Journal of Institute of Control, Robotics and Systems (2011) 17(12):1273-1277
http://dx.doi.org/10.5302/J.ICROS.2011.17.12.1273 ISSN:1976-5622 eISSN:2233-4335

무선 센서 네트워크에서 큐 관리 기반의 듀티 사이클 제어

Queue Management-Based Duty Cycle Control in Wireless Sensor Networks

변 희 정, 손 수 국*
(Heejung Byun[1] and Sugook Shon[1])
[1]Suwon University

Abstract: This paper proposes a control-based approach for duty cycle adaptation in wireless sensor networks. The proposed method, QCon, controls duty cycle through queue management in order to achieve high performance under variable traffic rates. To minimize energy consumption while meeting delay requirement, we design a feedback controller, which adapts the sleeping time according to dynamically changing traffic by constraining the queue length at a predetermined value. Based on control theory, we analyze the adaptive behavior of QCon and derive conditions for system stability. Results from asymptotic analysis and simulations indicate that QCon outperforms existing scheduling protocol by achieving more energy savings while satisfying delay requirement.

Keywords: duty cycle control, energy efficiency, wireless sensor networks

I. INTRODUCTION

WSNs (Wireless Sensor Networks) have a wide range of applications, such as environmental monitoring, target tracking, infrastructure security, fire detection, and traffic control. Typically, a WSN is composed of a large number of distributed sensor nodes that are battery-powered and often required to operate for years without human intervention after deployment. Therefore, a major problem in deploying WSNs is energy consumption.

Many research efforts in the recent years have focused on developing power saving methods for WSNs [1-12]. TDMA-based protocols [2,3] generally minimize energy consumption while guaranteeing the bounded latency and fairness in loaded traffic conditions. However, these reservation-based protocols require tight synchronization, which limits system scalability. Preamble sampling protocols [4,5] allow nodes to choose their schedules independently, thus removing synchronization requirement. However, these protocols require a longer preamble, which causes high collision rates. The protocols with common active periods are most well-known protocols [6-12]. The active periods are used for transmission and the sleep periods for power saving. These protocols require time synchronization, but not as tight as TDMA-based protocols. SMAC (Sensor MAC) [6] forces sensor nodes to operate at low duty cycle by repeatedly putting nodes in active and sleep periods. The sleep periods in SMAC save energy at the cost of extra end-to-end delay, i.e., sleep delay [6]. TMAC [7] improves on SMAC by using an adaptive duty cycle in which the duration of active periods is no longer fixed. If there is no activity for a certain time, the node switches its radio off before the active period ends. Therefore, nodes can go to sleep early, which further saves energy. To achieve a good tradeoff between energy consumption and delay, adaptive listening [9] suggests the use of overhearing to reduce the sleep delay. DSMAC [10] dynamically changes each node's duty cycle to meet applications' demands. In DSMAC, a node increases its duty cycle by adding extra active periods when small latency is required. U-MAC [11] tunes its duty cycle based on a utilization function, which is the ratio of the actual transmission and reception time of a node over the whole active period. DutyCon [12] proposes a feedback controller which controls the duty cycle to achieve energy efficiency while guaranteeing end-to-end communication delay. To do this, DutyCon decomposes end-to-end delay requirement into a set of single-hop delay requirements. The duty cycle of each node is determined based on the single-hop delay requirement and the actual packet delay, measured using time stamps. The problem with DutyCon is that when the queueing delay becomes high, response to changing network conditions becomes slow, resulting in degraded performance as shown in simulations.

In this paper, we propose QCon, an adaptive duty cycle control mechanism based on queue management with the aims of energy saving and delay reduction. Using the queue length and its variations of a sensor node, we present a control-based approach and design a distributed duty cycle controller, which adapts the sleeping time to the variable traffic rate. Based on the control theory, we derive the steady state and show system stability for QCon. Simulations show that QCon outperforms DutyCon in terms of packet delay and energy consumption, especially when the traffic load is high.

