

Supplementary material to the paper “ K -step and Definite Critical Observability in Networked Discrete Event Systems Under Replacement Attacks via Labeled Petri Nets”

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I. MAIN ALGORITHMS

In this section, three algorithms as well as their explanations are presented.

Algorithm 1: Algorithm 1 is used to compute $R(M, k)$ for given M and k , which is the set of basis markings in a replacement attack basis reachability graph (RABRG) reachable from marking M through k events in E . Note that if $k = 0$, we have $R(M, k) = UR(M)$.

Algorithm 1 Computation of $R(M, k)$ in an RABRG

Input: An RABRG $\mathcal{B}_A = (\mathcal{M}_B, Tr, \delta_A, M_0)$, a basis marking M , and an integer $k \in \mathbb{N} \setminus \{0\}$

Output: $R(M, k)$

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1:  $S_n := \{(M, 0)\}$  and  $R(M, k) := \emptyset$ ;
2: while  $S_n \neq \emptyset$  do
3:   pop a pair  $(M', i) \in S_n$ ;
4:   for all  $(t, \vec{y}_\sigma) \in \Gamma_A(M')$  do
5:     if  $\lambda((t, \vec{y}_\sigma)) \in E$  then
6:        $i := i + 1$  and  $y := \{(\hat{M}', i) | \hat{M}' \in \delta_A(M', (t, \vec{y}_\sigma))\}$ ;
7:     else if  $\lambda((t, \vec{y}_\sigma)) = \varepsilon$  then
8:        $y := \{(\hat{M}', i) | \hat{M}' \in \delta_A(M', (t, \vec{y}_\sigma))\}$ ;
9:     end if
10:    if  $i < k$  then
11:      for all  $(\hat{M}', i) \in y$  do
12:         $S_n := S_n \cup \{(\hat{M}', i)\}$ ;
13:      end for
14:    else if  $i = k$  then
15:       $R(M, k) := R(M, k) \cup UR(\delta_A(M', (t, \vec{y}_\sigma)))$ ;
16:    end if
17:  end for
18: end while

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Algorithm 2: Algorithm 2 is used to compute a set of fully-critical basis markings \mathcal{F} , a set of partially critical basis markings \mathcal{P} , and a set of non-critical basis markings \mathcal{N} , which directly follows from Definition 10 and Proposition 4.

Algorithm 2 Computing the sets \mathcal{F} , \mathcal{P} , and \mathcal{N}

Input: The set of basis markings \mathcal{M}_B of an RABRG and a set of critical markings C_R

Output: Sets \mathcal{F} , \mathcal{P} , and \mathcal{N}

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1:  $\mathcal{F} := \emptyset$ ,  $\mathcal{P} := \emptyset$ , and  $\mathcal{N} := \emptyset$ ;
2:  $\hat{\mathcal{M}}_B := \mathcal{M}_B$ ;
3: while  $\hat{\mathcal{M}}_B \neq \emptyset$  do
4:   select a basis marking  $M \in \hat{\mathcal{M}}_B$ ;
5:    $\hat{\mathcal{M}}_B := \hat{\mathcal{M}}_B \setminus \{M\}$ ;
6:   if the set of constraints (1) is feasible then
7:     assign  $M$  with tag “1”;
8:   else if the set of constraints (1) is infeasible then
9:     assign  $M$  with tag “2”;
10:  end if
11:  if the set of constraints (2) is feasible then
12:    assign  $M$  with tag “3”;
13:  else if the set of constraints (2) is infeasible then
14:    assign  $M$  with tag “4”;
15:  end if
16: end while
17: while  $\mathcal{M}_B \neq \emptyset$  do
18:   select a basis marking  $M \in \mathcal{M}_B$ ;
19:    $\mathcal{M}_B := \mathcal{M}_B \setminus \{M\}$ ;
20:   if ( $M$  is with tag “1” and “3”)  $\vee$  ( $M$  is with tag “2”  $\wedge$  there exists  $\phi \in (Tr'_u)^*$  such that  $M' \in \delta_A(M, \phi)$  and  $M'$  is with tag “1”)  $\vee$  ( $M$  is with tag “4”  $\wedge$  there exists  $\phi \in (Tr'_u)^*$  such that  $M' \in \delta_A(M, \phi)$  and  $M'$  is with tag “3”) then
21:      $\mathcal{P} := \mathcal{P} \cup \{M\}$ ;
22:   else if ( $M$  is with tag “2”  $\wedge$  for all  $\phi \in (Tr'_u)^*$  such that  $M' \in \delta_A(M, \phi)$  and  $M'$  is with tag “2”) then
23:      $\mathcal{F} := \mathcal{F} \cup \{M\}$ ;
24:   else if ( $M$  is with tag “4”  $\wedge$  for all  $\phi \in (Tr'_u)^*$  such that  $M' \in \delta_A(M, \phi)$  and  $M'$  is with tag “4”) then
25:      $\mathcal{N} := \mathcal{N} \cup \{M\}$ ;
26:   end if
27: end while

