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DYNAMICS OF SELF-REPAIRING NETWORKS: TRANSIENT STATE ANALYSIS ON SEVERAL REPAIR TYPES

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Abstract. *We discuss the problem of spreading of the normal state (rather than spreading of the abnormal state), which is formalized as cleaning a contaminated network by mutual-copying and self-copying. Repairing by copying is a "double-edged sword" that could spread contamination unless properly used. We also focus on the transient states of self-repairing networks involving several types of repair. Some implications for the framework of antivirus systems (against computer viruses and worms) will be discussed comparing mutual-repair and self-repair of nodes in the network.*
Keywords: Self-repairing network, Distributed autonomy, Antivirus program, Infection model

1. **Introduction.** As information systems become larger and more complex, it becomes increasingly difficult to maintain the systems. Conventional reliability theory based on redundancy assumes passive components, while information systems include active components. Inspired by biological systems, von Neumann in his probabilistic logic [1] speculated on system level reliability using components with limited reliability. Although he suggested the importance of autonomy, components are assumed to have limited operations. With the advent of high-performance computers and information processing components, it is tempting to develop a new theory of biological system reliability assuming active components that are capable of diagnosing each other and rearranging or repairing each other, as is often the case in multi-cellular organisms. There has been landmark theoretical work to make cellular automata more reliable with self-organization [2].

Intra-computer technology such as multi-core processors as well as inter-computer technology such as networking computers have made computer systems more complex and larger in scale. The introduction of computers not only allows but also requires computers to monitor themselves in an intra- and inter-computer fashion [3-6]. As human nervous systems created consciousness to monitor themselves (and multi-cellular organisms created the immune system to monitor themselves), computers that have exceeded some threshold of complexity will need self-recognition and self-reaction.

Extensive studies have been done to make computer systems more fault-tolerant and dependable [7,8], autonomous and self-managing [5,6]. Autonomic computing [5] has been extensively studied and autonomic computer systems have actually been implemented. The self-aware computing project [6] applies control theory to the components of computers based on signal level controls. It should be noted that many studies have pointed out the importance of self (as evidenced by such terms as self-monitoring, self-managing, self-repair, self-recognition, self-aware), and self-star (wildcard) properties have been studied [9].

We proposed a self-repairing network for networked computers and sensors/actuators to repair the self [10-12] to deal with the network cleaning problem: can a collection of computers capable of repairing themselves and others actually resolve abnormal states (or reset the states of all the nodes)?

This paper extends the self-repairing network by combining two typical repairs: self-repair and mutual-repair. Two types of hybridization, mixed-repair and switching-repair, are investigated to broaden the parameter region (called "frozen phase") where all the abnormal nodes are eradicated. Simulations as well as analysis based on the mean-field approximation are used to draw a phase diagram that separates the frozen phase from the parameter region (called "active phase") where some abnormal nodes remain.

Section 2 revisits the self-repairing network involving infections. Two types of primitive repair, self-repair and mutual-repair, as well as two types of their combination, mixed-repair and switching-repair, are presented. Section 3 examines the model with a steady-state analysis and a computer simulation for these repairs. Section 4 presents a transient-state analysis by introducing variations of the phase diagrams. Section 5 discusses the implications of the model and simulation targeting antivirus software under the restrictions assumed for the model. Section 6 concludes the paper.

2. Basic Model.

2.1. Definitions and extensions.

The self-repairing network consists of autonomous nodes capable of repairing neighboring nodes (i.e., connected nodes) and themselves (i.e., nodes with a loop). Repairing may be implemented in many ways depending on target systems. One way is overwriting the contaminated contents with normal contents by copying the normal contents. (Other ways include removing contaminated parts and resetting the state.) Each node has a binary state: normal (0) or abnormal (1). We further assume the simplest network: a ring structure when the nodes are networked (Figures 1(b) and 1(c)).

In the self-repairing network, repair may be divided into two types depending on the target of repair: *self-repair* (Figure 1(a)) targets the repairing node itself; *mutual-repair* (Figure 1(b)) targets the nodes connected to the repairing node. In the self-repair by each node, there is no interaction among nodes. As a result, only two cases take place: normal node repairs the normal node; and abnormal node repairs the abnormal node. The other

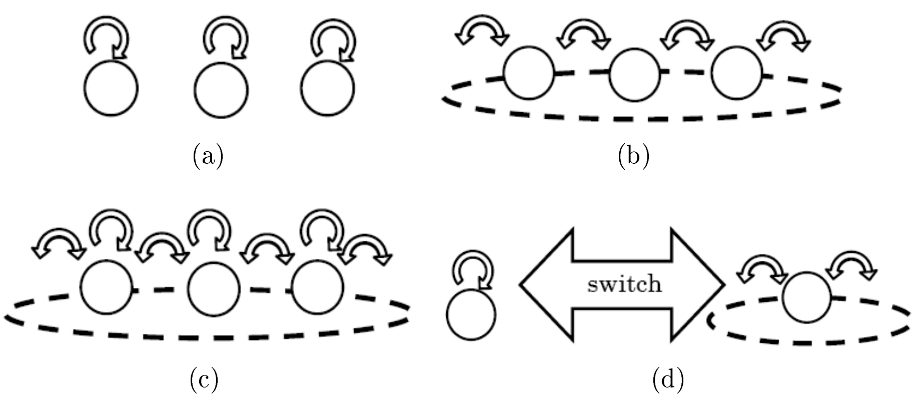

FIGURE 1. (a) Self-repair, (b) mutual-repair, (c) mixed-repair, and (d) switching-repair

two cases, normal node repairs the abnormal node and abnormal node repairs the normal node, will not take place in the self-repair.

Each node repairs the neighboring nodes with a probability P_r (called the repair rate). The repair will succeed with a probability P_{rn} (called the repair success rate by normal nodes) when it is done by a normal node, but with a probability P_{ra} (called the repair success rate by abnormal nodes) when done by an abnormal node. Infection occurs only when at least one infected node exists in the neighborhood. Infection occurs with a probability P_i (called the infection rate). Infected nodes are also considered as abnormal.

When many repairs are applied to one node simultaneously (called *simultaneous repair*), the repair can be further subdivided into two types: AND-repair and OR-repair. In the AND-repair, all the repairs must be successful for the simultaneous repair to be successful, while the OR-repair requires at least one repair to be successful out of multiple repairs done simultaneously.

