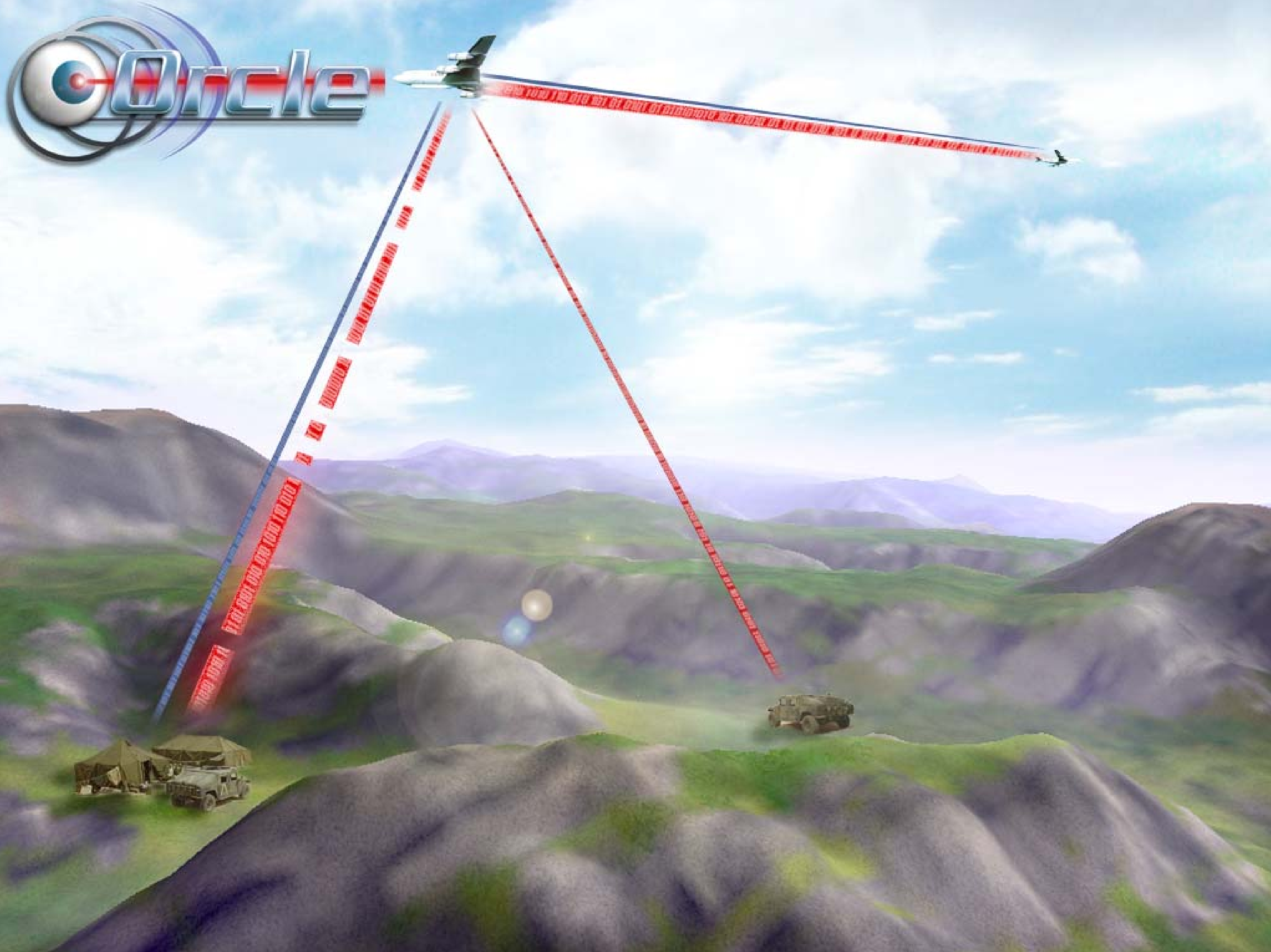
Orcle

ORCLE

Optical & **R**f **C**ombined **L**ink **E**xperiment

19 November 2003

Advanced Technology Office

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I rarely end up where I was intending to go, but often end up somewhere that I needed to be.

Douglas Adams
The Long Dark Tea–Time of the Soul

Where We've Been……

THOR Phase 1 Summary

THOR Proposed Architecture & CONOPS

Problem: High bandwidth access to the GIG to/from the battlespace

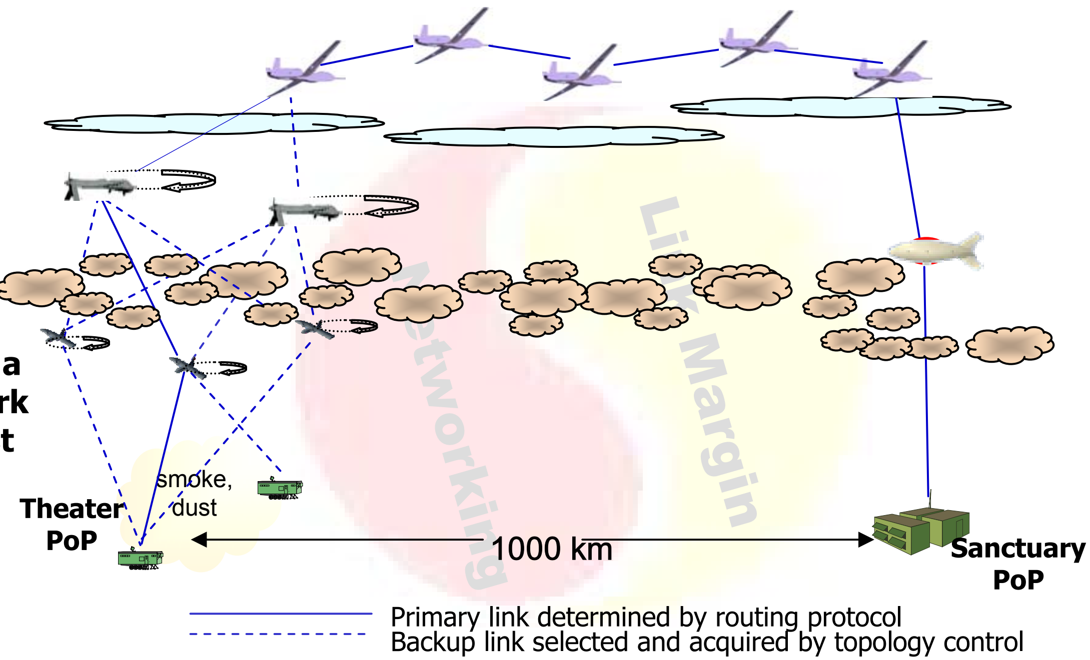
Solution: Mobile Free Space Optical

- Challenges
  - Variable channel characteristics (turbulence induced fading)
  - LOS limitations (cloud blocking concentrated at lower altitudes)
  - Bandwidth consistent with GIG, OC-48 (10X CDL)

Large link margins (~30dB) forgive many of the sins of scintillations (turbulence fades)

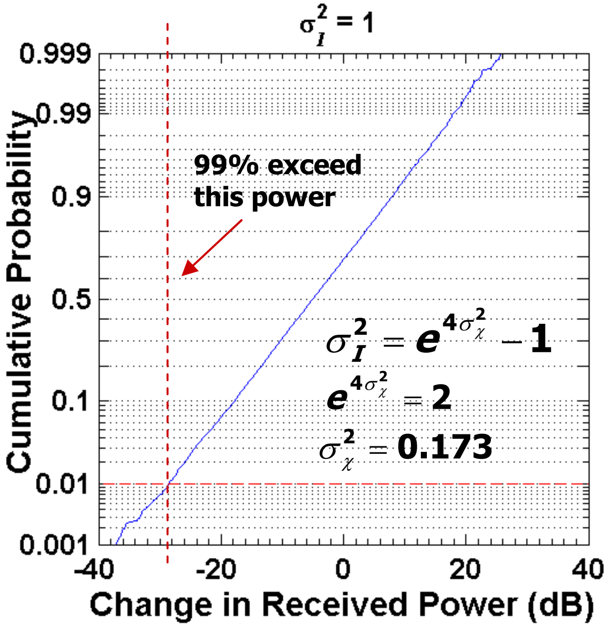
Networking (path diversity) forgives many of the sins of path blocking (clouds)

Taken together, these two attributes of a THOR network enable robust connectivity.

