A Dynamic Guaranteed Time Slots Allocation Scheme In Wireless Sensor Networks

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Abstract

In this paper, we propose a novel Qos guaranteed scheme, called Dynamic GTS (Guaranteed Time Slot) allocation Algorithm, for mobile users' real-time applications in wireless sensor networks with IEEE 802.15.4 standard. The fundamental idea is that networks reserve time slots for the mobile users to access, transmission and receiving. To estimate the mobile users' movement state, an extended Kalman filter model is used. Then, we employ the proposed allocation algorithm with the predicted information to reserve resources. Simulation results show that the introduced algorithm can improve the connectivity and system reliability in mobile wireless sensor network.

Keywords: Wireless Sensor Networks; IEEE Std 802.15.4; Quality of Service; System Reliability; Mobility Prediction

1. Introduction

The progressive nature of the Information Age creates increasing demands for processed data, and the consistent fulfillment of Moore's Law produces smaller hardware devices with improved capabilities to gather and process new data. As world business becomes more mobile and computational applications become widely distributed, wireless networks bridge the gap by making distance and movement seamless. As an effective way to receive and transmit data, wireless sensor networks (WSN) are becoming increasingly attractive for a variety of application areas including industrial automation, security, weather analysis, and a broad range of military scenarios [1-3]. However, low mobility performance of traditional sensor network makes sensors could not follow the step today when more and more users and devices are equipped with vehicles or moving facilities. For instance, the fireman needs motion network to detect the lives; the scout should move to gather the information of military field. On the other hand, to balance the network energy consumption, sink must move around the network coverage area [4-6]. And with the rapid development of integrated circuit, smart-home also needs numerous wire or wireless appliances moving here and there [7]. Accordingly, the mobility supporting mechanism involving cluster handover [8], reassociation [9], resource reservation [10] and related solutions poses a great challenge to battery-supported or power-constrained wireless sensor networks.

In previous work on mobility support protocols for wireless sensor networks, researchers mostly envision the nodes are static or with low mobility. The node joining or departure activity could not be followed and preprocessed in time for the investigated network. In our paper, we focus on the MAC layer, which is likely aware of the mobility affair, and shows the current protocols are not suit for the mobile environment. Then, a protocol based on the 802.15.4[11] MAC layer is proposed with join or leaving awareness and resources reservation.

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July, 2010
We show the related works in section 2. Section 3 presents the mobility state prediction algorithm employing Kalman forecasting model and section 4 gives the resources reservation scheme in 802.15.4 networks. Simulation and testing results are given in section 5.

2. Related Works

In mobile environments the fixed schedule and frame period causes performance and worsen. In traditional MAC protocols, such as S-MAC [12], the typical contention based MAC, or LEACH [13], the representative of TDMA based cluster protocols, are both suffering performance degradation in mobile background. S-MAC introduced a low duty cycle by making the sensors active and sleep periodically. Typically, S-MAC executes the 10 seconds synchronization process once in 120 seconds. Without synchronization, nodes cannot communicate normally with others. However, if the mobile nodes miss the synchronization period, it will wait at most 110 seconds. Within this duration, the nodes may move to and join other virtual clusters thus leading to a low throughput and delivery ratio. LEACH introduces cluster head election algorithm and assigns a fixed probability to every node to be head. When clusters form, the heads allocate slots to nodes for communication. However, mobile nodes have great possibility to miss the slots allocation and become orphans due to the fixed assignment to slots.

IEEE 802.15.4 MAC specification combine CSMA/CA and TDMA access mechanisms into a superframe. It in nature has the ability to handle static and mobile nodes together. In contention period, coordinator can detect the join/departure/failure/wakeup events, whereas the static or low mobility ones can transmit or receive in contention free period. Our work has modified the 802.15.4 specification to introduce resource reservation scheme.

MS-MAC [14] is designed based on S-MAC for supporting mobility events. It increases the synchronization frequency within the virtual clusters which the mobile nodes will pass through. Thus, the mobile ones would not wait a long time to join the cluster for communication. MAC [15] inherits the TRAMA [16] superframe structure and handles the mobility by dynamic adjusting the ratio of contention period length to contention free period. When mobility extent increases, more contention time is required to give chances for nodes detecting. On the contrary, most time would be used for low mobility or static ones as slots.

