Recovery of Lost Connectivity in Wireless Sensor and Actor Networks using Static Sensors as Bridge Routers

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Abstract

The actor nodes are the backbone of wireless sensor and actor networks (WSANs) in an unsupervised and hostile environment. Their failure rate is also high in hostile scenario due to many reasons like breakdown of electronic circuitry or complete battery power exhaustion of devices or software counter fault in nodes or physical damage of actor nodes, etc. The most serious side effect may occur in the network when connected network converts into multiple sub-networks due to permanent failure of cut-vertex backbone actor nodes in the network. This loss of connectivity among backbone actor nodes creates an adverse effect on the overall performance of the network. Therefore, the network partition problem in WSANs is most challenging issue in the real environment where we cannot control or reduce the failure of backbone cut-vertex actor nodes in the network. Recently, many approaches have been proposed to recover the lost connectivity among disjoint sub-networks using actors’ controlled mobility. However, it is also possible to rehabilitate the disconnected network by efficient use of high power sensor nodes as bridging routers without using actor’s movement. In this paper, we propose a new energy efficient recovery approach based on two point crossover genetic algorithm (GA) to reconnect the partitioned network. The simulation results confirm the effectiveness of our proposed over state-of-the-art approaches.

Keywords: network partition recovery; wireless sensor and actor networks, cut-vertex nodes; two point crossover genetic algorithm.

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1. Introduction

WSANs are the extension of wireless sensor networks (WSNs) which include both actor and sensor nodes. Actors are resourceful devices that can make decisions and coordinate with each other to perform action(s) on the basis of information reported by sensor node(s). Sensors are small in size, low cost with limited energy, limited computation capability and transmission power. More precisely, sensor nodes are passive while actors are active in nature, having more energy power, more computation capabilities and better transmission range. Due to random deployment of actor nodes in WSANs, connectivity among actor nodes is a critical issue. The overall performance of the network should not hamper due to failure of one or more backbone nodes. The neighboring node(s) must take over the task of failed node(s) until permanent solution takes place. Due to the infeasibility of replacing or recharging of nodes when nodes are deployed in unattended environment, a self-healing solution must be used to recover the lost connectivity. Several approaches have been suggested in the literature to optimize the lost connectivity using heuristics, but none of these approaches have considered sensor nodes as bridging routers to recover lost connectivity due to failure of backbone cut-vertex actor node. However, Handigol et al. [7] proposed a reliable data transport protocol for partitioned WSAN, but they do not consider the case of failure of cut-vertex backbone actor nodes. Moreover, in our previously published work [11], we have proposed a cluster based coordination and communication framework for WSANs using GA but without considering the case of failure of backbone cut-vertex actor nodes in the network. In this paper, we enhance our previously published research work to optimize lost connectivity of backbone actor nodes using sensor nodes as bridging routers. Further, for energy efficiency and longer network lifetime, we consider three important parameters, i.e. distance of neighboring sensor node to failed actor node, residual power and energy decay rate (EDR) of sensor nodes to choose any node as bridging router. In the nutshell, we choose only those sensor nodes for the recovery of lost connectivity that are stable on the route to take the load of failed actor node(s).

The remainder of the paper is organized as follows: In Section 2, related work is explained. Section 3 describes models of the proposed approach. In Section 4, two point crossover genetic algorithm is briefly discussed and explained. Section 5 shows the proposed solution. Section 6 explains performance evaluation of the proposed solution through simulations and compares with a traditional approach, i.e. Handigol’s approach to prove its effectiveness. In section 7, the article is concluded with future scope.

2. Related works

Several interesting nature inspired approaches like evolutionary approaches, i.e. neural networks, particle swarm optimizations (PSO) and ant colony optimizations (ACO) have been implemented to tackle different WSNs problems in an optimized way [1-9]. Genetic algorithm (GA) is another powerful meta-heuristic approach which can be used to solve backbone actor nodes failure in an energy efficient manner. A hybrid GA approach was used by Tzu-Chiang et al. [1], to improve the performance of shared multicast trees. A similar idea was used by Zhou et al. [2], in two-tiered wireless sensor networks (WSNs). Xu et al. [3] proposed GA in NS-2 for analyzing topology control in an ad-hoc network. Reina et al. [4] proposed an approach for optimizing network connectivity in a disaster scenario. They solved the connectivity problem using GA. They took different real-life mobility models to simulate their results. The authors of [5] developed a parallel version of traditional GA which improves the efficiency of traditional approaches. An ant based node failure management is proposed in [6] in which authors evaluated various network parameters. Most of the approaches proposed in the current literature for handling failure of cut-vertex actor nodes use actor's controlled mobility and ignore static sensor nodes during recovery of partitioned network. We argue here that actor node's movement consumes more energy as compared to communication energy [7] and sometimes terrain constraint also limit the movement of actor nodes in the network. Hence, static sensor nodes can be used as bridging routers for recovery of partitioned network until some alternate solution is not done. Moreover, actors' mobility should be avoided in the network so that network can operate for longer period of time. With this intention, in this paper, we propose our work without considering the node's (i.e. sensor nodes or actor nodes) mobility with the fact that static sensor nodes can act as bridging routers in case of network partitioning in the network. The distinction of our work is that the lost connectivity due to failure of
backbone cut-vertex actor node issue is addressed and solved using two point crossover genetic algorithm which is not yet seen in the literature.

