Tier based Anycast to Achieve Maximum Lifetime by Duty Cycle Control in Wireless Sensor Networks

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Abstract—In a wireless sensor network, the routing control overhead is prohibitive because mostly many nodes are involved in routing. To overcome the overhead problem, tier based anycast protocol was proposed in [1]. However, it has a shortcoming of using much more energy compared to other competitors of deterministic routing protocols in transmitting data packets towards the sink node. In this paper, we visited the tier based anycast protocol in depth and presented a new analytic framework by using the concept of sub-tiering. Firstly, we formulated the problem for finding an optimal duty cycle for each tier as a minimax optimization problem, and proved that the solution exists and it is unique. From the analysis results, we found that the network lifetime can be improved very much by allocating a duty cycle adaptively for each tier. Through simulations, we also confirmed that our duty cycle control algorithm increases the network lifetime by approximately 30%.

I. INTRODUCTION

A wireless sensor network (WSN) is designed to provide application services of event reporting or environmental monitoring such as temperature and humidity. It has the unique features of being battery limited, high node density, and unidirectional in terms of data transmission. The high node density comes from a node’s short sensing range compared to its transmission range and, therefore, a node has many one-hop neighbors [5][6]. These characteristics of the WSN prohibit many previous routing and MAC protocols from being deployed in reality. The problems that we currently confront are: excessive energy consumption by routing setup, low scalability due to control overhead, high packet delay due to periodic sleeping of sensor nodes, and low reliability in packet delivery.

Many WSN specific solutions have been proposed to overcome these problems and tier based anycast protocol is one of the most realistic solutions. It adopts a cross layer approach that unifies MAC and routing protocols together, which results in very low routing control overhead. It provides high robustness of not being affected by some node failures. This is because it doesn’t use a deterministic routing path. But, if it is with power saving nodes that sleep and wake up periodically, it will experience the drawback of consuming a huge amount of energy because a transmitter must send a control packet repeatedly until it receives a reply from any awake receiving node [1][2][4]. To mitigate this defect, some protocols prefer using a low cost path to a randomly selected path [2], and others coordinate the wakeup time of each node [3]. These approaches, however, incur the additional control messages and require each sensor node to keep information about some others, which apparently weakens the merits of the original tier-based scheme, i.e., scalability and robustness.

In this paper, we introduce a new analytic approach of sub-tiering, which enables us to analyze the performance of the tier based anycast protocol numerically. The observations on the numerical results motivate us to control the duty cycle of each tier in order to increase the lifetime of the WSN, against the original scheme that uses a homogeneous duty cycle for all the nodes. We find an optimal duty cycle for each tier by solving a minimax problem under a constraint of worst case delay, and show that a unique solution always exists. The simulation results confirm that our duty cycle allocation algorithm considerably improves the network lifetime. The important thing is that our scheme preserves the merits of the original tier based anycast protocol without incurring extra control overhead.

The rest of this paper is organized as follows. In Section II, we propose a new analytic framework and analyze the tier based anycast protocol. Some numerical results are presented to support our analysis. In Section III, we formulate the problem of allocating an optimal duty cycle for each tier and solve it. Simulation results are present to manifest the performance of our duty cycle allocation algorithm in Section IV, and concluding remarks follow in Section V.

II. ANALYSIS OF TIER BASED ANYCAST PROTOCOL

Tier based anycast protocol is known to be very difficult to analyze numerically because of its unique forwarding process. In some previous works, the protocol has been analyzed for 1-hop scenario and assumed to have \( N \) times of the 1-hop scenario result for \( N \)-hop environments without justification. It is clear, however, that we cannot obtain the accurate result by following this approach. In this section, we present a new analytic method of dividing each tier into multiple sub-tiers, which highly improves the accuracy of numerical analysis.
A. Tier based anycast forwarding process

Each node in the WSN is assigned its tier ID (identification number) according to the distance from the sink node as shown in Fig. 1. The width of each tier is set to be equal. The sink node has a tier ID of 0 and the tier closest to the sink has a tier ID of 1. Likewise the tier ID of a tier is assigned higher by 1 compared to that of inner tier. We do not get into detail to explain the way of assigning a tier ID for each node, and assume that each node has a proper tier ID already [1].

