Efficient self-stabilizing construction of disjoint MDSs in distance-2 model
Colette Johnen, Mohammed Haddad

To cite this version:
Colette Johnen, Mohammed Haddad. Efficient self-stabilizing construction of disjoint MDSs in distance-2 model. [Research Report] Inria Paris, Sorbonne Université; LaBRI, CNRS UMR 5800; LIRIS UMR CNRS 5205. 2021. hal-03138979

HAL Id: hal-03138979
https://hal.science/hal-03138979
Submitted on 11 Feb 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Efficient self-stabilizing construction of disjoint MDSs in distance-2 model *

Colette Johnen¹ and Mohammed Haddad²

¹ INRIA Paris, LIP6, UMR 7606, France
Université de Bordeaux, LaBRI, UMR 5800, France
johnen@labri.fr

² Université Claude Bernard Lyon, LIRIS, UMR 5205, France
mohammed.haddad@univ-lyon1.fr

Abstract. We study the deterministic silent self-stabilizing construction of two disjoint minimal dominating sets (MDSs) in anonymous networks. We focus on algorithms where nodes share only their status (i.e. the name of their MDS to which they belong, if they belong to a MDS). We prove that such an algorithm cannot be designed in distance-1 model under a central daemon; therefore, we study this problem in the distance-2 model under a central daemon.

We present an algorithm building two disjoint minimal dominating sets such that one of them is also a maximal independent set (MIS). Any execution of this algorithm converges in $5n$ moves. Our approach to compute this value is novel: the number of moves is not computed per node.

We propose a second algorithm faster than the first one at the expense of the independence property of one of the constructed sets. A node executes at most 2 moves.

If the network is not anonymous, the presented algorithms can be translated into a silent self-stabilizing algorithms converging in $O(n \cdot m)$ moves in the distance-1 model under the distributed daemon where $m$ is the number of edges and $n$ the number of nodes. This improves the complexity of $O(n \cdot m)$ moves of proposed algorithms with the same assumptions.

Keywords: algorithmic graph · distributed algorithm · self-stabilization · minimal dominating set · maximal independent set · distance-2 model · convergence time

1 Introduction

The distance-2 model or the expression model permits a higher-level description of a self-stabilizing distributed algorithm. Some authors prefer to use the distance-2 model [3,2,4,5] or the expression model [10,11,12,1] to design self-stabilizing algorithms for solving graph problems. In the distance-2 model, a

* This study was partially supported by ANR project ESTATE : ANR-16 CE25-0009-03
node \( v \) can access to the state information of neighbors at distance 2 from it. In the expression model, a node \( v \) does not have access to the states of nodes at distance two, but has access only to aggregates of these states through the *expressions* of its neighbors. An *expression* on a node \( u \) is a value computed according to \( u \) and \( u \)’s neighbors states. Nevertheless, the distance-2 model and the expression model are similar in terms of computation power (*i.e.* the translation of an algorithm in the expression model to the distance-2 model has no overhead in terms of moves).

As shown in [3] an algorithm designed for the distance-2 model or the expression model under the central daemon (*i.e.* at each step only a single node executes an action) can be translated into another algorithm for distance-1 model with distributed daemon (*i.e.* at each step one or several nodes execute an action) assuming a non-anonymous network. The slowdown is \( O(m) \) per move in the expression model [10] where \( m \) is the number of edges.

In [6], deterministic self-stabilizing algorithms building two disjoint MDSs in the distance-2 model under the central daemon are presented, they converge in \( O(n^2) \) moves. Their translations give self-stabilizing algorithms in the distance-1 model under the unfair distributed daemon converging in \( (n^2 \cdot m) \) moves.

In [7,9] self-stabilizing distributed algorithm for finding two disjoint dominating sets are presented in distance-1 model where nodes have identifiers. The algorithm presented in [7] ensures safe convergence. The number of moves during any execution of algorithm in [7] is not computed. In [9] a central daemon is assumed, this algorithm converges in \( O(n^3) \) moves where \( n \) is the number of nodes.

Contribution

We study the deterministic self-stabilizing construction of two disjoint minimal dominating sets (MDSs) in anonymous networks. We focus on algorithms where nodes share only their status (*i.e.* the name of their MDS to which they belong, if they belong to a MDS).

In Section 3, we prove that such an algorithm cannot be designed in distance-1 model even under a central daemon.

In Section 4, we present an algorithm building two disjoint sets: a maximal independent set and a minimal dominating set. Any execution of that algorithm converges in \( 5n \) moves. Our approach to calculating the number of moves is new; the limit is not established on the number of moves of each node but on the number of executions of each rule. This algorithm improves the convergence time by a factor \( n \) of existing algorithms solving the same problem (self-stabilizing constructions of disjoint MIS and MDS) in distance-2 model.

In Section 6, we present an algorithm building two disjoint MDSs. During any execution, a node executes at most 2 moves. This algorithm is faster than the first one at the expense of the independence property of one of the constructed sets.

Using the transformer of [10], algorithms converging in \( O(n \cdot m) \) moves under the unfair distributed daemon in distance-1 model are obtained from the presented algorithms. The transformed algorithms are the first ones building two
disjoint MDS to converge in $O(nm)$ moves under the unfair distributed daemon in distance-1 model.

