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CONCERTO and BRAVO

Experiences with practical, full implementations of Network Coding systems

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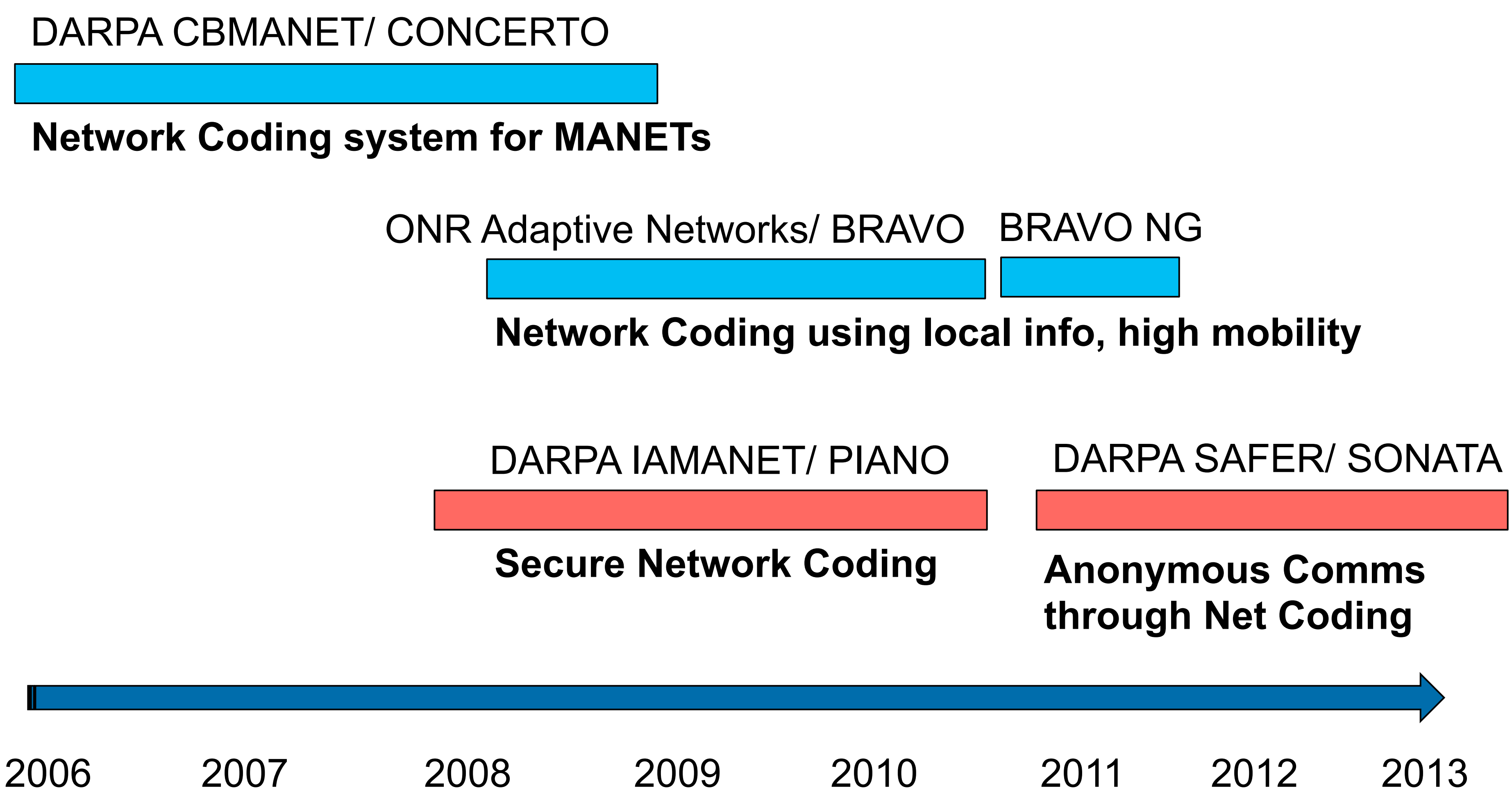
Projects in Networking and Communications



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CBMANET/ CONCERTO Motivation

Challenges in Wireless MANETs

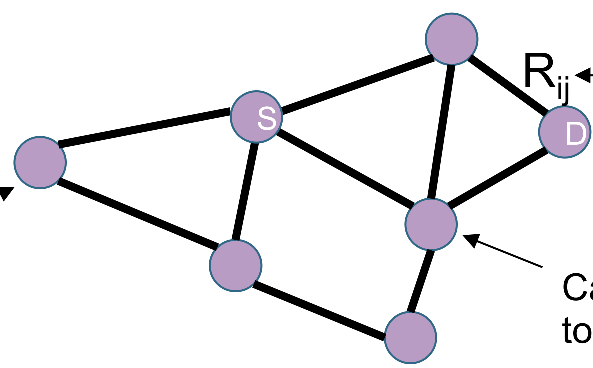
- Wireless communication
  - MANET Broadcast transmissions – use Rx is better than ignore
  - Reception is prone to errors – needs as much help as can get
- Mobility removes certainty from traditional routing

CONCERTO Approach

- Clean slate network and transport layers
- Network Coding Transport: fluid model
- Routing on Subgraphs
  - Enabled by fluid model
  - Robust to link errors and topo change

Subgraph Computation

- Optimal Subgraph computation is complex (exponential in no. neighbors)
- Simplified approach: similar to MORE by Katabi et al
  - Requires Link State information
  - Computational complexity is $O(n^2)$ (n nodes in network)
  - Computes rate at which nodes should participate in forwarding mixtures
- Basic Concept
  - Forwarding nodes are chosen from those that are most probable to advance the information propagation to each destination
  - Forwarding intensity is related to the probability of contributing to info advance



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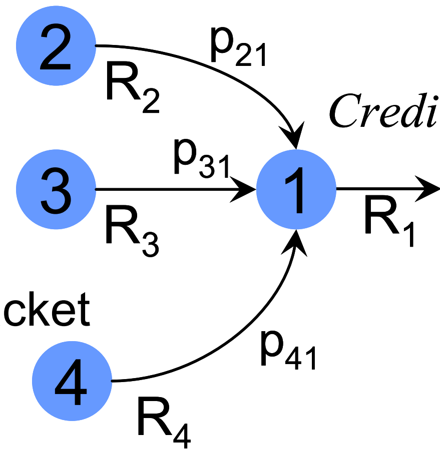
Packet Forwarding

- Packet Forwarding
  - Uses transmit rates computed by Subgraph computation
  - Computes "receive credit" as ratio of transmit rate to expected receive rate
  - Node earns credit when it receives innov. packet
  - Spends credit when it transmits packets
  - Provides automatic scaling to source rate



$$Credit_1 = \frac{R_1}{\sum_{i \in upstream} p_{i1} R_i}$$

- Repair process, semi-reliable protocol (media streaming)
  - Nodes request **locally** extra transmissions if necessary
  - Requests are piggy-backed on forwarded packets when possible
- Fully reliable protocol (file transfer)
  - Additional algorithm for propagation of repair requests, detection of missing generations, beginning/end of files, late join, etc.

