A Topic-Based Data Distribution Management for HLA

Alberto Falcone\textsuperscript{a} and Alfredo Garro\textsuperscript{b}

Department of Informatics, Modeling, Electronics and Systems Engineering, University of Calabria, Via P. Bucci 41/C, Rende, Italy

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Abstract: Modeling and Simulation (M&S) represents a fundamental technology for designing and studying complex systems in various industrial and scientific domains, when real-world testing is too costly to perform in terms of safety, time, and other resources. To promote the reusability and interoperability of simulation models allowing them to interoperate without geographic constraints, distributed simulation has been introduced. One of the most widely adopted standards for distributed simulation is IEEE 1516-2010 - High Level Architecture (HLA). Among the services provided by HLA, a key one is the Data Distribution Management (DDM) that allows to reduce the transmission and reception of unnecessary data in order to improve communication effectiveness among simulation models. Although many matching algorithms have been proposed in the literature, the upcoming HLA 4.0 standard defines a DDM that still relies on performing matching verification by calculating the overlap between regions using their dimensions. In this paper, a novel topic-based publish-subscribe messaging system is proposed to improve the performance, reliability, and scalability of DDM services. Experiments show that the proposed topic-based approach achieves better performance than the standard one.

1 INTRODUCTION

In the last years, the complexity of Cyber-Physical Systems (CPSs) has increased exponentially, mainly due to the heterogeneity of the involved components and related interactions that connect the cyber world, through a network of interconnected computational resources (e.g., sensors, actuators, and processing units), to the physical one (Lee, 2008; Falcone et al., 2020; Falcone et al., 2022). CPSs are characterized by being highly automated, intelligent, and collaborative. The design and implementation of CPSs represent a challenging task due to the vast network and computing resources connected to the physical environment involving multiple domains such as controls, network protocols, and software engineering. To capture the structure and behavior of such systems, researchers rely on Modeling and Simulation (M&S) techniques (Bouskela et al., 2021; Derler et al., 2012; Falcone et al., 2014). M&S represents a pillar technology for designing and studying complex systems in various industrial and scientific domains, when real-world testing is too costly to perform in terms of safety, time, and other resources. To promote the reusability and interoperability of simulation models allowing them to interoperate without geographic constraints, Distributed Simulation (DS) has been introduced (Fujimoto, 2000). One of the most widely adopted standards for distributed simulation is IEEE 1516-2010 - High Level Architecture (IEEE Std. 1516-2010, 2010).

The HLA standard defines a generic architecture to support reusability and interoperability across simulation models. The standard was developed in 1996 under the guidance of the United States Department of Defense (DoD) Modeling and Simulation Coordination Office (M&S CO). After its definition, HLA caught the interest in the industrial and scientific domains, so it was later moved into an IEEE international standard with the official name “IEEE 1516”. In the HLA terminology, a distributed simulation is called Federation, which is composed of many HLA simulation applications called Federates. Federates interact with each other, in the same Federation, using the services provided by the Run-Time Infrastructure (RTI) that represents the communication middleware that implements the HLA interface specifications and rules. The structure and semantics of the data exchanged are delineated following the Object Model.

\textsuperscript{a} https://orcid.org/0000-0002-2660-1432
\textsuperscript{b} https://orcid.org/0000-0003-0351-0869
Template (OMT) specifications. The RTI provides six service groups to handle the distributed simulation execution: Federation Management, Declaration Management, Object Management, Ownership Management, Time Management, and Data Distribution Management (DDM).

DDM provides a set of services to minimize the transmission and reception of unnecessary data and then maximize communication effectiveness among Federates, letting them specify the data of interest. Specifically, the interest in specific information is expressed as bounded portions of a n-dimensional space of user-defined dimensions. Both consumer and producer federates specify the upper and lower bounds for a specific portion, thus creating a so-called region. Federates that produce data define update regions; whereas, federates that consume data specify subscription regions.

At the core level, DDM services use an algorithm that scans all n-dimensional regions to find the pairs of regions (update, subscription) that generate overlap. The RTI routes data from producer federates to consumer ones if and only if there is an overlap, i.e., a match between their update and subscription regions. According to the HLA standard, a match must be reported to the RTI exactly once by the DDM services. This problem is well-known in theoretical computer science and can be solved using suitable algorithms with ad-hoc spatial data structures. However, many DDM implementations tend to rely on less efficient algorithms that adopt complex spatial data structures whose manipulation may have a significant impact on computational resource utilization (Marzolla and D’angelo, 2020).

