Abstract

Wired networks and MANETs are substantially different, yet many deeply embedded design decisions and assumptions from wired networks can be discerned in emerging MANET solutions. To identify potential MANET research opportunities and breakthroughs, this talk critically examines some of these assumptions and questions their applicability. Because wireless communications to the edge are so essential, it would not be surprising if a dramatically superior MANET solution ultimately proved disruptive to the dominant DOD networking paradigms or even to aspects of the commercial Internet Protocols.

MANETs as the driver of disruptive innovation in networking

Presentation for AFCEA SPAWAR MANET Symposium, San Diego, CA

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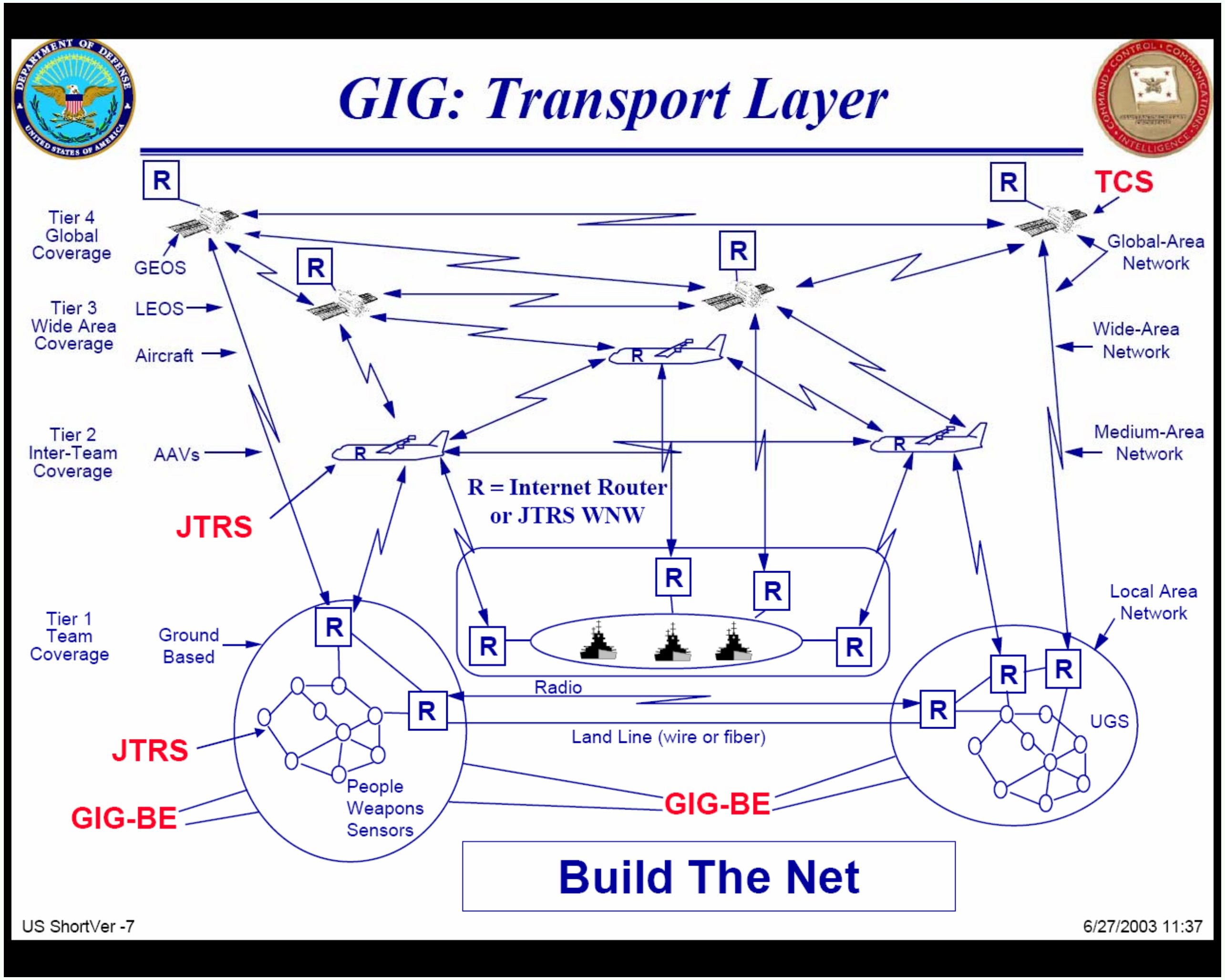
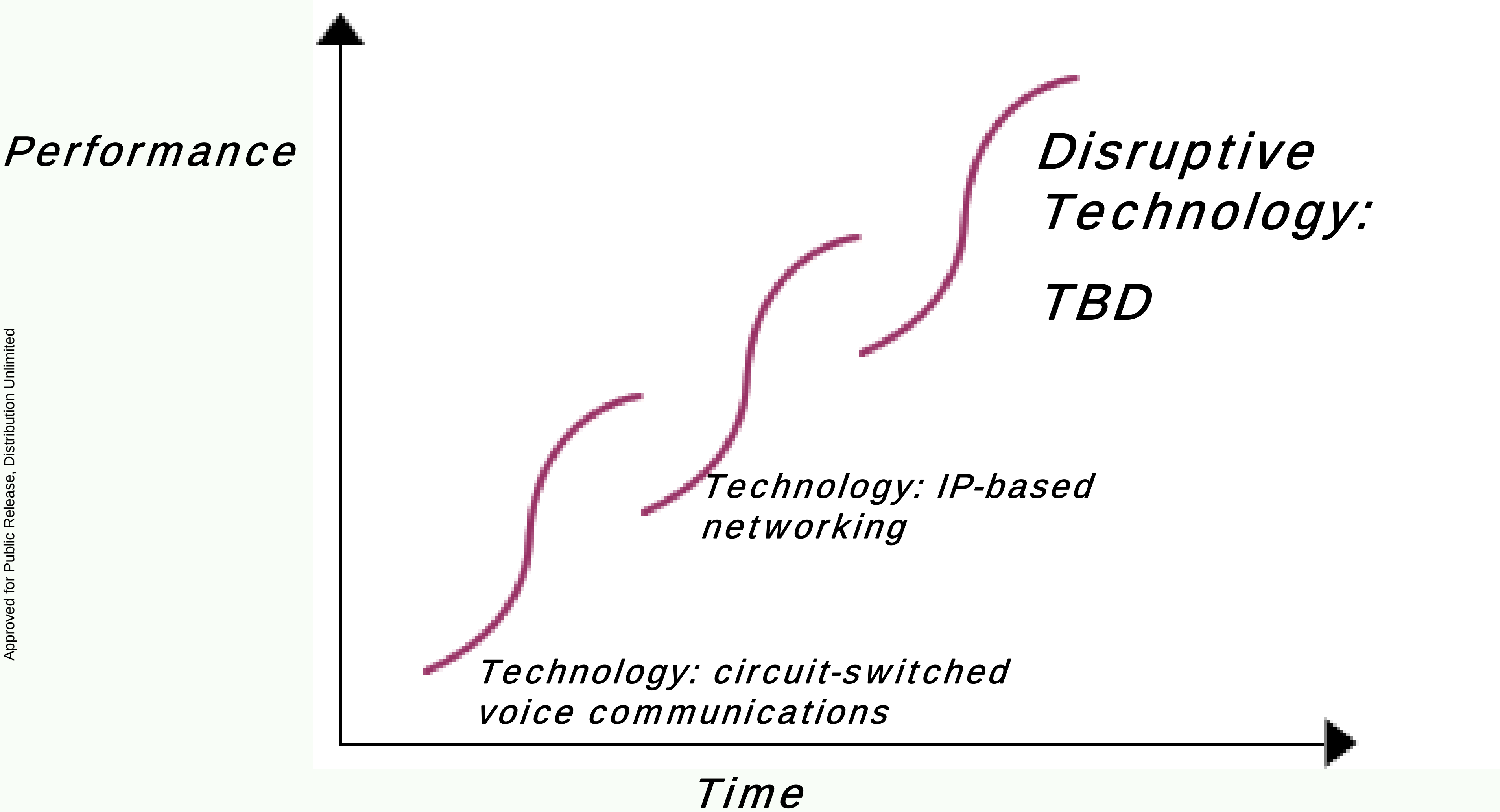
"Network Centricity" requires ubiquitous, secure connectivity



Our collective objective is a secure wireless systems-of-systems. The candidate technical approach is largely IP-based.

Technology adoption S-curves



Question: what ideas might displace the Internet protocols and why?