We can control only the repair rate P_r but not other parameters: the repair success rates P_{rn} and P_{ra}, and the infection rate P_i. These parameters are determined based on the environment of the network and computers. We cannot choose between the AND-repair or OR-repair which provides the theoretical worst case or best case, respectively. In reality, the case will be between these two extremes depending on the protocol and synchrony of the network.

2.2. **Combining self-repair and mutual-repair.** The two types of repair, self-repair (Figure 1(a)) and mutual-repair (Figure 1(b)), can be combined in two ways: mixed-repair (Figure 1(c)) and switching-repair (Figure 1(d)). The mixed-repair just uses both self-repair and mutual-repair, while the switching-repair switches these two repairs. That is, each node executes the self-repair with a switching rate P_{sr}, and the mutual-repair with $1 - P_{sr}$. For the switching-repair, mutual OR-repair has a large area of frozen phase (Figure 2) and need not be switched to the self-repair. Therefore, we consider only AND-repair for the switching-repair.

Although mutual-repair and switching-repair can involve up to two simultaneous repairs (Figures 1(b) and 1(d)) and mixed-repair can involve up to three simultaneous repairs (Figure 1(c)), self-repair includes only the single repair (Figure 1(a)). In AND- (OR-) repair, because the repair success rate of single (simultaneous) repair is greater than that of simultaneous (single) repair, single (simultaneous) repair is favored. Since the higher the repair rate P_r, the higher the probability of simultaneous repair, a smaller repair rate is favored for AND-repair and a larger repair rate is favored for OR-repair.

The transition probabilities for probabilistic rules are listed in the Appendix: Table 3 (mutual-repair), Table 5 (mixed-repair) and Table 7 (switching-repair). Those for the self-repair are listed in [12].

3. Analysis and Simulations.

3.1. **Steady-state analysis.** In a mathematical formulation, the model consists of three elements $(\boldsymbol{U}, \boldsymbol{T}, \boldsymbol{R})$ where $\boldsymbol{U}$ is a set of nodes, $\boldsymbol{T}$ is a topology connecting the nodes, and $\boldsymbol{R}$ is a set of rules for the interactions among nodes. A set of nodes is a finite set with $\boldsymbol{N}$ nodes, and the topology is restricted to a one-dimensional array as shown in Figure 1. Also, we restrict the case where each node has a binary state: normal (0) and abnormal (1).

As a probabilistic cellular automaton similar to the Domany-Kinzel model motivated by the Ising model [13], the transition rules of AND-repair assuming the repair success rate $P_{rn} = 1$ [10], for example, are as follows (where the state of the node of interest is the center in parentheses and the states of the two neighboring nodes are at the left and the right in parentheses; the self-state will be changed to the state indicated to the right of the arrow, with the probability indicated after the colon):

(000)→0: 1, **(010)→1:** $(1-P_r)^2$,
(001)→1: α, **(011)→1:** $\alpha+(1-P_r)^2$,
(101)→1: $2(1-P_r)\alpha+\beta$, **(111)→1:** $2(1-P_r)\alpha+\beta+(1-P_r)^2$,
where $\alpha=P_r(1-P_{ra})$, $\beta=P_r^2(1-P_{ra}^2)$.

Under the approximation that the probability of the state of a node being abnormal is constant and equated with a density ρ_1 ($\rho_0=1-\rho_1$) of abnormal nodes (mean field approximation and steady state), the following differential equation is obtained [12]:

$$\frac{d\rho_1}{dt}=A\rho_1^3+B\rho_1^2+C\rho_1+D, \tag{1}$$

where the coefficients A, B, C and D are constants determined by the parameters of the self-repairing network. Three solutions are obtained in the third-order algebraic equation given by the steady state, that is, the solutions of $A\rho_1^3+B\rho_1^2+C\rho_1+D=0$. These three solutions are fixed points of the differential equation above, and we can obtain the density of abnormal nodes in the steady state determined by the stable points corresponding to the solutions. Figure 2 and Figure 3 plot the density of abnormal nodes obtained by a numerical study of the solution of the above algebraic Equation (1).

Coefficients A, B, C and D of the equation expressed by parameters for several types of repair are listed in Table 4 (mutual-repair), Table 6 (mixed-repair) and Table 8 (switching-repair) in the Appendix. Those for the self-repair are listed in [12]. Both mutual-repair and mixed-repair are further divided into AND-repair and OR-repair. For any type of repair, $D=0$ when we limit ourselves to the case in which the repair by normal nodes always succeeds ($P_{rn}=1$).

3.2. **Simulation results.** Computer simulations are conducted with the parameters listed in Table 1. under the conditions that the repair by normal nodes always succeeds ($P_{rn}=1$) and infections occur ($P_i=0.1$) [12] as well as repairing ($P_r>0$).

Figure 2 and Figure 3 show the density of normal nodes, which is similar to the phase diagram but including detailed information on any region (called extended phase diagram). The curves in each plot separate the area into two parameter regions: lower-left (including the origin) and upper-right (including upper-right $P_r=1$ and $P_{ra}=1$). The lower-left region is the *active phase* where some abnormal nodes remain in the network, and the upper-right region is the *frozen phase* where all the nodes become normal.

The shape of the border between two phases may be explained qualitatively. Generally, there is a trade-off between the repair rate (P_r plotted on the vertical axis of the diagram) and the repair success rates (P_{ra} plotted on the horizontal axis of the diagram), for the decrease of the repair success rate must be compensated by the increase of the repair rate to attain the same level of the eradication of abnormal nodes. As observed in Figure 2, the

Table 1. Parameters for the simulations of the self-repairing network with infection

Number of nodes	1000
Initial number of normal nodes	500
Number of steps	500
Repair rate P_r	0.00-1.00 (in 0.01 increments)
Repair success rate by normal nodes P_{rn}	1.0
Repair success rate by abnormal nodes P_{ra}	0.00-1.00 (in 0.01 increments)
Infection rate P_i	0.1