2 Model and Concepts

A distributed system $S$ is an undirected graph $G = (V, E)$ where the vertex set, $V$, is the set of nodes and the edge set, $E$, is the set of communication links. We have $|V| = n$ and $|E| = m$. A link $(u, v) \in E$ if and only if $u$ and $v$ can directly communicate (links are bidirectional); so, the nodes $u$ and $v$ are neighbors. $N(v)$ denotes the set of $v$'s neighbors: $N(v) = \{u \in V \mid (u, v) \in E\}$. $N[v]$ denotes the closed neighborhood of $v$ (i.e. the set of nodes at distance less than 2 from $v$): $N[v] = N(v) \cup \{v\}$.

**Dominating set** A subset $D$ of $V$ is dominating if any node of $V - D$ is neighbor of a node of $D$. A dominating set $D$ is minimal if any subset of $D$ is not a dominating set of $V$.

**Independent set** A subset of $V$, $I$, is independent if its does not contain two neighboring nodes. A independent set $I$ is maximal (denoted MIS) if the adding of any node to $I$ would falsify the independence property. A maximal independent set is also a minimal dominating set.

Ore [8] observed that any graph without isolated nodes always contains a pair of disjoint dominating sets. A corollary of Ore’s observation is that in any graph without isolated nodes, two disjoint minimal dominating sets exist.

For the rest of this paper, we assume that there are not any isolated nodes.

**Deterministic Algorithm** Each node maintains a set of variables. A node can modify only the values of its own variables. The state of a node is defined by the values of its variables. The Cartesian product of states of all nodes determines the configuration of the system. The program of each node is a set of deterministic rules. Each rule has the form: Rule$_i$ : $<\text{Guard}_i > \rightarrow <\text{Action}_i >$. The guard of a $v$’s rule is a Boolean expression. If $\text{Guard}_i$ is satisfied by $v$ then Rule$_i$ is enabled by $v$; $v$ is said to be enabled. A move by a node $v$ is the execution of an enabled rule by $v$ (i.e. the updating of $v$’ variables as it is defined in the deterministic action part of the executed rule).

A computation $e$ is a sequence of configurations $e = c_0, c_1, \ldots, c_i, \ldots$, where $c_{i+1}$ is reached from $c_i$ by a computation step, $\forall i \geq 0$. A computation $e$ is maximal if it is infinite, or if it reaches a terminal configuration. A configuration is terminal, if and only if no node is enabled.

**Anonymous network.** In an anonymous network, nodes do not have identifiers or node identifiers are not used by the algorithm; so all nodes execute the same algorithm (i.e. set of rules). In a non-anonymous network, every node $v$ in the network has an identifier, denoted by $id_v$. It is possible to order the identifier values.

**Distance-2 versus distance-1 model.** In the distance-1 model, the guard of a rule on the node $v$ is a Boolean expression involving the state of the nodes
in the closed neighborhood of \( v \) (i.e. states of nodes in \( N[v] \)). In the distance-2 model, the guard of a rule on the node \( v \) is a Boolean expression involving the state of the nodes in the closed neighborhood of any node of \( N[v] \) (i.e. states of nodes in \( N[u] \) with \( u \) being any node of \( N[v] \)).

**Central daemon versus distributed daemon.** Under the central daemon, during a computation step, a single enabled node executes a move (it is chosen without any fairness constraint). Under the distributed daemon, during a computation step, one or several enabled nodes are chosen without any fairness constraint to execute simultaneously a move.

**Silent Deterministic Self-Stabilization.** Let \( L \) be a predicate on the configurations. A distributed system \( S \) is a silent deterministic self-stabilizing system to \( L \) if and only if (1) all terminal configurations satisfy \( L \); (2) all computations reach a terminal configuration.

**Stabilization time of a deterministic algorithm.** The stabilization time of a deterministic algorithm may be estimated in term of the total number of moves required in the worst case to reach a terminal configuration. Under a central daemon, the number of moves is the number of computation steps; but under a distributed daemon, the number of moves may be as large as \( n \) times the number of steps.

**Closure of Predicate.** Let \( P \) be a predicate on the configurations. Let \( L_P \) be the set of configurations satisfying \( P \). \( L_P \) is closed, if and only if any step from a configuration of \( L_P \) reaches a configuration of \( L_P \).

### 3 Complexity of Self-stabilizing construction of two disjoint MDSs

In this section, the complexity of a self-stabilizing algorithm building two disjoint minimal dominating sets is studied. The status of a node has three possible values: either it belongs to the first minimal dominating set, to the second one or it does not belong to any minimal dominating set.

**Theorem 1.** In the distance 1-model, there is no deterministic silent self-stabilizing construction of two disjoint MDSs converging under the central daemon, if nodes share only their status.

**Proof.** Let us study the 3 following local configurations on node \( v \):

1. no node of \( N[v] \) belongs to a MDS (local configuration \( l_1 \)).
2. no node of \( N(v) \) belongs to a MDS and \( v \) belongs to the second MDS (local configuration \( l_2 \)).
3. no node of \( N(v) \) belongs to a MDS and \( v \) belongs to the first MDS (local configuration \( l_3 \)).