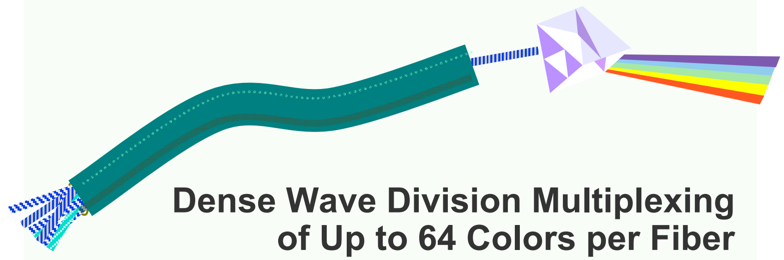
General signs of impending disruption

- A new use case puts emphasis on different metrics
- Fundamental assumptions of the previous technology are violated
- “Crossover” theories and technologies emerge
- There is disagreement amongst recognized experts about the new technology

Disruptive technologies begin in a niche and then expand their reach

“New” use case: resource-constrained communications

FIBER:
Bandwidth is PLENTIFUL
Inefficiency Not Noticed

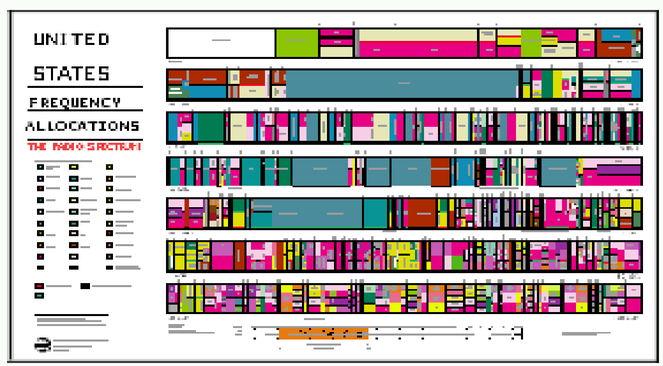


Dense Wave Division Multiplexing of Up to 64 Colors per Fiber – with 20 Fibers per Bundle

Each Color = 10 GHz

ONE BUNDLE= 12,800 GHz

WIRELESS:
Bandwidth is SCARCE
Overhead Limits Applications



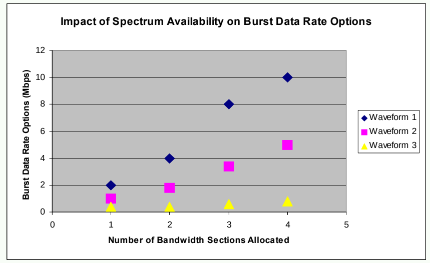
Each spectrum region has different properties & “owner”

USEABLE MOBILE= 3 GHz

Wireless networking puts a renewed emphasis on efficiency

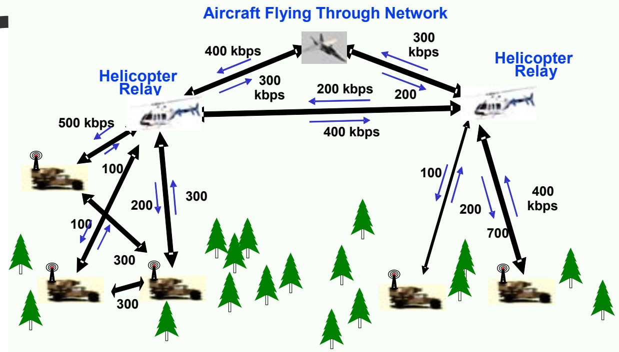
Throughput of Mobile Ad Hoc NETworks (MANETs)

MANET capacity



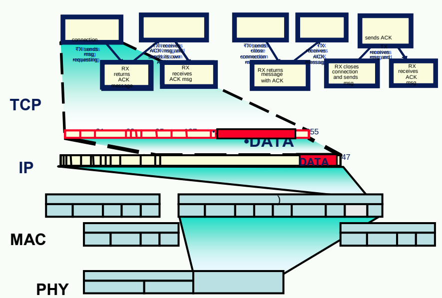
The advertised network throughput of many MANETs is often given as the maximum burst rate on a single link

…is shared within a region



However, the burst rate figure is misleading because it represents capacity that must be shared by other network users, not the capacity that each user can expect. Individual users generally obtain only a fraction of the maximum burst rate.

…and largely wasted by suboptimal designs

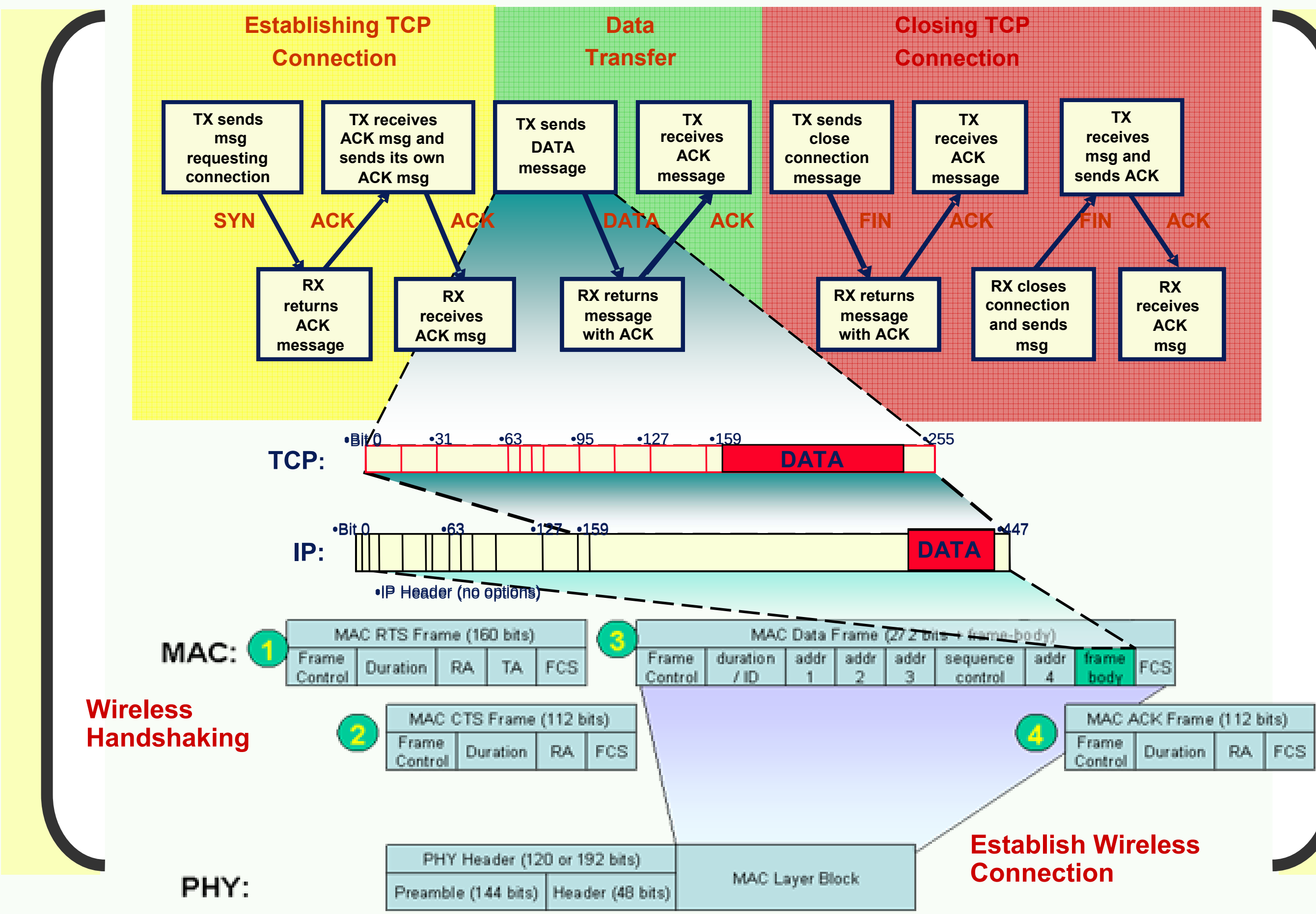


Also, the burst rate does not reflect data transfer efficiency, which may be low because of large protocol overhead per frame, limited cross-layer coordination, the absence of network resource management, etc.

