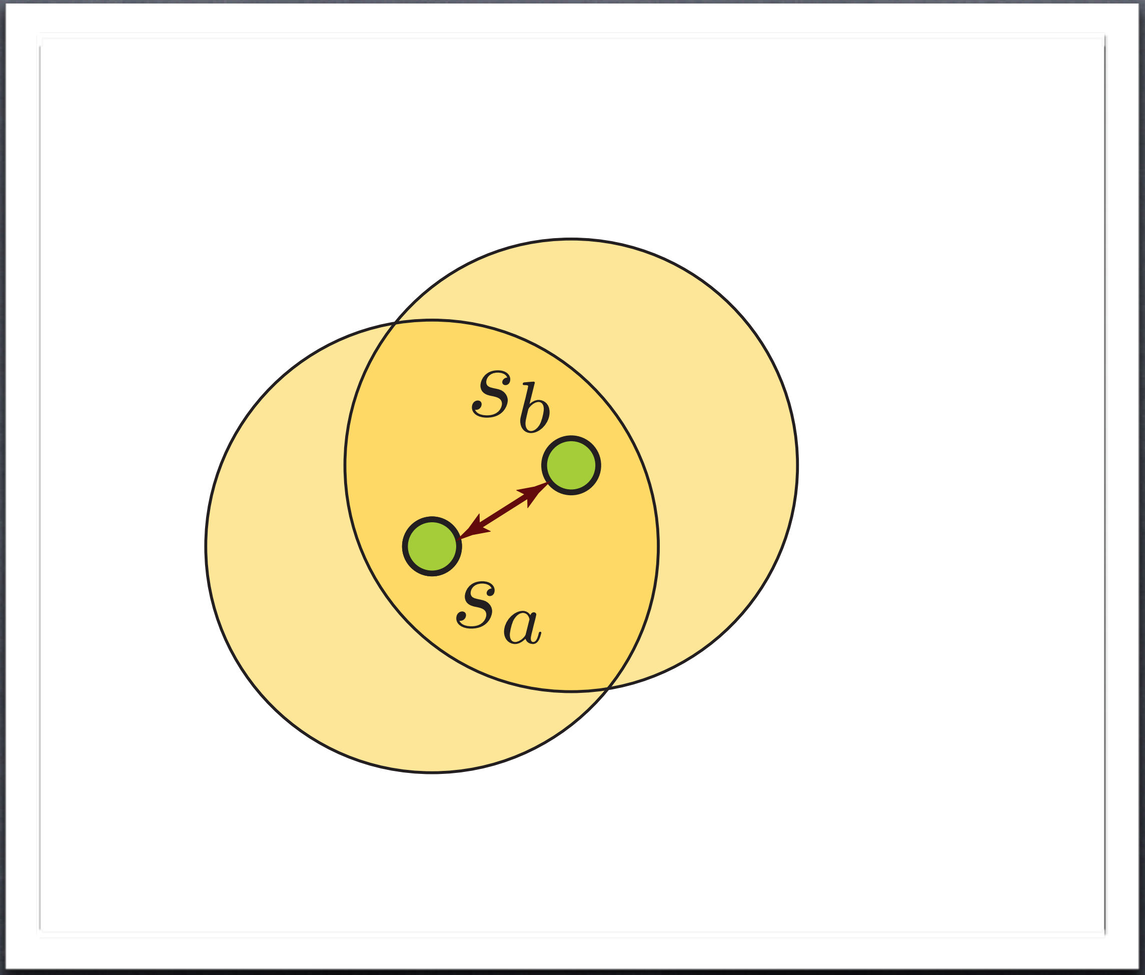
Network Connectivity

- Definition: for every node pair there exists at least one path connecting them.

- RGG connectivity: How do physical layer communication parameters affect probability of network connectivity?
  - asymptotic methods
  - probabilistic approaches

