Role of Information and Organization Structures on Distributed Auction Algorithms: Point-to-Point Communication Architecture*

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ABSTRACT

This paper presents how information organizational structures with point-to-point communication structure impact team coordination in a distributed task-asset allocation problem. A key distinguishing characteristic of this problem is that each DM knows only a part of the weight matrix and/or controls a subset of the assets. Here, we extend the distributed algorithm developed for blackboard communication structure in [11] to the point-to-point communication structure. Our results indicate that edge organizations with horizontal and vertical information structures exhibit shorter delays than block diagonal and checkerboard information structures.

1.0 INTRODUCTION

The optimal organizational design problem is primarily one of finding the structure, viz., decision hierarchy, asset-task allocation, role definition, grouping DMs into organizational cells, and specifying coordination and synchronization mechanisms, viz., tactics, techniques and procedures, such that the organization achieves superior performance in executing a specified mission [1], [2]. In the face of environmental stressors and mission changes (such as time stress, delayed and uncertain information, the emergence of unforeseen tasks, new technologies, different strategic options on the part of one's adversaries, etc.), organizations must be flexible to maintain superior performance. By flexibility, we mean the attributes of robustness (i.e., the ability to maintain short-term performance in the presence of environmental changes through process modifications), and adaptivity (i.e., the ability to maintain high quality performance in the presence of mission changes by adjusting decision processes and team structures). Motivated by the mission planning and monitoring activities associated with the Navy's maritime operations centers (MOC), we are developing analytical and computational models for multi-level coordinated mission planning and monitoring processes associated with MOCs, so that they can function effectively in dynamic, asymmetric, and unpredictable mission

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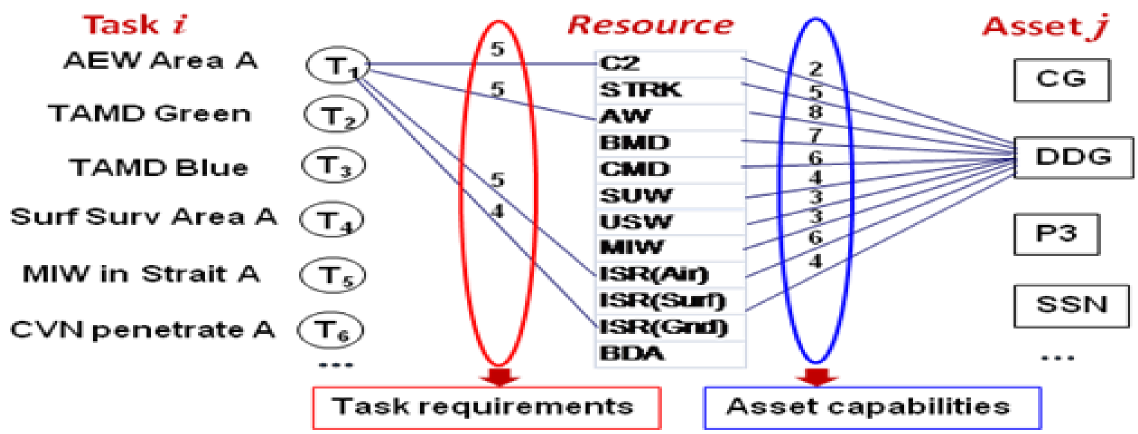
environments. MOCs emphasize standardized processes and methods, centralized assessment and guidance, networked distributed planning capabilities, and decentralized execution for assessing, planning and executing missions across a range of military operations [3].

In [11], we considered a distributed assignment problem with partial information as a simplified and abstracted version of the collaborative planning problem. In this problem, each DM only knows the partial elements of the benefit matrix, but can communicate relevant information with other DMs via blackboard(s) (information sharing space) as constrained by the organizational structure. Each DM "owns" a set of assets and is responsible for planning certain tasks. Each task is characterized by a vector of resource requirements, while each asset is characterized by a vector of resource capabilities (see Fig. 1). Multiple assets (from the same DM or multiple DMs) may be required to process a task. The similarity between the task-resource requirement vector and asset-resource capability vector determines the accuracy of task execution. In addition, the elements of task-resource requirement and asset-resource capability vectors may be affected by the mission environment (e.g., weather), and there may be precedence constraints on tasks. This leads to a stochastic allocation problem of matching the task requirements with the asset capabilities to maximize the task execution accuracy.



Legend	Description	Legend	Description
AEW	Airborne early warning	USW	Undersea warfare
TAMD	Theater air/missile defense	BDA	Battle demage assessment
MIW	Mine warfare	ISR	Intelligence, surveillance and
C2	Command and control		reconaissance
STRK	Strike	CVN	Nuclear aircarft carrier
AW	Air warfare	CG	Guided-missile cruiser
BMD	Ballistic missile defense	DDG	Guided-missile destroyer
CMD	Cruise missile defense	P3	Anti-submarine aircraft
SUW	Surface warfare	SSN	Nuclear submarine

Figure 1: Illustration of task-asset matching problem.

We considered four types of partial information structures, viz., horizontal, vertical, block diagonal and checkerboard patterns. We showed that the distributed organization can collaboratively reconstruct a centralized solution by transmitting local information, viz., bid, best profit and second best profit, to the blackboard(s). This paper extends the results of [11] to point-to-point communication structure. We show empirically that the blackboard communication structure exhibits faster information sharing among DMs than the point-to-point communication structure. This is because the point-to-point communication can result in significant time delays in propagating the global information due to many communication iterations among DMs, viz., multi-hop information propagation [4], [5].

The paper is organized as follows. The organizational model and the information structures considered in this paper are described in section 2. In section 3, the distributed auction algorithms for the four information structures are developed. Performance results for the algorithms are given in section 4. The paper concludes with a summary and future research directions in section 5.

