International Journal of Control and Automation
Vol.8, No.11 (2015), pp.157-168
http://dx.doi.org/10.14257/ijca.2015.8.11.16

Intelligent Conversion Method of Wireless Sensor Network Node of High Efficiency and Energy Saving

Huaping. Zhou, Shaojuan Wang and Jingzhao Li

Faculty of Computer Science & Engineering Anhui University of Science and Technology, HuaiNan, China
hpzhou@aust.edu.cn, 1115801059@qq.com, jzhli@aust.edu.cn

Abstract

Energy efficiency is the primary goal of wireless sensor network. An energy conversion model in wireless sensor network node's different state is established by an analysis of energy consumption of wireless sensor network, node composition and working state, considering the wireless sensor network node's working condition and the other nodes' data acquisition, transmission and other factors within the wireless sensor network. Optimized Kalman filtering is used for estimating the event information to be transmitted. We can obtain the more accurate distance between the nodes by using the maximum likelihood estimation. Also we can derive the time value of uncertain events occurring in the wireless sensor network by using fuzzy predictor according to the distance between nodes and the amount of information to be transmitted. Then the wireless sensor nodes state transition can be controlled intelligently through combining its occurrence with the time value of deterministic event nodes and the input signal of the nodes. Simulation and experimental results show that energy-saving effect is very obvious by this state conversion strategy of energy saving for a large data quantity and data frequent acquisition.

Keywords: *energy efficiency, wireless sensor network, node state transition, time of events occurrence*

1. Introduction

The wireless sensor network by self-organizing mode, made up of micro sensor nodes which have the ability of perceptual, computing and communication, can monitor the targets and collect the information of the environment through the cooperation of large amount of sensors. And the information is processed in order to obtain detailed and accurate data then transmitted to users who need them [1]. At present, the sensor nodes are powered by batteries. Usually, nodes limited energy in consumption cannot be timely supplement because of wireless sensor network application environment and the large number of nodes [2]. In view of the characteristics of wireless sensor network, how to save energy and balance the node energy becomes one of the main research directions of wireless sensor network.

2. Analysis of Energy Consumption of Wireless Sensor Nodes

The energy consumption module of sensor node is made up of wireless communication module, processing module, memory module and sensor module. With the development of IC technology, energy consumption of processor, memory and sensor module is lower; therefore most of the energy consumption of wireless sensor nodes is consumed in a wireless communication module [3]. Usually, the energy of transmission of 1B information needed in the 100m is roughly equivalent to execute 3000 instructions for computing [4].

ISSN: 2005-4297 IJCA

In wireless sensor networks, although there are energy consumptions of conflicts, control message overhead, idle listening, load fluctuation, inappropriate transmission and data redundancy, the main energy consumption is caused by inappropriate working state of the node [5]. A key problem is that nodes into sleep state to meet what conditions will save more energy than to maintain a normal state.

Recently, the domestic and foreign research on energy consumption of wireless sensor nodes is more. The main research is mostly based on dynamic energy management [6] and dynamic voltage scaling technique for node [7], rarely from overall energy of state of the module nodes cooperative work.

By studying the nodes and their overall status in this article, we do an in-depth analysis of the wireless sensor node's state transition. Optimized Kalman filtering is used for obtaining the event information to be transmitted. We can obtain the distance between the nodes by using the maximum likelihood estimation. Also we can derive the time value of uncertain events occurring in the wireless sensor network by using fuzzy predictor according to the distance between nodes and the amount of information to be transmitted. Then the wireless sensor nodes state transition can be controlled through combining its occurrence with the time value of deterministic event nodes and the input signal of the nodes. For the purpose of high efficiency and energy saving, we need to do intelligent handover for wireless sensor nodes so that it always works in the best state.

3. Analysis of Working Mode and Overall State of Wireless Sensor Nodes

3.1. The Working Mode of RF Communication Module

The Radio Frequency communication module of wireless sensor nodes has six working modes, respectively as follows:

1) Shutdown mode, the relative value of power consumption is 1
2) Sleep mode, the relative value of power consumption is 103
3) Idle mode, the relative value of power consumption is 5* 104
4) Listening mode, the relative value of power consumption is 106
5) Sending mode, the relative value of power consumption is 106
6) Receiving mode, the relative value of power consumption is 106

The power consumption of after three modes is no difference. In some RF modules, the power consumption of sending mode is slightly larger than receiving mode [8-9] .However, in some RF modules the power consumption of receiving mode is slightly larger than sending mode, the listening mode is slightly less than the sending or receiving mode, but the difference is not large. These three modes can be boiled down to an order of magnitude here.