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Algorithm 3 Computing maximal k for k -CO w.r.t. a replacement attack, a communication delay, and a critical marking set

Input: A bounded LPN $G = (PN, M_0, E, \lambda)$ w.r.t. a labeling function A_D associated with a replacement attack \mathcal{A} and a delay upper bound $N \in \mathbb{N}$, and a set of critical markings C_R

Output: A maximal k such that G is k -CO w.r.t. A_D and C_R , or “NA”

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1: Compute the robust basis  $n$ -extended networked detector  $\hat{\mathcal{B}}_{d,n}$ , where  $n = |\mathcal{M}_B|^2 - 1$ ;
2: find all the negative cycles in the corresponding underlying digraph  $\mathcal{B}$  of  $\hat{\mathcal{B}}_{d,n}$ ;
3: if there exists no negative cycle on any path from  $z'$  to  $z$  for all the states  $z' \in Z_0$  and  $z \in Z_v$  then
4:   output “def-CO” and exit;
5: end if
6:  $i := 1$  and  $j := |\mathcal{M}_B|^2 - 1$ ;
7: while  $i \leq j$  do
8:    $k := \lfloor \frac{1}{2}(i + j) \rfloor$ , where  $\lfloor \frac{1}{2}(i + j) \rfloor$  represents the largest integer not greater than  $\frac{1}{2}(i + j)$ ;
9:   compute the robust basis  $k$ -extended networked detector  $\hat{\mathcal{B}}_{d,k}$ , find all the negative cycles in the corresponding underlying digraph  $\mathcal{B}$  of  $\hat{\mathcal{B}}_{d,k}$ ;
10:  if there exists a negative cycle on a path from  $z'$  to  $z$  for a state  $z' \in Z_0$  and a state  $z \in Z_v$  then
11:     $j := k - 1$  and  $flag := 1$ ;
12:  else
13:     $i := k + 1$  and  $flag := 2$ ;
14:  end if
15: end while
16: if  $flag = 1$  then
17:   if  $k \neq 1$  then
18:     output  $k - 1$ ; “ $(k - 1)$ -CO” and exit;
19:   else
20:     output “NA” and exit;
21:   end if
22: else
23:   output  $k$ , “ $k$ -CO” and exit;
24: end if

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Algorithm 3: Algorithm 3 is used to compute a maximal k for k -CO w.r.t. a labeling function A_D associated with a replacement attack \mathcal{A} and a delay upper bound $N \in \mathbb{N}$, and a set of critical markings C_R (if it exists). Now we briefly explain how Algorithm 3 works. First, steps 1 to 5 check def-CO by constructing the robust basis $(|\mathcal{M}_B|^2 - 1)$ -extended networked detector and checking whether there exists no negative cycle on any path from z' to z for all the states $z' \in Z_0$ and $z \in Z_v$. If the LPN is not def-CO w.r.t. A_D and C_R , then steps 6 to 24 compute a maximal k for k -CO by using the binary search. In particular, step 6 initializes the lower and upper bounds of the search interval as $i = 1$ and $j = |\mathcal{M}_B|^2 - 1$, respectively. Step 8 computes the midpoint of the interval $[i, j]$ as k ; step 9 determines whether the LPN G is k -CO w.r.t. A_D and C_R . If G is not k -CO w.r.t. A_D and C_R , by Proposition 2, it cannot be k' -CO for any $k' > k$. Thus, step 11 sets the upper bound as $j = k - 1$. If G is k -CO, then step 13 sets the lower bound as $i = k + 1$. Steps 7 to 15 execute iteratively until the lower bound is greater than the upper bound. Finally, if G is verified to be not k -CO in the final iteration, step 18 outputs $k - 1$ as the maximal value if $k \neq 1$, and step 19 outputs “NA” if $k = 1$. If G is verified to be k -CO in the final iteration, step 23 outputs k as the maximal value.