Assume that a node in the local configuration \( l_1, l_2, \) or \( l_3 \) is enabled. Let us study the algorithm on a chain of 3 nodes \( (v_1, v_2, \) and \( v_3) \). From a configuration where \( v_1 \) and \( v_3 \) are not in a MDS, there is an infinite execution where \( v_2 \) is the only node to execute a rule at each step. So no one can design a silent self-stabilizing
algorithm where a node in the local configuration $l_1$, $l_2$, or $l_3$ is enabled. It is easy to see that any self-stabilizing algorithm would have to ensure that a node $v$ in the local configuration $l_1$ is enabled. So either a node is disabled in the local configuration $l_3$ or in the local configuration $l_2$.

Without any loss of generality, we study in the following the algorithms where a node in the local configuration $l_3$ is disabled.

The label of a node in a configuration of the Figure 1 is the name of its local configuration. The configuration in Figure 1.a and the configuration in Figure 1.b have two disjoint MDSs: these configurations are the only legitimate ones up to a rotation in a ring of size 5. So in at least one of these 2 configurations, no node is enabled as we study silent algorithms. In the both configurations, there is a node having one of the following local configurations:

- a node in the first MDS having its two neighbors in the second MDS (local configuration $l_4$)
- a node in the second MDS having a single neighbor in the first MDS (local configuration $l_5$).
- a node not belonging to any MDS has a neighbor in the first MDS and the other one in the second MDS (local configuration $l_6$).

The local configuration of any node in the configuration Figure 1.c is $l_i$ with $i \in \{3..6\}$. We conclude that all nodes are disabled in this configuration. So this configuration is terminal for any deterministic silent self-stabilizing construction of two disjoint MDSs where nodes share only their status.

In the configuration Figure 1.c, the ring is proper colored (the coloration is greedy); but there is not two MDSs. Thus this configuration is not legitimate, so we have established the impossibility result. □
4 Self-stabilizing algorithm of disjoint MIS and MDS

The algorithm 1 builds a MIS (the set RedSet) and a MDS (the set BlueSet). A node $v$ belongs to RedSet (resp. BlueSet) if $\text{color}(v) = \text{red}$ (resp. $\text{color}(v) = \text{blue}$). The membership to one of this set is determined by the value of a single shared variable $\text{color}$. So, the intersection of RedSet and BlueSet is empty.

If $v$ is not dominated by a red node then $v$ can take the color red ($\text{notRedDom}(v)$ is verified). If a red node $v$ is dominated by another red node then it can quit RedSet ($\text{beNotRed}(v)$ is verified).

The construction of RedSet is priority to the construction of BlueSet. A node $v$ can join of quit the set BlueSet only when the red domination over itself is permanent (i.e. $\text{redOk}(v)$ is verified). When $v$ is dominated by a node $u$ verifying the predicate isolatedRed. The node $u$ is a red node having not red neighbor; so $u$ will stay in RedSet forever.

If every node of $N[v]$ is dominated by several blue nodes then $v$, a blue node verifying $\text{redOk}(v)$, may quit BlueSet - beNotBlue($v$) is verified.

If $v$ verifying $\text{redOk}(v)$ is not dominated by a blue node then $v$ can take the color blue (beBlue2($v$) is verified). If a neighbor of $v$ verifying isolatedRed is not dominated by a blue node then $v$ can take the color blue (beBlue1($v$) is verified).

To compute the value of redOk($v$), beBlue1($v$), and beNotBlue($v$) the node $v$ has to know the color of nodes at distance-2 of itself.

The Figure 2 illustrates the algorithm execution. During the first step, the node $x$ quits the BlueSet (executing $\text{RBlueOut}$) because all nodes of $N[x]$ has several blue neighbors. During the second step, the node $v$ executes $\text{RRedOut}$ because it has a red neighbor. During the third step, $w$ takes the red color (i.e. it executes $\text{RRedIn}$); now RedSet is a maximal independent set (configuration d). In the sequel of the execution, no red move will be executed (RedSet will stay unchanged). In the configuration d, beBlue1($x$) is verified: $w$ verifying isolatedRed($w$) has not blue neighbor. So the node $x$ takes the color blue by executing $\text{RBlueIn}$: to give to $w$ a blue neighbor. In the configuration e, beBlue2($v$) is verified; so, the node $v$ takes also the blue color. In the configuration f, BlueSet is a dominating set not minimal, beNotBlue($x$) and beNotBlue($z$) are verified. After the execution of $\text{RBlueOut}$ by $x$ a terminal configuration is reached. BlueSet is a minimal dominating set (configuration g).

