Markov Model for Reliable Packet Delivery in Wireless Sensor Networks

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Abstract

This paper presents a model for reliable packet delivery in Wireless Sensor Networks based on Discrete Parameter Markov Chain with absorbing state. We have demonstrated the comparison between cooperative and non cooperative automatic repeat request (ARQ) techniques with the suitable examples in terms of reliability and delay in packet transmission.

Keywords: *Reliability, Absorbing State, Wireless Sensor Network, Markov chain.*

1. Introduction

Wireless sensor networks (WSNs) [1][2] are the topic of intense academic and industrial studies. Research is mainly focused on energy saving schemes to increase the lifetime of these networks [4][5]. There is an exciting new wave in sensor applications-wireless sensor networking-which enables sensors and actuators to be deployed independent of costs and physical constraints of wiring. For a wireless sensor network to deliver real world benefits, it must support the following requirements in deployment: scalability, reliability, responsiveness, power efficiency and mobility.

The complex inter-relationships between these characteristics are a balance; if they are not managed properly, the network can suffer from overhead that negates its applicability. In order to ensure that the network supports the application's requirements, it is important to understand how each of these characteristics affects the reliability.

1.1. Scalability and Reliability

Network reliability and scalability are closely coupled and typically they act against each other. In other words, it is very difficult to build a reliable ad hoc network as the number of nodes increases [7]. This is due to network overhead that comes with increased size of network. In ad hoc network, there is no predefined topology or shape. Therefore, any node wishing to communicate with other nodes should generate more control packets than data packets. Moreover, as network size increases, there is more risk that communication links get broken, which will end up with creating more control packets. In summary, more overhead is unavoidable in a larger scale wireless sensor network to keep the communication path intact.

1.2. Reliability and power efficiency

Power efficiency also plays a very important role in this complex equation. To design a low power wireless sensor network, the duty cycle of each node needs to be reduced. The drawback is that as the node stays longer in sleep mode [3] to save the power, there is less probability that the node can communicate with its neighbors and may also lower the reliability due to lack of exchange of control packets and delays in the packet delivery.

1.3. Reliability and responsiveness

Ability of the network to adapt quickly the changes in the topology is known as responsiveness. For better responsiveness, there should be more issue and exchange of control packets in ad hoc network, which will naturally result in less reliability.

1.4. Mobility and reliability

A wireless sensor network that includes a number of mobile nodes should have high responsiveness to deal with the mobility. The mobility effect on responsiveness will compound the reliability challenge.

Many applications for wireless sensor networks require immediate and guaranteed action; for example medical emergency alarm, fire alarm detection, instruction detection [6]. In these situations packets has to be transported in a reliable way and in time through the sensor network. Thus, besides the energy consumption, delay and data reliability becomes very relevant for the proper functioning of the network.

Direct communication between any node and sink could be subject only to just a small delay, if the distance between the source and the destination is short, but it suffers an important energy wasting when the distance increases. Therefore often mutihop short range communications through other sensor nodes, acting as intermediate relay, are preferred in order to reduce the energy consumption in the network. In such a scenario it is necessary to define efficient technique that can ensure reliable communication with very tight delay constraint. In this work we focus attention on the control of data and reliability in multihop scenario.

A simple implementation of ARQ is represented by the Stop and Wait technique that consists in waiting the acknowledgement of each transmitted packet before transmitting the next one, and retransmit the same packet in case it is lost or wrongly, received by destination [8].

We extend here this analysis by introducing the investigation of the delay required by the reliable data delivery task. To this aim we investigate the delay required by a cooperative ARQ mechanism to correctly deliver a packet through a multihop linear path from a source node to the sink. In particular we analyze the delay and the coverage range of the nodes in the path, therefore the relation between delay and the number of cooperative relays included in the forwarding process.

2. System Model

Fig. 1 shows the network structure with linear multihop path consist of source node (node n =1), destination (node n = N) and (N-2)*t intermediate relay nodes deployed at equal distance where t is the number of parallel path of intermediate relay nodes between source and destination. Each path is composed by Z = N – 1 links. Suppose that all the nodes have circular radio coverage with the same transmission range Rt. When a sensor transmits a packet, it is received by all the sensors in a listen state inside the coverage area of the sender.