3.2. The Working Mode of Microprocessor Module

The microprocessor module of wireless sensor nodes has three working modes, respectively as follows:

1) Sleep mode, the relative value of power consumption is 1
2) Idle mode, the relative value of power consumption is 30
3) Run mode, the relative value of power consumption is 5*104

3.3. The Working Mode of Sensor Module

The sensor module of wireless sensor nodes has two working modes, respectively as follows:

1) Shutdown mode, the relative value of power consumption is 1
2) Work mode, the relative value of power consumption is 2*103

3.4. The Working Mode of Memory Module

The memory module of wireless sensor nodes has three working modes, respectively as follows:

1) Sleep mode, the relative value of power consumption is 1
2) Idle mode, the relative value of power consumption is 20
3) Activity mode, the relative value of power consumption is 104

3.5. The Overall Working State of Node

The four modules work together, and there are nine overall working states of wireless sensor network node. Table 1 show corresponding relation between the four modules work modes and nine kinds of working state.

Table 1. Overall Working State of Wireless Sensor Network Node

The overall working state	The RF communication module	The microprocessor module	The memory module	The sensor module	power consumption
S0	send-receive	run	Activity	Work	high
S1	receive	run	Idle	Work	high
S2	idle	run	Idle	Work	high
S3	receive	idle	Idle	Work	high
S4	listen	idle	Sleep	Sleep	high
S5	sleep	work	Sleep	Work	lower
S6	sleep	sleep	Sleep	Work	low
S7	sleep	sleep	Sleep	Shutdown	very low
S8	shutdown	sleep	Sleep	Shutdown	very low

4. Analysis of Switching Time of Node Working State

It takes time and energy to switch wireless sensor network node state. The more deep the node is in the sleep state, the more time and the more energy consume [9]the node is wakened up and returned to full work state or other shallow sleep state required.
The assumption that nodes were working in the high energy state of the work, and the consumption of the energy is Ph. We need to switch the power consumption from high state to low state of Pl in the period t0.

If in the time t1 (t1>t0) the wireless sensor network nodes are in work state and events occurrence, the node has been in high energy consumption state and the total energy consumption is shown in formula (1):

$$Eh=Ph(t1-t0) \tag{1}$$

If the node transform time is τ c1 from the high energy state to a low energy state in the wireless sensor network, the total energy consumption in this time is required shown in formula (2):

$$\begin{aligned} El &= 0.5\tau c1(Ph+Pl)+(t1-t0-\tau c1)Pl \\ &= 0.5\tau c1Ph+ (t1-t0-0.5\tau c1)Pl \end{aligned} \tag{2}$$

Save energy for the switch process is shown in formula (3):

$$Es=Eh-El= (t1-t0-0.5\tau c1)(Ph-Pl) \tag{3}$$

Now the question is: when the event needs processing, wireless sensor nodes need to convert back to the high energy state to complete the event processing from the low consumption.

Assuming that the time of a state transition back to the high energy consumption state from the low is τ c2, and the average energy consumption is 0.5 (Ph+Pl), extra energy consumption it needs is shown in formula (4):

$$Ee=0.5\tau c2(Ph+Pl) \quad (4)$$

Obviously, in order to save energy consumption of wireless sensor network nodes from a high energy consumption state to a low energy consumption state, it must be satisfied:

$$Es-Ee>0$$

Mean:

$$(t1-t0-0.5\tau c1)(Ph-Pl)- 0.5\tau c2 (Ph+Pl)>0 \quad (5)$$

Thus can get formula (6):

$$Tmin=t1-t0>0.5\tau c1+0.5\tau c2(Ph+Pl)/(Ph-Pl) \quad (6)$$

That is the minimum time interval between the occurrence of the next event in the state transition. Obviously the longer time interval is more energy saving.