3. Models

3.1. System model

The system topology can be modeled as an undirected graph $G(N,E)$ where $N \in n_1, ..., n_j$ and $E \in e_1, ..., e_i$. A node $n_i$ in the network is represented with vertex $v_i$ in graph $G$. An edge $(e_i) \in E$ exists between $v_i$ and $v_j$ if there is communication link between corresponding nodes $n_i$ and $n_j$ i.e. $e_i \in E, \forall (i,j) \in E, d_{ij} \leq r, \forall n_{ij} \in N$. Sensor nodes communicate with each other on a short range channel while actor nodes communicate on a long range as well as short range.

3.2. Energy model

In this paper, we assume that each node has the capability of forwarding an incoming packet to its neighboring nodes and to receive information from the transmitting node. Each node also maintains a routing table to transfer sensed data to sink node. The energy needed to transmit a packet $P_{a}$ from node $i$ to node $j$ and to receive the packet at node $j$ respectively. In our proposed model, the power consumption is determined by taking power consumption at transmitter i.e. $T_{ij}$, power consumption at receiver i.e. $R_{ij}$. In particularly, the transmission power $T_{ij}$ is modeled as:

$$ T_{ij} = c_{ij}r_{ij} $$  \hspace{1cm} (2)

Where $r_{ij}$ is the data stream rate sending from node $i$ to node $j$, and coefficient $c_{ij}$ represents power expenditure cost per bit associated with edge $e_i \in E, \forall (i,j) \in E$ and it is modeled as:

$$ c_{ij} = d_{ij}^{\eta} $$  \hspace{1cm} (3)

Where $\eta$ shows the path loss index and having value $2 \ll \eta \leq 4$. $d_{ij}$ denotes the Euclidean distance between node $i$ and node $j$ and $r$ is the transmission range of sensor node. Similarly, the energy consumption during the packet reception at the node is modeled as:

$$ R_{ij} = \varepsilon r_{ij} $$  \hspace{1cm} (4)

Where $\varepsilon$ depicts the energy dissipation to receive one bit of information. In our proposed model, it is assumed that $\varepsilon$ is constant and same for every node (i.e. homogeneity) and $r_{ij}$ is the data rate from node $i$ to node $j$. Moreover, energy saving mechanisms based on only residual energy cannot directly be used to establish stable route among nodes. The reason is that in case a node is willing to accept all requests; because it has enough residual battery power, much more traffic will be injected to that particular node. In this sense, the energy decay rate of that particular node will tend to be high and causes a sharp decay of its backup battery power. As a consequence, it will exhaust its energy quickly and cause node to die sooner. To avoid this problem, metric based on traffic load characteristics can be used along with node residual energy metric. In particular, minimum node energy decay rate is applied as cost function that takes into account of node energy decay rate index ($DR$) and residual energy of nodes to ensure the energy dissipation rate. Each node $i$ monitors its energy consumption due to transmission, reception and overhearing activities, and computes its energy decay rate $DR_i$ for every $T$ second. The actual value of $DR_i$ is calculated by using well known method called Exponential Weight Moving Average (EWMA) as proposed by authors in [9] and applied on both previous energy decay rate as well as on current decay rate which is modeled as follow:

$$ DR_{curr,i} = DR_i(t) $$  \hspace{1cm} (5)

$$ DR_i(t) = \alpha DR_i(t-1) + (1-\alpha)DR_{curr,i} $$  \hspace{1cm} (6)

To take current condition of energy expenditure of node, our proposed approach takes the ratio of residual battery
power at node $i$ to the energy decay rate $DR_i(t)$ at time $t$ which is represented by $s_i(t)$. It can be modeled as:

$$s_i(t) = \frac{E_{res_i}(t)}{DR_i(t)}$$

(7)

The ratio mentioned above is very significant when left energy of node $i$ is observed in such a way that it can indicate the stability condition of node $i$. To find all stable nodes among stable neighboring nodes, the maximum value of $s_i(t)$ will be taken as:

$$= \max \sum_{v \in N_{neg_i}} s_i(t) : \forall(v) \in N_{neg}$$

(8)

Where $N_{neg}$ depicts neighbor nodes of a failed actor node $i$.