Each sensor node is allowed to send a data packet to the sink node after acquiring its tier ID, and it starts to sleep and wake up periodically to save the energy consumption. The wakeup time is selected randomly for each node and it remains if the node’s tier ID does not change. A node is able to receive a packet during the wakeup period only, but it may transmit packets whenever necessary. That is, if a node has a packet to send during a sleep period, it wakes up to send it and goes back to sleep after the complete transmission.

A transmission node (TX node) needs to find a reception node (RX node) to relay a packet to the sink node if the sink node is not directly reachable. The TX node broadcasts a small control packet containing its tier ID and waits for the acknowledgement packet (ACK) from a RX node. If the TX node receives an ACK, it transmits a data packet. If the node does not receive any ACK, it sends the control packet again. This procedure repeats until either TX node receives an ACK or the retry count reaches the predetermined maximum number.

A node receiving a packet during the wakeup checks the tier ID contained in the packet. If the indicated ID in the header is larger than its own tier ID, the node becomes a RX node and sends an ACK to the TX node. If the TX node receives an ACK, it transmits a data packet. If the node does not receive any ACK, it sends the control packet again. This procedure repeats until either TX node receives an ACK or the retry count reaches the predetermined maximum number.

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In the forwarding process, the tier width is a critical parameter that affects overall performance. Let $R$ be the transmission range of a sensor node and $w$ be the width of each tier. Then

$$w = \frac{R}{c},$$

where constant $c$ has 2.2 when optimal [1].

B. Average traffic load

Through analysis, we obtain the average packet transmission rate of each node assuming that

- All nodes are distributed uniformly over the network with density $\rho$.
- The network shape is circular and the sink node is located at the center.
- All nodes except the sink node transmit a sensing data to the sink periodically and the interval is $1/f$ sec.

All nodes repeat the sleep and wakeup periodically.

We divide each tier into multiple sub-tiers of an equal size of the width. Assuming that the nodes in a sub-tier are homogeneous, we analyze the average packet transmission rate and the average energy consumption of each node.

Let’s denote the number of total tiers as $N$, the number of sub-tiers in one tier as $M$ and the width of sub-tier as $1$ without loss of generality. From Fig. 1, we obtain

$$\theta = \arccos \left( \frac{\sqrt{2} + k^2 - R^2}{2ik} \right).$$

The area of sub-tier $i$, where nodes can receive packets from a node of sub-tier $k$, equals

$$S^i_k \approx 2 \cdot \left( \frac{1}{2} (i + 1)^2 \theta - \frac{1}{2} i^2 \theta \right) = \theta (2i + 1) \quad \text{for} \quad i < k,$$

with some approximation. Then the total area where nodes can receive packets from a node of sub-tier $k$, is given by

$$S_k = \sum_{i = \max([k/M-1], 1)}^{[k/M-1] \cdot M} S^i_k,$$

where $[\cdot]$ is the ceiling operator.

Because the nodes are uniformly distributed, the probability of a packet from sub-tier $k$ being received by sub-tier $i$ is given as

$$q_{ki} = \frac{S^i_k}{S_k}.$$ 

The total traffic that the nodes of sub-tier $i$ should forward is the sum of traffics generated by sub-tier $i$ itself as well as received from the higher sub-tiers. We calculate the total traffic of sub-tier $i$ as follows.

$$G_i = f \rho \pi (2i + 1) + \sum_{j=X}^{Y} G_j q_{ji},$$
where $X$ and $Y$ are the smallest and the largest high sub-tier ID among the sub-tier IDs that can directly send packets to sub-tier $i$, respectively. We can see that $X = \max(\lceil i/M \rceil M + 1, cM + 1]$ and $Y = \min(cM + i, NM - 1)$. Then we obtain the average packet transmission rate of each node in sub-tier $i$ from dividing the total traffic by the number of nodes in sub-tier $i$ as follows.

$$
 g_i = \frac{G_i}{\pi (2i + 1) \rho}.
$$

Fig. 2 compares the total traffic of each sub-tier obtained from (7) with that from the simulations. The parameters used are $M=5$ or 10, $\rho=10$, and $f=1/60$. The five points of each tier represent the 5 sub-tiers within the tier, respectively. To present the results in one figure, we plotted only the results of even sub-tier $i$ for $M=10$. For the small sized network ($N=5$), we did not present the results here as they showed a similar tendency to Fig. 2. Although the numerical analysis results closely matches the simulation results regardless of $M$, We observe some difference at tier ID 1 and 2, which is due to the approximation in (3) but the error is small.