II. PROOFS FOR THE MAIN RESULTS

Proposition 1: If an LPN G is (k, l) -CO w.r.t. a labeling function A_D associated with a replacement attack \mathcal{A} and a delay upper bound $N \in \mathbb{N}$, and a set of critical markings C_R , then G is (k, l') -CO w.r.t. A_D and C_R for any $l' \geq l$.

Proof: Since G is (k, l) -CO w.r.t. A_D and C_R , for all $s' = uvw' \in A_D(L_G(k, l')) \subseteq A_D(L_G(k, l))$ with $|v| = k$ and $|w'| \geq l'$, Condition (1) or (2) holds. Thus, G is also (k, l') -CO w.r.t. A_D and C_R . \square

Proposition 2: If an LPN G is k -CO w.r.t. a labeling function A_D associated with a replacement attack \mathcal{A} and a delay upper bound $N \in \mathbb{N}$, and a set of critical markings C_R , then G is k' -CO for any $k' \leq k$ w.r.t. A_D and C_R .

Proof: Suppose that G is (k, l) -CO w.r.t. A_D and C_R , i.e., for any $s = uvw \in A_D(L(G))$ with $|v| = k$ and $|w| \geq l$, Condition (1) or (2) in Definition 1 holds. Let $k' \in \mathbb{N}$ be an integer less than or equal to k . Due to $A_D(L_G(k, l)) = A_D(L_G(k', l + (k - k')))$, Condition (1) or (2) holds for any $s = uvw = uv'w'$ with $|v'| = k'$ and $|w'| \geq l + (k - k')$. \square

Proposition 3: Given an LPN G under a replacement attack \mathcal{A} , let $\mathcal{B}_A = (\mathcal{M}_B, Tr, \delta_A, M_0)$ be the RABRG w.r.t. $\pi = (T_E, T_I)$ with $T_E \supseteq T_o$. The following two statements are equivalent:

1) there is a path in the RABRG \mathcal{B}_A :

$$M_0 \xrightarrow{(t_1, \vec{y}_{\sigma_1})} M_1 \xrightarrow{(t_2, \vec{y}_{\sigma_2})} \dots \xrightarrow{(t_n, \vec{y}_{\sigma_n})} M_n;$$

2) there exists a marking M and a firing sequence $\sigma = \sigma_1 t'_1 \dots \sigma_n t'_n \sigma_{n+1}$, where $\sigma_i \in T_I^*$ for all $i \in \{1, \dots, n+1\}$, and $t'_i \in T_E$ for all $i \in \{1, \dots, n\}$ such that $M_0[\sigma]M$, $M \in R_I(M_n)$, $\lambda(t'_1) \in A(\lambda(t_1))$, \dots , and $\lambda(t'_n) \in A(\lambda(t_n))$.

Proof: This result follows from Theorem 1 in [1] by considering the transition function assignment in Definition 6. \square

Theorem 1: Given an LPN $G = (PN, M_0, E, \lambda)$, a set of critical markings C_R , a labeling function A_D associated with a replacement attack \mathcal{A} and a delay upper bound $N \in \mathbb{N}$, and two nonnegative integers $k, l \in \mathbb{N}$, G is (k, l) -CO w.r.t. A_D and C_R if and only if for all $z \in D_l(\hat{\mathcal{B}}_{d,k})$, $z \in Z_s$ holds.