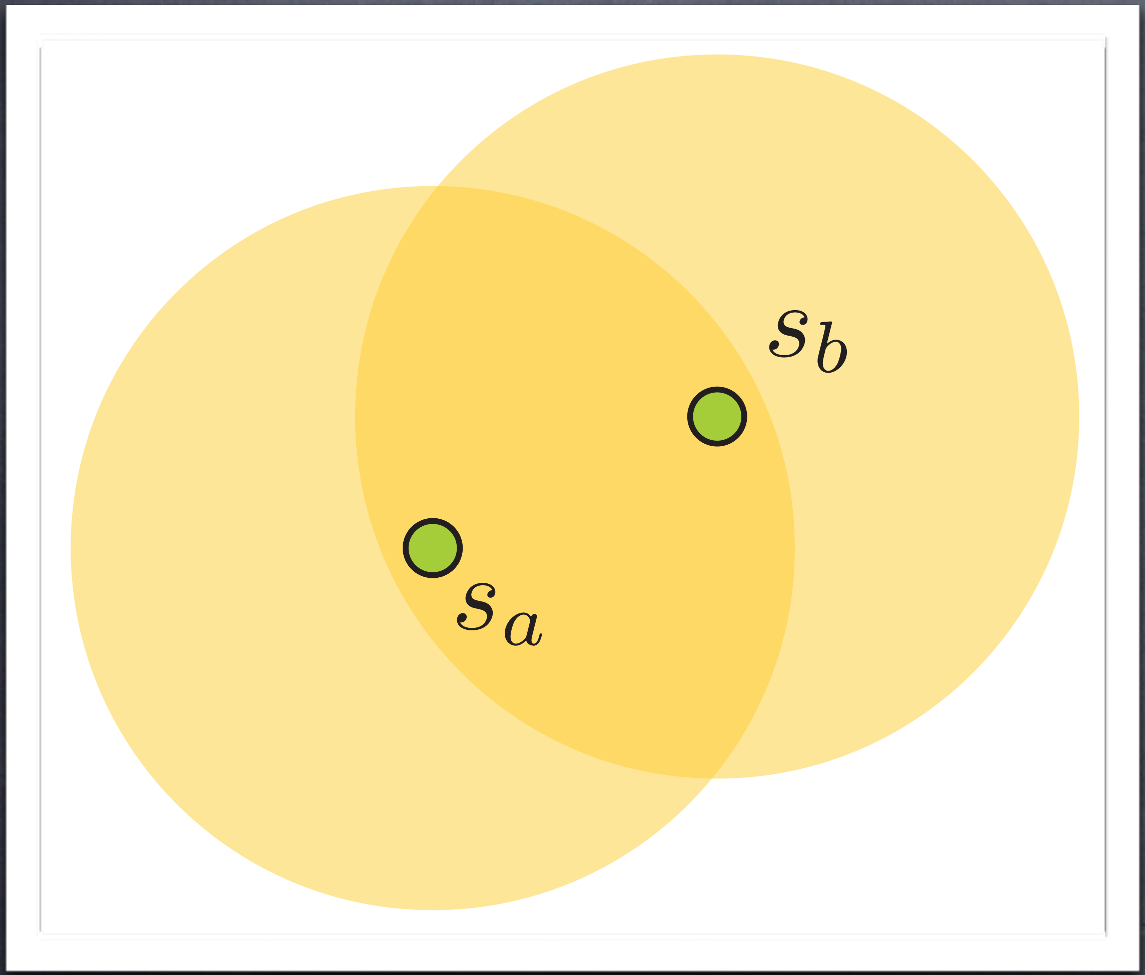
Omnidirectional Communications

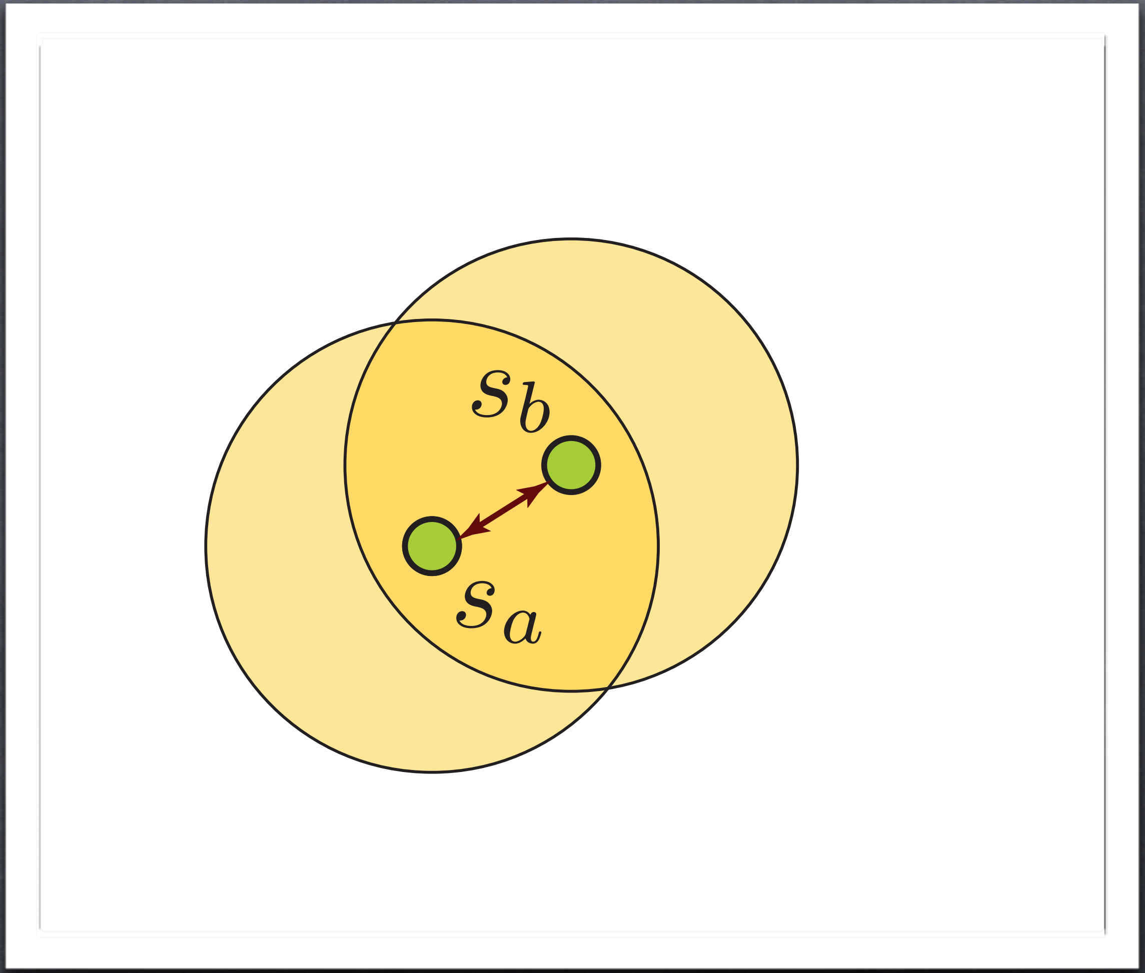




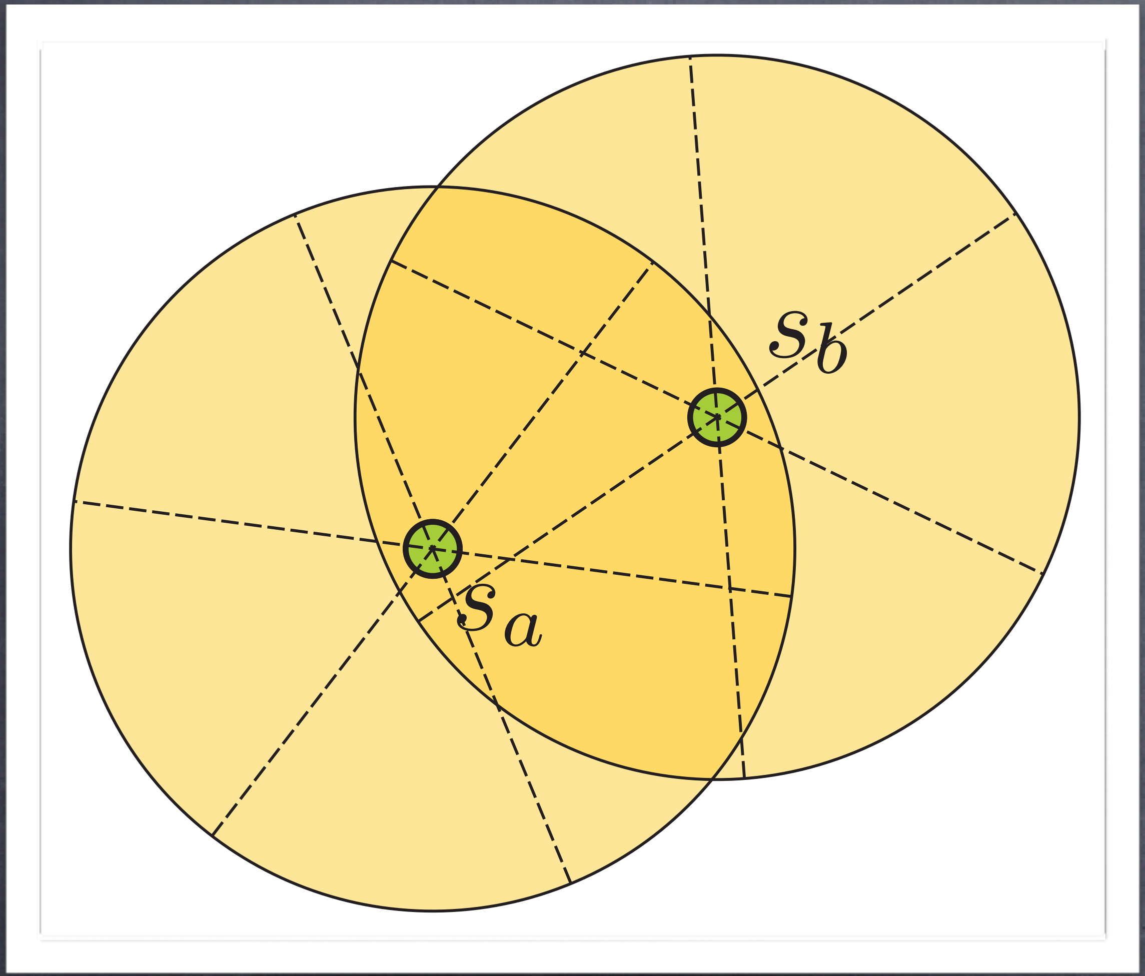
OUT OF RANGE, r

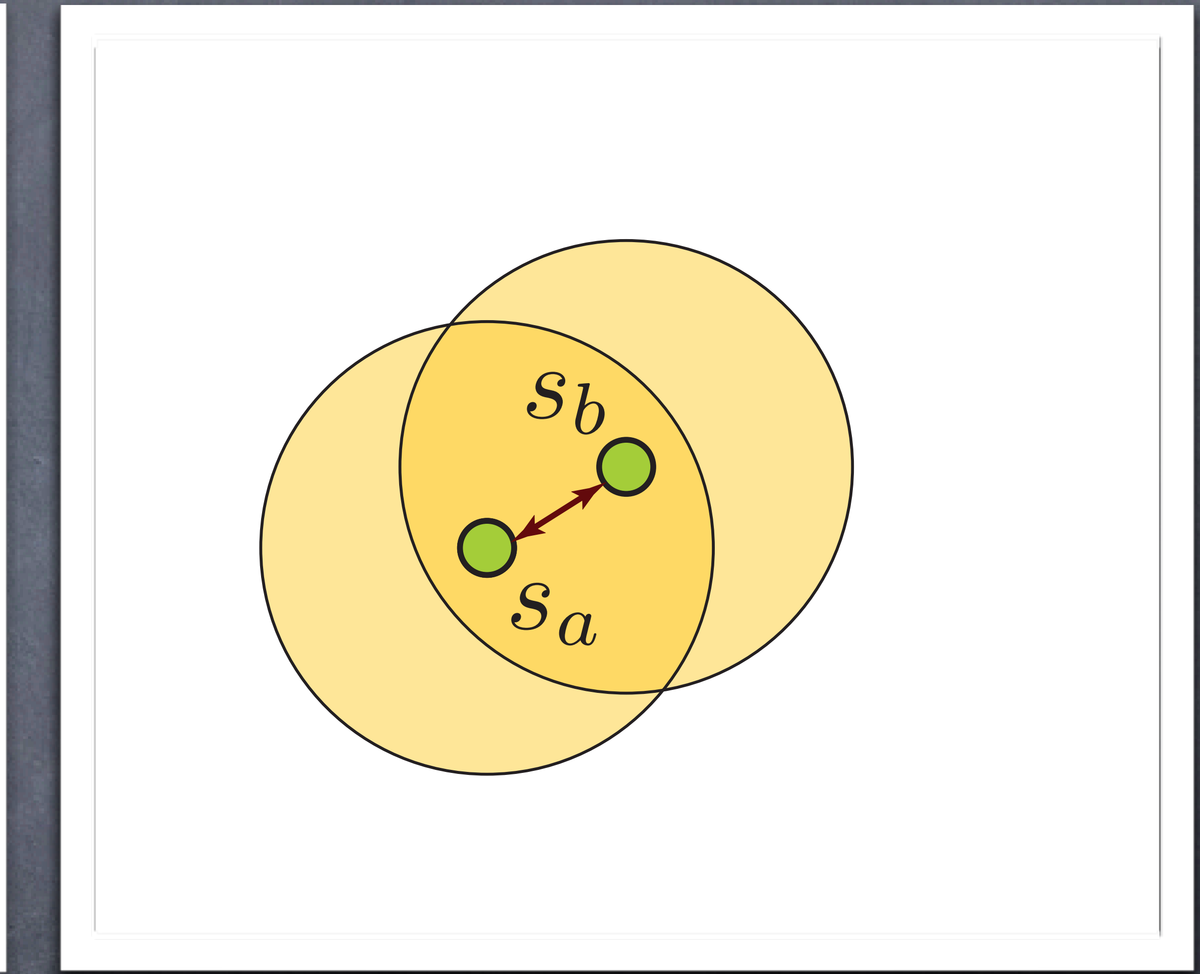
Omnidirectional Communications





Directional Communications





STEERED BEAM RF

SWITCHED BEAM RF

FSO (SPHERICAL/HONEYCOMB PHOTODETECTOR)

Directional Communications

- Transceiver configurations:

trans-recv

omni-omni

direc-omni

direc-direc

omni-direc

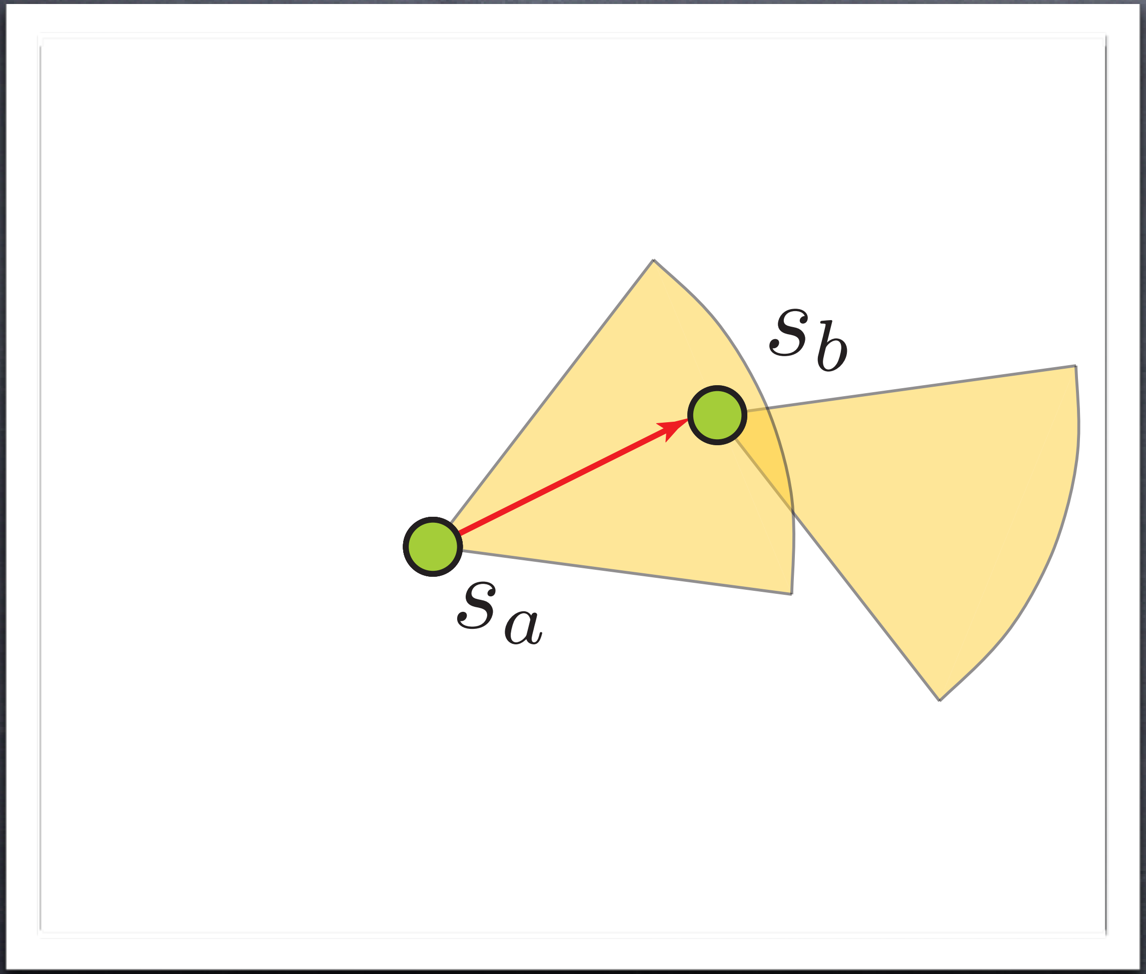
Directional Communications

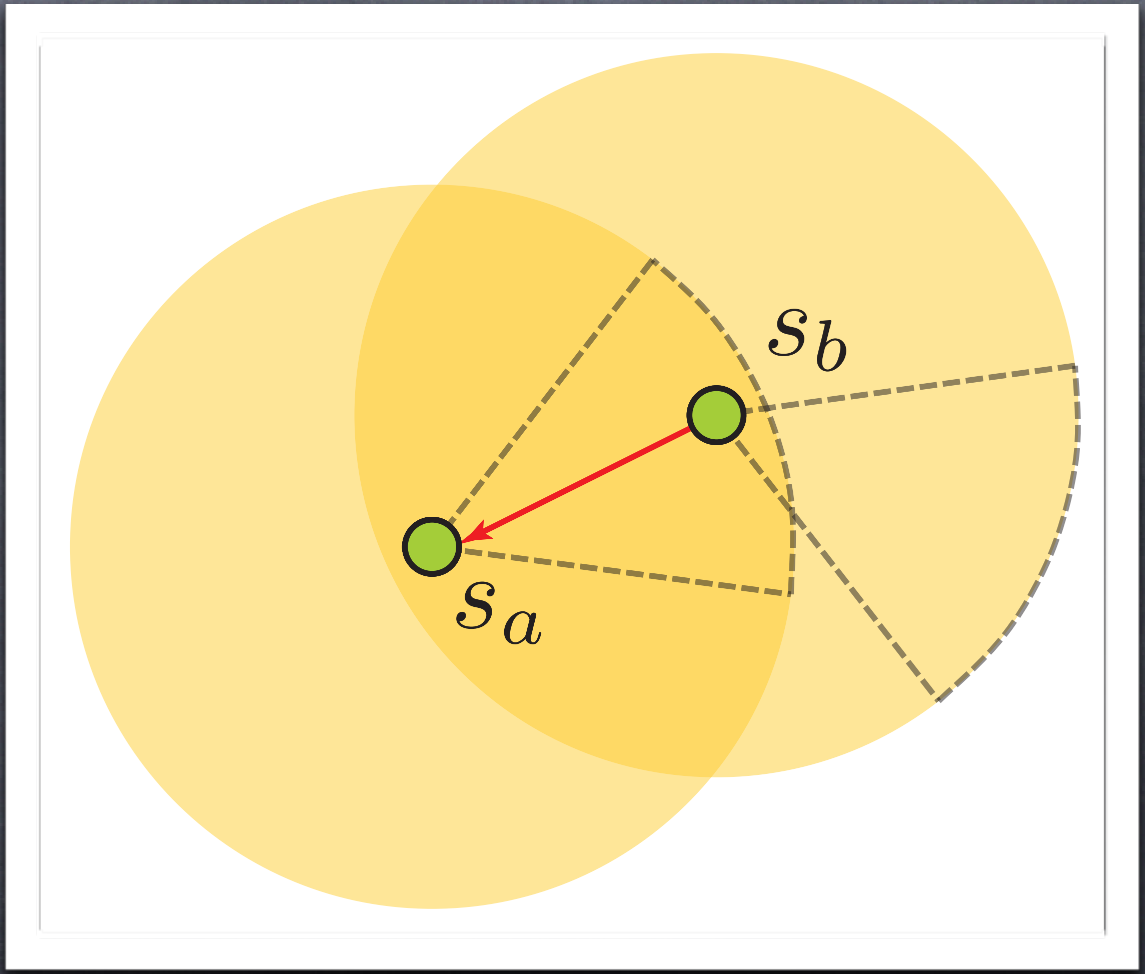
trans-recv	links	
	bidirectional	unidirectional
omni-omni	X	
direc-omni	x	X
direc-direc	X	x
omni-direc	x	X