### C. Average energy consumption

We calculate the average energy consumption of each node by using (7), considering the energy consumed for both listening a channel and receiving packets as the reception energy. The energy consumed for receiving packets is negligible compared to that for listening a channel because the data traffic is very low in the WSN. So, we assume the reception energy is the same as the energy for the channel listening. Then a node’s reception energy is determined by its duty cycle and wakeup period.

The average transmission energy depends on the duty cycle of possible receiving nodes. Let’s denote the average reception energy of nodes in sub-tier $i$ as $l_i$, and the average transmission energy of nodes as $\tau_i$. The energy consumptions per unit time for transmission and reception are supposed to have the same value $P$. Denoting the duty cycle of nodes in sub-tier $i$ as $\phi_i$, and the wakeup period as $T_w^i$, and the sleep period as $T_s^i$, we obtain

$$
 \phi_i = \frac{T_w^i}{T_w^i + T_s^i} \approx \frac{T_h^i}{T_s^i}, \quad \text{if} \quad T_w^i \ll T_s^i, \tag{8}
$$

and $l_i$ is given by

$$
 l_i = P \cdot \phi_i. \tag{9}
$$

As mentioned, all nodes use a network wide common duty cycle in the original tier based anycast protocol. We found an optimal, in the sense of maximizing the network lifetime, common duty cycle by some numerical analysis. Denoting it as $\phi$, we have

$$
 l = P \cdot \phi. \tag{10}
$$

For all numerical analyses and simulations, we use $\phi$ for the original tier-based protocol.

On average, it takes a half of the sleep period of RX node for a TX node to get an ACK from the RX node if there is one RX node. Likewise, the TX node needs $\frac{T_w^i}{2T_s}$ of the sleep period to receive an ACK if there are $Q$ RX nodes because each node is assumed to wake up randomly. The average transmission energy of nodes in sub-tier $i$ is given as

$$
 \tau_i = \sum_{h \in \{\text{IDs of all reachable sub-tiers}\}} q_{ih} \cdot \frac{T_h^i}{2S_h^i} \cdot \frac{P}{\phi_h}
 = \sum_{h \in [i-cM]} q_{ih} \cdot \frac{T_h^i}{2S_h^i} \cdot \frac{1}{\phi_h}, \tag{11}
$$

for $i > cM$, and $\tau_i=0$ for $i \leq cM$ because the sink node does not sleep at all and immediately replies with an ACK to the TX node.

Fig. 3 compares the analysis results with the simulation results in terms of the energy consumption of each sub-tier. For the small sized network ($N=5$), we didn’t show the results here as they had a similar tendency to Fig. 3.

For simplicity, we normalize the energy consumption by $l_i$, which is the reception energy of nodes in the original protocol. That is, the transmission energy in sub-tier $i$ is $\tau_i/l_i$, the reception energy is $l_i/l_i$, and the total energy is $(\tau_i + l_i)/l_i$. The transmission energies of tier ID 1 and 2 (sub-tier 1~11) are almost zero because $c=2.2$. So, the error in (3) shown in Fig. 2 is eliminated naturally, which makes our analysis more accurate. An interesting observation is that the most critical region, consuming the largest amount of energies, of tier $n$ is the boundary of tier $n$ and tier $n+1$, and the energy consumption decreases fast as tier ID increases. These results motivate us to adapt the duty cycle according to the tier ID to minimize the energy consumption.

### III. DUTY CYCLE ALLOCATION

We define the lifetime of a WSN as its duration from the deployment to the first breakdown of nodes. It is reasonable because a sensor network loses the value rapidly if it cannot
provide data for the region interested. Reminding the most common reason of outage for a sensor node is a battery run-out, we propose a duty cycle allocation algorithm to extend the lifetime of the WSN. Our algorithm makes the network survive longer by reducing the energy consumption of critical nodes efficiently.