From the above, whether the state transition of wireless sensor nodes based on energy saving can really save energy and be really energy-efficient is related with the parameters of next events' occurrence time. Some of these events have a deterministic time, such as the event that node performs its own sensor data acquisition; some events have uncertain time characteristics such as the event, the node as the other relay nodes to transmit other nodes' flow. Thus it is difficult to determine the occurrence time by forwarding node itself for the latter part. Therefore, in order to save the energy consumption and make the wireless sensor network node in the optimal operating mode, we need to estimate the occurrence time on the uncertainty event. The simulation results and experimental analysis, the occurrence time of the uncertainty is mainly composed of the distance between a wireless sensor network node and its perceived node and the amount of event transmission information. Optimized Kalman filtering is used for obtaining the event information to be transmitted. We can get the distance between the nodes by using the maximum likelihood estimation. Also we can derive the time value of uncertain events occurrence in the wireless sensor network by using fuzzy predictor. Then the wireless sensor nodes state transition can be controlled through combining its occurrence with the time value of deterministic event nodes and the input signal of the nodes.

5. Analysis of Distance between Nodes Based on Maximum Likelihood Estimation

Theory analysis and experiment show that, effected by many factors [11] like the dielectric coefficient around the wireless sensor network space, reflection coefficient of the environment, and electromagnetic wave transmission effects, the formula for calculating the distance between the wireless network nodes based on the sending and receiving signal strength is shown as formula (7):

$$d = A\times 10^{\frac{(C-q)}{10n}} + B \quad (7)$$

In formula (7), RF parameter C is defined as the absolute value [12] of the average energy from the transmitter 1 meters indicated by dBm; propagation factor or transmission coefficient n related with network environment reflects the rate of the signal energy decays with increasing distance to the transceiver; q, measured by experiment in the actual environment, is the signal intensity for the node received power.

By formula (7) we can get the distance between nodes. In many cases we need to get the precision distance value. Taking the distances between the nodes as input, RSSI distance algorithm based on maximum likelihood estimation is established.

We make a hypothesis that there are i nodes in communication radius of analyzed nodes, their coordinates (xi, yi, zi).The distance between the analysis node (x0, y0, z0) and the other node is recorded as di obtained by RSSI algorithm. The measurement error of each distance is recorded as edi, and then you can set up equations shown in formula (8):

$$\begin{cases} e_{d1} = d_1 - ((x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2)^{1/2} \\ e_{d2} = d_2 - ((x_2 - x_0)^2 + (y_2 - y_0)^2 + (z_2 - z_0)^2)^{1/2} \\ \cdots \\ e_{dn} = d_n - ((x_n - x_0)^2 + (y_n - y_0)^2 + (z_n - z_0)^2)^{1/2} \end{cases} \tag{8}$$

Then we need to be a coordinate (x0, y0, z0) so that the sum of error edi in the equation is the minimum shown in formula (9):

$$E(x_0, y_0, z_0) = \min(\sum_{i=1}^{n} e_{di}) \tag{9}$$

Generally, the estimated value of the (x0, y0, z0) is denoted as (x'0, y'0, z'0), and the deviation of estimated value and the true value is denoted as $(\Delta x_0, \Delta y_0, \Delta z_0)$. Similarly, the true value of the distance is di, estimated value is d'i, and deviation is Δd_i. Formula (8) is a nonlinear equation set. We can obtain the linear equations set shown in formula (10) by Taylor series:

$$\begin{cases} d'_1 = a_{x1}x_0 + a_{y1}y_0 + a_{z1}z_0 - e_{d1} \\ d'_2 = a_{x2}x_0 + a_{y2}y_0 + a_{z2}z_0 - e_{d2} \\ \cdots\cdots \\ d'_n = a_{xn}x_0 + a_{yn}y_0 + a_{zn}z_0 - e_{dn} \end{cases} \tag{10}$$

$$D' = [(d'_1)^2 + (d'_2)^2 + \ldots + (d'_n)^2]^{1/2} \tag{11}$$

Set certain deviation accuracy and execute iterative computation, estimated value D' can be obtained in the node and the average distance around the nodes.

