Computer Engineering and Applications Vol. 3, No. 3, September 2014

Network Survivability Performance Evaluation in Underwater Surveillance System Using Markov Model

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ABSTRACT

Underwater Wireless Sensor Network (UWSN) is a useful technology that can be used in Underwater Surveillance System (USS). USSs are mostly used in military purposes for detecting underwater military activities. One of the most important issues in USS is mission reliability or survivability. Due to harsh underwater environment and mission critical nature of military applications, it is important to measure survivability of USS. Underwater sensor node failures can be detrimental for USS. To improve survivability in USS, we propose a fault-tolerant underwater sensor node model. To the best of our knowledge, this is the first fault-tolerant underwater sensor node model in USS that evaluates survivability of an USS. We develop Markov models for characterizing USS survivability and MTTF (Mean Time to Failure) to facilitate USS. Performance evaluation results show the effectiveness of proposed model.

Keywords: **Fault tolerance, survivability, UWSN, USS.**

1. INTRODUCTION

Nowadays, underwater wireless sensor network (UWSN) is a powerful technique for exploring underwater environments. UWSNs are useful for aquatic applications such as disaster prevention, distributed tactical surveillance, water quality monitoring and environmental monitoring [1], [2], [3]. Due to electromagnetic signals have high attenuation in underwater environment; underwater sensors use acoustic signals for communication. An underwater surveillance system (USS) consists of underwater sensors spread over a certain underwater environment to sense data about events such as submarine rides, marine life, contaminants and report sensed data via multi hop routes to a distant command center or base station [4]. Usually USSs are mostly used in military purposes.

When the enemy submarines move around in an underwater environment that an USS is implemented, underwater sensor nodes detect the movement of the submarines and transmit sensed data to surface buoys using multi hop routes. Finally

ISSN: 2252-4274 (Print)
ISSN: 2252-5459 (Online)

sensed data are transmitted from surface buoys to onshore station. Figure 1 shows USS architecture.

Due to military applications are mission-critical, it is important to measure survivability of USS. Additionally, USS is implemented in unattended and hostile underwater environment. Therefore manual inspection of faulty underwater sensor nodes in an USS after deployment is impractical. Thus, in order to meet survivability, USS requires fault detection and fault tolerance mechanisms. The ability of a network to restore or maintain an acceptable level of performance in the event of deterministic or random failures is defined as survivability [5]. Measuring survivability or mission reliability of an USS is useful to evaluate and predict successfulness of USS. One of the fault tolerance techniques is to add hardware redundancy to the system [6]. Although redundancy increases costs, but in an USS, survivability is more important than costs and redundancy can help to increase survivability. Markov model is a useful method that can be used for evaluating reliability and survivability of many systems such an USS. In this paper we have used Markov model to evaluate survivability of USS.

In an USS there are some important questions like: how long USS performs mission? How can the USS deal with the underwater sensor nodes failure? And what is the effect of the failure of underwater sensor nodes to USS performance. These questions can be answered using the USS survivability model in this paper. To the best of our knowledge, we for the first time develop a Markov model for characterizing USS Survivability. The main focus of this paper is to propose a model to evaluate USS survivability in the presence of redundant underwater sensor nodes.

In the next section, we explain reliability and fault tolerance. In section 3, we present our proposed survivability performance evaluation model. Description of the performance evaluation and analysis of the experimental results can be found in section 4. Finally section 5 concludes the paper and discusses our future research plan.