Directional Links

direc-omni

omni-direc





NODE INVISIBILITY

NODE DEAFNESS

STATIC RF
FSO (Smart Dust)

Single Hop vs. Large Scale

- Directional links aid in connectivity (range extension) and security (low probability of detection) for a single hop
  - Can we exploit directional links for networking?
  - What are the implications to network connectivity?
  - What are the network security implications?

Directional Link Networks

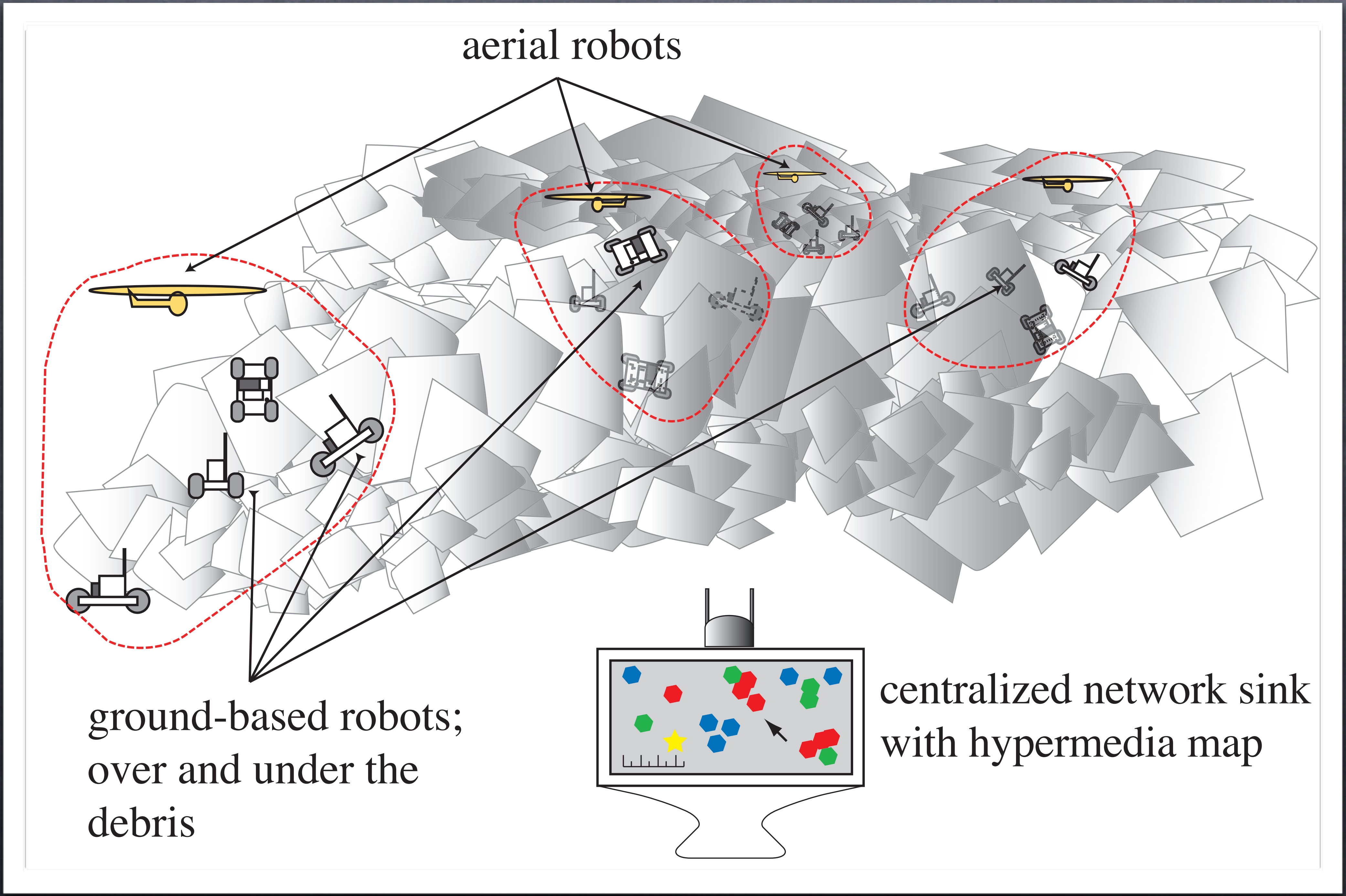
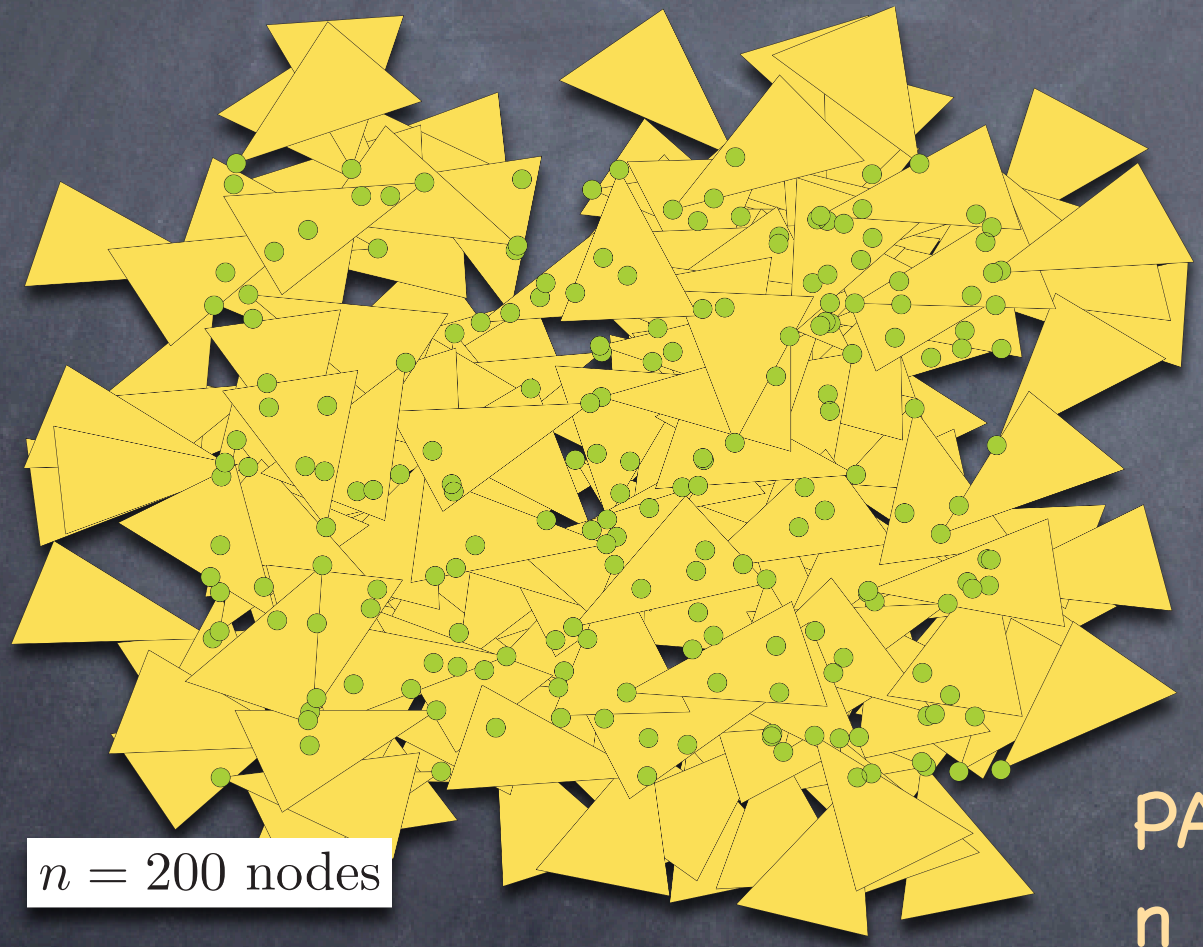

aerial robots
ground-based robots; over and under the debris
centralized network sink with hypermedia map

FIGURE COURTESY OF
DR. TAKIS ZOURNTOS

Directional Link Networks

directional-omni

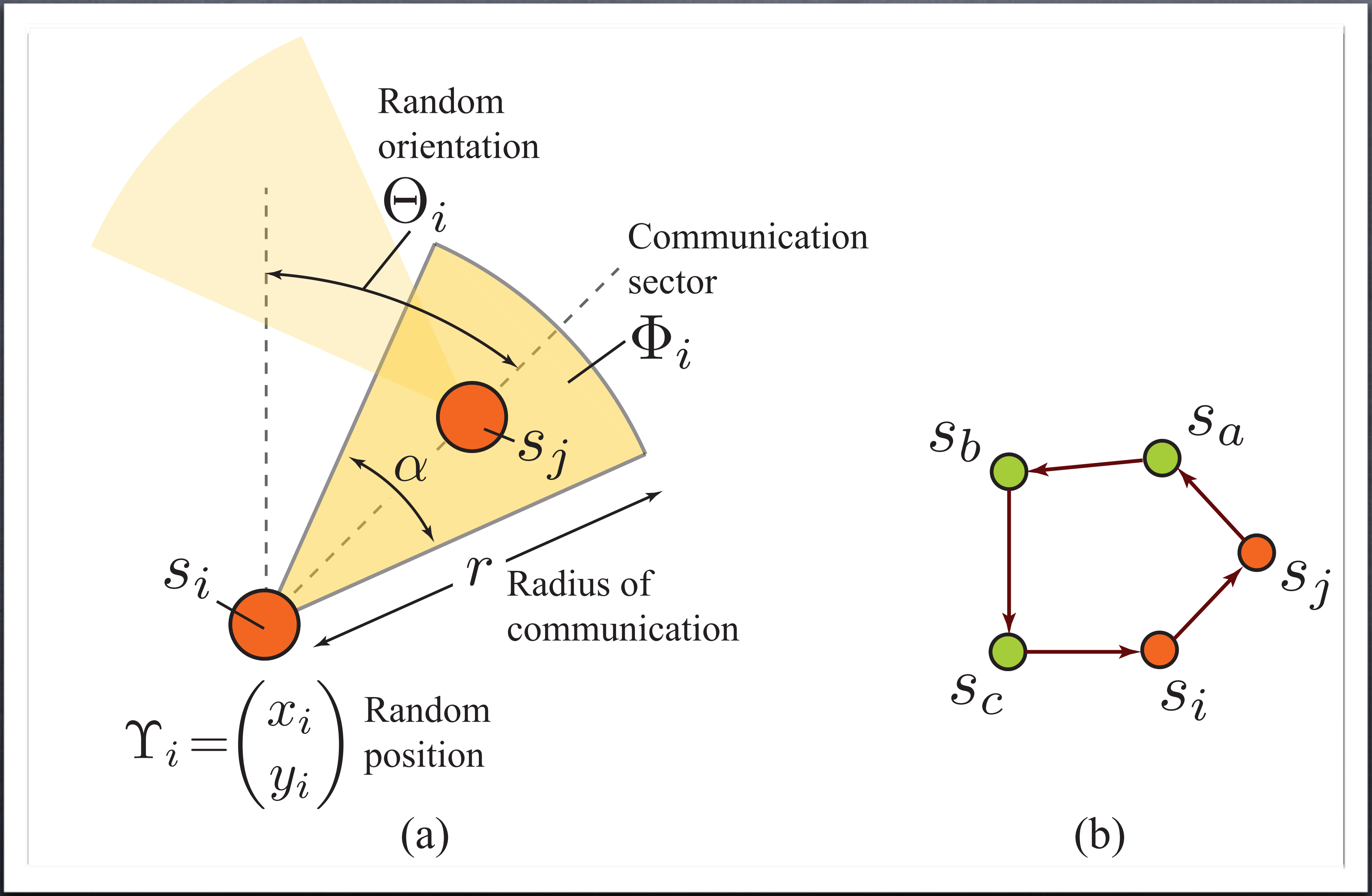


RANDOMLY DEPLOYED
NODES:

RANDOM LOCATION
RANDOM ORIENTATION
STATIC ORIENTATION

PARAMETERS
n = number of nodes
r = communication range
α = beam width

Directional Link Networks



Random Sector Graph

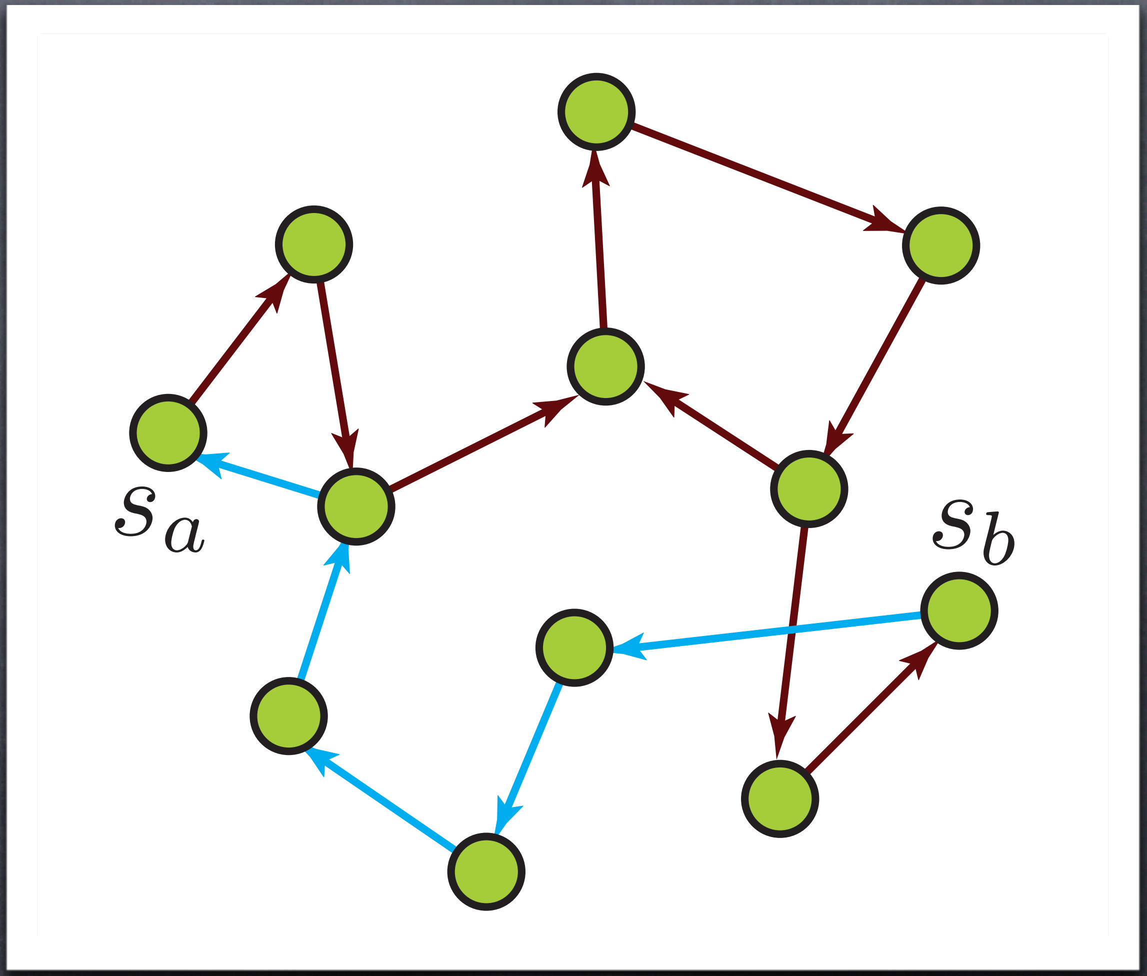
- links device parameters to large-scale network behavior
- models Smart Dust FSO sensor networks
- beam width α controls proportion of unidirectional and bidirectional links
  - $\alpha \rightarrow 2\pi$ approaches RGG model

Connectivity

- Definition: for every node pair (s_a, s_b), paths from s_a to s_b and from s_b to s_a exist

- connectivity is probabilistic

RANDOM DIRECTIONAL LINK NETWORK

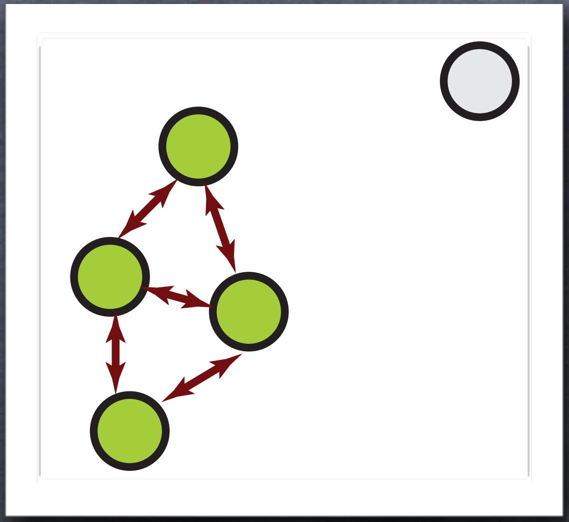


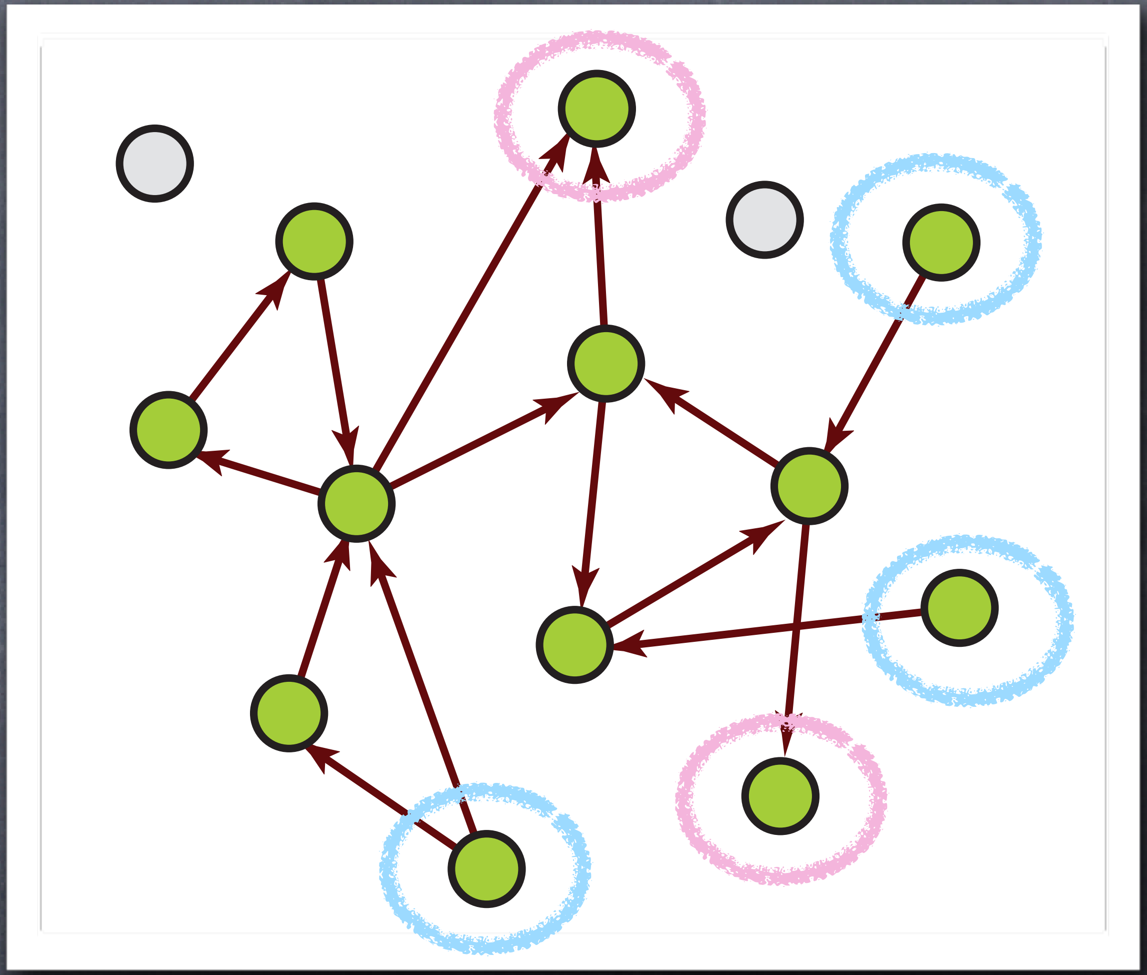
Connectivity

- exact expression relating (n,r,α) to connectivity likelihood is an open problem
- tractable approach: bound probability of connectivity with probability of no isolated node

