The Energy Cost of Control Packets in Hybrid MAC Protocols

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***Abstract*—This paper investigates the energy cost of control packets in schedule-based medium access control protocols in wireless sensor networks. Control packets can be useful not only to minimise collision, but also to avoid idle listening and overhearing. Therefore, whether or not to apply control packets is a trade-off. It will be shown that this trade-off mainly depends on the packet arrival rate at individual nodes, the transmission rate and the average number of active neighbours in the network.**

I. INTRODUCTION

This paper investigates the energy cost of control packets (i.e., RTS, CTS and ACK packets) in hybrid MAC protocols in wireless sensor networks. These protocols enable nodes to periodically sleep to avoid idle listening and overhearing, and apply carrier sense and back-off mechanisms to win the media for data transmission. During contention, some of them (such as BMAC [3], IEEE 802.15.4a [1] and XMAC [4]) do not employ control packets, while others do (such as T-MAC [2] and SMAC [11]) to avoid collision.

The decision of using collision avoidance mechanisms should take several aspects into consideration, such as the node architecture and technology; and the sensing task and the deployment setting. Particularly, it has to take packet arrival rate, transmission rate and average number of active neighbours into account. To justify this assertion, the trade-off between the energy costs introduced when control packets are activated and when they are deactivated should be quantified. This paper carries out this task.

The rest of the paper is organized as follows: in section II, related work is summarized. In section III, a brief introduction about hybrid MAC protocols is given. In section IV, an overlap neighbouring model is introduced. In section V and VI, the energy cost of control packets is analyzed in detail. In section VII, the energy trade-off is visualized and observations are discussed. Finally, in section VIII, concluding remarks are given.

II. RELATED WORK

Zhu et al. [5] evaluate the energy consumption of control packets and packet retransmission in both end-to-end and hop-by-hop cases. Dargie et al. [6] provide a comprehensive energy model for a fully operational wireless sensor network that monitors toxic gas detection during oil exploration and refinery; the MAC protocol employs control packets. Wang et al. [7] analyze the relationship between the energy consumption and the average hop number; and propose a method to reduce the hop number for minimizing the energy consumption during multi-hop transmissions. Bruno et al. [8] investigate the efficiency and the energy consumption of MAC protocols that can be described with a p-persistent CSMA. Sun et al. [9] apply two techniques to calculate the energy consumption of sensor nodes in cluster-based networks. One of them enables nodes to achieve the uniform energy consumption by taking different transmission radii according to their distances to the cluster-head. The other one is a probabilistic communication model that makes nodes to send data to the cluster-head either via a multi-hop link or directly. Similarly, Dong et al. [12] investigate the saturated and unsaturated situations in terms of the relationship between the sampling and transmission rates based on the IEEE 802.11 protocol, but the energy model leaves out sleeping schedules and the cost of switching the radio between on and off states.

III. HYBRID PROTOCOLS

Hybrid MAC protocols use three novel schemes to minimise the energy consumption of a wireless sensor network. The first scheme is the periodic sleeping schedule. This inherently assumes that nodes communicate with each other intermittently. Technically, this means that the packet arrival rate at the communication subsystem is much less than the transmission rate. Therefore, a node turns off its radio most of the time and wakes up to transmit the accumulated data sampled during its previous sleep phase once it is active. During the active period, a node performs a carrier sense and random back-off to win the medium for packet transmission. Secondly, in order to reduce the contention latency as well as the retransmission cost, some hybrid MAC protocols use message passing techniques. It is implemented by fragmenting a long data packet into several smaller fragments, which are then transmitted in a burst. Only a single RTS and CTS packets are used to reserve the medium for the data transmission. Thirdly, to prevent overhearing, the protocols enable nodes to turn off their radios during a communication between two communicating nodes once they overhear the RTS and CTS packets.