Risk: netcentric requirements may not be met by traditional protocols

Existing protocols waste precious spectrum

EXAMPLE #1 (Cont'd): TCP/IP/RTS-CTS – Transfer Inefficiencies, Excessive Overhead, Single 80-bit Payload



TCP/IP Protocols:

Payload: 80 Bits
Total Sent: 2,000 Bits
Transmissions: 6*

% Effective: 4 %

*could be 7 if receiver is not ready to close the connection

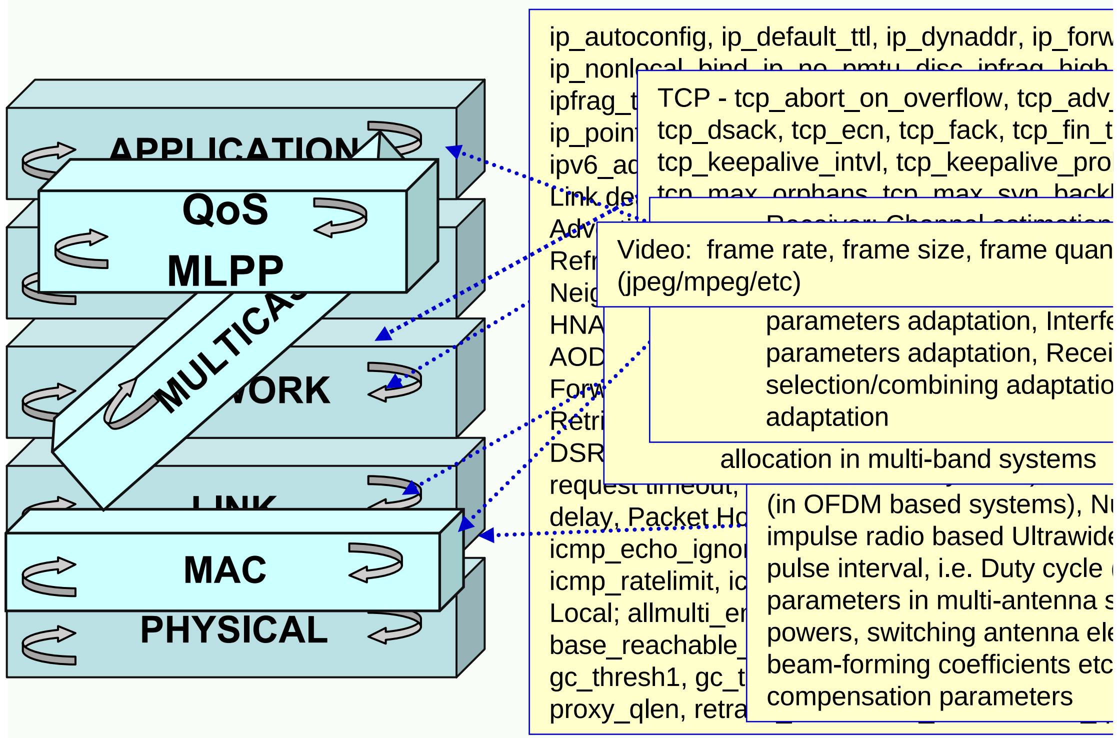
Wireless Protocols:

(802.11b)
Wireless Sent: 10,554 Bits
Transmissions 24

Short message BW Efficiency: 0.75 %

We may need to completely rethink wireless network protocols

"New" use case: mobile, dynamic context



Manual, static methods of configuration are still needed to optimize many MANET parameters

Routing notably excepted, many MANET protocols are not yet fully adaptive to mobility and other dynamics

Dynamic environments motivate adaptation

MISSION TRADEOFFS

Individual vs Mission:
Individuals look for high QoS, but LPI/LPD requirements may require minimal RF footprint

Layer 2 vs Layer 3:
Slot assignment at layer 2 should be coordinated with DIFFSERV allocations at layer 3

TECHNICAL TRADEOFFS

Routing vs Error recovery
UAV relay placement competes with OSPF area redesign as a solution to minimizing inter-area traffic

Individual vs Individual:
Some nodes may choose to operate as relays on behalf of others with less battery life

Node vs Node:
Spectrum Management and Power Control can prevent denial of service from “friendly interference”

Application vs Physics:
High data rate applications must make tradeoffs for lower frequency RF propagation in Urban environments.

SOCIAL TRADEOFFS

Individual vs Individual:
[General vs 1st LT and MLPP]
Seniority and the need for time-critical information, dictate network resource allocation

Military networks must manage trade-offs in a self-organizing and adaptive fashion

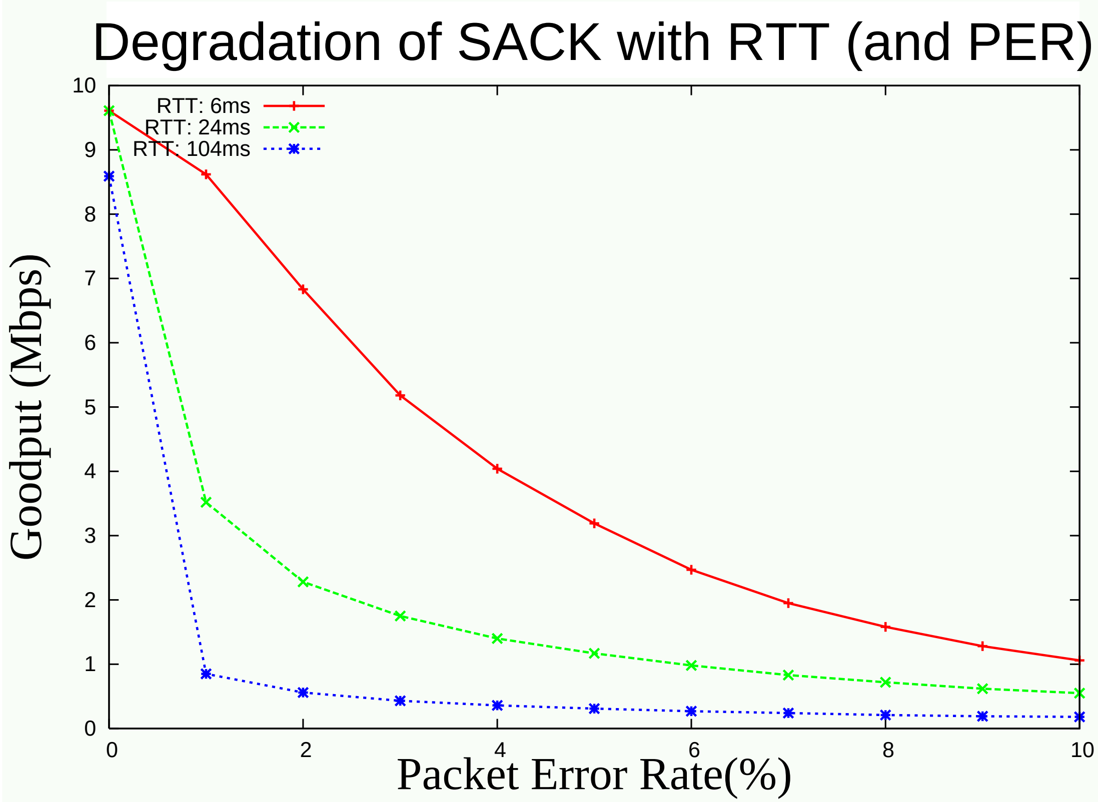
PHYSICAL TRADEOFFS

Environment vs Physics:
Terrain, weather, and environment limit allowable frequency bands due to terrain limitations, LOS, weather

Adaptive technology is essential for managing dynamic tradeoffs

The dynamics of mobility affect network design

EXAMPLE: TCP assumes low-latency, stable, fixed capacity, high-quality links



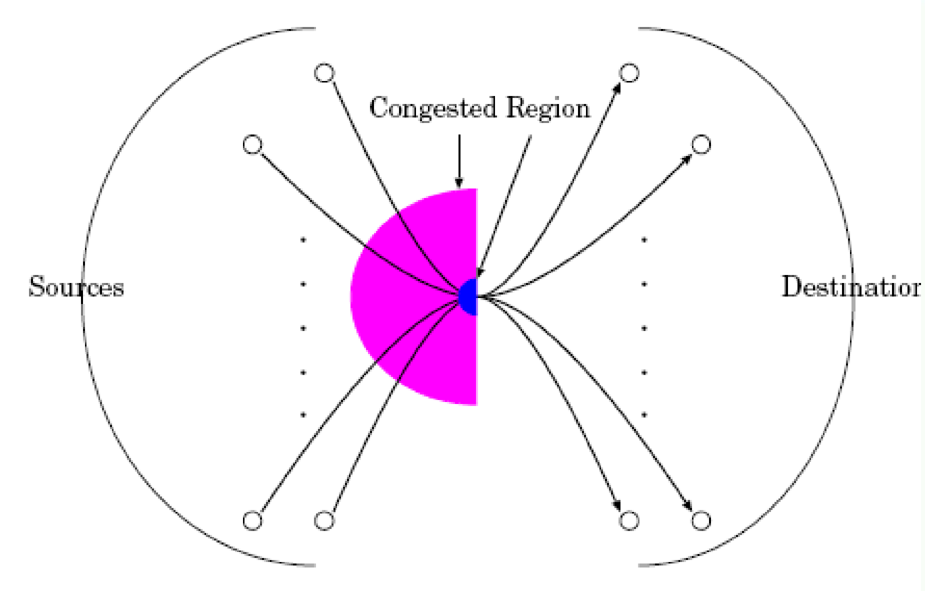
Source: Robust TCP for Large-Bandwidth Delay, Packet Erasure and Multi-Path Environments. Shivkumar Kalyanaraman (RPI), K.K. Ramakrishnan (AT&T Labs Research)