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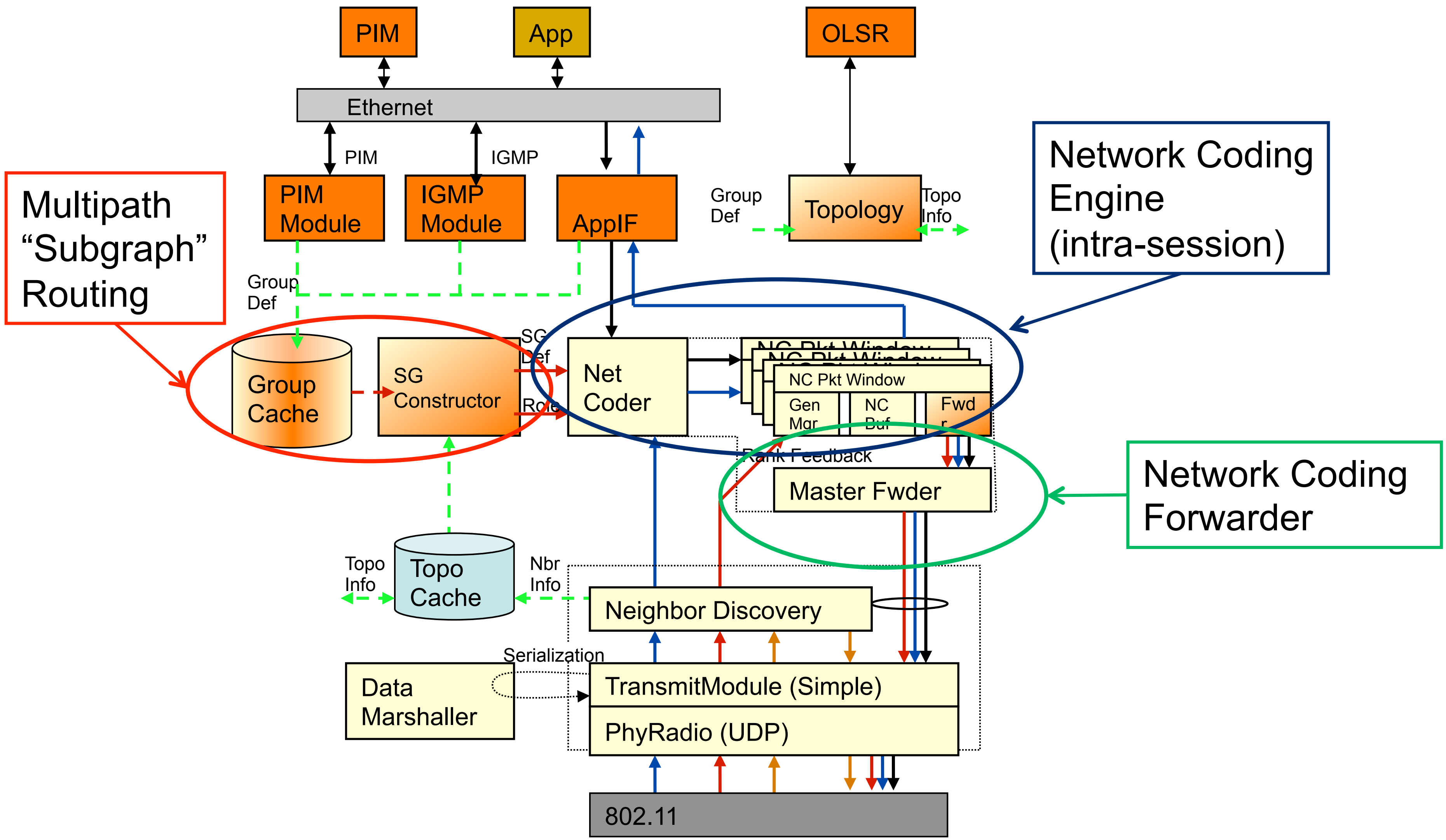
CONCERTO Architecture



Layerless Modular Architecture: module info sharing ➔ Adaptation to wireless dynamics

