Transmission manager in heterogeneous WSNs

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Abstract—The current generation of sensor networks are application-specific and exposed only to a limited set of users who need them. The new emerging IoT will run multiple applications that have diverse delay requirements for generated and received measurements. Transmission manager has been proposed for single application sensing infrastructures to get optimal transmission time for measurements with different timing requirements. In this paper, we propose a transmission manager that supports multiple applications with different timing requirements. We formulate the problem with Markov decision process and dynamically adjust transmission instances based on delay requirements of buffered packets. The results show that the proposed approach decreases the energy per bit by 47% on average while guarantee at most 7% of measurements expire before reaching the next node in the network. Under same conditions, other approaches have at most 30% expired measurements.

Index Terms—Wireless sensor network, Energy per bit, Markov Decision Process, Transmission manager

I. INTRODUCTION

The increasing deployment of Wireless Sensor Networks (WSNs) is driving towards a new generation that envisions commodity sensing & actuation infrastructure providing services. These WSNs convert physical qualities into measurements which can be used for wide-ranging spectrum of applications. The impact of such a development would be profound: the deployed WSNs will be shared among multiple applications deployed by multiple organizations. The applications running will vary in the sensors and will have diverse delay and accuracy requirements (i.e. time constraints). Consider a smart cities project that dramatically improves the quality of life of its residents by providing them detailed services with information about natural as well as man made infrastructure.

In the traditional approach, each city agency deploys its own WSNs and runs its own application although some of the sensors and parts of the physical infrastructure maybe common among applications of these agencies. This approach is costly because the ongoing maintenance of the WSNs is not shared among the organization. In contrast, in the new approach, one sensor networks can support multiple applications. The deployed sensors are able to monitor key factors such as air quality, traffic congestion, structural monitoring (e.g. impact of traffic on bridges), etc. This approach is much more economical than deploying single application running sensor network because the sensor cost as well as the deployment cost is shared among agencies. However, before this vision is realized we need to address the challenge of supporting multiple applications with a diverse set of delay tolerant requirements.

Fig. 1 describes the operation of a sensing platform which supports data collection of heterogeneous measurements in WSNs. Each sensing platform runs multiple applications that collects raw data from corresponding sensors. Applications then process this raw data to generate measurements and also includes the application-specific delay requirements for the measurement. Applications then send all these measurements to the data buffer in the transmission manager. In addition, the sensing platform also receives sequence of packets forwarded from its neighboring nodes as WSNs use multi-hop wireless links to move to the data to the sink node. Thus, the data buffer in the transmission manager has both the measurements generated by the node itself as well as the measurements received from its downstream neighbors.

Previous works in transmission manager [4][5][6] estimate optimal transmission instances based on determined local delay requirements in order to minimize energy consumption while minimize the percentage of expired measurements. The cascade time-out protocol (Cas) [4] considers a nodes distance to the sink node to decide the buffering delay.
The approach does not consider the fact that heterogeneous applications which require different timeout constraints run in WSNs. Transmission managers with single application that determine optimal transmission time of buffered measurements based on characteristic of running application are proposed by [5][6]. In contrast to above approaches, we propose transmission manager with multiple applications that determines optimal transmission instance that minimizes the percentage of measurements that are expired before reaching the next node in WSNs while minimizing the energy consumption. The proposed transmission manager achieves at most 23% less measurement expiration while decrease energy per bit measured by 47% on average.

This paper is organized as follows. In Section II, we formulate our problem based on Markov Decision Process (MDP). Experimental results are described in Section III. The results show that the proposed approach decreases the energy per bit measured by 47% on average with different measurements arrival rates while guarantee at most 7% of measurements are expired before reaching the next node in the network. Under same conditions, other approaches have at most 30% expired measurements.

II. Optimal Transmission Manager

In this section, we formulate a single node transmission manager with MDPs. We describe problem formulations and prove existence of optimal transmission time given problem formulation in Sec. II-A. The optimal criteria of the transmission is described in Sec. II-B.