TCP/SACK:

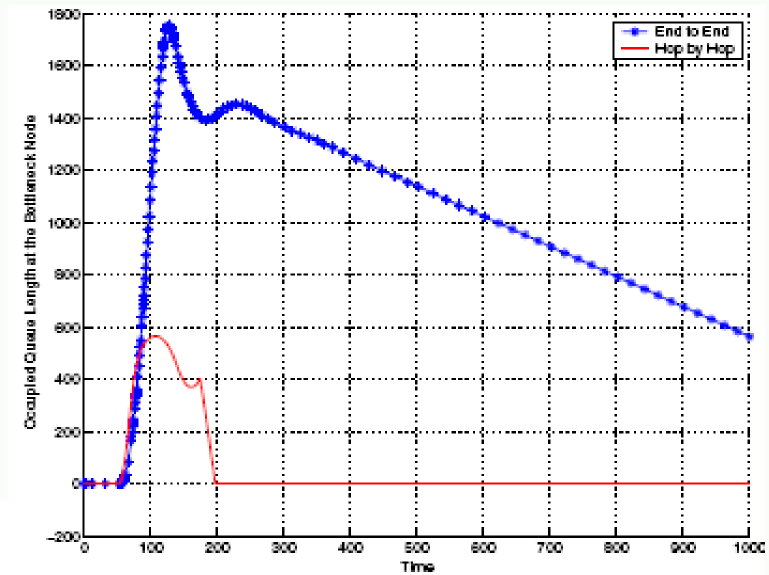
Long control loops. Rate control is the only adaptation mechanism.

The IP protocols were designed for static networks

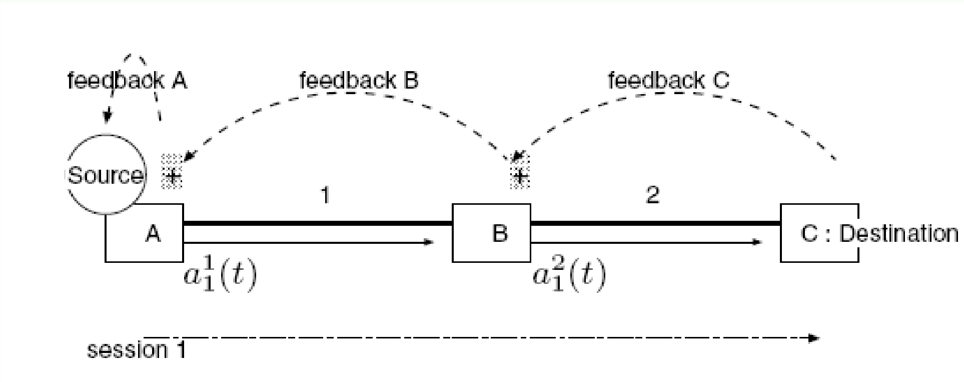
Example alternative: hop-by-hop congestion control



2-D Network



Occupied queue length at the bottleneck node ($D = 40$)



Source: Hop-by-hop Congestion Control over a Wireless Multi-hop Network
Yung Yi and Sanjay Shakkottai, IEEE Infocom 2004

Abandoning the “dumb network” philosophy might yield progress

Manual configurations underutilize resources

EXAMPLE: Military Manual Network Planning

	Channel 0	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5
LTS 0	BN C2/FTP @ 16.6kbps (2 Hop Net)					
LTS 4	BN SA (2 Hop Net)					
LTS 2	EPLRS Cordination, Position Location, and Net Monitoring					
LTS 6	BN Voice Nets 29.2kbps (2-hops)					
LTS 1	A CO VoIP 117kbps 16 @ 7.3kbps (simultaneous) per Radio (2 Hop Net) Anticiapted 13 talkers on CMD Net worst Case	B CO VoIP 117kbps 16 @ 7.3kbps (simultaneous) per Radio 2 Hop Net 13 talkers on CMD Net worst Case	C CO VoIP 117kbps 16 @ 7.3kbps (simultaneous) per Radio 2 Hop Net 13 talkers on CMD Net worst Case			
LTS 3						
LTS 5						
LTS 7						
	A Co	B Co	C Co			
	1 Bn					

EPLRS System:

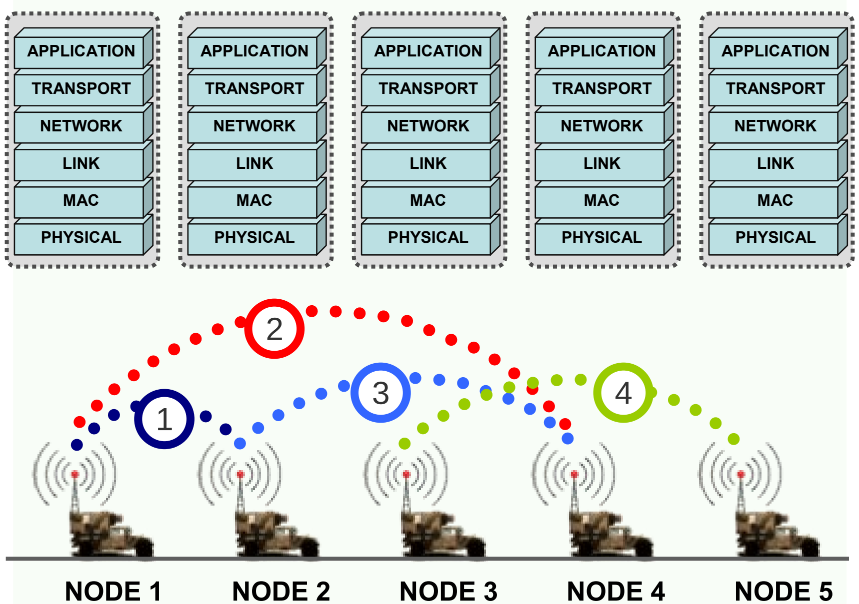
Manual methods of resource allocation are predictable yet inflexible

MANET resource allocation should be adaptive yet predictable

Independent layering impedes adaptation

Example: Uncoordinated Layering Leads To Uncoordinated Decisions

Thought Experiment: What to do when contention appears?

