Supplementary Material for Paper #1084

A AsymDPOP

A.1 Pseudo Code for AsymDPOP

Fig 1. gives the sketch of AsymDPOP, and the execution process can be divided into two phases: utility propagation phase and value propagation phase. The utility propagation phase begins with leaf agents sending their utility tables to their parents via UTIL messages (line 2-3). When an agent a_i receives a UTIL message from its child a_c, it joins its private functions w.r.t. its (pseudo) children in branch a_c (line 5-6), and eliminates all the belonging variables whose highest (pseudo) parent is a_i from the utility table (line 7). Here, $EV(a_i, a_c)$is given by

$$EV\left(a_i, a_c\right) = PC\left(a_i\right) \cap Desc\left(a_c\right) \cup \{a_c\} \setminus ID\left(a_i\right)$$

where $ID(a_i)$ is the set of a_i's interface descendants which are constrained with $Sep(a_i)$. After receiving all the UTIL messages from its children, a_i propagates the joint utility table to its parent if it is not the root agent. Otherwise, the value propagation phase starts.

The value propagation phase begins with the root agent selecting the optimal assignment for itself (line 10). Given the determined assignments either from its parent (line 14) or computed locally (line 11), agent a_i selects the optimal assignments for the eliminated variables in each branch $a_c \in C(a_i)$ by a joint optimization over them (line 15-18), and propagates the assignments together with the determined assignments to a_c (line 19-20). The algorithm terminates when each leaf agent receives a VALUE message.

Algorithm 1: AsymDPOP for a_i

When `Initialization`**:**
1 $util_i \leftarrow \bigotimes_{a_j \in AP(a_i)} f_{ij}$
2 **if** a_i *is a leaf* **then**
3 send UTIL($util_i$) to $P(a_i)$
When `received UTIL(`$util_c$`)` *from* $a_c \in C(a_i)$**:**
4 $util_i^c \leftarrow util_c$
5 **foreach** $a_j \in (PC(a_i) \cap Desc(a_c)) \cup \{a_c\}$ **do**
6 $util_i^c \leftarrow util_i^c \otimes f_{ij}$
7 $util_i \leftarrow util_i \otimes \min_{EV(a_i,a_c)} util_i^c$
8 **if** a_i *have received all UTIL from* $C(a_i)$ **then**
9 **if** a_i *is the root* **then**
10 $v_i^* \leftarrow \operatorname{argmin}_{x_i} util_i$
11 **PropagateValue**($\{(x_i = v_i^*)\}$)
12 **else**
13 send UTIL($util_i$) to $P(a_i)$
When `received VALUE(`$Assign$`)` *from* $P(a_i)$**:**
14 **PropagateValue**($Assign$)
Function `PropagateValue(`$Assign$`)`**:**
15 **foreach** $a_c \in C(a_i)$ **do**
16 $Assign_i^c \leftarrow Assign$
17 **if** $EV(a_i, a_c) \neq \emptyset$ **then**
18 $V^* \leftarrow \operatorname{argmin}_{EV(a_i,a_c)} util_i^c(Assign_{[dims(util_i^c)]})$
19 $Assign_i^c \leftarrow Assign_i^c \cup \{(x_j = V^*_{[x_j]}) | \forall x_j \in EV(a_i, a_c)\}$
20 send VALUE($Assign_i^c$) to a_c

Figure 1: The sketch of AsymDPOP

A.2 An Example for AsymDPOP

Fig.2 gives a pseudo tree. For better understanding, we take a_2 to explain the concepts in a pseudo tree. Since a_1 is the only ancestor constrained with a_2 via a tree edge, we have $P(a_2) = \{a_1\}$, $PP(a_2) = \emptyset$ and $Sep(a_2) = \{a_1\}$. Similarly, since a_3 and a_4 are the descendants constrained with a_2 via tree edge, we have $C(a_2) = \{a_3, a_4\}$, $PC(a_2) = \emptyset$, $Desc(a_2) = \{a_3, a_4\}$. Particularly, since $a_4 \in Desc(a_2)$ is constrained with $a_1 \in Sep(a_2)$, we have $ID(a_2) = \{a_4\}$.