The energy of a node is used for transmission and reception of packets. If we want to reduce the transmission energy of a node, we should increase the duty cycle of nodes in the receiving tier according to (9). On the contrary, if we decrease the duty cycle of a node to reduce the reception energy, the nodes in transmitting tier experience many control packet retransmissions and consume more energy. Therefore, to choose an appropriate duty cycle at each tier, we must consider the inter-tier dependency of energy consumption.

We observe two important things related to the inter-tier dependency of neighboring tiers. The first is that $S_k$ decreases as $k$ increases by (3), and the second is that the radio power decays rapidly with the distance. Fig. 4 shows that packets from the most critical node, located at the outer edge of the interested tier, in tier $n$ are received by nodes in tier $n-1$, with the probability of about 90%, and by nodes in tier $n-2$, with the probability of about 10%. This means that the energy consumption of the most critical node is determined by the adjacent tier with the tier ID smaller by 1.

Let’s denote the normalized energy consumption, as shown in Fig. 3, of the most critical node in tier $i$ as $t_i$. If we allocate a duty cycle $\alpha_i$ to the nodes in tier $i$, the normalized reception energy is modified as $\alpha_i$ and $t_i$ is redefined as $t_i/\alpha_i$ according to (9) and (11). So, if we want to extend the network lifetime for a total of $N$ tiers, the problem is formulated as follows. For the given constants $t_3, t_4, ..., t_{N-1}$ ($t_i \geq 0$ for $3 \leq i \leq N-1$), the problem is formulated as follows.

\begin{align*}
\text{subject to} & \sum_{i=1}^{N-1} \frac{1}{\alpha_i} = K(\leq N-1), \quad \alpha_i > 0 \quad \text{for} \quad 1 \leq i \leq N-1. \\
\end{align*}

The constraint of $\mathbf{P1}$ means that the worst case packet delay should not be increased by varying the duty cycle of each tier.

Before solving $\mathbf{P1}$, we consider $\mathbf{P2}$ first, where the inequality constraint is replaced with the equality.

\begin{align*}
\text{minimize} & \max\{\alpha_1, \alpha_2, \alpha_3 + \frac{t_3}{\alpha_2}, ..., \alpha_{N-1} + \frac{t_{N-1}}{\alpha_{N-2}}\} \\
\text{subject to} & \sum_{i=1}^{N-1} \frac{1}{\alpha_i} = K(\leq N-1), \quad \alpha_i > 0 \quad \text{for} \quad 1 \leq i \leq N-1. \\
\end{align*}

We show that the optimal solution for $\mathbf{P2}$ makes all the terms in $\max\{\} \text{ operator of the objective function equal.}

\textbf{Lemma 1:} If there exists a vector $\vec{\alpha}^* = (\alpha_1^*, \alpha_2^*, ..., \alpha_{N-1}^*)$ that satisfies the constraint of $\mathbf{P2}$ and
\begin{equation}
\alpha_1^* = \alpha_2^* + \frac{t_3}{\alpha_2^*} = ... = \alpha_{N-1}^* + \frac{t_{N-1}}{\alpha_{N-2}^*},
\end{equation}
then $\vec{\alpha}^*$ is the optimal solution of $\mathbf{P2}$.

\textbf{Proof:} Suppose a vector $\vec{\beta} = (\beta_1, \beta_2, ..., \beta_{N-1})$ that satisfies the constraint of $\mathbf{P2}$. If $\vec{\beta}$ gives the smaller value of the objective function than $\vec{\alpha}^*$ does, the following holds.
\begin{align*}
\beta_1 < \alpha_1^*, \beta_2 < \alpha_2^*, \beta_3 + \frac{t_3}{\beta_2} < \alpha_3^*, \beta_4 + \frac{t_4}{\beta_3} < \alpha_4^*, ..., \\
\beta_{N-1} + \frac{t_{N-1}}{\beta_{N-2}} < \alpha_{N-1}^* + \frac{t_{N-1}}{\alpha_{N-2}^*}.
\end{align*}

2We need not define $t_1$ and $t_2$. 

