

Self-Optimization in Future Hybrid Networks

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Abstract—Military networks have a huge range of performance requirements, many of which are continually changing in the face of evolving operations. In such circumstances, ensuring that network performance is adequate, let alone optimal, is a significant and ever more challenging management burden. The panacea to this problem is autonomous self-optimizing networks that continually adapt themselves as situations change. This work looks at some of the benefits and challenges of attempting to design such networks to address this uniquely military problem. Specifically we investigated simplified analytical problems on link state routing protocols, as a first step to gain insight that is more widely applicable. A crucial component of such protocols is the dissemination process by which links periodically broadcast their current state across the network. While this allows nodes to correctly compute routes, it also incurs significant control overhead that diminishes the effective capacity of the network. In this work, we study how nodes can make the best routing decisions as a fundamental tradeoff between link state dissemination cost and the accuracy of route computation. Using a Markovian model for link dynamics and a parameterized model for the state dissemination process, we investigate the impact of selectively sending link state updates on the packet delivery ratio performance in a lightly loaded dynamic network. Our analysis reveals the optimal state dissemination strategy that maximizes the packet delivery ratio given a total budget for the network-wide link state update rate, under sparse information flows. We instantiate our results explicitly for a simple path disjoint topology.

Keywords—*Self-Optimization, Routing Performance, Link State Dissemination, Network Management*

I. INTRODUCTION

Military network management is becoming an increasingly complex and challenging problem due to the volume of data needed, the huge parameter space to configure, and the interdependence of multiple locations, domains and coalition partners. Military networked systems, even those implementing established protocols, depend on a host of parameters. These parameters are nearly always set manually – e.g. during manufacture, system integration, deployment, or even during operations.

We posit that military networks significantly under perform as the parameter set is almost always non-optimal for the current (and changing) operating environment. Parameter tuning is an inexact science, often falling back to arbitrary defaults, values determined from other, possibly inapplicable, operational or simulation scenarios.

Rigorous parameter tuning relies on two kinds of information: Information about the state of the network; and Information about the desired performance objectives. Occasionally both of these types of information are immediately available, but more generally it is not directly observable, frequently obtained from a lower layer protocol that operates in a resource-constrained setting, or higher level policy or doctrine. Perfect information allows for optimal configuration, but usually there is some cost of obtaining the information. When this cost directly impacts network performance it is called overhead, and there is the familiar overhead versus performance trade-off. More generally we can say that the cost of the observation itself has to be taken into account in the optimization process.

The vision of this work is therefore to develop a general approach to real-time automatic network parameter tuning, based on the trade-off between the overhead in obtaining (observing) incomplete state information and the usefulness of that information to move the system closer to optimal. The motivation is to achieve the following benefits:

- Guaranteed continuous network optimization
- Resilience and robustness to network redeployment and network attack
- Operational cost savings – reduced management burden

Although these benefits might also apply to civil and commercial network operators, military networks face additional challenges. So for example a civil cellular or WiFi operator many experience variability in demand; however a military network may *also* be continuously evolving (e.g. during force buildup), need to accommodate heterogeneous (i.e. mission dependent) performance goals, and need to dynamically interwork numerous different networking technologies across domains. Cross domain interworking in particular, which we colloquially refer to as hybrid networking, is an ever-growing reality in the military context where multi-party coalitions are continuously forming and changing. Hybrid networks bring added challenges about constraints on control, restrictions on information that can be shared across boundaries, and impacts on performance due to inappropriate configuration. In such situations it is even more vital to understand the value of information being shared and how it can be used to allow complex networks to adapt.

The first step to achieving these benefits is to delineate the fundamental theory of the value of (partial) information about network state, and its practical usefulness. Secondly to characterize explicit ways of aggregating or selecting state

information in space and time so as to meet the theoretical limits of the tradeoff between the state gathering versus network performance. Thirdly to develop protocols & algorithm based on this understanding for a practical implementation of “self-optimization” in a dynamic, distributed, heterogeneous environment.

This paper outlines contributions to the first of these steps - characterizing the value of partial information in a theoretical framework. To gain insight we begin with simplified and abstract network topologies that capture the essence of the problem. Namely that it is impractical to obtain complete information, so given that only a subset of the information is to be collected, what are the implications of different accumulation strategies across the dimensions of scope, space, time and accuracy? In order to concentrate purely on the effects of state accumulation, we arbitrarily fix the network performance objective to be optimized, choosing routing performance as the exemplar.