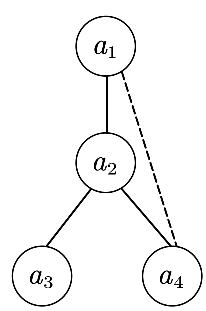


Figure 2: A pseudo-tree

Since a_3 and a_4 are the leaf nodes, they send UTIL messages with their utility tables $util_3$ and $util_4$ to their parent a_2, where $util_3 = f_{32}$ and $util_4 = f_{41} \otimes f_{42}$.

When receiving a UTIL message from a_3 (assume a_3's message has arrived earlier), a_2 stores the received message from a_3 ($util_2^3 = util_3 = f_{32}$), and then joins its private function f_{23} to update $util_2^3$ ($util_2^3 = f_{32} \otimes f_{23}$). According to the definition of $EV(a_i, a_c)$ that all the belonging variables' highest (pseudo) parent is a_i in branch a_c. Here, $EV(a_2, a_3)$ is given by

$$EV(a_2, a_3) = PC(a_2) \cap Desc(a_3) \cup \{a_3\} \backslash ID(a_2)$$
$$= \emptyset \cap \emptyset \cup \{a_3\} \backslash \{a_4\} = \{a_3\}$$

Thus, a_2 eliminates variable x_3 from $util_2^3$. After that, a_2 joins the eliminated result to the joint utility table $util_2$. Similarly, upon receipt of the UTIL message from a_4, a_2 saves the content as $util_2^4$ ($util_2^4 = util_4 = f_{41} \otimes f_{42}$), and updates it with joining the private function f_{24} ($util_2^4 = f_{41} \otimes f_{42} \otimes f_{24}$). Since $EV(a_2, a_4) = \emptyset$, a_2 joins $util_2^4$ to the $util_2$ directly without any elimination operation. Since a_2 have received all the UTIL messages from its children, it propagates $util_2$ to its parent a_1. Here, we have

$$util_2 = f_{21} \otimes (f_{41} \otimes f_{42} \otimes f_{24}) \otimes (\min_{x_3} f_{23} \otimes f_{32})$$

When receiving the UTIL message from a_2, a_1 saves the content as $util_1^2$ ($util_1^2 = util_2$) and joins the private functions f_{12} and f_{14} to update $util_1^2$ ($util_1^2 = util_1^2 \otimes (f_{12} \otimes f_{14})$). After eliminating x_2 and x_4 ($EV\,(a_1, a_2) = \{a_2, a_4\}$), a_1 joins the eliminated result into $util_1$. Here, we have

$$util_1 = \min_{x_2, x_4} f_{12} \otimes f_{14} \otimes (f_{21} \otimes (f_{41} \otimes f_{42} \otimes f_{24}) \otimes (\min_{x_3} f_{23} \otimes f_{32}))$$

Since a_1 is the root agent and receives all the UTIL messages from its children, it selects the optimal assignment v_1^* for itself and the optimal assignments v_2^* and v_4^* for the eliminated variables x_2 and x_4. That is,

$$v_1^* = \operatorname*{argmin}_{x_1} util_1,$$

$$(v_2^*, v_4^*) = \operatorname*{argmin}_{x_2, x_4} util_1^2(x_1 = v_1^*)$$

Then a_1 propagates a VALUE message including the optimal assignment to its child a_2, where the optimal assignment is $\{(x_1 = v_1^*), (x_2 = v_2^*), (x_3 = v_3^*)\}$.

