Preamble MAC Protocols with Non-persistent Receivers in Wireless Sensor Networks

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Abstract. In preamble sampling MAC protocols, nodes keep their radios off most of the time to reduce idle listening and periodically wake up for a short time to check whether there is an ongoing transmission on the channel. Such access methods result in substantial energy savings in low traffic conditions. In this paper, we compare several representative preamble sampling MAC protocols in which receivers are non-persistent. Our analysis takes into account bit error rate and traffic load to compute energy consumption and link reliability. Our results show that two access methods obtain the longest normalized lifetime for a wide range of bit error rates: MFP (Micro Frame Preamble) and DFP (Data Frame Preamble).

1 Introduction

We consider energy consumption and link reliability in Wireless Sensor Networks. Previous studies on evaluating various medium access methods in such networks have neglected the effect of transmission errors that have significant impact on reliability and energy consumption due to frame retransmissions.

In this paper, we analyze a class of access methods for sensor networks: preamble sampling schemes with non-persistent receivers (a companion paper considers the schemes with persistent receivers [2]). Preamble sampling, also referred to as LPL (Low Power Listening) [3,7], is one of the best methods for energy saving in low traffic conditions [8,4]. In preamble sampling (see Fig. 1), nodes keep their radios off most of the time to reduce idle listening and periodically wake up for a short time to check whether there is an ongoing transmission on the channel. If a node detects a transmission, it keeps its radio on to receive a data frame sent after the preamble. To avoid deafness, nodes precede each data frame with a preamble long enough to make sure that all the nodes will wake up at least once during the preamble. The initial idea of preamble sampling has inspired the design of many variants such as: WiSeMAC [4], XMAC [9], MFP (Micro Frame Preamble) [1], DFP (Data Frame Preamble) [1], CSMA-MPS [10], STEM [6], WOR (Wake On Radio) [5], and SCP [11]. However, their authors only considered the energy consumption of the MAC layer and neglected the effect of transmission errors.

We analyze several representative protocols of preamble sampling schemes with non-persistent receivers: LPL, MFP, DFP, XMAC, and WOR. Our analysis

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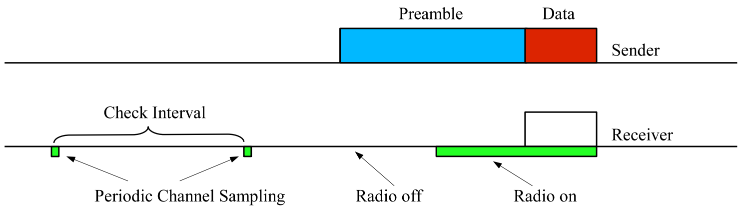

Fig. 1. Preamble sampling technique

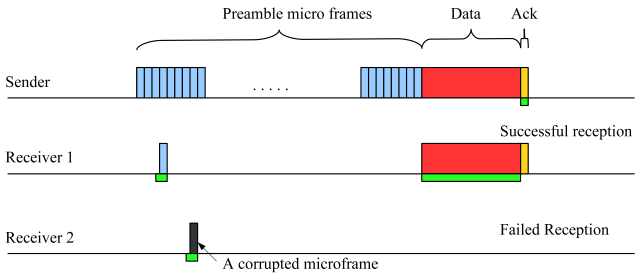

Fig. 2. Preamble composed of control frames—MFP

takes into account bit error rate and traffic load to compute energy consumption and link reliability. To obtain numerical comparisons we assume physical layer characteristics of the most efficient low power radio chips available on the market. Our analysis show that two access methods obtain the longest normalized lifetime for a wide range of bit error rates: MFP and DFP.

The rest of the paper is organized as follows. In Section 2, we describe the operation of variants of the basic preamble sampling protocol with non-persistent receivers. In Section 3, we define the metrics to compare the representative protocols and derive expressions for each specific variant in Section 4. In Section 5, we present numerical comparisons for various input parameters and conclude in Section 6.

2 Preamble Sampling Protocols

In basic preamble sampling protocols, the preamble consists of a specific pattern of bits to let the receiver know that a data frame will be transmitted. As the transmission of the preamble consumes energy, many other protocols proposed to transform the preamble into a series of frames, which we call preamble-frames in this paper. The frames transmitted in the preamble may be small control frames such as in MFP (Micro Frame Preamble) and in XMAC, or copies of the forthcoming data frame such as in DFP (Data Frame Preamble) and in WOR.