2.0 INFORMATION AND COORDINATION STRUCTURES

2.1 Information Structure and Organizational Models

We considered four information structures: horizontal, vertical, block diagonal and checkerboard (block matrix) structures (see Fig. 2). Let ⟨•⟩ denote entities for the reverse auction algorithm. In the horizontal ⟨vertical⟩ information structure, each DM knows certain rows ⟨columns⟩ of the benefit matrix corresponding to a set of tasks ⟨assets⟩. In the block diagonal information structure, each DM knows the benefits for his own task-asset pairs while the coordinator knows the benefits for the rest of the task-asset pairs (de-confliction among DMs is inherent in the structure). In the checkerboard information structure, each DM has its own assets and tasks, but with significant overlaps in both rows and columns. In this structure, each DM knows the benefits for his own task-asset pairs, but needs to coordinate horizontally and/or vertically to share the bid information. The information structure for the traditional assignment problem, where each DM knows the entire benefit matrix, is termed the centralized information structure.

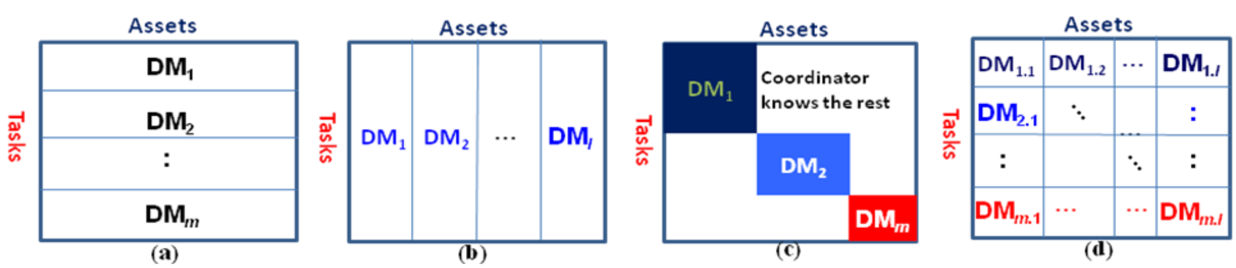


Figure 2: Information structures: (a) Horizontal; (b) Vertical; (c) Block diagonal; (d) Checkerboard.

The four information structures above correspond to a number of organizational models found in practice, viz., divisional, functional, hybrid and matrix organizations [1]. In a divisional organization (akin to the horizontal information structure), each DM "owns" all the necessary assets (corresponding to columns). Typically, the activities conducted by the members in this organization are restricted to certain geographic areas of responsibility (see Fig. 3). Thus, DMs are responsible for their respective tasks, but this may lead to operational inefficiencies when the task distribution among geographic areas changes. On the other hand, DMs in the functional organization (akin to the vertical information structure) control a single asset type having specialized knowledge of them, and perform a specialized set of tasks (all the tasks in the rows) (see Fig. 3). Thus, the activities of a functional organization may span multiple geographic regions. This structure leads to operational efficiencies within those DMs, but it could also lead to a lack of communication and coordination between the disparate functional DMs within an organization, making the organization slow and inflexible. The matrix structure (akin to the checkerboard information) groups DMs by both function and division so that they can take advantage of both structures, i.e., operational responsiveness of a divisional structure and efficiency of a functional structure. DMs must work with each other (both row-wise and column-wise), and collaborate to accomplish their activities; these activities require a great deal of time, communication, effort and skill to collaborate with other DMs. In the hybrid structure (akin to a block diagonal information structure), each DM mainly allocates his own assets to his own tasks, except that the coordinator facilitates supporting-supported relationships among team members. The four information structures provide a range of possible organizational constructs for evaluating the distributed auction algorithms [11].

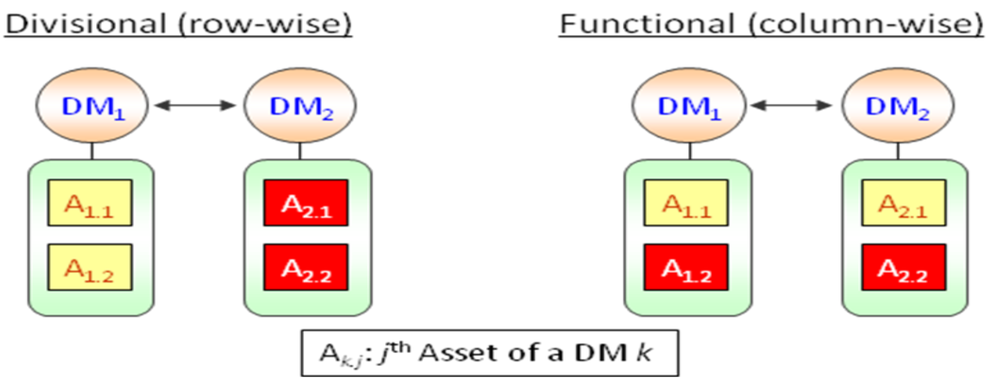


Figure 3: Information-based organization structures.