When receiving the VALUE message from a_1, a_2 assigns the value v_2^* for itself. Since $EV(a_2, a_3) = \{a_3\}$ and $EV(a_2, a_4) = \emptyset$, a_2 selects the optimal assignment for a_3 by performing optimization over $util_2^3$ with the determined assignment of x_2, that is

$$v_3^* = \operatorname*{argmin}_{x_3}(util_2^3(x_2 = v_2^*))$$

Then a_2 propagates the optimal assignment ($x_3 = v_3^*$) and ($x_4 = v_4^*$) to a_3 and a_4, respectively. Once a_3 and a_4 receives the VALUE messages, they assign for themselves. Since all leaf agents receives VALUE messages, the algorithm terminates.

B AsymDPOP with MBPS and MBES

B.1 Pseudo Code for AsymDPOP with MBPS and MBES

Fig.3 gives the sketch of AsymDPOP with MBPS and MBSE. Like Algorithm 1, the execution process consists of two

Algorithm 2: AsymDPOP(MBPS+MBES) for a_i

When Initialization:
- $util_i \leftarrow \emptyset$
- **if** *a_i is a leaf* **then**
  - send UTIL(**PartitionF**()) to $P(a_i)$

When received UTIL($util_c$) *from $a_c \in C(a_i)$*:
- $util_i^c \leftarrow util_c$
- **foreach** $a_j \in (PC(a_i) \cap Desc(a_c)) \cup \{a_c\}$ **do**
  - **if** $\exists u \in util_i^c, s.t. dims(f_{ij}) \subset dims(u)$ **then**
    - $u \leftarrow u \otimes f_{ij}$
    - **break**
- $util_i \leftarrow util_i \cup \mathbf{Min}(util_i^c, EV(a_i, a_c))$
- **if** *a_i have received all UTIL from $C(a_i)$* **then**
  - **if** *a_i is the root* **then**
    - $v_i^* \leftarrow \operatorname*{argmin}_{x_i}(\bigotimes_{u \in util_i} u)$
    - **PropagateValue**($\{(x_i = v_i^*)\}$)
  - **else**
    - send UTIL($util_i \cup$ **PartitionF**()) to $P(a_i)$

When received VALUE($Assign$) *from $P(a_i)$*:
- **PropagateValue**($Assign$)

Function PropagateValue($Assign$):
- **foreach** $a_c \in C(a_i)$ **do**
  - $Assign_i^c \leftarrow Assign$
  - **if** $EV(a_i, a_c) \neq \emptyset$ **then**
    - $u' \leftarrow \bigotimes_{u \in util_i^c} u(Assign_{[dims(u)]})$
    - $V^* \leftarrow \operatorname*{argmin}_{EV(a_i, a_c)}(u')$
    - $Assign_i^c \leftarrow Assign_i^c \cup \{(x_j = V^*_{[x_j]}) | \forall x_j \in EV(a_i, a_c)\}$
  - send VALUE($Assign_i^c$) to a_c

Function Min($util, EV$):
- $U \leftarrow util, G \leftarrow \mathbf{GroupEV}(EV)$
- $EVSet \leftarrow \bigcup_{\forall EV' \in G} \mathbf{PartitionEV}(EV', U)$
- **foreach** $EV' \in EVSet$ **do**
  - $F \leftarrow \{f | \forall f \in U, dims(f) \cap EV' \neq \emptyset\}$
  - $U \leftarrow (U \backslash F) \cup \{\min_{EV'} \bigotimes_{f \in F} f\}$
- **return** U

Function PartitionF():
- $u \leftarrow \emptyset, U \leftarrow \emptyset$
- order $AP(a_i)$ according to their levels
- **foreach** $a_j \in AP(a_i)$ **do**
  - **if** $\exists u' \in util_i, s.t. dims\,(f_{ij}) \subset dims\,(u')$ **then**
    - $u' \leftarrow u' \otimes f_{ij}$
  - **else**
    - **if** $|dims(u)| \geq k_p$ **then**
      - $U \leftarrow U \cup \{u\}$
      - $u \leftarrow f_{ij}$
    - **else**
      - $u \leftarrow u \otimes f_{ij}$
- **if** $u \neq \emptyset$ **then**
  - random select an element $u' \in U$
  - $u' \leftarrow u' \otimes u$
- **return** U