IV. OVERLAP NEIGHBOR MODEL

For the analytic model presented here, a detailed description of the deployment setting is given elsewhere [6]. The setting assumes the presence of N sensor nodes that are uniformly distributed in a rectangular area having the size of $(a \times b)$. The density of the network is: $\lambda = \frac{N}{a \times b}$. By considering the radio transmission range, R, the average number of nodes within a radio transmission area is expressed as: $N_a = \lfloor \frac{N}{a \times b} \times \pi R^2 \rfloor$. If one of the nodes is assumed to be located in the middle of the radio transmission area, the average number of neighbours, N_n, for a transmitter or a receiver can be expressed as:

$$N_n = \left\lfloor \frac{N}{a \times b} \times \pi R^2 \right\rfloor - 1 \tag{1}$$

The symbol $\lfloor \rfloor$ denotes the floor integer value, since the average number of neighbours should never be decimal. Equation 1 can only be used in the situation where a node is the neighbour of either the transmitter or the receiver. This, however, is not always the case, since the communication radio of two immediate nodes may intersect. But the radio intersection may not lead to the neighbour overlap, as it is also subjected to the network density and the overlap area of the communication radios.

When two nodes become neighbours, their radio transmission circles intersect. If the Euclidean distance between the transmitter and the receiver is assumed to be the average radio transmission length, $d_{avg} = \frac{R}{2}$, by considering the radio intersection area of two immediate nodes, $S = 2R^2 \cos^{-1}\left(\frac{d}{2R}\right) - \frac{1}{2}d\sqrt{4R^2 - d^2}$, the average radio intersection area of two neighbours can be expressed as:

$$S_o = 2.152R^2 \tag{2}$$

The average overlap nodes can be obtained by multiplying equation (1) by the network density. Since both the transmitter and the receiver are enclosed in the intersection area, two nodes should be excluded. Thus, the average number of intersection neighbours of the transmitter and the receiver is:

$$N_o = \frac{2.152NR^2}{ab} - 2 \tag{3}$$

V. ENERGY MODEL WITH CONTROL PACKETS

In this section, the energy cost caused by control packets in hybrid MAC protocols is analyzed. Compared with the situation in which control packets are deactivated, there are mainly four sources of extra energy cost.

A. Energy Model for RTS and CTS Packets

We begin the analysis by using a state diagram shown in Fig. 1. Initially, a node, i, uses control packets as the collision avoidance technique to communicate with one of its neighbours, j. The probability that j successfully receives the RTS packet from i is $(1 - p_{rij})(1 - p)$, where p_{rij} and p denote the error and collision probabilities on the RTS packet, respectively. $S2$ is the state in which i successfully receives the CTS packet from j with a probability of $(1 - p_{cji})$, where p_{cji} represents the error probability during the transmission of the CTS packet. For simplification, $(1 - p_{rij})$, $(1 - p)$, $(1 - p_{cji})$, $(1 - p_{ij})$, $(1 - p_{aji})$ are denoted by p^*_{rij}, p^*, p^*_{cji}, p^*_{ij} and p^*_{aji}, respectively. In addition, the transmission power, the receiving power, the transmission rate, the size of the RTS, CTS, data, fragment and ACK packets are presented by P_{tx}, P_{rx}, R_t, N_{rts}, N_{cts}, N_{data}, N_f and N_{ack}, respectively. Moreover, $\overline{x}$ is used to label the mean value of the variable x.

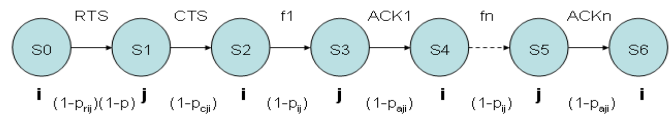

Fig. 1. State diagram for hybrid MAC protocols

From the state diagram, one can observe that the energy cost of control packets comes from the transmission and retransmission of the RTS packet due to transmission errors and collision as well as the transmission and retransmission of the CTS packet due to transmission errors alone.

Instead of focusing on the entire network, the energy cost caused by control packets is only analyzed on one dimensional path from a source to the sink, since it is sufficient enough for the energy comparison. The analysis is divided into two parts. In the first part, the energy cost is estimated between two single-hop nodes. In the second part, the energy cost is calculated for the whole multi-hop link.