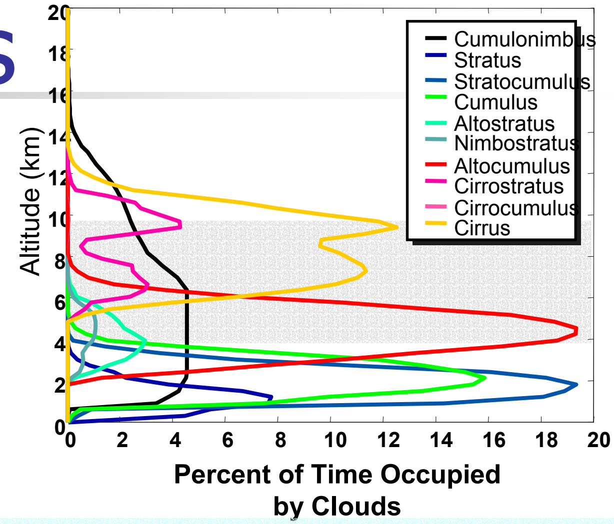


Scintillation & Clouds

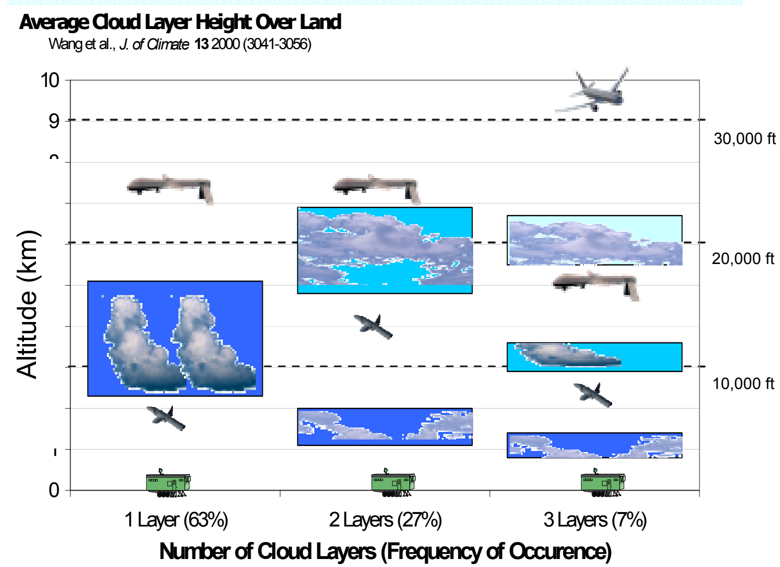
Cumulative Distribution of Intensity Fluctuations due to Scintillation At Onset of Saturation



Under the most severe scintillation, 30 dB is sufficient 99% of the time

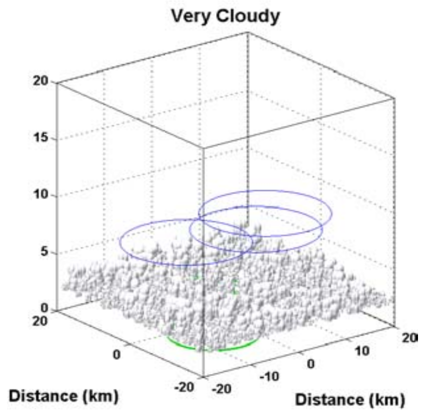


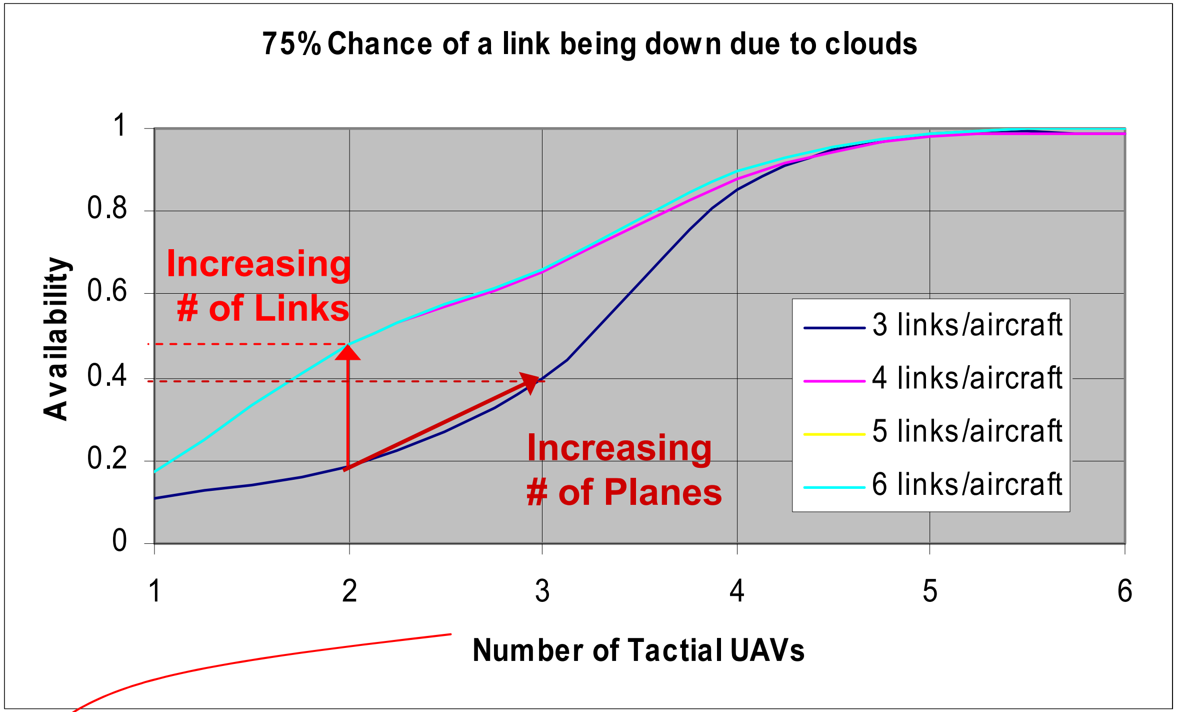
Clouds concentrated within 1-8 km altitude BUT the number of layers is important….