Function GroupEV($EV, util$):
- $Dims \leftarrow \{dims(u) \cap EV | \forall u \in util\}$
- **while** $\exists D, D' \in Dims, s.t. D \cap D' \neq \emptyset$ **do**
  - $D \leftarrow D \cup D', Dims \leftarrow Dims \backslash D'$
- **return** $Dims$

Function PartitionEV(EV):
- $EV' \leftarrow \emptyset, EVSet \leftarrow \emptyset$
- **foreach** $ev \in EV$ **do**
  - **if** $|EV'| \geq k_e$ **then**
    - $EVSet \leftarrow EVSet \cup \{EV'\}$
    - $EV' \leftarrow \{ev\}$
  - **else**
    - $EV' \leftarrow EV' \cup \{ev\}$
- **if** $EV' \neq \emptyset$ **then**
  - random select an element $EV'' \in EVSet$
  - $EV'' \leftarrow EV'' \cup EV'$
- **return** $EVSet$

Figure 3: The sketch of AsymDPOP with MBPS and MBES

phases: utility propagation phase and value propagation phase. The utility propagation phase also begins with leaf agents sending a set of utility tables to their parents via UTIL messages (line 2-3). The set of utility tables obtain from the Function **PartitionF**. In this function, agent a_i divides its private functions which are constrained with $AP(a_i)$ into several buckets, and joins the private functions in the same bucket into one utility table (line 32-40). If there is any residue, a_i joins them into an arbitrary bucket (line 41-43). Note that k_p is a parameter which controls the minimal number of dimensions of each bucket.

When receiving a UTIL message from its child a_c, a_i joins its private functions w.r.t. its (pseudo) children in branch a_c (line 6-8). Notice that the join operation of its private functions w.r.t. its children does not increase the number of dimensions and should be applied accordingly to the related utility tables. When performing eliminations, a_i uses Function **Min** to implement (line 9,24-29). To be more specific, instead of eliminating all the variables in $EV(a_i, a_c)$ directly, a_i first divides elimination variables into several groups whose variables share at least a common utility table in Function **GroupEV** (line 24). And then, for each variable group, a_i divides the variables into several sets (or batches) with the Function **PartitionEV** in the similar way as Function **PartitionF** (line 25). Specifically, k_e in **PartitionEV** specifies the minimal number of variables optimized in a min operator (i.e., the size of a batch). After getting elimination variable set ($EVSet$), a_i traverses the set to optimize $util$ that has been passed to Function **Min** (line 26). In detail, for each batch, we perform optimization to the utility tables that are related to the variables in the batch over the batch and replace these utility tables with the results. The process terminates when the all the variable batches are exhausted (line 27-28). Subsequently, a_i returns the new utility table set which has been eliminated properly (line 29).

When receiving all the UTIL messages from its children, a_i propagates the joint utility table set to its parent if it is not the root agent. Otherwise, the value propagation phase starts (line 13). The process is roughly as the same as Algorithm 1. Agent a_i selects the optimal assignments for itself and the eliminated variables in each branch $a_c \in C(a_i)$. And since it uses the MBPS, there may be not one joint utility table (in Algorithm 1) but a set of joint utility tables with the smaller size. So before selecting the optimal assignments for branch a_c, a_i joins all the tables in $util_i^c$ with the assignments received from its parent (line 16) or computed locally (line 13). After selecting the assignments for variables of $EV(a_i, a_c)$ in branch a_c (line 21-22), it sends a VALUE message to a_c (line 23). The algorithm terminates when each leaf agent receives a VALUE message.

B.2 An Example of AsymDPOP with MBPS and MBES

For the convenience of further explanation, we denote the joint utility table u_{ijk} as a function of three variables x_i, x_j and x_k. And the functions which have exact same dimensions but order their index in different sequences differ from each other (e.g., $u_{ijk} \neq u_{jki}$).

