ISSN 1726-5479

SENSORS & TRANSDUCERS

7 vol. 106 /09

Sensor Networks and Wireless Sensor Networks

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 106, Issue 7
July 2009

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Sensors & Transducers Journal

Contents

Volume 106
Issue 7
July 2009

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

Sensors & Transducers Journal, Vol. 106, Issue 7, July 2009, pp. 6-26

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Reliability Modeling of Wireless Sensor Network for Oil and Gas Pipelines Monitoring

[1]Khalid EL-DARYMLI, [2, 3]Faisal KHAN, [4]Mohamed H. AHMED

[1, 2, 4] Dept of Electrical and Computer Engineering
Faculty of Engineering & Applied Science
Memorial University, St. John's, A1B 3X5, NL, Canada
[3] College of Engineering, Qatar University, Doha, Qatar
Tel.: +1.709.351.2450
E-mail: eldarymli@ieee.org

Received: 7 June 2009 /Accepted: 15 July 2009 /Published: 20 July 2009

Abstract: Extensive network of pipelines carrying oil and gas is an integral part of any country's energy management plan. As oil and gas are characterized as highly hazardous, their transportation through pipelines warrants proactive continuous monitoring. Unfortunately, there has been limited continuous monitoring of this crucial infrastructure, which causes financial losses to the industry. This paper presents a wireless sensor network (WSN) system and its reliability assessment model for oil and gas pipelines condition monitoring.

As a first step, a wireless sensor system for pipeline monitoring is selected. The selected system is revised for oil and gas application considering long distance transportation. Upon system development, a reliability model for the system is developed. A simple bottom-up approach is followed to analyze the reliability of the components, subsystem, and the system. Two explanatory examples are presented to demonstrate the applications of the selected system and developed reliability model. These examples help to better understand the interrelation between the reliabilities, the components and the system. *Copyright © 2009 IFSA.*

Keywords: Reliability modeling, Wireless sensor networks, Pipelines condition monitoring, Wireless based condition monitoring

1. Introduction

Oil and gas pipelines are critical infrastructure for effective transportation and distribution of energy resources. It is an integral part of country's energy management plan. As being critical element of energy management plan, they could easily be a target of sabotage and terrorist attacks. Moreover, pipelines can unexpectedly fail for many reasons including, corrosions, cracking, process upsets, and external environment. As compared to other means of transportation, pipelines are expected to be highly reliable, safe and cost-effective. In fact, taking a deeper look at the current pipelines' status will make such expectations a blur.

In Canada alone there are about 580,000 kilometers of pipelines. About 2.65 million barrels of crude oil and equivalent daily travel through Canada's crude oil pipelines network. Approximately 17.1 billion cubic feet of natural gas per day travel through Canada's natural gas pipelines network [1].

There are pipelines underlie or in the proximity of some cities such as Medicine Hat, Red Deer and Calgary. Computerized control centers are used to remotely monitor most pipelines systems. Control valves situated at regular intervals along the pipelines close automatically when pressure drops are detected. Low-flying aircraft and ground crews with specialized detection equipment are also used for monitoring pipelines. Potential problems with the pipe and joints or welds can be detected using in-line inspection equipment. With the help of highly sensitive detection equipment pipelines operators can "walk the line" and locate any leaks. These condition monitoring are often carried out periodically ranging from months to year interval, but systems may fail between these intervals. It could be said, real-time, proactive and round-the-clock integrity monitoring of this fatal infrastructure is currently not available [1, 2].

Recent advancement in wireless sensors network can be appropriately exploited and deployed for integrity monitoring of pipelines to achieve the ultimate goal of safety enhancement. Among the main reasons that the wireless sensor network can be best deployed for this task are [3, 4]:

- Wireless (no wires involved) which means convenience of deployment for large scale, remote and scattered pipelines;
- Wireless means cost-effectiveness;
- Ease and convenience of maintenance;
- Time effective as per installation time;
- 24/7 reliable and proactive integrity monitoring.

Different kinds of sensors such as acoustic, vibration and temperature sensors can detect wall thinning or thickness through temperature or noise measurements, leakages by analyzing real-time flow, and pressure measurements etc. In addition to sensing and collecting data, these sensors are also equipped with processing capabilities to deduce how to route the data packets through the neighbors to a base station or sink. The wireless sensor nodes are usually battery powered or have energy harvesting units built in them to prolong their lifetime. Due to the small sizes of such wireless sensors, their sensing and communication capabilities are restricted to within a small neighborhood. Furthermore, the energy harvesting capabilities are also small implying that power consumption is important in prolonging the lifetime of a Wireless Sensor Network (WSN) [11].

This paper is organized as follows. First, a literature of related work is presented. Then, a WSN system for condition monitoring is adopted from the literature and appropriately revised for oil and gas pipelines. Subsequently, the reliability model is developed and analyzed using bottom-up approach for the WSN system. Finally, two illustrative examples are presented to demonstrate the application and effectiveness of the reliability model. These examples do help to better understand the interrelationship between component failure rates and overall system reliability.

2. Related Work

An exhaustive literature review find only few papers on the topic of WSN for condition monitoring, WSN application to the pipelines, and WSN in the oil and gas industry [5-9]. Awawdeh et al. shed some light on a model for tracking flow-induced vibration to provide means of detection and early warning of integrity loss in pipelines network [5]. Suheil and Garelli propose a model for pipelines monitoring, but the paper provides limited technical information and mainly focuses on the application [6]. Changsoo et al. propose a method for calculating the number of sinks and sensors required for pipelines monitoring [7]. Umeadi and Jones report some findings of a laboratory based test program to evaluate the potential for vibration sound emission detection in pipelines integrity monitoring [8]. Stoianov et al. present a system called PIPENET for monitoring large diameter bulk-water transmission pipelines [9]. The above review concludes that in public domain literature limited information are available for WSN based pipelines condition monitoring.

Related to reliability modeling of wireless sensor networks few related papers have been identified. It includes references [12-18]. Mainly, Cinque et al. address the current limitations and pose the reliability requirements for dynamic structure monitoring using wireless sensor network [12]. AboElFotoh et al. approach the problem of modeling and evaluate the coverage oriented probability of WSN subject to common cause failure [13]. Xing and Michel define a WSN reliability measure considering the aggregate flow of sensor data into a sink node [14]. Chiang et al. deal with the problem of reliability and security modeling in an integrated manner [15]. Cai et al. propose and evaluate scalable architecture of WSN nodes for increased availability [16]. Shrestha et al. shed some light on the problem of reliability modeling for large scale wireless sensor network [17]. Akan and Akyildiz present an event-to-sink transport protocol for reliable transport in wireless sensor network [18].

However, it should be noted that due to the unique arrangement of the wireless sensors in the case of pipelines monitoring none of the abovementioned models can be adopted for such a case. Based on the above review it may be observed that the topic of reliability of wireless sensor network for pipelines monitoring has not been approached.

This paper introduces a reliability model for a wireless sensor network system for pipelines condition monitoring.

3. System Overview

WSN for pipelines integrity monitoring is adopted as described in [6] and [7]. Fig. 1 depicts a simple description of the system.