The following sections of this paper summarize a number of related work strands that we undertook to investigate these issues. As such, this paper should be considered as an overview of how we have approached these questions from a number of different perspectives and provide the overall context. Although the work threads are highly correlated, there are slight variations in the setups of models/simulations¹, but space limitations prevent an in-depth explanation of many of the parameters. The interested reader is therefore directed to our related work [1], [2], [6] for more detailed explanations.

II. STRATEGIES FOR GATHERING NETWORK STATE

A. Link state probing models

In this section we examine the optimal dissemination and usage of *network state information* for routing in dynamic wireless networks, an area of research that has received copious attention in the past two decades. However, most of this work has been heuristic and there has almost been no systematic analysis to understand the effect of partial network state information under a resource constraint on routing performance—i.e., on how to gather that partial state and how to best use it for routing. This is a hard problem to solve in its full generality on a large complex network. In this section, we report results from our preliminary analysis of this problem for simple settings, which yields important insight that may be useful in more general networks and routing scenarios.

Broadly speaking, routing algorithms are classified as reactive or on-demand (e.g., AODV, DSR, etc.), where a source node probes the status of the current network topology just before it decides to send data; or proactive (e.g., OLSR, HSLS, etc.) where a node detects and floods any changes in its neighborhood topology through the network as link state updates (LSUs). While flooding topology changes instantly throughout the network keeps all nodes well-informed, it also consumes precious network resources such as bandwidth and also causes network congestion. There have been several proposals to reduce this control overhead by intelligently

controlling the scope and frequency of LSUs, e.g., in HSLS [7]. While these schemes intelligently disseminate the current state of neighboring links, they do not leverage any additional advantage obtainable by learning and predicting stochastic link dynamics that may result from space-time correlated mobility and fading, or other systematic effects.

A simple yet popular model for link dynamics that captures temporal correlations is the two-state (p, q) discrete-time Markovian model. In this model, at each instant a link may be on (or off), and the probability it is off (or on) in the next time instant is q (or p), respectively. The $p \gg q$ regime pertains to the network being more stable (i.e., links remain *up* more often than *down*), whereas the $q \gg p$ regime is when the links are rarely found up. Practical network dynamics (resulting from wireless mobility for instance) also suggests $p+q < 1$, a stable regime where a link is more likely to retain its state in the next time slot than to switch its state. So, we will restrict our attention primarily to this regime.

These Markovian dynamics allows one to probabilistically forward project the state of any link t time units later, given the current state of that link. This model is more powerful than the memoryless link-state model, e.g., when $p+q=1$, which would pertain to each link being off (or on) independent of one another with probability q (or p). Instead, we assume a spatially-homogenous link state dynamics, i.e., each link in the network is modeled using the same values of p and q . While this assumption may seem too restrictive for realistic scenarios, it is an important first step towards gaining valuable insights into the problem.

The core problem of interest is the following: if the underlying graph of the dynamic network is known and each link is obeying the Markov (p, q) model, then at what rate should each link’s state be disseminated through the network in order to achieve high packet delivery ratios and low end-to-end latency? We assume that the state dissemination occurs over a low-data rate connected network (i.e. a signaling channel). Although this is a simplification for initial investigation, in some situations it may in fact be a reasonable assumption, for example where nodes are equipped with high-rate yet intermittently connected radios (802.11n) as well as low-rate yet always connected radios (cellular), or other situations with a wide area signaling channel.

Recently, we studied a source-based “sampling” (or on-demand) variant of the problem where the underlying graph has N edge-disjoint paths between a source and a destination, with each path being L hops in length. Additionally, a budget of m link state samples was set, to answer the question of which m links should be sampled, in order to obtain the most useful network topology information? [1] First, we analytically studied the sampling problem in a single snapshot of time, and showed that distributing the available budget of m links into sampling contiguous links on the N paths closest to the source is always better, in terms of lowering the expected routing time (ERT), as compared to sampling links farther away from the source (at least for this topology). Additionally, for this idealized setting, depth-first sampling yields lower average latency when $p \gg q$, and breadth-first sampling yields lower average latency when $p \ll q$, with an intermediate sampling

¹ For example performance objectives, specific topologies etc

strategy being optimal elsewhere. This has been illustrated in Fig. 1 for different sampling budgets.