2.2 Point-to-Point Communication Structure

There are two aspects of coordination: communication, i.e., how the team of DMs 'shares bidding information' and organization, i.e., how the team is 'wired for control'. Here, we consider a parallel organization structure[1] with all DMs at the same level. For the communication structures, we considered the blackboard communication structure in [11]; the point-to-point communication structure is considered in this paper. Suppose there are M DMs, where $M = m$ $\langle l \rangle$ for the horizontal $\langle$vertical$\rangle$ information structure; $M = (m + 1)$ for the block diagonal information structure, and $M = (m \times l)$ for the checkerboard information structure. Here, m is the number of DMs row-wise and l is the number of DMs column-wise. Let $D_{k\{\bullet\bullet\bullet\}}$ = {bid, best profit, second best profit}$_k$ be the bidding data set of DM k, where '•' denotes the transmission status of bidding data. For example, $D_{k\{111\}}$ denotes that the transmitted data set includes the bid, the best profit and the second best profit, respectively. In the point-to-point communication structure (see Fig. 4), neighboring DMs communicate with each other row-wise (column-wise) to share their bidding data sets. Specifically, DMs communicate vertically (horizontally) with single-hop neighboring DMs toward or away from the median DM row-wise (column-wise) to send the bidding data set or to pass the final bidding decision of the median DM to the neighboring DMs, respectively; the median DM is the control DM getting bidding information from all DMs and this DM coordinates the bids vertically (horizontally), i.e., $\tilde{k} = \text{median}\{k\}_{k=1}^{m} = \lceil m / 2 \rceil$ (median $\{k\}_{k=1}^{l} = \lceil l / 2 \rceil$). We assume that DMs communicate column-wise first, and then communicate row-wise for the block diagonal and checkerboard information structures. The accumulated bidding data set of DM k from left/top to right/bottom (see Fig. 4) is

[1] The organization structure has been extended to hierarchical tree structure in an extended version of this paper

$$(\underline{D}_{\rightarrow/\downarrow})_k = \{\bigcup_{u=1}^{k} D_u\}; \quad (\underline{D}_{\leftarrow/\uparrow})_k = \{\bigcup_{u=k}^{M} D_u\}. \tag{1}$$

The bidding data set reaching $\tilde{k}$ from a DM k is

$$(\underline{D}_{\Rightarrow/\Downarrow})_k = \{\bigcup_{v=k+1}^{\tilde{k}} D_v\}; \quad (\underline{D}_{\Leftarrow/\Uparrow})_k = \{\bigcup_{v=\tilde{k}}^{k-1} D_v\}. \tag{2}$$

Then, the overall bidding data set at the control (median) DM is

$$\underline{D}_{\tilde{k}} = \{(\underline{D}_{\rightarrow/\downarrow})_k \cup (\underline{D}_{\Rightarrow/\Downarrow})_k \cup (\underline{D}_{\Leftarrow/\Uparrow})_k \cup (\underline{D}_{\leftarrow/\uparrow})_k\} = \{\{\bigcup_{u=1}^{\tilde{k}} D_u\} \cup \{\bigcup_{u=\tilde{k}+1}^{M} D_u\}\} = \{\bigcup_{u=1}^{M} D_u\}. \tag{3}$$

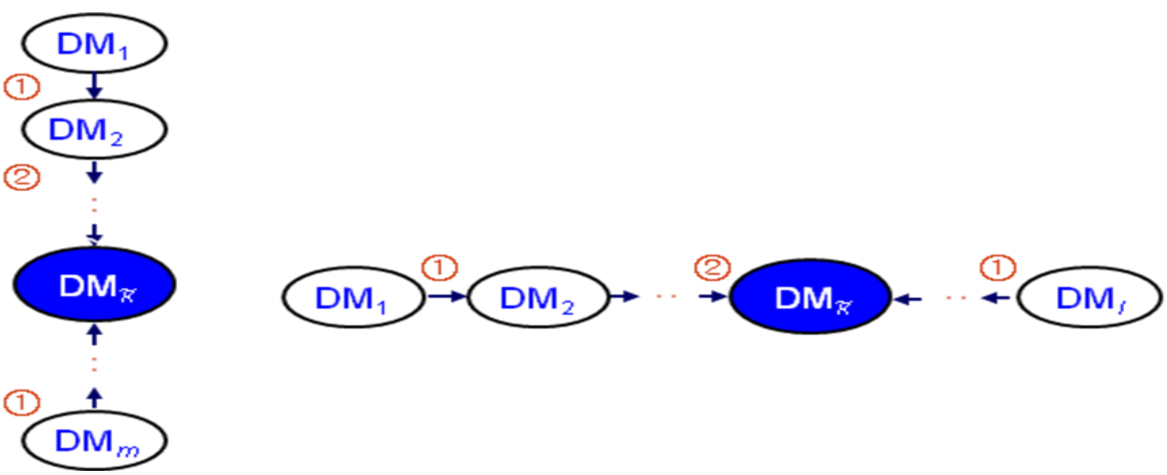


Figure 4: Point-to-point communication structure (row-wise and column-wise).

2.3 Parallel Organizational Structure

For the point-to-point communication structure, we also consider a parallel (single-level tree) structure. We define three DM types: 1) the root DM, *R* is the topmost DM with no superiors and is also the control DM; there is exactly one root DM in a tree, e.g., DM_3 in Fig. 5 (a) and $DM_{3.3}$ in Fig. 5 (b); 2) leaf DM has no subordinates, e.g., DMs 1, 2, 4 and 5 in Fig. 5 (a), and all DMs except $DM_{3.3}$ in Fig. 5 (b); 3) rank *h* is the number of levels from the bottommost DM to the root DM (including the root DM level) and h^* is the highest rank. Note that we designate the row-wise/column-wise median DM as a superior/root DM, while the bottommost/rightmost DM is designated as a superior DM in the blackboard communication structure since the location of the control DM is critical in the point-to-point communication structure. In the parallel structure (see Fig. 5), each DM shares the same horizontal position of power and authority, except the root DM who decides on the best bid by receiving the entire accumulated bidding information, and DMs communicate sequentially with only single-hop neighboring superior/subordinate DMs. Note that the bidding data set of the root DM for the parallel structure is the same as in (3).