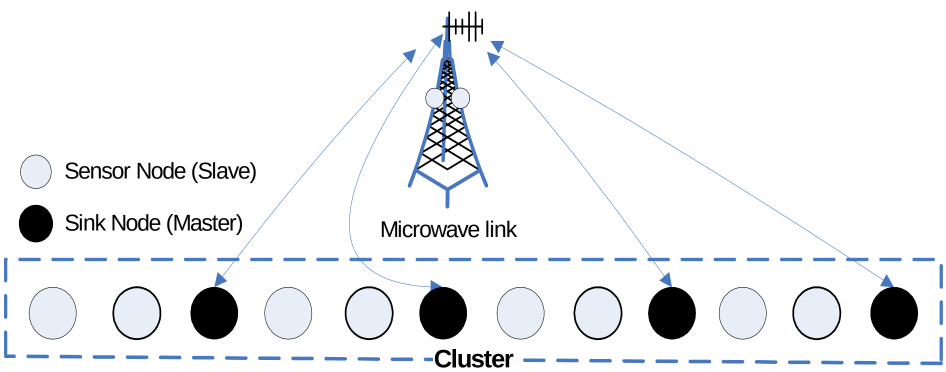

Fig. 1. Simplified sketch of WSN for pipelines monitoring.

The sensor and sink nodes are equally spaced along the pipeline. The power for sensor nodes is generated from energy scavenging module such as vibrations in the pipeline or from a long-lasting battery. The sink nodes power can be a reliable long-lasting battery; or other means of power supply such as a solar panel, which will depend on the vicinity of the pipeline as well as the ambient conditions. Every sensor node can choose its transmission distance dynamically depending on a set of permissible finite power levels and route information. If the closest sink is within a sensor's transmission distance then the information is sent to the sink directly. Otherwise, the information is sent via a neighboring senor in a multi-hop fashion to the closest sink node.

Unlike other applications of WSN (e.g. military application, environmental applications, etc.) where complicated clustering techniques can be used to form sensor clusters, the pipeline clusters are naturally available due to the linear arrangement of sinks and nodes throughout the pipeline. Accordingly, the closest sensor nodes to a sink node will remain the same throughout the entire lifetime of the application [7].

The sink nodes receive measurement information such as pressure every 30 seconds from neighboring sensors within the same cluster whereby the received data is relayed to an associated gateway. A point-to-multipoint master UHF towers can be installed alongside the pipeline network. The master UHF towers covering a pipeline in a diameter of about 100 km. These towers are linked to the main control room using a point-to-point microwave network. The gateways are scanned once per minute by an associated UHF base station. When the data is received by the base station, it is relayed to the main control room by a point-to-point microwave network [6].

Data packets sent by each sensor can uniquely categorize its location in the pipeline. This can be readily achieved through pre-specifying a certain ID and including it in each transmitted packet for each sensor. This ID is so important because in case of any problem with the pipeline it will easily determine the location of that problem. More information such as battery condition information and a sequence number should be incorporated in each transmitted packet.

4. System Design

In this section, a model for the wireless sensors for pipelines monitoring is introduced based on the earlier discussion. In the present study it is considered that pipeline is stretching linearly with a total length of 1000 km. This case can be generalized for any length as discussed below.

Consider that the UHF tower can cover an area of a 100 km [6]. This will make our sensor network naturally clustered into 1000/100 clusters. We have 10 clusters each of which covered by a UHF tower [See Fig. 2].

Reliability analysis is done for one cluster and it would be similar for the rest as clusters 2 to 10 are replicas of cluster 1. Number of sink nodes necessary to this network arrangement of sensors can be evaluated with following assumptions:

- Sensors are located every *20 meters* along the pipeline [7];
- *n*=Total number of sensors and sink nodes per one cluster = 100 km/20m=5000 sensors;
- Each sensor has *five* finite power levels, $\{P_1, P_2, P_3, P_4, P_5\}$;
- Reachable distance by each sensor increases by *20 meters* with each power level;
- $d_1=20\ m$, is the reachable distance by each sensor for P_1. Accordingly, $d_2 = d_1+20$, $d_3=d_1+40$, $d_4=d_1+60$, $d_5=d_1+80$;
- Packet size, k=1000 bit [7];
- Electric power generated by piezoelectric sensor, R_{EH}=1mW/sec [10];
- Sampling rate boundaries $S_{rate}^{upper}, S_{rate}^{lower}$ can be calculated as described in [7].

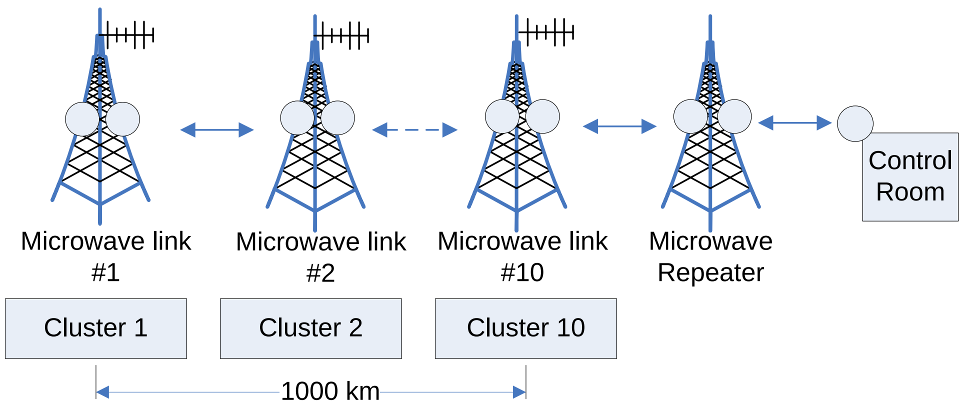

Fig. 2. UHF towers and corresponding WSN clusters.

$$a_o = S_{rate}^{lower} = \frac{R_{EH}}{k \times n \times (10^{-7} + 10^{-10} \times d_5^2)} =$$

$$= \frac{1 \times 10^{-3}}{1000 \times 100 \times (10^{-7} + 10^{-10} \times 100^2)} = 0.009091 \tag{1}$$

$$b_o = S_{rate}^{upper} = \frac{R_{EH}}{k \times (10^{-7} + 10^{-10} \times d_1^2)} =$$

$$= \frac{1 \times 10^{-3}}{1000 \times (10^{-7} + 10^{-10} \times 20^2)} = 7.142857 \text{ Hz} \tag{2}$$

For the above values the Maximum tolerable sampling rate is evaluated using algorithm provided in ref. [7] as:

$$S_{rate}^{*} = 0.071374\, Hz \tag{3}$$

The equivalent number of sensors for the above sampling rate is estimated as 100 samples per sink node. This arrangement is depicted in Fig. 3 below.

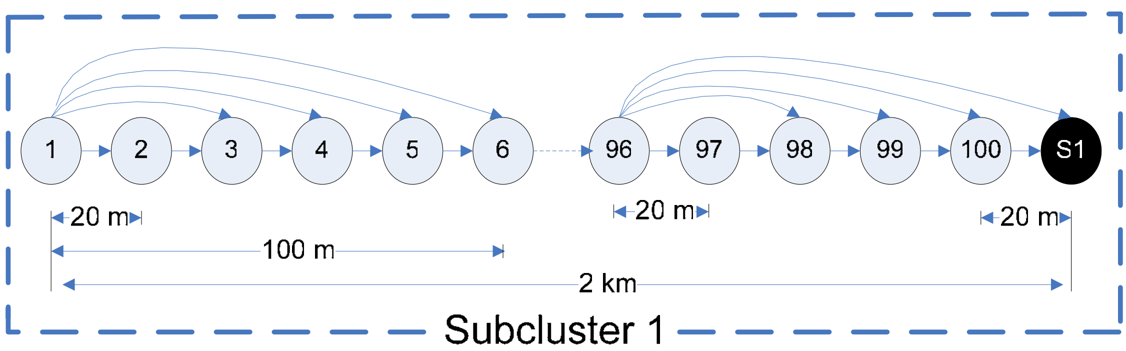

Fig. 3. A sub cluster is comprised of 100 sensors per sink node.