Proof: (If) By contrapositive, suppose that G is not (k, l) -CO w.r.t. A_D and C_R . There exist two event sequences $s = uvw \in A_D(L(G))$ and $s' = uv'w \in A_D(L(G))$ such that $\hat{\mathcal{C}}_D(s) \cap C_R \neq \emptyset$ and $\hat{\mathcal{C}}_D(s') \cap R(PN, M_0) \setminus C_R \neq \emptyset$ with $|v| = |v'| = k$, and $|w| \geq l$. Then, we have two sequences $\sigma_1 \sigma_2$ and $\sigma'_1 \sigma'_2$ such that $M_0[\sigma_1]M_1[\sigma_2]M_2 \in C_R$ and $M_0[\sigma'_1]M'_1[\sigma'_2]M'_2 \notin C_R$ with $uv \in A(\lambda(\sigma_1))$, $uv' \in A(\lambda(\sigma'_1))$, and $w \in A_D(\lambda(\sigma_2)) \cap A_D(\lambda(\sigma'_2))$. Since all confusable pairs of basis markings in \mathcal{B}_A are in $R(\Omega(\mathcal{B}_A), k)$ as soon as the communication loss stage completes, there exists a state (\hat{M}_1, \hat{M}'_1) in $R(\Omega(\mathcal{B}_A), k)$ such that $M_1 \in R_I(\hat{M}_1)$ and $M'_1 \in R_I(\hat{M}'_1)$ based on Proposition 3. Moreover, by the construction of a robust basis k -extended networked detector, there exists a path $z \xrightarrow{\phi} z'$ such that $(\hat{M}_1, \hat{M}'_1) \in z$, $(\hat{M}_2, \hat{M}'_2) \in z'$, $M_2 = R_I(\hat{M}_2)$, and $M'_2 = R_I(\hat{M}'_2)$ with $|\lambda(\phi)| \geq l$ and $w \in A_D(\lambda(\phi))$ based on Proposition 3. Thus, we have $z' \in Z_v$.

(Only if) By contrapositive, suppose that there exists a state $z \in D_l(\hat{\mathcal{B}}_{d,k})$ with $z \in Z_v$. Then, we have $(\hat{M}, \hat{M}') \in z'$, and one of the following two conditions holds: 1) $\hat{M} \in \mathcal{F}$ and $\hat{M}' \in \mathcal{N}$; 2) $\hat{M} \in \mathcal{P}$ based on Definition 11.

For the first case, there exists a path $z \xrightarrow{\phi} z'$ with $(\hat{M}_1, \hat{M}'_1) \in z$, $(\hat{M}, \hat{M}') \in z'$, and $(\hat{M}_1, \hat{M}'_1) \in R(\Omega(\mathcal{B}_A), k)$ such that $M \in R_u(\hat{M}) \cap C_R$ and $M' \in R_u(\hat{M}') \cap (R(PN, M_0) \setminus C_R)$ according to Definition 10 and the condition $T_I \subseteq T_u$. Based on Proposition 3 and the construction of a robust basis k -extended networked detector, we have $\hat{M}_1[\sigma]M$ and $\hat{M}'_1[\sigma']M'$ such that $w \in A_D(\lambda(\sigma)) \cap A_D(\lambda(\sigma'))$ and $|w| \geq l$. Moreover, since $R(\Omega(\mathcal{B}_A), k)$ contains all confusable pairs

in \mathcal{B}_A as soon as the communication loss stage completes, there exist two event sequences $s = uv$ and $s' = uv'$ such that $\hat{M}_1 \in \hat{\mathcal{C}}(s)$ and $\hat{M}'_1 \in \hat{\mathcal{C}}(s')$. Based on Proposition 3, we have two sequences σ_1 and σ'_1 such that $uv \in A(\lambda(\sigma_1))$, $uv' \in A(\lambda(\sigma'_1))$, and $|v| = |v'| = k$. By Definition 1, G is not (k, l) -CO w.r.t. A_D and C_R .

