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Abstract

In this paper, an average consumed energy for a unit data transmission is analyzed in frequency-agile cognitive radios. The average energy consumed by a random access protocol operated in a channel using a whole system bandwidth is compared with that operated in frequency-separated channels, which results in an energy saving ratio. The energy saving ratio quantitatively evaluates an energy saving effect by separating one whole bandwidth into more than one channel with a smaller bandwidth. Finally, it is shown that the frequency-separated channel can save energy of machine-to-machine communicating nodes using the random access protocol, so the battery life can be extended.

Keywords: Cognitive Radios, Random Access, Energy Saving

1. Introduction

Cognitive radios allow secondary users to access a spectrum exclusively allocated to a primary communication system for the efficient frequency resource utilization. IEEE 802.22 and IEEE 802.11af which can access temporarily unused spectra for television are representative examples of cognitive radios [1, 2]. Cognitive radios combining with the software-defined radio are able to dynamically change its communicating frequency and protocols in order to adapt to wireless communication environments [3].

Machine-to-machine communication (M2M) is a brand new wireless network to manage hundreds or thousands of wireless communication nodes in a small area. Hence, M2M network needs to be adapting its system parameters depending on the number of nodes or what services have to be supported. Such technical demands of M2M networks go with the technical characteristic of cognitive radios. From this technical penetration, it is expected that cognitive radios can give us an effective technical solution for the practical implementation of M2M networks [4, 5].

For example, a M2M network might consist of heterogeneous wireless communication systems with different purposes. There is no way to communicating each other among heterogeneous wireless communication systems because they may have different physical layers and protocols. In addition to that, we cannot imagine the scale of the M2M network. In such communication environments, cognitive radio can give a solution to the M2M network.
For instance, all M2M nodes which belong to different systems can harmonize their communications by changing their multiple access protocol to a random access protocol. Hence, they can share a spectrum by detecting other systems’ signal energy although there is no specified control information exchange.

A wireless communication module for M2M might be attached to small devices such as bio-sensors. Those devices are battery-based portable ones, which should be sensitive to the energy consumption [6, 7]. Moreover, it is known that a M2M network consists of hundreds of wireless nodes at least. Accordingly, an energy-efficient multiple access scheme has to be needed [8].

In this paper, the slotted ALOHA protocol is adopted for the multiple access of a M2M network. The slotted ALOHA protocol is a random access which does not require any additional access process and signaling overhead, which is an advantage for the low energy consumption. However, every random access protocol has the collision problem. Hence, using the frequency agility of cognitive radios, a whole bandwidth for the M2M system is separated into more than one slotted ALOHA channel. Due to the channel separation, the throughput of a separated channel is degraded, but the collision probability should be reduced. From this tradeoff relationship, the access probability of each M2M node to minimize the energy consumption is numerically analyzed.

2. System Model

The system model considered in this paper is depicted in Figure 1. A whole system bandwidth $B$ is separated into $N$ channels used for M2M communications. M2M nodes access the channel through the slotted ALOHA protocol. In each channel, ‘I’ means an idle slot where no M2M node transmits a signal. ‘S’ means a slot where a successful transmission occurs. The successful transmission can be made only when a M2M node transmit a signal in a slot. If more than one M2M node transmit signals in a slot, a collision occurs, which is symbolized as ‘C’ in Figure 1.

![Figure 1. System Model: Slotted ALOHA with Channel Separation](image-url)
The number of separated channels $N$ can be changed. For example, a channel can occupy the whole bandwidth, or it can be separated into plural channels if collisions frequently occur due to too many accesses by M2M nodes. Figure 2 shows the case that one channel with the bandwidth $B$ and the slot length $L$ is separated into four channels with the bandwidth $B/4$ and the slot length $4L$. The length of a slot is $L$ when the whole bandwidth is used for a channel. In order to maintain the throughput of a slot by the channel separation, the length of a slot becomes $N \cdot L$ when the whole bandwidth is separated into $N$ channels. This throughput normalization with respect to a slot provides fair comparison for the performance of the energy consumption because the energy for a transmission is identical.