The average energy cost of transmitting the control packets RTS and CTS between node i and its neighbour j is given as:

$$\overline{E^{tx}_{rts\ cts}(i,j)} = \frac{P_{tx}\frac{N_{rts}}{R_t}}{p^*_{rij}p^*p^*_{cji}} + \frac{P_{tx}\frac{N_{cts}}{R_t}}{p^*_{cji}} \tag{4}$$

Here, the first term refers to the transmission and retransmission costs of the RTS packet between i and j. In protocols which support message passings, the transmitter need only to re-notify the reserved transmission time for the retransmission once a fragment or an ACK fails in the transmission. In other words, a failed fragment or ACK packet does not result in the retransmission of the previous RTS and CTS packets. Subsequently, besides the collision and error probabilities of the RTS packet, only the error probability on the transmission of the CTS packet should be considered. The second term refers to the transmission and retransmission costs of the CTS packet between i and j. Similarly, the reception of the RTS packet makes sense only if the CTS packet is successfully received by node j. Then the average energy cost for successfully receiving the RTS and CTS packets between nodes i and j can be computed as:

$$\overline{E^{rx}_{rts\ cts}(i,j)} = \frac{P_{rx}\frac{N_{rts}}{R_t}}{p^*_{cji}} + P_{rx}\frac{N_{cts}}{R_t} \tag{5}$$

By combining equations (4) and (5), the energy cost of the transmission of the control packets RTS and CTS between nodes i and j can be obtained.

$$\overline{E(i,j)} = \overline{E^{tx}_{rts\ cts}(i,j)} + \overline{E^{rx}_{rts\ cts}(i,j)} \tag{6}$$

Suppose the average number of nodes along the path is $(M + 1)$. By adding $\overline{E(i,j)}$ at every hop along the path, the total energy cost of the transmission of the control packets RTS and CTS can be evaluated as:

$$\overline{E_{total}} = \sum_{i=0}^{M-1} \overline{E(i, i+1)} \tag{7}$$

B. Energy Model for Overhearing the RTS and CTS Packets

RTS and CTS packets can carry information pertaining to the duration of a data transmission, which can then be intercepted by any listening node. In which case, a neighbour hidden from either the transmitter or the receiver can learn about the duration for which the channel is busy, and thus can suitably delay its own transmission by entering into a sleep state. Consequently, if the medium access mechanism with control packets is applied, an overhearing would only occur in the RTS and CTS packets. Since overhearing means a node receives packets which are not destined to it, overhearing is actually receiving. Thus the energy cost of overhearing the RTS packet by the neighbours of transmitter i can be expressed as:

$$\overline{E_{rts}^{overhear}(i,j)} = P_{rx}\frac{N_{rts}}{R_t}N_n \tag{8}$$

Obviously, the overlapping neighbours will turn off their radios after overhearing the RTS packet transmitted by the sender. As a result, they can't receive the CTS packet transmitted by the receiver anymore. Thus the energy cost of overhearing the CTS packet should be evaluated by excluding those overlapping neighbours from all the neighbours of receiver j:

$$\overline{E_{cts}^{overhear}(i,j)} = P_{rx}\frac{N_{cts}}{R_t}(N_n - N_o) \tag{9}$$

By summing up equations (8) and (9), the total energy spent in overhearing the RTS and CTS packets between node i and its immediate neighbour j can be obtained.

$$\overline{E_{total}^{overhear}(i,j)} = P_{rx}\frac{N_{rts}}{R_t}N_n + P_{rx}\frac{N_{cts}}{R_t}(N_n - N_o) \tag{10}$$

By summing up $\overline{E_{total}^{overhear}(i,j)}$ at every hop along the path, the total energy cost of overhearing can be calculated as:

$$\overline{E_{total}^{overhear}} = \sum_{i=0}^{M-1} \overline{E_{total}^{overhear}(i, i+1)} \tag{11}$$

C. Energy Model for the Sleep Period

When control packets are applied, all the neighbours of the transmitter and all the left neighbours of the receiver (considering that the transmitter is on the left side of the transmitter) will go to sleep after overhearing the RTS and CTS packets, respectively. All these neighbours will wake up once the final ACK is successfully transmitted, as shown in Fig. 2. Compared with the situation in which control packets are not used, the neighbours of the transmitter and the left neighbours of the receiver will sleep an extra time expressed by: $(T_{cts} + T_{f1} + 2T_s)$ and $(T_{f1} + T_{ack1} + 2T_s)$, respectively, where T_s is the SIFS duration standing between every two neighbours packets.

