A Wake-up Radio protocol based on adaptive backoff and dynamic CCA in Wireless Sensor Networks

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Abstract. Asynchronous wake-up communication based on wake-up radio (WuR) is an important energy-saving method in wireless sensor networks (WSNs). The Clear Channel Assessment (CCA) is a major section of energy consumption in asynchronous WuR-based nodes. The traditional static backoff will lead to longer waiting delay which increase the energy consumption of successful sending packets when the network traffic becomes heavier. So a protocol DNAP-WuR is proposed to solve these problems in the terminal initiated (TI) communication mode. It first implements the dynamic CCA optimization (DCO) mechanism which allows nodes to interrupt the CCA process as soon as the channel is busy. Nodes can go to sleep faster during busy periods, instead of performing CCA detection until the counter is reduced to zero. And then, the WuR based adaptive logarithm backoff (WALB) algorithm is used to predict the backoff time sequences which can reduce the WuC’s collision probability and decrease the energy consumption according to the nodes number and the packet arrival rate. In order to avoid the phenomenon that the backoff window size is reduced too fast or increased slowly after packets transmitted. Compared with CSMA-WuR protocol, the DNAP-WuR has 4.6% reduction in energy consumption and 12.1% promotion in throughput.

1. Introduction
Asynchronous WuR can save more energy than the traditional duty-cycled mode in WSNs [1]. Under these circumstances, an ultra-low power WuR which is attached to the MCU of nodes is used in this paper [2]. The MCU is only waked up to start data communication by I/O ports when the wake-up receiver (WuRx) receives the wake-up call or the wake-up transmitter (WuTx) detects that the channel is idle. The networks using asynchronous WuR competition mode have three communication types, terminal initiated, sink initiated and bidirectional wake-up type [4-5].

Sink initiated mode can be used for smart meter reading system, vehicles, and aircrafts. When a sink needs to acquire data, it first sends WuCs to destination nodes, since the destination node's WuRx is always listening to the channel, the WuCs can be processed quickly. If the address segment in the WuC matches successfully, the WuR will generate an interrupt signal to wake up the MCU. And the MCU send packets to the sink, and the sink enters sleep state after returning Data-ACK. However, this mode wastes a lot of transmission opportunities when the network traffic is heavy.

TI mode can be used for wireless body area networks and environmental monitoring. The MCU sends a signal to the WuR to start the communication immediately when a terminal node (TN) has data to transmit. And the wake-up transmitter (WuTx) implements the backoff mechanism and CCA. The TNs in the DM-OH protocol [6] will monitor the state of the target node before transmission. When the destination node sends a WuC or other information, the source nodes consider that the destination node
has been woken up, so it sends the packet directly instead of WuC. Piyare [7] proposed a balance plan between delay and energy. The BoWuR protocol [8] uses the CSMA/CA medium access control (MAC) to check the channel state before sending the WuC. It reduces the collision probability of the WuC, but the delay and energy consumption are too high. Most WuR protocols are based on saturated networks in this mode, which are obviously not very accurate. The TNs can send packets in any time by itself, so there are three states in the network: idle state which means no data is in the queue; unsaturated state, some nodes are transmitted in the network, but two packets are sent at a larger interval; saturated state, multiple nodes sent packets in the same time period. Therefore, only the saturation state model using in this case could not analyse the state changing well. According to the extended Bianchi model for unsaturated networks [9], the M/G/1 queue and the Markov chain model can be used to analyse the discrete states of nodes in these networks.

The modes that support the two modes above can be used for smart grid and indoor positioning. In this mode, the nodes can select the communication mode according to the current network state or the beacon frame. When the traffic in the network is light, the sink initiated mode is adopted, in another hand, the TI mode is adopted. But nodes may not switch the mode in time to adapt to the network changing, so that some new problems will occur to increase the loss probability of packets.

In this paper, we consider the TI mode networks. The CCA-WuR and CSMA-WuR [10] are not very effective in this mode, so we propose a dynamic adaptation WuR protocol (DNAP-WuR) to improve performance of delay and energy consumption. The CCA process can be interrupted when the channel is busy and go to sleep earlier in DCO. And the backoff time sequences are predicted by the packet arrival rate and nodes number. Compared with the CSMA-WuR, our protocol’s energy consumption and packet loss probability are reduced. Moreover, we have developed a node’s collisions probability model using the queue model [11] to analyse the proposed protocol and other protocols.