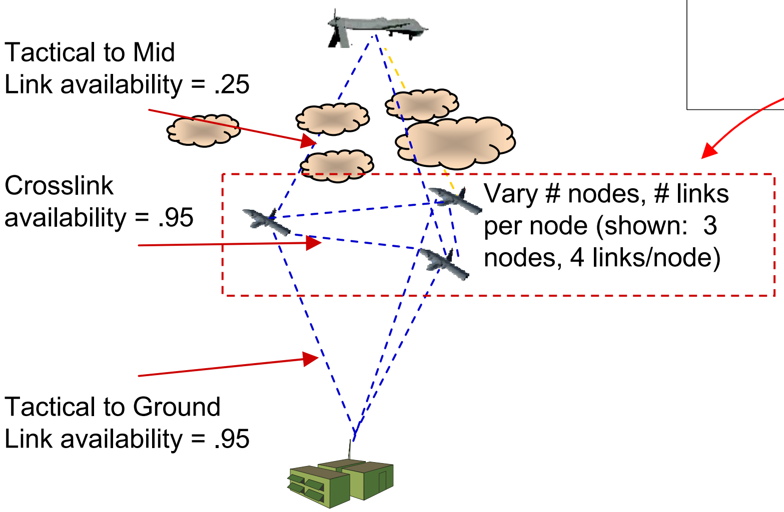


Network Availability versus Number of Links

Scene model





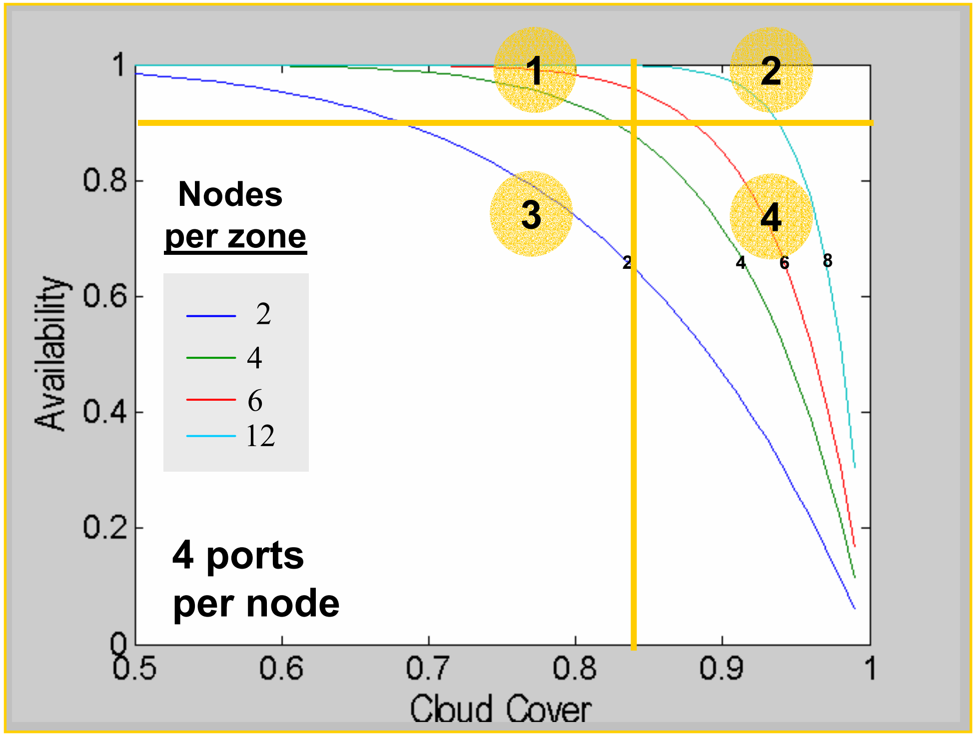


3 links per node introduces redundancy
4 links per node increases redundancy

FSO General Availability

Four Operational Quadrants

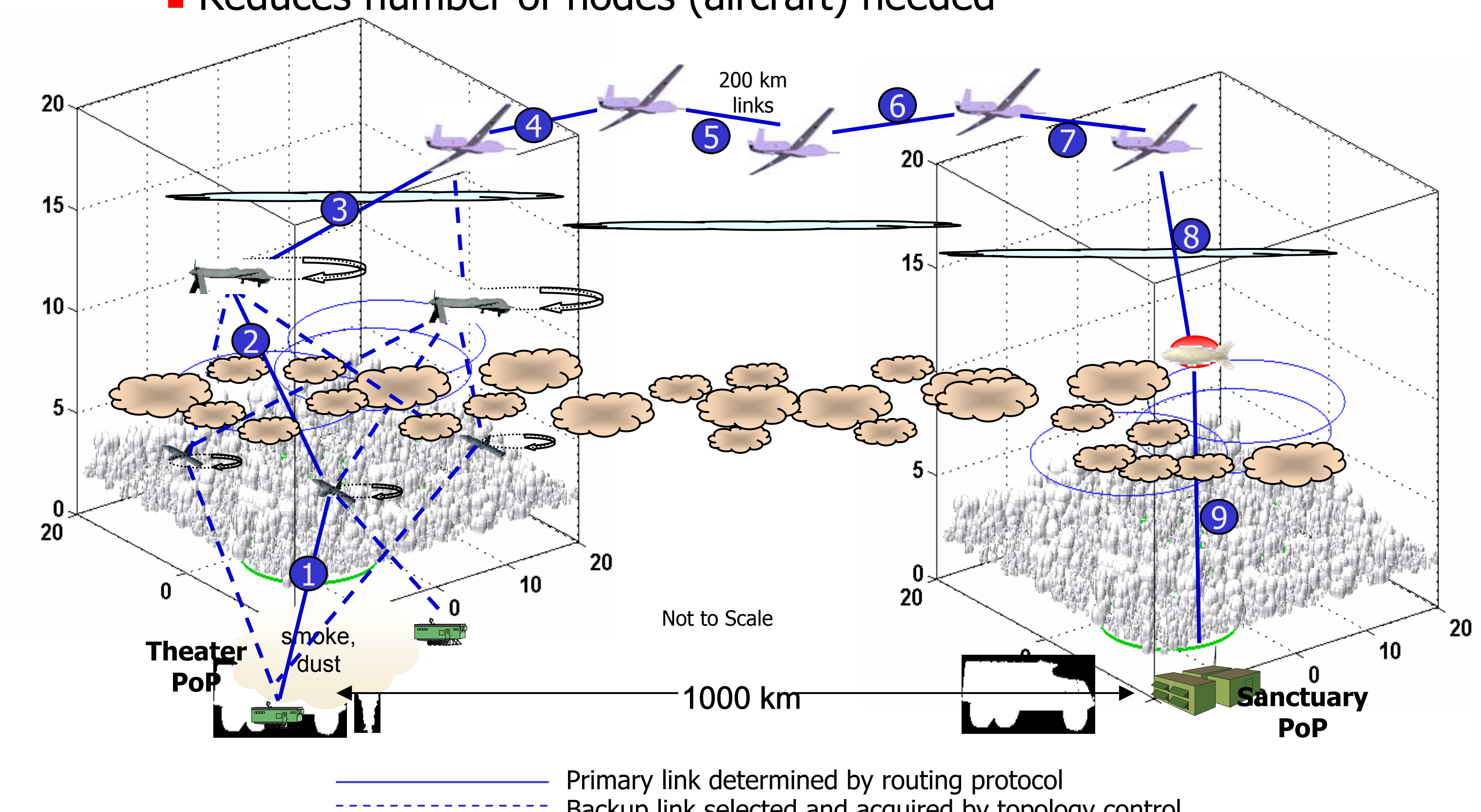
1. Feasible operating area
2. Expensive operating area - requires more nodes
3. Don't care [availability < 90%]
4. FSO falls apart



