Fair Buffer Allocation Scheme for Integrated Wireless Sensor and Vehicular Networks using Markov Decision Processes

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***Abstract*—In sparsely deployed Wireless Sensor Networks (WSNs) the end to end connectivity between sensor nodes and the sink is not always available. To allow communication between sensor nodes and the sink, mobile vehicular nodes often come into play to collect data from isolated nodes, temporarily store it in their buffer and ultimately deliver to the sink. In these store and forward networks, buffers at the roadside relay nodes become critical resources for overall network performance and need to be allocated fairly among sensor nodes. In this paper we have proposed a fair buffer allocation policy for roadside relay nodes in an integrated wireless sensor and vehicular network scenario. We have considered a network with sparsely deployed sensors for gathering desired information from surroundings which is ultimately delivered to the sink via vehicular nodes. In particular, we first present the model of the buffer at the road side relay node and then formulate constrained semi-Markov decision process (SMDP) for fair buffer management. The SMDP provides an optimal decision policy to achieve fair buffer allocation at the roadside relay nodes. The model is flexible and can be realized using look up table approach. Performance evaluation results reveal the significance of the proposed policy in achieving the fair buffer allocation for different number of buffer states as well as data arrival rates.**

I. Introduction

In the last few years, wireless sensor networks (WSNs) have gained an increasing attention from both the research community and industrial sector due to its widespread deployment worldwide. Though wireless sensor networks have found their way in wide range areas but environmental monitoring is a domain in which they may have a huge impact. A collaborative effort of environmental and computer science researchers to build a WSN-based measurement system is the ”SensorScope” project, which has the ability to immediately transmit gathered data to a distant server. As a result, it allows for real-time (e.g., pollution) as well as long-term (e.g., ice melting) monitoring of natural events in potentially large areas [1].

Wireless sensor networks offer many advantages like self-organization, simple extension, targeted coverage, low cost, etc. if end to end connectivity is assumed. However, sparsely deployed wireless sensor networks often results in some areas where communications infrastructure does not exist and end to end connectivity is not guaranteed. For example, in a project like air pollution monitoring in different areas of the city, sensor nodes have to be deployed at widespread locations where end-to-end network wide connectivity is not guaranteed.

To overcome this issue of disconnectivity we have considered the integration of WSNs and vehicular networks, where vehicular nodes (VNs) are used to transport data from isolated sensor nodes to the sink. However unlike mobile ad-hoc networks, in these integrated wireless sensor and vehicular networks (WSVNs), end-to-end path between a source node and the intended destination (sink) will only be available for a short period of time [2]. Since the path between the sensor nodes and the sink is not always available, so the information sensed by the sparsely deployed sensors has to be buffered at intermediate nodes, equipped with storage capacity and guaranteed communication with the vehicular nodes. The data is stored in the buffer of the relay nodes unless and until it comes into contact with any vehicular node. As the vehicular node comes in the communication range of the relay node, the stored data is relayed to the vehicular node which will ultimately reach the sink and delivers the data to it. In this manner, the vehicular nodes deployed over the sensor network serves as the remedial solution for disconnectedness in the sparsely deployed wireless sensor networks.

In WSVNs, we consider the sparsely deployed sensor nodes such that all of them cannot communicate directly to VNs, as they lie far away from the route of the VNs. For such a scenario, there is a need to formulate a decision policy which gives a fair chance to each sensor node to send its data to VNs through intermediate relay nodes (RRNs). In order to achieve this objective, we have proposed a fair buffer management mechanism for RRNs using a constrained semi-Markov decision process (SMDP) based approach. To obtain fair buffer allocation among different sensor nodes, we have defined minimum and maximum buffer occupancy constraints for each individual sensor node.