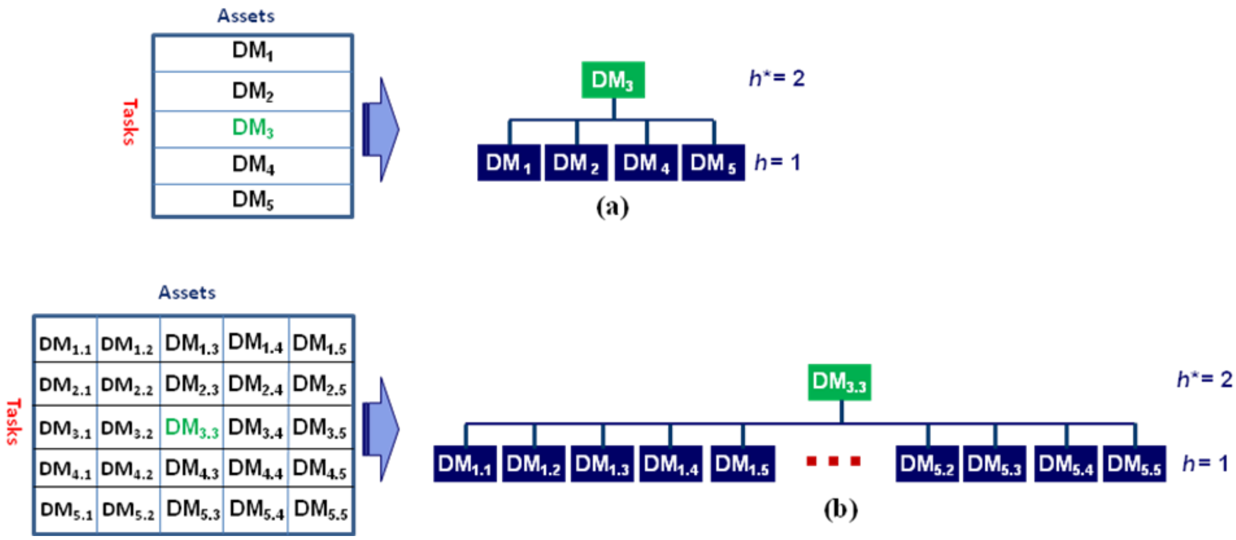


Figure 5: Parallel organizational structure for (a) horizontal and (b) checkerboard information structure.

2.4 Parameterization of Information and Parallel Organizational Structures

We parameterize the performance of each pair (information structure, organizational structure) by a function $f(\alpha, \mu)$

$$f(\alpha,\mu) = \frac{t(\alpha,\mu)}{t(centralized)} \qquad \alpha \in \{\alpha_1,\alpha_2,\alpha_3,\alpha_4\} \quad \mu = \mu_1 \tag{4}$$

where $t(centralized)$ is the centralized auction (termed the normal auction) time with centralized information structure; $t(\alpha, \mu)$ is the distributed auction time for the combinations of structures considered here: $\{(\alpha_1, \mu_1), (\alpha_2, \mu_1), (\alpha_3, \mu_1), (\alpha_4, \mu_1)\}$. Here α_1, α_2, α_3 and α_4 denote horizontal, vertical, block diagonal and checkerboard information structures, respectively; and μ_1 denote parallel organizational structure. The performance (speedup) is the ratio of (sequential) normal auction time and the distributed auction time. Efficiency is the ratio of speedup and the number of DMs. The relative performance measures (computation and coordination delays) are measured via numerical simulations in section 4.

3.0 AUCTION ALGORITHM WITH VARIOUS INFORMATION STRUCTURES

See Table 1 for variable definitions in this section.

Table 1: Variables used in the Distributed Auction Algorithms.

Variables	Definitions	Used in[a]	Variables	Definitions	Used in[a]
ε	The value for ε-complementary slackness (CS) [6]	1−3	i / j	A task / an asset	1−3
m / l	Number of DMs row-wise / column-wise	1−3	i_r / j_c	A task i / an asset j of a row-wise/column wise DM r / c	3
I/T (I_T / J_T)	Nonempty subsets of tasks / assets, that are unassigned (assigned to DMs)	1−3	$T_k(j_k)/A_k(i_k)$	The set of assets/tasks of a DM k from which a task i/ an asset j of a DM k receives a bid	2
I_k / J_k (I_r / J_c)	Sets of tasks / assets, that are assigned to a (row-wise/column-wise) DM k ()	1, 2 (3)	$\{\pi_i\}$, $\{p_j\}$	The dual prices: the profit of a task i, the price of an asset j	1−3
$i_k(i_{j_k})$ / $j_k(j_{i_k})$	A task / an asset of a DM k (bids for an asset / a task of a DM k)	1, 2	$\{b_{i_j}\}_k$	The set of bids of all the DMs in a row r	1

[a]1, 2 and 3 denote Algorithms 1, 2 and 3, respectively

3.1 Distributed Forward ⟨Reverse⟩ Auction with Horizontal ⟨Vertical⟩ Information Structure

Let ⟨•⟩ denotes entities for the reverse auction algorithm. The distributed forward ⟨reverse⟩ auction algorithm with horizontal ⟨vertical⟩ information structure has four processing steps: 1) for each assigned task ⟨asset⟩, each DM bids for assets ⟨tasks⟩ and finds the best asset ⟨task⟩ (we call this 'the common bidding step for each DM' for brevity because it is the same for all algorithms in this paper, even though they work differently for each information structure); 2) each DM communicates with the root (median) DM directly by sharing its bids, viz., $D_{k\{100\}}$ so that the centralized assignment is executed by the root DM (Note that each DM communicates with the root DM one-by-one, a situation that is different from the simultaneous posting on the blackboard by all DMs in the blackboard structure); and 3) the root DM assigns an asset j ⟨task i⟩ to the best task i ⟨asset j⟩ (it is the same for all algorithms in this paper; we call this 'the assignment step by the root DM' from now on); and 4) the root DM sends the bid to all subordinates and each DM updates his bid after receiving the bids from the root DM (it is the same for all the algorithms in this paper; we call this 'the bid update step' from now on).