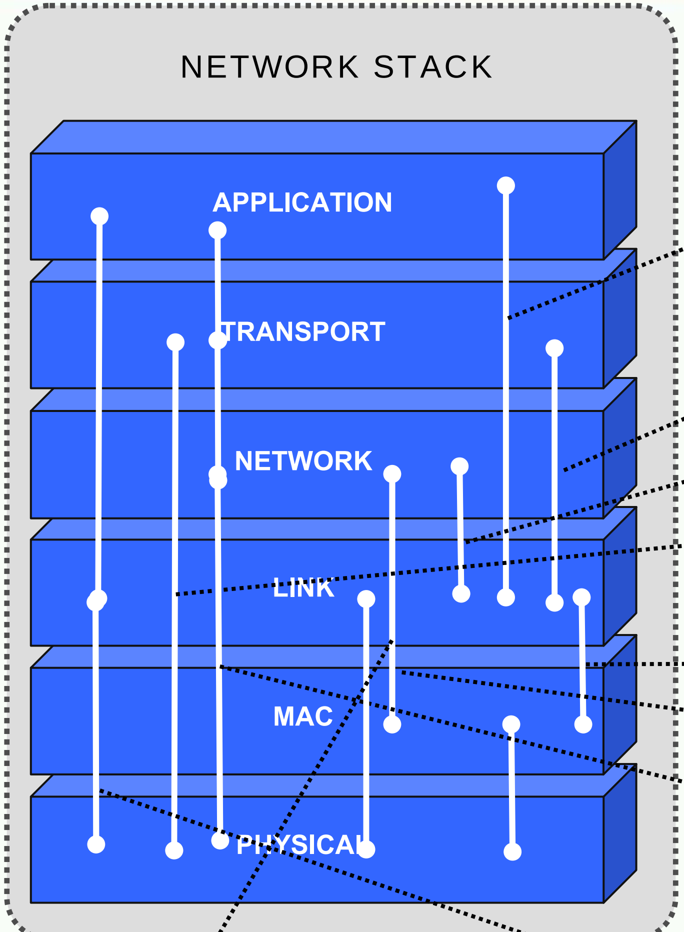


Layer/ Mechanism	Contention Mechanism	Potential Downside
Application	**Increase compression?**	**Processor Cycles**
QoS	**Eject a lower-priority session?**	**Other users affected**
Transport	**Reduce TCP Window Size?**	**Download takes longer**
Network/Routing	**Find an alternative route?**	**Other routes may be even worse**
MAC	**Allocate extra time slots; change channels?**	**Other users affected**
Physical	**Modify waveform parameters to increase capacity?**	**Interference with other users; LPD**

Without coordinated layers, there are too many independent answers even to simple questions

MANETs motivate new separations of concern & better coordination

Independent layering hampers performance



1000% gain in e2e SNR by joint channel coding and compression for video over wireless (Chen & Hsia 2004)

25% gain from adapting packet size to burst rate (NRL 2003)

30% improvement in percentage of packets not meeting a delay deadline through joint rate allocation and routing (Agarwal & Goldsmith 2004)

82% improvement in throughput per watt by joint TCP/PHY optimization (Chiang 2005)

175% multiuser diversity gain throughput if scheduling is based on link availability instead of FIFO (Shakkottai 2003)

30% gain in channel capacity via joint MAC/routing protocol design. 300% improvement for 802.11 (Goldsmith 2003)

50%-400% improvement in various delay, throughput, and efficiency metrics relative to min-hop routing (Pursley 2002)

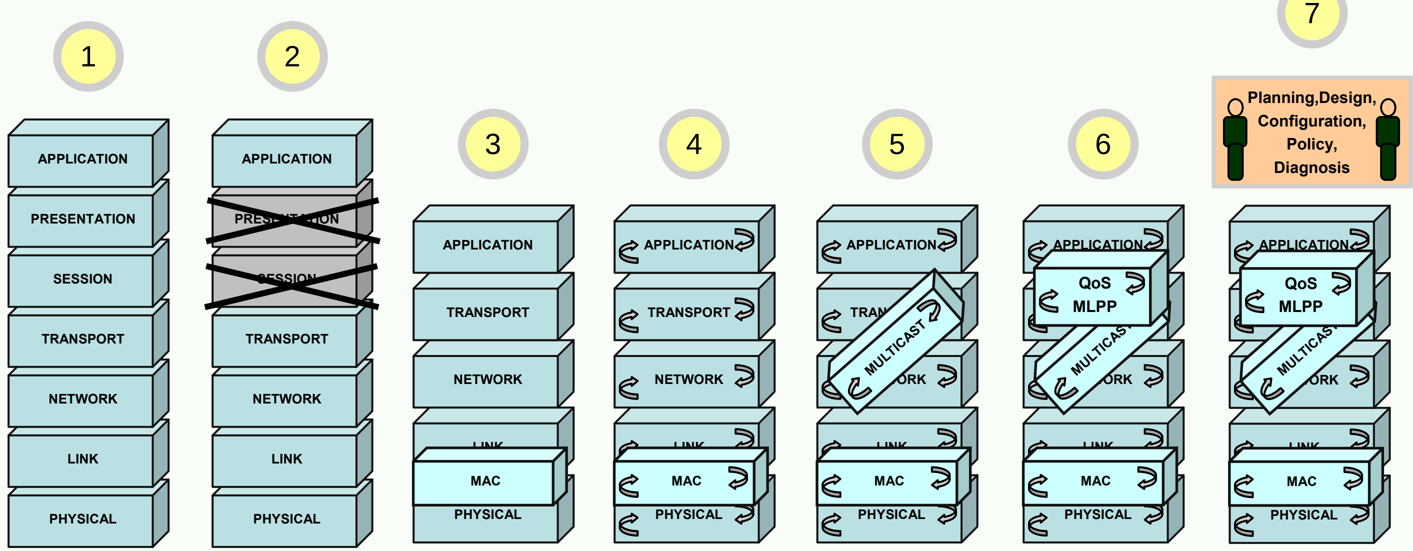
19%-50% improvement in multicast energy through network coding and joint network/MAC adaptation (Medard 2005)

50%-99% reduction in energy while meeting user requirements, depending on channel conditions, through joint application/link/physical design (Bougard et all 2004)

Cross-layer research is highlighting drawbacks of traditional layering

OSI model did not anticipate DoD MANETs

How did we get into this situation – and what do we need to do:



1. Abstract OSI network protocol model
2. As used in practice
3. As used in wireless networks
4. Tactical mobility requires adaptation at all layers
5. In contrast to Internet, multicast is the rule for DoD Manets, not the exception
6. Scarce spectrum and military emphasis on reliability force MLPP, QoS
7. Putting it all together requires lots of manual labor

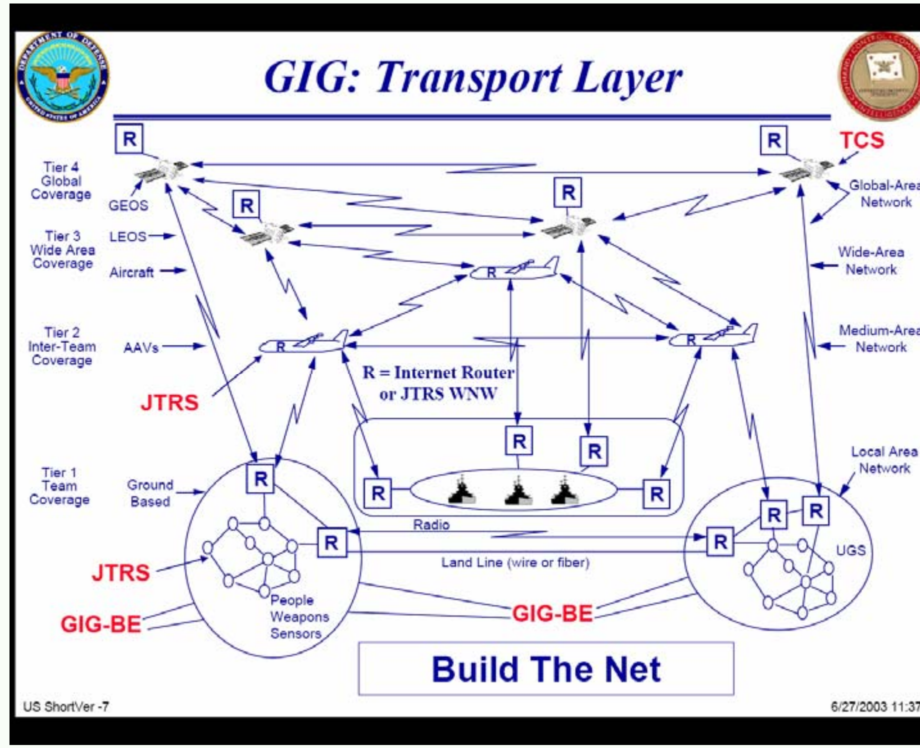
USER Concerns ≠ NETWORK Concerns	CAPACITY	DELAY	ENERGY	RELIABILITY
TRANSPORT	X	X		X
NETWORK		X		
LINK	X		X	X
MAC		X		X
PHY	X		X	

BOTTOM LINE:
It isn't clear why we went down this path in the first place, because the OSI layering doesn't modularize what the user cares about

We need a tabula-rasa rethinking of the network stack for DoD MANETs from the management and user perspectives

Beginning the process of innovation

- What has changed since MANET protocols were developed?
- What are the differences between wireless networks and the wired networks that most networking concepts target?
- Which architectural constraints are dictated by physics and which are merely self-imposed?
- Are problems really problems, or is there a perspective from which a problem conveys advantage?
- Have any new inventions or ideas arisen that can be leveraged?