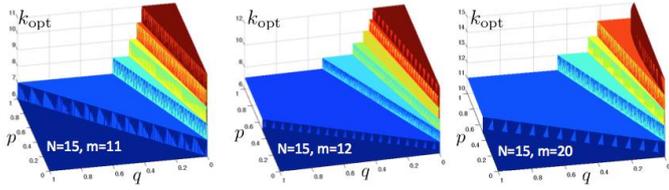


Fig. 1. Depth-first versus Breadth-first sampling of links in a $N=15$ edge-disjoint $L=2$ hop network topology

For networks with paths longer than $L=2$ hops, we numerically studied optimal probing allocations. Three hybrid sampling strategies were considered (see h1, h2 and h3 in TABLE I.), which transition progressively from breadth to depth first. The table shows how a budget of $m = 12$ links was distributed on the $N = L = 6$ network for each of the five different strategies.

TABLE I. STRATEGIES USED

Strategy	Path depth %	Links sampled on 6x6 network
Breadth	33	{2, 2, 2, 2, 2, 2}
h1	50	{3, 3, 3, 3, 0, 0}
h2	67	{4, 4, 4, 0, 0, 0}
h3	83	{5, 5, 0, 0, 0, 0} + 2 random
Depth	100	{6, 6, 0, 0, 0, 0}

In congruence to the analytical results for the $N>1, L=2$ case, numerical results on the larger network shows that (see Fig. 2) that there are large portions of the (p, q) space where the hybrid sampling strategies are optimal. Broadly, the larger the ratio of p/q (the more stable and connected the network), the more *depth-first* the sampling strategy should be. By contrast, a breadth first strategy is more likely to be optimal when networks are unstable, have a large number of disjoint paths or overhead allows a sampling of a larger fraction of links.

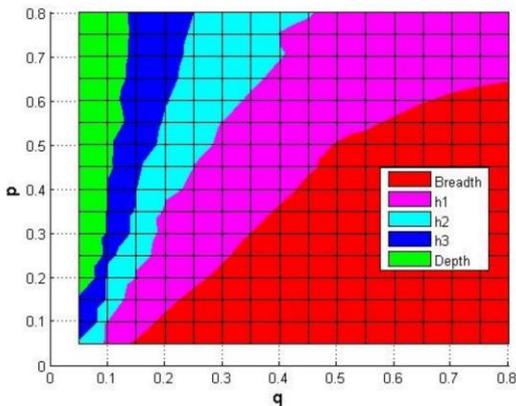


Fig. 2. Regions on (p, q) space where each of the five strategies is optimal in the $N = L = 6$ network ($m=12$)

In addition to *one-shot spatial sampling* methods illustrated so far, we studied the case where the sampling budget can be spent over multiple (typically, consecutive) time slots, i.e., as

the network evolves in time. We started with exploring various heuristic spatio-temporal strategies across a range of network shapes, sizes and stabilities [2] including:

1. Depth-first strategies: Sample k complete paths every k -th timeslot (for $k = \{1, 2, 3, 4, 5, 6\}$)
2. Breadth first strategies: Sample all links within k hops every k -th timeslot (for $k = \{1, 2, 3, 4, 5, 6\}$)
3. Hybrid and Randomized strategies
4. Trading sampling in distance, time and accuracy

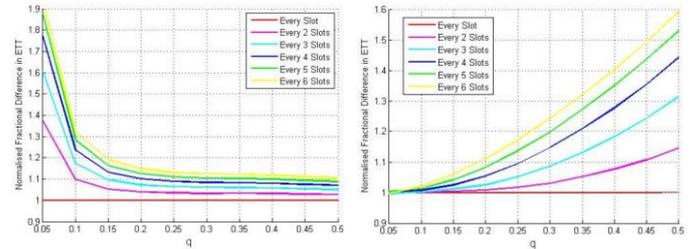


Fig. 3. Temporal sampling strategies in a $N = L = 6$ network ($p = 0.5$): (a) Depth first; and (b) Breadth-first

We concluded from Fig. 3 and [2] that it is never beneficial to delay gathering state information to perform synchronized sampling i.e. you should not amortize the cost of link sampling. Another key point is that the choice of strategy is fundamentally dependent on circumstances and network conditions. There is no one strategy that is dominant, and so a robust military routing protocol needs to adapt its sampling strategy dynamically based on the discovered network core. The best strategies are hybrid strategies that have a core “basic” component, but are designed to augment and skew the sampling beyond their “primarily favored” set of links.