As a running example, we consider a 5 × 5 benefit matrix A = {74 85 43 29 92; 95 59 57 94 97; 37 38 92 83 58; 85 52 51 14 20; 38 68 82 38 8} with initial prices p_j = {0, 0, 0, 0, 0}, the value for ε-complementary slackness (CS) [6], $\varepsilon = 0.2$, and 5 DMs having a row-wise task $i \in I_k = I_i$ and entire column-wise assets $j \in J_k = J_T$. The organizational structure is the same as in Figs 5 (a). The forward auction process steps are as follows: 1) Each DM k bids for its tasks $\{i_k\}$ and finds the best asset $j_{i_k} \in J_T$: bids = {7.2, 2.2, 9.2, 33.2, 14.2}; 2) DMs 1, 2, 4 and 5 send their bids to the root DM (DM_3) one-by-one: the accumulated bids for each DM, $\{b_{ij}\}_k$ are shown in Table 2 (a), where (•) denote the corresponding DM; 3) DM_3 assigns an asset j to the best task i attaining the maximum bid and sends the bid to his neighboring DMs; and 4) DM_2 updates his bid after receiving the bids from DM_3 (see Table 2 (b)).

Table 2: Illustration of Algorithm 1 (a) and (b): Accumulated bids of individual DMs sent by neighboring DMs and updated by the root DM for the parallel structure.

Bids	Asset 1	Asset 2	Asset 3	Asset 4	Asset 5
Task 1					7.2
Task 2					2.2
Task 3	33.2 (4)		9.2, 14.2 (5)		2.2 (2),7.2 (1)
Task 4	33.2				
Task 5			14.2		

(a)

Bids	Asset 1	Asset 2	Asset 3	Asset 4	Asset 5
Task 1	33.2 (4)		14.2 (5)		7.2
Task 2	33.2 (4)		14.2 (5)		~~2.2,~~ 7.2 (1)
Task 3	**33.2** (4)		~~9.2,~~ **14.2** (5)		~~2.2 (2),~~ **7.2** (1)
Task 4	33.2		14.2 (5)		7.2 (1)
Task 5	33.2 (4)		14.2		7.2 (1)

(b)

3.2 Distributed Forward Auction with Block Diagonal Information Structure

The coordinator communicates with DMs one-by-one and revises DMs' bids and a DM *k* communicates horizontally with the coordinator to possibly revise bids, and each DM communicates diagonally toward the root DM transferring the row-wise best bids. The distributed forward auction algorithm with the block diagonal structure also has five processing steps: 1) the common bidding step for each DM; 2) all DMs send their bids, as well as the best and the second best profits, viz., $D_{k\{111\}}$ to the coordinator; 3) if the coordinator can ensure a better profit for a task, the coordinator revises the bid and sends it to the root DM; 4) the assignment step by the root DM; and 5) the bid update step after receiving the bidding data from the root DM of each DM and the coordinator. If DMs employ reverse auction algorithm, the coordinator must employ reverse auction algorithm also. It can alternately use forward and reverse auction steps as well.

As an illustrative example, we consider the same benefit matrix *A*, initial prices p_j, ε (= 0.2) as in the horizontal information structure case with 5 DMs having a row-wise task $i \in I_k = I_i$ and column-wise assets $j \in J_k = J_i$, and the coordinator knowing the rest, i.e., $i \in I_6 = I_5 \backslash \cup_{k=1}^{5} I_k$ and $j \in J_6 = J_5 \backslash \cup_{k=1}^{5} J_k$. Here $\cup$ and \ denote set union and set subtraction, respectively. Note that the DM's tasks and assets are diagonal components as highlighted, *A* = {**74** 85 43 29 92; 95 **59** 57 94 97; 37 38 **92** 83 58; 85 52 51 **14** 20; 38 68 82 38 **8**}. The forward auction process steps are as follows: 1) The common bidding step for each DM involves the bids = {74.2, 59.2, 92.2, 14.2, 8.2}; 2) All DMs sequentially communicate their bids, as well as the best profits = {74, 59, 92, 14, 8} to the coordinator. Note that there are no second best profits in this example because all DMs have only one task and one asset; 3) The coordinator finds the best asset for each task $i_k \in T_k(j_k)$, i.e., best profits = {92, 97, 83, 85, 82} and 2nd best profits = {85, 95, 58, 52, 68}, decides on the best bids = {7.2, 2.2, 9.2, 33.2, 14.2}, and updates bids (see Table 3 (a)), and then sends bids to the root DM (DM_3) (see Table 3 (b)); 4) DM_3 assigns an asset *j* to the best task *i* and sends the bids to his immediate subordinates and the coordinator, DMs 1, 2, 4 and 5; and 5) DM_2 updates his bid after receiving the bids from DM_3 (same as in Table 2 (b)).

Table 3: Illustration of Algorithm 2 (a) Bids updated by the coordinator (b) Accumulated bids of individual DMs sent by the coordinator.

Bids	Asset 1	Asset 2	Asset 3	Asset 4	Asset 5
Task 1	~~74.2~~				7.2
Task 2		~~59.2~~			2.2
Task 3			9.2, ~~92.2~~		
Task 4	33.2			~~14.2~~	
Task 5			14.2		~~8.2~~

(a)

Bids	Asset 1	Asset 2	Asset 3	Asset 4	Asset 5
Task 1	74.2				
Task 2		59.2			
Task 3	33.2 (4)		9.2, ~~92.2,~~ 14.2 (5)		2.2 (2)
Task 4				14.2	
Task 5					8.2

(b)

3.3 Distributed Forward Auction with Checkerboard Information Structure

The distributed forward auction algorithm has five processing steps: 1) the common bidding step for each DM ($r.c$); 2) all subordinate DMs send their bids, as well as the best and the second best profits, viz., $D_{k\{111\}}$ to the root DM one-by-one. Note that multiple DMs may send bids for the same task i; 3) the root DM decides on the best bid of a task i for assets j_i of all DMs in the same row; 4) the assignment is made by the root DM after completing the bidding process for every row; and 5) the bid update step is performed after receiving the bidding data from the root DM.

