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DATAWorks 2022: Topological Modeling of Human-Machine Teams

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Executive Summary

In support of its mission to advance test and evaluation (T&E) and engage colleagues in discussion and sharing of T&E methodologies, the Institute for Defense Analyses' Test Science group presents recommended evaluation strategies for human-machine teams[1] (HMTs), to be presented as a brief topic talk at DATAWorks 2022. The briefing proposes, describes, and advocates for topological models as a framework for characterizing and evaluating HMTs. It is the follow-up to the 2021 briefing *Characterizing Human-Machine Teaming Metrics for Test & Evaluation* (IDA Document D-14349), where IDA recommended a collection of metrics for evaluation and assessment of HMTs.

Any realistic model of teams should capture the emergent property that a team is more than the sum of its parts, meaning that analysts cannot predict or assess team performance solely from knowledge of the individual team agents. How a team is organized and works together is as much a factor of team performance as any single agent's performance measures. As such, methods for evaluating HMTs should account for the collective-level team performance and the individual-level performances. The interactions between teammates add new predictors and new degrees of unpredictability, which exacerbates the issue of analyzing team performance. These interactions also enable comprehensive topological analysis, which is the recommended approach to modeling teams.

Every team or group of agents has a shape, and a topological model of a team is a set of metrics that describes that shape – the team's architecture, its organization, the interaction and information flow between agents and groups of agents, and the dynamics of how any of those metrics might change over time. All of these factors affect how well a team performs its tasks. For instance, simulations of search and rescue HMTs show that differences in team performance may be primarily due to topological characteristics, rather than individual performance metrics, which would be the traditional focus of a team analysis.

The data needed for such models will require some additions to current T&E data collection. In particular, data on team interaction – whether that be verbal communication, sensing and information flow, or some other means of agents working and

[1] An HMT is a team of human and computer agents working together to accomplish a mission.

acting together – will be essential for building the team's underlying topological structure or shape. The shape itself provides some global characterizing parameters that can be used as predictors of team performance. From that point, there are a number of other topological parameters and metrics that can be computed to gain information on the nature of the team's organization and interaction. The metrics we discuss in Part II include the following.

- ***Betti numbers*** count the number of holes and connected components in a structure, which provides a signature of a team's architecture.
- ***Clustering*** is a measure of the intensity or magnitude of interaction among an agent's or subgroup's neighbors.
- ***Embeddedness*** scores the extent to which an interaction is contained within larger interactions.
- ***Facets*** are the dominant interacting subgroups within the team.

These measures can act as additional predictors of performance and efficiency, providing – for example – quantifying and locality information for redundancies, weak points, and anomalies in the team, where individuals or subgroups might be either removed or supplemented with additional personnel or resources to enhance performance. This, in turn, provides a foundation for performance and efficiency optimization, especially in the face of resource constraints a team would confront in defense scenarios.

The software needed for a full, topological HMT modeling framework are primarily already in place and widely used in various other applications. It would not require a significant effort to bring these capabilities together into a single computational tool that could allow users to simulate and test various HMT structures in different scenarios, particularly in an effort to build test plans for T&E applications.

An Introduction to

Topological Modeling of Human-Machine Teams

Jay Wilkins, Caitlan Fealing, and John Haman

DATAWorks 2022

Institute for Defense Analyses

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Topological models of teams can help analysts characterize team interaction and performance.

Here, we will discuss some applications of these ideas to human-machine teams (HMTs).

What is a *Human-Machine Team*? An HMT is a group of agents containing at least one human and one machine, functioning collaboratively towards one or more common objectives.