In this paper, the novel Topic-Based Matching Algorithm (TBMA) is proposed to improve the performance, reliability, and scalability of DDM services. TBMA defines the concept of topic to handle a high number of regions, where the match operation is performed by using topics instead of calculating overlaps between regions’ coordinates.

The paper is structured as follows. Section 2 provides the problem statement along with key definitions. Section 3 discusses related work on the HLA DDM services and existing matching algorithms. Section 4 describes the proposed topic-based DDM approach. Section 5 presents experiments carried out to evaluate the performance of the proposed topic-based matching algorithm, where the simulation results have been compared with the standard one. Finally, conclusions are discussed in Section 6.

2 PROBLEM STATEMENT

The DDM services are based on the following definitions (IEEE Std. 1516-2010, 2010):

Definition 1: Dimension. It is a non-negative interval with an associated label. The interval is defined by an ordered pair of values \([d_{lb}, d_{ub}] := \{x \in \mathbb{R} \mid d_{lb} \leq x \leq d_{ub}\}\), with \(d_{lb} \leq d_{ub}\). The interval lower bound \(d_{lb}\) is 0 for every dimension, while the upper bound \(d_{ub}\) can vary for each dimension.

Definition 2: Range. It is a continuous semi-open interval defined on a dimension \(d\). It is defined by an ordered pair of values \([r_{lb}, r_{ub}] := \{x \in \mathbb{R} \mid r_{lb} \leq x < r_{ub}\}\), with \(r_{ub} - r_{lb} \geq 1\). The component of the range \(r_{lb}\) and \(r_{ub}\) are known as range lower bound and range upper bound, respectively.

Definition 3: Region Specification. It is defined as a set of ranges, named \(RS\). \(RS\) must contain at most one range \(r\) for any given dimension \(d \in D\), where the dimension set \(D\) is derived starting from the ranges that constitute \(RS\). Each range \(r \in RS\) is defined in terms of bounds \([0, d_{ub}]\), where \(d_{ub}\) is the corresponding dimension’s upper bound.

Definition 4: Region Template. It is defined as an incomplete region specification in which one or more dimensions have not been assigned ranges.

Definition 5: Region Realization. It is defined as a region specification that is associated with an instance attribute for update, a sent interaction, or a class attribute or interaction class for subscription. The term region may be used in cases where a region specification, a region realization, or both apply. The DDM process goes through four phases: (i) declaration, (ii) match, (iii) connect, and (iv) forward, which repeatedly occur throughout the federation execution (IEEE Std. 1516-2010, 2010; Zhu and Wang, 2022). In the declaration step, federates create regions with a specific set of dimensions, and declare the HLAObjectClass and/or HLADeclarationClass data that they intend to publish and/or subscribe, in terms of update and subscription regions, respectively. In the match phase, the overlap between each pair of update and subscription regions is calculated, and obtained pairs are reported to the RTI. After that, in the connect phase, the RTI establishes connections between the sending federate and receiving ones. Finally, in the forward phase, data are forwarded through the created connections.

The region matching problem can be defined as follow. Given an update region set \(U = \{u_1, u_2, \ldots, u_n\}\) and a subscription region set \(S = \{s_1, s_2, \ldots, s_m\}\), such that \(U \cap S \neq \{\emptyset\}\), and \(R = U \cup S\). An update \(u_i\) and a subscription \(s_j\) region overlap if and only if all ranges of dimensions that are contained in both regions over-
lap pairwise. If the regions do not have any dimensions in common, they do not overlap. Algorithm 1 delineates the steps to check for overlap between two ranges \(a = [a_{lb}, a_{ub})\) and \(b = [b_{lb}, b_{ub})\) for a given a dimension \(d\).

Algorithm 1: Calculation of an overlap between ranges for a given a dimension \(d\).