As an illustrative example, again we consider the same benefit matrix A, initial prices p_j, ε (= 0.2) as in the previous examples, except that we have 25 DMs ($\text{DM}_{r.c}$) having a row-wise task $i \in I_r = I_i$ and column-wise asset $j \in J_c = J_i$. Note that each cell (highlighted) corresponds to a DM, who is responsible for only one task and one asset, A = {**74**, **85**, **43**, **29**, **92; 95**, **59**, **57**, **94**, **97; 37**, **38**, **92**, **83**, **58; 85**, **52**, **51**, **14**, **20; 38**, **68**, **82**, **38**, **8**}. The organizational structure for this example is shown in Fig. 5 (b). The common bidding step for each DM is the same for both structures. The remaining forward auction process steps are as follows: 2) All leaf DMs, e.g., DMs (1.1), (1.2), (1.4) and (1.5) in row 1, send their bids, as well as the best and the second best profits, viz., $D_{k\{111\}}$ to the root DM, $\text{DM}_{3.3}$ (see Table 4 (a)); 3) $\text{DM}_{3.3}$ decides on the best bid of task $i_r \in I_r$ for assets $j_{i_k} \in J$ in the same row (see Table 4 (b)); 4) The assignment step by $\text{DM}_{3.3}$; and 5) The bid update step of each DM after receiving bids from $\text{DM}_{3.3}$ of each DM (same as in Table 2 (b)).

Table 4: Illustration of Algorithm 3 (a) and (b) Accumulated bidding data of individual DMs sent by DMs and updated by the root DM for the parallel tree structure.

Bids / Best profits	Asset 1	Asset 2	Asset 3	Asset 4	Asset 5
Task 1	74.2/74	…	43.2/43	…	92.2/92
Task 2	95.2/95	…	⋮	…	97.2/97
Task 3	37.2/37	…	{74.2, 85.2, 43.2, 29.2, 92.2, …} / {74, 85, 43, 29, 92, …}	…	58.2/58
Task 4	85.2/85	…	51.2/51	…	20.2/20
Task 5	38.2/38	…	⋮	…	8.2/8

(a)

Bids / Best profits	Asset 1	Asset 2	Asset 3	Asset 4	Asset 5
Task 1	74.2/74	…	43.2/43	…	92.2/92
Task 2	95.2/95	…	⋮	…	97.2/97
Task 3	~~37.2,~~ 33.2 (4)		9.2, ~~92.2,~~ 14.2 (5)		~~58.2,~~ 2.2 (2), 7.2 (1)
Task 4	85.2/85	…	51.2/51	…	20.2/20
Task 5	38.2/38	…	⋮	…	8.2/8

(b)

4.0 SIMULATION RESULTS

4.1 Numerical Model Setup and Performance (Delay) Measurement Model

Here, we compare the performance of distributed auction algorithms in terms of computation and coordination delays for the four information structures and the parallel organizational structure. Two key parameters for analyzing the performance of distributed auction algorithm are the size of benefit matrix for a fixed number of DMs, as well as the number of DMs for a fixed size benefit matrix. This enables us to synthesize the optimal number of DMs for a given benefit matrix size and vice versa. We also compare the performance of point-to-point and blackboard structures.

The computation delay setup is the same as in [11]. However, because the communication between DMs and control DM occurs sequentially, the overall coordination delay for distributed auction is modified as

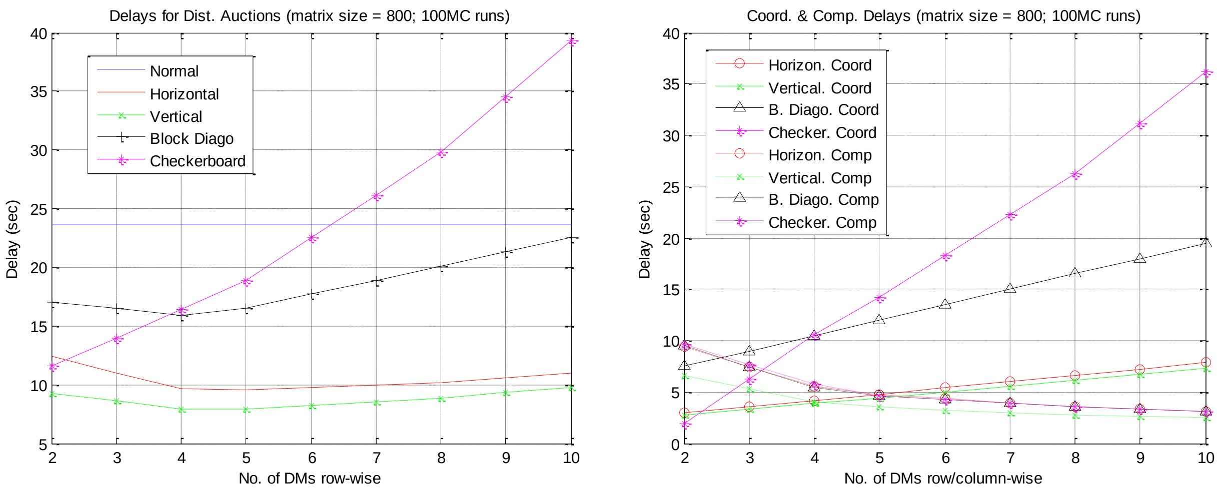
$$t_{coord} = t_{dist} + t_{post} + \sum_{k=1}^{M} (t_{comm})_k \,. \tag{5}$$

4.2 Numerical Results for Point-to-Point Structure

In this section, we discuss the results of applying the distributed auction algorithm using two cases. Our experimental setup is as follows: benefit matrix sizes range from 160 × 160 to 800 × 800, we vary the number of DMs from 2 to 10, and we average delay over 100 Monte Carlo simulation runs on a Quad-Core AMD Opteron™ Processor 2376 (3.29GHz, 15.9GB of RAM).