In literature there are some studies related to optimal buffer management in the context of WSVN. In [3] min-max fairness model and route based buffer allocation scheme is proposed in which the parameters can be tuned to minimize the packet delivery delay but only at the expense of more vehicular node resources. However in our implementation we do have a foreknowledge about the path and probability of arrival of mobile vehicular node (e.g., a university buses departure schedule) but we do not implement buffer efficient routing scheme to minimize node computational power overhead. In

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[4], an adaptive buffer management protocol is proposed exploiting the mobility characteristic according to the historical information of all nodes in the network. The authors have also provided the theoretical proof of two utility functions for optimal buffer dropping policies to maximize the delivery rate and minimize the delivery delay. The buffer storage performance for vehicular delay tolerant networks (VDTN) in terms of routing protocols and packet delivery probability is analyzed in [5]. The authors have shown that the message replication strategies lead to an increase in the buffer size requirement for a given network size. The implications of storage constraints on the performance of a VDTN, providing insights for future routing algorithm and buffer management theoretic studies as well as protocol design are outlined.

Our proposal differs from [6] because we have considered a more practical scenario where all the sensor nodes cannot communicate directly with the VNs. We proposed a model in which we buffer the data from different sensor nodes at roadside relay nodes before delivering to the vehicular node. In [7], optimal buffer management policies are defined that result in arbitrary packet drops but we do not drop packets unless buffer capacity is reached and provide a fair chance to all sensor nodes to transmit their data by introducing performance constraints. Rest of the paper is organized as follows.

In Section II we describe the WSVN model. The framework to achieve optimal buffer allocation using SMDP is outlined in Section III. Performance evaluation and conclusions are presented in Section IV and Section V respectively.

II. Network Model

We consider an integrated wireless sensor and vehicular network (WSVN) consisting of a sink node n_{sink}, collection of l vehicular nodes denoted by set V, with $V = \{v_1, v_2, \cdots, v_l\}$, k roadside relay nodes represented by set R with $R = \{r_1, r_2, \cdots, r_k\}$ and a set N of m sensor nodes with $N = \{n_1, n_2, \cdots, n_m\}$ as shown in Fig. 1. In WSVN, data from sensor nodes is collected at roadside relay nodes and is transferred to the VNs and data from VNs is later delivered to the sink. We consider the scenario where data from the sensor

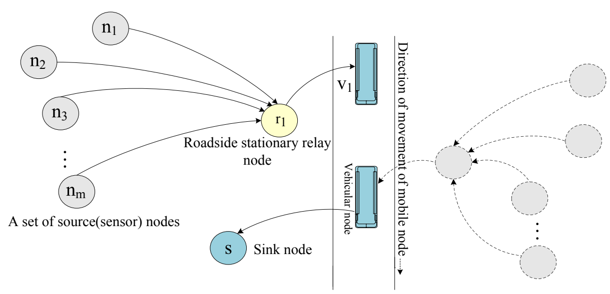


Fig. 1. Network model for integrated wireless sensor and vehicular network.

nodes, which are not reachable by the vehicular nodes, is to be stored at the RRNs. To achieve fair buffer occupancy for temporary data storage from the sensor nodes at the RRNs we develop a semi-Markov decision process based buffer allocation policy. We have made the following assumptions for our SMDP based allocation policy:

- The sensed data arrival rate from the sensor nodes follows Poisson distribution with mean arrival rate λ.
- The time duration for each buffer state is independent and identically distributed for all states.
- The mean holding time at different buffer states is small compared to data arrival time.

The first two assumptions mean that the our problem of fair buffer allocation with multiple state transitions can be modeled as a semi Markov decision process. The last assumption is necessary for the validity of the second assumption. The state transition diagram in Fig. 2 satisfies the Markov property, since the presence in any state depends only on the previous state and the action taken in that state and is independent of the prior visits to states. The underlying chain associated with the buffer state transitions is a semi-Markov chain as the time spent in each state is assumed to be a random fixed value. As a result, the problem of optimal buffer management and fair data storage at RRN's can be solved as a semi-Markov decision problem (SMDP).