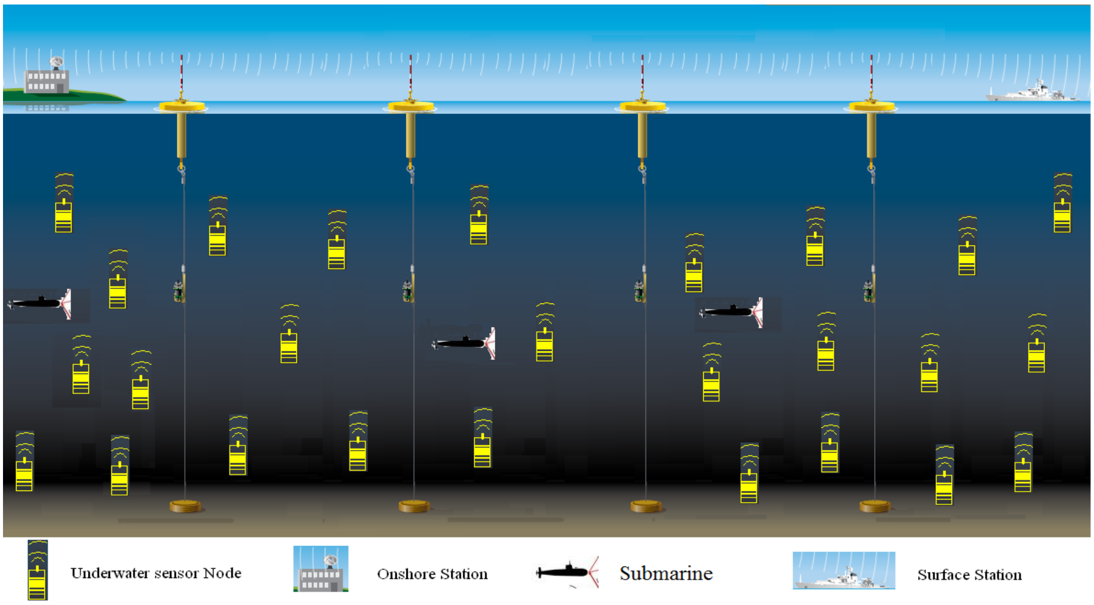

FIGURE 1. USS architecture

ISSN: 2252-4274 (Print)
ISSN: 2252-5459 (Online)

2. RELIABILITY AND FAULT TOLERANCE

There are several assumptions in different model of systems to consider fault tolerance, one of them is that the failures of the components are independent and another one is that one failure occurs at a time. Two failures that happen in the same time can be measured to happen sequentially. This assumption is not very limiting. One of the important design issues in wireless sensor networks spatially in USSs is the Mission Reliability of application services. This attribute should be taken into consideration when developing applications for such networks. Mission Reliability or Survivability R(t) of a system at time t is the probability that the system operates without failure in the interval [0,t] , assuming that it was operational at time 0 so any USS is correct performing at t=0 and if system fail at time t =Tf we have :

$$R(t) = \begin{cases} 1 & 0 \leq t < T_f \\ 0 & t \geq T_f \end{cases} \qquad (1)$$

Failure rate λ is the expected number of failures per unit time. For example, if a hardware unit fails, on average, once every 3000 hours, then it has a failure rate λ = 1/3000 failures/hour. Often failure rate is calculated in component level but there is no value of λ available in whole system. Because of a USS consists of electronic elements which have a very low failure rate, overall reliability of these systems are greater than other type of Networks.

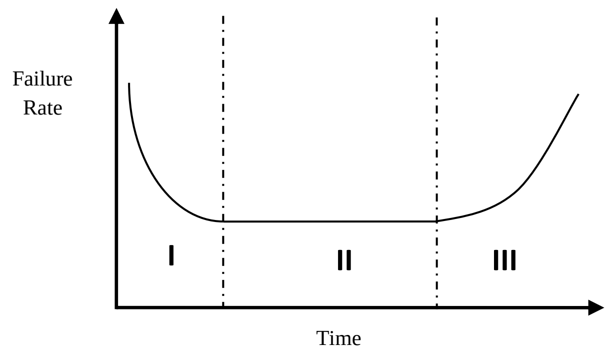

FIGURE 2. Typical evolution of failure rate over a life-time of a hardware system

Regard this point, the modeling of the a typical evolution of failure rate over a system’s life-time is described by the phases of (I) Early failures, (II) useful life and (III) wear-out failures. These phases are illustrated in Figure2. In first phase failure rate decreases because of frequent failures in weak components with fabricating defects overlooked during manufacturer’s testing, then failure rate becomes stable for definite time and in final phase it increases as electronic or mechanical components of the system physically wear out. During the phase II of the system, failure rate function is supposed to have a constant value λ. Then, the reliability of the system varies exponentially as a function of time:

$$R(t) = e^{-\lambda t} \qquad (2)$$

The exponential failure law is useful and applicable for analysis of reliability of components and systems in hardware. Another important factor that used in mission based systems like USS is mean time to failure (MTTF) defined as the expected time until the occurrence of the first system failure. The MTTF is defined by the following equations:

$$\mathrm{MTTF} = \int_0^\infty \mathrm{R(t)dt} \qquad (3a)$$

$$\mathrm{MTTF} = \frac{1}{\lambda} \qquad (3b)$$

Generally, MTTF is significant only for systems that perform without repair until a system failure is happen. In a real world, a complete check-out for mission critical systems is done before the next mission is started. For return the system to fully operational status, all failed redundant components are replaced or repaired. When evaluating the reliability of such systems, mission time should be greater than MTTF.

The Markov model for reliability of a system is demonstrated graphically by state transition diagrams. A state transition diagram is a directed graph G = (V; E), where V is the set of vertices representing system states and E is the set of edges representing system transitions. The failed state is shown by F and so the mission reliability of the USS is defined as sum of reliability of all states except F.

3. MARKOV MODELS FOR NETWORK RELIABILITY

In this section, we present our proposed Markov models for fault tolerance UWSNs. Our Markov model encompasses an underwater wireless sensor component and the overall UWSN.

An underwater wireless sensor component consists of an active underwater sensor node and k standby spare redundant underwater sensor node. Redundant sensors are considered to be hot-spare and they can replace without delay. When the active underwater sensor is failed, one of hot-spare underwater sensor will be replaced. Sensor replacement is done by fault detection algorithm. Fault detection algorithm can detect and replace standby spare sensor with probability c. Also the probability that fault detection algorithm can’t detect and replace standby spare sensor is 1-c. Because c is the probability that faulty sensor is correctly detected and replaced by a standby spare sensor, it can be concluded that c is coverage factor [7]. Failure rate of an underwater sensor during time t is λ and the probability of an underwater sensor can be represented using an exponential distribution. Thus the probability of an underwater sensor is:

$$\mathrm{p} = 1 - \mathrm{e}^{-\lambda \mathrm{t}} \qquad (4)$$

Figure 3 shows the Markov model for our proposed fault tolerance underwater wireless sensor component with one active sensor and two standby spare sensors. In Figure 3, the states in the Markov model indicate the number of intact sensors. State 0 indicates failure of component and state 3 indicates all three sensors in components are perfect.

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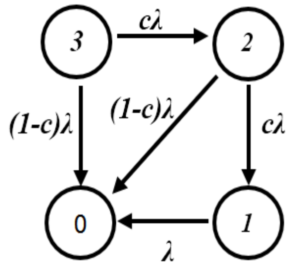

FIGURE 3. Markov model of one Component with three Sensors

The transition matrix describing the fault tolerance underwater wireless sensor component Markov model is:

$$\frac{d}{dt}\begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} 0 & \lambda & (1-c)\lambda & (1-c)\lambda \\ 0 & -\lambda & c\lambda & 0 \\ 0 & 0 & -\lambda & c\lambda \\ 0 & 0 & 0 & -\lambda \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix}$$

And the differential equations describing the fault tolerance underwater wireless sensor component Markov model are:

$$\frac{dP_3(t)}{dt} = -\lambda P_3(t) \quad (5)$$

$$\frac{dP_2(t)}{dt} = -\lambda P_2(t) + c\lambda P_3(t) \quad (6)$$

$$\frac{dP_1(t)}{dt} = -\lambda P_1(t) + c\lambda P_2(t) \quad (7)$$

$$\frac{dP_0(t)}{dt} = \lambda P_1(t) + (1-c)\lambda P_2(t) + (1-c)\lambda P_3(t) \quad (8)$$

where $P_i(t)$ denotes the probability that at time t, the underwater sensor node will be in state i and $\frac{dP_i(t)}{dt}$ represents the first order derivative of $P_i(t)$.The above simultaneous differential equations can be solved using the method of Laplace transforms as follows:

$$sP_3(s) - P_3(0) = -\lambda P_3(s) \quad (9)$$

$$sP_2(s) - P_2(0) = -\lambda P_2(s) + c\lambda P_3(s)) \quad (10)$$

$$sP_1(s) - P_1(0) = -\lambda P_1(s) + c\lambda P_2(s) \quad (11)$$

$$sP_0(s) - P_0(0) = -\lambda P_1(s) + (1-c)\lambda P_2(s) + (1-c)\lambda P_3(s) \quad (12)$$