Furthermore, within one cluster, there are 50 subclusters. These are defined throughout the 100 km distance over the pipeline, a group of sensors (slaves) to sink nodes (masters) are equally spaced (See Fig. 4).

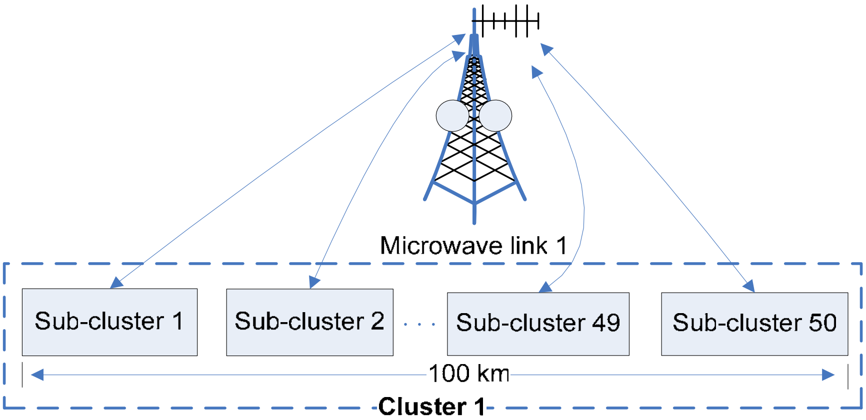

Fig. 4 Subclusters of cluster 1.

5. Reliability Modeling

A bottom-up reliability modeling approach is followed to analyze and understand the reliability of the system introduced earlier. This is accomplished through two main steps: i) introducing a reliability model developed for the system, and ii) application of the model with two numerical examples.

5.1. Sensor-Level Reliability

As described earlier, the system is comprised of identical sensors. Each sensor has “L” incremental power levels, $\{P_1, P_2, \ldots, P_L\}$; and these power values are corresponding to “L” incremental transmission distances $\{d_1, d_2, \ldots, d_L\}$. The objective is to minimize power consumption. Accordingly, each sensor will use its minimum power level $\{P_1\}$ for transmission to a corresponding distance “d_1”. In the event that the sensor fails to communicate with a neighboring sensor/sink in the range of “d_1”, it will automatically switch to a higher power level “P_2” to communicate with a senor in a longer range “d_2”. If more failures occur, the system will keep on switching the power levels until it reaches its maximum transmission distance “d_L” for corresponding power level “P_L”. Table 1 shows sensor states described above. A sensor will be in a failure state (N+1) if it either randomly fails or if it cannot satisfy the transmission distance due to power insufficiency or lack of power.

Table 1. States of a senor with finite power levels P_L and corresponding transmission distances d_L.

State	P_1, d_1	P_2, d_2	…	P_L, d_L
1	Active	Standby	Standby	Standby
2	Failed	Active	Standby	Standby
3	Failed	Failed	…	Standby
…	Failed	Failed	…	Standby
N	Failed	Failed	Failed	Active
N+1	Failed	Failed	Failed	Failed

5.2. Sensor-Level Reliability Model

In this step the sensor-level reliability is modeled. Sensors are identical and each sensor in the network has 5 power levels, $\{P_1, P_2, P_3, P_4, P_5\}$, corresponding to 5 transmission distances, $\{d_1, d_2, d_3, d_4, d_5\}$={20 m, 40 m, 60 m, 80 m, 100 m}. The sensor states are shown in Table 2 below.

Table 2. Sensor states for P= $\{P_1, P_2, P_3, P_4, P_5\}$; and corresponding transmission distance d= $\{d_1, d_2, d_3, d_4, d_5\}$.

State	P_1, d_1	P_2, d_2	P_3, d_3	P_4, d_4	P_5, d_5
1	Active	Standby	Standby	Standby	Standby
2	Failed	Active	Standby	Standby	Standby
3	Failed	Failed	Active	Standby	Standby
4	Failed	Failed	Failed	Active	Standby
5	Failed	Failed	Failed	Failed	Active
6	Failed	Failed	Failed	Failed	Failed

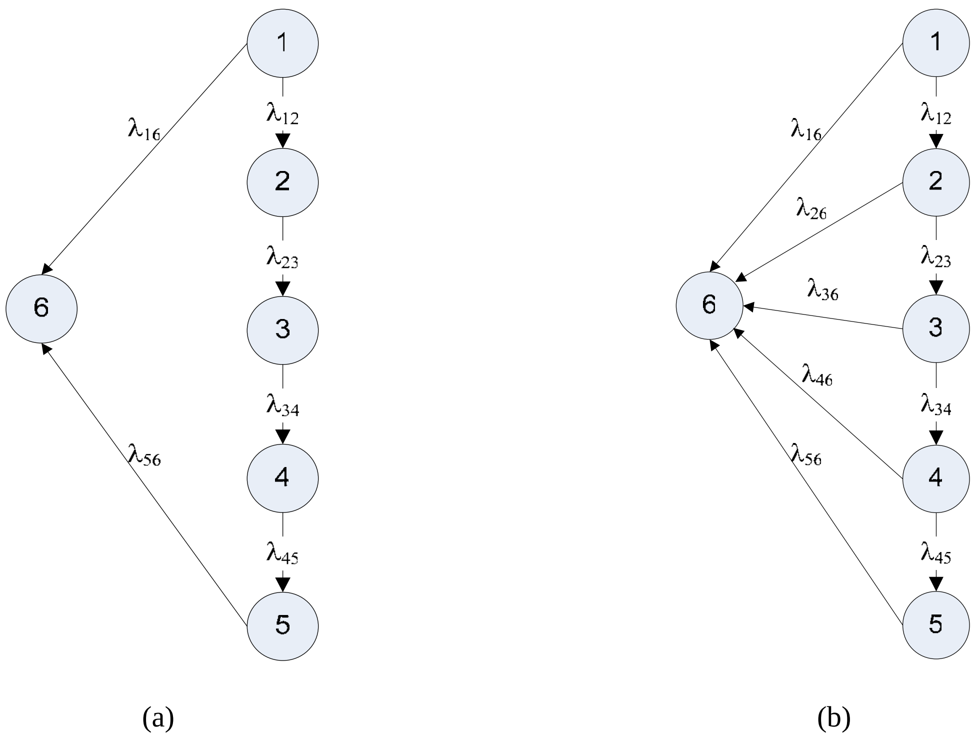

Fig. 5. Rate diagram for a sensor with 5 power levels and 5 corresponding transmission distances (a) Rate diagram for Scenario 1, (b) Rate diagram for Scenario 2.

A rate diagram based on Hidden Markov Models (HMM) is used to model the states of the sensor [11]. There are three scenarios that can be modeled from the table above. The first scenario is to consider that the sensor can only switch between states in this order: {State 1, State 2, State 3, State 4, State 5} with switching rates of $\{\lambda_{12}, \lambda_{23}, \lambda_{34}, \lambda_{45}\}$ respectively. Moreover, the sensor can be in a failure state due to insufficiency or depletion of transmission power as well as due to random failure. In this scenario it is considered that such failure occurs from states 1 and 5 only with a failure rate of $\{\lambda_{16}, \lambda_{56}\}$ respectively (See Fig. 5.a).

The second scenario is to incorporate failures from states {State 2, State 3, State 4} with failure rates of {λ_{26}, λ_{36}, λ_{46}} respectively into the first scenario (See Fig. 5.b).

The more wholesome scenario is scenario 3 which considers direct switching from {State 1} to {State 3}, from {State 1} to {State 4} and from {State 1} to {State 5} with switching rate of {λ_{13}, λ_{14}, λ_{15}} respectively; switching from {State 2} to {State 4}and from {State 2} to {State 5}with switching rate of {λ_{24}, λ_{25}} respectively; and switching from {State 3 to State 5} with switching rate of {λ_{35}}; and to incorporate it into the model developed in scenario 2 (See Fig. 6).