Figure 1. Application scenario.

2. Network scenario and proposed protocol

2.1. Network scenario

The network scenario in this paper is single hop, as shown in Figure 1. N nodes use asynchronous CSMA methods to send packets to the same sink. The WuR platform considered in this paper is the CSMA-WuR, which adopts a backoff mechanism similar to Binary Exponential Backoff (BEB) and fixed CCA detection time, and the WuCs and data are transmitted on the same channel by dynamically switching the antenna configurations.

2.2. DNAP-WuR: adaptive WuR MAC protocol

When the network traffic is light, DCO needs the same detection time as the CCA-WuR. When the network traffic increases, the DCO mechanism considers that when one of the CCA times display that channel is busy, the other CCAs also show the channel is busy. So it is not necessary to execute the remaining CCAs, and directly enters the next backoff phase or sleep state. If the channel is idle, the
MCU may send WuC in other nodes’ switching time, so the CCA is necessary to continuously detect the $T_{on} / T_{CCA}$ times. This allows the node to use less CCA time to achieve the same probability reducing effect and also reduces the consumption, as shown in Figure 2.

In DNAP-WuR protocol, each TN needs to set the backoff time of each transmission according to the backoff time sequences (BS) predicted by the WALB algorithm before communication. Figure 3 illustrates the working process of DNAP-WuR, where BN is the backoff times and BE is the maximum index of the backoff windows. The nodes initialize the backoff counter by randomly selecting a value from 1 to BS (BN). If the TN detects that the channel is idle after the backoff phase is completed, the second detection is continued until the CT times detection are all idle. If the channel is busy during the CCA time, the CT counter is reset and the next backoff phase is advanced. The process of BO and CCA is repeated until the transmission number reaches the upper threshold $M$.

3. Node collision probability model analysis
The node collisions model is based on the following assumptions. The node packets arrival rate is subject to the Poisson distribution with the parameter $\lambda$. The symbol error rate is zero and there are no hidden TNs in the network. Considering the characteristics of small sensor cache, this paper uses M/G/1/2 queue to model the collision process of TNs. We think that there are three kinds of node states in this model, WuR backoff state, WuR CCA state and MCU data transmission state. Therefore, the TN’s busy period is the sum of the three parts: WuR send WuC successfully after CCA, generate collisions during WuC sending time or discard the packets. If there is still a packet need to send after the first communication completed, the busy period will continue until the packet is sent. So the busy period can be calculated as:

$$W(k+1)=\max(\log_2 N+\log_2 \lambda + 1, (1-1/2(\log_2 N+\log_2 \lambda + 1)/W(k)))$$

$$W(k+1)=\min(\log_2 N+\log_2 \lambda + 1, W(k), 2^{BE})$$
\[NE[\Gamma](c_{sum}(s_{sum}T_{CCA} + T_{wac} + S_{MCU}) + d_{sum}(s_{sum}T_{CCA} + T_{wac} + F_{MCU})) \]

\(N\) indicates the TN number in the networks, \(E[\Gamma]\) means the average packet count sent by nodes during the busy period, \(c_{sum} = \sum_{k=0}^{M} \alpha^k (1 - \beta)\) and \(d_{sum} = \sum_{k=0}^{M} \alpha^k \delta(1 - \alpha)\) are the probability of successful transmission and WuC collision. \(T_{CCA}\) indicates the CCA unit time, \(g_{sum}\) is the average CCA times, \(T_{wac}\) is the WuC sending time, and \(\alpha\) represents the packets discard probability.

\[S_{MCU} = T_{on} + T_{h} + T_{SIFS} + T_{ack}\]

is the time required for the primary transceiver data sending and ACK receiving. Among them, \(T_{on} = \) is the delay that MCU switches the sleep state to normal state. \(T_{h}, T_{SIFS}\) and \(T_{ack}\) are the time required for the data header and load transmitting, the shortest frame interval and the ACK receiving. \(F_{MCU} = T_{on} + T_{h} + T_{i}\) is the time taked for the primary transceiver to send data but not receive an ACK. Because the CCA times is dynamically changing, the following specifically explain how to calculate \(g_{sum}\). If the channel is busy, it is no need to perform the CCA continuously. If the channel is idle, it needs to continuously detect the channel. The upper limit is equal to the value of state switching delay divided by CCA unit time and round toward the positive infinity. Therefore, \(g_{sum}\) can be expressed as:

\[g_{sum} = (\sum_{l=2}^{M}(D(k-1) - D(k-2) + T_{CCA} / (D(k-1))) * (c(k) + d(k)) / 2 \]

\[+ \sum_{l=0}^{k-1}(T_{CCA} / (D(k+1))) * (c(k) + d(k)) + (D(M) * \beta^{M-l} / (M+1))\]