The Pentagon Wants AI-Driven Drone Swarms for Search and Rescue Ops

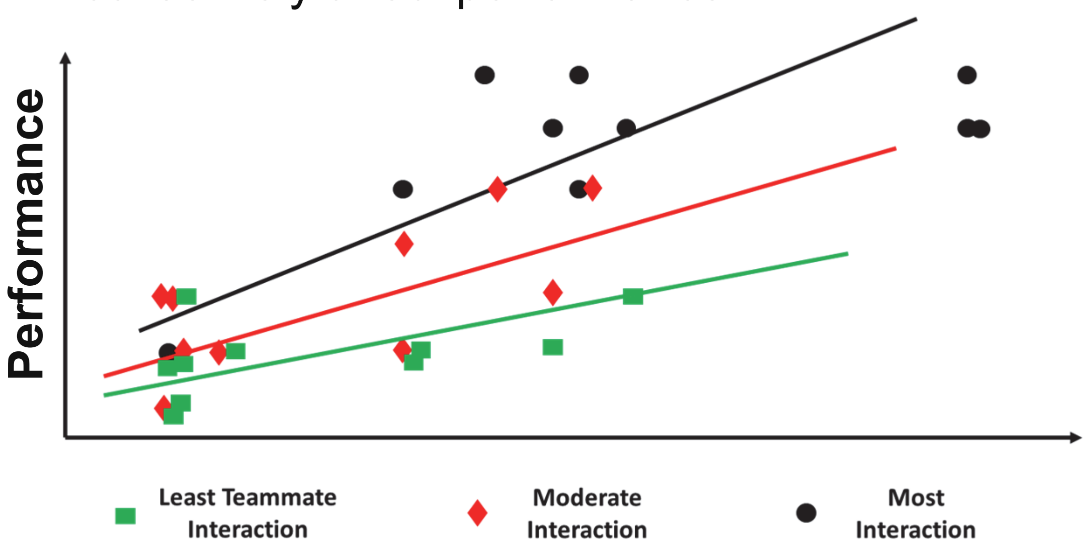
- **Examples**
  - Pilot-aircraft teaming (e.g., loyal wingman)
  - Search & rescue drones
  - Self-driving cars
  - Human and UAV/UAS reconnaissance and task teams

A *Topological Model* is a predictive framework for analyzing how team organization and interaction affect performance.

- ***A team is not just the sum of its parts*: Team performance cannot accurately and realistically be predicted only using data from individual team agents.

- Traditional teaming models have really only shown how individual teammates affect collective performance.

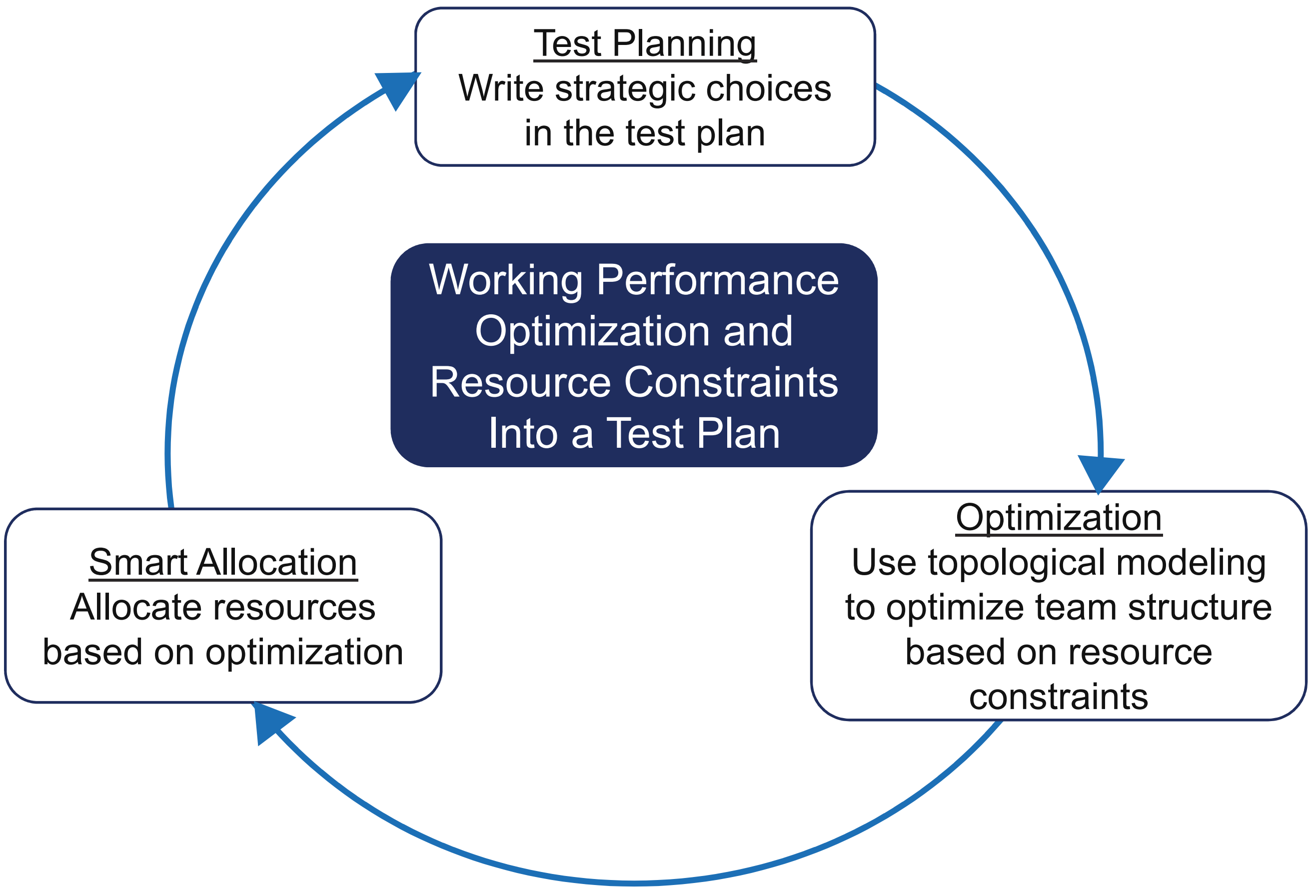
- Topological models provide a groundwork for assessing how teammates collectively affect performance.