**Figure 2. One Channel is Separated into Four Channels**

An M2M node consumes different amounts of energy depending on its state. Two states are basically assumed, which are idle and transmission states. In the transmission state, a M2M node consumes energy $E_T$ regardless of the number of the separated channels because the multiplication of time, frequency resources and transmission power is always the same value due to the throughput normalization. However, the consumed energy in the idle state is proportional to only the time. Hence, in the idle state, the consumed energy of a slot in the $N$-separated channel case is $N \cdot E_I$ when $E_I$ is the energy consumed in an idle slot if the whole bandwidth is used for a channel.
3. Numerical Analysis of Average Consumed Energy

A whole bandwidth is separated into $N$ channels, and there are $M$ M2M nodes in each channel. If the probability that a certain node transmits a signal in a slot is $p_M$ [9], the probability that a data frame is transmitted at the $k$-th slot is calculated as:

$$p(k) = p_M \cdot (1 - p_M)^{k-1}$$

(1)

Because $k$ slots are consumed for a data transmission, the total consumed energy for the data transmission can be calculated as:

$$E(k) = N \cdot (k - 1)E_I + E_T$$

(2)

From the equation (1) and (2), the average energy consumption for a data transmission at each slot can be calculated as:

$$E_{AVG} = \sum_{k=1}^{\infty} P(k) \cdot E(k) = \left( \frac{1}{p_M} - 1 \right) \cdot N \cdot E_I + E_T$$

(3)

Detailed derivation process is presented in Appendix.

The equation (3) does not consider collisions among M2M nodes. Hence, the collision probability should be applied to (3), then we can finally derive the practical energy consumption for a data transmission per a slot.

The probability that there is no collision at a slot is formulated as a conditional probability as:

$$P_s = \text{prob}[P_0 \mid P_1] = (1 - p_M)^{M-1},$$

(4)

where $P_0$ is the probability that a certain node transmits data, and $P_1$ is the probability that the other $M-1$ nodes keep silence. Accordingly, the probability that $l(l \in \{0,1,2,...,\infty\})$ collisions occasionally occur before a successful transmission can be calculated as:

$$E_{off} = \sum_{l=0}^{\infty} E_{AVG} \cdot P_s \cdot (1 - P_s)^l,$$

(5)

which is the effective energy consumption. Hence, the effective energy consumption is an average power consumption considering not only the last successful transmission but also collided transmissions for the only the last successful transmission. Performance comparisons with respect to the transmission probability of a M2M node $p_M$ and the number of the separated channels $M$ let us know how to efficiently operate the slotted ALOHA protocol for an energy-efficient M2M network.

The effective energy consumption is normalized by $E_T$. The effective energy consumption is expressed as a multiple of $E_T$. The energy consumption in the idle state $E_I$ is also expressed as $R \cdot E_T$, and it can be generally assumed $R << 1$.

In Figure 3, the effective energy consumption with respect to $p_M$ is plotted. Thinking about the result intuitively, more energy is consumed for idle slots while the
probability $p_M$ is getting lower. However, for too high probability $p_M$, there might be many collisions for a successful transmission. From this penetration, we can expect that there could be the value of probability $p_M$ in order to minimize the effective energy consumption when the tradeoff between energy consumption for idle and collision slots is considered.

As we can see in Figure 3, an M2M network with 128 nodes needs less effective energy consumption than that with 256 nodes. Such phenomenon occurs because there is more collisions expected as the number of M2M nodes in a channel increases. When the value of $R$ increases (more energy consumption for the idle state), the effective energy consumption also increases. The value of $R$ depends on what communication processes are running in the idle period, which can be varied by the purpose of the communication system. The most important observation of this figure, there exists the minimum transmission probability $p_M^*$, which can be obtained by numerical analysis such as the half-separation methodology [10]. The effective energy consumption of the case that $M = 256$ is more sensitive to $p_M$ than The effective energy consumption of the case that $M = 128$ due to more collisions when $M = 256$. The optimum values of $p_M^*$ with respect to the number of M2M nodes $M$ and the value of $R$ are presented in Table 1.