Scenario 3 is used for calculating the sensor's reliability. First, the rate diagram equations based on scenario 3 as depicted in Fig. 6 are developed as follows:

$$\frac{dP_1(t)}{dt} = -(\lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15} + \lambda_{16})P_1(t)$$

$$\text{Let, } \lambda_1 = \lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15} + \lambda_{16} \quad (4)$$

$$\frac{dP_1(t)}{dt} = -\lambda_1 P_1(t) \quad (5)$$

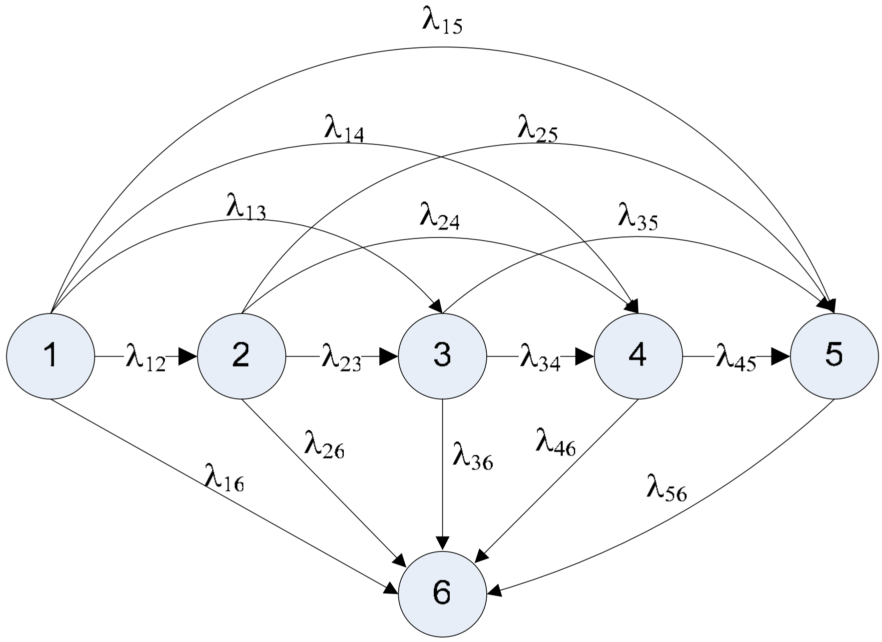

Fig. 6. Rate diagram for the wholesome scenario, Scenario 3.

$$\frac{dP_2(t)}{dt} = \lambda_{12}P_1(t) - (\lambda_{23} + \lambda_{24} + \lambda_{25} + \lambda_{26})P_2(t)$$

$$\text{Let, } \lambda_2 = \lambda_{23} + \lambda_{24} + \lambda_{25} + \lambda_{26} \quad (6)$$

$$\frac{dP_2(t)}{dt} = \lambda_{12}P_1(t) - \lambda_2 P_2(t) \quad (7)$$

$$\frac{dP_3(t)}{dt} = \lambda_{13}P_1(t) + \lambda_{23}P_2(t) - (\lambda_{34} + \lambda_{35} + \lambda_{36})P_3(t)$$

$$\text{Let, } \lambda_3 = \lambda_{34} + \lambda_{35} + \lambda_{36} \tag{8}$$

$$\frac{dP_3(t)}{dt} = \lambda_{13}P_1(t) + \lambda_{23}P_2(t) - \lambda_3 P_3(t) \tag{9}$$

$$\frac{dP_4(t)}{dt} = \lambda_{14}P_1(t) + \lambda_{24}P_2(t) + \lambda_{34}P_3(t) - (\lambda_{45} + \lambda_{46})P_4(t)$$

$$\text{Let, } \lambda_4 = \lambda_{45} + \lambda_{46} \tag{10}$$

$$\frac{dP_4(t)}{dt} = \lambda_{14}P_1(t) + \lambda_{24}P_2(t) + \lambda_{34}P_3(t) - \lambda_4 P_4(t) \tag{11}$$

$$\frac{dP_5(t)}{dt} = \lambda_{15}P_1(t) + \lambda_{25}P_2(t) + \lambda_{35}P_3(t) + \lambda_{45}P_4(t) - \lambda_{56}P_5(t) \tag{12}$$

$$P_6(t) = 1 - P_1(t) - P_2(t) - P_3(t) - P_4(t) - P_5(t) \tag{13}$$

The initial condition is at time $t=0$, the system is in state 1, which means the sensor can be only in one state at any given point of time. This implies:

$$P_1(0) = 1,\ P_2(0) = 0,\ P_3(0) = 0,\ P_4(0) = 0 \ \& \ P_5(0) = 0 \tag{14}$$

To determine the sensor's probability of being in a certain state, equations from (5) to (13) need to be solved given the initial conditions defined by equation (14). The above differential equations can be rewritten in matrix format as follows:

$$\vec{P}'(t) = \begin{bmatrix} P_1' \\ P_2' \\ P_3' \\ P_4' \\ P_5' \end{bmatrix} = \begin{bmatrix} -\lambda_1 & 0 & 0 & 0 & 0 \\ \lambda_{12} & -\lambda_2 & 0 & 0 & 0 \\ \lambda_{13} & \lambda_{23} & -\lambda_3 & 0 & 0 \\ \lambda_{14} & \lambda_{24} & \lambda_{34} & -\lambda_4 & 0 \\ \lambda_{15} & \lambda_{25} & \lambda_{35} & \lambda_{45} & -\lambda_{56} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} \tag{15}$$

And the initial conditions can be rewritten as

$$\vec{P}(0) = \begin{bmatrix} P_1(0) \\ P_2(0) \\ P_3(0) \\ P_4(0) \\ P_5(0) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{16}$$

If the sensor is either in state 1, 2, 3, 4, or 5 it will be operating, moreover, the sensor can be in only one state at any given point of time, thus, the reliability of the sensor is given as

$$R_{Sensor}(t) = P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t) \tag{17}$$

The mean time to failure (MTTF) of the sensor can be calculated as follows

$$MTTF_{Sensor} = \int_0^\infty R_{Sensor}(t)\ dt = \int_0^\infty \left(P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t)\right)dt \tag{18}$$

The probability of the sensor failure is calculated as follows:

$$F_{Sensor}(t) \ = P_6(t) = 1 - P_1(t) - P_2(t) - P_3(t) - P_4(t) - P_5(t) \tag{19}$$

5.3. Subcluster-Level Reliability

In the previous Section sensor-level reliability was modeled and defined as $R_{Sensor}(t)$. In this section, the reliability model for the subcluster (i.e., the reliability of sensors per sink as well as the reliability of the sink) is introduced.

Consider the wireless sensors model introduced earlier in Fig. 3, following random failure and binomial process. The probability of exactly "*x*" sensors operating can be calculated as

$$P(x) = \binom{n}{x} R^x (1-R)^{n-x} , \tag{20}$$

where,

- $\binom{n}{x} = \dfrac{n!}{x!(n-x)!}$, is the number of ways (arrangements) in which *x* successes (nonfailures) can be obtained from *n* sensors.
- $R^x(1-R)^{n-x}$ is the probability of "*x*" successes and *(n-x)* failures for a single arrangement of successes and failures. Therefore,

$$R_{Sensors\ Per\ Sink} = \sum_{x=k}^{n} P(x) \tag{21}$$

is the probability of *k* or more successes from among the *n* sensors.
For the subcluster model:

- *n* (number of sensors per sink)=100

We assume that the system (subcluster) is operable if at least *75* out of *100* sensors are operable, *k*=75.
Accordingly

$$R_{Sensors\,Per\,Sink}(t) = \sum_{x=75}^{100} \binom{100}{x} [R_{Senor}(t)]^x [1 - R_{Senor}(t)]^{100-x} ,\ \binom{100}{x} = \frac{100!}{x!(100-x)!} \tag{22}$$

The reliability of the sink as shown in Fig. 3 is

$$R_{Sink}(t) = e^{-\lambda_{Sink}\, t} , \tag{23}$$

where λ_{Sink} is the failure rate of the sink.