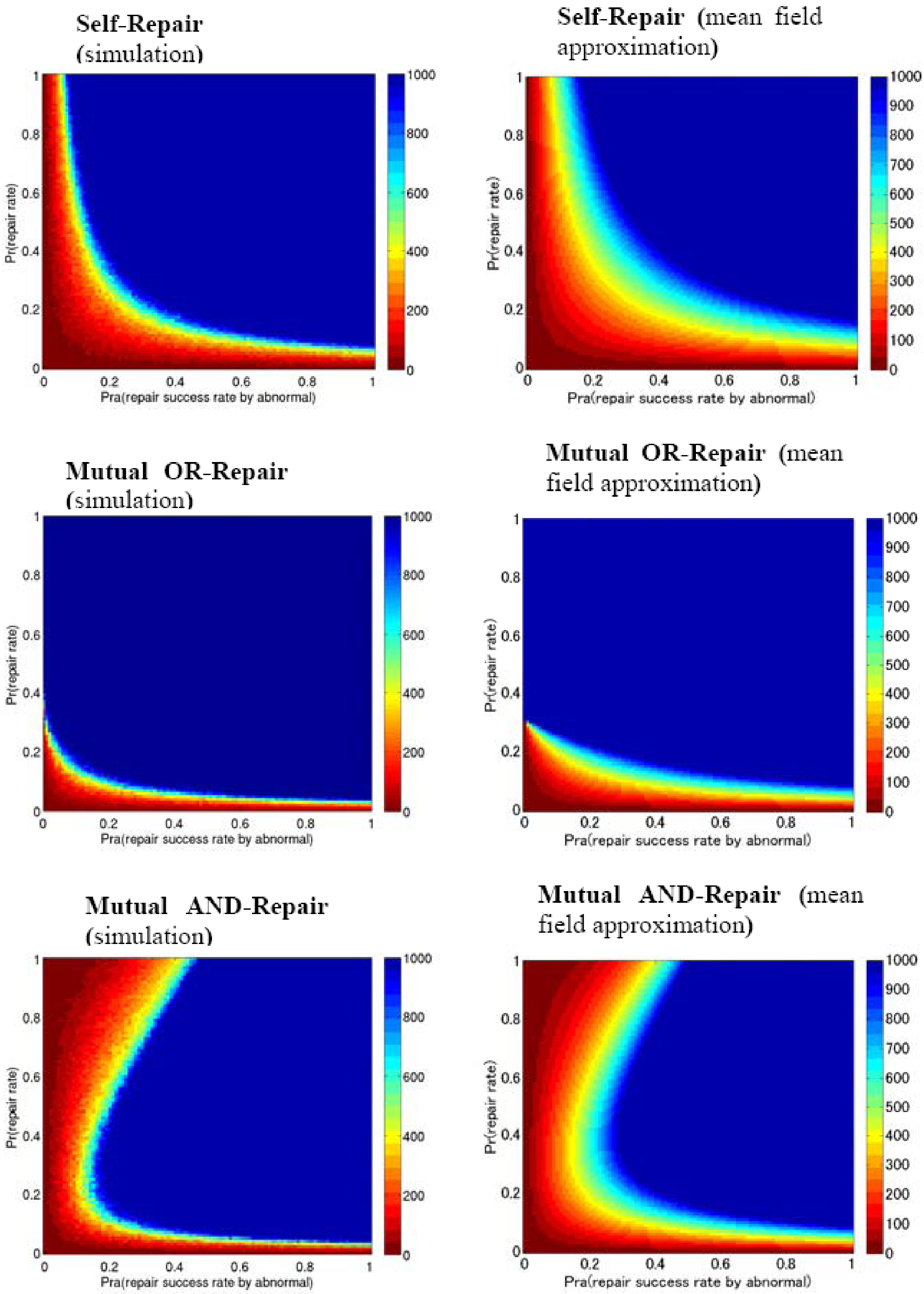

FIGURE 2. Density of normal nodes in the steady state with $P_i = 0.1$. By simulation (left) and by mean field approximation (right); self-repair (top row), mutual OR-repair (middle row), mutual AND-repair (bottom row).

trade-off is obvious for the self-repair which does not have repairs between nodes. When there are repairs between nodes, OR-repair gives the best bound, for only one success of the repair (among the repairs done by the two neighbor nodes) suffices for a node to be repaired, while AND-repair gives the worst bound, for all the repairs must be successful.