4.2.1 Case I: Benefit Matrix is Fixed

In this case, we fix the benefit matrix size as 800 × 800 and test the algorithms by varying the number of DMs from 2 to 10 (see Fig. 6 and Table 5). Fig. 6 (a) shows total delays for the parallel organizational structure with each information structure. Here, distributed auction algorithms for horizontal and vertical information structures exhibit less total delay than the normal auction, while the delays of distribution auctions with block diagonal and checkerboard information structure are larger than that of normal auction for more than 8 DMs and 64 DMs (8 DMs row-wise and 8 DMs column-wise), respectively. Note that the total delay for normal auction is 24.7 (sec.). The numbers of DMs having least total delay for the parallel structure is 5, 4, 5 and 4 (2 DMs row-wise and 2 DMs column-wise) for the horizontal, vertical, block diagonal and checkerboard information structures, respectively (see Figs. 6 (a) and Table 5).



(a) (b)

Figure 6: Performance measures for Case 1 (a) Total (b) Coordination/Computation delays.

Table 5: Numerical Results for Case 1 (800 × 800 Matrix / up to 10 DMs. Checkerboard: up to 100).

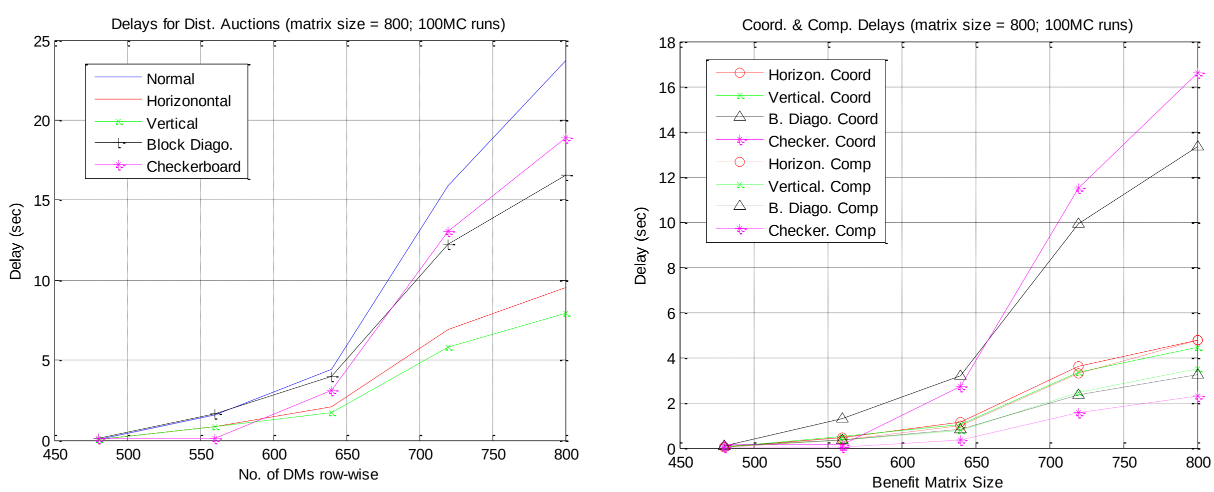
Auction	# of DMs (Checkerboard)	Horizontal	Vertical	Block Diagonal	Checkerboard
Delay[a] (sec.)	2 (4)	12.39	9.30	17.06	11.59
	4 (16)	9.67	7.89	15.88	16.36
	5 (25)	9.54	7.96	16.55	18.89
	6 (36)	9.75	8.25	17.72	22.53
	8 (64)	10.18	8.85	20.07	29.79
	10 (100)	11.00	9.76	22.57	39.30
Speedup	2 (4)	1.9	2.6	1.4	2.0
	4 (16)	2.5	3.0	1.5	1.4
	5 (25)	2.5	3.0	1.4	1.3
	6 (36)	2.4	2.9	1.3	1.1
	8 (64)	2.3	2.7	1.2	0.8
	10 (100)	2.2	2.4	1.1	0.6

[a] The corresponding delay for normal auction is 24.7 (sec)

Fig. 6 (b) displays the coordination and computation delays of distributed auction for the parallel (μ_1) structure. The performance of distributed auction becomes worse with increasing number of DMs because the coordination delay increases linearly for more than 2 DMs (4 DMs with checkerboard information structure) and its increase is more than the decrease in computation delay for more than 5, 5, 3 and 16 DMs for the horizontal, vertical, block diagonal and checkerboard information structures, respectively (see Fig. 6 (b)). This implies that the coordination delay including data distribution time, bid-update/posting time and communication time are not significant up to the corresponding number of DMs. The speedups (the ratio with the normal auction) with optimal numbers of DMs for distributed auction with horizontal, vertical, block diagonal and checkerboard information structures for the parallel structure are 2.5, 3.0, 1.5 and 2.0, respectively (see Table 5). The corresponding efficiencies (ratios of speedup and number of DMs) are 0.50, 0.75, 0.3 and 0.51. The distributed forward/reverse auction with horizontal/vertical information structure for the parallel structure provides the best performance for 5 / 4 DMs, while the distributed auction with block diagonal information structure has the best performance for 5 DMs because it has less coordination delay than other structures.

4.2.2 Case II: Number of DM is Fixed

Here, we fix the number of DMs as 5 and test the algorithms for various sizes of the benefit matrix up to 800 × 800 (see Fig. 7 and Table 6). Fig. 7 (a) shows delays for the parallel organizational structures. Beyond 500 × 500 benefit matrix size, all the distributed auction algorithms except for checkerboard information structure show gradually less delay than the normal auction algorithm because the computation delay of normal auction increases rapidly, while the increase of coordination delay of distributed auction is relatively slow (see Fig. 7 (b)). The delay of the distributed auction with checkerboard information structure is lager than the normal auction algorithm for more than 500 × 500 benefit matrix size because of significant coordination delay among DMs. For more than 500 × 500 benefit matrix size, the matrix size having maximum speedup is 800 × 800 for distributed auction algorithms with horizontal, vertical, block diagonal and checkerboard information structures, and the corresponding speedups for the parallel structure are 2.5, 3.0, 1.4 and 1.3, respectively (see Table 6). The corresponding efficiencies are 0.50, 0.60, 0.24 and 0.05. The horizontal/vertical information structure has better performance than other structures.