5 Proof of correctness of algorithm 1

Lemma 1. In a terminal configuration $c$, RedSet is a maximal independent set, and BlueSet is a minimal dominating set

Proof. Let $c$ be a terminal configuration.
In $c$, no node verifies the predicate notRedDom; so a node that does not have the color red has a neighbor having the color red. In $c$, no node verifies the predicate
Algorithm 1: self-stabilizing construction of disjoint MIS and MDS

Shared variable of $v$
- $\text{color}(v) \in \{\text{red}, \text{blue}, \perp\}$

Macro on $v$
- $#\text{Blue}(v)$ is $|\{w \in N[v] \mid \text{color}(w) = \text{blue}\}|$
- $\text{myRedNgb}(v)$ is the nodes set defined as $\{u \in N(v) \mid \text{isolatedRed}(u)\}$

Predicates in $v$
- $\text{isolated}(v) \equiv \forall w \in N(v) \text{ we have } \text{color}(w) \neq \text{red}$
- $\text{notRedDom}(v) \equiv \text{color}(v) \neq \text{red} \land \text{isolated}(v)$
- $\text{beNotRed}(v) \equiv \text{color}(v) = \text{red} \land \neg \text{isolated}(v)$
- $\text{isolatedRed}(v) \equiv \text{color}(v) = \text{red} \land \text{isolated}(v)$
- $\text{redOk}(v) \equiv \exists u \in N[v] \text{ verifying } \text{isolatedRed}(u)$
- $\text{beBlue1}(v) \equiv \text{color}(v) = \perp \land \exists u \in \text{myRedNgb}(v) \text{ verifying } #\text{Blue}(u) = 0$
- $\text{beBlue2}(v) \equiv \text{color}(v) = \perp \land #\text{Blue}(v) = 0$
- $\text{beNotBlue}(v) \equiv \text{color}(v) = \text{blue} \land \forall u \in N[v] \text{ we have } #\text{Blue}(u) > 1$

Rules on $v$
- $\text{RRedIn}(v) : \text{notRedDom}(v) \rightarrow \text{color}(v) := \text{red}$
- $\text{RRedOut}(v) : \text{beNotRed}(v) \rightarrow \text{color}(v) := \perp$
- $\text{RBlueIn}(v) : \text{redOk}(v) \land (\text{beBlue1}(v) \lor \text{beBlue2}(v)) \rightarrow \text{color}(v) := \text{blue}$
- $\text{RBlueOut}(v) : \text{redOk}(v) \land \text{beNotBlue}(v) \rightarrow \text{color}(v) := \perp$

\begin{itemize}
  \item $\text{beNotRed}$; so all neighbors of a red node have not the color red. We conclude that in $c$, $\text{redOk}(v)$ is verified by any node and $(\text{isolated}(v) \iff \text{color}(v) = \text{red})$.
  \item Assume that a node $v$ verifies $#\text{Blue}(v) = 0$, in $c$. By hypothesis, $v$'s color is not blue. $v$ has the color red otherwise $v$ could executed the rule $\text{RBlueIn}$. The node $v$ has a least a neighbor $u$ (there is no isolated node) : $v \in \text{myRedNgb}(u)$. The color $u$ is $\perp$ by hypothesis and because $\text{isolatedRed}(v)$ is verified in $c$. So, $u$ verifies the predicate $\text{beBlue1}(u)$: $u$ is enabled in $c$. There is a contradiction. We conclude that in a terminal configuration, BlueSet is a dominating set.
  \item In $c$ no node verifies the predicate $\text{beNotBlue}$; so BlueSet is a minimal dominating set.
\end{itemize}

5.1 Convergence of algorithm 1

First, we compute the number of red moves along any execution; then the number of blue moves. The execution of the rule $\text{RBlueIn}$, or $\text{RBlueOut}$ (resp. $\text{RRedIn}$ or $\text{RRedOut}$) by a node is a blue (resp. red) move.
Fig. 2. an execution of algorithm 1 reaching a terminal configuration

**Number of Red moves.** We prove that a node executes at most one time the rule $RRedIn$ - Lemma 3. Then, we prove a node executes at most one time the rule $RRedOut$ - Lemma 4.

**Lemma 2.** The predicate $isolatedRed(v)$ is closed.

*Proof.* Let $c_1$ be a configuration where $isolatedRed(v) = true$. Let $cs$ be a computation step from $c_1$ reaching the configuration $c_2$. The node $v$ is disabled in $c_1$; so $v$ has the red color in $c_2$. Let $u$ be a node of $N(v)$. $u$ verifies $\neg notRedDom(u)$ in $c_1$. So, the node $u$ cannot take the red color during $cs$. We conclude that in $c_2$, $isolatedRed(v)$ is still verified. $\square$

**Corollary 1.** The predicate $redOk(v)$ is closed.

On a node verifying the predicate $redOk(v)$, the rule $RRedIn$ is disabled.

**Lemma 3.** A node $v$ is disabled forever after executing a $RRedIn$ move.

*Proof.* Assume that from the configuration $c$, $v$ executes the rule $RRedIn$ to reach the configuration $c'$. In $c$, none $v$’s neighbor has the color red.
As \( v \) is the single node to execute an action during this computation step; in \( c', \) we have \( \text{isolatedRed}(v) \). A node verifying \( \text{isolatedRed} \) is disabled.