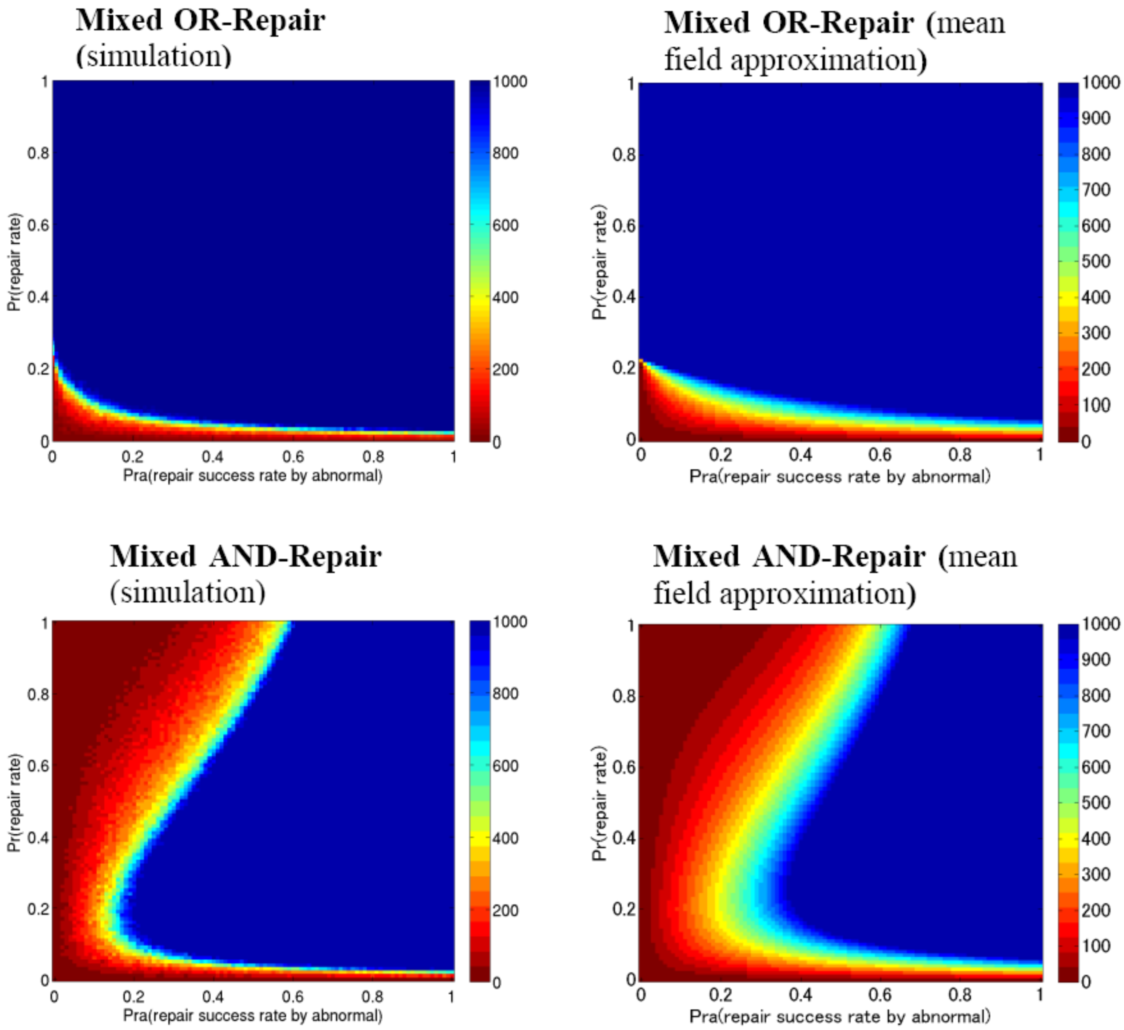

FIGURE 3. Density of normal nodes in the steady state with $P_i = 0.1$. By simulation (left) and by mean field approximation (right); mixed AND-repair (below) and mixed OR-repair (above).

For this reason, the increase of the repair rate of AND-repair would lead to the contrary of the eradication of abnormal nodes (Figure 2).

The extended phase diagram shows not only the qualitative aspects of active and frozen phases, but also the quantitative aspect of the ratio of the number of normal nodes in the steady state. The parameter regions are colored blue when normal nodes are dominant and red when abnormal nodes are dominant. Thus, the frozen phase is colored blue.

It can be observed that the frozen phase has one color because there are only normal nodes, while the color is graded in the active phase where the number of normal nodes decreases further away from the boundary.

The extended phase diagram obtained by simulations and by numerical studies based on the mean field approximation (Figure 2) indicates that the density decreases as the parameter region is further away from the upper-right where the eradication of abnormal nodes can be done most efficiently.

The density of normal nodes obtained by simulations qualitatively matches the density of normal nodes obtained by mean field approximation (Figure 2 and Figure 3), although they do not match exactly (due to the approximation). The region of the frozen phase by mean field approximation tends to shrink. The mean field approximation uses the density

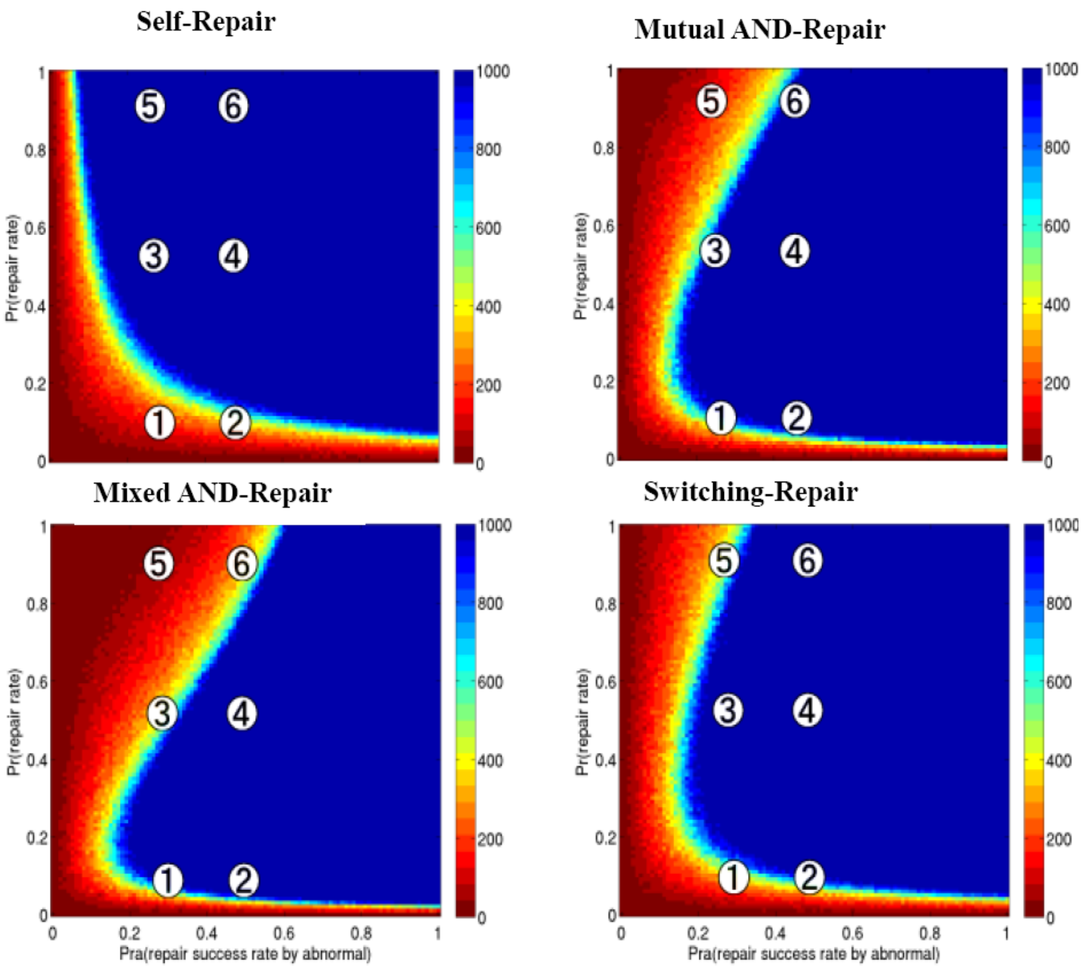

FIGURE 4. Extended phase diagrams of the four types of repair. The parameter regions are colored blue when normal nodes are dominant and red when abnormal nodes are dominant. Self-repair (top, left); mutual AND-repair (top, right); mixed AND-repair (bottom, left); switching-repair (bottom, right).

ρ_1 in evaluating a probability of having abnormal neighbor nodes even when they are all normal nodes. Hence, the number of normal nodes is underestimated.

Comparing self-repair and mutual AND-repair, Figure 2 indicates that self-repair outperforms mutual AND-repair when the repair rate is high, while mutual AND-repair outperforms when the repair rate is low. Mutual OR-repair outperforms self-repair when the repair rate is high, and its performance is similar to that of mutual AND-repair when the repair rate is low.