For the second case, there exists a path $z \xrightarrow{\phi} z'$ with $(\hat{M}_1, \hat{M}'_1) \in z$, $(\hat{M}, \hat{M}') \in z'$, and $(\hat{M}_1, \hat{M}'_1) \in R(\Omega(\mathcal{B}_A, k))$ such that $M \in R_u(\hat{M}) \cap C_R$ and $M' \in R_u(\hat{M}') \cap (R(PN, M_0) \setminus C_R)$ according to Definition 10 and the condition $T_I \subseteq T_u$. Based on Proposition 3 and the construction of a robust basis k -extended networked detector, we have $\hat{M}_1[\sigma]M$ and $\hat{M}'_1[\sigma']M'$ such that $w \in A_D(\lambda(\sigma)) \cap A_D(\lambda(\sigma'))$ and $|w| \geq l$. Moreover, due to $(\hat{M}_1, \hat{M}'_1) \in R(\Omega(\mathcal{B}_A, k))$, there exist two event sequences $s = uv$ and $s' = uv'$ such that $\hat{M}_1 \in \hat{\mathcal{C}}(s) \cap \hat{\mathcal{C}}(s')$. Based on Proposition 3, we have two sequences σ_1 and σ'_1 such that $uv \in A(\lambda(\sigma_1))$, $uv' \in A(\lambda(\sigma'_1))$, and $|v| = |v'| = k$. By Definition 1, G is neither (k, l) -CO w.r.t. A_D and C_R . \square

III. CASE OF MULTIPLE COMMUNICATION LOSSES

In this section, we present the procedure to apply the proposed method in [2] recursively to the case where there exists more than one communication loss stage. Given a sequence $s = uv_1w_1v_2w_2 \cdots v_nw_n \in A_D(L(G))$ in an LPN G under a replacement attack and a communication delay, and the communication losses occur for all v_i substrings for n times, where $|v_i| = k_i$ and $|w_i| = l_i$ for $i = 1, 2, \dots, n$. Now, the following steps are used to check critical observability in a general case.

- 1) No communication failure state N: compute the set $\Omega(\mathcal{B}_A)$ of all confusable basis marking pairs under \mathcal{A} .
- 2) Communication loss stage L1: compute the k_1 -step reach $L_1 = R(\mathcal{B}_A, k_1)$.
- 3) Communication recover state R1: construct the robust basis k_1 -extended detector \mathcal{B}_{d,k_1} starting from the set of initial markings L_1 , and then compute the l_1 -step reach of L_1 in \mathcal{B}_{d,k_1} , denoted as $R_1 = R(L_1, l_1)$.
- 4) Communication loss stage L2: compute the k_2 -step reach $L_2 = R(R_1, k_2)$.
- 5) Communication recover stage R2: construct the robust basis k_2 -extended detector \mathcal{B}_{d,k_2} starting from the set of initial markings L_2 , and then compute the l_2 -step reach of L_2 in \mathcal{B}_{d,k_2} , denoted as $R_2 = R(L_2, l_2)$.
- 6) ...
- 7) Communication loss stage Ln: compute the k_n -step reach $L_n = R(R_{n-1}, k_n)$.

- 8) Communication delay stage D: construct the robust basis k_n -extended networked detector $\hat{\mathcal{B}}_{d,k_n}$ starting from the set of initial markings L_n .

For brevity, after constructing the set $\Omega(\mathcal{B}_A)$, we iteratively compute the corresponding k_i -step reach for n times, and the l_i -step reach in the corresponding robust basis extended detector for $n - 1$ times, and check if the final robust basis extended networked detector $\hat{\mathcal{B}}_{d,k_n}$ satisfies the condition in Theorem 1.

Example 1: Let us consider the LPN in Fig. 1(a). Let $C_R = \{M_c^1 = [0010000001]^T\}$, A_D be a labeling function associated with a replacement attack $\mathcal{A} = \{(b, c)\}$ and a delay upper bound $N = 1$. First, we construct the RABRG in Fig. 1(b). Assume that the communication loss occur twice and $k_1 = 1$, $k_2 = 2$, $l_1 = 1$, and $l_2 = 2$.