Node Isolation

TRADITIONAL ISOLATION

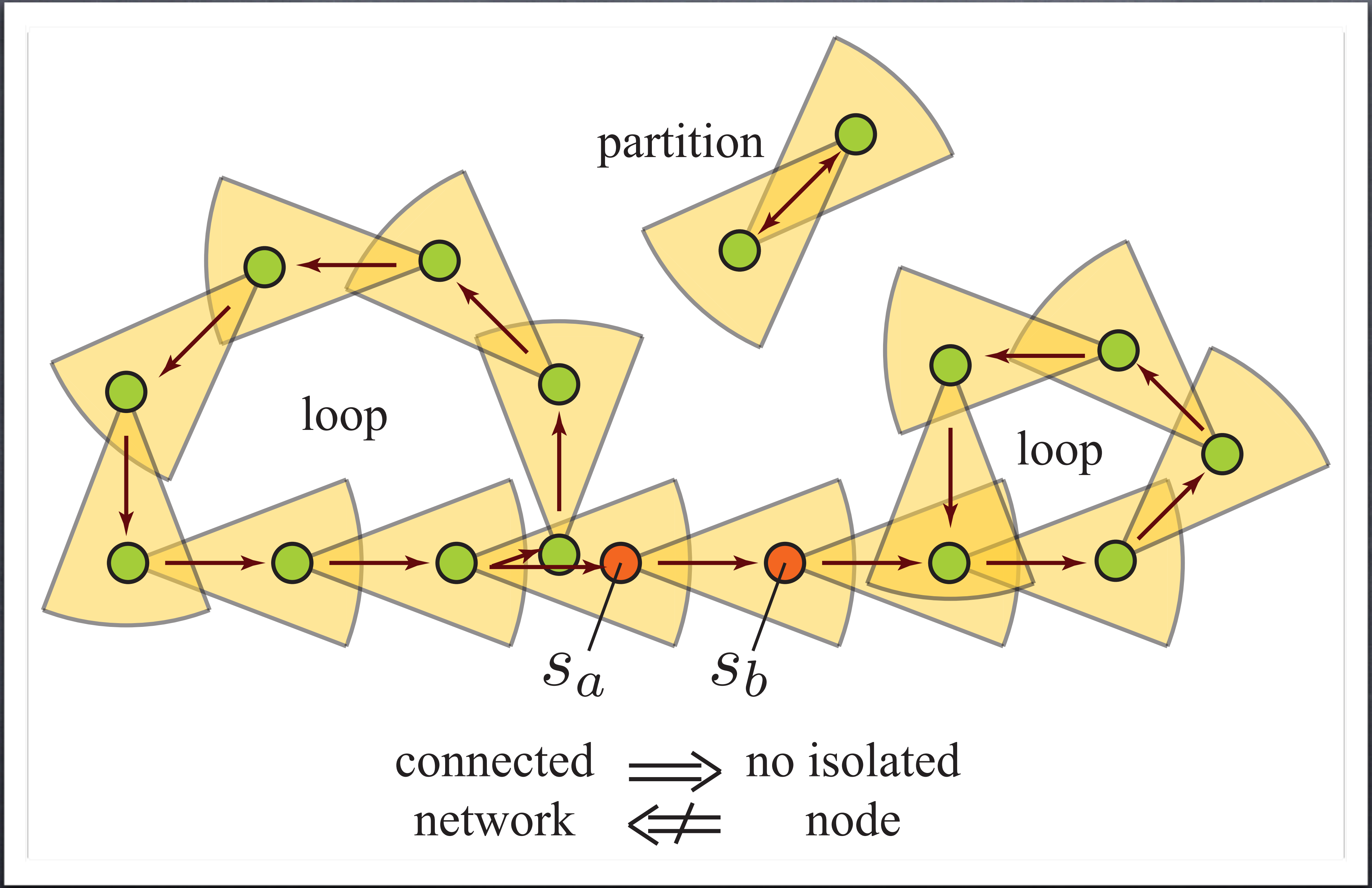




FORWARD ISOLATION

BACKWARD ISOLATION

Connectivity vs. No Isolated Node

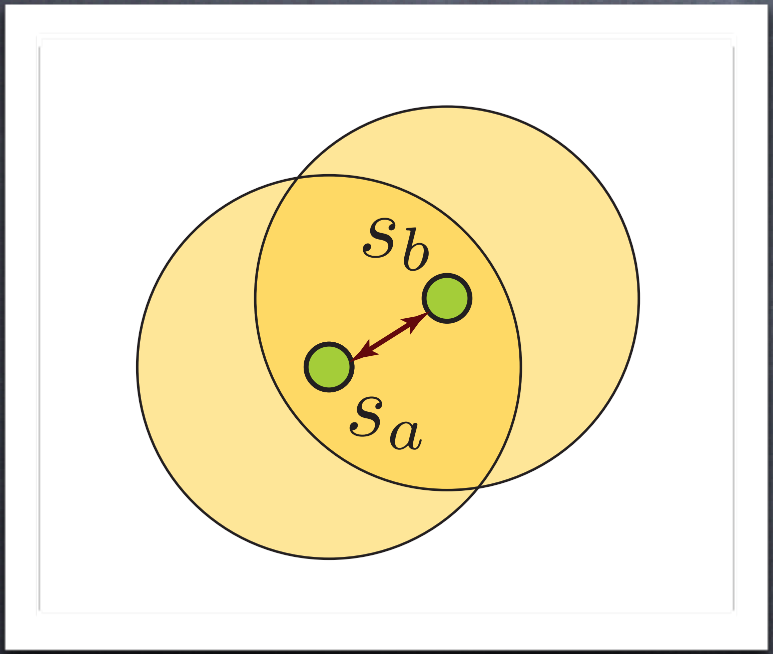


probability of connectivity ≤ probability of no node isolation

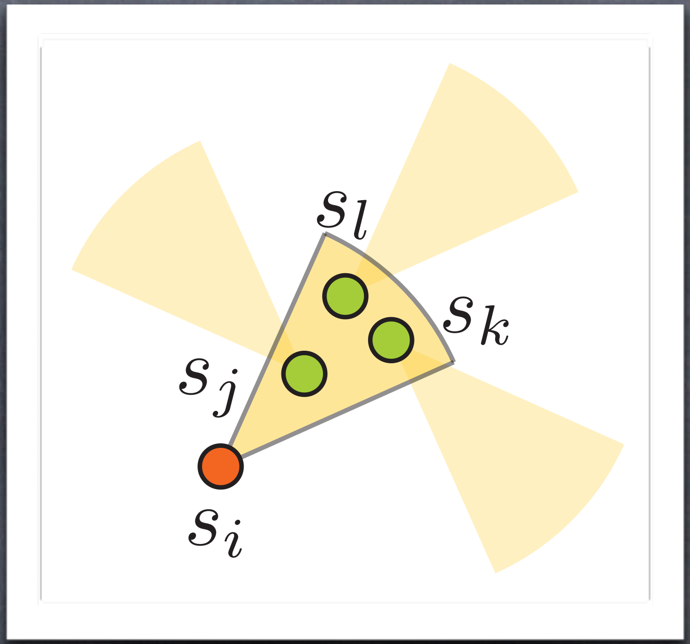
$p_c \le p_d$

Probability of No Isolated Node

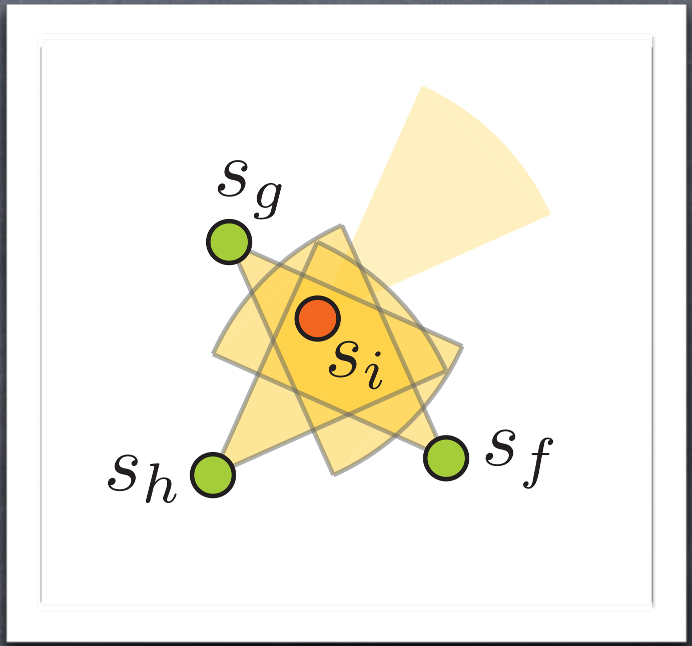
NEIGHBORS



FORWARD NEIGHBORS



BACKWARD NEIGHBORS

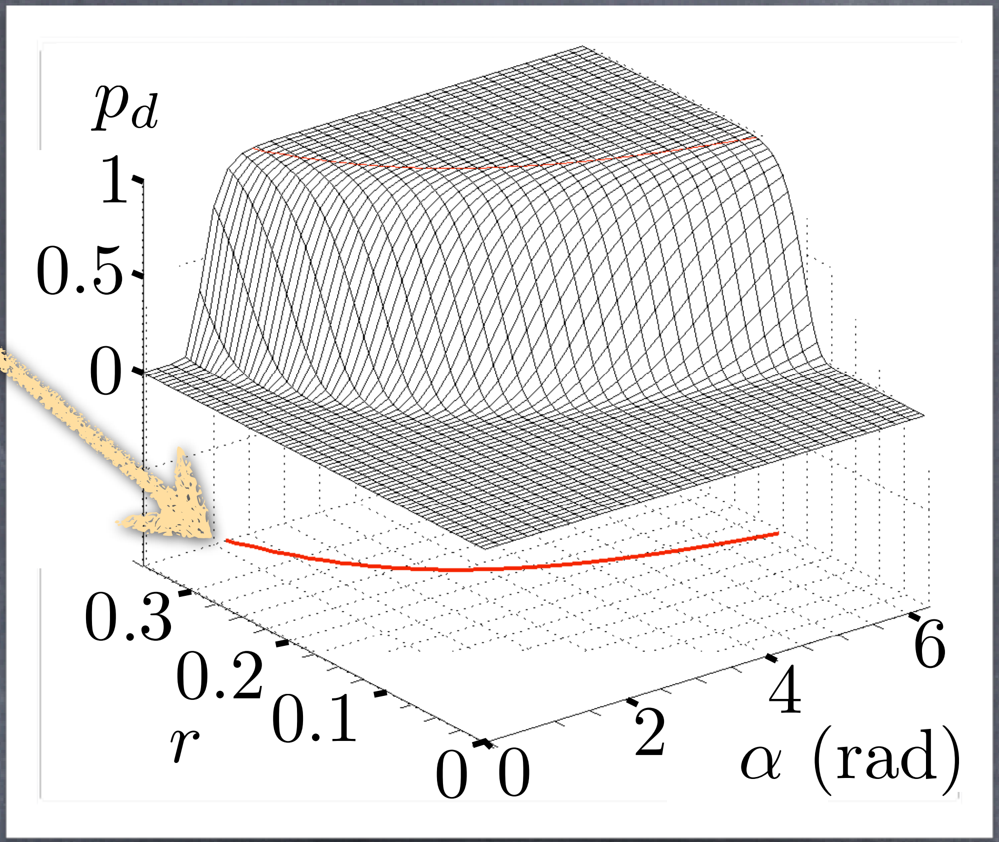


$$p^i_{\text{not isol}} = p^i_{f \cap b} = p^i_f \cdot p^i_{b|f}$$

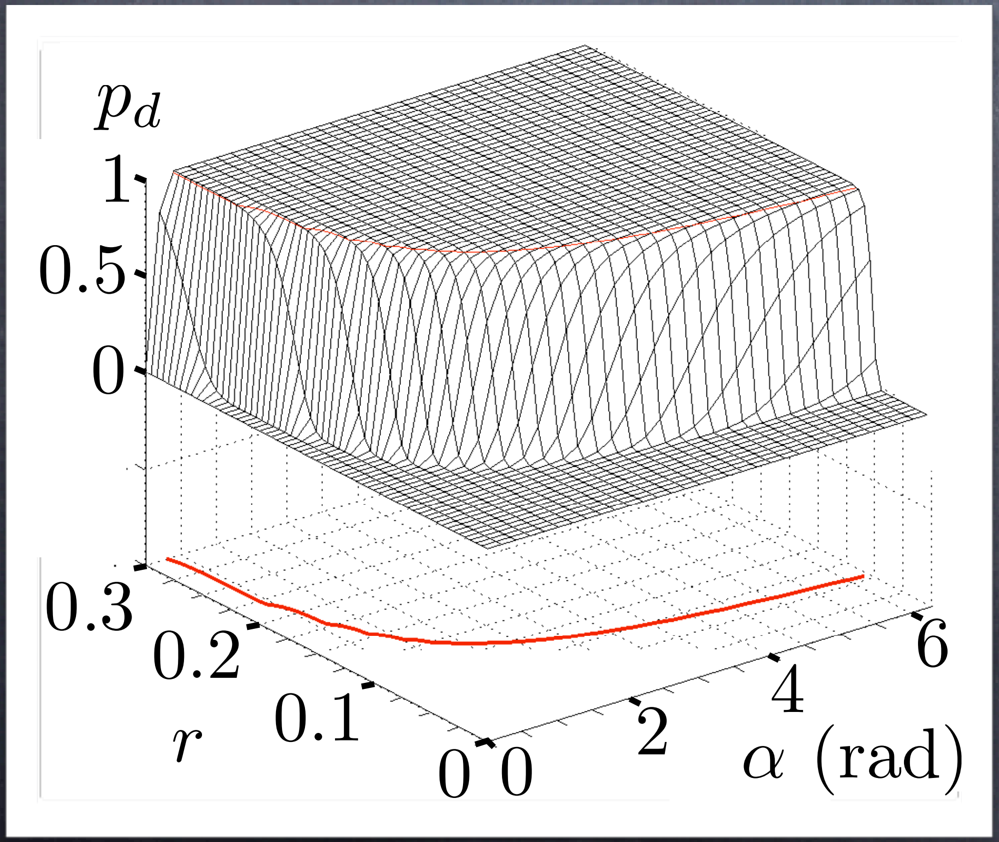
$$p_d = \left[1 - e^{\frac{-n\alpha r^2}{2}}\right]^n \left[1 - \frac{e^{\frac{-n\alpha r^2}{2}}}{1 - e^{\frac{-n\alpha r^2}{2}}} \left(1 - \frac{\alpha r^2}{2}\right)^{n-1} \cdot \left(e^{\left[\frac{n\alpha r^2 (2\pi - \alpha)}{2\pi(2 - \alpha r^2)}\right]} - 1\right)\right]^n$$