Higher performance (broader frozen region) of OR-repair compared with AND-repair when the repair rate is high can be observed both in the density of normal nodes (Figure 2 and Figure 3) and the time steps required to eradicate abnormal nodes (Figure 5).

The shrinking of the frozen region caused by simultaneous repair is more severe in mixed AND-repair (Figure 3) than mutual AND-repair (Figure 2), for in a ring structure up to three simultaneous repairs can occur in the mixed AND-repair while up to two simultaneous repairs can occur in the mutual AND-repair.

Table 2 summarizes the characteristics of the four types of repair: self-repair, mutual-repair, mixed-repair and switching-repair. Among the last three repairs having simultaneous repairs, we consider AND-repair and OR-repair for the mutual-repair and the

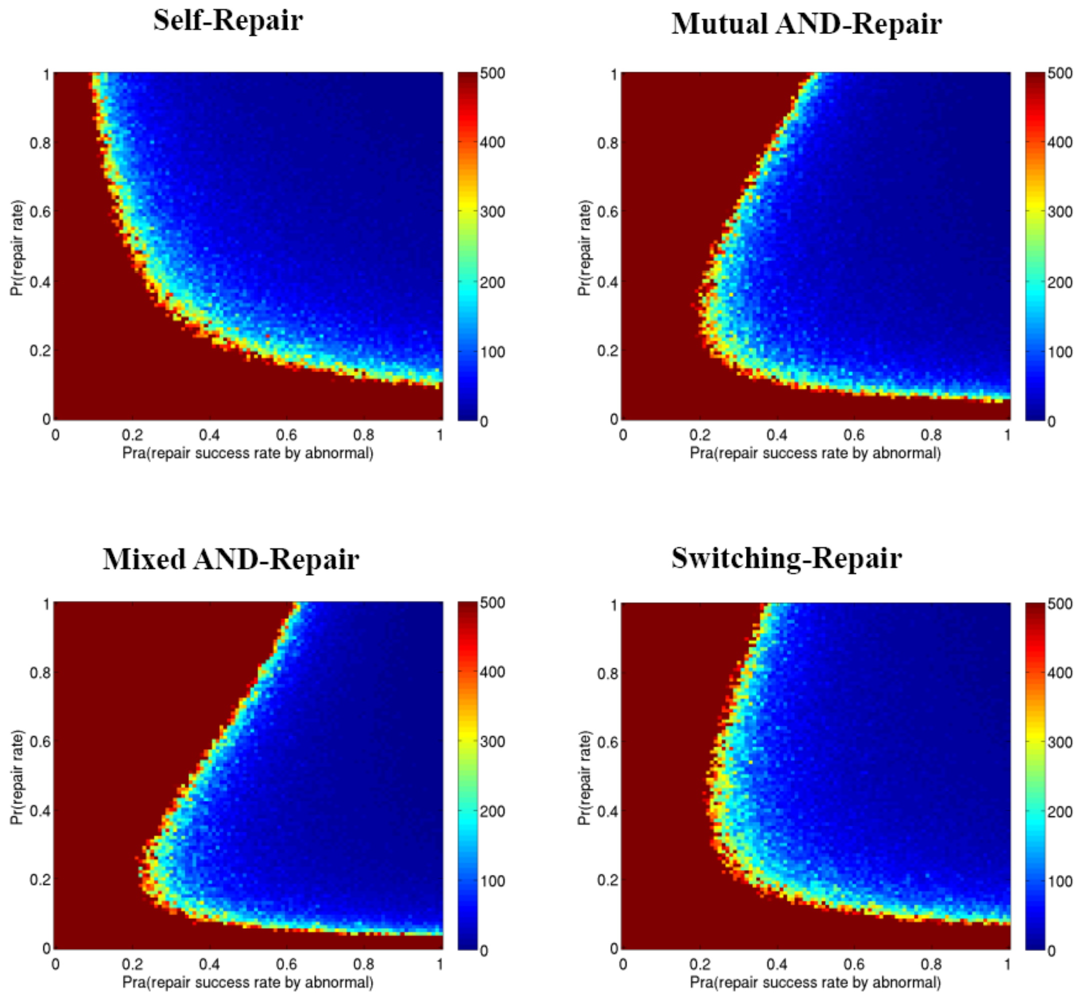

Figure 5. Transient phase diagrams (obtained by simulations) indicating the number of steps required to eradicate the abnormal nodes with $P_i = 0.1$. Self-repair (top, left); mutual AND-repair (top, right); mixed AND-repair (bottom, left); switching-repair (bottom, right).

Table 2. Summary of the characteristics of each repair

Repair Type	Parameter Characteristics	Simultaneous Repair
Self	Higher performance with higher repair rate P_r	No Simultaneous Repair
OR (Mutual, Mixed)	Highest performance	Simultaneous Repair
AND (Mutual, Mixed)	Higher performance with lower (but not zero) repair rate P_r	
AND Switching	The repair rate P_r can be adjusted by changing the switching rate P_{sr}	

mixed-repair, resulting in six repairs in total. We will focus on the mixed-repair and switching-repair in the next section.

4. **Transient-State Analysis to Combine Self- and Mutual-Repair.** To investigate the steady state, we can carry out not only simulations but also mathematical analysis

such as mean field analysis and pair approximation. To study the transient state, however, we can do only simulations. We use the parameters listed in Table 1 for simulations to study the transient state.

Figure 4 shows the extended phase diagrams of the four types of repair: self-repair, mutual-repair, mixed-repair and switching-repair.

In practice, even if the parameters are in the frozen region and hence abnormal nodes can be eradicated, it would be virtually meaningless if the eradication takes a very long time. Figure 5 shows the time steps required to eradicate the abnormal nodes to investigate the transient state before reaching the steady state. The diagram is again similar to the phase diagram but includes detailed information on any region (called transient phase diagram). The transient phase diagram shows not only the active and frozen phases, but also the number of steps taken to reach the steady state. The parameter regions are colored blue when the number of steps is small and red when large. Thus, the frozen phase (*right region* where all the nodes are normal) is colored blue.

In contrast to an extended phase diagram which has one color in the frozen phase and graded in the active phase, the transient phase diagram has one color in the active phase (infinite number of steps required to eradicate abnormal nodes) while the color is graded in the frozen phase where the number of steps required decreases further away from the boundary.

It can be observed from Figure 5 that within the frozen phase, the number of steps required to eradicate the abnormal nodes differs. The top-right region requires the fewest steps, but the required steps for eradication increases as the parameter region moves further away from the top-right region. In other words, abnormal nodes are eradicated faster when the repair efficiency is high (both parameters P_r and P_{ra} are high in this self-repair case).