According to Lemma 2, \( \text{isolatedRed}(v) \) stays verified along any execution. So, the node \( v \) is and stay disabled along any execution after its \( RRedIn \) move. □

**Lemma 4.** Along any execution, a node executes at most one time a \( RRedOut \) move.

*Proof.* Between two consecutive \( RRedOut \) moves by a node \( v \), this node executes at least one time the rule \( RRedIn \). After a \( RRedIn \) move, a node \( v \) is disabled forever (Lemma 3). So a node \( v \) cannot execute several \( RRedOut \) moves. □

**Number of Blue moves.** We compute the number of blue moves along any execution. Notice that the execution of \( RBlueIn \) (or \( RBlueOut \)) may be not the last move of a node as show in the execution of the Figure 2. We does not compute the number of blue moves done by a node but the global number of blue moves during an execution. We prove that after a computation step where a node execute \( RBlueIn \) a new node verifies the following predicate \( \text{blueOk}(u) \land \#\text{Blue}(u) \geq 1 \) (Lemma 7). This predicate is closed (Lemma 6).

A blue node verifying \( \text{BlueStable}(v) \) will never take the red color.

**Definition 1.** \( \text{BlueStable}(v) \equiv (\text{color}(v) \neq \text{blue} \lor \text{redOk}(v)) \)

**Lemma 5.** The predicate \( \text{BlueStable}(v) \) is closed.

*Proof.* Let \( c_1 \) be a configuration where \( \text{BlueStable}(v) \) is verified.

Assume that in \( c_1, \text{color}(v) \neq \text{blue} \). Till \( v \) does not execute the rule \( RBlueIn \) \( \text{BlueStable}(v) \) is verified (as \( \text{color}(v) \neq \text{blue} \)). Let \( cs \) be a step from \( c \) to \( c' \) where the node \( v \) executes a \( RBlueIn \) move. The predicate \( \text{redOk}(v) \) is verified in \( c \) according to the guard rule.

If \( \text{redOk}(v) \) is verified in \( c \) then \( \text{BlueStable}(v) \) is verified along any execution from \( c \) because \( \text{redOk}(v) \) is closed (Corollary 1). □

**Corollary 2.** \( \text{blueOk}(v) \equiv (\forall u \in N[v] \text{ we have } \text{BlueStable}(u)). \) The predicate \( \text{blueOk}(v) \) is closed.

If a node \( v \) verifying \( \text{blueOk} \) has a Blue neighbor then along any execution it will have at least a Blue neighbor (because \( v \)'s blue neighbor can only execute the rule \( RBlueOut \)).

**Lemma 6.** On node \( v \), the predicate \( \text{blueOk}(v) \land \#\text{Blue}(v) \geq 1 \) is closed.

*Proof.* The predicate \( \text{blueOk}(v) \) is closed (Corollary 2).

Let \( c_1 \) be a configuration where \( \text{blueOk}(v) \land \#\text{Blue}(v) = 1 \). Let us name \( u \), the single node of \( N[v] \) having the color blue in \( c_1 \). The node \( u \) verifies \( \neg \text{notRedDom}(u) \) in \( c_1 \) because \( \text{redOk}(u) \) is verified.
The node $u$ verifies $\neg \text{beNotBlue}(u)$ in $c_1$ because $\#\text{Blue}(v) = 1$. So, the node $u$ is disabled in $c_1$. We conclude that in the reached configuration after any computation step from $c_1$, we have $\#\text{Blue}(v) \geq 1$.

Let $c_2$ be a configuration where $\#\text{Blue}(v) > 1$. We denote by $nb$ the value of $\#\text{Blue}(v)$ in $c_2$. During any computation step from $c_2$, a single node of $N[v]$ executes a move (because a central daemon is assumed). So, in the reached configuration, we have $\#\text{Blue}(v) \in [nb - 1, nb + 1]$.

We conclude that $\#\text{Blue}(v) \geq 1$ in $c_2$.

\[\Box\]

**Lemma 7.** Let $c \rightarrow c'$ be a computation step where a node $v$ executes a $\text{RBlueIn}$ move. There is at least a node $u$ such that (1) the predicate $\text{blueOk}(u) \land \#\text{Blue}(u) \geq 1$ is not verified in $c$ but (2) it is verified in $c'$.

**Proof.** Let $cs$ be a step from $c_1$ to $c_2$ where a node $v$ executes a $\text{RBlueIn}$ move. Assume that $\text{beBlue}_2(v)$ is verified in $c$. We have $\#\text{Blue}(v) = 0$ in $c$. The predicate $\text{blueOk}(v)$ is verified in $c$. The predicate $\text{blueOk}(v)$ is closed (Corollary 2). As $v$ is the single node to execute an action during $cs$; $\text{blueOk}(v) \land \#\text{Blue}(v) = 1$ is verified, in $c'$ but not in $c$.