- 1) No communication failure state to Communication recover stage R1: According to the robust basis 1-extended detector $\mathcal{B}_{d,1} = Ac(X_d, Tr', \delta_d, X_{d,0})$ shown in Fig. 2, we obtain $R_1 = R(X_{d,0}, 1) = \{(M_2, M_2), (M_2, M_4), (M_4, M_2), (M_4, M_4), (M_3, M_3), (M_2, M_3), (M_3, M_2), (M_4, M_3), (M_3, M_4)\}$, i.e., after observing one observable event, the set of confusable basis marking pairs are collected in R_1 .
- 2) Communication loss stage L2: compute $L_2 = R(R_1, 2) = R_1$, i.e., the set of confusable basis marking pairs are collected in L_2 after losing two observable events.
- 3) Communication delay state D: construct the robust basis 2-extended networked detector $\hat{\mathcal{B}}_{d,2}$ shown in Fig. 3. By Theorem 1, the plant is not critically observable due to the existence of a negative cycle from $z_0 \in Z_0$ to $z_3 \in Z_v$ in the underlying digraph \mathcal{B} of $\hat{\mathcal{B}}_{d,2}$.

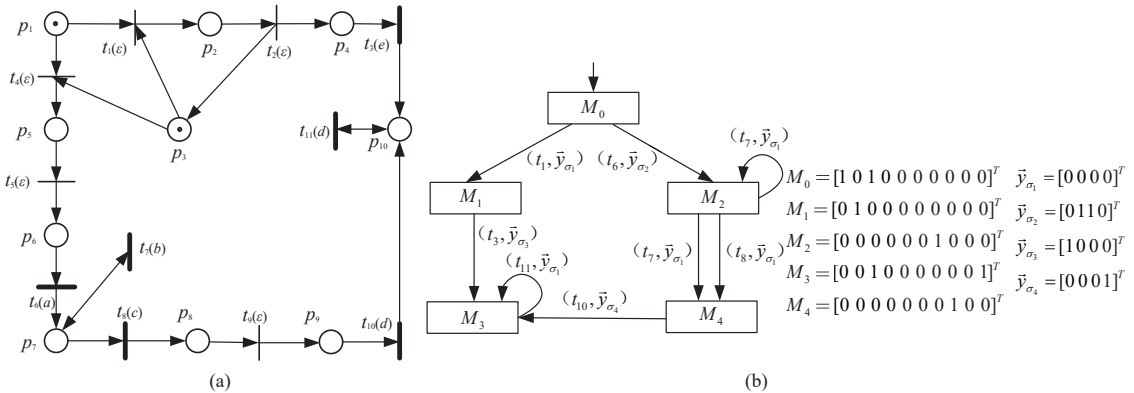


Fig. 1: (a) A bounded LPN under a replacement attack and (b) its RABRG.

Note that the operator of a plant net may not know the forthcoming disturbance a priori. That is to say, it does not know the exact communication loss times in practice. Thus, if the

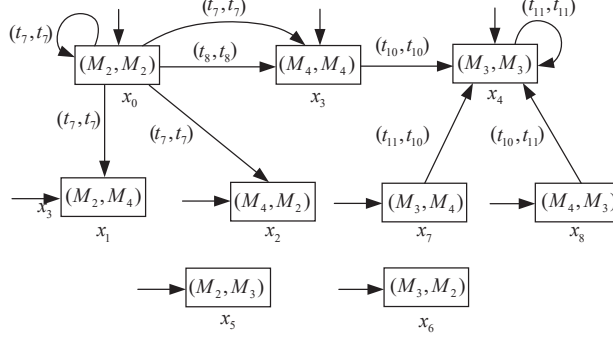


Fig. 2: The robust basis 1-extended detector.