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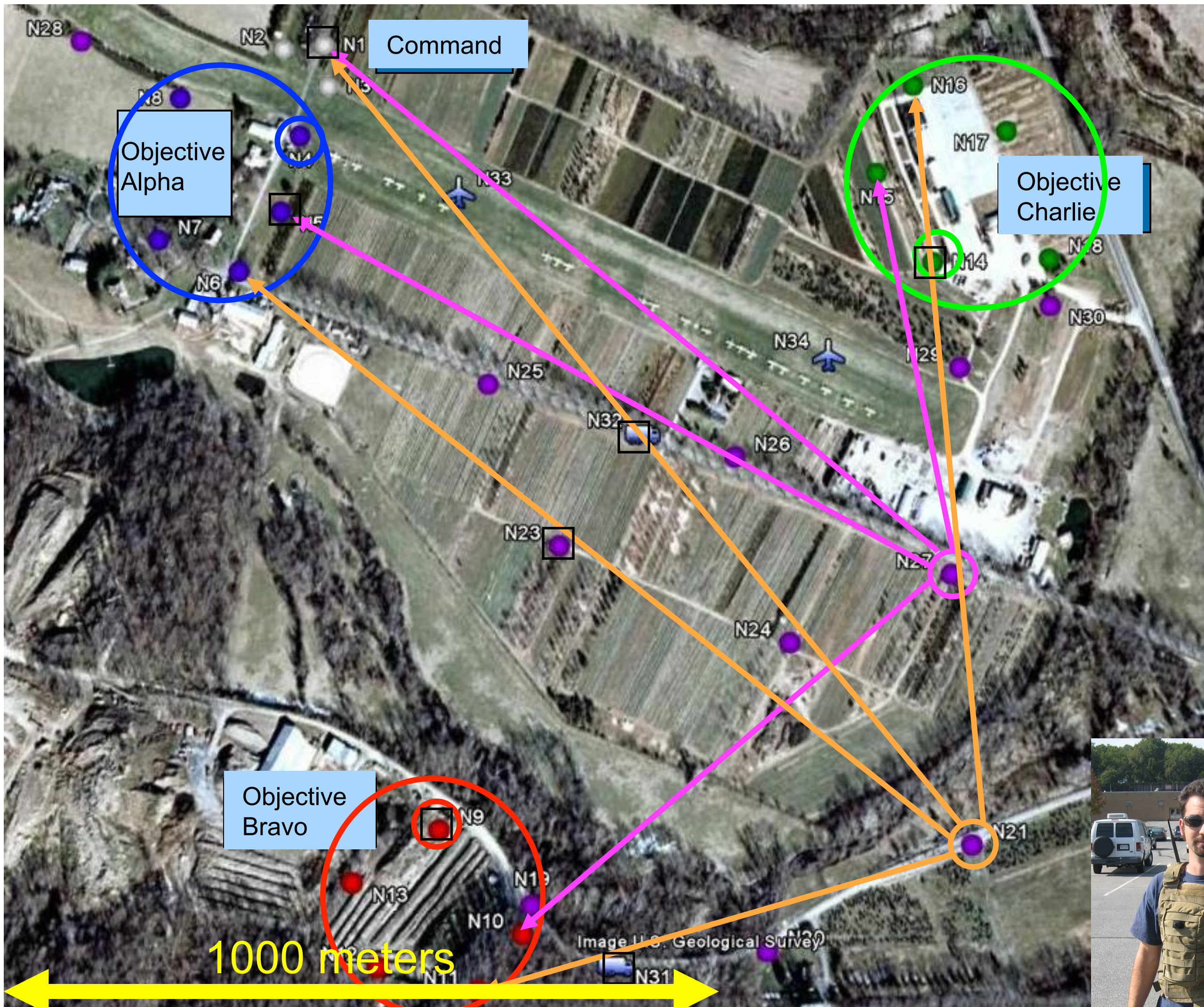
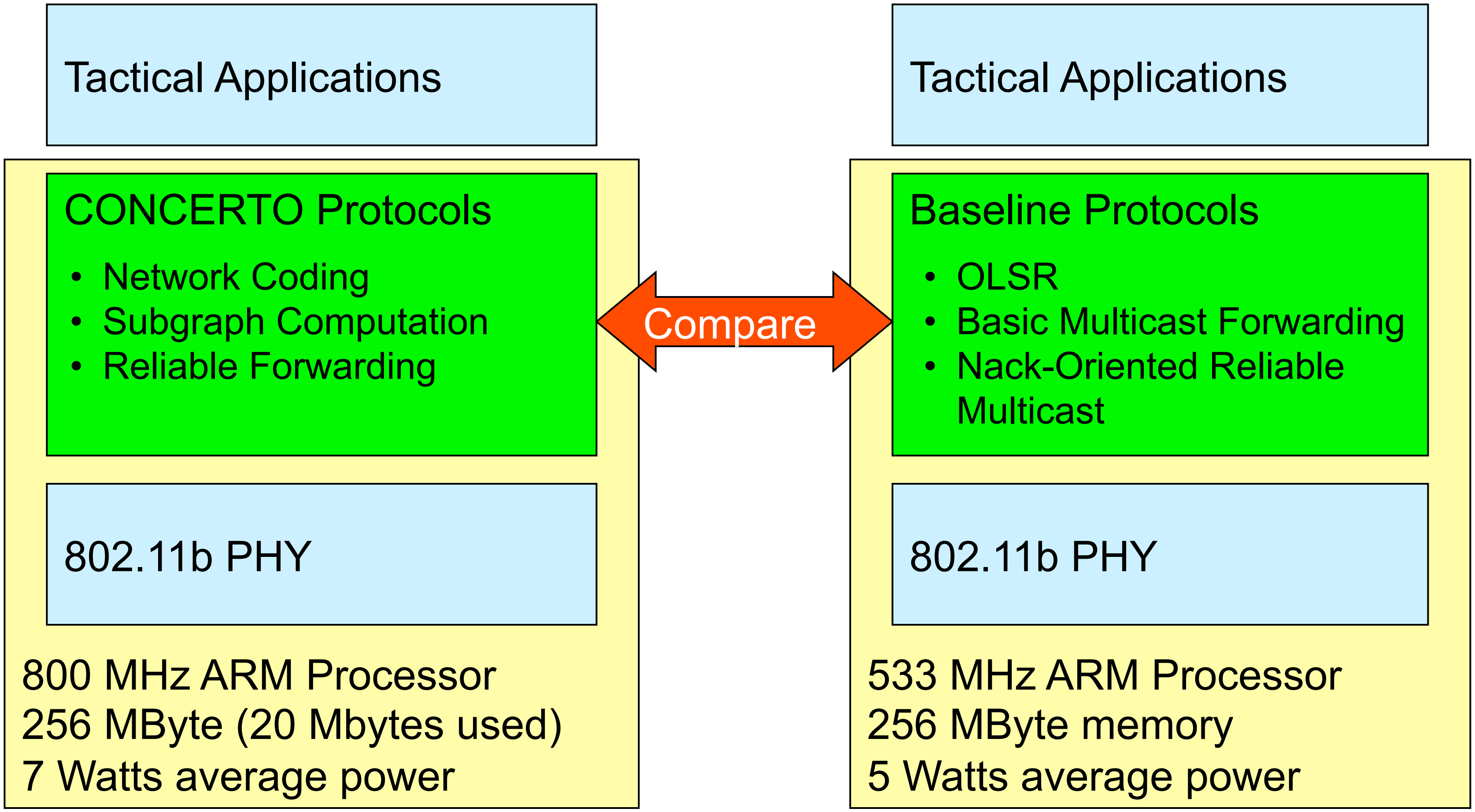
Scenario



☐ Indicates FX node

- 31 mobile nodes:
- 3 moving groups of 5 people each
- 2 Vehicles traveling on access roads
- Tested ***with and without*** 2 aircraft
- Applications
  - Chat
  - Video
  - File Exchange

CONCERTO-Baseline Comparison



Common applications and PHY allow “apples-to-apples” comparison

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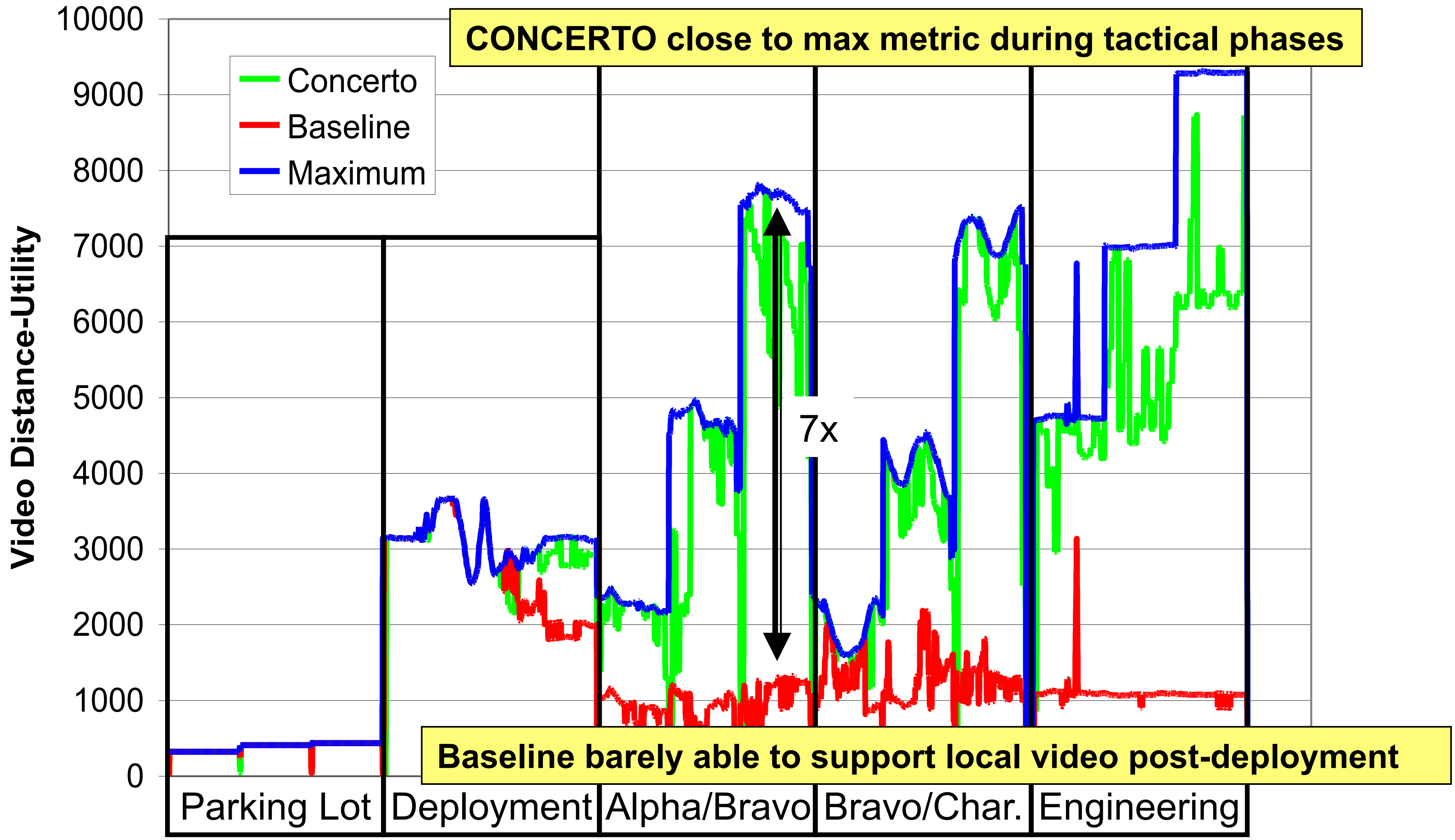
Air Scenario – Distance Utility Metric