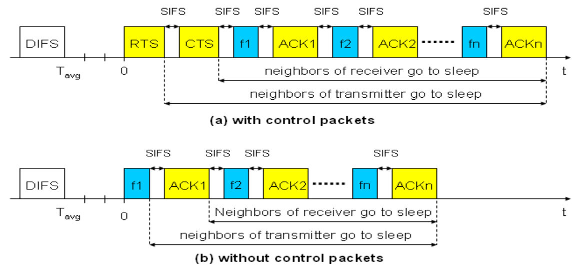

Fig. 2. Sleeping durations with and without control packets

So the average energy cost of the extra sleep time of the neighbors of transmitter i can be formulated as:

$$\overline{E_i^{sleep}} = P_{sleep}\Big(\frac{N_{cts} + N_{f1}}{R_t} + 2T_s\Big)N_n \tag{12}$$

And the energy cost of the extra sleep time of the left neighbours of receiver j can be evaluated as:

$$\overline{E_j^{sleep}} = P_{sleep}\Big(\frac{N_{f1} + N_{ack1}}{R_t} + 2T_s\Big)(N_n - N_o) \tag{13}$$

By adding up equations (12) and (13), the total energy cost of the extra sleep time of the neighbours of transmitter i and receiver j can be obtained as:

$$\overline{E_{total}^{sleep}(i,j)} = \overline{E_i^{sleep}} + \overline{E_j^{sleep}} \tag{14}$$

The overall energy cost of the extra sleep time can be then expressed as:

$$\overline{E_{total}^{sleep}} = \sum_{i=0}^{M-1} \overline{E_{total}^{sleep}(i, i+1)} \tag{15}$$

D. Energy Model for Switching the Radio Mode

Hybrid MAC protocols are optimized by introducing the duty cycle as well as the overhearing avoidance technique that reduces the idle time in a frame and the idle time of the neighbours of the transmitter and receiver in a transmission process. However, this results in an extra energy cost, namely, switching the radio between the sleeping and receiving modes.

Since the packet transmission error is very low, the energy cost of the retransmission due to packet errors will not be considered here. Therefore, switching between the radio's operational modes occurs only three times in a single transmission round. Note that switching a radio "on" and "off" does not happen instantaneously. Typically, this may take about $20\mu s$ [11].

After the neighbors of the transmitter overhear the RTS packet, they will go to sleep by changing their radios from receiving to sleeping mode. The corresponding energy cost is expressed as:

$$E_1 = \frac{1}{2}T_{down}(P_{receiving} - P_{sleeping})N_n \tag{16}$$

Similarly, the energy cost of switching the radio from receiving to sleeping status after the left neighbours of receiver j overhear the CTS packet can be evaluated as:

$$E_2 = \frac{1}{2} T_{down} (P_{receiving} - P_{sleeping})(N_n - N_o) \quad (17)$$

Both neighbours of the transmitter and the receiver will wake up by switching their radios back from sleeping to receiving mode once the NAV inside the RTS and CTS packets decreases to zero. By considering the total number of neighbours of both the transmitter and receiver, the corresponding energy cost can be successfully obtained as:

$$E_3 = \frac{1}{2} T_{up} (P_{receiving} - P_{sleeping})(2N_n - N_o) \quad (18)$$

By summing up E_1, E_2 and E_3, the energy cost of switching the radio in a single transmission round between i and j can be estimated:

$$E = E_1 + E_2 + E_3 \quad (19)$$

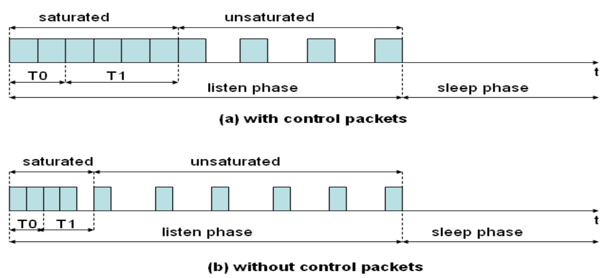

Fig. 3. T1 for different scenarios

The frequency of switching the radio within a single round of transmission is the same regardless of the control packets. In fact, it does not depend on either the length of a transmission round or the number of packets transmitted during a transmission round. But it is only related to the number of data packets transmitted within a certain time period.