![Figure 3. Effective Energy Consumption with Respect to $p_M$](image-url)
Table 1. \( p_M^* \) to Achieve the Minimized \( E_{\text{eff}} \)

<table>
<thead>
<tr>
<th></th>
<th>( M = 256 )</th>
<th>( M = 256 )</th>
<th>( M = 128 )</th>
<th>( M = 128 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R = 0.01 )</td>
<td>( R = 0.005 )</td>
<td>( R = 0.01 )</td>
<td>( R = 0.005 )</td>
</tr>
<tr>
<td>( p_M^* )</td>
<td>0.0030</td>
<td>0.0026</td>
<td>0.0052</td>
<td>0.0042</td>
</tr>
<tr>
<td>( E_{\text{eff}} )</td>
<td>9.3015</td>
<td>5.6677</td>
<td>5.6482</td>
<td>3.7298</td>
</tr>
</tbody>
</table>

4. Effective Energy Consumption when using Channel Separation

The effective power consumption is evaluated when the channel separation is adopted. As we assumed in the system model, the whole bandwidth is separated into \( N \) channels, and \( M/N \) M2M nodes access each channel. While the length of a slot increases proportional to \( N \) by the channel separation, the number of M2M nodes which access a channel linearly decreases as \( N \) increases, which results in less collisions. Hence, it is expected that the effective energy consumption decreases.

Figure 4 shows the effective energy consumption with respect to \( p_M^* \) as the number of separated channels increases from 1 to 16 and 128. In legends of this figure, ‘A’ means analytical value obtained by the equation (5) and ‘S’ means simulation results. Values of \( p_M^* \) to achieve the minimum effective power consumption are marked by *.

As we can see in Figure 4, the effective energy consumption is minimized by a certain value of \( p_M^* \). Moreover, the minimum effective energy consumption decreases although the energy consumption for the idle state increases as the number of separated channels increases. Therefore, we can know that the proposed channel separation scheme in the slotted ALOHA protocol is effective to reduce the energy consumption to transmit the same amount of data although the energy consumption for the idle state increases by the channel separation.
In the simulation result in Figure 5, it is assumed that $M = 256$. In order to observe the effective energy consumption with respect to $R$, it is assumed that $E_I$ is 2%, 1% and 0.5% of $E_T$.

Figure 5 shows that the effective energy consumption decreases as the number of separated channels increases. In this result, the value of $p^*_M$ is used just as in Figure 4. In the equation (3), although it is formulated that the energy consumption of the idle state is increased by the channel separation, resultant effective energy consumption decreases due to saving energy by less collisions.

Next, a new performance evaluation parameter is defined in order to relative comparison of $E_{eff}$ as:

$$S(N) = \frac{E_{eff}(N)}{E_{eff}(1)}$$

(6)

The evaluation parameter $S(N)$ in the equation (6) is a ratio of the energy consumed with no channel separation and the energy of consumed with $N$-separated channels. We call this parameter energy saving rate. The energy saving rate let us quantitatively measure how much amount of energy is saved by the channel separation.

Figure 6 shows the energy saving rate obtained by the equation (6). As an overall observation, it is seen that the larger the value of $R$ is, the more the amount of saved energy is as the number of separated channels increases. More specifically, when $R = 0.01, 0.02$, 

![Figure 5. Reduced $E_{eff}$ by Channel Separation](image-url)
only half amount of energy is consumed for the same amount of data transmission, compared with the energy consumption with no channel separation. In other words, the node operation time is lengthened two times although the same capacity of the battery is used through the channel separation. The case of \( R = 0.005 \) consumes only a very small amount of energy for the idle state. However, even in such case, the node operation time becomes seventy percentile longer by using the channel separation.