Our most recent work looks towards implementing abstractions of actual protocols with state information being forwarded in a hop by hop approach. So for example we have investigated a conceptually OLSR like strategy that broadcasts information about two hop neighbors. Whereas OLSR broadcasts this information to the entire network², we have compared the performance impact of a similar family strategies that broadcasts information but only to a finite hop count. As the amount of network overhead incurred scales polynomially with broadcast hop count, we can show that for a fixed network overhead, reducing the overall transmission range can potentially increase performance as networks scale.

B. Dissemination based approaches

While the source-based sampling methods presented thus far have yielded significant insight into the value of link state information for the purpose of efficient routing in dynamic networks, in order to be useful in most common settings, these insights need to be adapted to dissemination-based state sharing approaches. Since a single LSU may affect multiple source-destination pairs, the overall performance of the

² Actually with an optimisation to remove redundant transmissions

network is expected to be dependent on the rates of dissemination for each link in the network.

Abouzeid et al [3] attempted to solve this problem for a random network with independent up-down dynamic link states using tools from Information Theory, in particular, Rate Distortion theory [4]. Rate Distortion is a useful technique that allows us to characterize the information content of network state information as it is disseminated. Formulating a network state dissemination problem in this way therefore mathematically determines upper and lower bounds on what will ever be possible, and then approach those bounds via protocol development. However, there are several issues in the Abouzeid analysis that limits its current usefulness. One underlying assumption in Shannon’s rate-distortion function—to characterize the optimal compressibility of a random source (in this case, the random source is the link up-down process)—is availability of a long sequence of source symbols (which in this case would involve looking ahead into future link dynamics), which isn’t useful because the link state information must be sent instantaneously for it to be most useful for routing. However, a more applicable tool is Causal Rate Distortion Theory [8] a relatively fledgling field of active research—where looking ahead into the future symbols is not permitted, i.e., the source (the link) and the decoder (the routing source node that uses the link state information) must use a causal encoder-decoder pair. The second deficiency with the analysis in [3] is the evaluation of the effective network transport capacity by subtracting the protocol overhead (estimated from rate distortion theory) from the throughput capacity of a static network [5], without specifying an actual protocol that achieves such performance.

In this paper, instead of applying information theoretic tools, we use estimation theory techniques to characterize the optimal spatio-temporal distribution of link state updates across the network, using a local tunable probabilistic link state dissemination rule, and a maximum-a-posteriori-probability (MAP) aggregation of the link state information at the source-routing node. The performance goal of this approach is to now modified to be optimal spatial distribution of transmit power for LSUs (given an overall mean power budget) and a local update rule (at the links whose state is being disseminated) such that, a source node (or a set of source nodes) can achieve the best routing performance (packet delivery ratio in the metric we analyze), with a given time-averaged power consumption across the entire network for sending link state updates.

We have investigated a simple probabilistic rule for Markov (p, q) link dynamics, which works as follows. In every time step, a link uses the binary-valued triplet $(X_{\text{last}}, X_{t-1}, X_t)$ to choose a probability $P_{X_{\text{last}}, X_{t-1}, X_t}$ with which it decides to send an update of the current state X_t of the link. X_{t-1} is the state of the link in the previous time, and X_{last} is the last update about this link’s state that was disseminated. These 8 probabilities $(P_{000}, P_{001}, \dots, P_{111})$ determine the total power used for the updates (assuming that the “link up” and “link down” updates consume an equal amount of energy). Given a total LSU power budget across the network, these probability-octets are optimally chosen for each link (over the entire network)—

using a simulated annealing optimization routine—such that the MAP estimate of the maximum-probability-of-delivery-ratio (PDR) path yields the highest expected network-wide PDR. We have done preliminary investigation of this optimal rate profile for the disjointed path topology with a single flow, and work is underway to extend our results to more complicated network topologies (such as a square grid) and a sparse set of (multiple) independent data flows. Our preliminary results show that for the probability of delivery ratio (PDR) metric, under a total dissemination rate constraint, allocating that rate in a pure depth-first fashion (i.e., giving the maximum update rate one path needs to the first path, and giving the left over rate to the next path, and so on) seems optimal. Indeed, for time-independent on-off dynamics ($p + q = 1$), and for the two path case, we have been able to show analytically that this depth-first strategy is optimal. Furthermore, for time-independent dynamics, we proved that the available LSU rate for a link should be used to split between two probabilistic update parameters P_0 and P_1 , the probabilities of sending a LSU given the link is 0 or 1 in the current time slot, respectively. If $p > q$, the P_0 driven update rate budget of a link should be filled first, and give the rest to the P_1 driven rate. For time-dependent Markovian dynamics, our simulated annealing optimization – whose initial results evidence depth-first rate allocation to be optimal for PDR maximization, also tells us which of the eight probabilities $(P_{000}, P_{001}, \dots, P_{111})$ to allocate and in what order, which easily turns into a link-state-routing protocol with partial state.