In MFP, the preamble is composed of a series of small control frames, referred to as *micro-frames*. Each micro-frame carries information on the forthcoming data frame: its contents and the instant at which it will be transmitted. Thus,

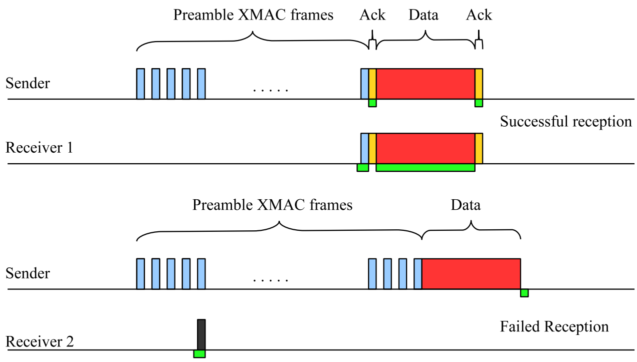

Fig. 3. Preamble composed of control frames—XMAC

when the receiver wakes up to sample the channel, it receives a micro-frame from which it learns when the forthcoming data will be transmitted. In the meantime, after the reception of the micro-frame and before the arrival of the data frame, the receiver goes to sleep mode to save energy. The receiver wakes up again only to receive the data frame.

XMAC uses a similar approach to MFP, however it inserts gaps between each two consecutive control frames called XMAC-frames so that the receiver can send an ACK-frame back to the transmitter, which in turn stops transmitting the preamble and sends the data frame. The main advantage of XMAC-frames is to avoid the transmission of a full-length preamble, thereby reducing energy at both the transmitter and the receiver. However, this technique applies only to unicast frames since broadcast frames are not acknowledged.

In DFP, the preamble frames are copies of the forthcoming data frame. The advantage of DFP is that the node that wakes up to check the channel can immediately receive the data frame. DFP also presents another advantage: duplicating the data in preamble frames increases transmission reliability. However, the node cannot avoid receiving irrelevant data, which may consume non-negligible energy if data frames are large or when they are transmitted at low bit rates.

WOR uses a similar approach to DFP: preamble frames called WOR-frames are copies of the forthcoming data frame. However, in contrast to DFP, WOR-frames are not transmitted in a contiguous way, but they are separated by gaps to let the receiver send an ACK-frame. As in XMAC, when the transmitter receives an ACK-frame, it stops the transmission of WOR-frames and considers the whole transmission successful.

In this paper, we consider the variant of the above protocols in which the receiver is non-persistent: it goes back to sleep mode if it fails to receive the first preamble frame it samples.

3 Performance Evaluation Metrics

We consider that two nodes communicate over a wireless link modeled as the Binary Symmetric Channel (BSC) in which a bit has constant and independent

Table 1. Notation for the analysis

p	bit error probability
m	micro-frame size in bits
d	data frame size in bits
a	ack-frame size in bits
x	xmac-frame size in bits
p_m	probability that a micro-frame is corrupted, $p_m = 1 - (1-p)^m$
p_d	probability that a data frame is corrupted, $p_d = 1 - (1-p)^d$
p_a	probability that an ack-frame is corrupted, $p_a = 1 - (1-p)^a$
p_x	probability that an xmac-frame is corrupted, $p_x = 1 - (1-p)^x$
T_m	transmission time of one micro-frame
T_d	transmission time of one data frame
T_a	transmission time of one ack-frame
T_x	transmission time of one xmac-frame
τ	transition time from sleep mode to active mode
T_{CS}	the carrier sense duration
T_{CI}	the check interval duration
P_r	power drained in receive mode
P_t	power drained in transmit mode
P_s	power drained in sampling mode
r_m	number of frames transmitted in MFP, $r_m = \lceil T_{\text{CI}}/T_m \rceil$
r_d	number of frames transmitted in DFP, $r_d = \lceil T_{\text{CI}}/T_d \rceil$
r_w	number of frames transmitted in WOR, $r_w = \lceil T_{\text{CI}}/(T_w + T_a) \rceil$
r_x	number of frames transmitted in XMAC, $r_x = \lceil T_{\text{CI}}/(T_x + T_a) \rceil$

error probability p. We want to find the energy cost of transmitting a data frame over the link (the amount of energy drained both at the transmitter and the receiver) and estimate its reliability (the probability that the receiver correctly decodes the data frame). Although BSC is a simple error model, our results provide an interesting insight into the main properties of preamble sampling protocols. Table 1 presents the notation used in our analysis.