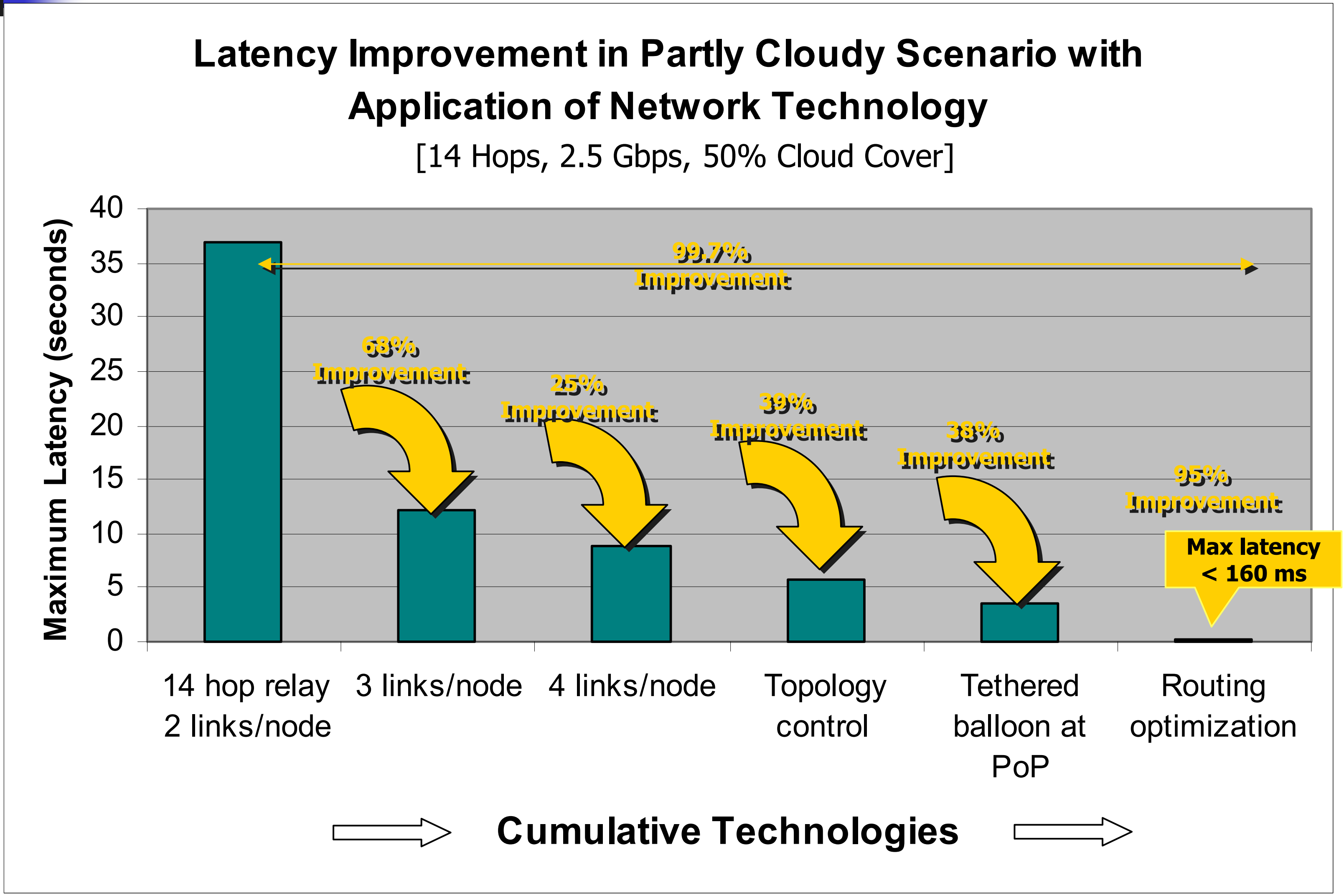
Power of Path Diversity

Path Diversity Needed to Route Around Blockages

- Concentrate Nodes at Lower Altitudes (< 8 km)
- Multiple Ports per Node to Achieve Route Diversity
  - Yields high *network* availability (under all but extreme cloud cover)
  - Reduces number of nodes (aircraft) needed