As Fig. 3 describes, the total number of data packets transmitted during $T0$ is the same for both situations since they are both equal to the number of data packets accumulated during the previous sleep phase, though the single transmission length is different. However, it's not the case for $T1$. In a hybrid MAC protocols, such as SMAC, $T1$ completes only if the accumulated data sampled during the saturated interval (the summation of $T0$ and $T1$) are all sent out. Since the sampling rate, R_s, and the duty cycle, D, are the same in both situations and the length of a transmission round in the situation with control packets is larger than that of without control packets, the saturated period in the situation with control packets, T_{sa}^{with}, will be larger than that of without control packets, $T_{sa}^{without}$. Consequently, the number of data packets transmitted during $T1$ in the situation with control packets, n_{T1}^{with}, is larger than that without control packets, $n_{T1}^{without}$.

$$n_{T1}^{with} = \frac{R_s T_{sa}^{with}}{N_{data}} > n_{T1}^{without} = \frac{R_s T_{sa}^{without}}{N_{data}} \quad (20)$$

Since the energy cost switching the radio is considered in terms of the number of data packets being transmitted during the whole frame, a coefficient should be inserted in front of the term E, which is equal to the difference between the ratios that contain the terms: n_{T1}^{with} and $n_{T1}^{without}$ and the total number of data packets transmitted during the whole frame, $n_{frame} = \frac{R_s T_{frame}}{N_{data}}$:

$$a = \frac{T_{sa}^{with} - T_{sa}^{without}}{T_{frame}} \quad (21)$$

By solving the saturated and unsaturated durations, a can be evaluated as [12].

$$a = -\frac{\left(T_a\sigma + T_d + (2n-1)T_s + \frac{nN_{ack}}{R_t} + \frac{nN_f}{R_t}\right)\frac{R_s(1-D)}{nN_f}}{1 - \frac{R_s}{R_t} - \left(T_a\sigma + T_d + (2n-1)T_s\right)\frac{nN_f}{R_t}} + \frac{\left(T_a\sigma + T_d + (2n+1)T_s + \frac{N_{rts}+N_{cts}+nN_{ack}}{R_t} + \frac{nN_f}{R_t}\right)\frac{R_s(1-D)}{nN_f}}{1 - \frac{R_s}{R_t} - \left(T_a\sigma + T_d + (2n+1)T_s + \frac{N_{rts}+N_{cts}+nN_{ack}}{R_t}\right)\frac{R_s}{nN_f}} \quad (22)$$

By combining equations (19) and (22), the weighted average energy cost of the radio switch during the communication of i and j can be calculated.

$$\overline{E_{total}^{radio}(i,j)} = a\frac{1}{2}(P_{receiving} - P_{sleeping}) \times (2T_{down}N_n - T_{down}N_o + 2T_{up}N_n - T_{up}N_o) \quad (23)$$

The energy cost of switching the radio between receiving and sleeping modes in the entire multi-hop link can be obtained as:

$$\overline{E_{total}^{radio}} = \sum_{i=0}^{M-1} \overline{E_{total}^{radio}(i,i+1)} \quad (24)$$

VI. Energy Model Without Control Packets

A. Energy Model for the 1st Fragment Retransmission due to Collision

If control packets are not employed during contention, only data fragments and ACK packets are involved in the communication. As a result, collision can only occur on the first data fragment. Therefore, compared with the situation where control packets are used, the extra energy consumed in the situation without control packets is the retransmission of the first data fragment caused by only collision. The energy cost of the transmission and retransmission of the first data fragment caused by both errors and collision between nodes i and j should be firstly calculated as:

$$\overline{E_f^{tx}(i,j)} = \frac{P_{tx}\frac{N_{f1}}{R_t}}{p_{ij}^* p^* p_{aji}^*} \tag{25}$$

If collision is assumed not to occur during the transmission of the first data fragment, the retransmission is then caused by errors alone. Therefore, the energy cost of the transmission and retransmission of the first collision-free data fragment between nodes i and j can be estimated as:

$$\overline{E_f^{tx'}(i,j)} = \frac{P_{tx}\frac{N_{f1}}{R_t}}{p_{ij}^* p_{aji}^*} \tag{26}$$

By subtracting equation (26) from (25), the retransmission energy of the first data fragment due to only collision between nodes i and j can be expressed as:

$$\overline{E_f^{col}(i,j)} = \frac{P_{tx}\frac{N_{f1}}{R_t} - p^* P_{tx}\frac{N_{f1}}{R_t}}{p_{ij}^* p^* p_{aji}^*} \tag{27}$$

The energy cost of the retransmission of the first data fragment caused by collision in the entire link can be quantified as:

$$\overline{E_f^{col}} = \sum_{i=0}^{M-1} \overline{E_f^{col}(i,i+1)} \tag{28}$$

B. Energy Model for Overhearing the 1st Fragment and ACK Packet

Since a NAV vector is inside each packet, the first data fragment and ACK packet in the absence of control packets can actually play the role of the RTS and CTS packets to contend for the medium. Consequently, overhearing can only occur during the transmission of the first data fragment and ACK packet when control packets are deactivated.