<u>Example</u>
Increased team connectivity and interaction may enhance team performance. In other cases, this may not be so.

Topological models provide more than just a geometric and statistical groundwork for analyzing performance as a function of the team's collective properties.

We can physically locate weak points in the team – e.g., specific subgroups of agents and interactions, certain lines or groupings of communication – yielding performance optimization strategies within resource constraints.



IDA published an HMT Evaluation Framework (2021), proposing metrics and metric categories for HMT evaluation, particularly in test & evaluation (T&E) scenarios.

– Team Measures –

Capability		
Communication structure	Structure-based interaction	Architecture
Interaction		
Team perspective	Cooperative behavior	Workload
Performance		
Collective decision making	Collective task performance	

Depending on context and the specific choice of parameter, topological parameters may affect capability, interaction, or both together.

– Team Measures –

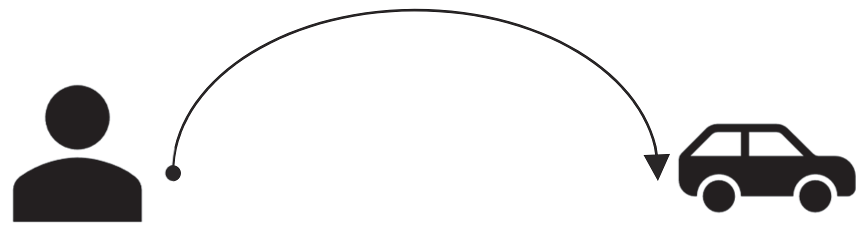
Capability		
Communication structure	Structure-based interaction	Architecture

Interaction		
Team perspective	Cooperative behavior	Workload

Performance	
Collective decision making	Collective task performance

NOTE: The team's topology may also be the ***response*** in a testing scenario.

Example 1. A driver and a self-driving car.



This team consists of one human and one machine.

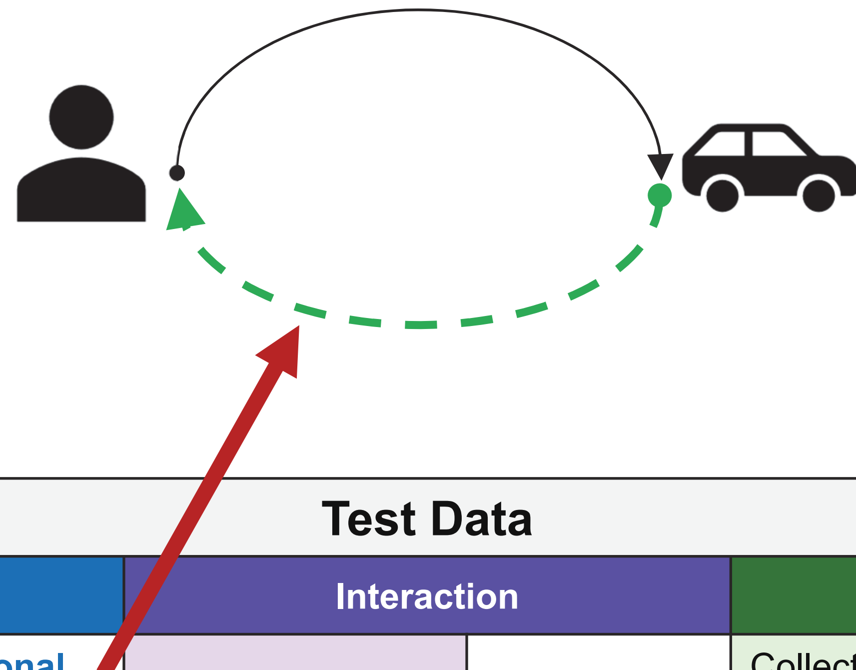
The team's mission is to simply navigate a course.