Where P3(s), P2(s), P1(s), and P0 (s) are the Laplace transforms of p3 (t), p2 (t), p1 (t), and p0 (t), respectively. We assume that the system starts out in perfect shape at time t = 0, and so, p3 (0) =1, and p2 (0)=p1(0)=p0(0)=0. The Laplace transforms can be written as:

$$P_3(s) = \frac{1}{s+\lambda} \quad (13)$$

$$P_2(s) = \frac{c\lambda}{(s+\lambda)^2} \quad (14)$$

$$P_1(s) = \frac{(c\lambda)^2}{(s+\lambda)^3} \quad (15)$$

Taking the inverse Laplace transforms, we obtain

$$P_3(t) = e^{-\lambda t} \quad (16)$$

$$P_2(t) = c\lambda t e^{-\lambda t} \quad (17)$$

$$P_1(t) = \frac{(c\lambda t)^2}{2} e^{-\lambda t} \quad (18)$$

$$P_0(t) = 1 - (P_1(t) + P_2(t) + P_3(t)) = 1 - \left(e^{-\lambda t} + c\lambda t e^{-\lambda t} + \frac{(c\lambda t)^2}{2} e^{-\lambda t}\right) \quad (19)$$

The reliability of the fault tolerance underwater wireless sensor component is given by:

$$R_{component} = 1 - P_0(t) = e^{-\lambda t} + c\lambda t e^{-\lambda t} + \frac{(c\lambda t)^2}{2} e^{-\lambda t} \quad (20)$$

The MTTF of the fault tolerance underwater wireless sensor component is

$$MTTF_{component} = \int_0^\infty R_{component} dt = \frac{1}{\lambda} + \frac{c}{\lambda} + \frac{2c^2}{\lambda} = \frac{2c^2+c+1}{\lambda} \quad (21)$$

The average failure rate of the fault tolerance underwater wireless sensor component is given by:

$$\lambda_{component} = \frac{1}{MTTF_{component}} = \frac{\lambda}{2c^2+c+1} \quad (22)$$

As described in section I, an USS consists of many underwater sensors. To increase mission reliability of USS, we assume USS consists of many fault tolerance underwater wireless sensor component which each component has one active sensor and two standby spares.

In our model USS consists of N fault tolerance underwater wireless sensor component. We assume that the mission of USS is failed, if W components of N components are failed. Figure 4 shows Markov model for an USS with N fault tolerance underwater wireless sensor components.

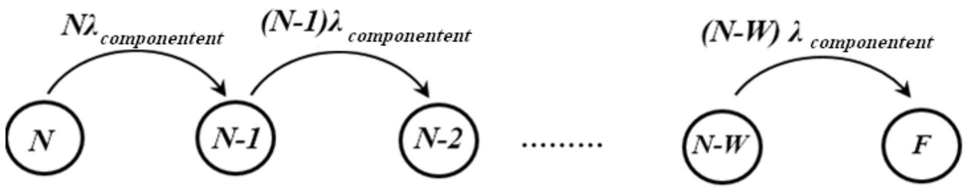

FIGURE 4. Markov model for Network with N fault tolerance components.

The transition matrix describing the USS Markov model is:

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$$\frac{d}{dt}\begin{bmatrix} P_F \\ P_{N-W} \\ . \\ . \\ . \\ P_{N-2} \\ P_{N-1} \\ P_N \end{bmatrix} = \begin{bmatrix} 0 & (N-W)\lambda_{component} & . & 0 & 0 \\ 0 & -(N-W)\lambda_{component} & . & 0 & 0 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & (N-1)\lambda_{component} & . \\ 0 & 0 & . & -(N-1)\lambda_{component} & N\lambda_{component} \\ 0 & 0 & . & 0 & -N\lambda_{component} \end{bmatrix} \begin{bmatrix} P_F \\ P_{N-W} \\ . \\ . \\ . \\ . \\ P_{N-1} \\ P_N \end{bmatrix}$$