6. Event Information amount Estimation Based on Kalman Filtering

Kalman filtering algorithm is a kind of optimal auto regression data processing algorithm. That algorithm take the minimum mean square error as the convergence conditions, use many times measuring to minimize system noise, and make use of a state estimation of a system and the observed value of the current system state to update the current system state so as to obtain the optimal estimation[10].

The author try to obtain the more accurate event information monitoring method by the RSSI to estimate event information and establish the monitoring event information model based on the Kalman filtering.

Establish the system state equation according to the event information as follows:

$$Q(k+1) = A(k)x(k) + \omega(k) \tag{12}$$

In formula (12): Q (k) is the event information; A (k) is the system matrix. The observation equation system is shown in formula (13):

$$s(k) = H(k)Q(k) + \upsilon(k) \tag{13}$$

Formula (13): $s(k)=[s_k^x,s_k^y,s_k^z]^T$ is the observation equation system. H (k) is the state matrix.

ω (k), V (k) in formula (12) and (13) respectively is the system noise and observation noise and both obey the Gauss white noise of Gauss distribution.

$$\omega(k)=[w_k^x,w_k^x,w_k^x]^T;\omega(k)\in N(0,J)$$

$$Covar[\omega(k)]=E[\omega(k).\omega(k)^T]=J$$

$$\upsilon(k)=[v_k^x,v_k^x,v_k^x]^T;\upsilon(k)\in N(0,R)$$

$$Covar[\upsilon(k)]=E[\upsilon(k).\upsilon(k)^T]=R$$

The covariance of ω (k), V (k) is J and R, and we assume that w (k), V (k) does not vary with the system state change. For a linear stochastic differential system which meets the above conditions, process and measurement are both Gauss white noise. Kalman filtering is the optimal information processor. We combine covariance of ω (k), V (k) to estimate the optimal output.

Kalman filtering algorithm is divided into prediction and correction process .Prediction equations are shown in formula (14):

$$\begin{cases}Q'(k|k-1)=A(k-1)Q'(k-1|k-1)\\P(k|k-1)=A(k-1)P(k-1|k-1)A^T(k-1)+J\end{cases}\tag{14}$$

State correction equation is shown in formula (15):

$$\begin{cases}K(k)=P(k|k-1)H^T(k)[H(k)P(k|k-1)H^T(k)+R]^{-1}\\Q'(k)=Q'(k|k-1)+K(k)[s(k)-H(k)Q'(k|k-1)]\\P(k)=[I-K(k)H(k)]P(k|k-1)\end{cases}\tag{15}$$

Among them, P is the covariance error matrix of the system; K is kalman gain and is also known as the correction matrix, which corrects the state of the system. I am a unit matrix.

But in the process of calculation error will be considered repeatedly, so the original data will have an impact on the current data, and even lead to the algorithm misconvergence. In order to mitigate this effect, the author proposes an adaptive Kalman filtering of optimization function, which improves the above conventional Kalman filtering, and introduce "forgetting" factor during the prediction so that "forget" "the past" data to avoid the error of the algorithm because of data redundancy. The prediction process equation (14) is modified as shown in formula (16).

$$\begin{cases}Q'(k|k-1)=A(k-1)Q'(k-1|k-1)\\P(k|k-1)=\lambda(k)\cdot A(k-1)P(k-1|k-1)A^T(k-1)+J\end{cases}\tag{16}$$

In formula (16), λ(k) is forgetting factor. λ(k) is a number not less than 1. Generally it increases with the increase of the system error because the system error is larger, the effect of cumulative error on the system is earlier. So in the filter more data should be "forgotten". A forgetting factor is introduced to higher filtering accuracy, and makes the filter error not increase with the error accumulation.

Put the unknown node location estimation as system state initial conditions, and iterate the prediction and correction. Preset accuracy ε, when they meet the following conditions:

$$\sqrt{Q'^2(k)+Q'^2(k|k-1)}\le\varepsilon$$

End of iteration, we can get more precise event information Q '.

7. Input Signals and State Transition of Wireless Sensor Network Node

Two dimensional structure is adopted to predict fuzzily the occurrence time of uncertain events in the sensor network. Two inputs are respectively the average distance of D ' between the analyze node and the around nodes and event information Q'. The output of fuzzy predictor is the predict time T to the next event. Fuzzy set of D ', Q' and T is {PZ (zero) PS (positively small) PM (positively median) PB (positively large) PV (positively great)}.