CONCERTO provides 7x higher performance than baseline in Air Scenario

Challenges In Subgraph Construction

- Requires Link State from all network
- Inaccurate LS info results in inefficient or defective subgraph

Solution: subgraph construction based on local info

- Gradient-based Routing
- Constructs field and currents for information flow
- Made possible by network coding fluid flow
- Provides natural properties of (Electric) Potential Fields
  - Efficient flow allocation
  - Locality of perturbation, Stability
  - No local minima: data never stalls in the middle

Gradient-based Routing
Information Flow Modeled on Electric Network

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Objective: Minimize total transmissions: ***G=Σ{all links ab} |Iab|/Qab***

- ***Iab*** = Information rate from a to b; ***Qab*** = P[success Tx from a to b]

Solution: Data network – equivalent to electric network:

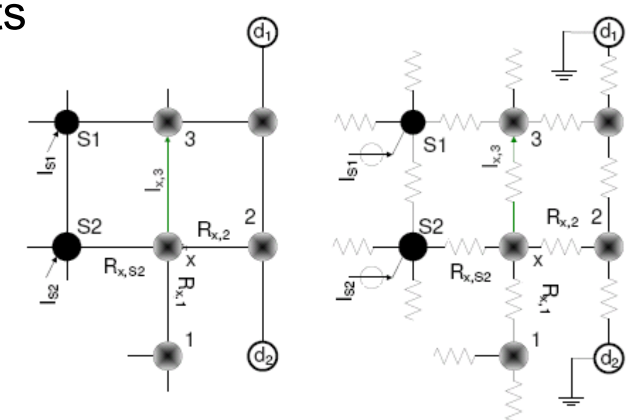
- Approximation: minimize ***G=*** $\boldsymbol{\Sigma(Iab)^2/Qab}$ ➔ minimize ***E=*** $\boldsymbol{\Sigma(Iab)^2Rab}$
- Information rate from a to b ➔ intensity of current ***Iab***
- Link quality from a to b = ***Qab*** ➔ 1/Resistance = ***1/Rab***
- Minimize Data Transmission: reduced to minimizing total electric energy
  - –Classic problem of solving electric circuits

- **Network Level**

$$E = \frac{1}{2}\sum_{x,y} I_{x,y}^2 R_{x,y} = \frac{1}{2}\sum_{x,y} g_{x,y}(V_x - V_y)^2$$

Flow Level

$$I_{x,y} = \frac{(V_x - V_y)}{R_{x,y}}$$



(a) Communication Network

(b) Equivalent Electric Network

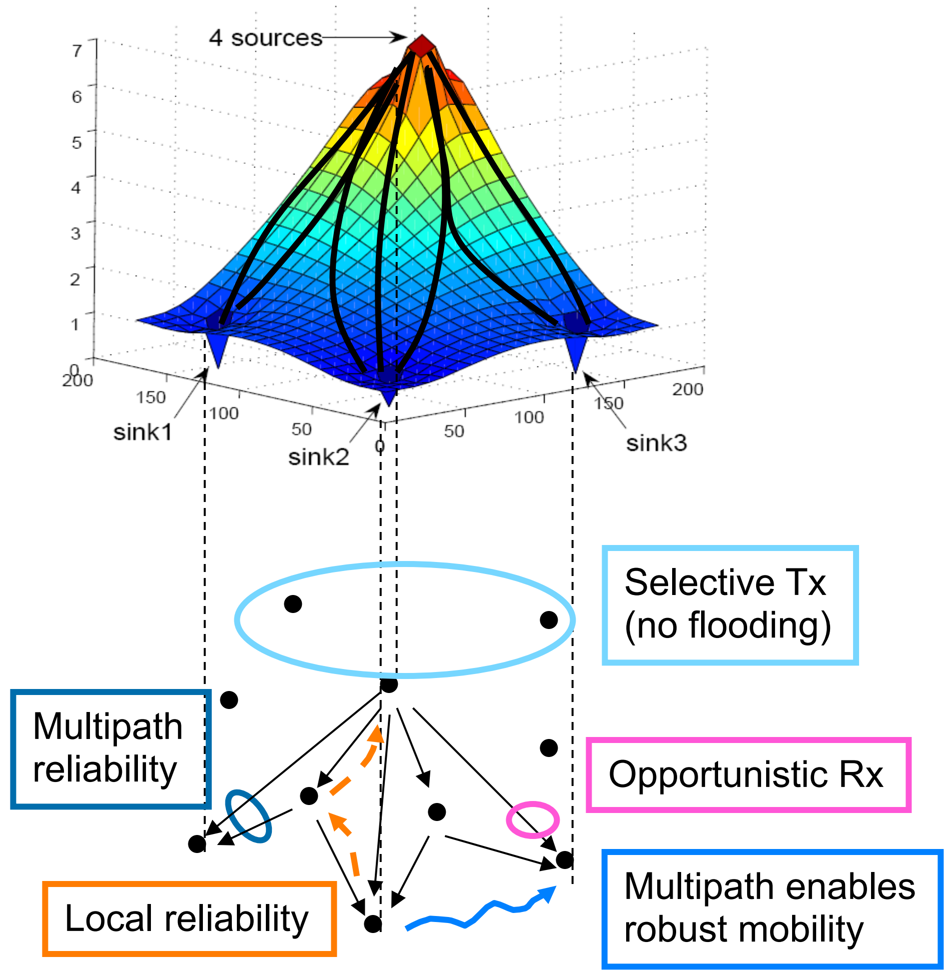
BRAVO: Network Coding over Gradient-based Subgraphs

Routing Challenges

- Reduced overhead through local info
- Multipath increases stability

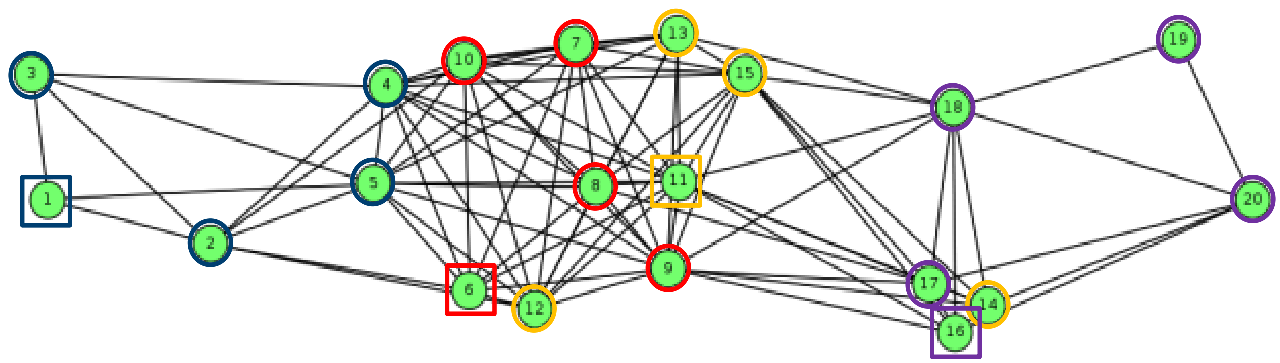
Data Transport Challenges

- Selective Tx is efficient
- Opportunistic Rx increases Tx efficiency
- Local & multi-path reliability increases end-end goodput effectiveness