II. DUTY CYCLE CONTROL

In this section, we describe the duty cycle controller of QCon, and analytically show that system stability can be achieved by properly setting parameters.

* 책임저자(Corresponding Author)
논문접수: 2011. 3. 10., 수정: 2011. 4. 1., 채택확정: 2011. 4. 27.
변희정, 손수국: 수원대학교 IT대학 정보통신공학과
(heejungbyun@suwon.ac.kr/sshon@suwon.ac.kr)
※ This research was supported by the GRRC SUWON 2011-B5 program of Gyeonggi province and also supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (grant number 20110026740).

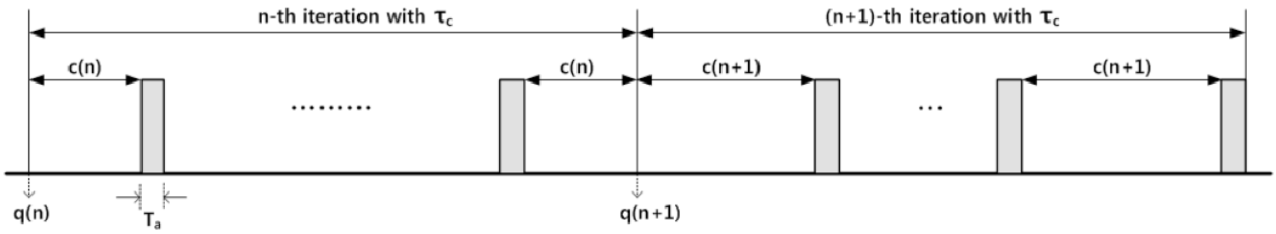

그림 1. 망 모델.
Fig. 1. Network model.

1. Network modeling

To model the network, we introduce the following notations.

- $G = (\mathbf{M}, \mathbf{L})$, a WSN where **M** is the node set and **L** is the link set of the network.
- l_m, the outgoing wireless link of node m ($0 \le m \le M - 1$) where M is the cardinality of **M**.
- τ_c, the time period of duty cycle control. Specifically, the time duration of iteration $[n, n+1)$.
- D_{l_m}, the link transmission rate at link l_m.
- q_{l_m}, the queue length of link l_m.
- c_m, the time length of the sleep interval of node m.
- w_m, the number of packets that arrive during time slot [n,n+1) of node m including the forwarding traffic.

The queue length of link l_m at the (n+1)-th iteration can be modeled as:

$$q_{l_m}(n+1) = [q_{l_m}(n) + w_m(n) - D_{l_m} k_m(n) T_a]^+ \quad (1)$$

where $k_m(n) = \left\lfloor \frac{\tau_c}{c_m(n) + T_a} \right\rfloor$ and $[\cdot]^+ = \max(\cdot, 0)$. The value of T_a stands for the active period with a fixed size. The value of $D_{l_m} k_m(n) T_a$ is the number of packets transmitted during time slot [n, n+1). Note that the value of $c_m(n)$ remains constant during iteration [n, n+1). Active periods are of fixed size whereas the length of sleep periods depends on a value determined by the duty cycle controller. Fig. 1 illustrates the network model. During a single control period, there may be multiple active times and the queued packets are transmitted during active times. We assume that the average network condition of a link does not change frequently. Thus, we simplify the value of D_{l_m} to be stable during a control period [12].

2. Duty cycle controller design

We design the distributed duty cycle controller, which adjusts the sleep time under variable traffic conditions. In each control period, the controller controls a node's sleeping time using the local information available at the node. One of the significant components of end-to-end delay is the queueing delay, especially in WSN applications with unpredictable packet generating time. The trajectories of the queue potentially imply the network status, such as traffic changes, delay variations, route depth, or link quality. Based on the information of queue length and its variation, we can infer the changes of traffic or network conditions. Using this local information, we propose a dynamic duty cycle control scheme to meet time-varying or spatially non-uniform traffic loads by constraining the queue length at a predetermined threshold. To do this, we design the following controller:

$$c_m(n+1) = c_m(n) + \beta\left(q_{l_m}^{th} - q_{l_m}(n+1)\right) - \gamma(q_{l_m}(n+1) - q_{l_m}(n)) \quad (2)$$

where β and γ are the control parameters to be chosen, and $q_{l_m}^{th}$ is the queue threshold of link l_m. According to (2), the sleep time increases linearly as the queue length becomes smaller than the queue threshold. Meanwhile, the sleep time decreases as the forward difference of queue length becomes larger than zero because the increased forward difference of queue length means increased latency. Therefore, the control algorithm is supposed to adjust the sleeping time so that the queue length at the steady state is a predetermined queue threshold. Faster updates of c_m lead to shorter settling time and an increase in the control overhead. Meanwhile, the increase in τ_c leads to longer settling time and the smother evolution of the queue length because of fewer update. Therefore, the choice of the update period can be approached as a multicriteria optimization problem. The values of β and γ determine the stability of the controller. The range of β and γ for the stable behavior is established using a stability analysis of a closed-loop system shown in the next section.

Since each node can be assigned different duty cycle, the sender has to synchronize its duty cycle with the receiver such that receiver and sender node are active at the same time. Therefore, it needs to exchange its determined schedule with its neighbors. As in SMAC [6], we assume that each node maintains a schedule table that stores the schedules of all its neighbors and the sensor nodes exchange schedules using ACK packet with their neighbors.

3. Analysis

Based on the network model, we analyze the system stability of QCon. The system can be represented by a discrete-time model where the duration of control period equals τ_c. Let $q_{l_m s}$ and c_{ms} denote the average steady-state solutions of queue length $q_{l_m}(n)$ and sleep time $c_{ms}(n)$ respectively. Note that in the neighborhood of the steady state, we ignore the saturation nonlinearity. From (1)-(2), we obtain the average steady points of the queue length and sleep time based on the asymptotic theory [13-15]:

$$q_{l_m s} = q_{l_m}^{th}, \quad c_{ms} = T_a\left(\frac{D_{l_m}\tau_c}{w_{ma}} - 1\right) \quad (3)$$

where the value of w_{ma} denotes the average value of w_m. For the purpose of analytic simplicity, we concentrate on the networks where the traffic load is arbitrarily constant as average steady point. However, the results of this paper can be generalized to the stochastic traffic load. From (3), we can see that the queue length converges to the predetermined threshold and the sleeping time is adapted in inverse proportion to the traffic rate.

Now we analytically show the stability of QCon around the steady point. Let

$$\begin{aligned}\delta q_{l_m} &= q_{l_m} - q_{l_m s}\\ \delta c_m &= c_m - c_{ms}\\ \delta w_m &= w_m - w_{ma}\end{aligned}$$

Then (1)-(2) can be rewritten as:

$$\begin{aligned}\delta q_{l_m}(n+1) &= f_1\left(\delta q_{l_m}(n), \delta c_m(n)\right)\\ \delta c_m(n+1) &= f_2(\delta q_{l_m}(n), \delta c_m(n))\end{aligned} \quad (4)$$

where

$$\begin{aligned}f_1(\delta q_{l_m}(n), \delta c_m(n)) &= \delta q_{l_m}(n) + \delta w_m(n) + \varsigma(\delta c_m(n))\\ f_2(\delta q_{l_m}(n), \delta c_m(n)) &= \delta c_m(n) - \beta \delta q_{l_m}(n)\\ &\quad -(\beta+\gamma)(\delta w_m(n) + \varsigma(\delta c_m(n)))\end{aligned} \quad (5)$$

and $\varsigma(\delta c_m(n)) = \frac{\mathrm{D}_{l_m} T_a \, \tau_c}{T_a + c_{ms}} \frac{\delta c_m(n)}{\delta c_m(n) + T_a + c_{ms}}$.