Fig. 3. Normalized energy consumption of the numerical analysis and the simulation ($M=5$ and $N=10$).

Fig. 4. The reception probability of nodes in each tier for packets from the most critical node in tier $n$ ($N=10$).
From this, we obtain
\[ \beta_1 < \alpha_1^* \leq \beta_2 < \alpha_2^*, \beta_3 - \alpha_3 < t_3(\frac{1}{\alpha_2^*} - \frac{1}{\beta_2}) < 0, \ldots, \]
\[ \beta_{N-1} - \alpha_{N-1} < t_{N-1}(\frac{1}{\alpha_{N-2}^*} - \frac{1}{\beta_{N-2}}) < 0. \]
(16)
That is, \( 0 < \beta_i < \alpha_i^*, \forall i. \)

But, this contradicts the assumption that \( \tilde{\beta} \) satisfies the contract of P2 because
\[ \sum_{i=1}^{N-1} \frac{1}{\beta_i} > \sum_{i=1}^{N-1} \frac{1}{\alpha_i^*} = K. \]
(17)
Therefore, such vector cannot exist and we conclude that \( \alpha^* \) is the optimal solution of P2.

**Lemma 1** gives a key property of the optimal solution, but we do not know such vector \( \alpha^* \) exists or not yet. The following lemma shows that \( \alpha^* \) always exists and is unique.

**Lemma 2:** The vector \( \alpha^* \) uniquely exists.

**Proof:** Let\’s define \( f_i(x) \) as
\[ f_i(x) = \begin{cases} x & \text{for } x \geq 0, \text{ if } i = 1 \text{ and } 2, \\ x - \frac{t_i}{f_{i-1}(x)} & \text{for } x > z_{i-1}, \text{ otherwise}, \end{cases} \]
where \( z_{i-1} \) is the zero of \( f_{i-1}(x) \). Then, \( \frac{df_i}{dx} > 0 \) for any point in the domain. In addition, because \( \lim_{x \to x_{i-1}} f_i(x) \to -\infty \), \( \lim_{x \to \infty} f_i(x) \to \infty \), and \( f_i(x) \) is continuous and increases monotonically, the zeros of \( f_i(x) \)’s satisfy \( z_{N-1} > z_{N-2} > \ldots > z_2 = z_1 = 0. \)

Let\’s define the function \( f(x) = \sum_{i=1}^{N-1} \frac{1}{f_i(x)} \) for \( x > z_{N-1} \). \( f(x) \) decreases monotonically because \( f_i(x) \) is always greater than 0 and increases monotonically. And, we can see that
\[ \lim_{x \to z_{N-1}} f(x) = \lim_{x \to z_{N-1}} \sum_{i=1}^{N-1} \frac{1}{f_i(x)} \to \infty \]
(19)
and
\[ \lim_{x \to \infty} f(x) = \lim_{x \to \infty} \sum_{i=1}^{N-1} \frac{1}{f_i(x)} = 0. \]
(20)
In summary,
\[ i) \lim_{x \to z_{N-1}} f(x) \to \infty(> K), \]
\[ ii) \lim_{x \to \infty} f(x) = 0(< K), \]
\[ iii) f(x) \text{ is a continuous and monotonically decreasing function.} \]
Therefore, there exist \( x^*(> z_{N-1}) \) such that \( f(x^*) = K \) and \( x^* \) is unique.

Because \( x^* \) uniquely exists, so does \( f_i(x^*) \), \( \forall i. \) We define \( \alpha_i^* = f_i(x^*). \) Then, \( \alpha_i^* = x^* \) for \( i = 1 \) and 2, and
\[ \alpha_i^* = f_i(x^*) = x^* - \frac{t_i}{f_{i-1}(x^*)} = x^* - \frac{t_i}{\alpha_{i-1}^*} \]
(21)
for \( 3 \leq i \leq N-1 \), which indicates that \( x^* = \alpha_1^* + \frac{t_3}{\alpha_2^*} + \ldots = \alpha_{N-1}^* + \frac{t_{N-1}}{\alpha_{N-2}^*}. \)
Therefore, we obtain
\[ x^* = \alpha_1^* = \alpha_2^* = \ldots = \alpha_{N-1}^* + \frac{t_{N-1}}{\alpha_{N-2}^*}, \]
(22)
and \( \alpha^* = (\alpha_1^*, \ldots, \alpha_N^*) \) satisfies the property of lemma 1.