Netcoded data over gradient routes gains from multipath, opportunistic network usage

BRAVO Performance



The Gauntlet Scenario

- 20 nodes, 2 stationary, 18 moving in random in regions

Scenario	Mean duration [s]	Std dev [s]
Full speed	42.275	54.530
Half speed	80.338	88.238
Quarter speed	138.518	143.131

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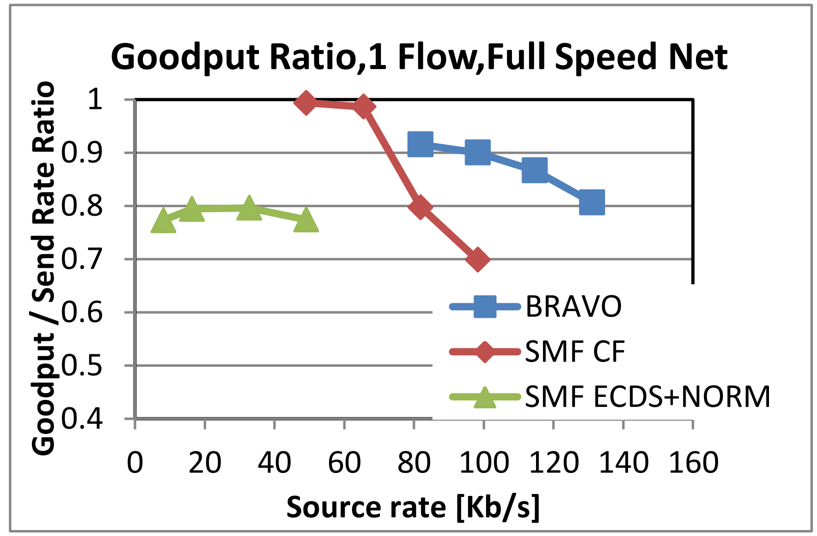
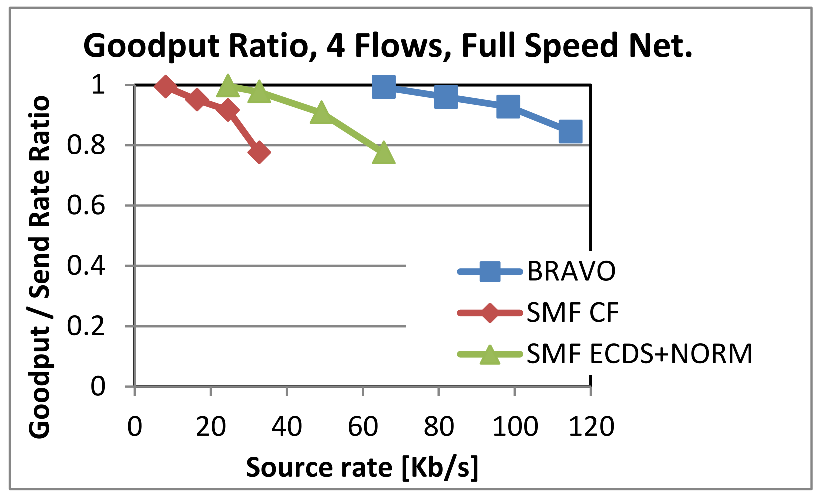
BRAVO Outperfroms SMF + NORM

- BRAVO robust at high speeds

Why:

- Gradient-based subgraph ajdusts locally to topo changes
- Multi-path routing compensates the temporary lack of a link
- Network Coding adds redundancy: help deliver data, no matter where they come from





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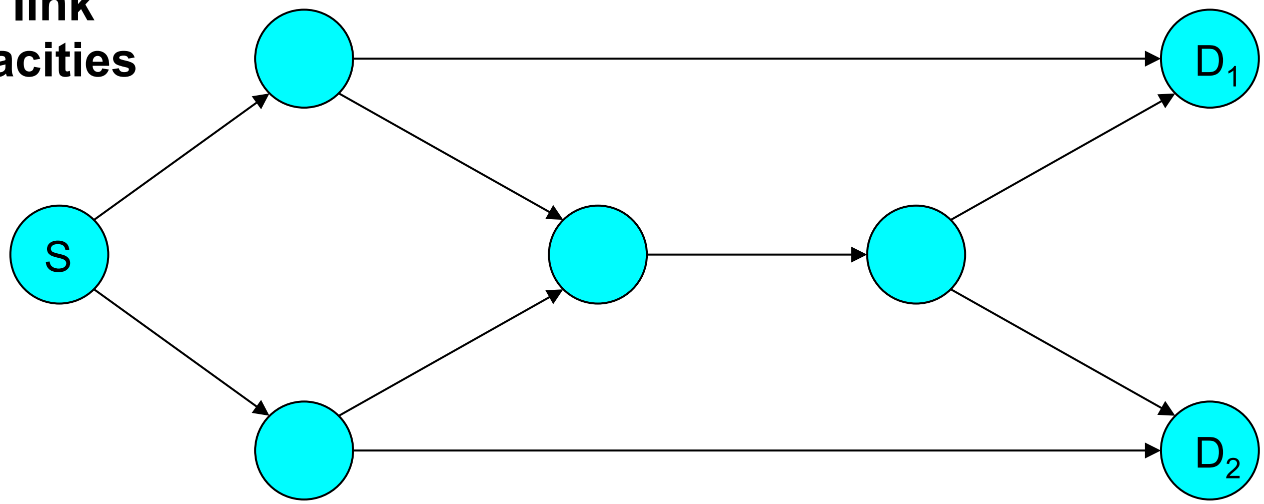
Conclusions

- Gains achieved besides information theoretical
- Network Coding enables multi-path reliability
- Network Coding enables hop-by-hop reliability
- Gradient-based subgraph routing
  - More efficient and scalable multipath routing