p_d =0.99

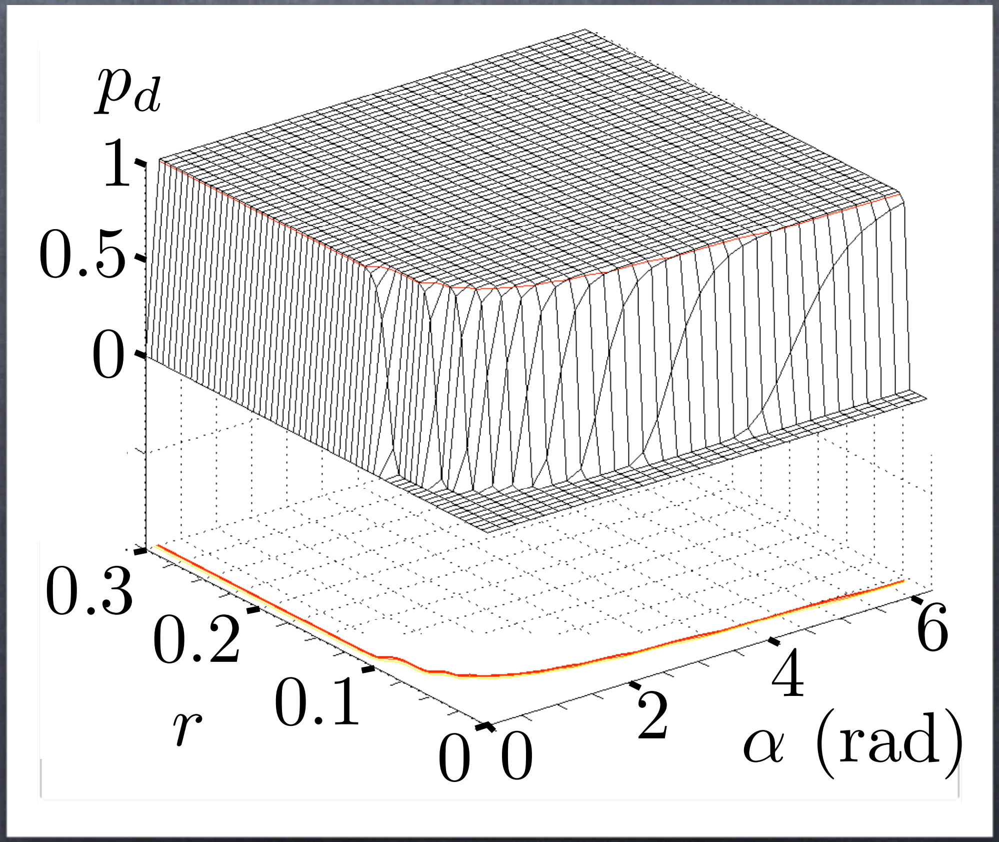
n=100



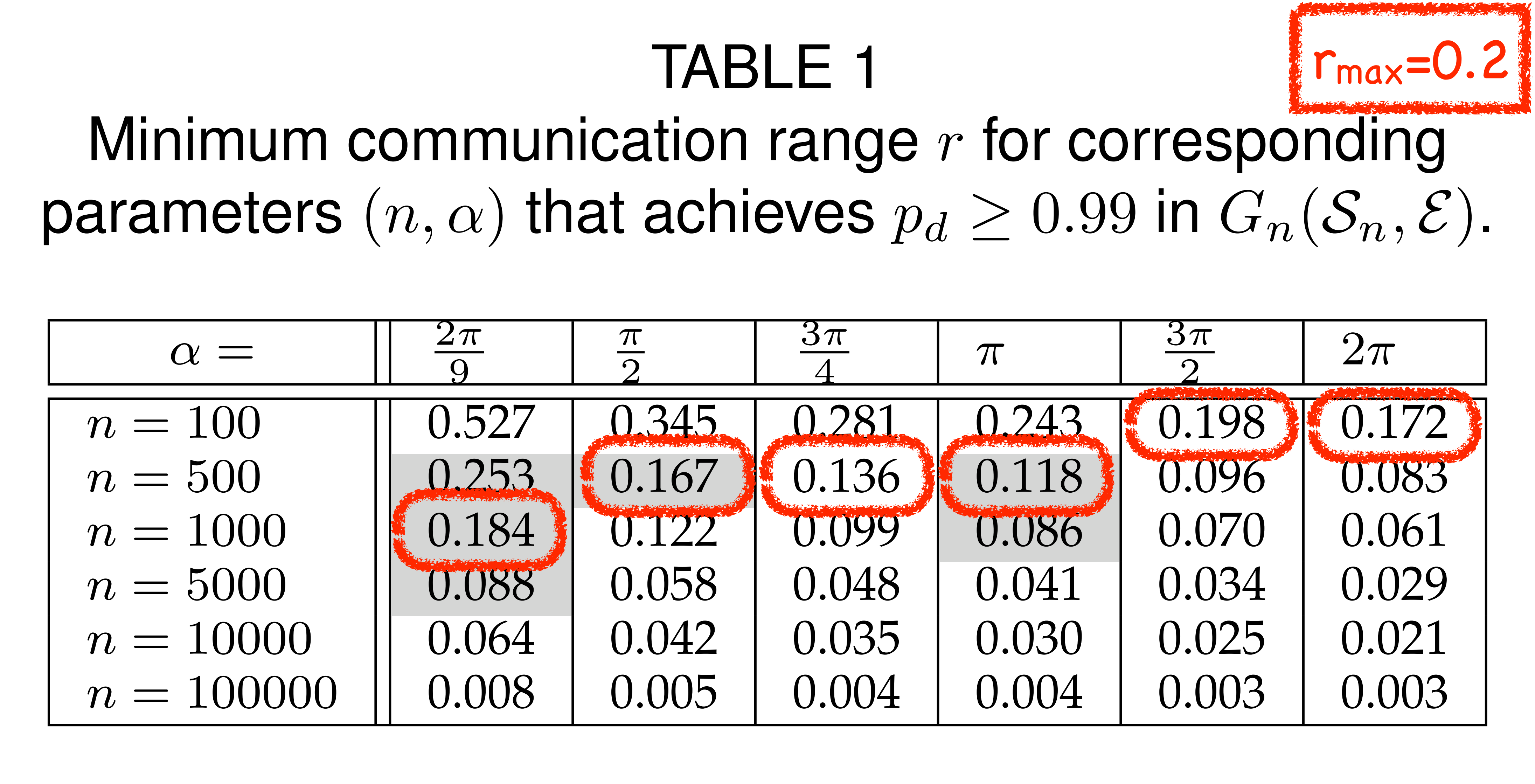
n=1000



n=10000



Parameter Assignment Problem



r_{max}=0.2

TABLE 1

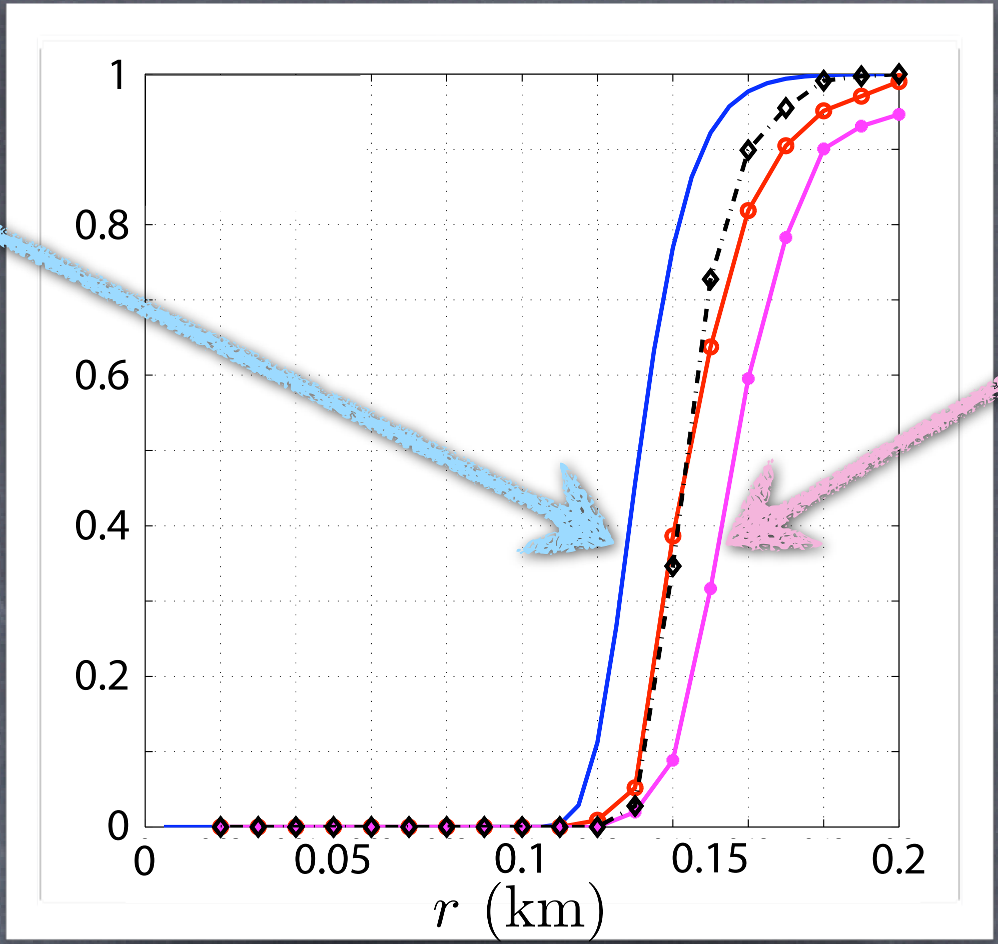
Minimum communication range r for corresponding parameters (n, α) that achieves $p_d \geq 0.99$ in $G_n(\mathcal{S}_n, \mathcal{E})$.