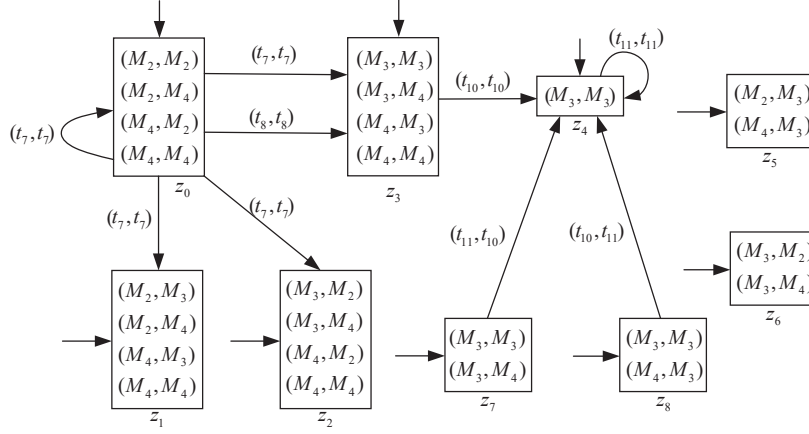


Fig. 3: The robust basis 2-extended networked detector.

communication suffers from multiple communication losses, it is more realistic to consider def-CO. In particular, if an LPN is def-CO, then it is critically observable for all n , k_1, \dots, k_n , and l_1, \dots, l_n . In a word, the k -CO defined in [2] characterizes the robustness of a system against casual single-time communication loss, and the def-CO defined in [2] characterizes the robustness against multiple communication losses.

IV. CASE STUDY

Some experimental results are provided in this section about the application of the proposed methodology for the k -CO verification in NDESs under replacement attacks. The results are obtained by a laptop under Windows 10 operating system with Intel CPU 2.3 GHz and 16 GB memory.

To this aim, we take into account two groups of LPNs with fixed numbers of places and transitions. For each group of the nets, we consider the same net structure with two different initial markings. In particular, the net systems presented in this section can model two different communication systems [3]. More precisely, each place of LPNs 1–4 can represent the replay station that implements the information transfer. Each marking $M(p_i) = 1$ ($M(p_i) = 0$) indicates the busy (free) status of each relay station. For the safety of the information transfer in the system, the situations of some important information shared by some particular stations are regarded as the critical states in the system.

The net structure of the first group of LPNs is shown in Fig. 4, which has 19 places and 11 transitions (five observable transitions and six unobservable transitions). There are four labels in this net structure. Assuming that the set of critical markings for LPNs 1 and 2 is $C_R = \{M \in \mathbb{N}^{19} | M(p_2) + M(p_4) + M(p_6) + M(p_{19}) \geq 1\}$. Let $k = 1$ and A_D be a labeling function associated with a replacement attack $\mathcal{A} = \{(a, b)\}$ and a delay upper bound $N = 1$.

The net structure of the second group of LPNs is shown in Fig. 5, which has 23 places and 23 transitions (four observable transitions and 19 unobservable transitions). There are four labels in this net structure. Assuming the set of critical markings for LPNs 3 and 4 is $C_R = \{M \in \mathbb{N}^{23} | M(p_5) + M(p_6) \geq 1\}$. Let $k = 1$ and A_D be a labeling function associated with a replacement attack $\mathcal{A} = \{(a, b)\}$ and a delay upper bound $N = 1$.

Table I shows the performance of the proposed method applied to LPNs 1–4: column two represents the number of tokens in p_1 for LPNs 1–4, columns three and four represent the number of basis markings and that of arcs in the RABRGs that associate with LPNs 1–4, respectively. Column five and six represent the number of markings and that of arcs in the reachability graphs of LPNs 1–4 under replacement attacks by using the PN analysis software TINA [4], respectively. The last column shows whether the LPN is k -CO w.r.t. A_D and C_R . From the experimental results shown in Table I, we can see that the proposed method is more efficient than the one generating the full state space.

REFERENCES

- [1] Ma, Z., Tong, Y., Li, Z., & Giua, A. (2017). Basis marking representation of Petri net reachability spaces and its application to the reachability problem. *IEEE Transactions on Automatic Control*, 62(3), 1078–1093.