A. Optimal TM

We assume that there are $M$ different types of applications running in WSNs. Parameter $b_k$ is the number of buffered measurements at time $k$ and each measurement has own time constraint based on related application. The $l = \{l_1, l_2, \ldots, l_{b_k}\}$ indexes the corresponding applications of the buffered measurements. Then, the time constraints of all buffered measurements at time $k$ can be formulated as \(\{d_{l_1}, d_{l_2}, \ldots, d_{l_{b_k}}\}\). Optimal TM checks state of the buffered measurements at every decision epoch as following rules in Fig. 2. The goal of MDP is to find optimal total cost at each step (ref. Fig. 2) with parameters in the following:

- **States** ($S = \{s_{\text{best}}, s_{\text{not}}\}$): Transmission manager (TM) checks state of measurements in data buffer at every step. When total reward at current step is the largest seen so far, its state is $s_{\text{best}}$. When total reward of current step is not the largest seen so far, its state is $s_{\text{not}}$. Each step corresponds to the distance from current decision epoch. The upper bound of steps, $N$, is the largest time constraint of buffered measurements.
- **Actions** ($A_s = \{C, Q\}$) and Reward ($r_k(\Delta_{k,i}) = y_i \cdot e^{-\Delta_{k,i}}$): The reward sum of all measurements in the data buffer is defined as total reward. $r_k(\Delta_{k,i}) = y_i \cdot e^{-\Delta_{k,i}}$ is the reward of measurement $i$ with time constraint $d_{l_i}$. The $y_i$ is the gain of measurement $i$. $\Delta_{k,i} = d_{l_i}/d_{l_i}$ represents the effect of elapsed time to the time constraint. Exponential discount function on delay can be a good indicator on the information accuracy [5]. Fig. 3 is the example of time constraints and elapsed time (i.e. $\delta_k$, the amount of time spent in the data buffer after time constraint at step $k$). Even though, TM calculates total reward at every step, it can actually receive the total reward when it decides to quit at the step as following rule of optimal stopping theorem [7]. Based on calculated total reward, TM decides whether continue (C) or quit (Q). When TM decides to continue, TM checks total reward at next step and also decides one of two actions. When TM decides quit at current step, current step become the optimal transmission time that maximize total reward.

- **Transition probability**: $P_k(s|s, a) = P_k(\bar{s}|s, a)$. This is the probability of transitioning from current state, $s$, to next state $\bar{s} \in S$ given current action, $a$. The current step is $k$. When action at step $k$ is quit (i.e. $a = Q$), TM transmits all buffered measurements and stop operation. It means that transmission probability is zero. Thus, transition probability exists only when action is continue (i.e. $a = C$). Transition probabilities for the uncontrolled system are independent of the system state [7]. Thus, $P(\bar{s}_{\text{best}}|s_{\text{not}}) = P(\bar{s}_{\text{best}}|s_{\text{best}}) = P(s_{\text{not}})$ and $P(s_{\text{not}}|s_{\text{not}}) = P(s_{\text{not}}|s_{\text{best}}) = P(s_{\text{not}})$. The probability that the next step is the optimal transmission time is $P(s_{\text{best}})$. This is described in Eq. (1). As $s_{\text{best}}$ and $s_{\text{not}}$ are mutually exclusive events, $P(s_{\text{not}}) = 1 - P(s_{\text{best}})$.

$$P_k(s_{\text{best}}) = \frac{1}{k} \quad \text{and} \quad P_k(s_{\text{not}}) = 1 - P_k(s_{\text{best}}) \quad (1)$$

We next show the existence of the optimal transmission time given the reward function which is formulated above. The optimal transmission time exists when the reward satisfies Theorem 1 [7].

**Theorem 1.** Under A1 and A2, there exists a transmission time $k^*$ such that maximize total reward, $r_*(x)$ denotes reward at any steps with delay $x$.

- **A1.** $E\{\sup_x r_*(x)\} < \infty$
- **A2.** $\lim_x \sup_{x \to \infty} r_*(x) \leq r(\infty)$ a.s.
Proposition 1. The \( r_k(\cdot) \) for all measurements at step \( k \) is bounded above.

The proof of this proposition is trivial because all components of \( r_k(x) \) are bounded above. Thus, the formulated reward function satisfying the A1 in Theorem 1.