The reliability of "subcluster 1" which is similar to the rest of our identical subclusters in the system is:

$$R_{Subcluster} = R_{Sensors\ Per\ Sink} \times R_{Sink} \tag{24}$$

$$R_{Subcluster}(t) = e^{-\lambda_{Sink}t} \times \sum_{x=75}^{100} \binom{100}{x} [R_{Sensor}(t)]^x [1 - R_{Sensor}(t)]^{100-x} \tag{25}$$

5.4. Cluster-Level Reliability

As explained earlier, each cluster in the network covers an area of 100km, which comprised 50 subclusters within each cluster.

In order for the measurement to be reliable there has to be at least *45* subclusters operable. As subclusters are comprised of identical sensors which imply subclusters are identical too. Therefore, the cluster reliability can be mathematically written as

$$R_{Cluster}(t) = \sum_{x=45}^{50} \binom{50}{x} [R_{Subcluster}(t)]^x [1 - R_{Subcluster}(t)]^{50-x}, \quad \binom{50}{x} = \frac{50!}{x!(50-x)!}, \tag{26}$$

where $R_{Subcluster}(t)$ is given by equation (25).
Consider that the tower reliability can be written as:

$$R_{Tower}(t) = e^{-\lambda_{Tower}t}, \tag{27}$$

where λ_{Tower} is the failure rate of the tower.
The reliability of the cluster and its corresponding UHF Tower can be written as:

$$R_{Block} = R(t)_{Tower} \times R(t)_{Cluster} \tag{28}$$

Substituting equation (26) and (27) into equation (28) yields,

$$R_{Block} = e^{-\lambda_{Tower}t} \times \sum_{x=45}^{50} \binom{50}{x} \left(\left[e^{-\lambda_{Sink}t} \sum_{x=75}^{100} \binom{100}{x} [R_{Sensor}(t)]^x [1 - R_{Sensor}(t)]^{100-x} \right]^x \times \left[1 - e^{-\lambda_{Sink}t} \sum_{x=75}^{100} \binom{100}{x} [R_{Sensor}(t)]^x [1 - R_{Sensor}(t)]^{100-x} \right]^{50-x} \right), \tag{29}$$

where R_{Sensor} (t) is the sensor's reliability given by equation (17).

5.5. Overall System Reliability

The reliability of the identical blocks shown in Fig. 2 (i.e., cluster and its corresponding UHF tower) from 1 to 10 can be modeled by equation (29). Our concern at this stage is to calculate the overall system reliability.

Consider that the microwave repeater has a failure rate of $\lambda_{Repeater}$. Accordingly, the microwave repeater reliability can be written as

$$R_{Repeater} = e^{-\lambda_{Repeater} t} \tag{30}$$

Consider that the control room communication equipments have a failure rate of $\lambda_{Control\_Room}$. Accordingly, the control room communication equipments reliability can be written as

$$R_{Control\ Room} = e^{-\lambda_{Control\ Room} t} \tag{31}$$

Now the overall system reliability can be modeled. Consider that at least 8 out of 10 blocks are required to function in order for the system to function. Given this requirement, the system reliability can be written as

$$R_{System}(t) = \left(\sum_{x=8}^{10} \binom{10}{x} [R_{Block}(t)]^x [1 - R_{Block}(t)]^{10-x} \right) \times R_{Repeater} \times R_{Control\ Room} \tag{32}$$

where,

- R_{Block}: block reliability given by equation 29.
- $R_{Repeater}$: microwave repeater reliability given by equation 30.
- $R_{Control\ Room}$: control room's communication equipment reliability given by equation 31.

6. Numerical Example No. 1

In this section some numerical assumptions are presented to demonstrate the feasibility of calculations and to further understand the interrelationship between the system reliability and other elements involved.

Choosing arbitrarily a reasonable failure data as given in Table 3, the rate diagram as introduced in Fig. 6 is re-sketched with the above values is shown in Fig. 7.

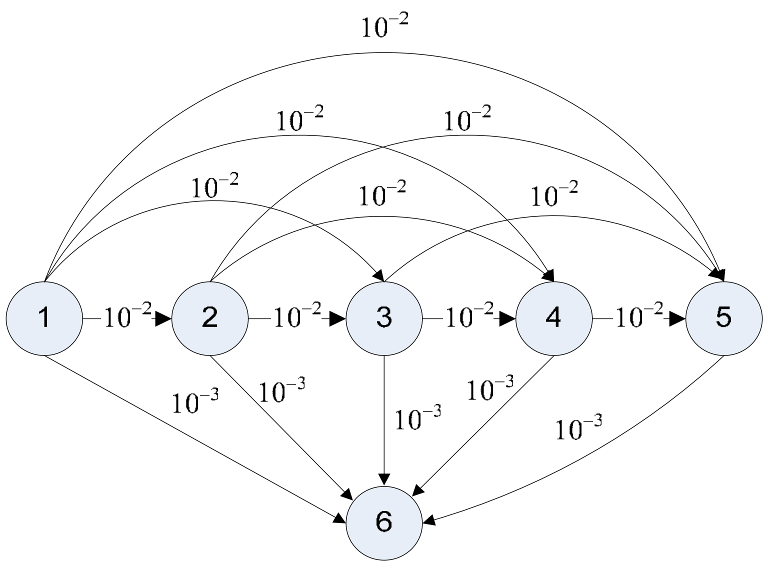

Fig. 7. Rate diagram with the numerical assumptions.

Table 3. Switching and failure rates for our example (per hour).

Switching/failure rate	Assumption (per hour)
λ_{12}	10^{-2}
λ_{13}	10^{-2}
λ_{14}	10^{-2}
λ_{15}	10^{-2}
λ_{16}	10^{-3}
λ_{23}	10^{-2}
λ_{24}	10^{-2}
λ_{25}	10^{-2}
λ_{26}	10^{-3}
λ_{34}	10^{-2}
λ_{35}	10^{-2}
λ_{36}	10^{-3}
λ_{45}	10^{-2}
λ_{46}	10^{-3}
λ_{56}	10^{-3}
λ_{Sink}	10^{-4}
λ_{Tower}	10^{-7}
$\lambda_{Repeater}$	10^{-7}
$\lambda_{Control\ Room}$	10^{-6}

Accordingly, the system of equations can be written in matrix format as described in equation (15) as follows

$$\vec{P}'(t)=\begin{bmatrix} P_1' \\ P_2' \\ P_3' \\ P_4' \\ P_5' \end{bmatrix}=\begin{bmatrix} -0.041 & 0 & 0 & 0 & 0 \\ 0.01 & -0.031 & 0 & 0 & 0 \\ 0.01 & 0.01 & -0.021 & 0 & 0 \\ 0.01 & 0.01 & 0.01 & -0.011 & 0 \\ 0.01 & 0.01 & 0.01 & 0.01 & -0.001 \end{bmatrix}\begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} \quad (33)$$

