Communication Networks Academic Research Center: Quality of Information-Aware Networks for Tactical Applications

Tom La Porta – Director

Greg Cirincione, US-ARL Lead

Penn State – Prime

General Members

City University of New York
University of California, Davis
University of California, Santa Cruz
University of Southern California

Sub-Awardees

BBN

University of California, Riverside
Stanford
North Carolina State
Perform foundational, cross-cutting research on network science leading to:

– A fundamental understanding of the interplay and common underlying science among social/cognitive, information, and communications networks
– Determination of how processes and parameters in one network affect and are affected by those in other networks
– Prediction and control of the individual and composite behavior of these complex interacting networks

Resulting in:

– Optimized human performance in network-enabled warfare
– Greatly enhanced speed and precision for complex military operations

$\sim 160M$ for 10 years
Network Science CTA

Interdisciplinary Research Center (IRC) – led by BBN

• Ensure research directions of the three ARCs is focused on fundamental network science issues that are military relevant and achievable; perform basic research

Information Networks Academic Research Center (INARC) - UIUC

• To develop theories, experiments, measurements and metrics, and ultimately predictive models that will anticipate the behavior of information networks

Social and Cognitive Networks ARC (CNARC) - RPI

• To develop theory, measures and understanding of social and cognitive networks as applicable to both individual and organizational decision making of networked information systems

Two cross-cutting research thrusts

• Evolution and Dynamics of Integrated Networks (EDIN)
• TRUST in a decision making environments
CNARC Vision

Develop foundational techniques to model, analyze, predict and control the behavior of secure tactical communication networks as an enabler for information and command-and-control networks

Network is an information source
  – Understand and optimize operational information content capacity

Approach
  – Understand information needs (context, purpose)
  – Understand impact of network on information

Science
  – Characterize network data delivery in terms of impact on information
  – Characterize security properties in terms of impact on information
  – Develop models that jointly consider overall network impact on information

$35M for 10 years
Overall View of Information Flow

**Information Sources**
- Modality(ies)
- Location(s)
- Environmental Conditions
- Accuracy
- …

**Network**

**Data Delivery**
- Rate/capacity
- Transformations
- Latency
- Jitter
- …

**Security**
- Authentication
- Integrity
- Provenance
- …

**QoI degraded depending on network behavior and application needs**

**Information (Quality, Trust)**

-Algorithms trade off delivery, security to optimize OICC

Best possible information given sources and state of network
Overview of CNARC Work

- Modeling
  - Modeling Data Delivery (Theoretical Limits w.r.t. OICC)
  - Modeling Security (Fundamental Relationship to OICC)
- Networking Paradigms
- Theoretical Limits on Operational Information Content Capacity

Gain Insight into Models and Protocols
Close Performance Gap

- Protocol Analysis
  - Protocol Analysis (Structural Barriers to Achieving Limits)
  - Realistic Limits
  - Protocol Restructuring (Remove Barriers)
- Remove Bottlenecks
  - Isolate Protocol Limitation

Refine Models
Determine Limitations

Experimentation

Networking Paradigms

Realistic Limits

Protocol Restructuring (Remove Barriers)

Protocol Analysis (Structural Barriers to Achieving Limits)

Remove Bottlenecks
Isolate Protocol Limitation
C1: Modeling and Optimizing Operational Information Content Capacity (Govindan, USC)

C1.1 Characterizing and Optimizing QoI
- Lead: Govindan (USC)
- Bar-Noy (CUNY), Krishnamurthy (UCR), Neely (USC), La Porta (PSU)

C1.2 Modeling and Operational Information Content Capacity and Factors that Impact OICC
- Lead: Yener (PSU)
- La Porta (PSU), Ramanathan (BBN), Psounis (USC), Brass (CUNY)

C1.3 Market-Based Approaches for QoI Aware Networking Using Virtual Currencies
- Lead: Bar-Noy (CUNY)
- Goel (Stanford), Krishnamachari (USC)

C2: Networking Paradigms to Increase OICC (Cao, PSU)

C2.1 In-Network Storage: Characterizing the Benefits of Cooperative Caching
- Lead: G. Cao (PSU)
- Krishnamachari (USC), La Porta (PSU)