<table>
<thead>
<tr>
<th>Require: (d)</th>
<th>(\triangleright) dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Require: (a, b)</td>
<td>(\triangleright) ranges defined both on (d)</td>
</tr>
<tr>
<td>1: overlap (\leftarrow) ({(a_{lb} = b_{lb}) \lor (a_{lb} &lt; b_{ub} \land b_{ub} &lt; a_{ub})})</td>
<td></td>
</tr>
<tr>
<td>2: return overlap</td>
<td></td>
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</tbody>
</table>

Figure 1 depicts an example of a two-dimensional region matching problem composed of two subscription regions \(S = \{s_1, s_2\}\) and one update region \(U = \{u_1\}\) both specified on the dimensions \(X\) and \(Y\), where, for example, \(X\) and \(Y\) can represent latitude and longitude, respectively (Möller et al., 2016). It is easy to identify that the pair \(\{(s_2, u_1)\}\) is the solution to the region matching problem, since their ranges overlap on both dimensions. The pair \(\{(s_1, u_1)\}\) is not part of the solution; therefore, \(s_2\) will receive data from \(u_1\) while \(s_1\) will not.

The correct definition of the region matching algorithm is crucial for the network and processing cost (Raczy et al., 2005). This problem can be reduced to the rectangles intersection problem. To find the intersections between two-dimensional rectangles, in (Bentley and Wood, 1980), the authors developed an algorithm with computational complexity equal to \(O(N \cdot \log(N) + K)\), where \(N\) is the number of two-dimensional rectangles and \(K\) is the number of intersecting pairs discovered. However, the proposed algorithm can only be applied to two-dimensional rectangles and does not offer a generic solution for \(n\)-dimensional rectangles.

The following section reviews the existing literature contributions dealing with both the DDM services and region matching algorithms.

3 RELATED WORK

Four relevant DDM matching algorithms have been developed, i.e., Region-Based Matching (RBM), Grid-Based Matching (GBM), Hybrid-Based Matching (HBM), and Sort-Based Matching (SBM).

3.1 Region-Based Matching

The Region-Based Matching algorithm is also known as Brute-Force Matching algorithm. Given a dimension \(d\), it finds overlaps by comparing each update region with all the subscription ones. The RBM matching algorithm is simple to implement and allows to derive exact overlapping information. The computational complexity is \(O(n \cdot m)\), where \(n\) and \(m\) are the number of update and subscription regions, respectively. However, this computational complexity is affected by the number of dimensions; therefore, in the generic \(d\)-dimensional case, i.e., running the RBM algorithm for each dimension \(d\) and calculating intersections between regions, the computational complexity is \(O(d \cdot (n \cdot m))\).

The main advantage of this algorithm is its simplicity, but it has scalability issues as regions and dimensions grow. RBM was adopted in the first version of the Defense Modeling and Simulation Office (DMSO) RTI implementation of the HLA 1.3 specifications, and in the MAK High-Performance RTI (Wood, 2002; Pan et al., 2011).

3.2 Grid-Based Matching

The Grid-Based Matching algorithm works by partitioning the Multi-Dimensional Coordinate Space (MDCS) into a grid of cells. Each region \(r\) is then mapped, through a function \(f(r)\), to the corresponding cells of the grid. In GBM, an overlap between an update and a subscription region happens if and only if they have at least one cell of the grid in common (Boukerche et al., 2005).

While the GBM algorithm has a lower computational overhead than the RBM one, the overlapping information is not exactly determined. Therefore, irrelevant data may be received by a subscribing federate \(f_s\) even if it has no region overlaps with the updating federate \(f_u\), but only because \(f_s\) and \(f_u\) have at least one cell in the grid in common. Obviously,
this leads to unnecessary consumption of network resources, and $f_s$ has to discard irrelevant data it receives. To overcome this issue, many RTI implementations with GBM-based DDM services adopt an additional data filter on the receiving side.

The computational complexity is $O(c + n \cdot m/c)$, where $c$ is the number of cells, $n$ and $m$ are the number of update and subscription regions, respectively. In the generic $d$-dimensional case, i.e., running the GBM algorithm for each dimension $d$, the computational complexity is $O(d \cdot (c + n \cdot m/c))$ (Marzolla and D’angelo, 2020).