3. Kalman Filter Prediction Model

Kalman filter has various applications in tracking and location area. Besides, it is also used in many areas involving military field for its reliability. Its essence is to search the minimum mean square error of $S_i$ with $m$ observed value $z_1, z_2, \ldots, z_m$, $m \geq 1$. The state for moment $n$ in our scheme is:

$$\mathbf{s}(n) = [x(n), \dot{x}(n), \ddot{x}(n), y(n), \dot{y}(n), \ddot{y}(n)]^T$$

(1)

where $x(n), y(n)$ is the value of mobile nodes in Descartes coordinates; $\dot{x}(n), \ddot{x}(n)$ and $\dot{y}(n), \ddot{y}(n)$ is the speed and acceleration vector respectively. Observed value $p_{n,i}$ is the RSS (Received Signal Strength) of moment $n$ from the $i$-th Coordinator at $(a, b)$ and the unit of $p_{n,i}$ is dBm. After duration $t$, mobile nodes’ state transforms from $\mathbf{s}(n)$ to $\mathbf{s}(n+1)$ and the process equation can be expressed as:

$$\mathbf{s}(n+1) = \mathbf{F}s(n) + \mathbf{u}(n) + \mathbf{G}w(n)$$

(2)

where

$$
\mathbf{F} = \begin{bmatrix}
1 & t & 0 & 0 & 0 & 0 \\
0 & 1 & t & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & t & 0 \\
0 & 0 & 0 & 0 & 1 & t \\
0 & 0 & 0 & 0 & 0 & 1 
\end{bmatrix}
$$

(3)
and $\mathbf{u}(n)$ is the acceleration value from acceleration sensor embedded in nodes. The vector $\mathbf{u}(n)$ is

$$\mathbf{u}(n) = [0 \quad 0 \quad a_x(n) \quad 0 \quad a_y(n)]^T$$

and $G$ is the Kalman gain matrix. $\mathbf{v}_i(n)$ is the innovations process of acceleration and can be expressed as:

$$\mathbf{v}_i(n) = [0 \quad 0 \quad v_x(n) \quad 0 \quad v_y(n)]^T$$

With the distance increase, the signal strength decrease pro rata. So the distance between mobile nodes and the i-th coordinator is indicated by $p_{n,i}$. The mapping relationship between $p_{n,i}$ and $d_i$ under logarithmic-normality channel model is

$$p_{n,i} = p_{ref} - 10n \log d_{n,i} + \psi_{n,i}$$

where $p_{ref}$ is the referenced RSS value when $d_{n,i} = 1m$; $n$ is the channel attenuation indication; $\psi_{n,i}$ is the stationary white Gaussian noise with mean 0 and variance $\sigma^2_{\psi}$. The mapping relationship between $d_{n,i}$ and mobile nodes’ coordinate $x(n), y(n)$ is:

$$d_{n,i} = \sqrt{(x(n) - a_i)_i^2 + (y(n) - b)_j^2}$$

For determine the mobility state of nodes, at least 3 independent observed values are required [17]. Then the observed value at moment $n$ is:

$$\mathbf{z}(n) = (p_{n,1}, p_{n,2}, p_{n,3})^T$$

Considering equation (6), (7), (8) together, we can get the observation equation as:

$$\mathbf{z}(n) = h(\mathbf{s}(n)) + \mathbf{v}_2(n)$$

$$h(\mathbf{s}(n)) = p_{ref}[1 \quad 1 \quad 1]^T - 10n \log(d(n))$$

$$\mathbf{v}_2(n) = [\psi_{n,1} \quad \psi_{n,2} \quad \psi_{n,3}]^T$$

$$\mathbf{d}(n) = [d_{n,1} \quad d_{n,2} \quad d_{n,3}]^T$$

Making the nonlinear observation equation linearized, then we can deduce the linear observation equation as:

$$\mathbf{H}(n) = \begin{bmatrix}
-10n & 0 & 0 \\
0 & -10n & 0 \\
0 & 0 & -10n \\
\end{bmatrix}
\begin{bmatrix}
[x(n) - a_i]_i \\
[y(n) - b_j]_j \\
[y(n) - b_j]_j \\
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
0 \\
\end{bmatrix}$$

For the initial condition: $\mathbf{s}(0, -1) = 0, \mathbf{M}(0, -1) = \mathbf{I}_o$, we can predict the mobility state with Kalman filter algorithm [18]. The detailed steps are showed in (14).