We take Fig.4 as an example to demonstrate the Algorithm 2. Suppose that $k_p = 3$ and $k_e = 1$. Since a_5 is the leaf node, it sends a UTIL message with a set of utility tables obtained from Function **PartitionF** to its parent a_4. In **PartitionF**, a_5 first orders $AP(a_5)$ according to their levels. And it divides its private functions which are related with $AP(a_5)$ into buckets. Because the size of $AP(a_5)$ is two, the biggest dimension of the joint utility table is 3 which just equals to k_p. So there is only one bucket. And a_5 joins the functions in the bucket to get a 3-ary utility table u_{541} ($u_{541} = f_{54} \otimes f_{51}$), and sends the set including the joint utility table u_{541} to its parent a_4.

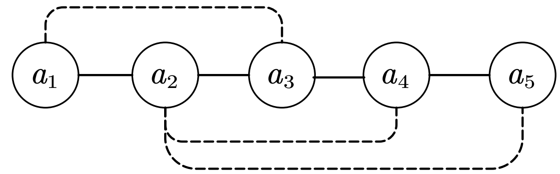


Figure 4: A chain-like pseudo tree

When a_4 receives the UTIL message from its child a_5, it saves the utility set and updates the element u_{541} to u_{451} by joining its private function f_{45}. And since a_4 is not the highest (pseudo) parent of any descendants ($EV(a_4, a_5) = \emptyset$), there is no elimination operation. Next, since it has received all the UTIL messages from its children, a_4 sends a set which contains the joint utility table u_{432} and u_{451} to its parent a_3. Here, u_{432} is given by joining the private functions f_{43} and f_{42}.

When receiving the UTIL message from a_4, similarly, a_3 saves the utility set and updates u_{432} to u_{342} by joining its private function f_{34}. Also, a_3 is not the highest (pseudo) parent of a_4 or any other descendants so no elimination occurs. Then it deals with the residual private functions (f_{31} and f_{32}) with Function **PartitionF** by joining them into a 3-ary utility table u_{321}. And it sends the utility table set $\{u_{451}, u_{342}, u_{321}\}$ to its parent a_2.

Once a_2 receives the UTIL message from a_3, it also saves the utility table set firstly, and joins the relative private function f_{23} into u_{321} getting u_{231}. Since a_2 is the highest (pseudo) parent of a_4 and a_5, that is $EV(a_2, a_3) = \{a_4, a_5\}$, the eliminations are preformed by Function **Min**. Firstly, a_2 groups variables x_4 and x_5 into one group, as they share a common utility table f_{451}. Since $k_e = 1$, variables x_4 and x_5 are separated in two batches automatically, and they are eliminated from the utility functions in the set $\{u_{451}, u_{342}, u_{231}\}$ one by one. After eliminating x_5, we get a new utility table set $\{u_{41}, u_{342}, u_{231}\}$. Before eliminating x_4 from this new set, it needs to join the function u_{41} with u_{342}. Finally, a_2 gets a set containing u_{231} and u_{213}. Here, u_{213} is derived by eliminating x_4 from the utility table which is got by joining f_{41} into u_{342}. And then, a_2 send the new set to its parent a_1.