The domain D 'and Q' s takes as {0, +1, +2, +3 , +4, +5, +6}

The domain T takes as {0,+1,+2,+3,+4} = {Ta,Tb,Tc,Td,Te}

The membership functions of D’,Q' and T are all triangle. Membership function of D’ is shown in figure1 a). Membership function of Q’ is asymmetric, as shown in Figure 1 b). The membership function of T is shown in Figure 1 c).

According to the experiment and experience, fuzzy control rules of D ', Q' and T are shown in Table 2.

The fuzzy control rules in table 2 can get fuzzy control table of D ', Q' and T by fuzzy set operation and min-max- method of center of gravity defuzzification.

According to the rule of fuzzy set operation control quantity of the first statement is shown in formula (17):

$$T_1 = D'\circ\left[\left(NBD'\times NBT\right)\right]\cap Q'\circ[(NBD'\cup NSQ')\times NBT] \tag{17}$$

In formula (17), the " $\circ$ ", " $\cup$ ", " $\times$ ", " $\cap$ " expresses respectively four kinds of operations: synthesis, union, Cartesian product and intersection.

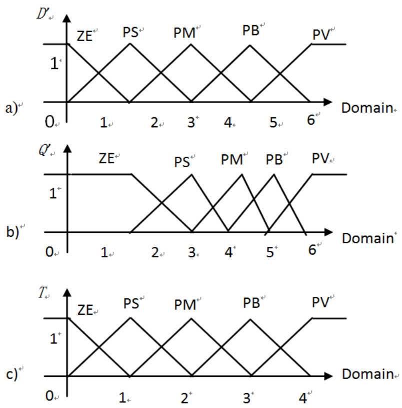

Figure 1. Membership Function of D, Q and T’

In fact, the membership functions of D 'and Q' are zero in addition to 1, so the type (17) can be simplified as:

$$T_1 = \min_x\{\mu_{NBD'}(i);\max[\mu_{NBQ'}(j),\mu_{NSQ'}(j)];\mu_{NBT}(x)\} \tag{18}$$

In formula (18), $\mu_{NBD'}(i)$ is the membership of the ith elements in fuzzy set NBD '.

Similarly, we can calculate other events time by the rest of the various statements, and then get the fuzzy set T of event time value. The events control table can be got by using min-max- method of center of gravity defuzzification.

8. Input Signals and State Transition of Wireless Sensor Network Node

Table 2. The Fuzzy Control Rules Of D ',Q', And T

D' \ Q'	PZ	PS	PM	PB	PV
PZ	PZ	PZ	PZ	PS	PS
PS	PZ	PS	PS	PM	PM
PM	PS	PS	PM	PB	PB
PB	PM	PM	PB	PV	PV
PV	PB	PB	PV	PV	PV

8.1. Node Input Signal

Based on the analysis of wireless sensor nodes, the input signal is as follows:
CPU control off the crystal oscillator I0
CPU control on the crystal oscillator I1
CPU control off the RF communication I2
CPU control on the RF transmission I3
CPU control on the RF receiver I4
CPU control on the RF listeners I5
CPU control off the RF listeners I6
CPU control on sensor data acquisition I7
CPU control off sensor data acquisition I8
CPU sleep command I9
RF data sent command I10
RF transmit buffer capacity little I11
RF receiver command I12
RF receiver waiting buffer overflow I13
CPU timer start I14
CPU external interrupt response I15
Send node packet incident response I16
Unexpected events sensor trigger I17
Node data packets received incident response I18
RF data receiving end signal I19
CPU timer overflow I20

8.2. Node State Transition

The overall state, State signals= {S0, S1,... S8},of wireless sensor node's conversion mainly depends on the event triggering signals Input_signals= {I0, I1,... I20} of cooperative work between each module in nodes and event time signal, Time_signals= {Ta, Tb,... Te}, of transmitting the sensor data intra node and inter node.

According to the composition, operation principle of wireless sensor nodes, the transition relation is shown in Figure 2.