III. HYBRID AND HETEROGENEOUS NETWORKS

In the previous section, we considered stateful point-point routing and the challenge of determining the optimal rates at which to share state information – information that necessarily utilizes bandwidth that could otherwise be used for data packet transmission. Our previous research [6] has shown that there are network operating regimes where links are so ephemeral (e.g., in highly mobile scenarios) that traditional stateful approaches perform quite poorly, since link state is obsolete by the time it is received. In this case, packet flooding performs better the stateful approaches. Our research in considered the case that all network nodes are homogeneous and have identical mobility characteristics. In this section, we consider the heterogeneous case that some nodes may be stationary (and hence stateful approaches are preferred) while others may be highly mobile. In this case, we consider the question of determining which nodes should perform stateful routing, and which should perform flooding.

To make this problem concrete, let us consider a 1152-node network, where nodes are arranged in a 24x48 grid. Nodes are divided into 3 regions: a static region to the right and left, and a central mobile region where nodes move equi-probably up, down, left, or right within the central 24x16 region every 50 transmission time slots. Traffic is uniformly distributed between each source-destination pair. Each node has a finite buffer of 300 packets and nodes can communicate with nearest neighbors on grid points, only using directional transmission. We thus avoid the challenges imposed by wireless interference and more sophisticated forwarding strategies [7], as our main consideration here is the effect of mobility on state

maintenance. We do not consider packet loss due to transmission errors, although the Markov (p, q) model from the previous section could easily be accommodated. We consider four cases for state sharing:

- **All Routers:** All nodes perform stateful routing, with link state updates being sent every 1500 transmission time units.
- **All Flooders:** All nodes perform stateless flooding.
- **Mobile Flooders:** The central 384 mobile nodes perform flooding, while the remaining static nodes perform stateful routing.
- **Greedy-iterative:** An algorithm in which all nodes are initially classified as routers, and then a node is iteratively selected to be changed to a flooder. This router-to-flooder conversion is based on (i) the amount of traffic carried on the link, and (ii) on the quality of the link.

Fig. 4 shows the simulation results plotting the delivery ratio as a function of the normalized per-node arrival rate. We see that single regime (all flooder, all router) solutions generally perform poorly, demonstrating the value of selective classification.

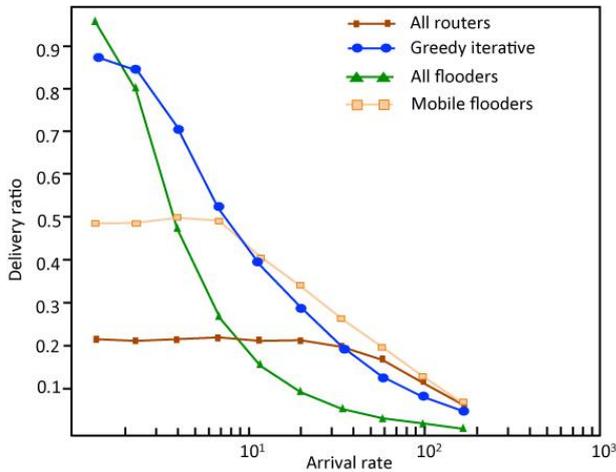


Fig. 4. 1152 node simulation scenario: flows originate in static region, cross mobile region, terminate in static region

Our results offer the following insights. At extremely low loads, homogenous flooding achieves the highest delivery ratio - the network is highly uncongested and with multiple copies of a packet made within a static region, one or more (flooded) packet copies are likely to traverse the mobile region to a destination in the mobile or other static region. As traffic increases, the delivery ratio of flooding quickly drops due to congestion losses. The “all routers” case corresponds to stateful routing at all nodes. Here, the delivery ratio is low for low traffic loads, since only a single copy of the packet will be routed from source to destination, and that single copy is unlikely to traverse the mobile center of the network to a destination in the mobile or other static portion of the network.

The “mobile flooders” case in Fig. 4 corresponds to the case that all mobile nodes flood all traffic they receive (with duplicate suppression); static nodes perform stateful routing.