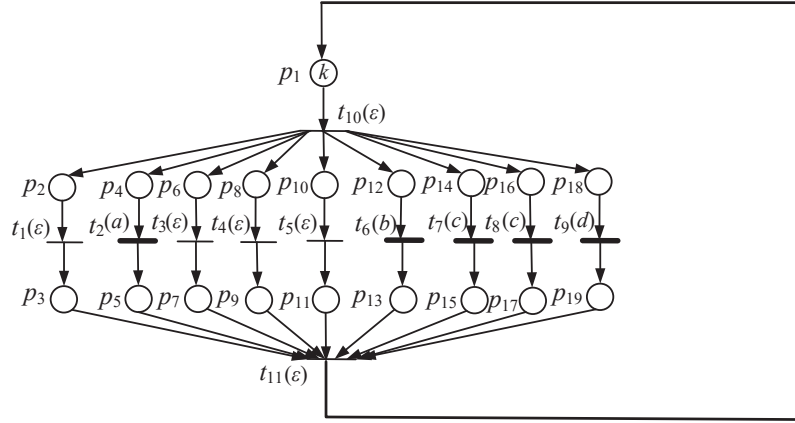


Fig. 4: Net structure of LPNs 1 and 2.

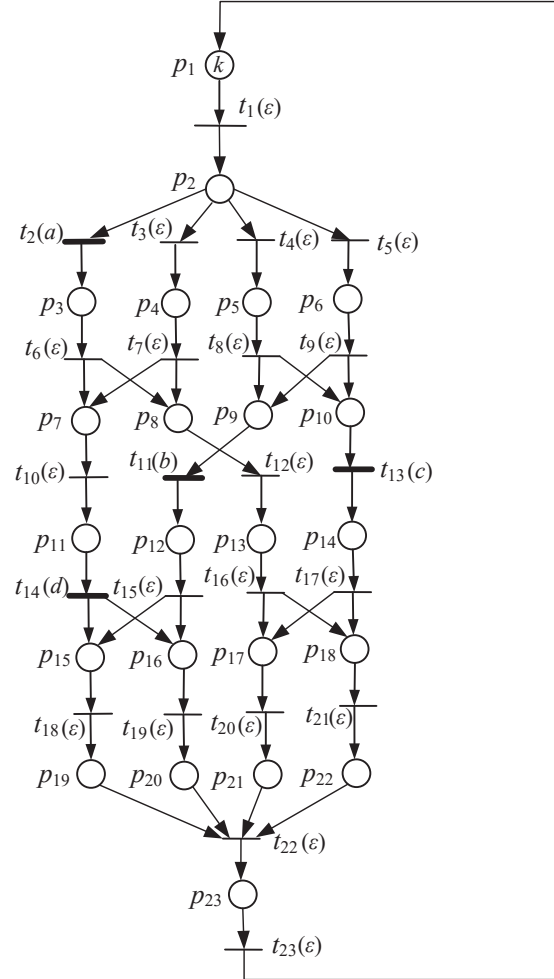


Fig. 5: Net structure of LPNs 3 and 4.

TABLE I: Experimental results for the LPNs 1–4

	k	$ \mathcal{M}_B $	$ \delta_A $	$ R_A(PN, M_0) $	$ \bar{\delta}_A $	K -CO
LPN1	1	33	90	513	2562	Yes
LPN2	2	276	1071	20196	134806	Yes
LPN3	1	7	14	63	129	Yes
LPN4	2	55	185	1683	6159	Yes

- [2] Cong, X., Yu, Z., Fanti, M. P., Mangini, A. M., & Li, Z. (2025). K -step and definite critical observability in networked discrete event systems under replacement attacks via labeled Petri nets, submitted to *Automatica*.
- [3] Cong, X., Fanti, M. P., Mangini, A. M. & Li, Z. (2022). Critical observability of discrete-event systems in a Petri net framework. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 52(5), 2789–2799.
- [4] TINA (Version 3.8.0): Time Petri Net Analyzer 2024. [Online]. Available: <http://projects.laas.fr/tina//download.php>