When a_1 receives the UTIL message from a_2, it saves the utility set, and then joins the relative private functions f_{12} and f_{13} into u_{231} getting u_{123}. Since $EV(a_1, a_2) = \{a_2, a_3\}$ and the variables x_2 and x_3 are both relative to the utility table u_{123}, they are grouped into one set. But since $k_e = 1$, a_1 still eliminates the variables x_2 and x_3 from the utility tables in the set $\{u_{123}, u_{213}\}$, respectively, and gets a new set as its own utility table set. Since it is the root agent and has received all the UTIL messages from its children, a_1 joins all the utility tables in the set derived from eliminating x_2 and x_3, and chooses the optimal value v_1^* for itself. Thus, the value propagation phase starts. a_1 selects the values v_2^* and v_3^* for a_2 and a_3, and propagates the assignment $\{(x_1 = v_1^*), (x_2 = v_2^*), (x_3 = v_3^*)\}$ to a_2. Then, a_2 selects the optimal assignments for a_4 and a_5 after receiving the VALUE message from a_1, and sends the assignment $\{(x_1 = v_1^*), (x_2 = v_2^*), (x_3 = v_3^*), (x_4 = v_4^*), (x_5 = v_5^*)\}$ to a_3. Upon receipt of the VALUE message, a_3 assigns for itself and sends the assignments received from a_2 to its child a_4. And a_4 performs just like a_3. The algorithm terminates after the leaf agent a_5 receives the VALUE message and assigns for itself.

C Experiment Results

C.1 The Experimental Configuration

The Experiment with Different Agent Numbers

- Problem type: Random ADCOPs
- Agent numbers: [8, 24]
- Density: 0.25
- Domain size: 3

The Experiment with Different Densities

- Problem type: Random ADCOPs
- Agent numbers: 8
- Density: [0.25, 1.0]
- Domain size: 8

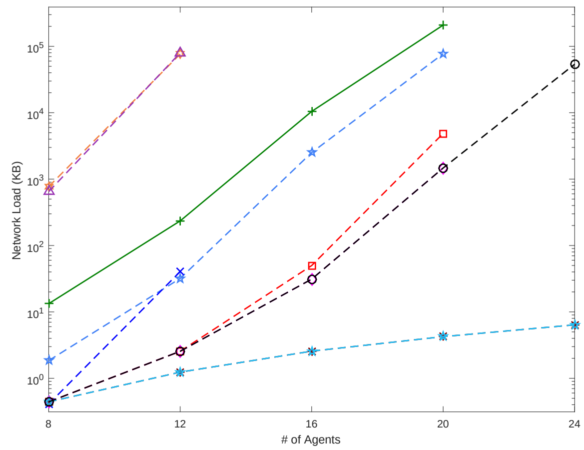
The Experiment with Different Domain size

- Problem type: Random ADCOPs
- Agent numbers: 8
- Density: 0.4
- Domain size: [4, 14]

The Experiment with Different Tightness

- Problem type: ADCSPs
- Agent numbers: 10
- Density: 0.4
- Domain size: 10
- Tightness: [0.1, 0.8]

C.2 The Experiment Results



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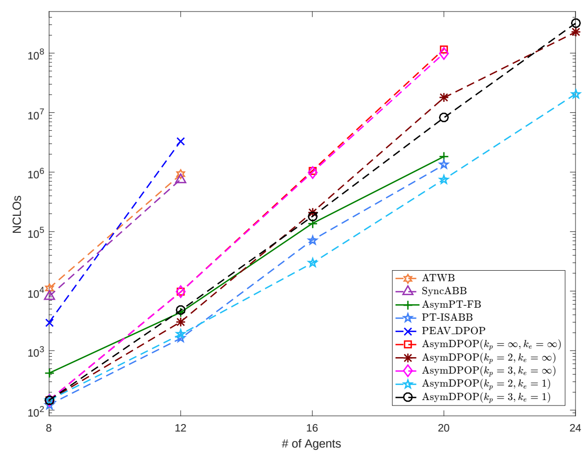
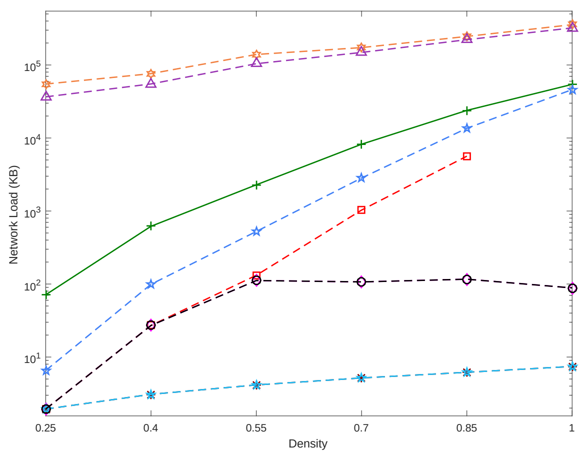