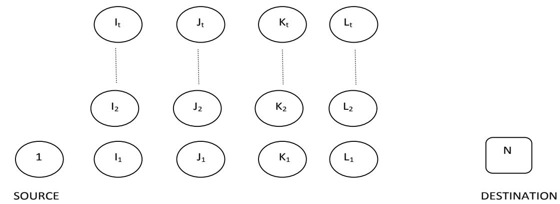

Fig.1 Network structure with Linear Multi-hop path

When a packet is transmitted, it can be forwarded towards the destination by only those nodes which are closer to the destination, then the transmitter.

2.1 Discrete Parameter Markov Chain with Absorbing State

Packet transfer from source to destination via intermediate forwarders can be treated as a state diagram of discrete parameter Markov chain with absorbing state. An absorbing state is a state from which there is zero probability of exiting. An absorbing Markov system is a Markov system that contains at least one absorbing state, and is such that it is possible to get from each non absorbing state to some absorbing state in one or more time steps. Consider p be the probability of successful transmission of a packet to an intermediate relay node inside the coverage range. Therefore 1-p will be the probability of unsuccessful transmission of packet.

For each; node n, the probability to correctly deliver a packet to a node that is R_t links distant is equal to p. So the probability that the packet is not correctly received by this node (1 – p), while it is correctly received from the immediately previous node with a probability p; so with a probability (1 – p) p the packet will be forwarded by the previous node. If also this node has not correctly received the packet send by node n, event that occur with a probability $(1- p)^2$, with a probability $(1 –p)^2$ p the packet will be forwarded by the node previous to previous. If none of the node in the coverage area of the transmitter receives a correct packet it is necessary to ask the retransmission of the packet by the source node. It is possible to describe the process concerning one data packet forwarding from the source node n = 1 to the destination n = N with a discrete time Markov chain with absorbing state. Packet transmitted by a node will be further forwarded by a node in the coverage range of the transmitter which is furthest node from the source and has correctly received the packet.

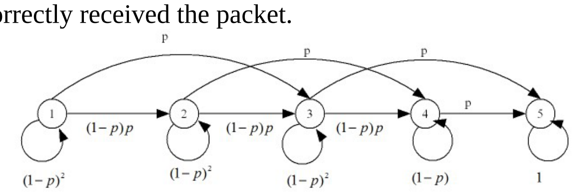

Fig 2 Packet transmission in Cooperative ARQ as a discrete parameter Markov Chain with absorbing state

Consider a single multihop linear path consisting five sensors with four links as shown in fig. 2. Assume transmission range of each sensor node is R_t=2 unit. State transition probability matrix for a successful transmission of a packet under cooperative automatic repeat request will be as under:

$$P_{Success}=\begin{bmatrix}(1-p)^2 & p(1-p) & p & 0 & 0\\ 0 & (1-p)^2 & p(1-p) & p & 0\\ 0 & 0 & (1-p)^2 & p(1-p) & p\\ 0 & 0 & 0 & (1-p) & p\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}$$

Similarly we can find the probability matrix for link error by replacing (1-p) with q. In fig. 2 states 1 through 4 are transient state while state 5 is an absorbing state.

In general, we consider a Markov chain with n states, s_1, s_2, …, s_n. S_n will be the absorbing state, and the remaining state will be transient. The transition probability matrix of such a chain may be partitioned so that

$$P=\left[--\frac{Q}{0}--|--\frac{C}{1}--\right]$$

Where Q is an (n-1) by (n-1) substochastic matrix, describing the probabilities of transition only among the transient states. C is a column vector and 0 is a row vector of (n-1) zeros. Now the k-step transition probability matrix P^k has the form

$$P^k=\left[--\frac{Q^k}{0}--|--\frac{C'}{1}--\right]$$

Where C' is a column vector whose elements will be of no further use and hence need not be computed. The (i, j) entry of matrix Q^k denotes the probability of arriving in (transient) state s_j after exactly k steps starting from (transient) state s_i. It can be shown that $\sum_{k=o}^{t} Q^k$ converges as t approaches infinity. This imply that the inverse matrix $(I-Q)^{-1}$, called the fundamental matrix, M, exists and is given by

$$M=(I-Q)^{-1}=I+Q+Q^2+...=\sum_{k=0}^{\infty} Q^k$$

. The fundamental matrix is used for calculating the expected no. of steps to absorption. The number of times, starting in state i, and expected to visit state j before absorption is the ij^{th} entry of M. The total no. of steps expected before absorption equals the total no. of visits expected to make to all the non absorption states. This is the sum of all the entries in the i^{th} row of M.