The result is a crash when the vehicle attempts to keep moving at a point where the driver manually applies the brakes.

Test Data					
Capability		**Interaction**		**Performance**	
Communication Structure	Broken Vehicle Driver Interface	Team Perspective	Accurate	Collective Decision Making	Moderate
Structure-Based Interaction	Efficient	Cooperative Behavior	Cohesive	Collective Task Performance	Poor
Architecture	Efficient	Workload	Low		

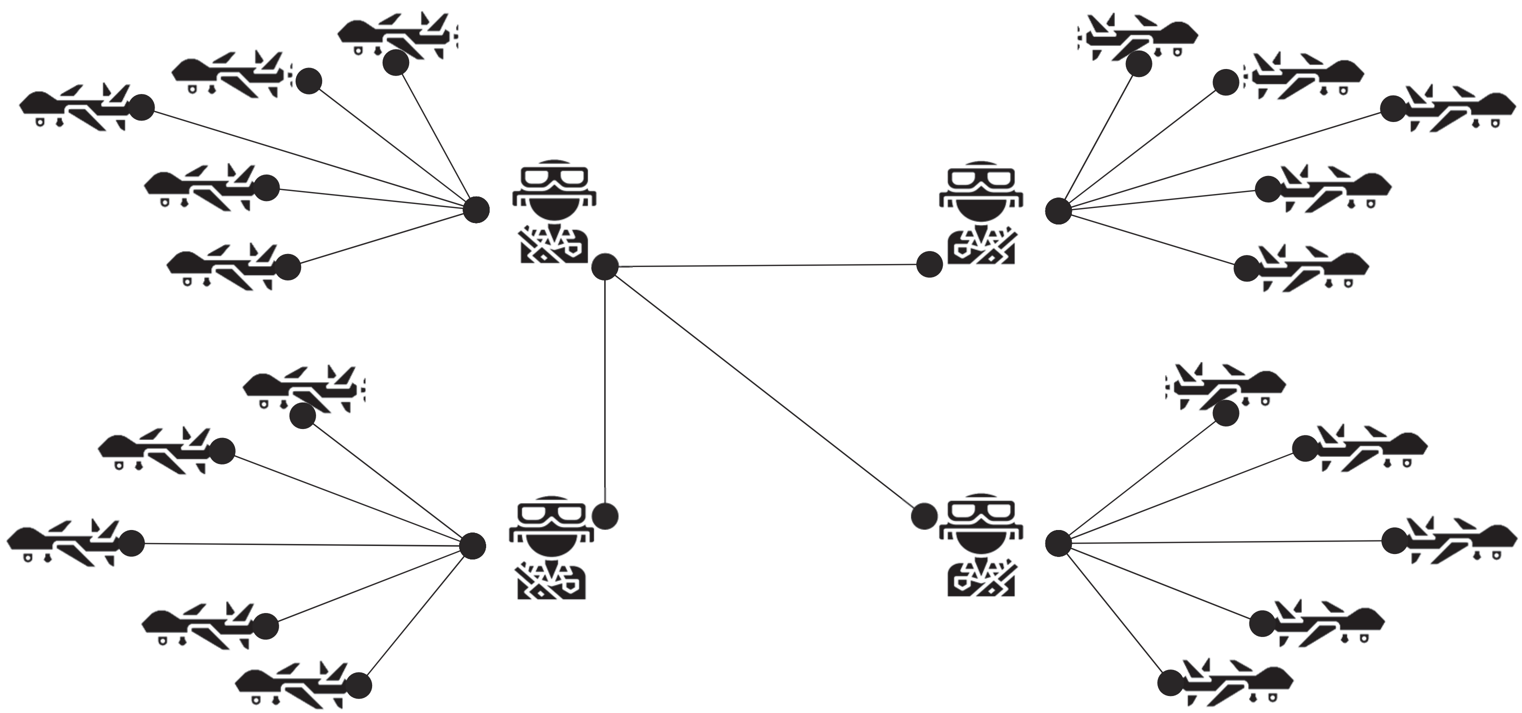
Vehicle could not communicate to driver that it had assessed the upcoming point of concern as safe.

Example 1. The obvious solution of fixing the broken interface is equivalent to a change in the team's topology of the team, from a one-way communicating line segment to a two-way communicating loop or circle.