$\alpha =$	$\frac{2\pi}{9}$	$\frac{\pi}{2}$	$\frac{3\pi}{4}$	π	$\frac{3\pi}{2}$	2π
$n = 100$	0.527	0.345	0.281	0.243	0.198	0.172
$n = 500$	0.253	0.167	0.136	0.118	0.096	0.083
$n = 1000$	0.184	0.122	0.099	0.086	0.070	0.061
$n = 5000$	0.088	0.058	0.048	0.041	0.034	0.029
$n = 10000$	0.064	0.042	0.035	0.030	0.025	0.021
$n = 100000$	0.008	0.005	0.004	0.004	0.003	0.003

n=500

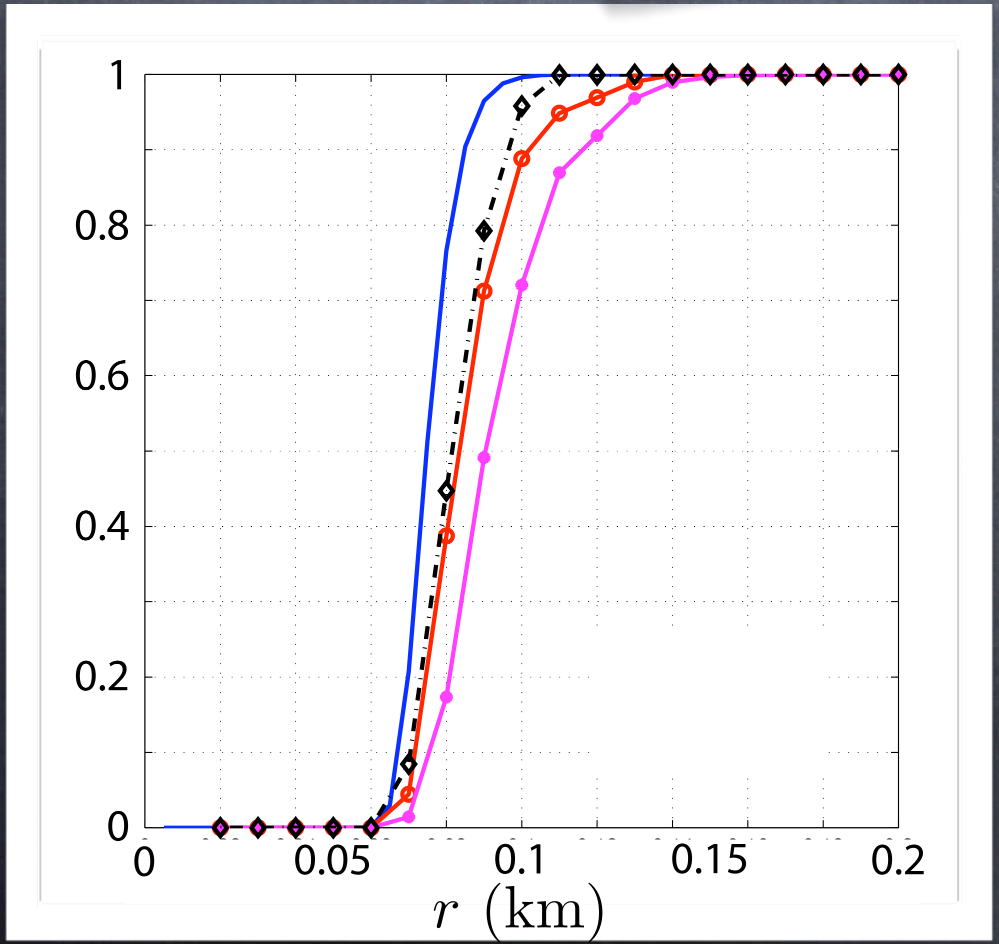
$\alpha=\pi/2$

p_d

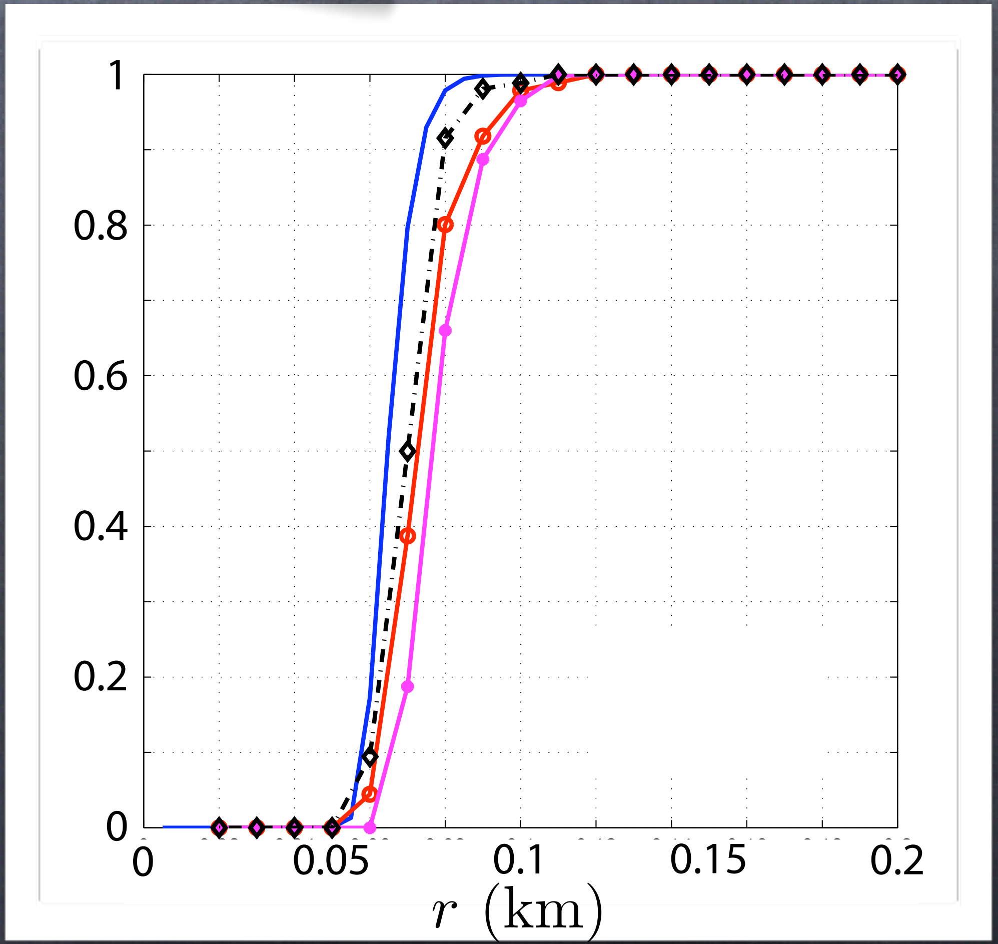


p_c

$\alpha=3\pi/2$



$\alpha=2\pi$



Connectivity Insights

- analytically, an increase in n, r and/or α all improve likelihood of no isolated node
- empirically, for $\alpha \rightarrow 2\pi$ $p_c \leq p_d$ bound is tighter
  - r has most influence on the p_d-bound
  - α has more influence on the actual p_c

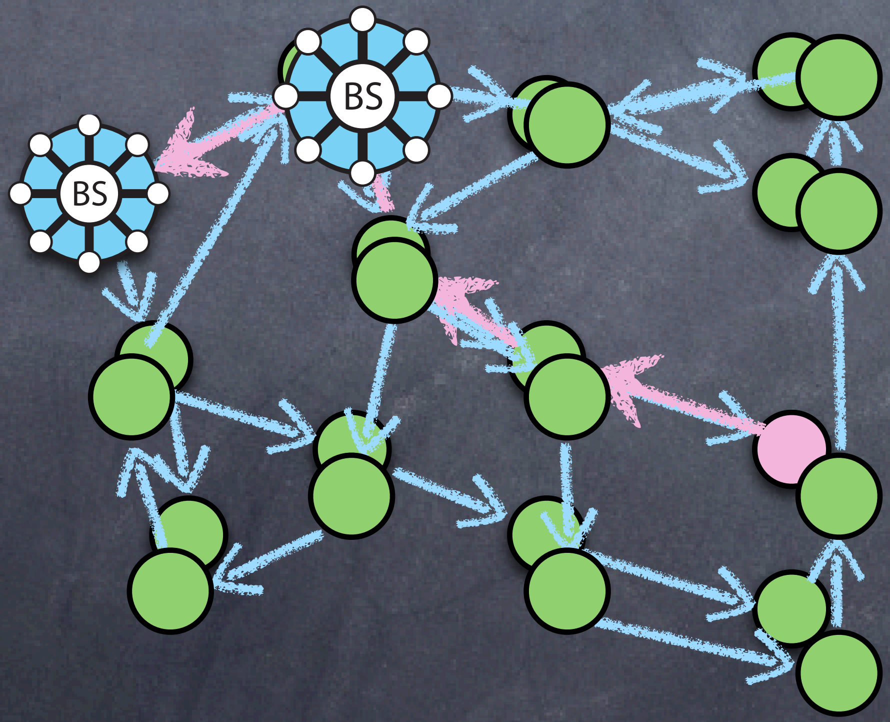
What are the implications for security?

Sensor Network Security

- Threat:
    - high likelihood insider attack for sensor networks
    - high degree of cooperation increases possible degree of damage

Routing in Directional Link Networks

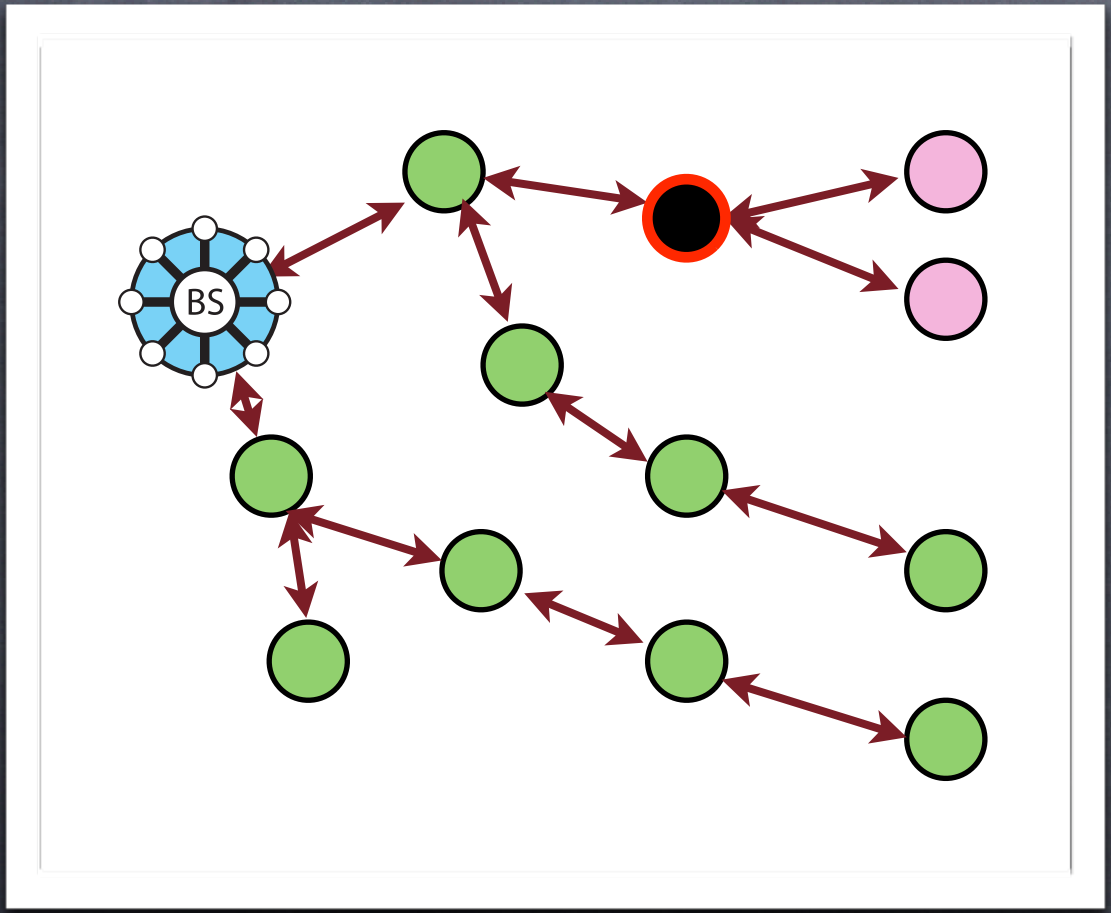
- existing sensor network research does not apply