We must first <u>recognize</u> limiting assumptions to overcome them

Deeply embedded design points to revisit

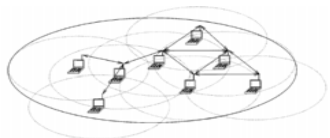
- **Network layers based on only two primitive operations (“copy” and “forward”)**
  - Existing protocols were designed memory and processing were scarce
- **Protocols based on concept of “link”**
  - Existing protocols were designed for wired networks
- **The Internet “dumb network” philosophy**
  - Wired networks are low-latency and reliable but MANETs are not
- **Point-to-point traffic emphasis**
  - DOD applications are often focused on multicast and allcast
- **Strict, traditional layering**
  - Existing separations were designed for non-dynamic nets
- **Opaque packets**
  - Existing protocols take little advantage of packet information content
- **Independent node operation**
  - Existing protocols tend toward asynchronous, unilateral primitives

Modern technology and the unique DOD context motivate new thinking

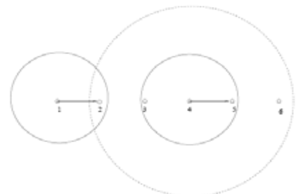
Where to Look for Breakthroughs

2000 2001 2002 2003 2004 2005 2006 2007 2008

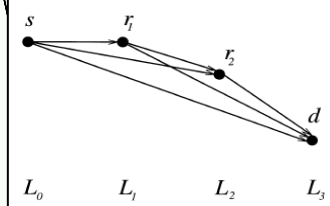
***A scare for MANETworking*.** (Gupta and Kumar 2000)



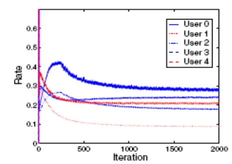
Topology and traffic patterns matter. (Li *et al* 2001)



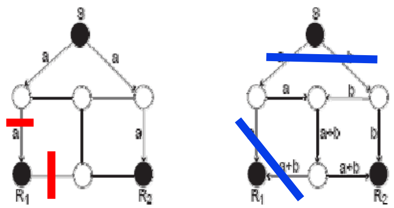
Multiuser coding matters. (Gupta and Kumar 2003)



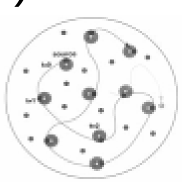
Cross-layering matters. (Chiang 2005, Lin and Shroff 2005)



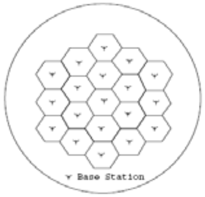
Network coding matters. (Ahlswede *et al* 2000)



Mobility matters. (Grossglauser and Tse 2001)



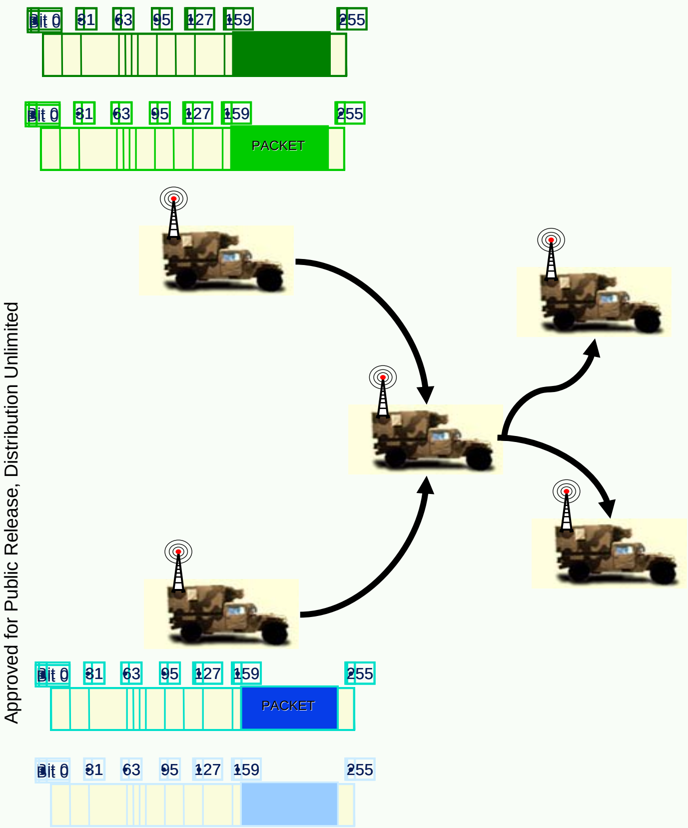
Hybrids and Hierarchy matter. (Liu *et al* 2003)



Network Theoreticians Point the Way Ahead

The traditional networking paradigm: networks that transport packets on links

Open in slideshow, then click to see animation



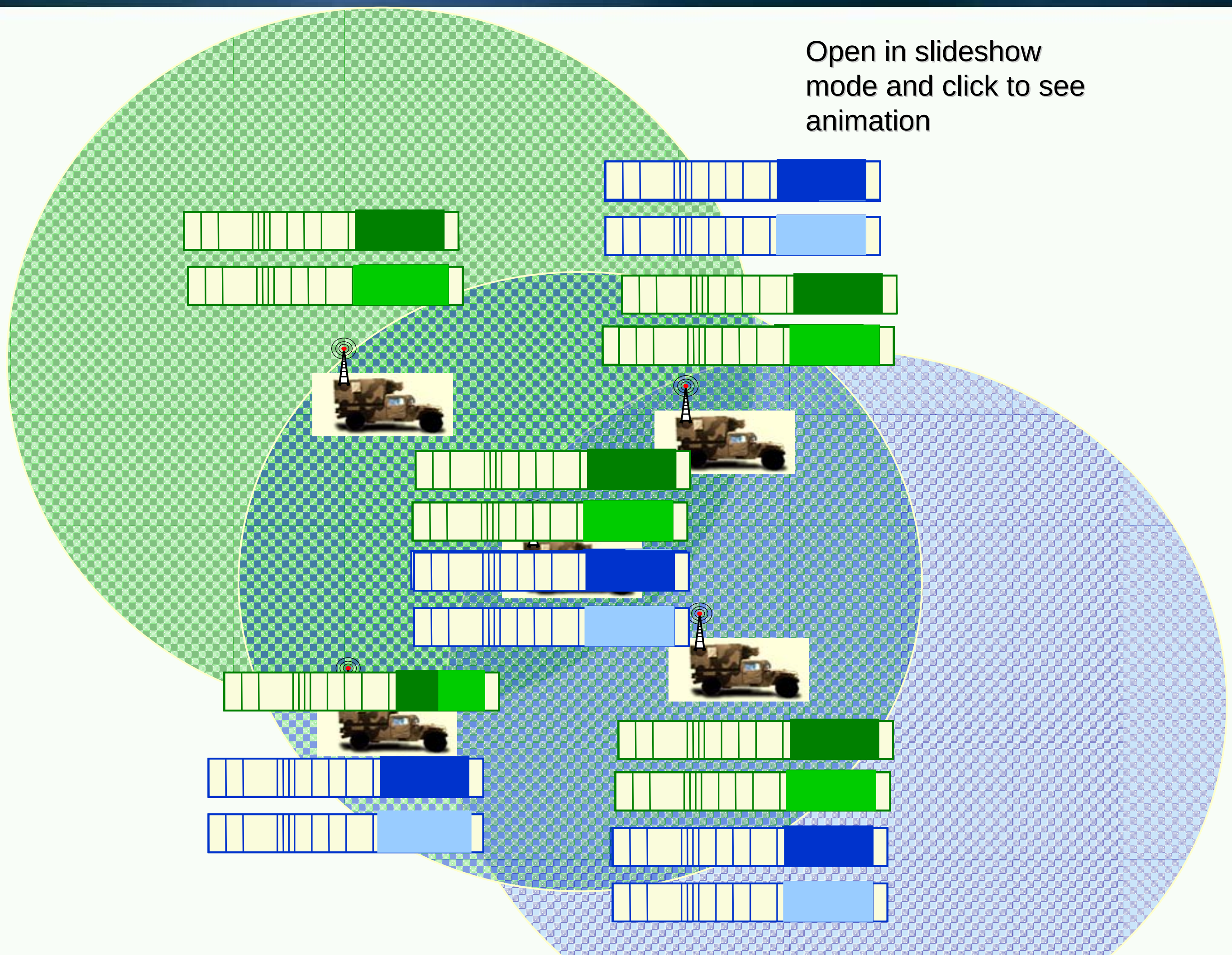
Key disadvantages of status quo

- **Link paradigm is unsuitable for tactical networks because of unicast (point-to-point) emphasis even though most tactical traffic is multicast or broadcast**
- **Insufficiently robust because of poor performance in lossy environments (forward error correction, erasure coding, retransmits operate independently)**
- **Poor performance in dense deployments (point-to-point model means that density cannot be exploited)**
- **Poor performance under heavy loads (no advantage to the fact that heavy loads transmit more information)**
- **Inefficient because a full transmit per packet per hop is required**