Suppose p=0.8, then Q will be as under

$$Q_{Success}=\begin{bmatrix}.04 & .16 & .8 & 0\\ 0 & .04 & .16 & .8\\ 0 & 0 & .04 & .16\\ 0 & 0 & 0 & .2\end{bmatrix}$$

Therefore fundamental matrix $M=(I-Q)^{-1}$

$$=\begin{bmatrix}25/24 & 25/144 & 775/864 & 305/864\\ 0 & 25/24 & 25/144 & 155/144\\ 0 & 0 & 25/24 & 5/24\\ 0 & 0 & 0 & 5/4\end{bmatrix}$$

Thus the states 1, 2, 3 and 4 are respectively executed 25/24, 25/144, 775/864, 305/864 times on the average. If t_1,t_2, t_3 and t_4 respectively is the time for one time execution of the states 1,2,3 and 4 then total time required to transmit a packet from source node 1 to destination node 5 is equal to :

T=25/24 t_1 + 25/144 t_2 + 775/864 t_3 + 305/864 t_4 unit times.

If t_1=t_2=t_3=t_4=t then T=2.4645 unit times.

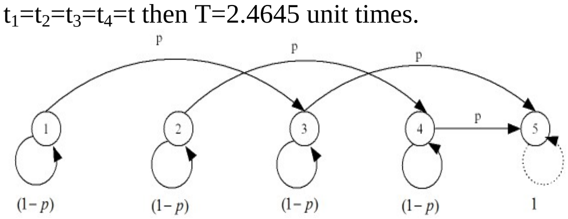

Fig 3 Packet transmission in Non-Cooperative ARQ as a discrete parameter Markov Chain with absorbing state

In non-Cooperative ARQ, a packet transmitted by source node is received by a node at distance R_t towards the destination from source and is forwarded by the node if packet received correctly otherwise transmitter is forced for retransmission. Other intermediate nodes between the transmitter and the node at distance R_t remains in sleep mode as they will never be involved in packet forwarding process. State transition probability matrix for successful transmission of the packet for non-cooperative ARQ will be as under:

$$P_{Success}=\begin{bmatrix}1-p & 0 & p & 0 & 0\\ 0 & 1-p & 0 & p & 0\\ 0 & 0 & 1-p & 0 & p\\ 0 & 0 & 0 & (1-p) & p\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}$$

Suppose p=0.8, then Q will be as under

$$Q_{Success}=\begin{bmatrix}.2 & 0 & .8 & 0\\ 0 & .2 & 0 & .8\\ 0 & 0 & .2 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

Therefore fundamental matrix

$$M = (I - Q)^{-1}$$

$$= \begin{bmatrix} 5/4 & 0 & 5/4 & 0 \\ 0 & 5/4 & 0 & 1 \\ 0 & 0 & 5/4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Thus the states 1, 2, 3 and 4 are respectively executed 5/4, 0, 5/4, 0 times on the average if source node is considered as node 1. If t_1,t_2, t_3 and t_4 respectively is the time for one time execution of the states 1, 2, 3 and 4 then total time required to transmit a packet from source node 1 to destination node 5 is equal to :

$T=5/4\ t_1 + 5/4\ t_3$ units times.

If $t_1=t_2=t_3=t_4=t$ then T=2.5 unit times.

Conclusion

In this work we have presented Markov model to analyze the performance of cooperative and non cooperative ARQ in terms of delay and power efficiency. It has been observed that packet delivery is more reliable and timely in case of cooperative ARQ, where as non cooperative ARQ is better in terms of power efficiency of sensor nodes as most of the sensors do not participate in packet forwarding process.

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Author Biography

Prof. Vijay Kumar born in Kanpur, India, on 30th June 1972. He received his B.E & M.E. degrees from Kumaon University Nainital (U.P) and Thapar University Patiala (Punjab) respectively. He has supervised 8 M. Tech and 1 M. Phil candidates. His research interests are in Wireless Sensor Networks, Reliability Theory and Artificial Neural Networks, etc. He has about 16 years experience in teaching. He is also a member of IEEE.

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