Like RBM, this algorithm is simple to implement but is more scalable than the first one. The performance of the GBM algorithm depends not only on the grid size but also on the size of the individual cells that compose it. Indeed, the larger the cell size, the greater the amount of irrelevant data transferred, but the shorter the time the GBM algorithm takes to detect overlaps between regions. On the other hand, the smaller the cell size, the less irrelevant data will be transferred, but the GBM algorithm needs much more computational resources to determine overlaps. For this reason, the choice of the cell size represents a crucial aspect as it impacts the performance of the DDM services based on GBM (Ayani et al., 2000; Tan et al., 2000a).

### 3.3 Hybrid-Based Matching

The Hybrid-Based Matching algorithm combines the GBM and RBM algorithms. Specifically, GBM is used to partition the MDCS into a grid of cells, then map regions to grid cells; while RBM is used to perform exact matching between update and subscription regions that overlap the same cells in the grid (Tan et al., 2000b).

This approach has two advantages. On the one hand, it has a lower computational cost than the RBM algorithm in determining the overlap information. On the other hand, it overcomes the issue of the GBM algorithm since it allows obtaining exact overlapping information. Nevertheless, the main issue of the HBM algorithm is that it has the same drawbacks as GBM, i.e., the performance depends on the size of both the grid and cells.

### 3.4 Sort-Based Matching

The Sort-Based Matching algorithm improves matching performance by sorting the boundaries of regions before evaluating their overlap (Pan et al., 2007; Raczy et al., 2005).

The algorithm uses a bit-matrix $M \in \mathbb{R}^{n \times m}$, where $n$ and $m$ are the number of update and subscription regions, respectively. Semantically, a row $n_i$, with $i = 0, ..., |n|$ indicates the update region, while a column $m_j$, with $j = 0, ..., |m|$ the subscription region. Each element $M_{ij}$ is defined as follow:

$$
\begin{cases}
1, & \text{if the regions } i, j \text{ overlap}, \\
0, & \text{otherwise}. 
\end{cases}
$$

Two sets of subscription regions ($\text{SubSetBefore}$ and $\text{SubSetAfter}$) are defined as $n$-bit vectors to track regions. The algorithm operates as follows. Given a dimension $d$, it begins by assuming that each update region overlaps each subscriber region; as a consequence, each matrix element is initialized to 1. Then, it inserts the ranges’ bounds of all regions into an ordered list $ordJist$, initializes $\text{SubSetBefore} = \{\emptyset\}$, and adds all subscription regions into $\text{SubSetAfter}$. Upon the initialization is completed, $ordJist$ is scanned from bottom to top and operates, for each element $l_i$, with $i = |ordJist|, ..., 0$, as follows. If $l_i$:

- a lower bound of a subscription region $R$, then $\text{SubSetAfter} \setminus \{R\}$;
- an upper bound of a subscription region $R$, then $\text{SubSetBefore} \cup \{R\}$;
- a lower bound of an update region $R$, then all regions in $\text{SubSetBefore}$ do not overlap with $R$, then $M$ is updated;
- an upper bound of an update region $R$, all regions in $\text{SubSetAfter}$ do not overlap with $R$, then $M$ is updated.

The computational complexity is $O(n \cdot m)$, where $n$ and $m$ are the number of update and subscription regions, respectively. In the generic $d$-dimensional case, i.e., running the SBM algorithm for each dimension $d$, the computational complexity becomes $O(d \cdot (n \cdot m))$ (Raczy et al., 2005).

### 4 A TOPIC-BASED PUBLISH-SUBSCRIBE APPROACH FOR DDM

Despite research progress, most of the existing region-matching algorithms need to scan every region to find overlaps with others, resulting in a waste of computing resources. To face these needs and shortcomings, the Topic-based publish-subscribe messaging system (TBMS), of which the Topic-Based Matching algorithm (TBM) is part, has been defined. The idea behind this new messaging system is to have an
“exchanger” with a queuing system that mediates the communication between federates, minimizing mutual awareness, i.e., what federates should have of each other to be able to exchange messages, effectively implementing decoupling. A producer federate sends a message to the exchanger, which in turn forwards it, by using the TBM algorithm, to the corresponding queue that consumer federates use to get the message. A key advantage of TBMS is that the exchanger forwards messages to queues without needing to know consumer federates.