BACKUP

Intra-Session Coding: Wireline Butterfly

Unit link capacities



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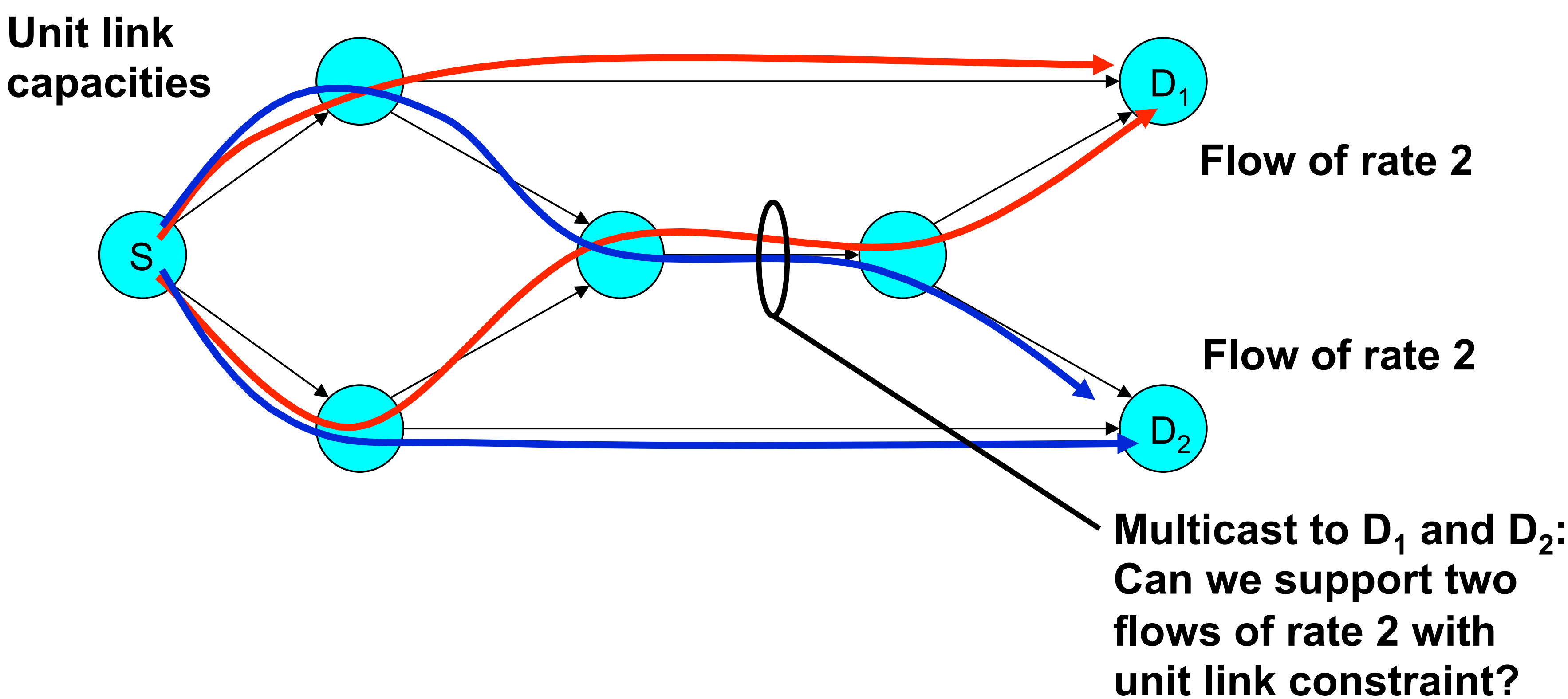
Wireline Butterfly with Multicast Routing



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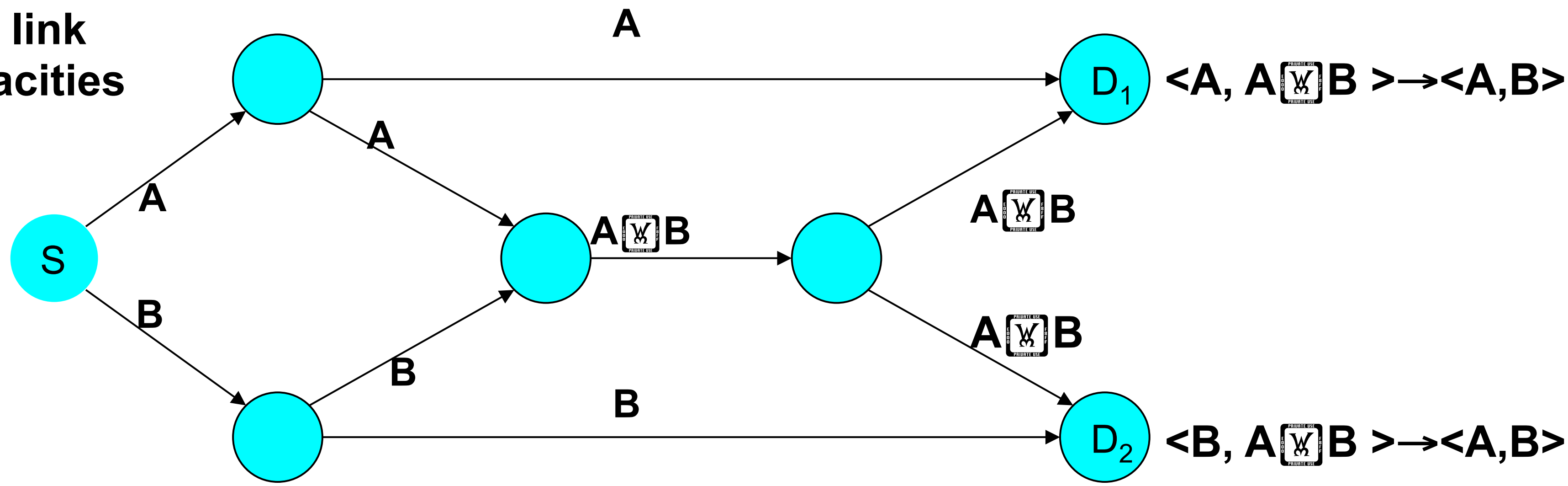
Wireline Butterfly with Intra-Session Network Coding:

Unit link capacities



We can support "full rate" multicast to both destinations by XORing packets

Routing: Sum of "per destination" flows on a link must be less than link capacity

Network Coding: Maximum over "per destination" flows on a link must be less than link capacity

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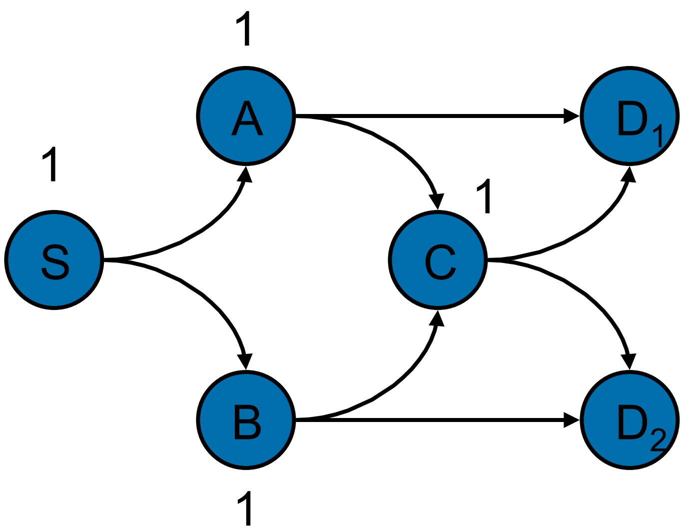
Wireless Butterfly with Multicast Routing