Assume that $\text{beBlue}_1(v)$ is verified in $c$. In $c$, $v$ has a neighbor $u$ verifying $\#\text{Blue}(u) = 0$ and $\text{isolatedRed}(u)$. The predicate $\text{blueOk}(u)$ is verified in $c$ because ($\text{isolatedRed}(u) \Rightarrow \text{blueOk}(u)$). As $v$ is the single node to execute an action during $cs$; $\text{blueOk}(u) \land \#\text{Blue}(u) = 1$ is verified, in $c'$ but not in $c$. \[\Box\]

**Theorem 2.** Along any execution, there is at most $n \text{RBlueIn}$ moves and $2n \text{RBlueOut}$ moves.

**Proof.** After a $\text{RBlueIn}$ move a new node $u$ verifies the predicate $\text{blueOk}(u) \land \#\text{Blue}(u) \geq 1$ (Lemma 7). As this predicate is closed (Lemma 6), we conclude that any execution has at most $n \text{RBlueIn}$ moves. On a node, the number of $\text{RBlueOut}$ moves is at most the number of $\text{RBlueIn}$ moves plus one more. We conclude that any execution has at most $2n \text{RBlueIn}$ moves. \[\Box\]

### 6 Self-stabilizing algorithm building two disjoint MDSs

The algorithm 2 builds the sets $\text{RedSet}$ and $\text{BlueSet}$. These set are two disjoint MDSs. The algorithm 2 is a self-stabilizing algorithm in the distance-2 model under a central daemon; the two disjoint MDSs are built in less than $2n$ moves.

A node $v$ belongs to $\text{RedSet}$ (resp. $\text{BlueSet}$) if and only if $\text{color}(v) = \text{red}$ (resp. $\text{color}(v) = \text{blue}$). As, the membership to one of these sets is determined by the value of a single variable shared: $\text{color}$; the intersection of $\text{RedSet}$ and $\text{BlueSet}$ is empty. Moreover, macros $\#\text{Red}(u)$ and $\#\text{Blue}(u)$ may also be considered as expressions in the expression model.

The construction of $\text{RedSet}$ has priority over the construction of $\text{BlueSet}$. If a node $v$ has not a closed neighbor belonging to $\text{RedSet}$ (i.e. the predicate
notRedDom(v) is satisfied) then v can join the RedSet (i.e. the guard of the rule RRedIn is satisfied). If every nodes of closed neighborhood of v has several nodes belonging to RedSet and v belongs to RedSet (i.e. the predicate beNotRed(v) is satisfied) then v can quit RedSet (i.e. the guard of the rule RRedOut or the guard the rule RBlueIn is satisfied).

Algorithm 2: self-stabilizing construction of two disjoint MDSs

Variable of v shared
- color(v) ∈ {red, blue, ⊥}

Macros on v
- #Red(u) is |{w ∈ N[u] | color(w) = red}|
- #Blue(u) is |{w ∈ N[u] | color(w) = blue}|

Predicates on v
- notRedDom(v) ≡ (#Red(v) = 0)
- beNotRed(v) ≡ (∀u ∈ N[v] | (#Red(u) > 1)) ∧ (color(v) = red)
- beNotBlue(v) ≡ (∀u ∈ N[v] | (#Blue(u) > 1)) ∧ (color(v) = blue)
- redOk(v) ≡ (∀u ∈ N[v] | (#Red(u) ≥ 1))
- blueOk(v) ≡ (∀u ∈ N[v] | (color(u) ≠ red) ∨ (#Blue(u) ≥ 1)) ∧ (#Blue(v) ≥ 1)
- canBeBlue(v) ≡ redOk(v) ∧ (color(v) = ⊥)

Rules on v
- RRedIn : notRedDom(v) → color(v) := red;
- RRedOut : beNotRed(v) ∧ blueOk(v) → color(v) := ⊥;
- RBlueIn : (beNotRed(v) ∨ canBeBlue(v)) ∧ ¬blueOk(v) →
  color(v) := blue;
- RBlueOut : redOk(v) ∧ beNotBlue(v) → color(v) := ⊥;

If a node v has not a closed neighbor belonging to BlueSet then the predicate ¬blueOk(v) is satisfied. If every nodes of closed neighborhood of v has several nodes belonging to BlueSet and v belongs to BlueSet then the predicate beNotBlue(v) is satisfied. The verification of ¬blueOk(v) (resp. beNotBlue(v)) is not enough to allow the node v to quit BlueSet (resp. to join it).

A node v can join or quit the set BlueSet (i.e. executing the rule RBlueIn or the rule RBlueOut) only when the red domination in its neighborhood is certain; more precisely, when every node in its neighborhood is dominated by at least node of RedSet (i.e. the predicate redOk(v) is satisfied).

Notice that the condition to join RedSet is not similar to the condition to join BlueSet. If a red neighbor of node v, u is not dominated by a blue node (i.e. the following predicate is verified (color(u) = red) ∧ (#Blue(u) = 0) then
¬blueOk(v) is verified. So the node v may join BlueSet even if v is dominated by a blue node; in the case where one of its red neighbor is not dominated by a blue node.

The Figure 3 illustrates the algorithm execution. During the first step, the node u executes the rule RRedIn. Now, RedSet is a minimal dominating set; hence no red move will be executed during the end of the execution. In the configuration b, #Blue(v) = 0 and #Blue(z) = 0; so, the node v joins BlueSet, then the node z does the same move. In the configuration d, #Blue(x) = 0 and color(x) = red so ¬blueOk(z) is verified, during the last step, w executes the rule RBlueIn.

Fig. 3. an execution of algorithm 2 reaching a terminal configuration

7 Proof of correctness of Algorithm 2

Observation 1 If a node satisfies the predicate notRedDom(v) (resp. ¬blueOk(v)) then color(v) ≠ red (resp. color(v) ≠ blue).

Lemma 8. In a terminal configuration RedSet and BlueSet are minimal dominating sets.