(a) (b)

Figure 7: Performance measures for Case 2 (a) Total (b) Coordination/Computation delays.

Table 6: Numerical Results for Case 2 (5 DMs, Checkerboard: 25 / up to 800 × 800 Matrix).

Auction	# of DMs (Checkerboard)	Horizontal	Vertical	Block Diagonal	Checkerboard
Delay[a] (sec.)	480	0.04	0.04	0.15	0.14
	640	2.11	1.74	3.99	3.09
	800	9.54	7.96	16.55	18.89
Speedup	480	1.7	1.7	0.5	0.5
	640	2.1	2.5	1.1	1.4
	800	2.5	3.0	1.4	1.3

[a] The corresponding delay for normal auction is are {0.09, 0.12, 0.07, 4.55, 24.78}

4.2.3 Numerical Results Comparison for Blackboard and Point-to-Point Structures

Here, we compare the performance point-to-point and the blackboard communication structures for a parallel organization (see Fig. 8). The performance of the blackboard communication structure for all information structures is better than the point-to-point communication structure. Specifically, for a 800 × 800 benefit matrix, the blackboard structure is 1.1, 1.11, 1.93 and 2.16 times faster than the point-to-point communication structure for the horizontal, vertical, block diagonal and checkerboard information structures, respectively. Note that the performance difference of the blackboard and point-to-point structures for checkerboard information structure is significant because the coordination load increases very quickly with increase in the number of DMs. Similarly, the performance difference between the two communication structures for block diagonal information is more profound than those for horizontal and vertical information structures because of the increase in coordination between the coordinator and the diagonal DMs.

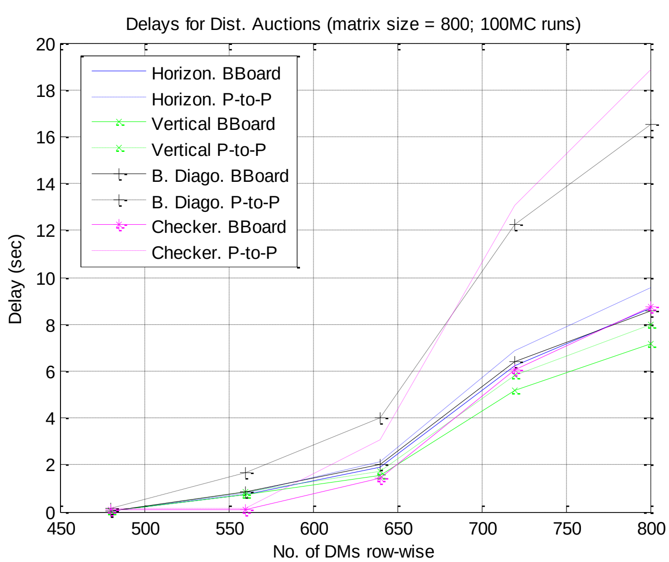


Figure 8: Delay of blackboard and point-to-point communication structures.

4.3 Discussion

Now we point out several practical insights into organizational design with the quantified impacts of our experiments. In our experiments, the horizontal/vertical information structure (akin to a divisional/functional structure) with 4 DMs is the best for a 800 × 800 matrix size showing best efficiency (0.58/0.75). Experiments suggest that horizontal and vertical structures have better performance than block diagonal and checkerboard information structures; specifically, checkerboard information structure (akin to a matrix structure) shows the worst performance due to significant coordination delays and overlap among DMs. However, this structure may be robust to changes in elements of reward matrix and number of DMs. Block diagonal information structure (akin to a hybrid structure) shows reasonable performance because the coordinator resolves row-wise (divisional) and column wise (functional) conflicts. Thus, this structure is applicable to either divisional (horizontal) or functional (vertical) structures. Consequently, the horizontal/vertical information structure (with parallel structure) is consistent with edge organizations being pursued in network-centric warfare in terms of speed of command and information transfer.

5.0 CONCLUSION AND FUTURE WORK

In this paper, we introduced a novel variation of the assignment problem, wherein there are multiple DMs and each DM knows *only a part* of the weight matrix and controls a subset of the assets. This work was motivated by our ongoing work on analytical and computational models for multi-level coordinated mission planning and monitoring processes associated with MOCs. Here, we extended the auction algorithm to such realistic settings with partial information structures. We show that by posting the bid, the best and the second best profits to the blackboard, the DMs can reconstruct the centralized assignment solution. The performance of the parallel organizational structure with various information structures was evaluated by comparing the delays. The distributed auction model in this paper provides a nice analytical framework for formalizing how team members build internal models of other DMs and achieve team cohesiveness over time. In addition, our distributed auction model can be applied to network centric enterprises [10] for quantifying the roles of 1) Distributed information structure in generating awareness, 2) Communication structure, e.g., blackboard or point-to-point, for sharing/improving awareness, and 3) Organizational structure for exploiting awareness.

There are numerous extensions of this research. We mention three here. First, how to develop collaborative planning algorithms with partial information and partial control of assets, wherein each task is characterized by a vector of resource requirements, and each asset is characterized by a vector of resource capabilities? Second, how to design information and coordination structures to maximize organizational efficiency and be robust to a range of missions? Third, given that DMs in hierarchical organizations operate at multiple time scales, how to synthesize multi-level coordination structures that link tactical, operational and strategic levels of decision making is a major research issue.

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