The buffer at the roadside relay node (RRN) is divided into b states represented by the set S, $S = \{s_1, s_2, \cdots, s_b\}$. In state s_1 buffer is either empty or filled less than $\frac{1}{b}$ fraction of the buffer size, while in state s_b the buffer is completely filled. A transition from state $s_i,\ i \in \{1, 2, \cdots, b-1\}$ to state s_{i+1} occurs with probability $p_{s_i s_{i+1}}$ when the data is stored into the buffer, while a state transition from state s_i to state s_j with $j < i$ occurs with probability $p_{s_i s_j}$, when the data is delivered to the VN. Whether data from a sensor node is stored into the buffer or is dropped, depends on the corresponding action taken by the buffer policy manager. This leads to an action space given by set A with $A = \{0, 1, \cdots, m\}$ which will be explained in detail in Section III.

III. Semi Markov Decision based Framework

In this section we outline all the details of basic building blocks which are needed to form the semi-Markov decision framework providing an optimal buffer management and resulting fair policy for data storage at the roadside relay nodes.

A. Action Space

As mentioned in Section II, at each buffer state a decision is to be made by policy manager whether to accept the packets from the sensor nodes or to drop them, which give rise to an action space A. Let A be the set of all possible actions in any state and $A(s_i)$ is the set of actions possible in state s_i then an action $a \in A(s_i) \subseteq A$, can have following values:

$$a = \begin{cases} 0 & \text{maintains its state or delivers data to VN and} \\ & \text{transition to any previous state.} \\ 1 & \text{transition to next state due to sensor node } n_1. \\ 2 & \text{transition to next state due to sensor node } n_2. \\ \vdots & \vdots \\ m & \text{transition to next state due to sensor node } n_m. \end{cases} . \quad (1)$$

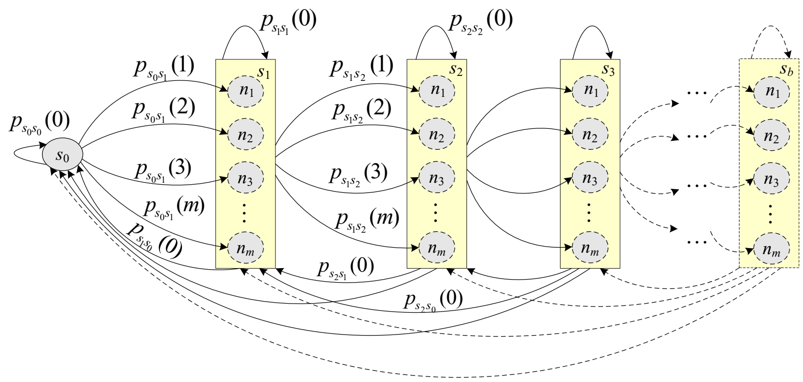


Fig. 2. State transition diagram along with transition probabilities and associated actions.

When the action $a = 0, a \in A$ is taken, buffer remains in the same state and the data from any of the sensor nodes is not accepted. Since we have assumed half duplex communication, so an action $a = 0$ does not imply that the same buffer state is maintained due to equal number of data arrivals and departures. On the other hand if the RRN is in buffer state $s_i, i < b$,, and if action $a = j$, $a \in A$, is taken then data from sensor node n_j is put into the buffer. Hence an action $a = j$, $j \in \{1, \cdots, m\}$, corresponds to putting data from sensor node n_j into the buffer. It should be noted that data from multiple sensor nodes can be put into the buffer, while buffer maintains its state.

B. State Dynamics, Policy and Cost Function

The state transition probabilities along with $\tau_{s_i}(a)$, which is the expected time in state s_i when action a is taken, describe the dynamics of the system. The state transition probabilities are given by:

$$p_{s_i s_j}(a) = \begin{cases} p_{s_i s_i} & j = i, a = 0, \\ & i \in \{0, 1, \cdots, b\} \\ p_{s_i s_k} & k < i, a = 0, \\ & i \in \{1, 2, \cdots, b\} \\ 1 - p_{s_i s_i} - p_{s_i s_k} & j = i + 1, k < i, \\ & a \in \{1, \cdots, m\}, \\ & i \in \{1, \cdots, b-1\} \end{cases} \tag{2}$$