Where \(D(k-1)\) is the average CCA detections count when the k-th WuC is issued. \(c(k) = \alpha^k (1 - \beta)\) and \(d(k) = \alpha^k \delta(1 - \alpha)\) are the average probability of the successful data sending until the k+1-th data transmitted in the busy period or produced collisions. Where k is the current number of retransmissions, \(M=7\) means the maximum retransmission number allowed by nodes; \(\beta = \alpha + \delta(1 - \alpha)\) represent the sum of the channel busy periods and collisions probability, and \(\delta(1 - \alpha)\) is generated that the collisions probability when the WuC was sent. Two or more nodes may simultaneously perform the CCA, the \(\delta\) represents the probability above and can be expressed as \(\delta = 1 - P_{N-1}^{SC}\). \(P_{N-1}^{SC}\) is the probability that N nodes detected that channel was idle simultaneously in the k backoff phases, and \(P_{SC}\) can be written as:

\[P_{SC} = 1 - T_{slot}^{2C} / (W_{BO}(k) + W_{CCA}(k))\]

The DNAP-WuR protocol uses the WALB algorithm to predict the backoff time sequences. When the traffic is small, a smaller window is used, when the traffic is large, window size must increase. Therefore, the average backoff time \(W_{BO}\) of the k-th transmission attempt can be expressed as:

\[W_{BO}(k) = 1 / 2 \times \sum_{i=1}^{k} CW(v) T_{BO}\]

\[T_{BO} = T_{CCA} = T_{slot}\]

means the unit time of a slot. Because the CCA time may be different, and there is also a delay from MCU switching, so \(W_{CCA}\) can be calculated as:

\[W_{CCA}(k) = \sum_{l=1}^{k} C_{CCA} + D(k-2) T_{CCA} / D(k-2) T_{CCA} \]

\[k = 2, ..., M \]

\[k = M + 1 \]

In the DCO mechanism, when \(k=1\), only CCA was performed before the WuC transmission, so there is no need to calculate the value of backoff. When \(k\) is equal to other values, the nodes randomly select the backoff window size from 1~CW before each transmission, and then perform CCA mechanism. \(D(k)\) is the average CCA counts required for \(k+1\) transmission attempts, expressed as:

\[D(k) = \sum_{i=0}^{k-1} C_{k+1} P_{C}^{k+1-v} P_{B}^{v} * ((k+1-v) * 1 + C_{f} / 2 + v) + P_{B}^{k+1} \delta(k+1)\]

Thence, the expectation of backoff and CCA delay of packets waiting time can be calculated as:

\[E[D_{ho.}] = \sum_{k=1}^{M+1} \alpha^{k-1} (1 - \alpha)(W_{BO}(k) + W_{CCA}(k)) + \alpha^{M+1} D_{WuR}\]
$D_{WUR}$ indicates the WuR takes time from CCA detecting to packets dropping. In the nodes’ collisions probability model, we use $a_0$ to represents the probability that the packet is the only one in the queue. According to the same reason in [10], We can get the expected number of service packets in the system during busy period, probability $0a_0$ is showed as follows, and $E[\Gamma] = 1/a_0$:

$$a_0 = \sum_{k=0}^{M} \alpha^k \delta(1-\beta)e^{-(W_{BO}(k)+W_{CCA}(k)+S_{MCU}+F_{MCU})}, \quad + \alpha^{M+1}e^{-D_{back}}. \quad (8)$$

According to the formula in [11], the probability can be write as:

$$\alpha = NE[\Gamma](c_{sum}(g_{sum}T_{CCA}+T_{wuc}+S_{MCU})+d_{sum}(g_{sum}T_{CCA}+T_{wuc}+F_{MCU}))/((1/\lambda + E[\Gamma])E[D_{Hol}]). \quad (9)$$

4. Performance analysis

4.1. Loss probability of WuC

The simulation parameter settings in this chapter are shown in table 4. When the nodes detect that the channel is busy after M times backoff and CCA, they will discard the packets. If the collisions occurred, the packets will be also discarded. Therefore, the packet loss probability $\beta$ can be calculated as the sum of the two parts above.