So the energy cost of overhearing the first data fragment and ACK packet by the neighbours of i and j can be evaluated as:

$$\overline{E_{total}^{overhear}(i,j)} = P_{rx}\frac{N_{f1}}{R_t}N_n + P_{rx}\frac{N_{ack1}}{R_t}(N_n - N_o) \tag{29}$$

The total energy cost of overhearing the first data fragment and ACK packet in the entire route can be evaluated as:

$$\overline{E_{total}^{overhear}} = \sum_{i=0}^{M-1} \overline{E_{total}^{overhear}(i,i+1)} \tag{30}$$

C. Energy Model for Idle Listening

In the saturated period of both cases, idle listening between every two transmissions is avoided since T – the time between the last received ACK packet and the CCA (DIFS) time – equals zero. On the contrary, T is nonzero in the unsaturated period, since newly sampled data will not arrive in the queue immediately after the last data transmission. The length of T is different with and without control packets, as Fig. 4 displays. $T3$ is larger than $T2$ since the extra RTS and CTS packets are transmitted when control packets are activated.

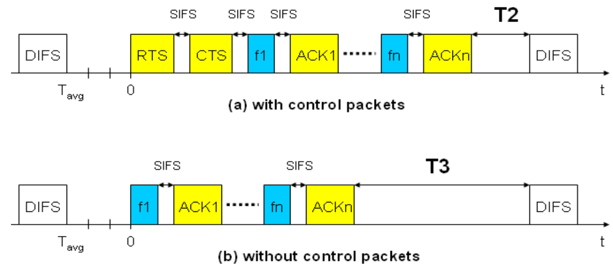

Fig. 4. Different idle listening scenarios

If retransmission circumstances are assumed to be exactly the same in both cases, the extra idle listening is $(T3 - T2)$ in each transmission round, where $T2$ and $T3$ are the idle listening time in the situation with and without control packets, respectively.

$$T3 - T2 = \frac{N_{rts} + N_{cts}}{R_t} + 2T_s \tag{31}$$

By considering the fact that all the neighbours as well as the transmitter and the receiver are in the listen mode during $T2$ and $T3$, the energy cost of the idle listening during a single transmission round can be expressed as:

$$\overline{E_{unsa}^{idle}(i,j)} = P_{idle}\Big(\frac{N_{rts} + N_{cts}}{R_t} + 2T_s\Big)(2N_n - N_o + 2) \tag{32}$$

However, the idle listening only occurs in the unsaturated period rather than in an entire frame. Thus in order to give an effective comparison, the weighted average of the energy cost should be computed by introducing a coefficient which equals the ratio of the number of data packets transmitted during the unsaturated period,$n_{unsa}^{without}$ to that during both the saturated, $n_{sa}^{without}$, and unsaturated phases.

$$b = \frac{n_{unsa}^{without}}{n_{sa}^{without} + n_{unsa}^{without}} \tag{33}$$

Actually, the number of data packets transmitted in the saturated period is equal to the number of data packets sampled during both the previous sleep and the current saturated phases.

$$n_{sa}^{without} = \frac{R_s T_{sleep}}{N_{data}} + \frac{R_s T_{sa}^{without}}{N_{data}} \tag{34}$$

Since the frame length is the summation of the saturated, unsaturated and sleep intervals, the number of data packets transmitted during the unsaturated period can be expressed as:

$$n_{unsa}^{without} = \frac{R_s(T_{frame} - T_{sleep} - T_{sa}^{without})}{N_{data}} \tag{35}$$