(b)

Figure 5: Performance comparison under different agent numbers



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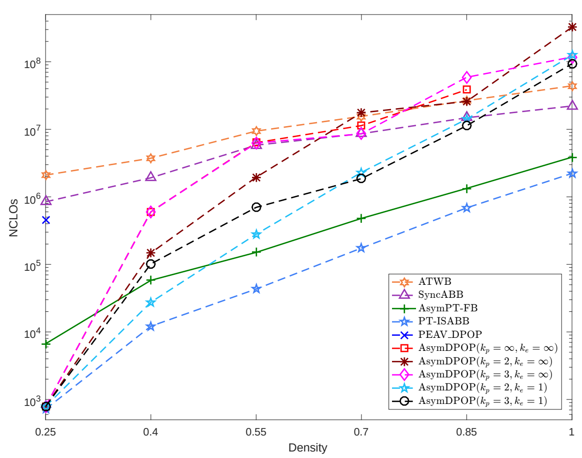

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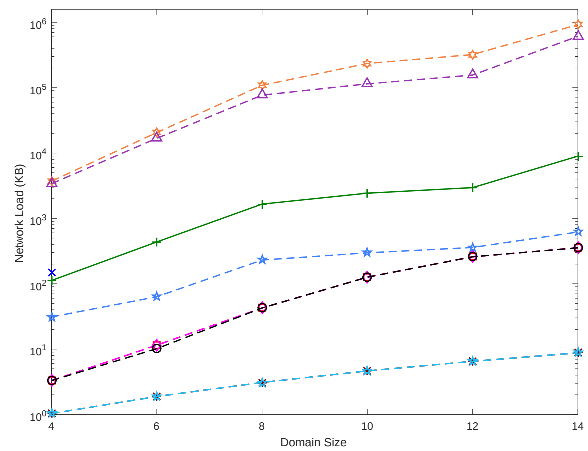
Figure 6: Performance comparison under different densities



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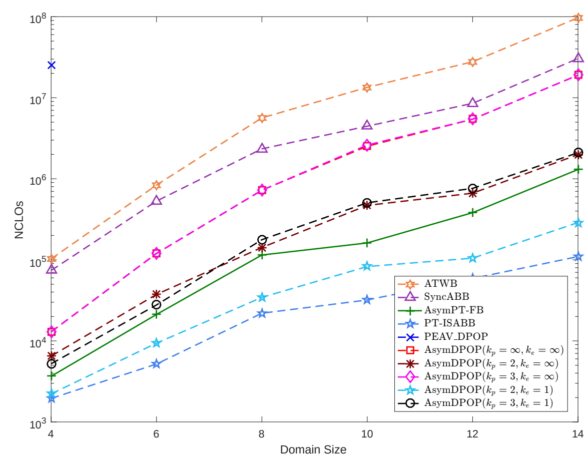

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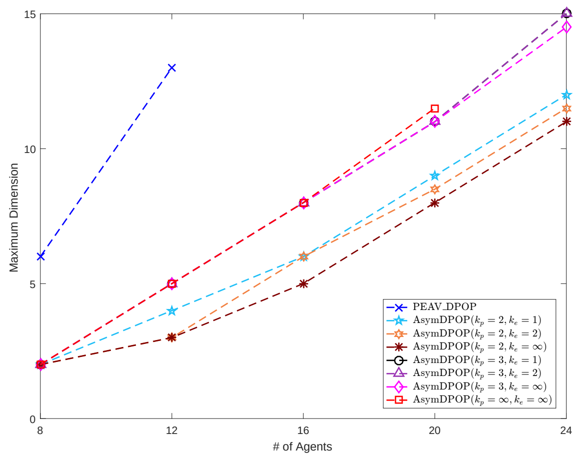
Figure 7: Performance comparison under different domain size