A Cumulative Solution
Improvements in Latency QoS

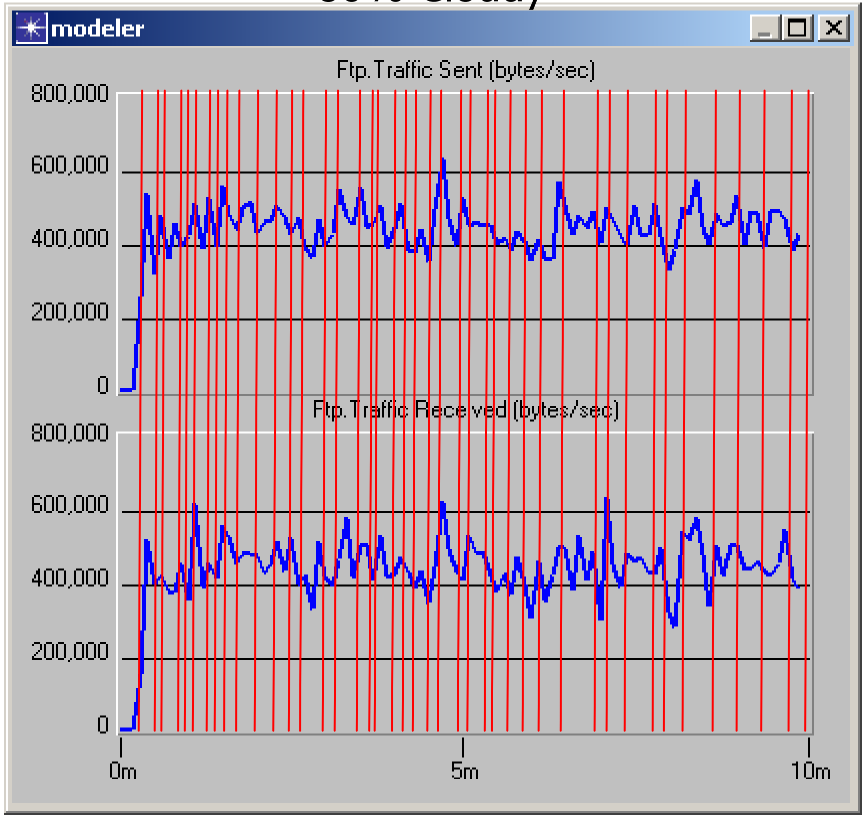


Networking to Route Around Blockages

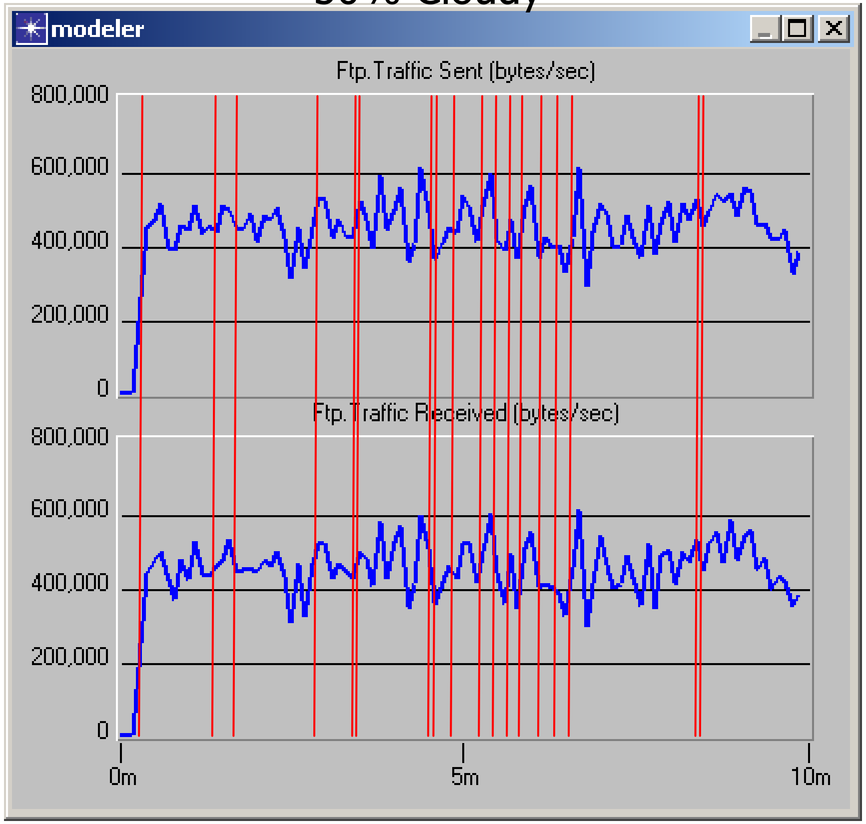
Routing Diversity enables sustained data rate under cloudy conditions [14 hop scenario]

The vertical red lines are the times that the link failed and required rerouting.

80% Cloudy



50% Cloudy



End-to-End Networking Results Summary

TCP Segment Delay
TCP Delay (95%)
Max TCP Delay

Network Configuration		Cloud Cover 0%	Cloud Cover 50%	Cloud Cover 80%
Aerostat 14 hops	TCP Segment Delay	N/A	4.3 ms	4.3 ms
	TCP Delay (95%)	N/A	0.11 sec	0.69 sec
	Max TCP Delay	N/A	0.16 sec	0.81 sec
Aerostat 9 hops	TCP Segment Delay	N/A	4.1 ms	8 ms
	TCP Delay (95%)	N/A	0.1 sec	0.8 sec
	Max TCP Delay	N/A	0.13 sec	1.05 sec
No Aerostat 10 hops	TCP Segment Delay	4.3 ms	6.6 ms	6.3 ms
	TCP Delay (95%)	0.098 sec	0.14 sec	0.83 sec
	Max TCP Delay	0.108 sec	0.23 sec	1.31 sec

THOR Phase 1 Architecture Summary

Cloud mitigation:

- Route diversity is an effective cloud mitigation strategy
- Use switching and self-correcting power of the network to get around clouds at PoPs
  - ✓ Airborne nodes clustered around PoPs for cloud mitigation [Combination of resources of opportunity and dedicated aircraft]
  - ✓ Link redundancy required: minimum 4 links per node
  - ✓ Smart flying improves performance and connectivity
- Diminishing returns above 80% cloud cover
- Use of aerostat is an option to reduce node count and get above worse atmosphere

Channel loss mitigation:

- High bandwidth tip/tilt correction, active tracking on both transmit and receive
- Use of towed bodies to mitigate FOR, boundary layer limitations

WDM for link isolation

- Topology control assigns wavelengths

MRR implementation:

- Shuttered MRRs with IFF can be used to support link acquisition
- Potential for use on small platforms in store-and-forward configurations
- Secondary dissemination

THOR Phase 1 Terminal Summary

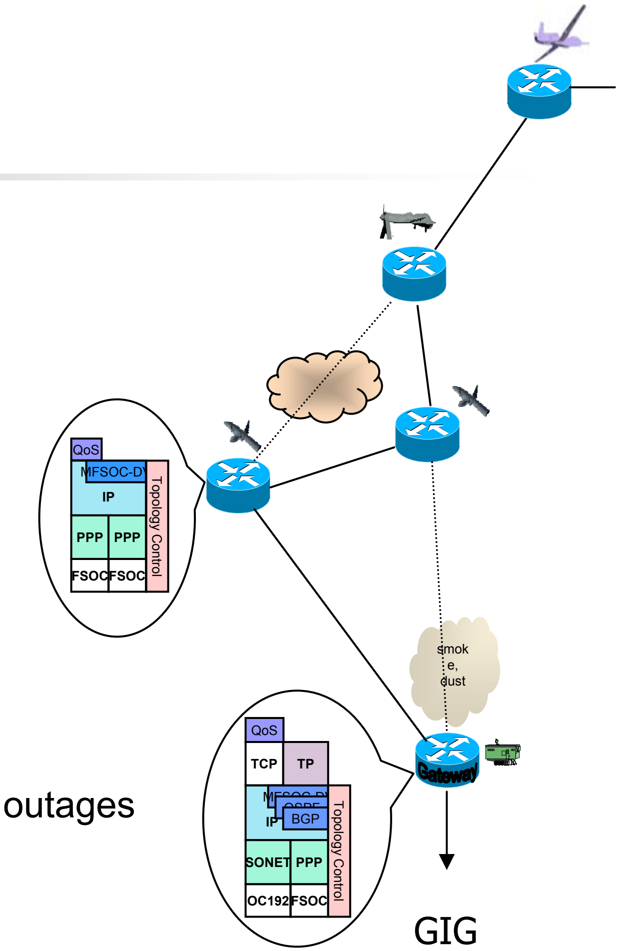
Terminal:

- Large link margins able to compensate for scintillations
- Develop multiple access receiver technology to reduce size and weight by sharing receive optical hardware
- Technologies to reduce SWaP
  - ✓ Develop non-mechanical beam steering to same or higher performance levels as mechanical
  - ✓ Increase efficiency and reduce SWaP of support equipment for high-power lasers
- Increase STAB aperture so it can be used both on transmit and receive
- Mature volume hologram beam steering technology
  - ✓Develop solutions for tracking with holographic beam steerer
  - ✓Develop solutions for bit rate limitations of holograms
  - ✓Leverage/mitigate chromatic dispersion to support WDM
  - ✓Increase aperture size supported
- Develop transmissive LC SLM technology with performance of reflective to reduce size
- Increasing FOR of non-gimbal beam steering
- Develop MRR technology
  - ✓Higher data rates, larger aperture size, cat's eye

THOR Phase 1 Networking Summary

Network:

- Physical layer
  - ✓RF links as back-up
  - ✓Forward error correction coding
  - ✓'Long' interleaver
- Link layer
  - ✓Link layer retransmission as appropriate
  - ✓Rate adaptation and RF links as backup
- Network layer
  - ✓Smart routing to quickly respond to cloud-induced outages
  - ✓QoS-based service provisioning
- Transport layer
  - ✓Alternatives to TCP (e.g., SCPS-TP, SCTP, XCP) that are more tolerant to RTT variance and appropriately respond to packet loss
- Topology control / Resource management: Further development is required
  - ✓Discover potential neighbors
  - ✓Coordinate link acquisition to maintain optimal network connectivity
  - ✓Controls pointing, wavelength assignment