TBMS changes the way with which DDM services manage regions and find overlaps by introducing the concept of “topic”. A topic is a well-structured string defined using a dot-delimited format, and it is used to filter and deliver HLAObjectClass and HLAInteractionClass messages. The structure of a topic is composed of three parts:

\[
\text{region}_1\cdot \text{object}\cdot \text{interaction}\cdot \text{instance}_1 \quad (2)
\]

where:

- \text{region}_1\text{ represents the identifier of the region;}
- \text{object}\cdot \text{interaction} \text{ specifies the supported datatype: object, for managing HLAObjectClass and interaction for handling HLAInteractionClass (IEEE Std. 1516-2010, 2010);}
- \text{instance}_1\text{ represents the identifier of the instance.}

Figure 2 depicts the architecture of TBMS along with the key parts: Producer Federates, Exchanger, Bindings, Queues, and Consumer Federates.

Producer Federates (see, Federate (A) in Figure 2) are responsible for creating regions by using the createRegion() method, with a specific set of dimensions. For every dimension, the lower and upper bounds of the range of that region are defined through the setRangeLowerBound() and setRangeUpperBound() methods, respectively (IEEE Std. 1516-2010, 2010).

A Producer Federate sends HLAObjectClass and HLAInteractionClass messages to the Exchanger component. When the Exchanger receives the message, it is responsible for routing it to different Queues by using the message’s topic information and Bindings, which connect the exchange and queues.

The wildcard “*” has been defined to identify all elements in a specific position of the topic structure. This wildcard may be used to define a binding over a topic following the same topic’s structure and Rule 1:

**Rule 1.** If the second part of the binding uses the wildcard, then the last part must have the wildcard.

For example, < region_id > .* .*, and < region_id > .object .* are valid bindings; whereas, < region_id > .*. < instance_id > is invalid.

The Exchanger component forwards messages to queues depending on wildcard matches between the message’s topic and the queue binding’s routing pattern. It is important to note that once the Producer Federates sends a message to the Exchanger, it does not wait for a response, i.e., it is not blocked.

**Consumer Federates** (see, Federates (B) and (C) in Figure 2) defines one or more bindings and subscribe to the related queues in order to receive messages from **Producer Federates**, and then process them.

In order to explain the **Topic-based publish-subscribe messaging system** more easily, a scenario related to a drone patrol system is examined, as reported in Figure 3. In this scenario, Federate (A) simulates three cars in the New York area, and related data are published/updated on the RTI using the DDM services extended with the proposed solution. Federates (B) and (C) simulate two drones used to patrol the New York area, with the difference that Federates (B) is interested in tracking and monitoring all cars, whereas Federates (C) wants to track only “car1”.

When the simulation starts, Federate (A) creates the region $r_1$ and simulates the movement of the three cars (car1, car2, and car3) in the New York area. Federates (B) and (C) define the bindings $r_1\cdot\text{object} .*$ and $r_1\cdot\text{object} .\text{car}_1$, respectively, and subscribe to the related queues. Every time Federate (A) updates data related to a car and publishes it on the RTI, the federate sends a message consisting of two parts: (i) the reference topic; and (ii) the car’s data (see Figure 3b - step 1). Upon the Exchanger receives the message (see Figure 3b - step 2), it uses the TBM algorithm to forward the message to the corresponding queues (see Figure 3b - step 3), and then to the subscriber Federate(s) (see Figure 3b - step 4).

### 4.1 Topic-Based Matching Algorithm

The Topic-Based Matching algorithm allows the **Exchanger** component to deliver messages to queues based on wildcard matches between the topic and the binding patterns, which is specified by queues. All
Car1
Car2
Car3
(a)

Run-time Infrastructure (RTI)
Data Distribution Management (DDM)
Federate
Algorithm 2: The Topic-Based Matching algorithm.

Require: \( t, m \) \( \triangleright \) \( t \) - topic, \( m \) - message

1: \( \text{bindings} = \text{Map} < \text{binding, pattern, queue} > \)
2: for \( \text{entry} \) in \( \text{bindings} \) do
3: \( \text{bind} \leftarrow \text{entry.binding, pattern, queue} \)
4: if wildcardMatch(bind, \( t \)) then
5: \( q \leftarrow \text{entry.queue} \)
6: \( q\_\text{enqueue}(m) \)
7: else
8: discard \( m \)
9: end if
10: end for

The "wildcardMatch" method has a computational complexity of \( O(m) \), where \( m \) is the length of the topic (Hajiaghayi et al., 2021). Since it is called for each entry in bindings, the computational complexity of TBM algorithm is \( O(n \cdot m) \).