Initial conditions are given by equation (16) as

$$\vec{P}(0)=\begin{bmatrix} P_1(0) \\ P_2(0) \\ P_3(0) \\ P_4(0) \\ P_5(0) \end{bmatrix}=\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (34)$$

The solution to the above system of equations is

$$P_1(t)= exp(-41/1000*t) \quad (35)$$

$$P_2(t)= -exp(-41/1000*t)+exp(-31/1000*t) \quad (36)$$

$$P_3(t)= -exp(-31/1000*t)+exp(-21/1000*t) \quad (37)$$

$$P_4(t)= -exp(-21/1000*t)+exp(-11/1000*t) \quad (38)$$

$$P_5(t)= -exp(-11/1000*t)+exp(-1/1000*t) \quad (39)$$

$$R_{Sensor}(t) =P_1(t)+P_2(3)+P_3(t)+P_4(t)+P_5(t)$$

$$R_{Sensor}(t) =exp(-1/1000*t) \quad (40)$$

Probability of sensor failure is, $P_6(t)= F(t)=1-R_{Sensor}(t)$

$$F(t)=1- exp(-1/1000*t) \quad (41)$$

$$MTTF_{Sensor} = \int_0^{\infty} R_{Sensor}(t)\,dt = \int_0^{\infty} \left(e^{-t/1000}\right)dt = \int_0^{\infty} \left(e^{-t/1000}\right)dt = 1000\,hours \quad (42)$$

Fig. 8 depicts the probability of a sensor being in a certain state from 1 to 6.

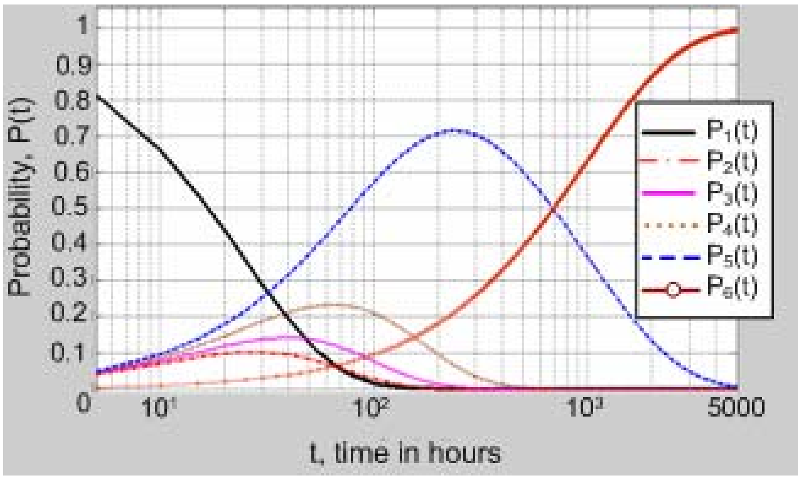

Fig. 8. Sketch for the six states of the sensor.

Fig. 9 depicts the sensor reliability $R_{Sensor}(t)$. It is the summation of curves from $P_1(t)$ to $P_5(t)$ depicted in Fig. 8 above.

The subcluster reliability can be calculated using equation (25) as follows:

$$R_{Subcluster}(t) = e^{-0.0001t} \times \sum_{x=75}^{100} \binom{100}{x} [\exp(-1/1000*t)]^x [1-\exp(-1/1000*t)]^{100-x},$$

where:

$$\binom{100}{x} = \frac{100!}{x!(100-x)!} \quad (43)$$

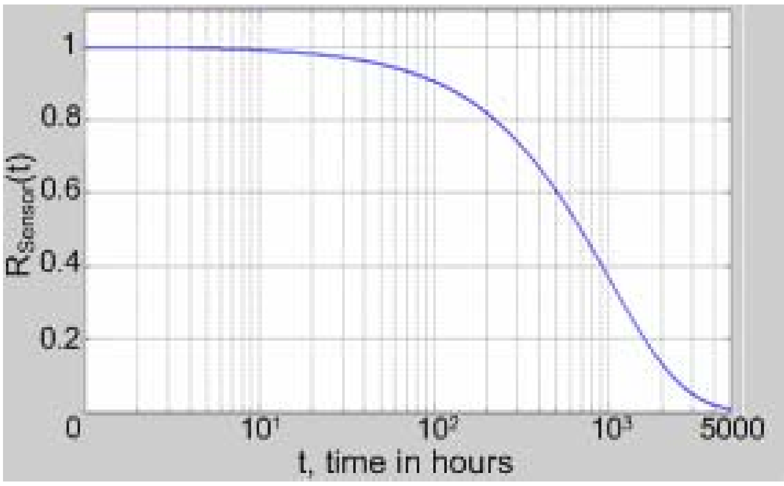

Fig. 9. Reliability of a sensor, R_{Sensor} (t).

Fig. 10 depicts the subcluster reliability, $R_{Subcluster}(t)$.

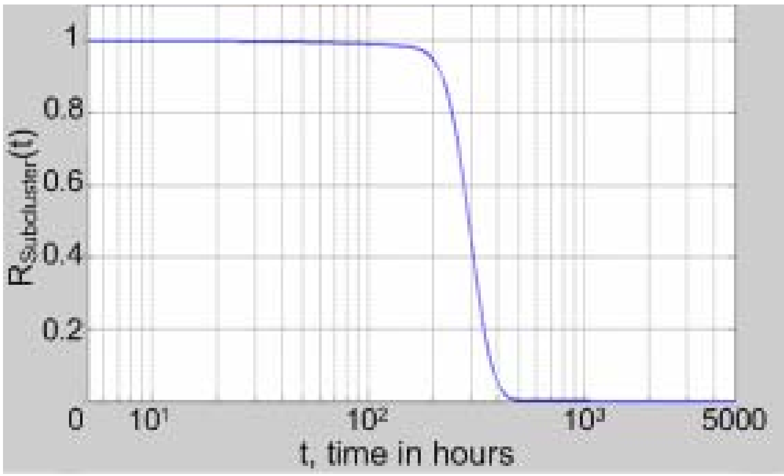

Fig. 10. Subcluster Reliability, $R_{Subcluster}$(t).

The reliability of a block (i.e., reliability of a cluster and its corresponding UHF tower) is done using equation (29):

$$R_{Block}(t) = e^{-0.0000001t} \times \sum_{x=45}^{50} \binom{50}{x} [R_{Subcluster}(t)]^x [1 - R_{Subcluster}(t)]^{50-x} ,$$

where:

$$\binom{50}{x} = \frac{50!}{x!(50-x)!} \tag{44}$$

Fig. 11 illustrates the block reliability, $R_{Block}(t)$.

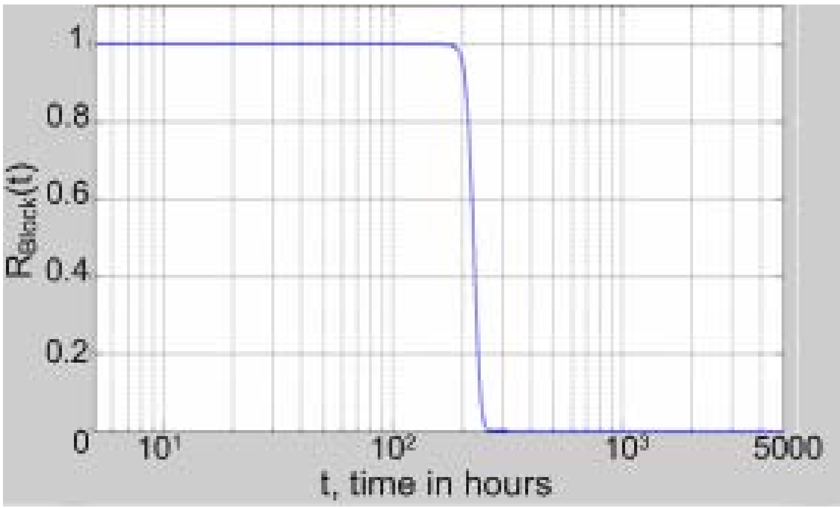

Fig. 11. Block reliability, $R_{Block}(t)$.