Key limitations: a conceptual model that does not exploit memory, processing, density, or traffic load

Potentially disruptive paradigm: networks diffuse information on hyperarcs

Open in slideshow mode and click to see animation



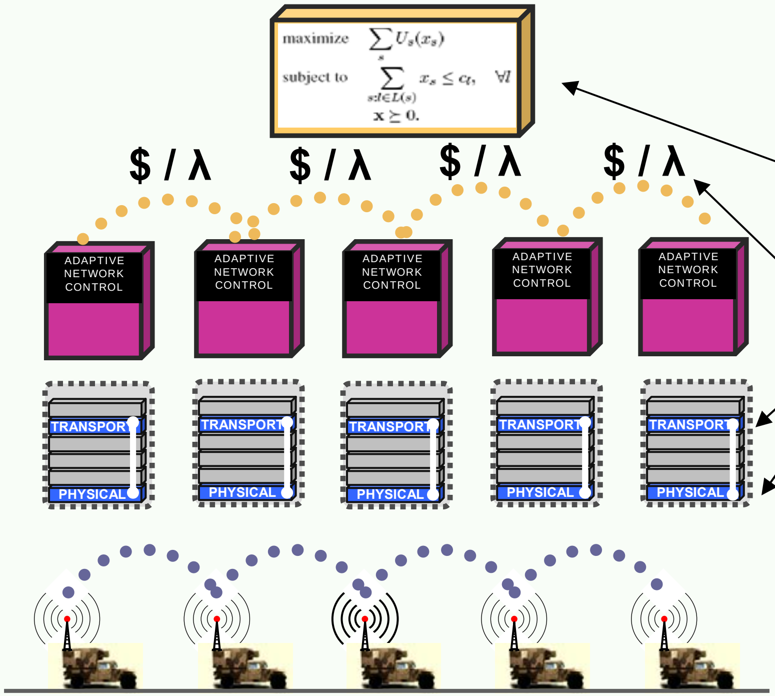
“Network coding” could become the central concept in future networking architectures

How might network coding affect MANETS?

- Network coding achieves strictly superior network throughput for multicast (very important to the DOD!)
- NC can exploit pre-positioned information to send multiple packets in 1 transmit
- NC might subsume forward error correction, erasure coding, multipath routing
- NC offers robustness in lossy situations
- NC can exploit dense deployments and heavy traffic loads
- NC can exploit hyperarcs instead of links
- NC can accommodate probabilistic delivery
- NC might reduce risk of eavesdropping a single link
- NC might subsume encryption
- NC allows certain P-time optimizations where ordinary multicast routing implies NP challenges

Network Coding: a "Swiss Army Knife" for networking (if we can make it work in practice!)

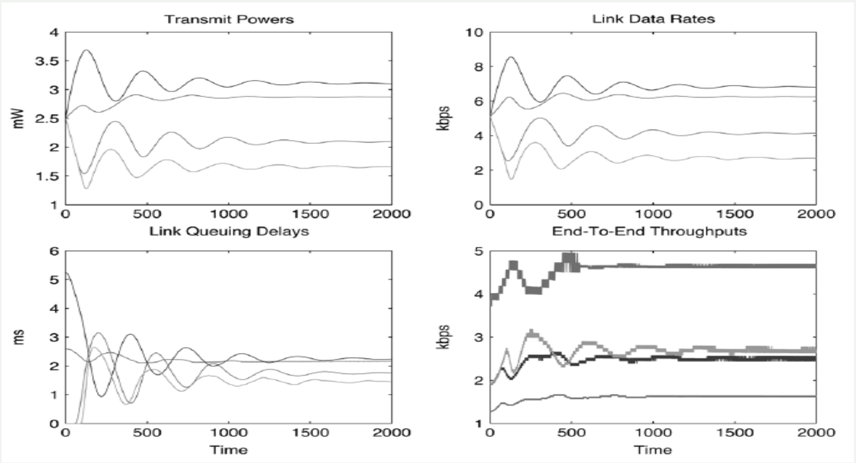
A potential paradigm shift in stack design



If implemented, even a narrow 2-way cross-layer coupling could nearly double end-to-end throughput

Emerging "Optimization Decomposition" method:

1. Formulate an optimization problem
2. Decompose optimization problem, if possible along horizontal (node) or vertical (network stack) lines such that each subproblem refers only to local variables
3. Couple the problems at runtime by passing joint "pricing" feedback appropriately



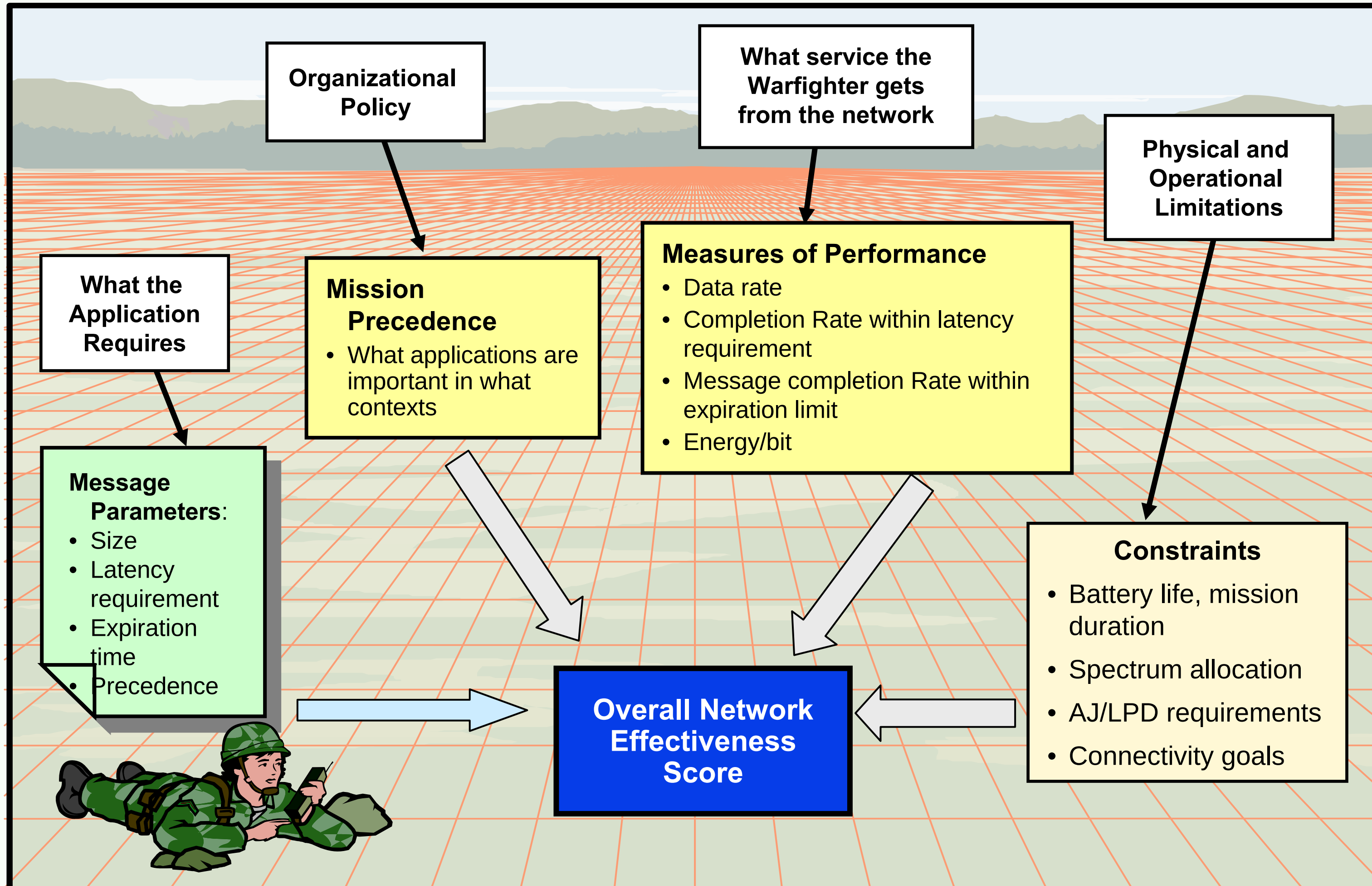
A theory for jointly optimizing transport and physical layers was shown to ***increase end-to-end throughput by 82% per watt of power*** transmitted (Chiang 2005)