Test Data					
Capability		**Interaction**		**Performance**	
Communication Structure	**Functional Interface**	Team Perspective	Accurate	Collective Decision Making	**Acceptable**
Structure-Based Interaction	Efficient	Cooperative Behavior	Cohesive	Collective Task Performance	**Success**
Architecture	Efficient	Workload	Low		

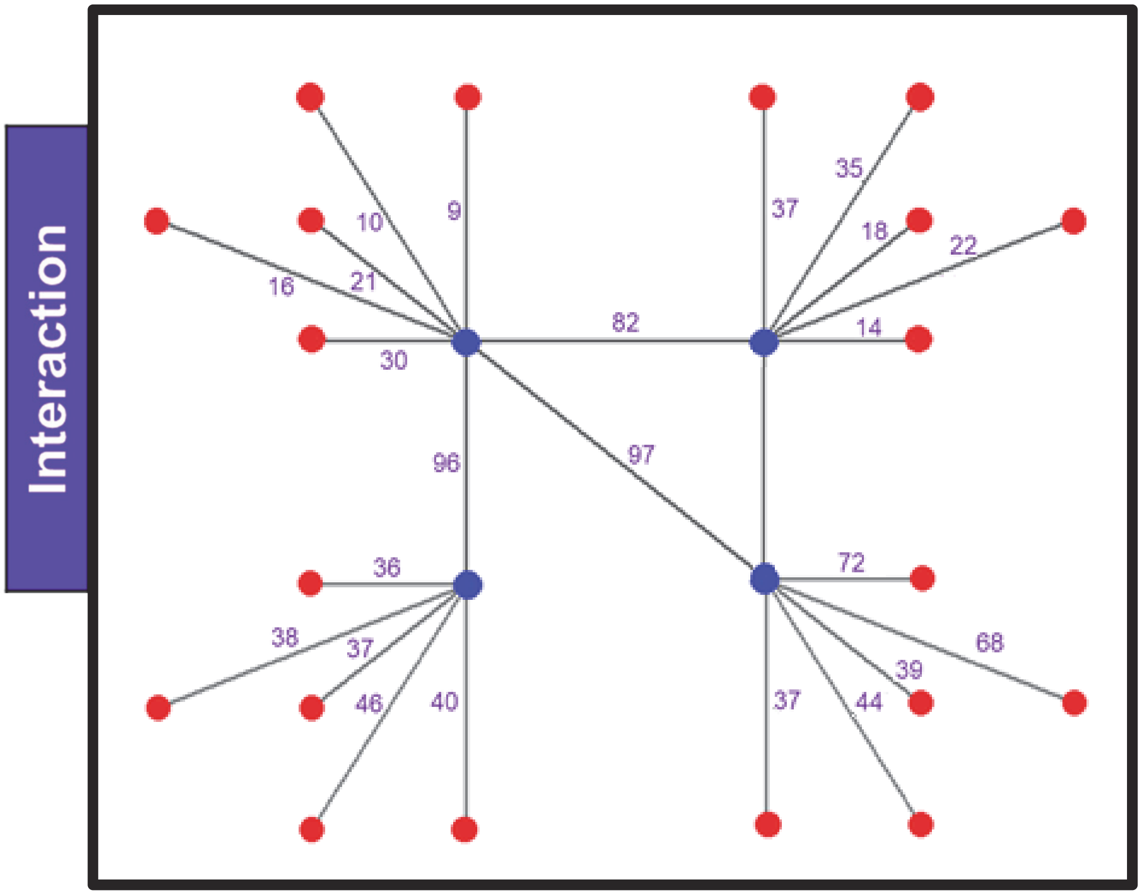
Example 2. Four swarms of Shadows (RQ-7Bs) controlled by four human operators – a group leader and three subordinates, each operating independently from the other subordinates.



This team consists of four humans and twenty machines.

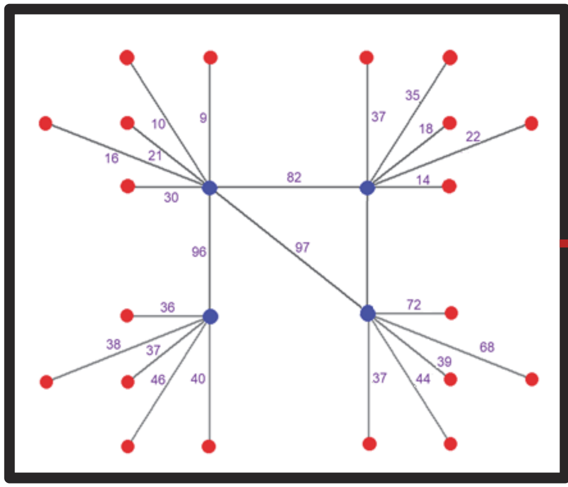
The team's mission is adversary detection, with each drone assigned to a coverage sector.