The differential equations describing the USS Markov model are:

$$\frac{dP_F(t)}{dt} = (N-W)\lambda_{component}P_{N-W}(t) \quad (23)$$

$$\frac{dP_{N-W}(t)}{dt} = -(N-W)\lambda_{component}P_{N-W}(t) \quad (24)$$

…

$$\frac{dP_{N-1}(t)}{dt} = -(N-1)\lambda_{component}P_{N-1}(t) + N\lambda_{component}P_N(t) \quad (25a)$$

$$\frac{dP_N(t)}{dt} = -\lambda_{component}P_N(t) \quad (25b)$$

Solving (2) with initial conditions

$P_N(t) = 1$, $P_{N-1}(t) = P_{N-2}(t) = \cdots . = P_F(t) = 0$ for W=2, the reliability of USS is given as:

$$P_N(t) = e^{-N\lambda_{component}t} \quad (26a)$$

$$P_{N-1}(t) = \frac{-1}{\lambda_{component}}\left(e^{-N\lambda_{component}t} - e^{-(N-1)\lambda_{component}t}\right) \quad (26b)$$

$$P_{N-2}(t) = 8N(N-1){\lambda_{component}}^2 e^{-N\lambda_{component}} - 9N(N-1){\lambda_{component}}^2 e^{-(N-1)\lambda_{component}t} + 2N(N-1){\lambda_{component}}^2 e^{-(N-2)\lambda_{component}t} \quad (27)$$

$$P_F(t) = 1 - P_{N-2}(t) - P_{N-1}(t) - P_N(t) \quad (28)$$

$$R_{Total}(t) = P_{N-2}(t) + P_{N-1}(t) + P_N(t) \quad (29)$$

The MTTF of the fault tolerance underwater wireless sensor component is

$$\mathrm{MTTF_{Total}} = \int_0^\infty \mathrm{R_{Total}}\mathrm{d}t = \frac{(8*\mathrm{N(N-1)}\lambda_{\mathrm{component}}{}^2 - \mathrm{N}+1)}{\mathrm{N}\lambda_{\mathrm{component}}} - \frac{2\mathrm{N(N-1)}\lambda_{\mathrm{component}}}{(\mathrm{N}-2)} - \frac{9\mathrm{N(N-1)}\lambda_{\mathrm{component}}{}^2 + \mathrm{N}}{(\mathrm{N}-1)\lambda_{\mathrm{component}}} \quad (30)$$

The average failure rate of USS with W=2 is given by:

$$\lambda_{\mathrm{Total}} = \frac{1}{\mathrm{MTTF_{Total}}} \quad (31)$$

4. PERFORMANCE EVALUATION

For study affective of the number of redundant spare on the overall reliability of the USS we calculate behavior of network in several states. It was considerate a USS that uses N component. Each component contains 3 sensors, 1 active sensor and 2 standby spares and also the case of network without redundant spares.

All of sensors in components, both active and spares, are in the maturity period, and the failure rate is constant, equal with 5 failures at 106 seconds. This is a not limitative since in USS, is recommended to keep away from the usage of components that oversteps their nominal lifetime, or components that did not pass a minimal burn-in process, because of the large areas covered.

The resulted reliability is illustrated in Figure 5. It can be concluded that if we use Standby Spares in components then the overall reliability function is enhanced whenever factor C (probability of faulty is correctly detected) is perfect and equal 1. This figure also illustrate that reliability of component with Standby Spares is greater than normal state in all times from begin to end.

Figure 6 shows that the effective of using detection algorithm with different probability of detection. We calculate several times by probability of 0, 0.2, 0.4, 0.8 and 1. The results illustrated that the reliability of USS is better if the algorithm can detect faulty sensor by high chance.