Where We're Going…

ORCLE

High Data Rate with High Availability for Communications On The Move

DIRO Direction

The central challenge is to enable optical communications bandwidth without giving up RF reliability and "all-weather" performance.
Refocus efforts to ***also*** address achieving **high <u>Availability</u>**

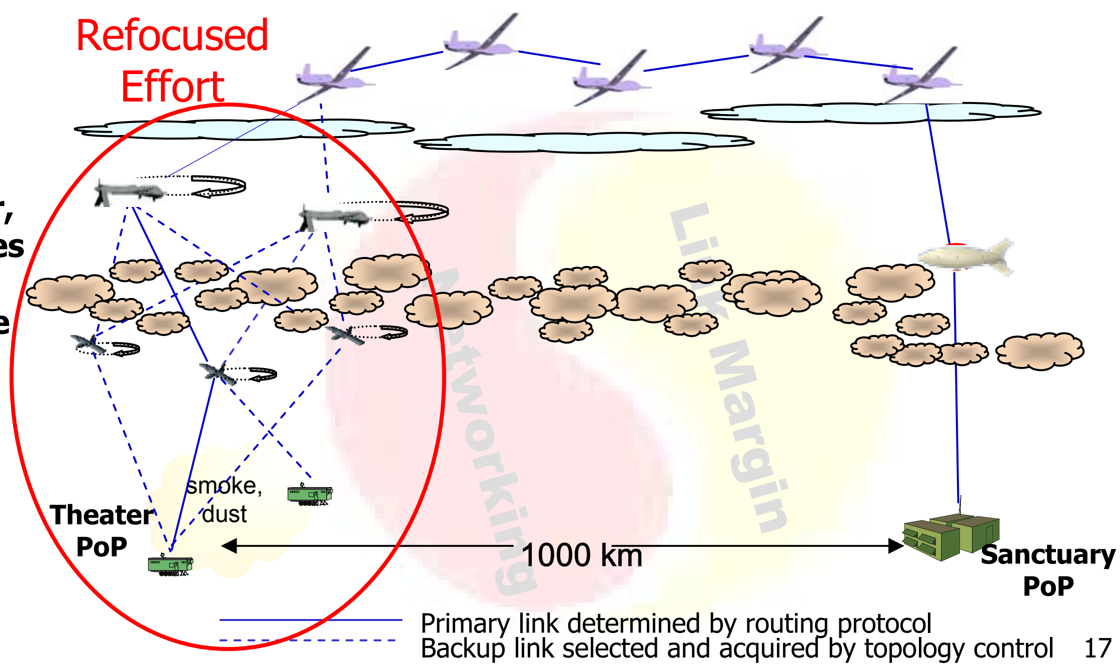
- Ground to Air / Air to Ground (Surface ~10 km altitude)
  - Desired Availability: >95% under all conditions
  - Data Rate: >2 Gbps (average under all conditions)

Large FSO link margins (~30dB) forgive many of the sins of scintillations (turbulence fades)

Radio Frequency layer to increase availability in times of sever cloud blocking or insufficient nodal density

Networking (path diversity) forgives many of the sins of path blocking (clouds)

Taken together, these attributes of an ORCLE network enable a resilient high average data rate network

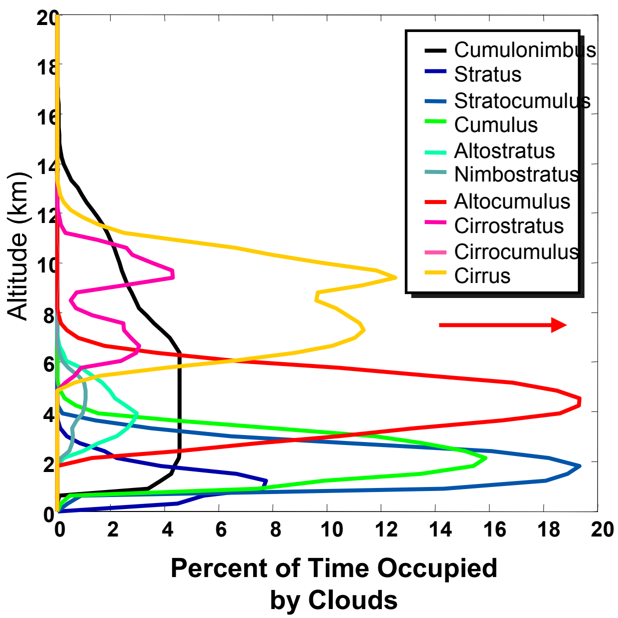


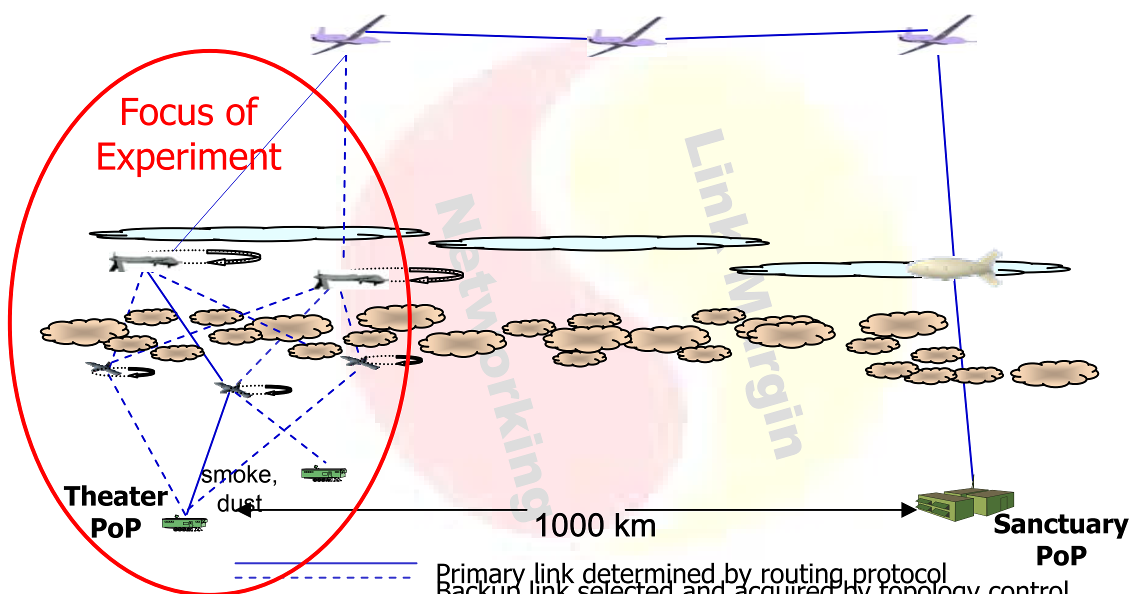
ORCLE

The central challenge is to enable optical communications bandwidth without giving up RF reliability and "all-weather" performance.