Proof. A node satisfying the predicate notRedDom is enabled (it can execute the rule RRedIn). A node satisfying the predicate beNotRed is enabled (it can execute the rule RBlueIn or the rule RRedOut). We conclude that RedSet is a minimal dominating set.

Let c be a terminal configuration. In c, the predicate redOk is satisfied by every node. So, no node satisfies the predicate beNotBlue in c.
Assume that a node \( v \) satisfies \#\( \text{Blue}(v) = 0 \), in \( c \). As \( v \) is not isolated, we have \(|N[v]| > 1\).

If \( \text{color}(v) = \perp \) then \( v \) can execute the rule \( R\text{BlueIn} \) from \( c \). So, \( \text{color}(v) = \text{red} \).

Let \( u \) be a neighbor of \( v \). If \( \text{color}(u) = \perp \) then \( \neg\text{blueOk}(u) \) is satisfied so \( u \) can execute the rule \( R\text{BlueIn} \) from \( c \).

Therefore, all nodes of \( N[v] \) have the color \( \text{red} \) in \( c \). So \( \forall w \in N[v] \) we have \#\( \text{Red}(w) > 1 \). We conclude that \( v \) satisfies the predicate \( \text{beNotRed}(v) \). So, \( v \) is enabled: there is a contradiction.

Hence, in \( c \), every node \( v \) satisfies \#\( \text{Blue}(v) > 0 \). We conclude that \( \text{BlueSet} \) is a minimal dominating set, as no node satisfies the predicate \( \text{beNotBlue} \) in \( c \). \( \square \)

### 7.1 Convergence of Algorithm 2

After the execution of \( R\text{OutBlue} \) or \( R\text{OutRed} \), a node is disabled forever - Lemma 12. The execution of \( R\text{RedIn} \) is the last move of a node - Lemma 14.

Assume that during its first move, a node \( v \) executes \( R\text{InBlue} \). The second move of \( v \) (if it exists), would be its last one as it would be the execution of rule \( R\text{BlueOut} \) or rule \( R\text{RedIn} \). So a node \( v \) executes at most two moves.

**Lemma 9.** The predicate \( \text{redOk}(v) \) is closed for every node \( v \).

**Proof.** We prove that the predicate \( \#\text{Red}(v) \geq 1 \) is closed for every node \( v \).

Let \( c_1 \) be a configuration where \( \#\text{Red}(v) = 1 \). Let \( u \) be the single node of \( N[v] \) having the color \( \text{red} \) in \( c_1 \). The node \( u \) satisfies \( \neg \text{beNotRed}(u) \), and \( \neg \text{canBeBlue}(u) \). So, the node \( u \) is disabled in \( c_1 \). We conclude that in the configuration reached after any computation step from \( c_1 \), we have \#\( \text{Red}(v) \geq 1 \).

Let \( c_2 \) be a configuration where \( nr = \#\text{Red}(v) > 1 \). During any computation step from \( c_2 \), a single node of \( N[v] \) executes a move (because a central daemon is assumed). So, in the configuration reached after any computation step from \( c_2 \), we have \#\( \text{Red}(v) \in \[nr-1, nr+1\] \). We conclude that \#\( \text{Red}(v) \geq 1 \) in \( c_2 \). \( \square \)

**Lemma 10.** The predicate \( \text{redOk}(v) \land \#\text{Blue}(v) \geq 1 \) is closed for every node \( v \).

**Proof.** Let \( c_1 \) be a configuration where \( \text{redOk}(v) \land \#\text{Blue}(v) = 1 \). Let \( u \) be the single node of \( N[v] \) having the color \( \text{blue} \) in \( c_1 \). The node \( u \) satisfies \( \neg \text{notRedDom}(u) \) in \( c_1 \) (because \( \text{redOk}(v) \Rightarrow \#\text{Red}(u) > 0 \)). The node \( u \) satisfies \( \neg \text{beNotBlue}(u) \) in \( c_1 \) (because \( \#\text{Blue}(v) = 1 \)). So, the node \( u \) is disabled in \( c_1 \). Therefore in the configuration reached after any computation step from \( c_1 \), we have \#\( \text{Blue}(v) \geq 1 \).

Let \( c_2 \) be a configuration where \( \text{redOk}(v) \land \#\text{Blue}(v) > 1 \). We denoted \( nb \) the value of \#\( \text{Blue}(v) \) in \( c_2 \). During any computation step from \( c_2 \), a single node of \( N[v] \) executes a move (because a central daemon is assumed). So, in the configuration reached after a computation step from \( c_2 \), we have \#\( \text{Blue}(v) \in \[nb-1, nb+1\] \). So, \#\( \text{Blue}(v) \geq 1 \) in \( c_2 \).

We conclude that \( \text{redOk}(v) \land \#\text{Blue}(v) \geq 1 \) is closed, as \( \text{redOk}(v) \) is closed (Lemma 9). \( \square \)
Lemma 11. The predicate $\text{redOk}(v) \land \text{blueOk}(v)$ is closed.