The qualitative behavior of a nonlinear system near a steady point can be determined via linearization with respect to that point. We approximate the nonlinear system as described in (4) and (5) by the following linear system:

$$\begin{aligned}\delta q_{l_m}(n+1) &= a_{11}\delta q_{l_m}(n) + a_{12}\delta c_m(n)\\ \delta c_m(n+1) &= a_{21}\delta q_{l_m}(n) + a_{22}\delta c_m(n)\end{aligned} \quad (6)$$

Let $X(n) = \left[\delta q_{l_m}(n)\ \delta c_m(n)\right]^T$. Rewriting this equation in a vector form, we obtain

$$X(n+1) = \mathbf{A}X(n) \quad (7)$$

where

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial \delta q_{l_m}} & \frac{\partial f_1}{\partial \delta c_m}\\ \frac{\partial f_2}{\partial \delta q_{l_m}} & \frac{\partial f_2}{\partial \delta c_m}\end{bmatrix}_{|\delta q_{l_m}=0, \delta c_m=0}$$

$$= \begin{bmatrix} 1 & \frac{\mathrm{D}_{l_m} T_a \, \tau_c}{(T_a + c_{ms})^2}\\ -\beta & 1-(\beta+\gamma)\frac{\mathrm{D}_{l_m} T_a \, \tau_c}{(T_a + c_{ms})^2}\end{bmatrix}$$

In order for the controller to be stable, the characteristic polynomial of (7) should have all zeros within the unit circle. Hence the system is asymptotically stable if the control parameters satisfy the following relations:

$$\frac{(\beta + 2\gamma)\mathrm{D}_{l_m} T_a \, \tau_c}{(T_a + c_{ms})^2} < 4 \quad (8)$$

Therefore, since the origin of the linearized state equation is stable in a small neighborhood of the steady point, the trajectories of the nonlinear state equation will behave like a stable node. Thus, the system stability can be achieved.

III. SIMULATION RESULTS

For simulations, we use the network model shown in Fig. 2. Nodes 0, 1, 2, and 3 are data sources, and packets are sent to node 4, which is the sink. We assume that each node transmits only once every active period. Initial duty cycle is set to 50% for all nodes. We compare performance of QCon and DutyCon [12] in terms of queue length, packet delay, and energy consumption. Poisson traffic is used, and average packet arrival rate is varied to study the impact of traffic load. For QCon, the queue threshold is set to 2 packets for all nodes. For DutyCon, delay requirement is set to 0.2 seconds. Each point in the graphs is the average of 20 iterations.

Fig. 3 shows the average queue length under different packet arrival rate. When the traffic load is light, DutyCon keeps the queue length at a low value. However, as the traffic load becomes heavy, the queue length of DutyCon increases rapidly. The reason for this result is that DutyCon controls the sleeping time with the slack time information. Therefore, DutyCon cannot react speedily to the increasing traffic, resulting in the large queue length. On the other hand, QCon successfully controls the queue length around the predetermined queue threshold regardless of the traffic load. This is because QCon adapts the duty cycle according to the traffic variation in a timely manner so that the queue length is converged to the queue threshold. Therefore, QCon avoids large backlogging packets in intermediate nodes. The optimal queue threshold of a node depends on delay requirement of packets going through the node. Here we assume that queue threshold of each node is preconfigured, as well as the routes between each source and sink. Computing optimal queue threshold will be considered in our future work.

Fig. 4 shows the average delay under different packet arrival rates. The results indicate that when the traffic rate is low, DutyCon can control the average delay very close to the desired

그림 2. 망 구성.

Fig. 2. Network topology.

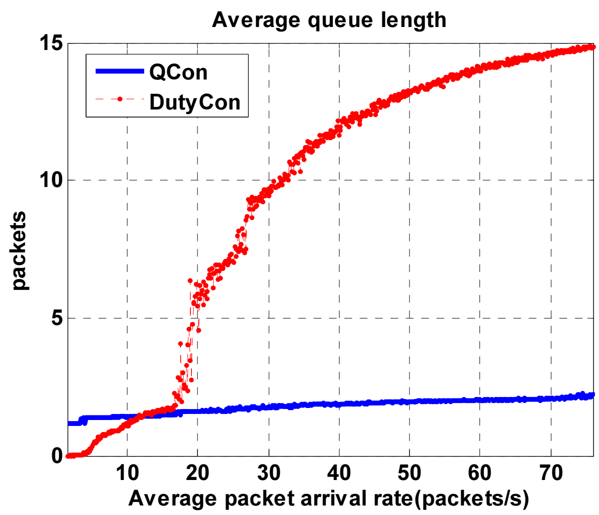

그림 3. 패킷 도착율에 따른 평균 큐 길이.