C2.2 Increasing the OICC of Disruption Tolerant Networks (DTN) Using Social and Information Links
- Lead: J.J. Garcia-Luna-Aceves (UCSC)
- G. Cao (PSU), Psounis (USC)

C2.3 Universal Scheduling
- Lead: Neely (USC)
- Krishnamahari (USC), Yener (PSU), La Porta (PSU)
Task C1.1: Characterizing and Optimizing Quality of Information (QoI) (USC, CUNY, UCR, PSU)

**Key Objectives:**
- Develop a multi-dimensional stochastic definition of QoI that captures trade-offs in terms of select intrinsic and contextual QoI attributes
- Formulate and solve optimization of QoI in terms of intrinsic and contextual QoI attributes (such as information credibility)

**Deliverables:**
- Q1: Characterization of impact of provenance on QoI
- Q2: Impact of corroboration on QoI
- Q4: QoI function for video in terms of accuracy, completeness, precision and timeliness (contextual)
- Q4: Stochastic optimization framework for QoI

**Impact:**
Will enable networks to adapt to maximize the information delivered to users based on the quality of information and the context of the decision

**Key Technical Innovations**
- Modeling and composing intrinsic QoI functions for several types of information and QoI attributes in forms that can lead to optimization of information quality
- Characterizing QoI as a stochastic measure on the network that considers complex attributes (i.e. information provenance) in the context of network performance
<table>
<thead>
<tr>
<th>Metric</th>
<th>General Definition</th>
<th>Image</th>
<th>Video</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QoI\text{_intrinsic}</strong></td>
<td>Correctness</td>
<td>Field of view, resolution</td>
<td></td>
<td>Truthfulness of report</td>
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<td></td>
<td>Closeness to ground truth</td>
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<td></td>
<td>Freshness</td>
<td>Age</td>
<td>Capture time</td>
<td></td>
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<tr>
<td></td>
<td>Precision</td>
<td>Extent of detail</td>
<td>Resolution</td>
<td>Resolution, Frame rate</td>
</tr>
<tr>
<td></td>
<td>Security</td>
<td>Protection of information and source</td>
<td>Provenance, authentication, integrity, non-repudiation, confidentiality</td>
<td></td>
</tr>
<tr>
<td><strong>QoI\text{_contextual}</strong></td>
<td>Accuracy</td>
<td>Resolution, field of view</td>
<td>Resolution, frame rate, field of view</td>
<td>Ability of reporter</td>
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<td></td>
<td>Specificity relative to need</td>
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<td></td>
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<tr>
<td></td>
<td>Timeliness</td>
<td>Availability</td>
<td>Delivery latency</td>
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<tr>
<td></td>
<td>Completeness</td>
<td>Total relevance to ground truth</td>
<td>Field of view</td>
<td>Field of view, frame rate</td>
</tr>
<tr>
<td></td>
<td>Credibility</td>
<td>Extent believable</td>
<td>Trust in information</td>
<td>Breadth of description</td>
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QoI Examples

To match a photo with a database of faces (match identity): 1 information bit (yes/no) per image of sufficient QoI

- Intrinsic metrics of interest: precision (bits/pixel), freshness (age of photo)
- Contextual metric of interest: completeness (field of view)
- Network metrics of interest: timeliness (latency), accuracy (bit errors)

Tradeoffs

- Compression will improve timeliness, but reduce precision
  • Perhaps lowering the 1 info bit/image
- Cropping an image may or may not reduce QoI (contextual)

QoI as a utility function

- Apply optimization techniques
  • Very difficult because on properties of such functions
- Sensitivity analysis needed
Task C1.2: Modeling Operational Information Content Capacity (OICC) and Factors that Impact OICC (PSU, USC, CUNY, BBN)

Key Objectives:
- Define/compute OICC in terms of information types/QoI
- Identify the fundamental limits of the OICC of realistic network tactical networks

Deliverables:
Q1: Symptotic expressions for capacity in grid networks with power law traffic
Q2: Computation of OICC for small networks
Q3: Transformation of symptotic rates to OICC
Q4: Joint OICC-QoI model

Impact:
Modeling the network as an information source that directly supports the information needs of users will provide design insights for maximizing relevant information delivered network-wide
Example