Example 2. We assess interaction and determine team structure in this case from communication data – counting the number of verbal or digital communications passed between agents.



For T&E scenarios, the data collection plan – including what specific data is to be used to determine team topology – needs to be addressed in the TEMP.

Example 2. Topological parameters and metrics will capture the team's organization and structure numerically. Those values are included with other performance predictors.



$$Performance = \boldsymbol{\alpha T} + \boldsymbol{\beta \Phi} + \boldsymbol{\varepsilon}$$

$$T = Topological\ Parameters$$

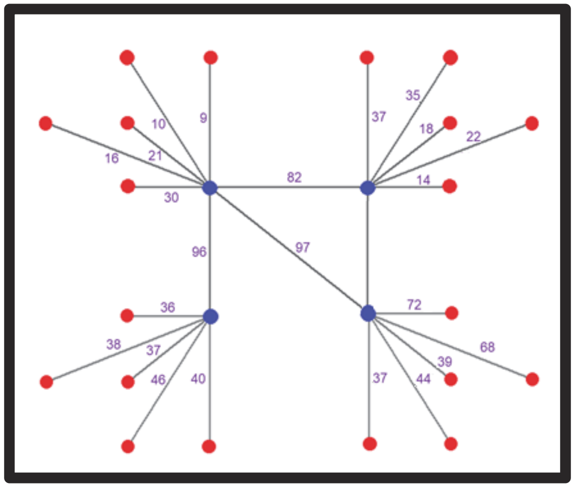
$$\Phi = Other\ Numerical/Categorical Parameters$$

Performance Data

	h1	h2	h3	h4	d11	d12	d13	d14	d15	d21	d22	d23	d24	d25	d31	d32	d33	d34	d35	d41	d42	d43	d44	d45
Percentage of Sector Observed	85.8	76.8	63.4	74.6	100	84	70	90	85	60	92	80	100	52	72	56	40	85	64	88	90	20	100	75
Adversarial Detections	0	0	0	0	4	3	3	1	0	1	0	2	0	0	2	4	3	3	4	2	2	3	1	2
Adversarial Detections Relayed	11	3	10	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

h_i refers to human i; d_{jk} refers to drone k under operator j.

Example 2. Simulating again – but with the four human operators fully connected – yields better coverage per drone.