REVERSE ROUTES
NOT AVAILABLE IN
DIRECTIONAL LINK
NETWORKS

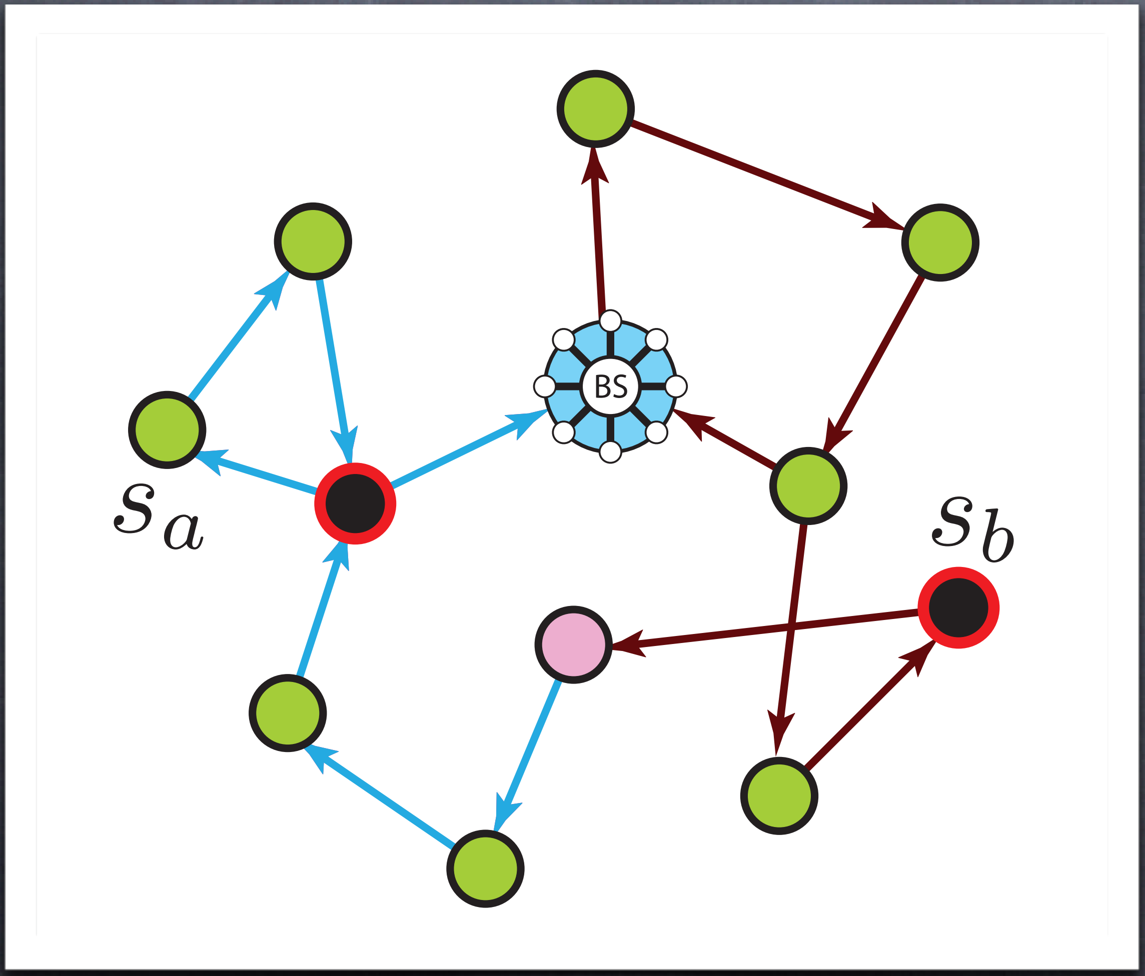
TRAVERSING
CIRCUIT-BASED

Routing Attacks



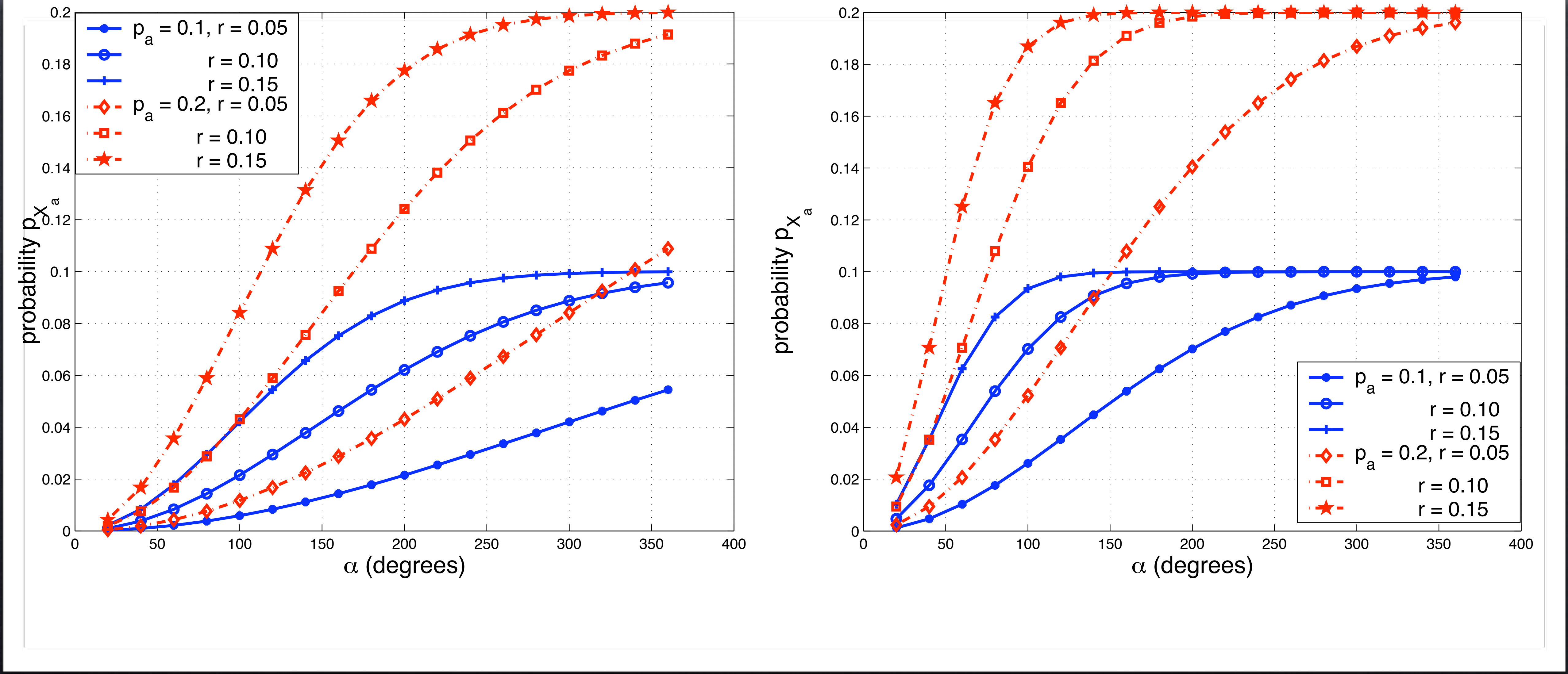
CORRUPT NODE MAY INFLUENCE TWO-WAY COMMUNICATION TO MAINTAIN COVERTNESS

Routing Attacks



IN DIRECTIONAL LINK NETWORKS, ATTACKER MUST INFLUENCE BOTH UP-LINK AND DOWN-LINK

Probability of Both Uplink & Downlink Corruption


n=100

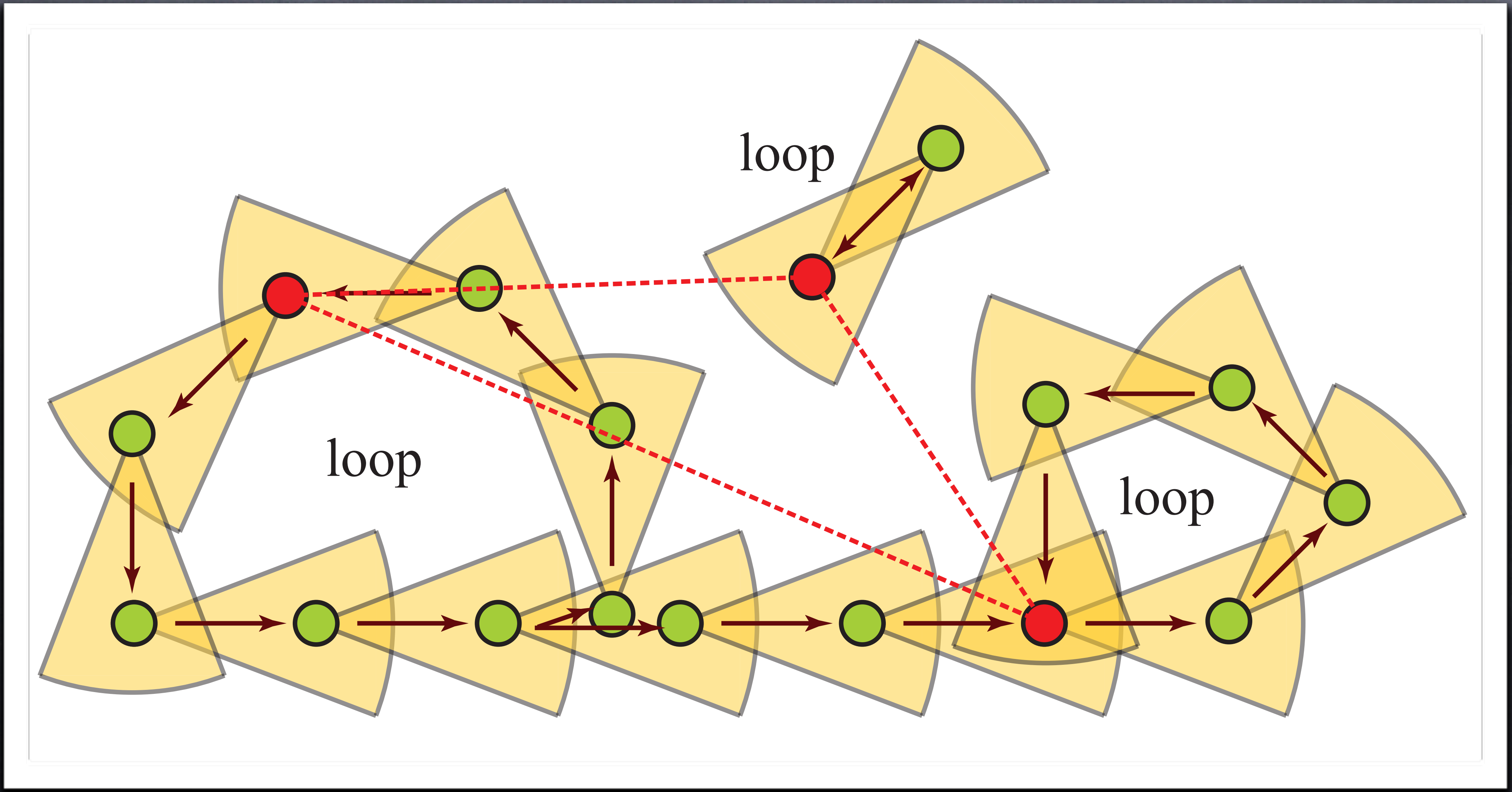
n=500

Connectivity vs. Security

- unidirectional links raise the required effort for an attacker
- decreasing (n,r,α):
  - increases required attacker effort ✓
  - decreases likelihood of connectivity ✗

How do you improve connectivity without sacrificing security?

Improving Connectivity



HIERARCHY CAN
IMPROVE CONNECTIVITY

Final Remarks

- Directional links must be leveraged in large-scale networks.
- Asymmetrical networking increases effort required for insider attacks.
- Hierarchy can mitigate compromises between connectivity and security.