The following pseudo code summarizes the procedure for calculating the optimal solution for P2.

**Algorithm 1** Calculate \( \alpha^*_i \) for P2

1: \( z_2 = 0 \)
2: for \( i = 3 \) to \( N - 1 \) do
3: \( \text{Find } z_i(> z_{i-1}) \text{ s.t. } f_i(z_i) = 0 \)
4: end for
5: \( \text{Find } x^*(> z_{N-1}) \text{ s.t. } f(x^*) = K \)
6: \( \alpha_i^* \leftarrow f_i(x^*), \forall i \)

We solved P2 instead of P1 but, with proper choice of the parameter, it leads to the optimal solution of P1.

**Proposition 1:** The optimal solution for P2 is equal to that for P1 if \( K = N - 1 \). 

**Proof:** Let\’s denote the optimal solution for P2 by \( \alpha^* = (\alpha_1^*, \alpha_2^*, \ldots, \alpha_{N-1}^*) \) if the constraint is \( \sum_{i=1}^{N-1} \frac{1}{\alpha_i} = K_1, \) and \( \beta^* = (\beta_1^*, \beta_2^*, \ldots, \beta_{N-1}^*) \) if the constraint is \( \sum_{i=1}^{N-1} \frac{1}{\beta_i} = K_2(\leq K_1) \), respectively. Defining \( x_1^* = f^{-1}(K_1) \) and \( x_2^* = f^{-1}(K_2) \), we obtain \( x_1^* \geq x_2^* \) because \( f(x) \) decreases monotonically. That is,
\[ \alpha_1^* = \alpha_2^* = \alpha_3^* + \frac{t_3}{\alpha_2^*} = \ldots = \alpha_{N-1}^* + \frac{t_{N-1}}{\alpha_{N-2}^*} = x_1^* \]
(23)
\[ \leq x_2^* = \beta_1^* + \beta_2^* = \beta_3^* + \frac{t_3}{\beta_2^*} = \ldots = \beta_{N-1}^* + \frac{t_{N-1}}{\beta_{N-2}^*}, \]
which shows that we can decrease the minimum of the objective function by increasing \( K \).

Therefore, the optimal solution for P1 is the same as that for P2 if \( K = N - 1 \).

**IV. PERFORMANCE EVALUATION**

To evaluate the performance of duty cycle control algorithm, we compare the numerical analysis and the simulation results for the total energy consumption of the most critical node in each tier. Figs. 5(a) and 5(b) show that the simulation results match well with the results derived from the numerical analysis, (22), for \( N=5 \) and 10 respectively.

The energy consumption in simulation is larger than that in analysis, but the difference is small regardless of the total number of tiers. Surprisingly, it is not optimal to allocate higher duty cycle to a tier closer to the sink node. Actually, we obtain the better performance by allocating the duty cycles as a convex shape against the tier ID as we can see in Fig. 5. The tier with the lowest duty cycle is tier 3 for \( N=5 \), and tier 4 for \( N=10 \). For all the cases, the delay constraint in (12) is always satisfied.

In Figs. 6(a) and 6(b), we compare the energy consumptions of the network with and without the duty cycle adaptation (i.e., original tier-based scheme) for \( N=5 \) and 10, respectively. The numerical results confirm that the network lifetime is increased by 29% and 26% for \( N=5 \) and 10, respectively. Similarly, the simulation results confirm the enhancement of 29% and 28%, respectively.
V. CONCLUSION

In this paper, we proposed an optimal duty cycle allocation algorithm for tier based anycast protocol. The algorithm is evaluated by numerical analysis and simulations, and shown to increase the network lifetime by approximately 30% compared to the original tier-based scheme. Against our intuition, we found that the best performance could not be achieved by allocating a higher duty cycle to a tier near to the sink node. Our duty cycle allocation algorithm can run at the top of any existing tier based anycast protocol to extend the network lifetime.

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