$$\mathbf{G}(n) = \mathbf{M}(n, n-1)\mathbf{H}^T(n)[\mathbf{H}(n)\mathbf{M}(n, n-1)\mathbf{H}^T(n) + \mathbf{Q}_e(n)]^{-1}$$

$$\dot{\mathbf{s}}(n, n) = \mathbf{s}(n, n-1) + \mathbf{G}(n)[\mathbf{z}(n) - h(\mathbf{s}(n, n-1))]$$

$$\mathbf{s}(n+1, n) = \mathbf{F}s(n, n)$$

$$\mathbf{M}(n, n) = [\mathbf{I}_e - \mathbf{G}(n)\mathbf{C}(n)]\mathbf{M}(n, n-1)$$

$$\mathbf{M}(n + 1, n) = \mathbf{F}(n + 1, n)\mathbf{M}(n, n)\mathbf{F}^T(n + 1, n) + \mathbf{Q}_e(n)$$
In (14), $\hat{s}(n, n-1)$ indicates the predicted result of moment $n$ using the observed value before $n$; $\hat{s}(n, n)$ denotes the state filter prediction of observed values before $n$ at moment $n$; $M(n, n-1)$ is the error correlation matrix of $\hat{s}(n, n-1)$; $M(n, n)$ is the error correlation matrix of $\hat{s}(n, n)$; $G(n)$ is the Kalman gain matrix at moment $n$; $Q_1(n)$ is the correlation matrix of process noise $v_1(n)$; $Q_2(n)$ is the correlation matrix of measurement noise $v_2(n)$.

With the obtained one-step prediction of mobility state, we can guarantee the connectivity by reserve slots for the mobile nodes.

4. Guaranteed Time Slot Dynamic Allocation Scheme

4.1. GTS Mechanism in IEEE 802.15.4

The GTS management mainly involves the allocation, utilization and retrieval procedures [11]. The process of GTS allocation is: firstly, users send out association request to coordinator; Secondly, if the association and utilization request is successful, then coordinator sends back the packet with allocated time slot, including start time, end time etc., Nodes can immediately transmit or receive packets during the allocated slots as soon as allocation is completed. And then, when the utilization procedure is finished, coordinator begins to retrieve the time slots. The retrieve process can be classified as active or passive, namely actively abandon the time slot or passively be withdrawn by the coordinators.

4.2. Proposed GTS Allocation Scheme Based on Resource Reservation

From previous description of GTS mechanism, we can conclude that GTS can guarantee the nodes’ delay constraint and connectivity. But the GTS scheme itself introduces additional delay during time slots request, allocation and retrieval and it is intolerant for real-time service especially when a node moves from one PAN to another. In such case, the node should reassociate with the coordinator of new PAN and request GTS leading to longer delay and worse QoS. In our solution, we reserve GTS at the predicted coordinator for the coming nodes in advance to reduce the total delay. When nodes move to the predicted position, they can immediate use the reserved slots within the range of the anticipated PAN. Therefore, additional delay brought by GTS management is decreased and the network connectivity and service QoS can be guaranteed.

The topology discussed in this paper adopts the Cluster Tree structure defined in IEEE 802.15.4 standard. Figure 1 depicts the detailed topology structure. The coverage range of all PANs are the same and the position of every coordinator is known. Every PAN has a unique ID for identification. PAN coordinators take charge of beacon broadcast and PAN maintenance. Communication between different PANS is supervised by gateway.

![Fig.1 Cluster Tree Structure](image)

![Fig.2 Pseudocode of GTS Reservation Scheme](image)

If $$(x_{\text{predict}} - a_{\text{current}})^2 + (y_{\text{predict}} - b_{\text{current}})^2 > R_c^2$$

&

$$(x_{\text{predict}} - a_{\text{current neighbor}})^2 + (y_{\text{predict}} - b_{\text{current neighbor}})^2 < R_c^2$$

Then

Request neighbor PAN Coordinator to reserve resource for mobile user
Fig. 3 GAINZ

The detailed steps for GTS allocation in our scheme is:

**Step1. Network initialization stage:** PAN coordinator chooses an unique ID and broadcasts beacons for network establishment. Any node receiving beacons from different coordinators at the same moment will be tagged as the alternative gateway node, and the one with the smallest 64bits IEEE address will be considered as the gateway by coordinators. All PAN coordinators determine the position of their own and neighbors using gateway.