- Lossless links

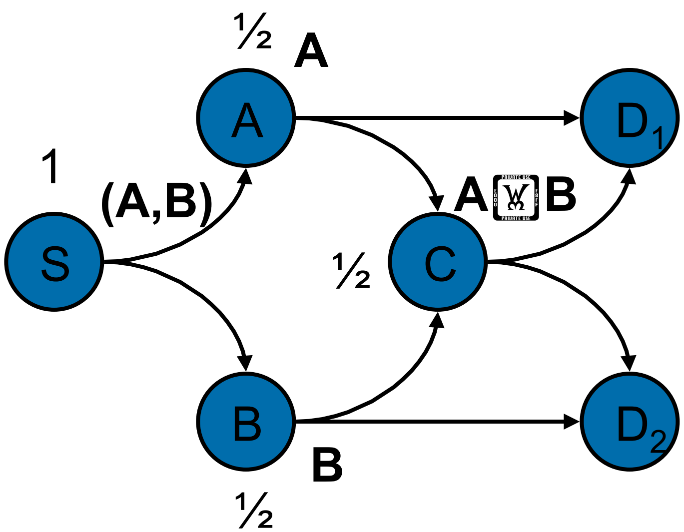


Routing: Sum of Tx Rates / symbol = 4

Contention-free schedule: S, A, B, C

Wireless Butterfly with Intra-Session Network Coding

- Lossless links



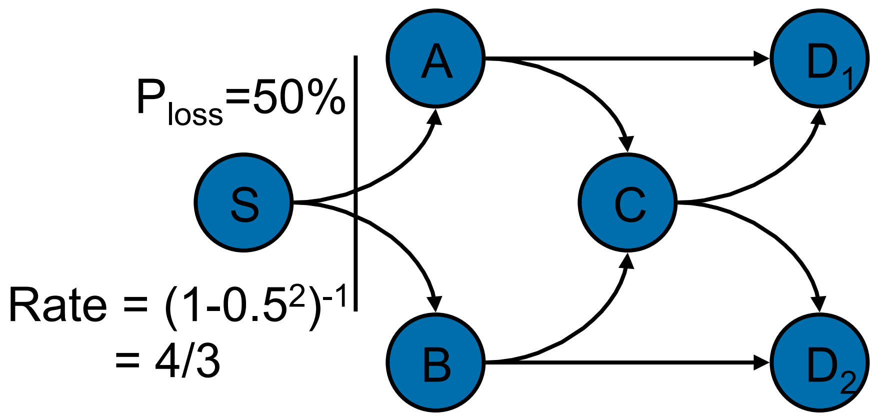
(Routing: Sum of Rates = 4)

NC: Sum of Tx Rates / symbol = 2.5

Contention-free schedule: S, S, A, B, C

Wireless Butterfly with Intra-Session Network Coding

- Lossy links



- When links are lossy, need only send at rate which transfers info to *some* next node on the other side of a cut set…

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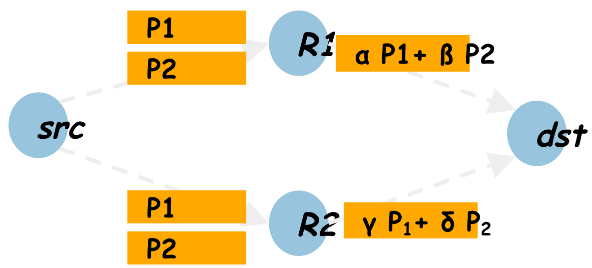
Intra-Session Network Coding

- Ahlswede et al. proved that for a single multicast session, network coding achieves the maximum possible rate allowed in the network

- Problem Decomposition
  - Computing Mixtures
    - How to combine packets into mixtures that “work”
  - Subgraph Construction
    - Which nodes forward mixtures and how much do they participate

Computing Mixtures: Random Linear Coding

- Ho et al.: **Random Linear Coding**
  - Encoding: $$Q_j = \sum_{i=1,n} A_{ij} P_i \quad or \quad \overline{Q} = A\overline{P}$$
  - Identity of packets received – does not matter
  - Only matters: Quantity of mixed packets = group size

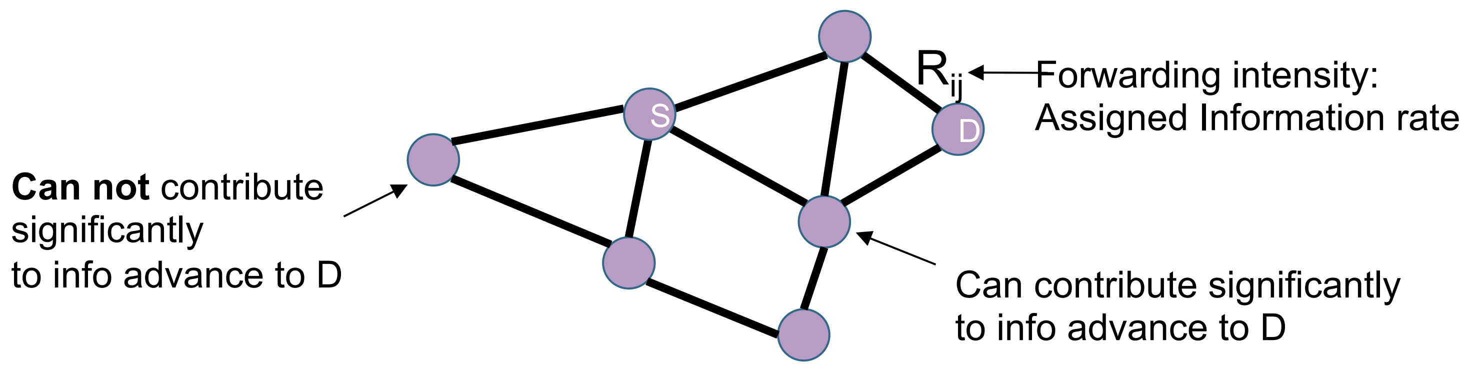


- Practical Network Coding (Chou et al.)
  - Break file into N packets
  - Collect packets into groups of G packets (generations)
  - Source/intermediate nodes transmit random mixtures from generations
  - Innovative (linearly independent) packets are stored for future mixtures
  - Packet headers collect coefficients used in random coding
  - Destination collects G linearly independent coded packets
  - Inverts the matrix of random coefficients to recover original packets $$\overline{P} = A^{-1}\overline{Q}$$

- Intra-session coding is basically matrix inversion

Subgraph Construction

- Not all nodes in a network should participate in each multicast flow
  - Want to maximize network capacity by minimizing transmissions
- Subgraph
  - The nodes which participate in random linear coding for a multicast flow
  - The rate at which these nodes forward random linear combinations



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Subgraph Computation: Optimization Problem

$$\min \sum_{(i,j)\in A} f_{ij}(z_{ij}, R) \longleftarrow$$

Convex cost function can capture goals of minimum energy, congestion, cost or maximum throughput

$$\text{subject to } z_{ij} \geq x_{ij}^{(t)} \qquad \forall (i,j)\in A,\ t\in T,$$

netcoded transmissions on link (i, j) greater than *maximum* per dest flow

$$\sum_{\{j|(i,j)\in A\}} x_{ij}^{(t)} - \sum_{\{j|(j,i)\in A\}} x_{ji}^{(t)} = \begin{cases} R & \text{if } i = s, \\ -R & \text{if } i = t, \quad \forall i\in N,\ t\in T, \\ 0 & \text{otherwise} \end{cases}$$