By inserting equations (34) and (35) into (33) and taking into account of the duty cycle, b can be expressed as:

$$b = \frac{T_{frame}D - T_{sa}^{without}}{T_{frame}} \tag{36}$$

The value of $T_{sa}^{without}$ is given elsewhere [12]. After transformation, equation (36) can be rewritten as:

$$b = D - \frac{\left(\frac{nN_f}{R_t} + T_d + T_a\sigma + \frac{nN_{ack}}{R_t} + (2n-1)T_s\right)\frac{R_s(1-D)}{nN_f}}{1 - \frac{R_s}{R_t} - \left(T_d + T_a\sigma + \frac{nN_{ack}}{R_t} + (2n-1)T_s\right)\frac{R_s}{nN_f}} \quad (37)$$

By combining equation (37) with (32), the energy cost of idle listening in one hop can be obtained as:

$$\overline{E_{total}^{idle}}(i,j) = bP_{idle}\Big(\frac{N_{rts}+N_{cts}}{R_t} + 2T_s\Big)(2N_n - N_o + 2) \quad (38)$$

The energy cost of idle listening in the multi-hop link can be quantified as:

$$\overline{E_{total}^{idle}} = \sum_{i=0}^{M-1} \overline{E_{total}^{idle}(i,i+1)} \quad (39)$$

D. Energy Model for Switching the Radio Mode

No matter control packets are used or not, the frequency of switching the radio mode in a single transmission round is three. Since all the parameters are the same in both cases, equation (19) can also be adopted to express the energy cost of switching the radio when control packets are deactivated.

From the unsaturated period on, nodes transmit data once they are sampled. So the transmission rate is equal to the sampling rate during this period in both situations. As a result, the number of data packets transmitted during the unsaturated period depends only on the unsaturated duration. Recall that the saturated duration with control packets is larger than that without control packets. Since the listen phase is the same for both cases, the unsaturated duration with control packets is smaller than that without control packets. Subsequently, the number of data packets transmitted during the unsaturated period without control packets is larger than that with control packets, which is used for averaging the energy cost of switching the radio mode by introducing a coefficient, a'.

$$a' = \frac{\frac{R_sT_{unsa}^{without}}{N_{data}} - \frac{R_sT_{unsa}^{with}}{N_{data}}}{\frac{R_sT_{frame}}{N_{data}}} \quad (40)$$

After simplification, equation (40) reduces to:

$$a' = \frac{T_{sa}^{with} - T_{sa}^{without}}{T_{frame}} \quad (41)$$

Clearly, a' is exactly the same as the one described in equation (21). Therefore, the energy cost of switching the radio between the sleeping and receiving modes in the entire route without control packets can also be expressed by equation (24).

VII. SIMULATION AND DISCUSSION

A. Simulation Setup and Parameters

Matlab version 7.0.1 was employed to verify and visualize the correlation between the energy cost and the node's sampling rate in a hybrid MAC protocol with and without control packets. The analytic model was applied to a network in which nodes were uniformly distributed in an area of (160×200) meters. One of these nodes is the information sink. We assume that the transmission rate is 2 Mbps and the network operates under stationary and ideal channel conditions.

During the simulation, the transmission rate was described in terms of byte per microsecond in order to comply with the way DCF in IEEE 802.11 specification (the time unit of SIFS, DIFS and the slot time as well as the length unit of control packets and normal data packets) is expressed. Due to the limitation of the time intervals $T2$ and $T3$, even the maximum sampling rate is much smaller than the transmission rate in both cases with and without control packets. The number of fragmentations for a single message is selected to be 4. This makes the average size of a data fragment equal to 34 bytes. And the error probability is the same for all types of packets.

TABLE I
SIMULATION PARAMETER LIST

Basic Parameter	Default Value
Control packets RTS/CTS/ACK	10bytes
Data message	136bytes
Fragmentation	4
Transmission rate	2Mbps
Maximum backoff stage	5
Maximum transmission attempt	8
Minimum contention window	31
Sensing field	$32000m^2(160m \times 200m)$
Total sensor node	50
Nominal transmission range	40m
SIFS	10μs
DIFS	50μs
Slot time	20μs
Transmission power	31.2mW
Receiving/idle power	22.2mW
Sleep status	3μW
Error probability	0.001
hops in a route	5
Duty cycle	80%

The aim of the simulation is to examine the influence of the sampling rate and control packets on the energy cost of a hybrid MAC protocol in a wireless sensor network. For efficiency reasons, the duty cycle is kept constant throughout the simulation. All the other parameters are presented in Table I.