Proposition 2. The \( r_k(\cdot) \) satisfy A2

Proof: It is obvious that \( r(\infty) = 0 \) as \( c^{-\infty} = 0 \). With the same reason, \( \lim_{x \to \infty} r(x) \to 0 \). This satisfies the equality condition. □

B. Criteria for optimal transmission time

In this subsection, we derive the optimality criteria of the transmission manager by using backward iteration approach [7]. Based on the principle of optimality, this approach starts from final step \( n \) and check optimal total reward at each step. The optimal total reward at stage \( k \), \( k < N \), can be calculated as described in Eq. (2). When \( k = N \), the \( u_N^*(s_N) = R_N(s_N) \).

\[
u_k^*(s_k) = \max \left\{ R_k(s_k), E(u_{k+1}^*(s_{k+1}), s_k) \right\}
\]

The \( R_k(s_{\text{best}}) \), \( k \leq N \) is total reward of buffered measurements at step \( k \), \( s_{\text{best}} \in S \) (ref. Eq. (3)) when TM takes 'Quit' action. As our goal is maximize total reward, we denote reward at stage \( s_{\text{not}} \) as 0. Thus, TM can decides actions based on current stage.

\[
R_k(s_{\text{best}}) = \sum_{i} r_k(\Delta_{k,i}) \text{ and } R_k(s_{\text{not}}) = 0
\]

The \( E(u_{k+1}^*(s_k), s_{k+1}) \) is the expected total reward when TM take 'Continue' action. As the stage of next step is random variable, the expectation is reasonable choice.

\[
E(u_{k+1}^*(s_k), s_{k+1}) = \sum_{j} u_{k+1}^*(s_k = s_{k}, j)P(s_{k+1} = j)
\]

Let’s calculate the optimal total reward at each step. We denote \( u_k^*(s_{\text{best}}) \) as the optimal total reward at step \( k \) when current state is \( s_{\text{best}} \). The \( u_k^*(s_{\text{not}}) \) means the optimal total reward at step \( k \) when current state is \( s_{\text{not}} \). Then, for \( k < N \), \( u_k^*(s_{\text{best}}) \) and \( u_k^*(s_{\text{not}}) \) can be calculated as described below.

\[
du_k^*(s_{\text{best}}) = \max \left\{ R_k(s_{\text{best}}), E(u_{k+1}^*(s_{\text{best}}, s_{k+1})) \right\} = \max \left\{ R_k(s_{\text{best}}), \frac{1}{k+1} u_{k+1}^*(s_{\text{best}}) + \frac{k}{k+1} u_{k+1}^*(s_{\text{not}}) \right\}
\]

where \( P(s_{\text{best}}|s_{\text{best}}) = 1/k + 1 \) and \( P(s_{\text{not}}|s_{\text{best}}) = k/k+1 \).

\[
u_k^*(s_{\text{not}}) = \max \left\{ 0, \frac{1}{k+1} u_{k+1}^*(s_{\text{best}}) + \frac{k}{k+1} u_{k+1}^*(s_{\text{not}}) \right\}
\]

Because expected total reward is always positive (i.e. \( r_k(\Delta_{k,i} \geq 0) \)), we can simplify Eq. (5) and Eq. (6) to Eq. (7).

\[
u_k^*(s_{\text{not}}) = E(u_{k+1}^*(s_{\text{best}}, S_{k+1}))
\]

Solution of Eq. (7) yield an optimality criteria of transmission manager. In state \( s_{\text{best}} \), when \( R_k(s_{\text{best}}) \geq E(u_{k+1}^*(s_{\text{best}}, S_{k+1})) \) the optimal action is to quit, when \( R_k(s_{\text{best}}) < E(u_{k+1}^*(s_{\text{best}}, S_{k+1})) \) the optimal action is to continue. In state \( s_{\text{not}} \), the optimal action is to continue.

\[
N^* = \min \{ n \geq 0 : R_k(s_{\text{best}}) \geq u_k^*(s_{\text{not}}) \}
\]

The Algorithm 1 describes the optimal transmission manager. At each decision epoch TM checks the data buffer (i.e. \( B \)) and run the algorithm (line 1). As the first step, TM selects the largest time constraint among the measurements and defines as the step size \( N \) (line 2). Optimal action at each step is stored in \( A \) and reward at each step are stored in vector \( R \) (line 3:4). Total reward at each step is calculated in lines 5-7. Algorithm use Eq. (3) for the calculation. From line 8-18, TM selects appropriate action at each step based on Eq. 7. Multiple transmission instances can be obtained. Then, it selects the minimum one as described in Eq. (8) (line 19). The computation complexity of the algorithm is \( O(N) \).