We assume that a data frame can be retransmitted in case of errors. If p_f is the probability of a failed transmission, we define the reliability p_R as the probability of a successful delivery in n attempts $p_R = 1 - p_f^n$. There are no retransmissions for broadcasts, thus n is equal to 1.

3.1 Sampling Cost

The energy drained in sampling is $\mathcal{E}^s = T_s P_s$, where P_s is the power needed for listening to the channel and T_s is the time required to decide whether the channel is free or there is an ongoing valid transmission. The detection of the validity of a transmission depends on the protocol variant.

3.2 Transmission Cost

We distinguish between a *successful transmission* and a *single transmission*. A single transmission involves only the preamble and the data, whereas a sucessful transmission may include several (up to n) single transmissions. We use e^t_{succ} (resp. e^t_{fail}) to refer to the energy drained in the case of a successful (resp. failed) single transmission. We call $\mathcal{E}^t$ the average energy drained in n transmission attempts. We have:

$$\mathcal{E}^t = (1-p_f)\left(\sum_{i=0}^{n-1} p_f^i [ie^t_{\text{fail}} + e^t_{\text{succ}}]\right) + p_f^n n e^t_{\text{fail}} = \frac{1-p_f^n}{1-p_f}\left(p_f e^t_{\text{fail}} + (1-p_f)e^t_{\text{succ}}\right).$$

3.3 Reception Cost

Similarly, we derive the average energy drained in reception. Let e^r_{succ} (resp. e^r_{fail}) express the energy the receiver drains in receive mode in the case of a successful (resp. failed) single transmission. We thus obtain:

$$\mathcal{E}^r = \frac{1-p_f^n}{1-p_f}\left(p_f e^r_{\text{fail}} + (1-p_f)e^r_{\text{succ}}\right). \tag{1}$$

3.4 Normalized Lifetime

We define the lifetime duration of a node as

$$\mathcal{L}_\circ = \frac{E_{\text{initial}}}{\mathcal{P}_\circ}, \tag{2}$$

where $\mathcal{P}_\circ$ (joule/sec) is the average power a sensor node consumes and E_{initial} (joule) is its initial energy. Symbol '$\circ$' denotes a given protocol. For the sake of conciseness and simplicity, we only consider the power consumed by the radio—we assume that the overhead of the microcontroller is very small. Therefore, we have

$$\mathcal{P}_\circ = \mathcal{P}^t_\circ + \mathcal{P}^r_\circ + \mathcal{P}^s_\circ, \tag{3}$$

where $\mathcal{P}^t_\circ$ (resp. $\mathcal{P}^r_\circ$ and $\mathcal{P}^s_\circ$) is the average power drained in transmission (resp. reception and sampling). The average power drained during preamble sampling is

$$\mathcal{P}^s_\circ = \frac{\mathcal{E}^s_\circ}{T_{CI}}. \tag{4}$$

Similarly, we compute the average power drained during transmission

$$\mathcal{P}^t_\circ = \mathcal{E}^t_\circ \cdot T_{\text{traffic}} \tag{5}$$

and the average power drained during reception

$$\mathcal{P}^r_\circ = \mathcal{E}^r_\circ \cdot T_{\text{traffic}}. \tag{6}$$

where T_{traffic} is the average number of messages transmitted per unit time.

4 Evaluation of Preamble Protocols with Non-persistent Receivers

In this section, we evaluate the reliability and the energy consumption of preamble sampling MAC protocols with non-persistent receivers: LPL, MFP, DFP, WOR, and XMAC.

4.1 LPL (Low Power Listening)

To perform channel sampling, a node running LPL goes from sleep mode to active mode, which requires duration τ. In active mode, the node needs duration T_{CS} to determine whether it is receiving a signal. Therefore, the energy drained in channel sampling is:

$$e^s = (\tau + T_{\mathrm{CS}})P_s$$

The energy drained in channel sampling is the same whether the expected frame is broadcast or unicast. However, the other parameters differ depending on communications patterns: broadcast or unicast. In the rest of the paper, we compute these parameters only for unicast cases. Those for broadcast can be easily derived using a similar methodology while ignoring the ACK-frames.

A single transmission fails when either the data frame or the ACK-frame are corrupted, therefore, the probability of failure is $p_f = 1 - (1 - p_d)(1 - p_a)$.