Major technical approaches:

- ***Optimization-theoretic***: *distributed optimal solution algorithm (economic interpretation)*
- ***Game-theoretic***: *Nash equilibrium characterization and cooperative competition*

Optimization decomposition offers a formal basis for "stack" design

A potential paradigm shift in network evaluation

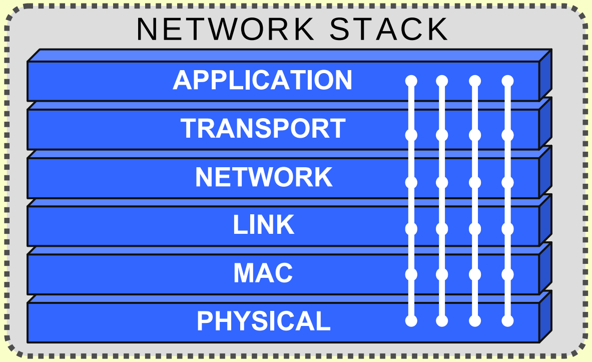


An end-user-oriented metric could drive network self-configuration

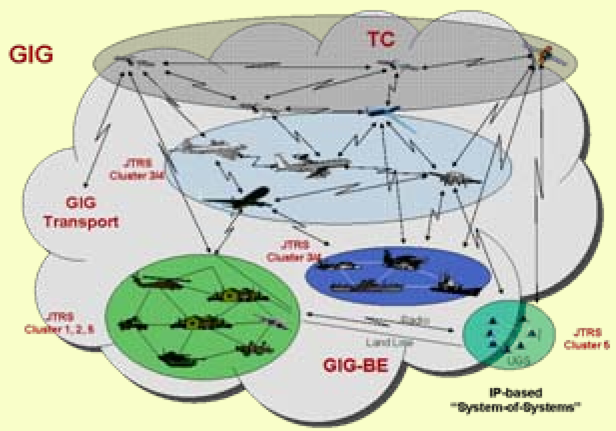
Key research issues

$$\begin{aligned}\text{maximize} \quad & \sum_s U_s(x_s, P_{e,s}) + \sum_j V_j(w_j) \\ \text{subject to} \quad & \mathbf{R}\mathbf{x} \preceq \mathbf{c}(\mathbf{w}, \mathbf{P}_e), \\ & \mathbf{x} \in C_1(\mathbf{P}_e) \bigcap C_2(\mathbf{F}), \\ & \mathbf{R} \in \mathcal{R}, \quad \mathbf{F} \in \mathcal{F}, \quad \mathbf{w} \in \mathcal{W}.\end{aligned}$$

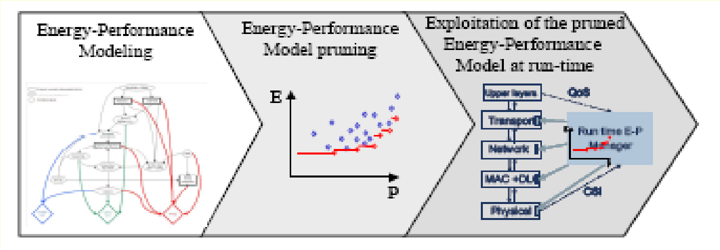
1. What is the proper metric/objective function for a general-purpose network?



2. What is the right layering? Can cross-layer optimizations be generalized without destroying the benefits of a layered architecture?



3. Are cross-layer approaches only good for optimizing “stovepipe” networks – or can they support general-purpose networks with widely varied applications?



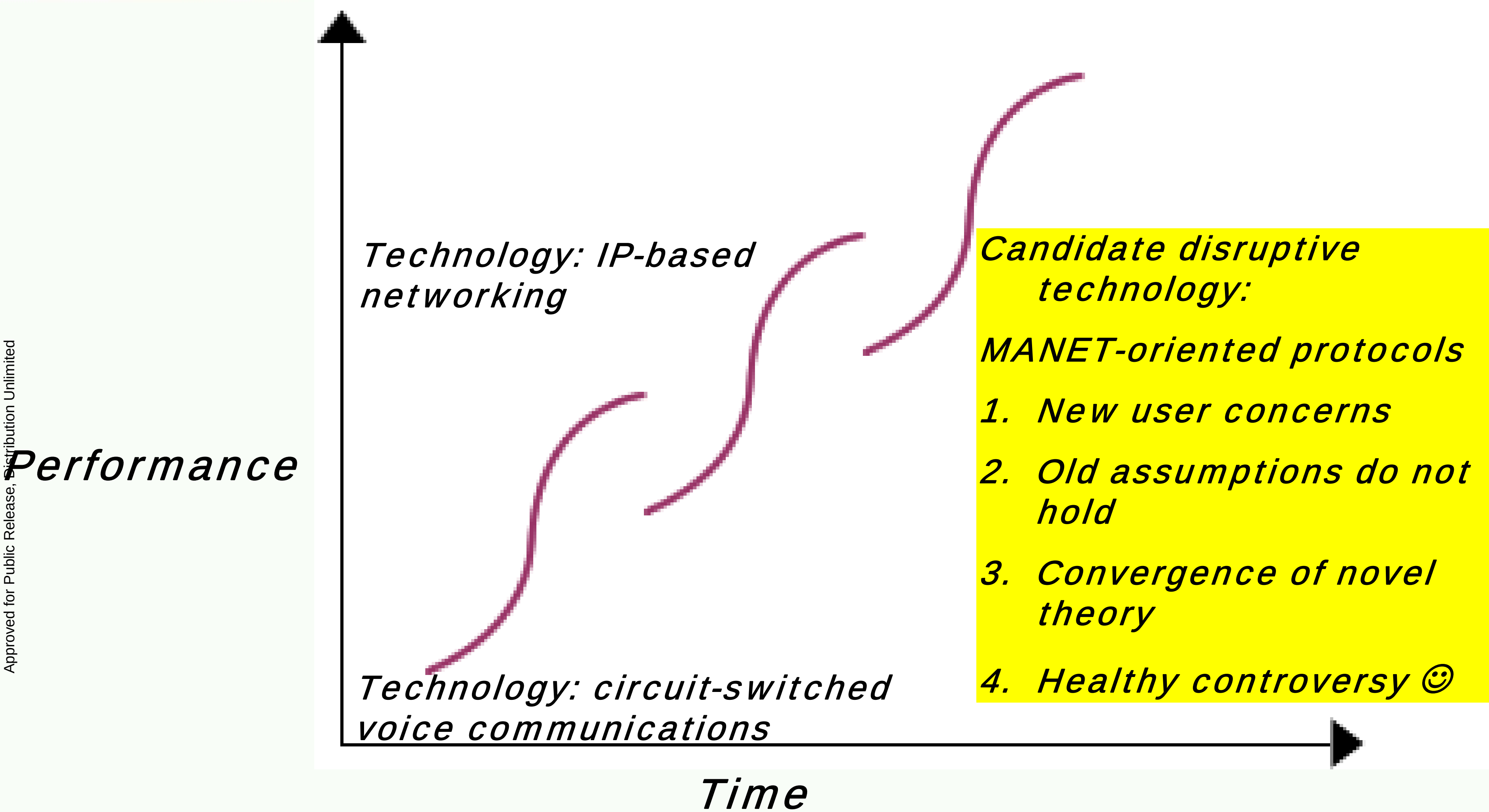
4. Can that objective function and network be tuned by a designer *at runtime* to effect trades in e.g. energy, capacity, delay? How much overhead exists and do the algorithms scale?

Exercise for the reader: revisit fundamental assumptions in problem dimensions other than performance (for example, security)

Control Based Tactical Networking Initiative

- **What**
  - Radical rethinking of the network stack and protocols
- **Why?**
  - Viability of historical & TCP/IP based approaches to tactical MANETworking are increasingly questioned
- **Why now?**
  - Network coding, Cross-layer design, distributed optimization, etc are emerging hot topics with powerful but scattered results, but nobody has ever put all the pieces together to see if they really work
- **Why DARPA?**
  - DARPA is interested in seeing if these high-risk/high-payoff ideas can be coherently assembled into a ***working system***

Summary: A superior MANET might disrupt even the IP protocol suite



Communications to the edge are necessary, so it would not be surprising if MANET protocols gradually displaced wired protocols