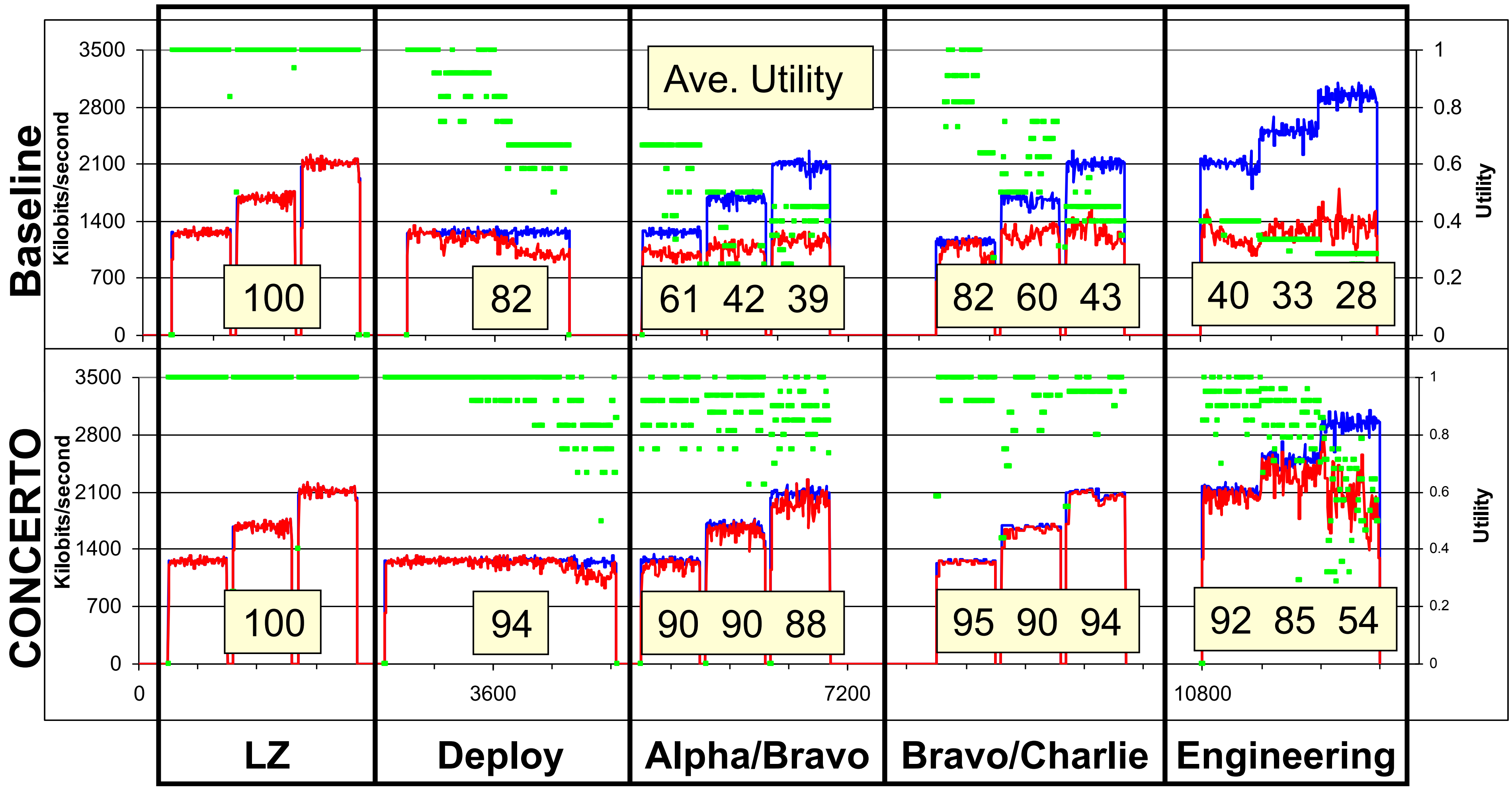
conservation of flow to destination t at node i

$$c_{ij} \geq x_{ij}^{(t)} \geq 0, \qquad \forall (i,j)\in A,\ t\in T$$

link capacity constraints

Optimal Subgraph computation is complex (exponential in no. neighbors)

Video Utility - Ground



Baseline barely usable at lowest load; CONCERTO works well at highest tactical loads

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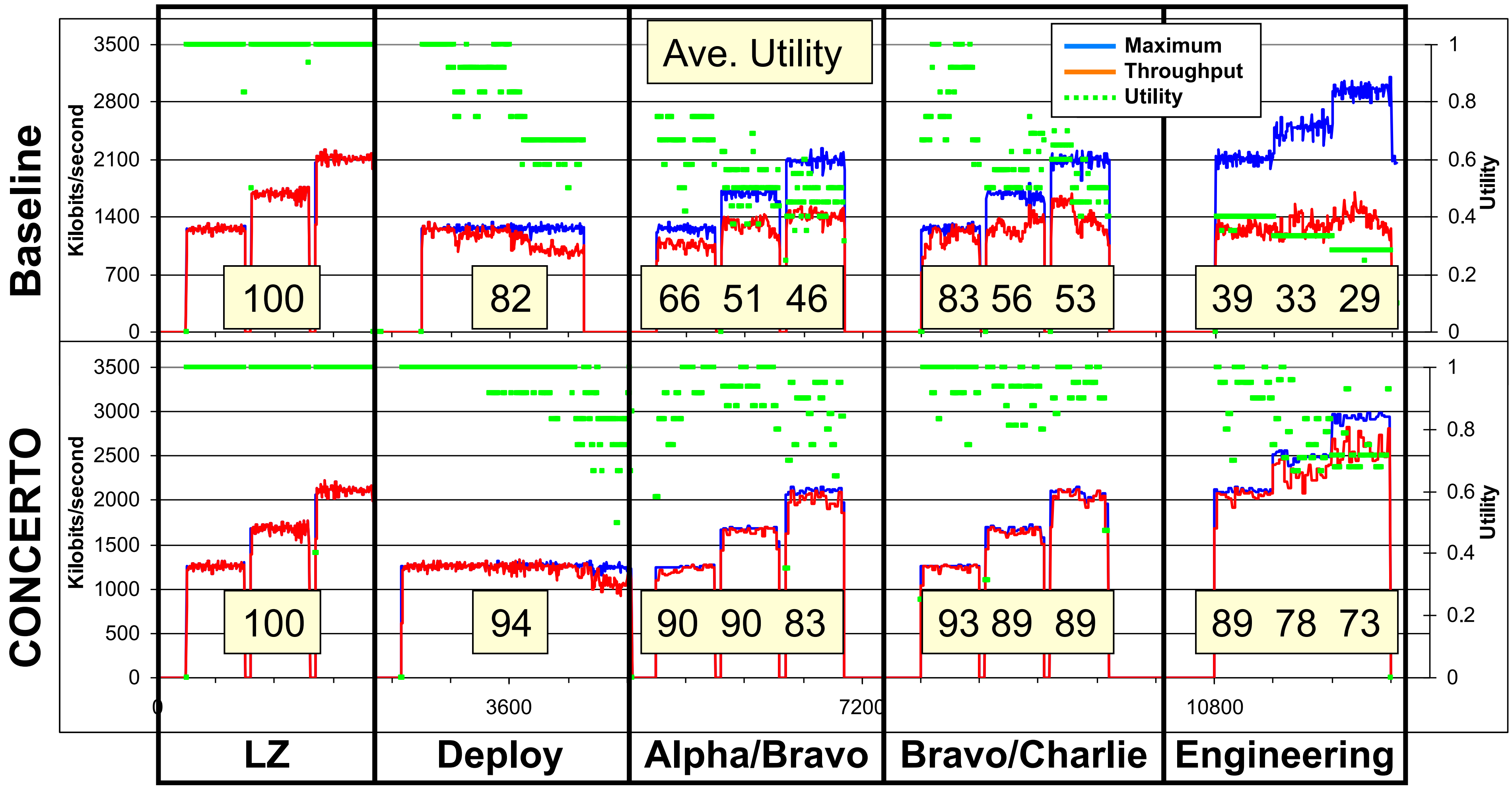
Video Utility - Air



Baseline barely usable at lowest load; CONCERTO works well at highest tactical loads