**Step2. Nodes access stage:** After nodes access to the network, they apply for the GTS according to the mechanism described before.

**Step3. Nodes mobility tracking and prediction:** With the Kalman filter prediction model described in section II, we can track the mobile nodes and give the predicted position. When the position information indicates that the node has already moved to another PAN, the current associated PAN will inform the target PAN to reserve time slots for the coming node. The pseudocode of described scheme above is shown in figure 2.

**Step4. Nodes mobility support:** If there are buffered packets in the former associated PAN when nodes enter into a new PAN, the former coordinator would forward those packets to the new one.

5. Simulation

5.1. Testbed Parameters Set and Performance Evaluation

Our testbed employs the GAINZ sensor nodes made by Chinese Academy of Sciences. As figure 3 indicates, GAINZ use CC2420 as RF chip and Atmega128L as MCU.

Simulation parameters are denoted in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 symbol/μs</td>
<td>16</td>
<td>Duty cycle</td>
<td>0.25</td>
</tr>
<tr>
<td>Super frame (symbols)</td>
<td>60×16</td>
<td>PPDU (Bytes)</td>
<td>100</td>
</tr>
<tr>
<td>SO</td>
<td>2</td>
<td>Transmitting power (dBm)</td>
<td>-5</td>
</tr>
<tr>
<td>BO</td>
<td>4</td>
<td>Simulation area (m²)</td>
<td>200×200</td>
</tr>
<tr>
<td>SD (symbols)</td>
<td>3840</td>
<td>Nodes number</td>
<td>50</td>
</tr>
<tr>
<td>BI (symbols)</td>
<td>15360</td>
<td>PAN number</td>
<td>10</td>
</tr>
<tr>
<td>Simulation time(s)</td>
<td>300</td>
<td>PAN radius (m)</td>
<td>20</td>
</tr>
</tbody>
</table>

When the mobile node first connects to the network, the source traffic generation rate is 4 packets/s, 2 packets/s, 1 packets/s respectively for different simulation scenarios. The mobile node is put on a remote control vehicle and the moving speed is 2km/h, 5km/h, 10km/h, 15km/h respectively for different simulation scenarios. The performance evaluation parameters include packets delivery ratio, packets transmission average delay, and average delay jitter.

5.2. Simulation Results

As is shown in Figure 4, the delivery ratio under static GTS allocation scheme becomes worse as the moving speed and source data rate increase. The reason behind it is that the users should at least wait for 3 BI when they move to a new PAN thus leading to a lower delivery ratio. Another reason is that the
intermediate nodes’ buffers overflow during the reassociation period resulting in large packets drop. If the speed increases further, the delivery ration will drop quickly due to frequently switch among different PANS. Figure 5 depicts that delivery ratio has been improved when dynamic GTS allocation scheme, namely Kalman filter user position prediction scheme, is employed. Figure 6 show that the static GTS allocation introduces larger jitter because the packets are intermittently transmitted to the destination due to mobility. Besides, delay jitter is highly increased when source data rate grows continuously. In Figure 7, resource reservation scheme presents better performance if packets can be forwarded to the destination uninterrupted and network connectivity is satisfactory. Figure 8 gives the evidence that dynamic GTS allocation and resource reservation can better satisfy users’ inquiry at medium moving speed.

Figure 4 depicts that delivery ratio has been improved when dynamic GTS allocation scheme, namely Kalman filter user position prediction scheme, is employed. Figure 6 shows that the static GTS allocation introduces larger jitter because the packets are intermittently transmitted to the destination due to mobility. Besides, delay jitter is highly increased when source data rate grows continuously. In Figure 7, resource reservation scheme presents better performance if packets can be forwarded to the destination uninterrupted and network connectivity is satisfactory. Figure 8 gives the evidence that dynamic GTS allocation and resource reservation can better satisfy users’ inquiry at medium moving speed.

Acknowledgement

This work is Supported by the Fundamental Research Funds for the Central Universities(JY10000901023, JY10000901002), the Key Program of the National Natural Science Foundation of China (60832005), the National Natural Science Foundation of China (60803151, 60962001,
References

[17] Z. R. Zaidi, B. L. Mark, Real-Time Mobility Tracking Algorithms for Cellular Networks Based on Kalman Filtering, IEEE transactions on Mobile computing, 2005