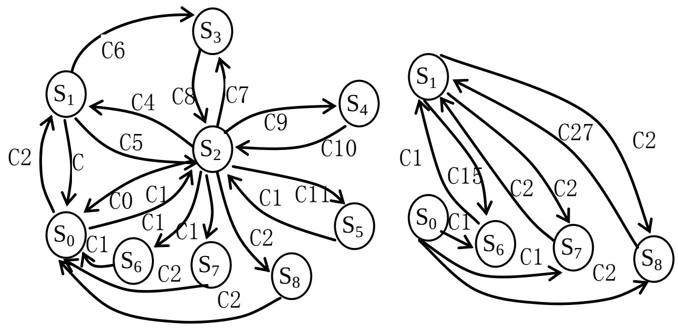

Figure 2. State Diagram Conversion Relationship of Wireless Sensor Node

State transition conditions between the nodes are as follows:

S2→S0：C0= I3∪I4∪I14∪I18

S0→S2：C1= (I3∪I4∪I14∪I18)∩ Ta

S0→S1：C2= I4∪I12∪I13∪I18

S1→S0：C3= I3∪I16

S2→S1：C4= (I4∪I12∪I13∪I18)∩ (not) I20

S1→S2：C5= (I2∪I19)∩ Ta
S1→S3：C6= I20

S2→S3：C7= (I4∪I12∪I13∪I18)∩I20

S3→S2：C8= I2∪I19
S2→S4：C9= I5
S4→S2：C10= I6

S2→S5：C11= I2∩I14∩ Tb
S5→S2：C12= I15

S2→S6：C13= I2∩I6∩I9∩ Tc

S0→S6：C14= (I2∪I10∪I11)∩I7∩I17∩ Tc

S1→S6：C15= (I3∪I16)∩I7∩I17∩ Tc

S6→S0：C16= I3∪I4∪I16

S6→S1：C17= I4∪I12∪I13∪I18

S2→S7：C18= I2∩I6∩I9∩ Td

S0→S7：C19= (I2∪I10∪I11)∩Td

S1→S7：C20= (I3∪I16)∩Td

S7→S0：C21= I3∪I4∪I16

S7→S1：C22= I4∪I12∪I13∪I18

S2→S8：C23= I2∩I6∩I9∩ Te

S0→S8：C24= (I2∪I10∪I11)∩Te

S1→S8：C25= (I3∪I16)∩Te

S8→S0：C26= I3∪I4∪I16

S8→S1 ：C27= I4∪I12∪I13∪I18.

The conversion is easier to achieve with wireless sensor nodes.

9. Summarization

In this paper we analyze the energy consumption of each module and the whole nodes of wireless sensor nodes in different states, establish the energy consumption model of wireless sensor network nodes in different state, give the conversion strategy of high efficiency and energy saving based on module event driven and inter node event time and the semaphore. Through simulation and experiment, as for the situation that its sampling period is 5ms and the node sensing range data acquisition of 1kB, this method of state transition can be saved about 85%. The energy-saving effect of this conversion strategy's application is very obvious for a large quantity of data collection and data acquisition frequent. The more amount of data information is, the better the energy-saving effect is.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51174257),Yong Backbone Teachers of Anhui University of Science and Technology and Colleges and universities in Anhui Province outstanding young talent support plan.

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Authors

Huaping Zhou, she was born in Henan province in China in 1979. She is graduated from Anhui University of Science and Technology. My major is computer, and she got her master degree after her graduation in the year of 2004. She is graduated from China University of Mining & Technology (Beijing) in 2009, and her major is computer application technology, and got Ph.D. Now, the main research areas are information fusion, data mining, pattern recognition and other aspects of the research.

Jingzhao Li, he received his M.A. degree from China University of Mine and Technology in 1992, and PhD. degree in the key Lab of Power Electronics and Power Drives at Hefei University of Science and Technology, in 2003. He is currently a Professor with the School of Computer Science and Engineering, Anhui University of Science and Technology, China. His research interests include Computer Control, Internet of Things Technology and Embedded Systems. He has published more than 50 papers in domestic and international academic journals and conference proceedings'. These papers are embodied more than 30 times by SCI and EI and are cited more than 50 times by others.