- Challenges
  - Lowest 10 km of atmosphere
    - LOS limitations (cloud blocking concentrated at lower altitudes)
    - Variable channel characteristics (turbulence induced fading)
  - High Availability in all weather conditions
    - FSO performance strongly tied to channel characteristic
    - RF relative immune to most channel characteristics
  - High average data rate
    - FSO high but *unreliable* data rate
    - RF low data rate but *reliable*

Even short opportunities to "burst" very high FSO data rates leads to much higher average data rates compared to RF





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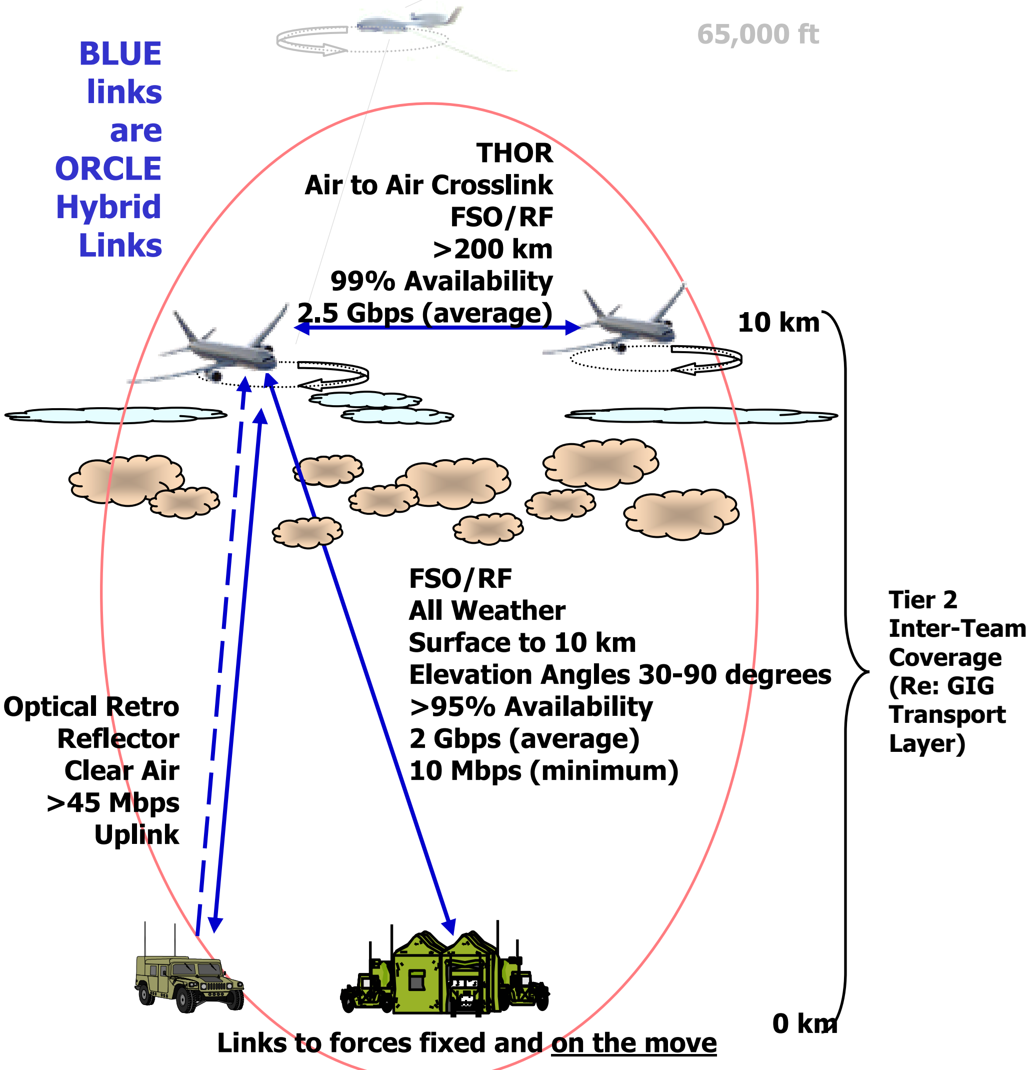
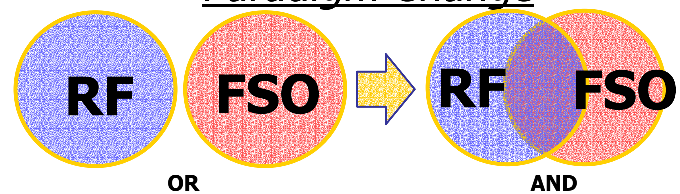
The plan is to demonstrate <u>three</u> links & simulate network performance



Paradigm Change



Generally complementary channel characteristics

- **Low Data Rate**
- **Stable Channel**
- **Relatively immune to cloud blocking**

- **High Data Rate**
- **Bursty Channel**
- **Must have generally clear LOS**

The resilience of the *combined* hybrid RF/FSO link will be in it's ability to achieve high availability with high average data rates.

- More options for adapting to weather
  - Minimum assured data rate
  - Maximum availability
- Physical Layer diversity improves Availability and Jam Resistance
- Networking to best match QoS of traffic needed to channel quality (RF <u>or</u> FSO; RF <u>and</u> FSO)
- Replace RF communications footprint with combined RF/FSO - SWaP Aware

ORCLE Considerations

- Networking Schema for QoS
  - RF for Latency sensitive assured delivery ("Dial tone")
  - FSO for bulk high bandwidth transfers that are less latency sensitive
  - Dynamic Allocatable Dual Physical Layer
- High Data rate Modulating Retro Reflectors
  - Greater than 45 Mbps
  - Wide FOV
  - Compact form factor
- Optical Channel Mitigation
  - Ultra short pulse lasers
  - Partially coherent beams
- Common/Combine FSO/RF Aperture
  - Enables transition to operational platforms as "replacement" rather than "in addition to" while maintaining current capabilities
  - Cohabitation of RF and FSO in same apertures long term goal

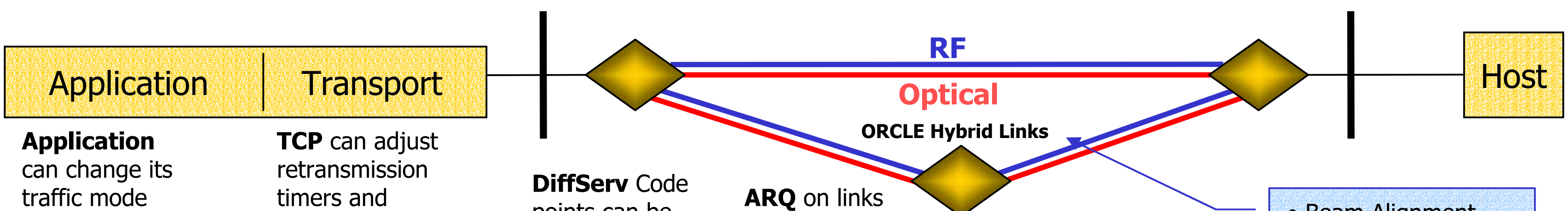
Hybrid Link
FSO + RF Considerations

Data Plane

- Traffic Management
  - Control plane enables multiple data level priorities through intelligent allocation of bandwidth
  - Hardware must be consistent with traffic management rules
    - e.g. Interfaces, RF/optical switching, RF/optical redundancy
- System requirements for high priority data
  - Max data rate determined by RF network
  - Latency must be minimized