4. **Two point crossover genetic algorithm**

Genetic algorithms are the family of computational intelligence tools inspired by evolution [8]. These algorithms have the capabilities to give a potential solution to a specific problem on a simple data structure called chromosome and evaluates functions in order to save more critical information. Due to space limit, we omit the beginning part of two point crossover GA but describe only crossover operation taken in the proposed solution.

4.1. **Two point crossover operation**

The new 80% of the next population is obtained using crossover operation. In the proposed approach, we use 2-point crossover technique. The chromosome is divided into three parts namely right part, middle part and left part i.e. $R_{par_1}$, $M_{par}$ and $L_{par}$ respectively. The two new chromosomes are then obtained by swapping $L_{par_1}$ by $L_{par_2}$ and $R_{par_1}$ by $R_{par_2}$ respectively as shown in Fig. 1, where $i_1$ and $i_2$ are chromosome $c_{i_1}$ and chromosome $c_{i_1+1}$ respectively. The probability $P_c$ of crossover operation is given as below, where $c \in \{0,1\}$:

$$P_c = \frac{f_m(C)}{\sum_{\forall c} f_m(c)}$$

(9)

Where $f_m(C)$ denotes fitness function for the chromosome $C$. In this way the best chromosomes are likely to be selected.

![Fig. 1. Two point crossover operation](image)

5. **Phases of proposed approach**

Our proposed approach has mainly three phases:

i. **Initialization phase**: In this phase, sensor and actor nodes are scattered randomly in the area of interest and it is assumed that these nodes form clusters using some clustering algorithm. It is also assumed that all sensor and actor nodes know the location of sink node. The status about cut-vertex actor node is computed and stored by all 1-hop neighboring nodes (i.e. sensor and actor nodes) at the time of deployment phase.

ii. **Failure detection phase**: All nodes are equipped with a failure detection system and able to detect the failure of cut-vertex actor nodes. After the failure of any cut-vertex actor node(s), nearby CHs will detect...
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its failure in the distributed manner. Many approaches have been proposed in the literature to detect the failure of backbone cut-vertex actor node in the network. The latest approach is published by Mahapatro et al. [9] and same is used in this paper. After the detection of failure of cut-vertex actor node, neighbor CHs broadcast Recovery required message to all its neighboring nodes toward sink node until next actor node or next CH is found for lost connectivity. Therefore, the main objective of our proposed approach is to find stable nearby actor or sensor nodes (CHs) for restoration of lost connectivity.

iii. **Recovery Phase**: After failure detection of cut-vertex actor node nearby CHs (which were directly attached with failed actor node before failure) will broadcast recovery required message to their 1-hop neighbor nodes. Further, these neighbor nodes will send their information to their respective CHs (if these nodes are not CHs). The CHs will wait for $T_{max}$ interval to collect information about their 1-hop neighbors and then choose the stable sensor CHs (as per GA based criterion) among their neighbor nodes as bridging router for connecting disjoint network. This process is repeated till next nearby CH or actor node is hit for recovery. Since actor nodes have more transmission power and can cover a larger area, hence, more than one CHs may be connected to one actor node. The schematic diagram is shown in Fig. 2 to understand the proposed approach.

![Fig. 2. Flow chart of proposed solution](image)

6. **Performance evaluation**

In this paper, we use MATLAB-2013 simulation environment with 1000m x 1000m area for nodes' deployment. We consider end-to-end delay, packet delivery ratio (PDR), network lifetime, packet loss (PL) and throughput. All metrics are evaluated based on the traffic generated from sensor node to sink node (destination), through actor nodes and CHs (sensor nodes). The results of the individual experiments are averaged over 30 trials at 95% confidence interval. The following parameters are used to evaluate the performance of our proposed approach.

A. **End-to-end delay**

This metric depicts the delay observed from sender to receiver node. We report it in milliseconds (ms). The end-to-end delay increases initially in our proposed approach due to start up period of our technique and then subsequently decreases as the number of rounds increases. The reason is that we use intermediate sensor nodes to
forward the data until deliver to next actor or sensor node on the path or the original receiver. The expected reduction of end-to-end delay is confirmed in Fig. 3. Fig. 3(a) shows end-to-end delay vs. rounds and Fig. 3(b) shows end-to-end delay vs. number of sensor nodes while actor nodes are constant (i.e. 50). Both simulation graphs show about 60% improvement of our proposed approach over Handigol’s approach (traditional approach).