B. Simulation Results and Discussion

The collision probability has different values when the sampling rate varies with respect to T [12]. Hence, the energy cost should also be analyzed under the four different conditions, where $T \in (0,\sigma)$, $T \in [\sigma, T_{avg}\sigma)$, $T \in [T_{avg}\sigma, T_{avg}\sigma + T_{DIFS} + T_{trans})$ and $T \in [T_{avg}\sigma + T_{DIFS} + T_{trans}, +\infty)$.

The energy cost of the hybrid MAC protocol with control packets varies from 61.67 to 63.10 micro joules as the sampling rate changes from 0 to 1.18 Mbps, as shown in Fig. 5. In the first condition where $T \in (0,\sigma)$ and thus the sampling rate is in the range of (1.15, 1.18) Mbps, the energy cost remains constant (63.03 micro joules), since it has nothing to do with the sampling rate. However, in the second, third and fourth

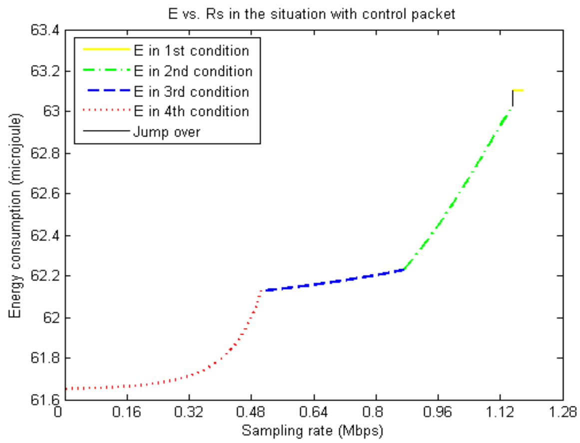

Fig. 5. Relationship between the extra energy cost and the sampling rate in the situation with control packets

conditions where the sampling rate belongs to (0.87, 1.15) (0.51, 0.87) and (0, 0.51) Mbps, respectively, the energy cost behaves as a curve instead of a straight line.

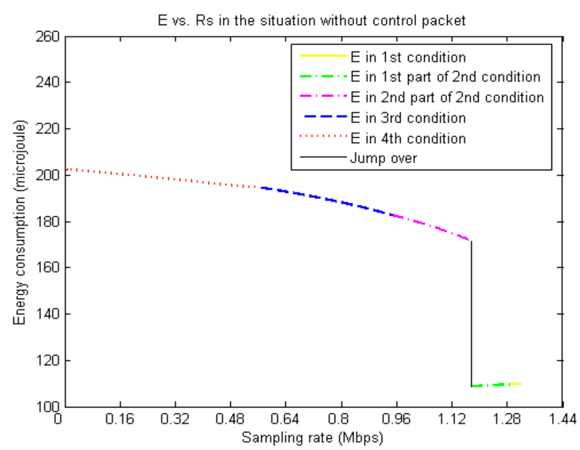

Fig. 6. Relationship between the extra energy cost and the sampling rate in the situation without control packets

In Fig. 6, the energy cost decreases as the sampling rate increases and the average energy cost is much larger when control packets are used in the MAC protocol. This is mainly because of the energy cost of the idle listening, since coefficient b is inversely proportional to the sampling rate.

The comparison of the energy cost only makes sense when the sampling rate has the same value in both cases. Since the maximum sampling rate with control packets (1.18 Mbps) is smaller than that without control packets (1.32 Mbps), the energy cost of the idle listening can only be evaluated when the sampling rate is smaller than 1.18 Mbps. Thus, such energy cost is not included in the overall energy cost in the first and in the first part of the second conditions. As a result, the curve representing the extra energy cost jumps off a big step from 171.4 to 108.7 micro joules as the sampling rate reaches 1.18Mbps as shown in Fig. 11. This indicates that the energy cost of the idle listening shares a high percentage of the overall energy cost when control packets are not used.

VIII. CONCLUSION

In this paper, we investigated the energy cost of hybrid MAC protocols – contention-based protocols with sleeping schedules – in wireless sensor networks and proposed an end-to-end energy model to quantify this cost. The energy model takes into consideration the sleeping schedule of individual nodes, idle listening, overhearing, and the cost of switching the radio on and off. It also takes into consideration the packet arrival and transmission rates. It has been shown that the extra energy cost due to control packets overhead was significant at low packet arrival rates, but when the packet arrival rate increased, the cost of control packets was much smaller.

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