In (2) $p_{s_i s_i}$ is the probability of maintaining the same buffer state and $p_{s_i s_k} = \frac{1}{\lambda}$. As we have assumed in Section II that the data arrival at RRN follows Poisson distribution so we have chosen the probability of going back to any previous buffer state as $\frac{1}{\lambda}$, knowing that the data inter arrival time has exponential distribution [8]. For each state $s_i \in \mathbf{S}$ an action $a \in A(s_i)$ is chosen according to a policy $h_{s_i} \in \mathcal{H}$, where $\mathcal{H}$ is the set of admissible policies given as

$$\mathcal{H} = \{h : S \to A | h_{s_i} \in A(s_i), \forall s_i \in S\} \tag{3}$$

The semi-Markov decision framework provides a policy resulting in a sequence of actions, which provides fair buffer utilization. Each state transition from buffer state s_i to state s_j, $i, j \in \{1, 2, \cdots, b\}$, when action a, $a \in A$ is taken, incurs an immediate fixed cost $C_{s_i s_j}(a)$ to account for relay node wakeup power and a running cost of $c_{s_i s_j}(a)$ to account the relay node power consumption in state s_j till the next action is taken. Mean expected cost in state s_i for action a is obtained as

$$\bar{C}_{s_i}(a) + \bar{c}_{s_i}(a)\tau_{s_i}(a) = \sum_{s_j} p_{s_i s_j} \left(C_{s_i s_j}(a) + c_{s_i s_j}(a)\tau_{s_i}(a) \right). \tag{4}$$

In (4), $\tau_{s_i}(a)$ is the expected time in state s_i when action a is taken.

C. Problem Formulation and Constraints

To achieve fairness in buffer allocation for different sensor nodes, we ignore the issues of overflowing and scheduling and introduce parameters B_{min} and B_{max}, which serves as lower bound and upper bound on the buffer occupancy for any of the sensor nodes [9]. Now the semi-Markov decision problem, providing a policy resulting in an optimal buffer utilization at relay nodes while ensuring fairness among the sensor nodes, is formulated as the following linear program:

$$\begin{aligned} &\textbf{minimize} \sum_{s_i \in S} \sum_{a \in A(s_i)} \left\{ \bar{C}_{s_i}(a) + \bar{c}_{s_i}(a)\tau_{s_i}(a) \right\} \pi_{s_i}(a) \\ &\textbf{subject to} \sum_{s_i \in S} \sum_{a \in A(s_i)} \tau_{s_i}(a)\pi_{s_i}(a) = 1, \quad 0 \le \pi_{s_i}(a) \\ &\sum_{a \in A(s_j)} \pi_{s_j}(a) - \sum_{s_i \in S} \sum_{a \in A(s_j)} p_{s_i s_j}(a)\pi_{s_i}(a) = 0, \ s_j \in S \\ &B_{min}(a) \le \sum_{s_i \in S} \tau_{s_i}(a)\pi_{s_i}(a) \le B_{max}(a) \quad \forall a \in A. \end{aligned} \tag{5}$$

In (5), $\pi_{s_i a}$ are the decision variables, and the term $\tau_{s_i}(a)\pi_{s_i a}$ is effectively the steady state probability of being in state s_i when action a is chosen. The first constraint in (5) represents the balance equations and the second constraint guarantees that the sum of the steady state probabilities is one. The last constraint ensures that individual contribution of a sensor

TABLE I
WAKE UP AND RUNNING COSTS FOR SENSOR NODES

Sensor Node	n_1	n_2	n_3	n_4
Wakeup Cost	90	100	40	100
Communication Cost	25λ	130λ	250λ	150λ

TABLE II
STATE TRANSITION PROBABILITIES

Symbol	Value	Buffer states
$p_{s_i s_i}$	0.1	$i \in \{1, 2, 3, 4\}$
$p_{s_i s_j}$	$\frac{1}{\lambda}$	$i \in \{1, 2, 3, 4\}$
$p_{s_i s_{i+1}}$	$1 - 0.1 - \frac{1}{\lambda}$	$i \in \{1, 2, 3\}$

node in a buffer cannot be less than B_{min} and exceed B_{max} and thus guarantees the fairness in buffer allocation among different active sensor nodes.