Control Plane

- Network control plane uses RF and optical channels to leverage the complementary powers of each domain
  - RF channel for neighbor discovery & acquisition
    - Sharing of GPS and INS data on aircraft position, velocity, and time
  - Optical channel for link quality probe
    - Uses a separate low rate optical tracking channel or data channel itself
    - Can also be used for operational control and signaling
  - The control plane integrates information from each domain, utilizing both to optimize network performance
    - Topology optimization and dissemination, physical provisioning, identification of back-up paths all flow from the control plane information
  - The control plane media is RF for out-of-band, inter-node control



Application can change its traffic mode based on Predictive DiffServ

TCP can adjust retransmission timers and congestion parameters based on Explicit Congestion control and Explicit Transport Error Notification

DiffServ Code points can be used to pick routing table, queue or change link processing

ARQ on links can make optical links more reliable (at the cost of more delay)

Routing can have multiple tables to allow for paths with Different QoS

- Beam Alignment
- Link ACKS
- Routing Updates (generally not desired)
- TCP ACKs
- Explicit Congestion Indicators
- Explicit Loss Indicators
- Topology Control Information

The <u>RF channel</u> can <u>reliably</u> carry control traffic that enables adaptation at multiple levels

ORCLE Acquisition Strategy

Contract Awards (up to 2) to System Integrators for Range Demonstration (~month 16-18) and Flight Demonstration (~month 28-30) of prototype system. Focus of the demonstrations will be to prove concepts for:

- Hybrid Networking
- High Data Rate Modulating Retro Reflector

The PRIMARY focus of ORCLE

Contract Awards (multiple) for innovative high risk and high payoff development and testing of concepts for:

- Common/Combine FSO/RF Aperture
- Optical Channel Mitigation
- Hybrid Routing Technology
- Compact Optical Beam Steering

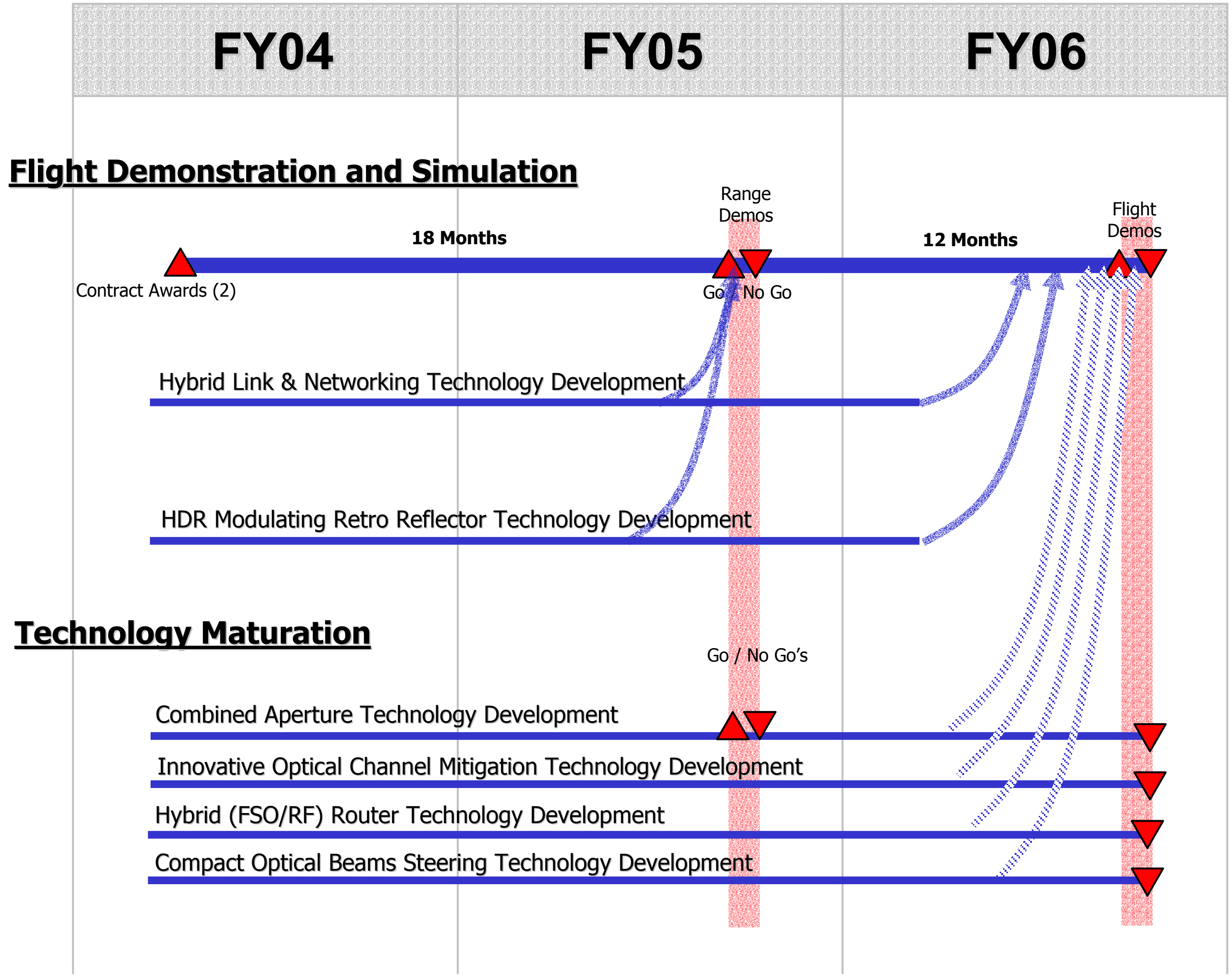
The technologies that will facilitate and enable ORCLE to transition to the warfighter

Notional
Evaluation Criteria

- Technical Approach
- Operational Utility
- Concept of Operations
- Management Approach
- Potential Contribution and Relevance to DARPA Mission
- Cost Realism

Notional

Schedule for ORCLE



Go / No Go Criteria and Conditions

Months After Contract Award	Event	Go / No Go Criteria	Conditions
18	**Range Demo [White Sands Missile range]**	✓RANGE DEMO of HYBRID FSO/RF Link ✓Mountain Top to Mountain Top as surrogate Air to Air (~50 km separation) ✓Mountain Top to Ground as surrogate Air to Ground Link (~12 km separation) ✓G-A, A-A Availability >95% ✓Demonstrate >2.0 Gbps *average* data rate ✓MRR data rate >45 Mbps at 12 km ✓Model performance for conditions in South East Asia during July for a 10 node hybrid network over a 400 km area with 2 ground nodes (one fixed and one mobile)	✓Place terminals on motion tables to simulate C135 flight vibration environment and aircraft motion. ✓Vary the optical opacity over time using screens (A-A and A-G tests) ✓40 hours simulated A-A test time ✓40 hours simulated A-G test time
30	**Flight Demo [Gov't Range]**	✓FLIGHT DEMO – Ground to Air to Air of HYBRID FSO/RF Link ✓G-A-A Availability >95% ✓Demonstrate >2.0 Gbps *average* data rate ✓Demonstrate Common / Combined FSO&RF Aperture ✓FLIGHT DEMO – Mobile Ground to Air ✓MRR data rate >45 Mbps at 20 km ✓Model performance for conditions in South East Asia during July for a 20 node hybrid network over a 1000 km area with 2 ground nodes (one fixed and one mobile)	✓40 hours of flight testing per a/c (80 hrs total). ✓Test Hybrid Link under a variety of environmental conditions (clear to cloudy).

Briefing Complete