Algorithm 1: Optimal transmission manager

```
1 Input: buffer B
2 N = max time constraint in B
3 A = zeros(1,N), this is action vector
4 R = zeros(1,N)
5 for k1 to N do
6     R(k) = total reward at step k, see Eq.(3);
7 end
8 for k2 to N-1 do
9     if R(k) \in s2 then
10         A(k) \leftarrow continue;
11     end
12     if R(k) \geq R(k+1) then
13         A(k) \leftarrow quit;
14     else
15         A(k) \leftarrow continue;
16     end
17 end
18 Select optimal transmission instance: see Eq. (8)
```

After Algorithm 1 terminates, TM pushes measurements in data buffer to MAC layer at the obtained optimal transmission instance as described in Fig. 1. The additional delay at network layer is routing table look up time that takes negligible amount of time. However, we need to consider the delay at the MAC layer. MAC layer creates packet from measurements. For example, 802.15.4 attaches 18 bytes packet header and checksum to payload. The payload consists of measurements. Its maximum size is determined by protocol definition. All packets wait for the next active cycle at queue in the MAC layer, so queuing delay is an important factors to be considered. As the proposed transmission manager can operate on top of any type of MAC layer, we don’t have the types of queue in MAC layer. The information about delay at MAC layer is non-causal. Thus, transmission manager follows queuing delay at MAC layer with Little’s law [8] with \( L \), the average number of packets in the queue, and \( \lambda \), the average packet arrival rate. The \( W \) is the average queuing time of packets.

\[
W = L/\lambda
\]
When transmission manager determines optimal transmission instances, it subtracts $W$ from the determined instance to ensure application delay constraints are met.

### III. Experimental Results

In order to verify the performance of optimal transmission manager, we analyze the percentage of measurements which expire and energy per bit compared to the state of art approaches of described below. In this paper, energy per bit is the ratio of total energy consumption per measurements that meet their deadline (energy per bit (mW/bit) = total energy consumption (mW) / (measurements generated - measurements expired)).

- Fixed [4]: All nodes have fixed buffering time limit and periodically transmit all buffered packets at every buffering time limit.
- Cas [4]: The cascade time-out protocol considers the distance to the sink node to evaluate the buffering time limit. Farther node has a shorter buffering time limit. In this simulation, we set up distance to sink as 1-hop. This returns the shortest time interval between transmission instances so that return the maximum percentage of measurements which expire.
- CL [5]: The control-limit transmission manager transmits all buffered measurements when the buffer size is over the predefined threshold. The threshold is a function of measurements arrival rate and time constraints of buffered measurements. The decision epoch can be random or deterministic.
- SF [6]: The selective forwarding transmission manager calculates threshold based on available energy and importance of a measurements. The importance is an inverse function of time constraints. It sends a measurement if the measurement’s importance is larger than calculated threshold. Otherwise, SF discards the measurement.
- OT: This is the proposed approach in this paper. Algorithm 1 is used to calculate the optimal transmission instance.

We use Matlab for analysis and generate measurements based on Poisson process with different arrival rates ($\lambda$ measurements/sec). As mentioned in Sec. I data buffer stores locally generated and relayed measurements. When we consider monitoring applications, we can model locally generated measurements as constant bit rate traffic since sensors periodically generate traffic. In case of event detection applications, the generated measurements is sporadic. Thus, the probability that the measurement generation occur at a time can be modeled with Poisson process. Experimental study [9] showed that the distribution of the arrived relay measurements follows Poisson process. Thus, we use Poisson process with the average measurements arrival rate, $\lambda$, to represent arrivals both generated and relay measurements. The time unit of the simulation is a second. We vary the arrival rate from 0.1 to 2 measurements per sec. Each measurement has its own time constraints which vary based on the types of applications. For analysis, we consider three different types of scenarios where i) all applications are delay-sensitive, ii) all applications are delay tolerant and iii) both delay-sensitive and delay-tolerant applications

#### A. Power model

This paper characterizes the operations of transmission manager. Thus, we only consider energy consumption of wireless transmission. As sensing platform has limited battery capacity, we use 802.15.4 as a transmission device. We use model in [10] which characterizes the energy consumption of CC1000 @433MHz [11]. MAC layer in 802.15.4 transforms packets from measurements. Each measurement is sensor reading such as temperature or humidity. Thus, it has 1 byte size, so $n$ measurements require $n \times 1$ payload size. The maximum payload size is 117 bytes, and the size of packet header and checksum is 18 bytes. Thus, the maximum size of data packet is 133 bytes [12]. Eq. (10) shows how we calculate the energy needed to transmit a packet

$$E_T = (P_{tx} + \frac{A \times d^\alpha}{\eta}) \times t_{tx}$$

(10)

The $A$ is determined by required minimum received power for reliable data reception given SINR and characteristics of transmitting and receiving antenna. The $\eta$ is the ratio of RF output power to DC input power. We set $A$ to 0.0005 and $\eta$ as 15.7% to just as in [10]. The $\alpha$ is path-loss factor and 2 is factor for free-space model. The $t_{tx}$ is required time to transmit data packet. The speed of this device is 192 kbps. $P_{tx}$ is the transmission power consumption and it is 15.9 mW.