As shown in Figure 4, the nodes in GWR-MAC protocol must wait for a beacon frame after each WuC, so the packets loss probability is high. The DCO mechanism based protocol and DNAP-WuR have 3.2% and 7.1% lower than the CSMA-WuR in packet loss probability, because the CSMA-WuR continuously monitor the channel regardless of whether it is idle or busy.

4.2. Average delay

There are three cases in the process when the nodes have packets to send: the packet is discarded and the WuC is not sent; the WuC is sent but collisions occurred; the WuC and packet are both successfully sent. So the average packet delay $T_A$ can be calculated as the sum of WuR and MCU:

$$T_A = S_{WUR} + c_{sum}S_{MCU} + F_{WUR} + d_{sum}F_{MCU} + (1-c_{sum}-d_{sum})D_{WUR} \quad (10)$$

$S_{WUR}$ and $F_{WUR}$ are the backoff and CCA time that WuR needs to perform when the packets are successfully transmitted or collisions occurred. Obviously, $D_{WUR}$ can be expressed as:

$$D_{WUR} = 1/2 \sum_{v=0}^{M} CW(v)T_{BO} + (C_T + D(M))T_{CCA} \quad (11)$$

Similarly, $S_{WUR}$ can be expressed as:

$$S_{WUR} = \sum_{k=1}^{M+1} \alpha^{k-1}(1-\beta)(W_{BO}(k)+W_{CCA}(k)+T_{wuc}) \quad (12)$$

$T_{wuc}$ is the time required to send a WuC, in the same reason $F_{WUR}$ is the delay that WuR send a WuC but generate a collision. It can be expressed as:

$$F_{WUR} = \sum_{k=1}^{M+1} \alpha^{k-1}(1-\alpha)(W_{BO}(k)+W_{CCA}(k)+T_{wuc}) \quad (13)$$

In Figure 5, the DCO mechanism based protocol is 51.6% and 17.5% lower than the CCA-WuR and CSMA-WuR in delay, because the they take too much time on CCA. The DNAP-WuR is due to the dynamically adjusted backoff window size, and the backoff time may be longer than other protocols. The nodes in GWR-MAC protocol sent WuC after the beacon frame comes and need long time waiting for beacon frame when the number of nodes is small, so delay may higher than CSMA-WuR.

But its delay approaches the CSMA-WuR when the nodes count increases.

4.3. Energy consumption

The formula is the same as the delay. So it can calculate as:

$$E_A = E_{WUR} + G_{WUR} + (1-c_{sum}-d_{sum})H_{WUR} + c_{sum}E_{MCU} + d_{sum}G_{MCU} \quad (14)$$
Table 1. Simulation parameter [1][9][10]

| Module type               | Parameter                  | Value | Unit |
|---------------------------|----------------------------|-------|------|
| Micro-Controller Unit     | Transmission power         | 52.2  | mW   |
|                           | Reception power            | 56.4  | mW   |
|                           | SIFS time                  | 192   | µs   |
|                           | Packet transmission time   | 1.472 | ms   |
|                           | ACK reception time         | 0.352 | ms   |
| Wake-Up Radio             | Transmission power         | 456   | mW   |
|                           | Reception power            | 24    | mW   |
|                           | Switching power            | 8.1   | µW   |
|                           | Backoff Mode power         | 15.48 | mW   |
|                           | CCA Mode power             | 60.84 | mW   |
|                           | Slot time                  | 320   | µs   |
|                           | WuC Send Time              | 12.2  | ms   |
|                           | Switching Time             | 1.79  | ms   |

Figure 4. Packet loss probability of DCO based protocol, DNAP-WuR and other protocols. (\(\lambda = 10 \text{ packets / s}, CW = 32 \text{ slots}\))

Figure 5. Average delay of DCO based protocol, DNAP-WuR and other wake-up protocols. (\(\lambda = 10 \text{ packets / s}\))