The reception starts when a node detects a preamble. As the receiver may wake up at any time during the preamble, it receives on the average the half of the preamble plus the data frame. In the case of unicast, the energy drained in reception is:

$$e^r_{\mathrm{succ}} = (\tau + T_{\mathrm{CI}}/2 + T_d)P_r + T_a P_t$$
$$e^r_{\mathrm{fail}} = (\tau + T_{\mathrm{CI}}/2 + T_d)P_r + (1 - p_d)T_a P_t$$

Before transmitting, the transmitter checks whether the channel is free, goes from carrier sensing mode to transmit mode, and transmits the full-length preamble followed by the data frame. The transition time from carrier sensing mode to transmit mode is short and thus can be neglected. Note that the energy drained in transmission is the same whether the single transmission succeeds or fails. In both cases, the transmitter goes to receive mode after transmission to wait for the ACK-frame. Thus:

$$e^t_{\mathrm{succ}} = e^t_{\mathrm{fail}} = e^s + (T_{\mathrm{CI}} + T_d)P_t + T_a P_r$$

4.2 MFP (Micro Frame Preamble)

In MFP, the energy drained during channel sampling is the same as for LPL, i.e. $e^s = (\tau + T_{\mathrm{CS}})P_s$. A single transmission succeeds when the receiver correctly decodes both a micro-frame and the forthcoming data frame, and the transmitter correctly decodes the ACK-frame. Therefore, the failure probability is:

$$p_f = 1 - (1 - p_m)(1 - p_d)(1 - p_a).$$

As the preamble in MFP is composed of micro-frames, the transmitter needs to transmit r_m micro-frames to cover the duration of the check interval thus draining the energy

$$e^t_{\text{succ}} = e^t_{\text{fail}} = e^s + (r_m T_m + T_d)P_t + T_a P_r.$$

As the receiver does not necessarily wake up at the beginning of a micro-frame, then it misses the half of a micro-frame on the average before it starts correctly receiving the subsequent micro-frame. Thus, the time needed to receive a complete micro-frame is $T_m/2 + T_m = 3T_m/2$. After that, the receiver goes back sleeping and then wakes up again to receive the data frame. The receiver sends an ACK-frame only if it correctly receives the data frame. Therefore, we obtain two different formula. For a successful single transmission, we obtain:

$$e^r_{\text{succ}} = (\tau + 3T_m/2 + \tau + T_d)P_r + T_a P_t.$$

A single transmission may fail due to a corrupted micro-frame or the error in the data frame. In the case of a corrupted micro-frame, the receiver listens for duration $3T_m/2$ on the average. Thus, we have:

$$e^r_{\text{fail}} = (\tau + 3T_m/2 + \tau + T_d)P_r + (1 - p_d)T_a P_t.$$

4.3 DFP (Data Frame Preamble)

The energy drained in channel sampling is the same as for MFP and LPL: $e^s = (\tau + T_{\text{CS}})P_s$. Using the same reasoning as for MFP, we obtain:

$$\begin{aligned} p_f &= 1 - (1 - p_d)(1 - p_a) \\ e^t_{\text{succ}} = e^t_{\text{fail}} &= e^s + (r_d T_d + T_d)P_t + T_a P_r \\ e^r_{\text{succ}} &= (\tau + 3T_d/2)P_r + (\tau + T_a)P_t \\ e^r_{\text{fail}} &= (\tau + 3T_d/2)P_r + (1 - p_d)(\tau + T_a)P_t. \end{aligned} \quad (7)$$

4.4 WOR (Wake On Radio)

As the receiver may wake up during the gaps separating WOR-frames, the sampling time should last for $T_{\text{CS}} + T_a$, where T_a is the gap duration. Thus

$$e^s = (\tau + T_a + T_{\text{CS}})P_s$$

With non-persistent receivers, the probability of a failed single transmission is equal to the probability that either a data-frame or an ACK-frame are corrupted: $p_f = 1 - (1 - p_d)(1 - p_a)$.