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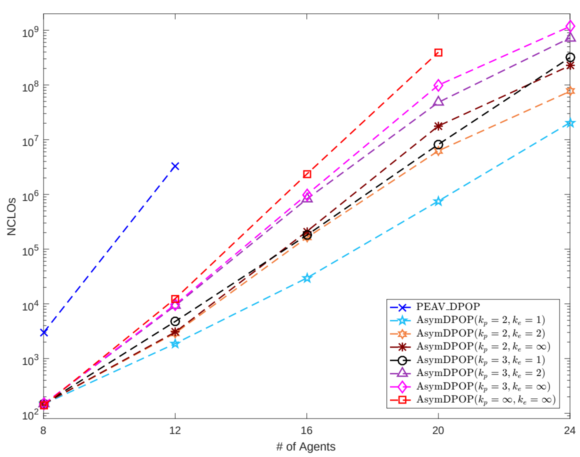
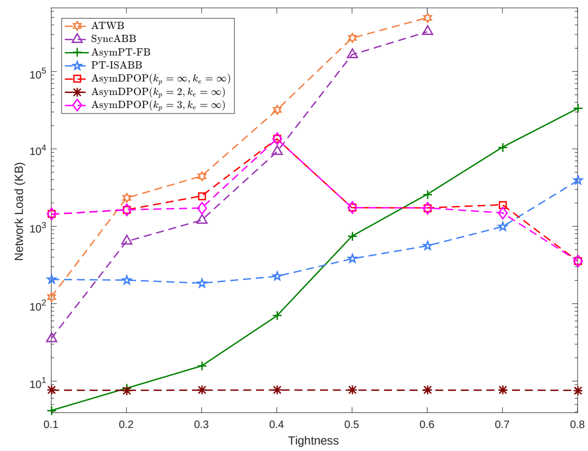


(b)

Figure 8: Performance comparison under different batch size



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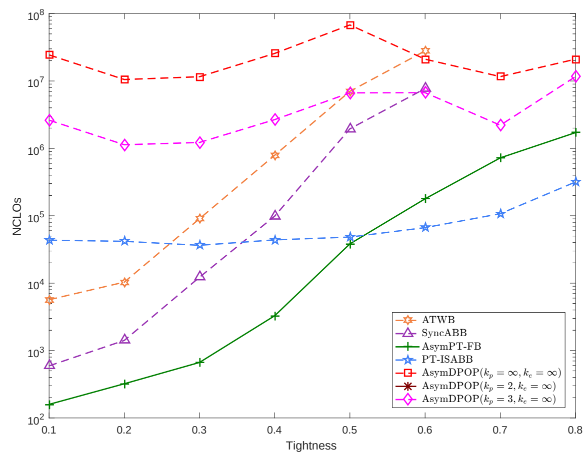

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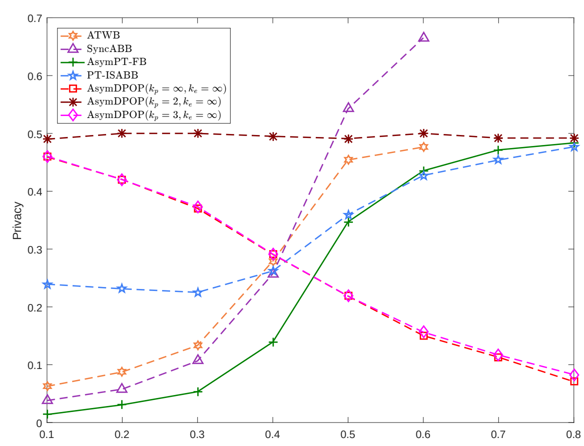

(c)

Figure 9: Performance comparison under different tightness