5. **Discussion: Implications for Antivirus Software.** It is pointed out that the critical point (above which an epidemic breaks out) in scale-free networks is 0; thus it is difficult to eradicate computer viruses and worms from the Internet [14], which may be a scale-free network [15]. However, from the viewpoint of the self-repairing network discussed above, the critical point is not 0, and computer viruses and worms may be eradicated if the network involves an active repair which has a certain probability of repair success.

As an application of the self-repairing network, we examine current antivirus software (against computer viruses and worms) and consider the potential of several types of repair. It should be stressed that the self-repairing network is a model to access the theoretical worst (or best) bounds, and is not a model that will directly lead to new antivirus software. Here, antivirus software is defined as follows:

- The antivirus software can detect and delete known viruses existing in a computer in which the antivirus software is installed. The frequency of the detection and deletion of detected viruses can be set by the user of the antivirus software.
- The antivirus software can protect against intrusion of known viruses to a computer in which the antivirus software is installed.
- Unknown viruses will become known viruses by downloading a definition file (signature file) of viruses to a computer in which the antivirus software is installed.

Furthermore, computers in which the antivirus software is installed are networked in a ring form: the topology assumed for the self-repairing network discussed in this paper.

If we view antivirus software in terms of the self-repairing network, the binary states of normal and abnormal of the self-repairing network respectively correspond to the state without viruses and the state with viruses in computers in which the antivirus software is installed. Repair in the self-repairing network corresponds to the detection and deletion of viruses in computers.

Among the parameters in the self-repairing network, namely P_r (repair frequency rate), P_{rn} (repair success rate by normal nodes), P_{ra} (repair success rate by abnormal nodes), and P_i (infection rate), only P_r can be set by the user of the antivirus software. This P_r corresponds to a frequency of virus detection/deletion by the antivirus software. Frequent detection/deletion by the antivirus software on a computer requires computational resources (CPU time and memory) and could interrupt or hamper the operation of the computer. Other parameters P_{rn}, P_{ra} and P_i depend on the performance of not only the antivirus software but also the computer environment including the computer, the computer network and the viruses, and hence cannot be set by the antivirus software.

The repair success rate by normal nodes P_{rn} corresponds to a success rate of detection/deletion of known viruses (i.e., a definition file of viruses is downloaded to the computer) by a *normal* computer (a computer not infected by viruses). Usually, an uninfected computer with antivirus software and definition file installed can successfully detect and delete viruses; hence P_{rn} can be assumed to be one ($P_{rn} = 1$).

The repair success rate by abnormal nodes P_{ra} corresponds to the success rate of detection/deletion of known viruses by an *abnormal* computer (a computer infected by viruses). Even an infected computer (in which antivirus software and definition file are installed) has a chance to detect and delete viruses successfully if the virus definition file is properly installed and the function of detection/deletion is not hampered by a virus; thus P_{ra} can be assumed to be greater than zero ($0 < P_{ra} < 1$).

The infection rate P_i is the rate with which viruses successfully enter a computer from the outside (through the network or other removable media). This rate depends upon whether the virus definition file has already been downloaded or not. If the definition file exists in the computer, the infection rate is very low but is high otherwise.

Since current antivirus software detects/deletes viruses in computers in which it is installed, the type of repair is *self-repair* rather than *mutual-repair*. Thus, the corresponding phase diagram is that of *self-repair* with an infection rate of greater than zero (Figure 4). For known viruses, the infection rate is small (but not zero) and the repair success rate by normal nodes (P_{rn}) and that by abnormal nodes (P_{ra}) are high. The phase diagram in Figure 4 (e.g., place indicated by the circled number 2) suggests that viruses can be eradicated even with low (but not zero) frequency of repair (P_r). For unknown viruses, however, lower repair success rate by abnormal nodes (P_{ra}) would require higher frequency of repair (P_r) for eradication (e.g., place indicated by the circled number 3 instead of 1 in Figure 4).

Current antivirus software adopts *self-repair*, which requires a high frequency of repair (P_r); however, a higher frequency of repair would not be favorable due to the larger computational resources required. To solve this problem, let us consider other types of repair in the context of the current antivirus software.

For the parameter region with high frequency of repair (P_r), *self-repair* would be favorable (as observed in Figure 4 comparing the places indicated by the circled numbers 3 and 5 to those of other types). In addition to performance, *self-repair* is free of psychological burden because it is an independent system and does not bother other computers for repairing and being repaired.

For the parameter region with low frequency of repair (P_r), *mutual-repair* and *mixed-repair* would be favorable (as observed in Figure 4 comparing the places indicated by the circled numbers 1 and 2 to those of *self-repair*). When the repair is *networked* as in *mutual-repair* and *mixed-repair* (Figure 1), simultaneous repair by multiple computers occurs, in which case the distinction between AND-repair and OR-repair should be taken into consideration. Again, it depends on the environment of the computer network and computers, and not our control (it could be controlled if we were to design the protocol for repairing). Generally, OR-repair may be favorable because of its broader area of frozen phase and mutual-repair does not need to be switched to self-repair if OR-repair is available (by avoiding simultaneous repair).

Since it would be impossible to evaluate the parameters beforehand and the parameters change dynamically, another option would be *switching-repair*. The switching parameter P_{sr} can be set depending on the other parameters so that each frozen region of the repairs involved together will cover a broader and practically important area of the phase diagram.

The above discussion does not consider the problem of privacy. If we place importance on privacy, *self-repair* would be more favorable than repairs involving *mutual-repair* such as *mutual-, mixed-* and *switching-repair*. If we restrict mutual-repair to intranets within the home, companies and schools, privacy would be less of a problem. More practically, mutual-repair may be restricted between the servers of the antivirus software provider and client computers, and repairs could also be restricted to only one way, from the servers to the clients. In fact, a *chain repair* is the dual of *chain failure* and is defined as a chain where node A repairs node B and then node B in turn repairs node C and so forth. Evidently, if the chain repair starts from a normal node and assuming P_{rn} equals one, then all the abnormal nodes will be eradicated.

For real deployment in an existing network such as the Internet, more comprehensive simulations and analysis are required using a more realistic (dynamic larger scale and complex topology) network to test and compare these different types of repair.