Fig. 3. Average queue length under different packet arrival rates.

requirement. However, as the traffic load becomes loaded, DutyCon does not have effective control of the average delay. This is because DutyCon responses slowly to the traffic change, which leads to a large queue length and long delay. QCon achieves a rather small delay because of the fast response to the traffic change and the low queue length.

We evaluate average power consumption under different packet arrival time. In our simulations, we set the transmitting power to 4.75mW and sleeping power to 15μW [11]. Fig. 5 shows that when traffic load is light, the average power consumption of both DutyCon and QCon is small due to low duty cycle. As the packet arrival rate increases, nodes have fewer chances to go to sleep and thus spend more time in transmission. In DutyCon, the average power consumption increases rapidly until the packet arrival rate reaches 17packets/s and then increases slowly after. This is because of the wide range of fluctuation of the duty cycle and this fluctuation comes from the slack time information and the gain of the controller determined by the link quality. The sleeping time

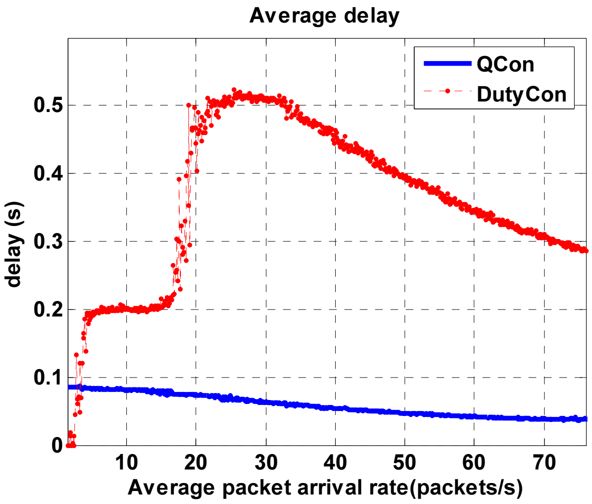

그림 4. 패킷 도착율에 따른 평균 지연 시간

Fig. 4. Average delay under different packet arrival rates.

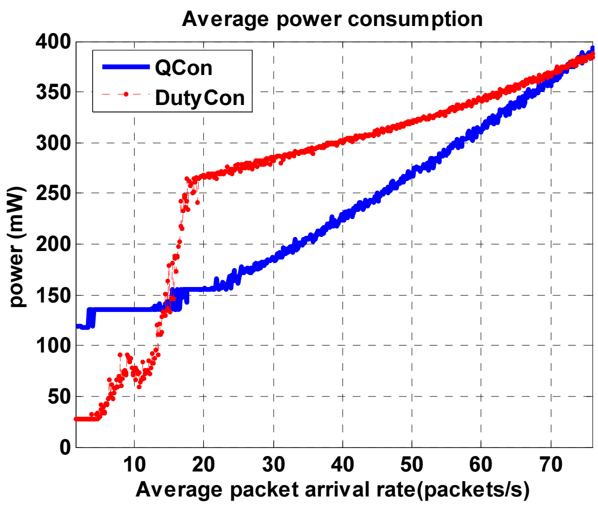

그림 5. 패킷 도착율에 따른 평균 전력 소모량

Fig. 5. Average power consumption under different packet arrival rates.

controlled by QCon remains stable by stabilizing the queue length at the desired value. Therefore, the average power consumption is much lower than that of DutyCon, which leads to longer lifetime with the heavy traffic load.

To summarize the results, when traffic load is low, both DutyCon and QCon works well. However, as the traffic load becomes heavy, DutyCon suffers significant performance degradation, while QCon maintains good level of performance. Controlling duty cycle based on queue length is effective, because it can quickly respond to changing network conditions.