We see here that at low loads, the delivery ratio is lower than that of flooding, since only a single (routed) copy of the packet can be routed into the mobile network from a static node to the mobile node indicated by static routing. Although the delivery ratio decreases as the arrival rate increases, mobile flooding soon surpasses the performance of pure flooding, which congests rapidly.

In the case of “greedy iterative,” the greedy algorithm selects mobile nodes as well as a relatively small number of static nodes at the edge of the mobile region to perform flooding, allowing multiple copies of a packet to enter the flooding region. In the example shown, all mobile nodes and all static nodes at the edge of the mobile region perform flooding, while all other static nodes perform stateful (single copy) routing. We see that the greedy iterative approach outperforms pure flooding over an interval of arrival rates, and achieves comparable, although slightly inferior performance that mobile flooding.

IV. FUTURE WORK

Some immediate next steps for the current research activities are to take the intuitions derived from our work on determining the optimal spatio-temporal schedules for link state acquisition, on simple disjoint-path topologies under a power constraint, and extend them to more complex and realistic networks. We are currently working on numerically evaluating the optimal spatial distribution of power—used for link-state updates—across a square grid network with periodic boundary conditions, using our local causal probabilistic scheme outlined in this paper. Our routing performance metric of choice is maximizing probability of delivery ratio under a cut-through link-forwarding model. However, our work should be easily generalizable to minimizing end-to-end routing latency. We are also working on exploring whether our solutions to the optimal spatial rate distribution for a single source-destination pair flow can be superposed in some way to obtain the optimal rate dissemination profile for more than one flow. Finally, we are looking at what effects spatial correlation and heterogeneity have on the optimal rate profiles and update protocols.

Work is also ongoing to reformulate the task as a distributed optimization problem using a dissemination based network model. This is a large step towards a more realistic network model as it is more representative of the way that most protocols operate, and it allows us to consider multiple concurrent traffic flows. Insight gained from our previous results will be used to design a state forwarding policy which each node will follow. Each node will then make state forwarding decisions independently, based on some local optimization goal. This optimization goal may well vary between nodes in a heterogeneous or hybrid network.

Our results also suggest the promise of mixing flooding and routing in heterogeneous and hybrid network environments. Our future research is therefore focused towards developing utility-based centralized (e.g., via a low-bandwidth wide-area broadcast channel) and decentralized router/flooder classification algorithms.

Future work should also focus on guaranteeing that this theoretical characterization of partial state information can be exploited in an operational setting. To ensure this, explicit theoretical limits for the tradeoff between network performance and state information gathering should be established for a realistic network topology. It would then be pertinent to understand how these limits can be applied to optimize and extend current protocols already in use in military systems. This approach would provide the quickest route to operational exploitation.

This paper has deliberately talked in terms of general "state information" because the techniques are widely applicable, well beyond just network routing. So for example, minimizing power consumption maybe of high priority with mitigating techniques such as retransmitting lost packets, or applying forward error correction "wasting" power. These techniques should be applied as sparingly as possible to conserve power for a particular target performance. However, both of these techniques require state information to be gathered (e.g. information about failed transmissions or the error rate on channel) and this gathering incurs a cost, in an analogous way to our modeling. These feedback mechanisms are so fundamental to the protocols that it is frequently difficult to separate the implicit state gathering (and its cost) from the actual protocol. A new error correction protocol might improve performance, but the purpose of this work is to understand how close that performance is to theoretical bounds in information theoretic terms. Where protocols are a long way from the bounds, revolutionary approaches are potentially attractive, and so further research can be focused in such areas.

Not only does this work indicate areas for improvement, but the theoretical underpinnings can be used to understand the form that potential solutions can take. The next steps for this work are therefore to generalize the techniques to larger and more realistic settings and then begin to develop frameworks to evaluate existing networking technologies. The results of this will give some real insight into the performance benefits that can be achieved, and can be used to make improvements to current protocols or influence the design of future systems.

V. CONCLUSIONS

This paper has provided contributions towards formulating a theoretical framework to understand the value of state information in distributed networking. Controlling the distribution of state information, is in some sense the most important part of any networking protocol, yet significant challenges remain before it can be theoretically characterized,

so as to move protocol research from relative and specific to absolute and general comparisons.

This work also adds crucial theory to enable the development of self-optimizing networks that are a unique challenge in the military environment with their ever-changing coalitions, missions, capability, and performance objectives. Self-optimizing networks potentially bring the benefits of not only improved and more resilient performance but also reduced operational management cost savings.

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