IV. PERFORMANCE EVALUATION AND RESULTS

A. Parameter setting

To evaluate the performance of our proposed SMDP based model, we consider a WSVN consisting of four sensor nodes, a single relay node and mobile node. To investigate the effect of increasing number of buffer states on fairness, we divide the buffer into multiple states and observe the contribution of every sensor node. The cost incurred at the relay node is measured in terms of its energy expended, which includes the fixed wake up cost as well as a cost rate for receiving data packets from a sensor node. The wake up and communication cost rate corresponding to four sensor nodes based on their distance and channel conditions are given in Table I. The mean data arrival rate from all the sensor nodes at the relay node is λ and is modeled by Poisson distribution. The basic time parameter τ is fixed at 1 ms. Keeping in mind the expected arrival rate of mobile node, we have assumed mean time spent in each buffer state and the state transition probabilities such that resources are utilized to their maximum e.g. buffer is utilized to its maximum, data is relayed to the VN such that there is no overflowing. The values chosen are tabulated in Table III. t_{s_0} is chosen in terms of λ as the incoming data will make the transition from buffer state s_0 to any other state. To evaluate the optimality of the proposed strategy we also consider the effect on fairness due to the variation in the number of buffer states as well as sensor nodes.

B. Numerical Results

The performance of the proposed policy can be evaluated by studying the percentage buffer utilization by each sensor node and overall fairness achieved for varying states and number of sensor nodes corresponding to different values of λ.

Fig. 3 shows the percentage buffer utilization by each of the sensor nodes as a function of parameter λ for different number of states. The results show that as we increase the number of buffer states each node tries to get a fair part of the buffer for data storage even for lower values of λ. However with an increase in the number of buffer states, the overall

TABLE III
MEAN STATE TIMES, BUFFER LOWER AND UPPER BOUNDS

Symbol	Value	Symbol	Value (%)
t_{s_0}	$\frac{0.1}{\lambda}$	$B_{min}(a)$	3
τ_{s_1}	30τ	$B_{max}(1)$	25
τ_{s_2}	20τ	$B_{max}(2)$	25
τ_{s_3}	18τ	$B_{max}(3)$	33
τ_{s_4}	12τ	$B_{max}(4)$	50

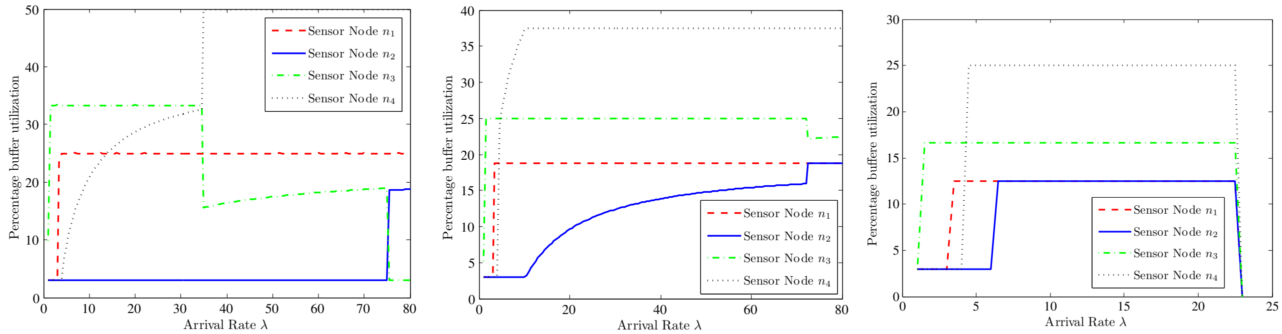
buffer occupancy decreases, which is obvious as anticipated. Increasing the number of states represent an increase in the probability of contact with vehicular nodes (VN) as well, which allow data to be delivered to VN more frequently even when the buffer is partly filled. Min-max fairness for buffer allocation as a function of number of states is shown in Fig. 4. It shows that fairness tends to increase with an increase in the number of buffer states for all λ.