The following section presents the experiments carried out to evaluate the performance of the Topic-Based Matching algorithm. The gathered results have been compared with the matching algorithm adopted in HLA 4.0 (see, Algorithm 1).

5 EXPERIMENTAL EVALUATION

This section presents the experiments carried out to evaluate the performance of the TBM algorithm. The experiments have been written in the Java language and performed on a MacBook Pro, equipped with MacOS Catalina 10.15, 16GB of RAM, and 1TB of HD. To promote comparability of the simulation results with those available in the literature, the two-dimensional case has been considered.

To perform the experiments a RabbitMQ infrastructure has been set up (Rostanski et al., 2014; Ayanoglu et al., 2016). RabbitMQ is a message-oriented middleware, also known as message-broker, that implements the Advanced Message Queuing Protocol (AMQP). It offers a common platform for sending/receiving messages, ensuring the security of communications. RabbitMQ acts as an intermediary between message consumers and producers, this peculiarity makes it easy to decouple the involved parts. RabbitMQ guarantees the delivery of messages, provides non-blocking features, and can be configured to push notifications to producers. Moreover, it provides support to the publish/subscribe mechanism, asynchronous processing, and message queues.

To conduct the experiments, three factors have been considered: Total number of regions, Overlap rate, and Update rate. The first one is the most obvious factor. If there are more regions, the matching algorithm will take longer to determine overlaps. The total number of regions, used in the experiments, varies from 1000 to 10000. Each region has a size of 20x20. All regions are evenly distributed in a 5000x5000 routing space.

The Overlap rate represents, as defined by Equation 3, the number of subscribed regions over the total number of regions. The higher this rate, the longer it takes for the algorithm to check whether or not two regions intersect. In the experiments, three different overlap rates were used: 0.25 (low), 0.50 (medium), and 0.75 (high). Finally, the Update rate represents...
the generation rate of update events on regions defined by using a probabilistic model. It is used by the producer federate to rate the generation of messages to subscriber federates. In the experiments, the Poisson distribution has been chosen with mean number of events per time interval \( \lambda = 0.8 \) in order to avoid an excessive generation of events.

\[
\text{Overlap rate} = \frac{|\text{subscribed regions}|}{|\text{total regions}|} \tag{3}
\]

Figure 4 shows the time performance comparison between \textit{TBM} and \textit{RBM} matching algorithms with a low overlap rate, i.e., 0.25. In this situation, since there is a low number of intersections between subscription and update regions, the computational cost for finding overlaps does not vary much between the two considered algorithms as long as the total number of regions remains relatively low, i.e., less than 6000 regions. While, with a large number of regions, more significant than 6000, the \textit{TBM} algorithm achieves much better performance than \textit{RBM}.

Figure 5 depicts the time performance comparison between the \textit{TBM} and \textit{RBM} matching algorithms with an overlap rate of 0.50. In this situation, the computational cost of both matching algorithms clearly increases with respect to the previous case, since there are more regions to evaluate. However, similar to the previous scenario, the performance trend remains, and the performance of the \textit{RBM} algorithm is very poor, while the proposed \textit{TBM} algorithm has a better processing time, especially when the total number of regions is greater than 6000.

Concerning the scenario with a high overlap rate, i.e., 0.75, there is a high degree of intersections between regions. The computational cost of both matching algorithms still increases compared to the previous cases, as both directly depend on the total number of regions. Similarly to the previous scenarios,

Figure 6 shows the time performance comparison between the \textit{TBM} and \textit{RBM} matching algorithms with a high overlap rate.

6 CONCLUSIONS

In this paper, the novel \textit{Topic-based publish-subscribe messaging system (TBMS)}, of which the \textit{Topic-Based Matching algorithm (TBM)} is part, has been defined to improve the performance, reliability, and scalability of DDM services in HLA. To evaluate the performance of \textit{TBM}, a set of experiments has been carried out by considering different overlap rates. The experiment results were compared with the ones obtained with the standard \textit{Region-Based Matching (RBM)} algorithm. Results highlight the fact that the proposed \textit{TBM} algorithm achieves better performance than the \textit{RBM} one in all considered overlap rates. Further investigation will focus on the reliability and scalability of the proposal.
REFERENCES


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