B. Packet delivery ratio or success rate

This is the ratio of total events received at the sink to the total number of events generated by the nodes in the network. We abbreviate it in percentage (%). Because our proposed protocol uses the buffer of intermediate actor nodes while transmission or retransmission. Therefore, original sender node transmits the segment to the next actor node on the path to the receiver. The intermediate actor node also stores the packets received from the previous actor or sender node until delivered to next actor or sensor node on path or the original receiver. When acknowledgement for the current segment is received from the intermediate nodes, actor node deletes that segment to use cache memory for next segment. Therefore, high value of packet delivery ratio (PDR) is shown in our proposed approach. Fig. 4(a) shows packet delivery ratio vs. rounds and Fig. 4(b) shows packet delivery ratio vs. number of sensor nodes while actor nodes are constant (i.e. 50). Both simulation graphs show effectiveness of our proposed approach over traditional approach. Our proposed approach shows its improvement about 58% over Handigol’s approach.

C. Network lifetime

This metric is used for observing lifetime of network. A node can be dead due to some physical damage or might be out of battery power due to complete battery exhaustion. A network is reliable if the node death rate is low i.e. number of alive nodes are more in the network. A reliable network will have a better data gathering rate i.e. data received at base station will also be high. Fig. 5 illustrates the number of rounds for last node death as function of number of nodes (i.e. sensor nodes and actor nodes) in the network. Our proposed approach outperforms due to use of stable nodes as CHs (bridging routers) to transmit data through multi-hop paths instead of direct transmission to BS. Moreover, as the network size increases, the probability to find eligible stable nodes is more which is also confirmed in Fig. 5. Fig. 5(a) shows dead nodes vs. rounds and Fig. 5(b) shows network lifetime vs. number of sensor nodes. Both simulation graphs show effectiveness of our proposed approach. Our proposed approach shows its improvement about 2.5 times over Handigol’s approach.

D. Packet loss

Fig. 8 depicts the packet loss in the network as the function of number of sensor nodes in the network. It is observed from the simulation graph that our proposed approach observes less packet loss compared with Handigol’s approach. The reason is that again our proposed approach uses intermediate acknowledgement packet during data transmission and avoid flooding mechanism every time to setup new data transfer path. This reduces packet loss in the subsequent rounds and consequently shows improvement in our proposed approach. Fig. 6(a) shows packet loss vs. rounds and Fig. 6(b) shows packet loss vs. number of sensor nodes while actor nodes are constant (i.e. 50). Both simulation graphs show effectiveness of our proposed approach. Our proposed approach shows its improvement about 35%-40% over Handigol’s approach.

E. Throughput

It is the average rate of successful packets delivered over the network. We abbreviate it in bits/sec. Due to high storage capability of the actor nodes and less packet loss, our proposed approach shows excellent results in terms of throughput. Moreover, direct communication between sensor's CHs and actor nodes also makes it faster. Furthermore, actor nodes are also capable to handle more than one cluster data in their memory, therefore, throughput further increases. Fig. 7 shows that advantage of our proposed approach over Handigol’s protocol. Fig. 7(a) shows throughput vs. rounds and Fig. 7(b) shows throughput as the function of number of sensor nodes while actor nodes are constant (i.e. 50). Both simulation graphs show its effectiveness of proposed approach over traditional approach. Proposed approach shows its improvement about 50%-55% over Handigol’s approach.
Fig. 3. End-to-end delay vs. (a) number of rounds (b) number of sensor nodes

Fig. 4. Packet delivery ratio vs. (a) number of round (b) number of sensor nodes

Fig. 5. Network lifetime vs. (a) number of rounds (b) number of sensor nodes
7. Conclusion and future scope

The recovery of lost connectivity due to failure of cut-vertex actor node is a most challengeable task when the failure rate of nodes increases in WSANs due to ill environment. To manage these failures, we use a two-point crossover GA approach that selects stable sensor node as bridge routers and transmit data in segmented form to the nearest actor node via sensor nodes as bridging routers. The proposed solution also avoids end-to-end retransmission and also provides the lost message immediately with intermediate sensor or actor nodes. The simulation results not only reduce end-to-end transmission delay, but also improve network coverage, packet loss rate, throughput and packet delivery ratio. In the future, our plan is to compare our proposed approach with different bio-inspired approaches (ACO or PSO) to evaluate more network parameters.

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