Proof. Let $c$ be a configuration where the predicate $\text{redOk}(v) \land \text{blueOk}(v)$ is satisfied. Let $c'$ be a configuration reached from $c$ by a single computation step. In $c$, we have $\text{redOk}(v) \land \#\text{Blue}(v) \geq 1$ by hypothesis. As this predicate is closed (Lemma 10), in $c'$ we have $\text{redOk}(v) \land \#\text{Blue}(v) \geq 1$.

Let $u$ be a neighbor of $v$ having the color $\text{red}$ in $c$. In $c$, by hypothesis we have $\#\text{Red}(u) \geq 1$ so the rule $\text{RRedIn}$ is disabled on $u$ in $c$. Therefore the color $u$ in $c$ is also $\text{red}$. By definition of $\text{blueOk}(v)$, we have $\#\text{Blue}(u) \geq 1$, in $c$. Therefore, in $c'$, we have $\text{redOk}(u) \land \#\text{Blue}(u) \geq 1$ as this predicate is closed (Lemma 10). Thus in $c'$, any neighbor, $w$ of $v$ satisfies the predicate $(\text{color}(w) \neq \text{red}) \lor (\#\text{Blue}(w) \geq 1)$. We conclude that $\text{redOk}(v) \land \text{blueOk}(v)$ is satisfied in $c'$.

If a node $v$ can execute the $\text{RRedOut}$ rule or the $\text{RBlueOut}$ rule in the configuration $c$; then it verifies the predicate $(\text{redOk}(v) \land \text{blueOk}(v))$ in $c$ and along any execution from $c$. So, the guard of rule $\text{RRedIn}$ and the guard of the rule $\text{RBlueIn}$ are never verified by $v$ along any execution from $c$.

Lemma 12. A node is disabled forever after executing the $\text{RRedOut}$ rule or the $\text{RBlueOut}$ rule.

Proof. Let $cs$ be a computation step from $c$ to $c'$ where a node $v$ executes a $\text{RRedOut}$ move or a $\text{RBlueOut}$ move. In $c$, the guard of the $\text{RRedOut}$ rule or the guard of the $\text{RBlueOut}$ rule is satisfied.

The predicate $\text{redOk}(v)$ is satisfied in $c$ (we have $\text{beNotRed}(v) \Rightarrow \text{redOk}(v)$).

In $c$, the predicate $\text{blueOk}(v)$ is satisfied as $(\text{beNotBlue}(v) \Rightarrow \text{blueOk}(v))$. The predicate $\text{redOk}(v) \land \text{blueOk}(v)$ is closed (Lemma 11). The rule $\text{RBlueIn}$ and the rule $\text{RRedIn}$ are and stay disabled on $v$ along any execution from $c$.

The next move by a node $v$ after executing a $\text{RRedOut}$ move or a $\text{RBlueOut}$ move would be a $\text{RRedIn}$ move or an $\text{RBlueIn}$ move because $\text{color}(v) = \bot$. We conclude that from $c'$, $v$ is forever disabled.

If a node $v$ verifies $(\#\text{Red}(v) = 1 \land \text{color}(v) = \text{red})$ in the configuration $c$; then $v$ is disabled in $c$ and $\text{RRedIn}$ is disabled on any $v$'s neighbor in $c$. So, this predicate is always verified by $v$ along any execution from $c$.

If this predicate is verified by $v$ then $v$ is disabled; this predicate is verified after the execution by $v$ of rule $\text{RRedIn}$.

Lemma 13. The predicate $\#\text{Red}(v) = 1 \land \text{color}(v) = \text{red}$ is closed.

Proof. Let $c$ be a configuration where $v$ satisfies the predicate $\#\text{Red}(v) = 1 \land \text{color}(v) = \text{red}$. $v$ is disabled in $c$ because the predicate $\neg\text{beNotRed}(v)$ is satisfied. So after any computation step from $c$, we have $\text{color}(v) = \text{red}$.

In $c$, the predicate $\neg\text{notRedDom}(u)$ is satisfied by any $v$'s neighbor; they cannot execute the rule $\text{RRedIn}$ in any computation step from $c$. So after any computation step from $c$, we have $\#\text{Red}(v) = 1$.

We conclude that after any computation step from $c$, we have $\#\text{Red}(v) = 1 \land \text{color}(v) = \text{red}$.
Lemma 14. A node $v$ is disabled forever after executing a $RRedIn$ move.

Proof. Assume that in the configuration $c$, $v$ executes the rule $RRedIn$ to reach the configuration $c'$. In $c$, none $v$'s neighbors has the color red. As $v$ is the single node to execute an action during this computation step; in $c'$, we have $\#Red(v) = 1 \land color(v) = red$. According to Lemma 13, along any execution from $c'$, we have $\#Red(v) = 1 \land color(v) = red$. We conclude that the node $v$ is and stays disabled along any execution after its $RRedIn$ move. \hfill \Box

Corollary 3. A node performs at most two moves.

Proof. If the first move of a node $v$ is $RRedIn$, $ROutBlue$ or $ROutRed$, it would be its last move (Lemma 12 and 14). Assume that the first move of a node $v$ is $RInBlue$. The second move of $v$ (if it exists), would be either a $RBlueOut$ move or a $RRedIn$ move. The second move would be its last one. So $v$ performs at most two moves. \hfill \Box

References