If the topology is different from a ring structure, the *degree* of each node changes and hence the number of simultaneous repairs may change. In fact, it may be possible to avoid simultaneous repairs by designing a protocol to handle the case where multiple repairs arrive at the same node and at the same time. The protocol could randomly choose one of the repairs and discard other repairs, or arrange for the repairs to be applied in serial fashion. Then, the success or failure of the repair depends on the success or failure of the chosen one (for the randomly chosen repair) and the last applied one (for the serially arranged repair).

6. **Conclusions.** The dynamics of abnormal node eradication in self-repairing networks were investigated by extending the conventional phase diagrams. Computer simulations as well as mean field analysis can be used to draw the conventional phase diagrams but only computer simulations can draw the extended and transient phase diagrams. Several repair types such as self-repair and mutual-repair and their hybrids were introduced. Some implications for antivirus software were also discussed.

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Appendix (Constants for the Steady State of the Five Repair Types: Mutual AND, Mutual OR, Mixed AND, Mixed OR and Switching AND).

Table 3. Transition probability in each state transition

State Transition	Transition Probability (mutual AND-repair)	Transition Probability (mutual OR-repair)
(000) →1	$P_r(1-P_{rn})(2-P_r+P_rP_{rn})$	$P_r(1-P_{rn})(2-P_r-P_rP_{rn})$
(001) →1	$P_r^2(1-P_{rn}P_{ra})+P_r(1-P_r)((1-P_{rn})+(1-P_{ra}))$ $+P_i(1-P_r)^2$	$-P_r^2(1-P_{rn}P_{ra})+P_r((1-P_{rn})+(1-P_{ra}))$ $+P_i\{1+P_r^2(1-P_{rn}P_{ra})-P_r((1-P_{rn})+(1-P_{ra}))\}$
(101) →1	$P_r(1-P_{ra})(2-P_r+P_rP_{ra})$ $+P_i(2-P_i)(1-P_r)^2$	$P_r(1-P_{ra})(2-P_r-P_rP_{ra})$ $+P_i(2-P_i)\{1-P_r(1-P_{ra})(2-P_r-P_rP_{ra})\}$
(010) →1	$1-P_rP_{rn}(2(1-P_r)+P_rP_{rn})$	$(1-P_r)^2+P_r(1-P_{ra})(2-P_r-P_rP_{ra})$
(011) →1	$1-P_r((P_{rn}+P_{ra})(1-P_r)+P_rP_{ra}P_{rn})$	$1-P_r(P_{rn}+P_{ra}-P_rP_{ra}P_{rn})$
(111) →1	$1-P_rP_{ra}(2(1-P_r)+P_rP_{ra})$	$(1-P_r)^2+P_r(1-P_{rn})(2-P_r-P_rP_{ra})$

TABLE 4. Coefficients of the equation expressed by parameters of the self-repairing network (mutual-repair)

Constant	Constants Expressed by Parameters (mutual AND-repair)	Constants Expressed by Parameters (mutual OR-repair)
A	$P_i^2(1-P_r)^2$	$2P_i\{1-P_r^2(P_rP_{ra}-1)-P_r(2-P_{rn}-P_{ra})\}$ $-P_i(2-P_i)\{1-P_r(1-P_{ra})(2-P_r-P_rP_{ra})\}$
B	$-P_r^2(P_{rn}-P_{ra})^2-P_i(2+P_i)(1-P_r)^2$	$P_r^2(P_{rn}-P_{ra})^2+4P_i\{1-P_r^2(P_rP_{ra}-1)-P_r(2-P_{rn}-P_{ra})\}$ $+P_i(2-P_i)\{1-P_r(1-P_{ra})(2-P_r-P_rP_{ra})\}$
C	$-2P_r(1-P_{rn})(P_r(P_{rn}-P_{ra})+1)+$ $P_r(P_r-2P_{ra})+2P_i(1-P_r)^2$	$P_r^2(1+2P_{rn}P_{ra}-2P_{rn}^2)+2P_r(-1+P_{rn}-P_{ra})$ $+2P_i\{1-P_r^2(P_rP_{ra}-1)-P_r(2-P_{rn}-P_{ra})\}$
D	$P_r(1-P_{rn})(2-P_r+P_rP_{rn})$	$P_r(1-P_{rn})(2-P_r-P_rP_{rn})$

TABLE 5. Transition probability in each state transition where the following conventions are used to accentuate the AND-OR duality [11]

$$Q_{rn} \equiv P_rP_{rn}-P_r+1 \qquad R_{rn} \equiv 1-P_rP_{rn}$$
$$Q_{ra} \equiv P_rP_{ra}-P_r+1 \qquad R_{ra} \equiv 1-P_rP_{ra}$$
$$Q_r \equiv (1-P_r)^3 \qquad R_r \equiv 1-P_r$$

State Transition	Transition Probability (mixed AND-repair)	Transition Probability (mixed OR-repair)
(000) →1	$1-Q_{rn}^3$	$R_{rn}^3-R_r^3$
(001) →1	$1-Q_{rn}^2Q_{ra}+P_i\{Q_{rn}Q_{ra}(Q_{rn}-Q_{ra})+Q_r\}$	$R_{rn}^2R_{ra}-R_r^3+P_i\{R_r^3-R_{rn}R_{ra}(R_{rn}-R_{ra})\}$
(101) →1	$1-Q_{rn}Q_{ra}^2+P_i(2-P_i)\{Q_{ra}^2(Q_{rn}-Q_{ra})+Q_r\}$	$R_{rn}^2R_{ra}-R_r^3+P_i(2-P_i)\{R_r^3-R_{ra}^2(R_{rn}-R_{ra})\}$
(010) →1	$1-Q_{rn}^2Q_{ra}+Q_r$	$R_{rn}^2R_{ra}$
(011) →1	$1-Q_{rn}Q_{ra}^2+Q_r$	$R_{rn}R_{ra}^2$
(111) →1	$1-Q_{ra}^3+Q_r$	R_{ra}^3

TABLE 6. Coefficients of the equation expressed by parameters of the self-repairing network (mixed-repair) where the following conventions are used to accentuate the AND-OR duality [11]

$$Q_{rn} \equiv P_r P_{rn} - P_r + 1 \qquad R_{rn} \equiv 1 - P_r P_{rn}$$
$$Q_{ra} \equiv P_r P_{ra} - P_r + 1 \qquad R_{ra} \equiv 1 - P_r P_{ra}$$
$$Q_r \equiv (1-P_r)^3 \qquad R_r \equiv 1 - P_r$$