$$Performance = \alpha T + \beta \Phi + \varepsilon$$

$$T = Topological\ Parameters$$

$$\Phi = Other\ Numerical/Categorical Parameters$$

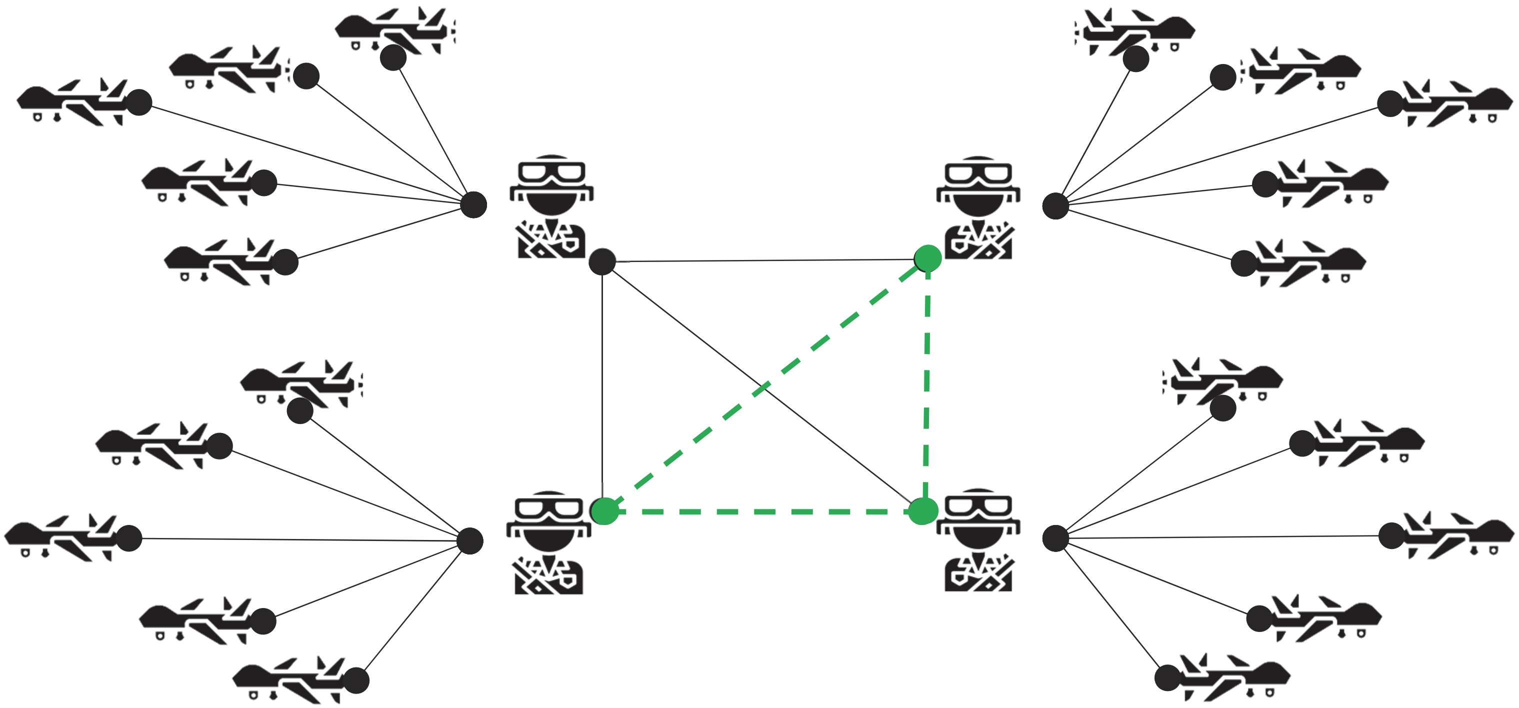
Performance Data

	h1	h2	h3	h4	d11	d12	d13	d14	d15	d21	d22	d23	d24	d25	d31	d32	d33	d34	d35	d41	d42	d43	d44	d45
Percentage of Sector Observed	85.8	76.8	63.4	74.6	100	84	70	90	85	60	92	80	100	52	72	56	40	85	64	88	90	20	100	75
Adversarial Detections	0	0	0	0	4	3	3	1	0	1	0	2	0	0	2	4	3	3	4	2	2	3	1	2
Adversarial Detections Relayed	11	3	10	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Performance With Greater Connectivity

	h1	h2	h3	h4	d11	d12	d13	d14	d15	d21	d22	d23	d24	d25	d31	d32	d33	d34	d35	d41	d42	d43	d44	d45
Percentage of Sector Observed	87.6	81.8	73.6	82.6	100	88	75	90	85	72	92	85	100	60	75	70	65	88	70	88	90	50	100	85
Adversarial Detections	0	0	0	0	4	3	3	2	0	1	1	2	1	0	3	4	3	3	4	2	3	3	1	3
Adversarial Detections Relayed	13	5	16	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Example 2. Topological Modeling tells us that changing the team structure will increase performance



OT Solution: All operators should communicate with each other instead of each communicating with one main operator

Note: If there are not enough resources to link all four humans, topological models can indicate other ways to increase performance within such constraints.

Summary

- Topological modeling can be a way to optimize team organization and, ultimately, performance in the face of resource constraints.
- *Every* team has a “shape” that can be modeled. That shape can and often does affect collective performance.
- Collect more interaction data at tests to most efficiently use topological modeling.
- Using topological modeling with IDA’s HMT Evaluation Framework will find inefficiencies in teams and show how to fix them.

Thank you!
Questions?
Comments?

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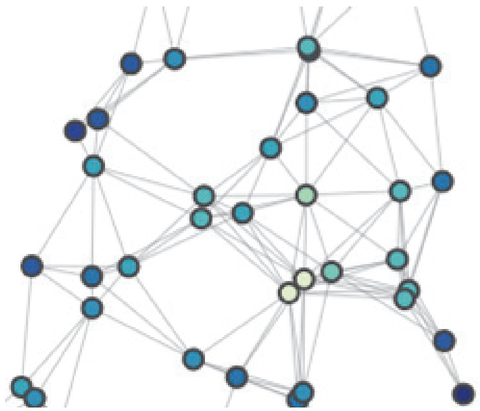
Backup

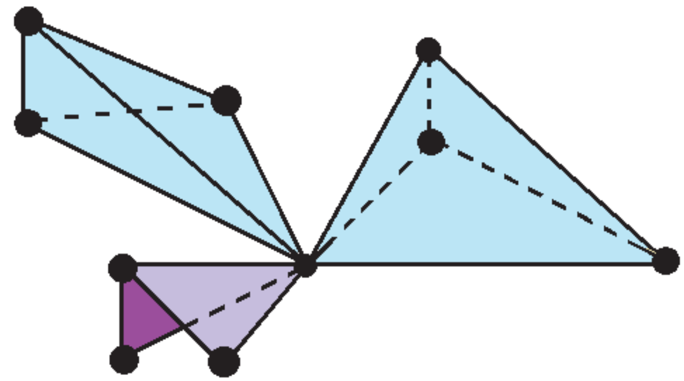
Topological Models analyze an accurate and complete team structure