To consider the effect of increasing number of sensor nodes on the fair buffer allocation of roadside relay nodes, we have also plotted fairness versus number of sensor nodes. Buffer allocation fairness as a function of number of connecting nodes is shown in Fig. 5. It also shows that SMDP based scheme tends to increase fair buffer allocation with an increase in the number of competing sensor nodes. However with the same number of connecting nodes a larger value of λ will have a lower value of fairness as a higher data rate from any sensor node will unfairly try to occupy the buffer.

Based on the results obtained it is concluded that SMDP based solution for optimal buffer management ensure each sensor node with minimum and maximum contribution in buffer storage which tends to achieve fairness. Fairness can be further improved by increasing the number of buffer states but at the expense of increased complexity and higher computation cost.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented a semi-Markov decision based fair buffer allocation policy for sensor nodes in an integrated wireless sensor and vehicular network. Our proposed model gives every sensor node a partly fair chance to transmit its data to the relay node and this fairness tends to increase with an increase in the number of states for different data arrival rate. However the power efficiency of the roadside relay node decreases with an increase in the number of buffer states. It is because of higher frequency of contact with the vehicular nodes which results in an increased wake up and communication cost. Hence there is a trade off between energy efficiency and fairness at the relay node. We have also shown that an increase in the number of nodes competing for buffer also results in an increased fair buffer allocation. The future work is to evaluate the optimal value of both of these parameters keeping in view the arrival rate of the mobile node and maximize the throughput and minimize the packet delivery delay.



(a) (b) (c)

Fig. 3. Percentage buffer utilization for each sensor node for (a) four (b) five and (c) seven buffer states.

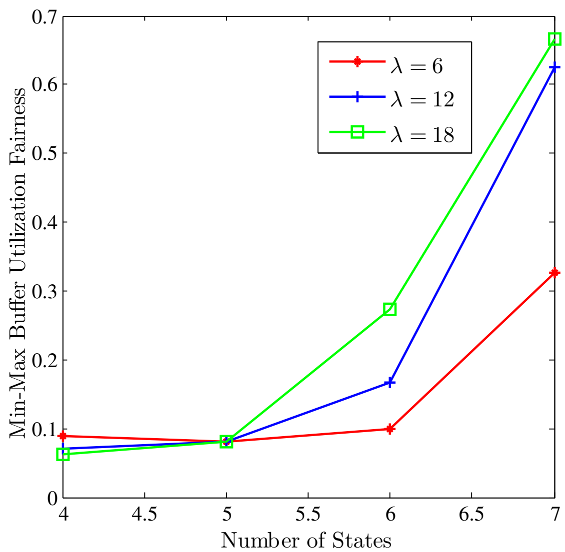


Fig. 4. Min-Max Fairness for buffer allocation as a function of number of states.

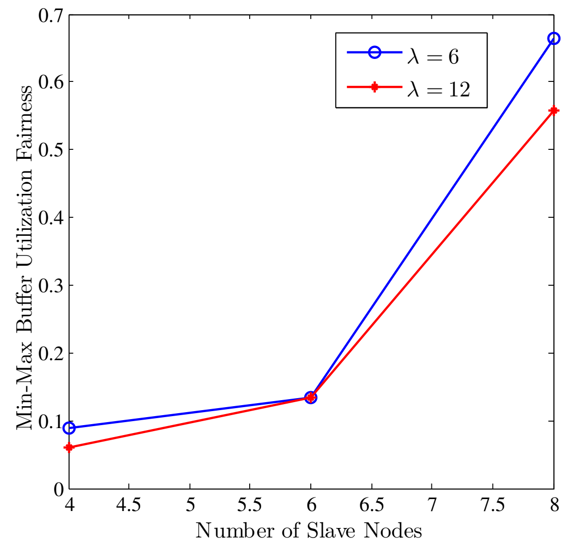


Fig. 5. Min-Max Fairness for buffer allocation as a function of number of sensor(slave) nodes.

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