IV. CONCLUSIONS

In this paper, we propose QCon, a control-based mechanism for adapting duty cycles in wireless sensor networks. QCon controls duty cycle based on queue length. Specifically, QCon controls sleep time of a node in order to maintain queue length under a predetermined threshold, so that delay requirements of packets are satisfied. Simulation results show that QCon outperforms existing duty cycle control mechanism in terms of packet delay and energy consumption, by reacting fast to changing network conditions.

REFERENCES

[1] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung, "MAC essentials for wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 2, pp. 222-248, 2010.

[2] S. C. Ergen and P. Varaiya, "PEDAMACS: power efficient and delay aware medium access protocol for sensor networks," *IEEE Transactions on Mobile Computing*, vol. 5, no. 7, pp. 920-930, 2006.

[3] T. Zheng, S. Radhakrishnan, and V. Sarangan, "PMAC: an adaptive energy-efficient MAC protocol for wireless sensor networks," *Proceedings of IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, 2005.

[4] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," *In Proc. of ACM SenSys*, pp. 95-107, 2004.

[5] S. Liu, K.-W. Fan, and P. Sinha, "CMAC: and energy efficient MAC layer protocol using convergent packet forwarding for wireless sensor networks," *In Proceedings of Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pp. 11-20, 2007.

[6] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wirelss sensor networks," *Proc. of IEEE Infocom*, pp. 1567-1576, New York, NY, Jul. 2002.

[7] T. Van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," *proc. of ACM Sensys*, pp. 171-180, Los Angeles, CA, Nov. 2003.

[8] P. Havinga and G. Smit, "E2MaC: an energy efficient MAC protocol for multimedia traffic," Technical Report, Univ. of Twente, Netherlands, 1998.

[9] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated, adaptive sleeping for wireless sensor network," *IEEE Trans. on Networking*, vol. 12, no. 3, pp. 493-506, 2004.

[10] P. Lin, C. Qiao, and X. Wang, "Medium access control with a dynamic duty cycle for sensor networks," *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, vol. 3, pp. 1534-1539, 2004.

[11] S. H. Yang, H-W. Tseng, E. Wu, and G.-H Chen, "Utilization

based duty cycle tuning MAC protocol for wireless sensor networks," *Proc. of IEEE GLOBECOM*, vol. 6, pp. 3258-3262, 2005.

[12] X. Wang, G. Xing, and Y. Yao, "Dynamic duty cycle control for end-to-end delay guarantees in wireless sensor networks," *International Workshop on Quality of Service (IWQoS)*, pp. 1-9, 2010.

[13] J.-T. Lim and K. H. Shim, "Asymptotic performance evaluation of token passing networks," *IEEE Trans. Industrial Electronics*, vol. 40, no. 3, pp. 384-385, 1993.

[14] K. H. Shim and J.-T. Lim, "Performance analysis and design of token-passing networks with two message priorities," *IEE Proc. Communications*, vol. 44, no. 1, pp. 11-16, 1997.

[15] K.-H. Shim and J.-T. Lim, "Extreme-point robust stability of a class of discrete-time polynomials," Electronics Letters, vol. 32, no. 15, pp. 1421-1422, 1996.

변 희 정

1999년 숭실대학교 정보통신공학과 학사. 2001년 한국과학기술원 전자전산학과 석사. 2005년 한국과학기술원 전자전산학과 박사. 2010년 삼성종합기술원, 삼성전자. 2010년~현재 수원대학교 IT대학 정보통신공학과. 관심분야는 네트워크 제어.

손 수 국

1982년 서울대학교 전기공학과 학사. 1984년 서울대학교 전기공학과 석사. 1996년 University of Texas at Austin, ECE Ph. D. 2003년~현재 수원대학교 IT대학 정보통신공학과. 관심분야는 컴퓨터 및 임베디드 시스템, 네트워크 프로토콜, 네트워크 시뮬레이션, 네트워크 프로그래밍.