Goal: match a photo to a person in a database via an image within 1 second

Network supports 10 Mbps perfectly shared by two flows

QoI specification 0
- To get 1 bit of information, requires QoI: (1Mb data, T < 1 second)

QoI specification 1
- To get 0.5 bits of information, requires QoI: (100Kb data, T < 1 second)
Example 2

Goal: match a photo to a person in a database via an image within 1 second

Network supports 1.9 Mbps perfectly shared by two flows

QoI specification 0 and 1

- To get 1 bit of information, requires QoI: (1Mb data, T < 1 second)
Realistic Scaling: Asymptotic vs Symptotic

**Asymptotic scalability**
- Order of growth of some “metric” (e.g. capacity) as a function of some “parameter” (e.g. number of nodes)
- **Unqualified** verb: “Network X does not scale with increasing size”
- *Does not say at what size it actually fails, only says some such size exists*

**Symptotic or “real world” scalability**
- Operational performance with a real world, non-asymptotic view, constants and lower order terms not ignored
- Given a network with certain parameters, the number of nodes beyond which adequate performance cannot be achieved
- **Qualified** verb: “Network with parameter values \{P\} scales to 450 nodes”
- Consider specific topologies, flows, protocols and radio capabilities and the meaning of “adequate performance”

*led by Ram Ramanathan of BBN*
Motivation: Real-world questions

To how many nodes does my network scale?
- What is the meaning of such “non asymptotic scalability”

Can you give me an equation governing my network’s behavior?
- different topology “classes” (line, grid, clustered etc)
- different information exchanges (not just uniform)
- different radio parameters?
- Incorporating the effect of social and information network considerations

Which parameters should I try and change to increase my scalability?
- Which ones give me most bang for buck, which ones are a waste of time
- Sensitivity or “change impact” analysis

Gupta-Kumar says MANETs are not scalable. Should I stop funding all research in MANETs?
- Or features that don’t result in O(1) transport capacity (e.g. beamforming)?
Symptotic Scalability

Components of A:
- Data rate, number of relays, number of radios, frequencies, spatial reuse etc.

Components of U:
- Traffic distribution, Routing overhead, MAC/link overhead, etc.

\[ R = A - \psi - (1 + \gamma_j) \sum U^j \]
- For each component \( j \) (overhead, traffic, etc)
- \( \gamma_j \) = contention factor, proportional to neighbor size
- \( \psi \) = fixed factor capacity loss

Symptotic scalability = \( n \) iff \( R(n) > 0 \), and \( R(>n) \leq 0 \)
Transforming Symptotics into OICC

\[ R = A - \psi - (1 + \gamma) \sum_j \zeta X/\alpha, \quad X/\alpha = QFR(q_j) \]

\( X \) is the offered rate of information bits
\( \alpha \) is the bits of information per bit of data

- **Challenges:**
  - Rationalizing units – bits of information with data bits
  - Determining \( \alpha \)
  - Handling non-binary information

- **Symptotic scaling (for a line network)**

\[
N \approx \frac{r}{3QRF(q_j)d \left(1 - \frac{1}{1-e} \right) + 5Q}
\]

\( N = \) number of nodes, \( r = \) rate of network, \( d = \) duty cycle, \( e = \) error rate, \( Q = \) routing overhead
Instantiating for a line network:

\( r(ate)=2 \text{ Mbps}, d(uty \ cycle)=100\%, \ e(rror \ rate)=0.05 \text{ and } Q=260\text{B every 5 seconds} \)

\[ QRF(q) = \begin{cases} 
10 \text{ kbps for } P \leq 24 \text{ Mpixel} \\
20 \text{ Kbps for } 24 < P \leq 48 \text{ Mpixel} \\
30 \text{ Kbps for } P > 48 \text{ Mpixel} 
\end{cases} \]

If \( P = 20 \text{ Mpixel} \), network can support 59 nodes
If \( P = 25 \text{ Mpixel} \), network can support 21 nodes

\[ N \approx \frac{r}{3QRF(q_j)d} \frac{1}{1-e} + 5Q \]
Task C1.3: Market-Based Approaches for QoI-ware
Network Using Virtual Currencies (CUNY, USC)

**Key Objectives:**
- Develop models of market environments for tactical networks to enable efficient market-based solutions to apply
- Characterize benefits of market-based solutions in different shared environments