Network Modeling



Network modeling measures connections only between connected pairs of teammates

Topological Modeling



Topological modeling can measure connections between more than two teammates at once, including subgroups

Team structure matters

Example 2. Complete Data Table

Test Data																													
	Capability Data		Interaction Data																								Performance Data		
	Human-Human Communication	Human-Machine Communication	Number of Communications Sent to Each Teammate																								Percentage of Sector Observed	Adversarial Detections (Human, vehicle, etc.)	Adversarial Detections Relayed to Commander
Agents	Radio	Display	h1	h2	h3	h4	d11	d12	d13	d14	d15	d21	d22	d23	d24	d25	d31	d32	d33	d34	d35	d41	d42	d43	d44	d45	PctS	AdvD	AdvDR
h1	1	1	NA	34	45	42	20	10	12	8	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85.8	0	11
h2	1	1	48	NA	0	0	0	0	0	0	0	23	23	10	13	7	0	0	0	0	0	0	0	0	0	0	76.8	0	3
h3	1	1	52	0	NA	0	0	0	0	0	0	0	0	0	0	0	35	33	20	21	18	0	0	0	0	0	63.4	0	10
h4	1	1	54	0	0	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	20	17	22	20	74.6	0	7
d11	0	1	10	0	0	0																					100	4	0
d12	0	1	6	0	0	0																					84	3	0
d13	0	1	9	0	0	0																					70	3	0
d14	0	1	2	0	0	0																					90	1	0
d15	0	1	3	0	0	0																					85	0	0
d21	0	1	0	14	0	0																					60	1	0
d22	0	1	0	12	0	0																					92	0	0
d23	0	1	0	8	0	0																					80	2	0
d24	0	1	0	9	0	0																					100	0	0
d25	0	1	0	7	0	0																					52	0	0
d31	0	1	0	0	37	0	[All Values = 0; No Communication between Drones]																				72	2	0
d32	0	1	0	0	35	0																					56	4	0
d33	0	1	0	0	24	0																					40	3	0
d34	0	1	0	0	18	0																					85	3	0
d35	0	1	0	0	19	0																					64	4	0
d41	0	1	0	0	0	18																					88	2	0
d42	0	1	0	0	0	18																					90	2	0
d43	0	1	0	0	0	20																					20	3	0
d44	0	1	0	0	0	24																					100	1	0
d45	0	1	0	0	0	10																					75	2	0

Simple Technical Definitions of Topological Modeling Terms

- Betti Numbers
  - Betti numbers $(\beta_0, \beta_1, \beta_2, \ldots)$ count the "holes" and connected components in a topological space.
- Adjacency Matrices
  - An adjacency matrix (nondirected) expresses any interaction between agents, disregarding any possible notion of direction of interaction.
    - These matrices contain *pairwise* parameters.
- Clustering/Closure
  - The proportion of an agent's neighbors that are also neighbors of each other in groups of comparable size.
- Facets
  - Are interacting subgroups of maximal size – i.e. not part of a larger subgroup.

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Lillard, Vincent

14. ABSTRACT
A Human-Machine Team (HMT) is a group of agents consisting of at least one human and at least one machine, all functioning collaboratively towards one or more common objectives. As industry and defense find more helpful, creative, and difficult applications of AI-driven technology, the need to effectively and accurately model, simulate, test, and evaluate HMTs will continue to grow and become even more essential.
Going along with that growing need, new methods are required to evaluate whether a human-machine team is performing effectively as a team in testing and evaluation scenarios. You cannot predict team performance from knowledge of the individual team agents, alone; interaction between the humans and machines – and interaction between team agents, in general – increases the problem space and adds a measure of unpredictability. Collective team or group performance, in turn, depends heavily on how a team is structured and organized, as well as the mechanisms, paths, and substructures through which the agents in the team interact with one another – i.e. the team's topology. With the tools and metrics for measuring team structure and interaction becoming more highly developed in recent years, we will propose and discuss a practical, topological HMT modeling framework that not only takes into account but is actually built around the team's topological characteristics, while still utilizing the individual human and machine performance measures.

15. SUBJECT TERMS
artificial intelligence (AI); human-machine teaming; metrics for human-machine teams; topological model

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