#### B. Result with delay tolerant applications

In this scenario, measurements are generated from delay tolerant applications. Time constraint of a measurements is between 15 and ‘max time constraint’ that varies from 15 to 35 sec in order to observe the effect of heterogeneous time constraints. For example, a measurement uniformly selects a number in [15, 35] when ‘max time constraint’ set to be 35 sec. We compare optimal transmission manager (i.e. OT) with others in terms of percentage of measurements expiring and energy consumption per bit. Fixed transmits all buffered measurements every 10 sec. Cas [4], CL [5], SF [6] and OT checks data buffer at every 3 sec.

Fig. 4a show the energy per bit normalized by Fixed. We can observe that OT consumes 25% to 33% less energy per bit than Fixed. In addition, OT decreases energy per bit while level of heterogeneity of measurements increase. This is because OT dynamically adjusts transmission instance based on time constraints of measurement. In Fig. 4b, OT shows the best performance in terms of percentage of measurements expired compared to other approaches. CL shows inconsistent performance. This is because they mainly concern buffer length which is calculated based on time constraints.

We vary arrival rate from 0.1 to 2 measurements per second and check the performance of transmission managers. Fig. 5a shows the energy per bit under different arrival rates. OT consumes at most 83% less energy per bit than all other approaches except Cas. Cas shows at most 5% better
Fig. 4: Delay tolerant applications ($\lambda = 2$)

(a) The normalized energy per bit

(b) The percentage of measurements expired

Fig. 5: When max time constraint is 15 sec ($\lambda = [0.1 \text{ to } 2]$)

performance in terms of energy per bit when $\lambda \in [0.6 \text{ to } 1]$. However, as we can observe in Fig. 5b, it has 15% more measurement expirations. Similar performances can be observed under different maximum time constraint.

C. Results in hybrid case

In this scenario, both delay sensitive and delay tolerant applications operate together. Time constraint of a measurement has a value between 1 and 'max time constraint' that varies from 15 to 35 sec in order to observe the effect of heterogeneous time constraints. Fig. 6a shows the normalized energy per bit. We can observe that OT consumes 19% to 26% less energy per bit than Fixed. Similar to Fig. 4a, performance of OT increases while the level of measurement heterogeneity increases. In Fig. 6b, OT expires at most 7% measurements out of all measurement generated. However, Other approaches have from 10% to 53% measurements lost because of expiration. Fig. 8a and Fig. 8b show the energy per

Fig. 6: When both delay sensitive and tolerant measurements exist ($\lambda = 2$)

bit and the percentage of measurements expired with the 70% delay sensitive measurements. OT consumes at most 14% less energy with around 9% measurement expirations. However, other approaches have from 42% to 70%.

D. Results with delay sensitive applications

We also evaluate the performance of transmission managers with delay sensitive applications. In this scenario, Fixed transmits all buffered measurements every 3 sec. CL, SF and OT also checks data buffer at every 1 sec. Measurements generated from delay sensitive applications have time constraints between between 4 and 'max time constraint'. Since Fixed transmits every 3 sec, we vary 'max time constraint' from from 4 to 8 sec. In Fig. 9b and Fig. 9a, OT has at most 3.5% higher measurement expirations. However, OT decrease energy per bit measured by 44% on average.

E. Compare with Fixed by varying transmission interval

We compare performance of OT and Fixed by varying time interval between transmission instances from 5 to 20 sec. We consider hybrid scenario when both delay sensitive and tolerant applications exist. Fig. 10b show the percentage of measurement expiring. Since all approaches delete a measurement from data buffer if its total delay is larger than its time constraint, measurements with longer time constraints

Fig. 7: The percentage of measurements expired when both delay sensitive and tolerant measurements exist ($\lambda = [0.1 \text{ to } 2]$)
We present the optimal transmission manager that dynamically adjusts transmission instance based on the time constraint of measurements. We find the optimal transmission time by using Markov Decision Process. Our approach do not requires complex learning algorithms to retrieve transition probability.