Where \(E_{WUR}\), \(G_{WUR}\), \(H_{WUR}\), \(E_{MCU}\) and \(G_{MCU}\) are the energy consumption of which the WuRs detect that the channel was idle and generate wake-up interrupts to the MCU after receiving the data transmission signal; WuRs detect that the channel is busy and drop the packets; WuRs send WuCs but...
make collisions; MCUs send packets and receive ACK, and send packets without receiving the ACK. \( E_{MCU} = E_m + E_{\text{ack}} + E_{WUR} + E_{WUR} \), where \( E_{MCU} \) is the energy consumption of the MCU switching from the sleep state to the normal state, \( E_m \) and \( E_{\text{ack}} \) are the energy consumption required to transmit the packet header and load, \( E_{WUR} \) is the energy consumption in the idle time, and \( E_{WUR} \) is the energy consumption required to receive the confirmation frame. \( WUR \) means the energy consumption of WuR successful sending a WuC, which can be expressed as:

\[
E_{WUR} = \sum_{k=1}^{M+1} \alpha^{k-1}(1 - \beta)(W_{BO}(k)P_{BO} + W_{CCA}(k)P_{CCA} + E_{wac})
\]

(15)

Where \( E_{wac} \) means the energy consumption for WuCs sending, so \( G_{WUR} \) can be expressed as:

\[
G_{WUR} = \sum_{k=1}^{M+1} \alpha^{k-1}(1 - \beta)(W_{BO}(k)P_{BO} + W_{CCA}(k)P_{CCA} + E_{wac})
\]

(16)

Similarly, the energy for dropping packets can be calculated as:

\[
H_{WUR} = 1/2 \sum_{v=0}^{M} CW(v)E_{BO} + (C_T + D(M)E_{CCA})
\]

(17)

As shown in Figure 6, the energy consumption of DCO mechanism based protocol is 25.8% and 19.3% lower than CCA-WuR and CSMA-WuR, because CCA-WuR and CSMA-WuR consume more energy in CCA and retransmission. The energy consumption of DNAP-WuR is reduced by 4.6%, because more energy is cost during the backoff phase. But overall, it is slightly lower than CSMA-WuR. And the GWR-WuR consumes more energy because it must wait for the beacon frame.
4.4. Throughput

The normalized throughput is defined as the packet sending time divided by the total sending time. So it can be expressed as:

\[
\text{Throughput} = \frac{N\mathbb{E}[\Gamma](1-\beta^{M+1})(T_{\text{wuc}} + S_{\text{MCU}})}{(1/\lambda + \mathbb{E}[\Gamma](E[D_{\text{col.}}]+T_{\text{wuc}}+S_{\text{MCU}}))}
\]  

(18)

As shown in Figure 7, the throughput of several protocols is increased first and then decreased. When the nodes count is small, the successfully transmitted packets count is greater than collisions, so it shows upward trend. And it is opposite when the nodes number reaches a certain extent. The DNAP-WuR uses a shorter backoff time when the network traffic is light, and then backoff time increases dramatically as the traffic become heavy. Compared with the CCA-WuR and CSMA-WuR, the throughput is improved 22.2 and 12.1 percent in our protocol. And DCO mechanism shortens the CCA time and has more opportunities to send data, so it increases about 9.1% and 7.9% in throughput.

5. Conclusion

The energy consumption and delay of traditional WuR protocols are too high in the traffic changing network. So a DCO mechanism and a WALB algorithm are proposed to solve these problems. They can effectively reduce the energy consumption of the WuR protocols which are based on the asynchronous CSMA mechanism and improve the networks throughput. And we consider the factor that multiple nodes will send WuCs simultaneously based on the M/G/1/2/N queue model. Compared with CCA-WuR, the DCO based protocol reduces the 25.8% in energy consumption, and reduces the 51.6% in delay. It is suitable for low delay requirements static networks. Compared with CSMA-WuR, the DNAP-WuR has a 4.6% reduction in energy consumption and 12.2% increase in throughput, so it is suitable for the traffic changing network. In the future, we will consider appropriate researches on the anti-jamming and packets loss probability model in static tree networks. With the rapid development of WSNs, it is hoped that the WuR based protocols can be applied in more aspects.

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