The reliability of the repeater as well as the control room communication equipments can be calculated using the respective failure rates provided as given in Table 3.

$$R_{\text{Re}\,peater} = e^{-0.0000001t} \tag{45}$$

$$R_{Control\ Room} = e^{-0.000001t} \tag{46}$$

Subsequently, the overall system reliability can be calculated using equation (32) as follows:

$$R_{System}(t) = \left(\sum_{x=8}^{10} \binom{10}{x} [R_{Block}(t)]^x [1 - R_{Block}(t)]^{10-x} \right) \times R_{\text{Re}\,peater} \times R_{Control\ Room} \tag{47}$$

Fig. 12 depicts the overall system reliability as given by equation 47.

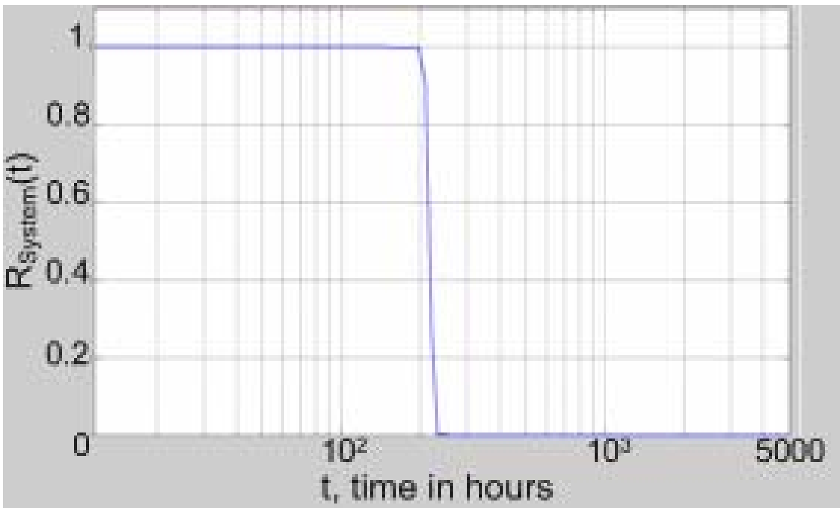

Fig. 12. The overall system reliability, $R_{System}(t)$.

6.1. Discussion

To visualize the relation between reliabilities of different elements of the system beginning from the sensor level and ending with the overall system it is a good to superimpose Figs. 9, 10, 11 and 12 on a single graph. Fig. 13 depicts the superimposed graph of reliabilities.

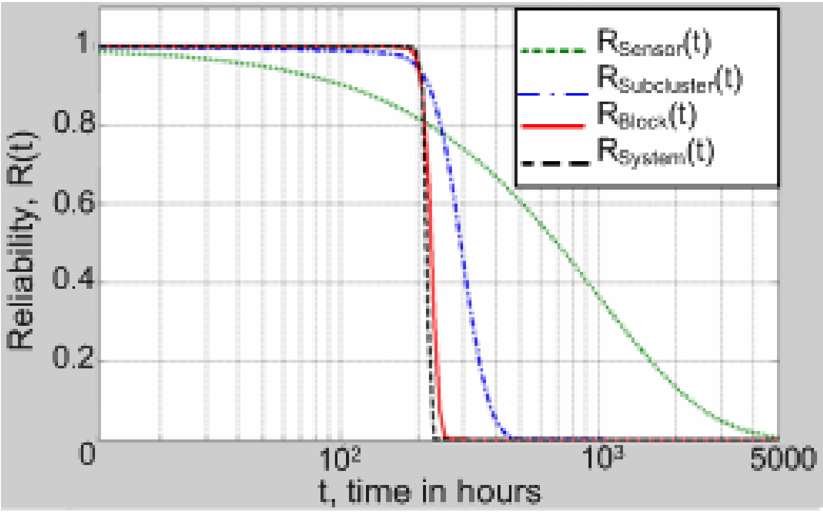

Fig. 13. R_{Sensor}(t), $R_{Subcluster}$(t), R_{Block}(t) and R_{System}(t) versus Time in Hours.

Fig. 13 depicts that the sensor reliability "$R_{Sensor}(t)$" deteriorates as *t* approaches *5000* hours; and eventually it is zero as *t* approaches infinity. The mean time to failure "*MTTF*" of the sensor is calculated for 1000 hours. It should be noticed that the degradation in the sensor reliability is rather gradual and it follows rather a smooth pattern. However, situation is drastically different for the subcluster, block and the overall system.

As to the subcluster reliability "$R_{Subcluster}(t)$", it has high reliability value until it reaches just above 200 hours where it begins rather a dramatic decrease. The cluster reliability "$R_{Block}(t)$" follows almost the same pattern as the subcluster reliability but it degrades faster than the subcluster reliability. In comparison to other reliabilities depicted in the graph above, the overall system reliability "$R_{System}(t)$" has the sharpest degradation which begins at about 200 hours.

It is obvious from the above graph, the sensor reliability alone can not dictate the overall system reliability, other elements including the sink, towers, repeater, control room communication equipments as well as the "k out of n" reliability requirement play an important role along with the sensor reliability in dictating the overall system reliability. This explains the sharp degradation in the reliability of the overall system in comparison to the individual sensor's reliability.

The point of intersection between the sensor and the overall system reliability depicted in Fig. 13 can be obtained through equating equations (40) and (47) and solving for "*t*". It is important to determine this point because it gives the designer a great idea about the relation between the sensor reliability and overall system reliability.

The above graph and analysis can help designer have a great insight into the interrelationship between the system elements and parameters; and subsequently could be utilized to fulfill the target reliability.
In this example it is noticed that the reliable life time of the system is about 200 hours which is impractical. In fact, this value is obtained because of the high failure rates assumed earlier. The next

example demonstrates how lower values of the failure rates can drastically improve the overall system reliability.

7. Numerical Example No. 2

The aim of this example is to show how the failure rates of the equipments involved in the system affect the overall system reliability.

The reliabilities calculated in the previous section are calculated after changing the failure rates to the values shown in **bold** in Table 4. These values were chosen reasonably.

The rate diagram introduced in Fig. 6 can be re-sketched for the above values as shown in Fig. 14 below.

Table 4. Switching and failure rates for example no. 2.

Switching or failure rate	Assumption (per hour)
λ_{12}	10^{-2}
λ_{13}	10^{-2}
λ_{14}	10^{-2}
λ_{15}	10^{-2}
λ_{16}	**10^{-5}**
λ_{23}	10^{-2}
λ_{24}	10^{-2}
λ_{25}	10^{-2}
λ_{26}	**10^{-5}**
λ_{34}	10^{-2}
λ_{35}	10^{-2}
λ_{36}	**10^{-5}**
λ_{45}	10^{-2}
λ_{46}	**10^{-5}**
λ_{56}	**10^{-5}**
λ_{Sink}	**10^{-7}**
λ_{Tower}	**10^{-9}**
$\lambda_{Repeater}$	**10^{-9}**
$\lambda_{Control\ Room}$	**10^{-7}**

Fig. 14 depicts superimposed sketches of the reliability profile.