**Deliverables:**
- Q1: Formulation of virtual currency framework for OICC optimization
- Q2: Characterization of credit network properties with respect to QoI
- Q3: Consider selfish users in a market and determine existence of Nash equilibrium
- Q4: Formal analysis of parameter space for credit networks

**Impact:**
Enables rich set of market based tools to be commonly applied across all genre of network

**Key Technical Innovations**
- Consideration of resource sharing in tactical networks as a market environment (joint with IRC)
- Maximizing QoI within a budget of shared discrete resources (joint with SCNARC)
- Maximization of QoI with continuous optimization of fine-grained resources
- Application of credit networks to bound risks of resource sharing (joint with IRC)
Task C2.1: In-Network Storage: Characterizing the Benefits of QoI-Aware Cooperative Caching (PSU, USC)

Key Objectives:

– Increase OICC by reducing bandwidth requirements and increasing QoI by making cache management more efficient and QoI-aware
– Understand impact of information links on cooperative caching performance

Deliverables:

Q1: Characterize impact of mobility on caching performance
Q2: Characterize QoI tradeoffs for cache management
Q3: Performance bounds of cache performance considering communities of interest
Q4: Obtain performance bounds on cooperative caching considering QoI-aware algorithms

Impact:

– Knowledge of underlying information network, mobility characteristics, and QoI requirements will provide 50%-200% gains in operational information content capacity

Key Technical Innovations

– Cache management (information replacement and admission) based on QoI metrics (timeliness, availability, freshness, accuracy)
– Impact of mobility on caching strategies and performance
– Explicit consideration of information links (joint with INARC) and social relationships to drive cache management
– Evaluation on mobile phone platforms
Task C2.2: Increasing the OICC of Disruption Tolerant Networks (DTNs) Using Social and Information Links (PSU, USC, UCSC)

Key Objectives:
- Develop replica placement strategies that are highly efficient to improve the OICC of a network by leveraging knowledge of node and information relationships
- Determine strategies and tradeoffs for sharing information to enable replica replacement algorithms

Deliverables:
Q2: Characterize impact of contact patterns on replica placement
Q3: Define control plane of DTN for dissemination of social and information links
Q4: Characterize impact of node relationships
Q4: Determine bounds on the benefits of DTNs given storage bounds and knowledge of social/information links

Impact:
- Improve OICC of a tactical network by better using node storage and mobility to deliver the best information to decision makers

Key Technical Innovations
- Use of contact patterns (not statistics), interests (jointly with INARC) and relationships to locate replicas for data delivery
- Explicit consideration of overhead required to disseminate information amongst nodes
- Introduction of contextual database and low-overhead techniques for updating information
- Validation using tactical mobility traces generated by EDIN
Task C2.3: Universal Scheduling (PSU, USC)

Key Objectives:
- Develop scheduling algorithms that are provably robust to time-varying traffic, channel, and mobility processes considering QoI
- Apply several theories to scheduling framework to optimize OICC in realizable manner

Deliverables:
Q1: Contingency-based scheduling algorithm
Q2: Characterize history-based QoI
Q3: Characterize impact of limited information of tactical networks (e.g., mobility model) on universal scheduling
Q4: Integrate LIFO scheduling with mobility to improve OICC

Impact:
Provides a theory of scheduling in networks that is robust in terms of events, traffic, and QoI metrics

Key Technical Innovations
- Develop a “universal scheduling” theory for QoI that provably learns efficient decisions without knowing the future
- Apply utility maximization and Lyapunov optimization techniques to tactical mobile networks
- Integrate place-holder bit theory and LIFO scheduling into backpressure algorithms
**Key Objectives:**
- Develop models statistically equivalent to military movements
- Generate realistic traces which may be used throughout NS-CTA for evaluation

**Deliverables:**
Q1: Initial hidden Markov Models of generated scenarios
Q2: Traces of pincer movement and repeated traversal under several scenarios
Q3: Initial parameterized models including information overlays
Q4: Validation of models against further traces

**Impact:**
- Mathematical models for realistic military mobility patterns available for insight into key metrics driving network evolution
Summary

NS-CTA program ongoing
– collaborative efforts starting between all centers

Research Challenges
– integration and co-evolution of multiple genres of network