From these results, the proposed channel separation scheme can effectively reduce the energy consumption for a successful transmission even in wireless communication environments using the random access with the massive number of M2M nodes. Accordingly, energy constrained-M2M devices such as bio-sensors using the battery can lengthen the change cycle of the battery, which might be helpful for the practical implementation of wireless-communication-aided M2M devices.

Although the channel separation scheme is proposed in order to save energy for the M2M network in this paper, it is yet mathematically analyzed that how much energy saving can be achieved by what number of channel separation. This paper is partially providing a mathematical approach. Analyzing the equation (6) with respect to \( p_m \) and \( N \) let us know what number of channel separations is the optimum value in order to minimize the effective energy consumption, which is left as a future work.

![Figure 6. Energy Saving by Splitted Channels](image)

5. Conclusion

In this paper, using the frequency agility of cognitive radios, the effect of the channel separation on the energy consumption was evaluated. For the practical evaluation, we considered the energy for both the transmission and idle states. From this investigation, it is
known that plural narrow band channels by the channel separation is more effective for the energy saving than the whole bandwidth for one channel in the wireless communication environments using the slotted ALOHA protocol, which can be practically applied to energy-constrained M2M devices. This work reduces the energy consumption for a successful transmission even in wireless communication environments using the random access with the massive number of M2M nodes, which contribute to the practical implementation of wireless-communication-aided M2M devices such as bio-sensors using the battery because the change cycle of the battery can be lengthened.

Appendix

Derivation process of (3) is as follows. The equation (3) is rewritten as:

$$E_{AVG} = \sum_{k=1}^{\infty} p(k) \cdot E(k)$$

$$= \sum_{k=1}^{\infty} \left( N \cdot (k-1) \cdot E_i + E_T \right) \cdot p_M \cdot (1 - p_M)^{k-1}$$  \hspace{1cm} (A-1)

$$= \frac{p_M \cdot N \cdot E_i \sum_{k=1}^{\infty} (k-1)(1-p_M)^{k-1}}{A} + \frac{p_M \cdot E_T \sum_{k=1}^{\infty} (1-p_M)^{k-1}}{B}$$

For the sake of the computational convenience, two terms $A$ and $B$ are separately calculated.

In the term $A$, what we should calculate is a power series the term $C$ in the following equation as:

$$A = p_M \cdot N \cdot E_i \sum_{k=1}^{\infty} (k-1)(1-p_M)^{k-1}$$  \hspace{1cm} (A-2)

In the equation (A-2), $\sum_{k=1}^{\infty} (k-1)(1-p_M)^{k-1}$ can be simply substituted by $\sum_{k=0}^{\infty} (1-p_M)^{k}$. In order to calculate the power series in (A-2), the term $C$ is differently expressed by two equations as:

$$C = 0 + (1-p_M) + 2(1-p_M)^2 + 3(1-p_M)^3 + \cdots$$

$$(1-p_M) \cdot C = 0 + (1-p_M)^2 + 2(1-p_M)^3 + \cdots$$  \hspace{1cm} (A-3)

By subtracting the second equation from the first equation in (A-3), we can get an intermediate solution for (A-1) as:

$$C -(1-p_M) \cdot C = \sum_{k=1}^{\infty} (1-p_M)^k = \frac{(1-p_M)}{p_M}$$  \hspace{1cm} (A-4)
Simplifying (A-4), the term C is calculated as:

\[ C = \frac{(1 - p_M)}{p_M^2} \quad \text{(A-5)} \]

Applying (A-5) to (A-2), the term A is derived as:

\[ A = \left( \frac{1}{p_M} - 1 \right) \cdot N \cdot E_t \quad \text{(A-6)} \]

Similar to the derivation process of the term A, the term B is easily calculated, and finally derived as:

\[ B = E_t \quad \text{(A-7)} \]

Combining (A-6) and (A-7) together, the equation shown in (3) is completely derived.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(2012R1A1A1042813).

References


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