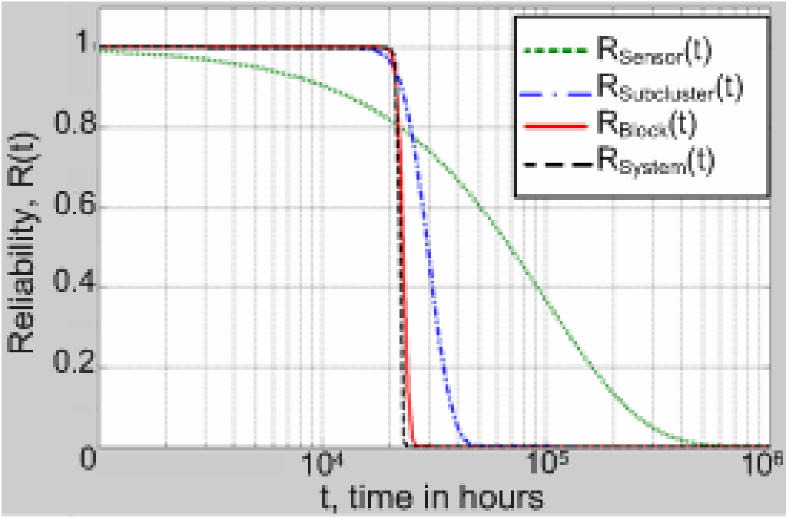

Fig. 14. Superimposition of reliabilities provided in example 2.

Comparing Figs. 13 and 16, it may be observed that the life time of the overall reliability of the system is drastically increased from about 200 hours to about 20, 000 hours.

This improvement is due to the reduction in the failure rates of the components involved. This implies an increase in the sensor reliability which in turn increases the overall system reliability.

This example clearly illustrates the importance of selecting reliable system elements and parameters to fulfill the overall system reliability.

8. Conclusions and Future Work

This paper has proposed a model to assess the reliability of wireless sensor network (WSN) for pipelines condition monitoring. A wireless sensor model for pipelines monitoring was adopted from the literature and revised to suite present application.

After the system is presented; reliability modeling was approached accordingly in a bottom-up approach. First, the individual sensor's reliability was modeled using Hidden Markov Models (HMM) approach. Then the cluster reliability was modeled using binomial process (using at least a 75 out of 100 sensor reliability requirement).

Subsequently, the block reliability was modeled with at least a 45 out of 50 subcluster reliability requirement. Finally, the overall system reliability was introduced considering at least an 8 out of 10 block reliability requirement.

Two numerical examples were presented to demonstrate the application of the proposed approach. From the reliability sketches developed for the case study it was evident that besides the wireless sensors reliability other reliability requirements play an important role in dictating the overall system reliability. Finally, a simple approach for maximizing the overall system reliability was discussed.

The following issues will be considered for future work:

- Varieties of wireless sensors are commercially available from different vendors. These sensors need to be surveyed so that an appropriate off-the-shelf sensor can be chosen for pipelines monitoring.

- While choosing wireless sensor many factors need to be considered such as energy scavenging module, maximum transmission distance, ambient conditions …etc.
- More investigation is required concerning routing the sensor (slave) information to the sink (master) node.
- Given the developed reliability model, to allocate target reliability to the overall system a top-down approach for reliability allocation can be deployed.
- Fault tree analysis (FTA) may be used to develop system failure mechanisms and the reliability analysis.
- Non-linear structures of pipelines may be considered. This requires revised system design and the reliability modeling.

References

[1]. Canadian Energy Pipeline Association. URL: http://www.cepa.com

[2]. DOT, Initiative on damage prevention. URL: http://www.rspa.dot.gov

[3]. N. Xu, S. Rangwala, K. Chintalapudi, D. Ganesan, A. Broad, R. Govindan and D. Estin, A Wireless Sensor Network for Structural Monitoring, in *Proc. of ACM Conference on Embedded Networked Sensor Systems (Sensys04)*, 2004, p. 504.

[4]. C. R. Ferrar, S. W. Deobling and D. A. Nix., Vibration-based structural damage identification, in *Proc. of Philosophical Transactions of the Royal Society of London A*, 2001, Vol. 359.

[5]. A. Awawdeh, S. T. S. Bukkapatnam, S. R. T. Kumara, C. Bunting and R. Komanduri, Wireless Sensing of Flow-Induced Vibrations for Pipeline Integrity Monitoring, in *Proc. of IEEE Workshop on Sensor Array and Multichannel Signal Processing,* 2006.

[6]. Sami Suheil and Roberto Garelli, Wireless Sensors Enhance System Safety and Efficiency for Mexico's Pemex, *Oil and Gas Journal*, 2007, PennWell Publishing Company.

[7]. Changsoo Ok, Thadakamalla, H., Raghavan, U., Kumara, S., Sang-Gook Kim, Xiang Zhang and Bukkapatnam, S., Optimal transmission power in self sustainable sensor networks for pipeline monitoring, in *Proc. of IEEE International Conference on Automation Science and Engineering (CASE 2007), 2007,* Scottsdale, AZ, pp. 591-596.

[8]. Bonny B. N. Umeadi and K. G. Jones, Integrated Wireless Sensors in Oil Pipeline Integrity Monitoring, (Poster), University of Greenwich UK.

[9]. Stoianov, I., Nachman, L., Madden, S., Tokmouline, T. and Csail, M, PIPENET: A Wireless Sensor Network for Pipeline Monitoring, in *Proc. of the 6th International Symposium on Information Processing in Sensor Networks (IPSN 2007),* 2007, pp. 264-273.

[10].Heinzelman, W. R., Chandrakasan, A., Balakrishnan, H., Energy-Efficient Communication Protocol for Wireless Microsensor Network, in *Proc. of the 33rd Annual Hawaii International Conference on System Sciences,* 2000, MA, USA, Vol. 2, pp. 10.

[11].Charles E. Ebeling, *An Introduction to Reliability and Maintainability Engineering,* 1997, Waveland Press Inc.

[12].Marcello Cinque, Domenico Cotroneo, Gianpaolo De Caro and Massimiliano Pelella, Reliability Requirements of Wireless Sensor Networks for Dynamic Structural Monitoring, in *Proc. of the International Workshop on Applied Software Reliability (WASR 2006)*, 2006, Philadelphia, USA, pp. 8-13.

[13].AboElFotoh, H. M. F., ElMallah, E. S. and Hassanein, H. S., On the Reliability of Wireless Sensor Networks, in *Proc. of IEEE International Conference on Communications* ICC apos, 06, 2006, pp. 3455 – 3460.

[14].Liudong Xing and Michel, H. E., Integrated Modeling for Wireless Sensor Networks Reliability and Security, *Annual Reliability and Maintainability Symposium RAMS apos,* 06, 2006, pp. 594-600.

[15].Man Wah Chiang, Zilic, Z., Radecka, K. and Chenard, J. -S, Architecture of Increased Availability Wireless Sensor Network Nodes, in *Proc. of the International Test Conference (ITC 2004),* 2004, pp. 1[16].2-1241.

[16].Wenyu Cai, Xinyu Jin, Yu Zhang, Kangsheng Chen and Jun Tang, Research on Reliability Model of Large Scale Wireless Sensor Networks, in *Proc. of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2006*), 2006, pp. 1-4.

[17].Shrestha, A., Liudong Xing and Hong Liu, Modeling and Evaluating Reliability of Wireless Sensor Networks, in *Proc. of the Annual Reliability and Maintainability Symposium RAMS '07*, Orlando, FL, 2007, pp. 186.
[18].Akan, O. B. and Akyildiz, I. F., Event-to-Sink Reliable Transport in Wireless Sensor Networks, in *Proc. of IEEE/ACM Transactions on Networking*, Oct 2005, Vol. 13, Issue 5, pp. 1003-1016.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information