ISSN: 2252-4274 (Print)
ISSN: 2252-5459 (Online)

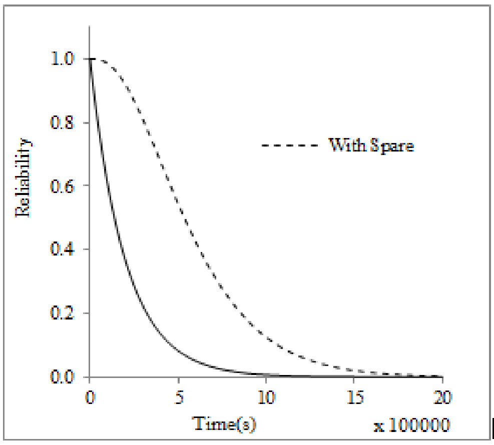

FIGURE 5. Reliability of USS component with and without standby spares.

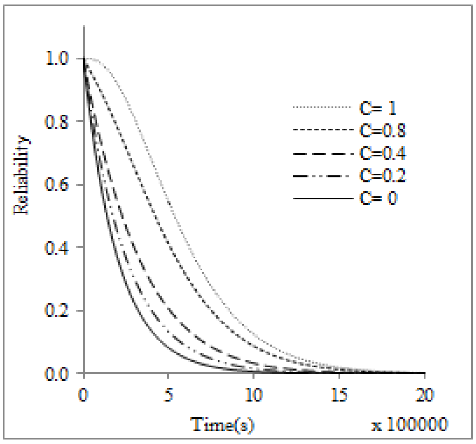

FIGURE 6. Reliability of USS with different value of C factor.

The same USS structure was considered to compute the cost of MTTF (measured in seconds) factor. The corresponding cost of the MTTF is depicted in Figure 7.

Like in the previous figure, it can be noticed the effective of the fault detection algorithm in MTTF. By using improved detection algorithm MTTF increased so reliability of USS is superior. For calculation overall reliability of system we use section 3, by those equations results computed for 3 condition of different number of components (N). Figure 8 shows that use large number of N can cause reliability of system decrease fast. For example for N=1000 after 900s reliability of system was 0.5 since for N=100 this reliability get after 3300s. So we must use appropriate number of component according coverage and other issues. It can be resulted that by using redundant hot spares, the reliability and the overall lifetime of the USS can be highly increased; with a small number of spares that adds only small additional costs to the whole system. For example, increasing the total redundant of the USS with 2 spare, the overall reliability is increased with 60%.

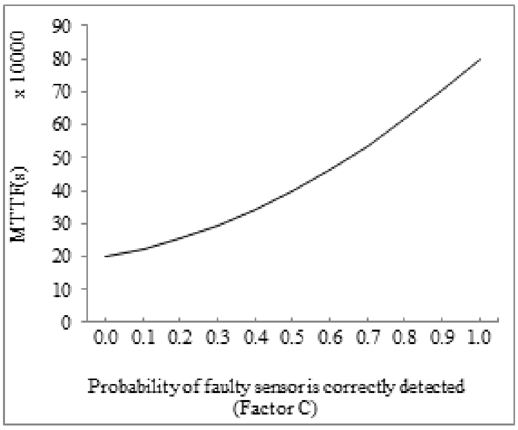

FIGURE 7: MTTF values for a USS with different probability of C in each component.

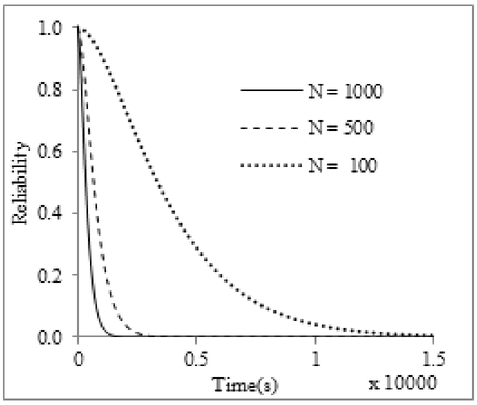

FIGURE 8. Overall reliability of USS with different number of component (N)

5. CONCLUSIONS

In this paper we proposed a fault-tolerant underwater sensor node model in USS. We developed Markov models for characterizing USS survivability and MTTF. Our Markov model helps evaluate survivability and MTTF of USS, which is more vital in USS design. We concluded that by using redundant hot spare underwater sensor nodes, the reliability and the overall lifetime of the USS can be highly increased. Performance evaluation results show that increasing the total redundant of the USS with 2 spare underwater sensor nodes, the overall reliability is increased with 60%.

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