Constant	Constants Expressed by Parameters (mixed AND-repair)	Constants Expressed by Parameters (mixed OR-repair)
A	$(Q_{rn}-Q_{ra})^3 + 2P_iQ_{ra}(Q_{rn}-Q_{ra})^2$ $+P_i^2\{Q_{ra}{}^2(Q_{rn}-Q_{ra})+Q_r\}$	$-(R_{rn}-R_{ra})^3 - 2P_iR_{ra}(R_{rn}-R_{ra})^2$ $+P_i^2\{R_r{}^3 - R_{ra}{}^2(R_{rn}-R_{ra})\}$
B	$-3Q_{rn}(Q_{rn}-Q_{ra})^2 + 2P_i\{Q_{ra}(Q_{rn}-Q_{ra})(Q_{ra}-2Q_{rn})-Q_r\}$ $-P_i^2\{Q_{ra}{}^2(Q_{rn}-Q_{ra})+Q_r\}$	$3R_{rn}(R_{rn}-R_{ra})^2 - 2P_i\{R_r{}^3 - R_{ra}(R_{rn}-R_{ra})(2R_{rn}-R_{ra})\}$ $-P_i^2\{R_r{}^3 - R_{ra}{}^2(R_{rn}-R_{ra})\}$
C	$3P_{rn}{}'^2(P_{rn}'-P_{ra}')+P_r'-1$ $+2P_i\{P_{rn}'P_{ra}'(P_{rn}'-P_{ra}')+P_r'\}$	$-3R_{rn}{}^2(R_{rn}-R_{ra})+R_r{}^3-1$ $+2P_i\{R_r{}^3 - R_{rn}R_{ra}(R_{rn}-R_{ra})\}$
D	$1-Q_{rn}{}^3$	$R_{rn}{}^3 - R_r{}^3$

TABLE 7. Transition probability in each state transition (switching AND-repair)

State Transition	Transition Probability (switching AND-repair)
(000) →1	$P_r(1-P_{rn})\{1-(1-P_{sr})P_r(1-P_{rn})\}\{P_{sr}+(1-P_{sr})(1-P_{sr}P_r+P_{sr}P_rP_{rn})\}+(1-P_{sr})P_r(1-P_{rn})$
(001) →1	$P_r\{1-(1-P_{sr})P_r(1-P_{rn})\}\{P_{sr}(1-P_{rn})+(1-P_{sr})(1-P_{ra})(1-P_{sr}P_r+P_{sr}P_rP_{rn})\}+(1-P_{sr})P_r(1-P_{rn})$ $+P_i[P_{sr}P_r(P_{rn}-P_{ra})\{1-(1-P_{sr})P_r(1-P_{rn})\}\{1-(1-P_{sr})P_r(1-P_{ra})\}+(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2]$
(101) →1	$P_r\{1-(1-P_{sr})P_r(1-P_{ra})\}\{P_{sr}(1-P_{rn})+(1-P_{sr})(1-P_{ra})(1-P_{sr}P_r+P_{sr}P_rP_{rn})\}+(1-P_{sr})P_r(1-P_{ra})$ $+P_i(2-P_i)[P_{sr}P_r(P_{rn}-P_{ra})\{1-(1-P_{sr})P_r(1-P_{ra})\}^2+(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2]$
(010) →1	$P_r\{1-(1-P_{sr})P_r(1-P_{rn})\}\{P_{sr}(1-P_{ra})+(1-P_{sr})(1-P_{rn})(1-P_{sr}P_r+P_{sr}P_rP_{ra})\}$ $+(1-P_{sr})P_r(1-P_{rn})+(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2$
(011) →1	$P_r(1-P_{ra})\{1-(1-P_{sr})P_r(1-P_{rn})\}\{P_{sr}+(1-P_{sr})(1-P_{sr}P_r+P_{sr}P_rP_{ra})\}$ $+(1-P_{sr})P_r(1-P_{rn})+(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2$
(111) →1	$P_r(1-P_{ra})\{1-(1-P_{sr})P_r(1-P_{ra})\}\{P_{sr}+(1-P_{sr})(1-P_{sr}P_r+P_{sr}P_rP_{ra})\}$ $+(1-P_{sr})P_r(1-P_{ra})+(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2$

TABLE 8. Coefficients of the equation expressed by parameters of the self-repairing network (switching AND-repair)

Constant	Constants Expressed by Parameters (switching AND-repair)
A	$P_{sr}(1-P_{sr})^2 P_r^3 (P_{rn}-P_{ra})^3 + 2P_i P_{sr}(1-P_{sr}) P_r^2 (P_{rn}-P_{ra})^2 \{1-(1-P_{sr})P_r(1-P_{ra})\}$ $+P_i^2 P_{sr} P_r (P_{rn}-P_{ra})\{1-(1-P_{sr})P_r(1-P_{ra})\}^2 + P_i^2(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2$
B	$(1-P_{sr})P_r^2(P_{rn}-P_{ra})^2\{3P_{sr}P_r(1-P_{rn})(1-P_{sr})-P_{sr}-1\}$ $-4P_i P_{sr} P_r (P_{rn}-P_{ra})\{1-(1-P_{sr})P_r(1-P_{rn})\}\{1-(1-P_{sr})P_r(1-P_{ra})\}$ $+P_i(2-P_i)P_{sr}P_r(P_{rn}-P_{ra})\{1-(1-P_{sr})P_r(1-P_{ra})\}^2 - P_i(2+P_i)(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2$
C	$P_{sr}^3 P_r^3\{3(1-P_{rn})^2(P_{rn}-P_{ra})-1\} + P_{sr}^2 P_r^2[2(1-P_{rn})(P_{rn}-P_{ra})\{-3P_r(1-P_{rn})+1\}+2P_r-1]$ $+P_{sr}P_r[(P_{rn}-P_{ra})\{3P_r^2(1-P_{rn})^2-1\}-P_r^2+1] + 2P_r(P_{rn}-P_{ra})(P_rP_{rn}-P_r+1)+P_r(P_r-2)$ $+2P_i[P_{sr}P_r(P_{rn}-P_{ra})\{1-(1-P_{sr})P_r(1-P_{rn})\}\{1-(1-P_{sr})P_r(1-P_{ra})\}+(1-P_{sr}P_r)\{1-(1-P_{sr})P_r\}^2]$
D	$P_r(1-P_{rn})\{1-(1-P_{sr})P_r(1-P_{rn})\}\{P_{sr}+(1-P_{sr})(1-P_{sr}P_r+P_{sr}P_rP_{rn})\}$ $+(1-P_{sr})P_r(1-P_{rn})$