The receiver that wakes up to sample the channel receives a WOR-frame, which is a copy of the data frame. Then, the receiver sends an ACK-frame that stops the transmission of WOR-frames. As the wakeup time of the receiver is random, the transmitter transmits the half of the WOR-frames on the average in the case of a successful single transmission. Thus

$$e^t_{\text{succ}} = e^s + \frac{r_w + 1}{2}(T_d P_t + T_a P_r) + (T_d P_t + T_a P_r).$$

However, in the case of a failed single transmission, the transmitter transmits all WOR-frames. So, we have

$$e^t_{\text{fail}} = e^s + r_w(T_d P_t + T_a P_r) + (T_d P_t + T_a P_r).$$

The energy drained in reception of a successful single transmission is:

$$e^r_{\text{succ}} = \Big[\tau + (T_a + T_d)/2 + T_d\Big] P_r + T_a P_t.$$

In case of a failed transmission the energy is different, because the receiver does not transmit an ACK-frame if it does not correctly decode a data frame. Therefore, we have:

$$e^r_{\text{fail}} = \Big[\tau + (T_a + T_d)/2 + T_d\Big] P_r + (1 - p_d) T_a P_t.$$

4.5 XMAC

As in WOR, the inter preamble-frame gaps cause the energy drained in channel sampling to become:

$$e^s = (\tau + T_a + T_{\text{CS}}) P_s.$$

A single unicast transmission with XMAC succeeds when the receiver correctly receives a XMAC-frame, the data frame, and the transmitter correctly receives the ACK-frame after the data frame. Note that a single transmission may be successful even if the acknowledgment of the XMAC-frame is not correctly received by the transmitter. In this case, the transmitter does not cut its preamble transmission, so that the receiver goes back to sleep and wakes up again to receive the data. Therefore, the probability of failure is:

$$p_f = 1 - (1 - p_x)(1 - p_d)(1 - p_a).$$

The energy drained in successful reception also depends on whether the acknowledgment of the XMAC-frame is correctly received by the transmitter or not. Therefore, in p_a of cases, the node goes back to sleep and wakes up again to receive the data frame, hence the presence of τ preceding T_d in the following expression:

$$e^r_{\text{succ}} = \Big[\tau + (T_a + T_x)/2 + T_x\Big] P_r + T_a P_t + (p_a \tau + T_d) P_r + T_a P_t.$$

The energy drained in failed reception is the following:

$$e^r_{\text{fail}} = \Big[\tau + (T_a + T_x)/2 + T_x\Big] P_r + (1 - p_x)\Big[T_a P_t + (p_a \tau + T_d) P_r + (1 - p_d) T_a P_t\Big].$$

In the case of failure, the transmitter sends a series of XMAC-frames and waits for the acknowledgment after transmitting the data frame. Therefore, we obtain:

$$e^t_{\text{fail}} = r_x (T_x P_t + T_a P_r) + T_d P_t + T_a P_r.$$

In the case of success, either the transmitter receives an acknowledgment during the transmission of XMAC-frames, which cuts their transmissions, or it does not receive such an acknowledgment so it continues to transmit XMAC-frames. Therefore, we have:

$$e^t_{\text{succ}} = (1 - p_a)\left[\frac{r_x + 1}{2}(T_x P_t + T_a P_r) + T_x P_t + T_a P_r + T_d P_t\right] + p_a \Big[r_x (T_x P_t + T_a P_r) + T_d P_t + T_a P_r\Big].$$

5 Performance Comparisons

For the evaluation of preamble sampling protocols, we compute the numerical values of p_f, e^r_{fail}, e^r_{succ} and use them in the formula derived in Section 3 to find p_R, $\mathcal{E}^t$, $\mathcal{E}^r$, and $\mathcal{L}$ for each protocol. We consider micro-frames of 18 bytes, ACK-frames and XMAC-frames of 16 bytes, data frames and WOR-frames of 138 bytes. We use the characteristics of the CC 2500 chip for radio parameters [5].

5.1 Transmission and Reception Costs

Fig. 5.1 presents the mean energy drained in transmission. It shows that LPL, MFP, and DFP consume almost the same amount of energy during a transmission. Recall that in these protocols, all nodes transmit a full-length preamble followed by a data frame. Small differences in the figure are due to the differences in the preamble length: for example MFP and DFP use preambles a little bit longer than that of LPL, because they are formed of an integer number of preamble frames, the sum of which should be at least as long as the check interval.

We notice that all the protocols converge to the same value when the bit error rate increases, specifically when the bit error rate is larger than 0.04. In such conditions, reliability is extremely low (see Fig. 6) so that all single transmissions fail. Our comparisons considered the maximal number of retransmissions $n = 3$, so the energy drained is three times greater than the energy drained in a single transmission. When the bit error rate is low, the energy drained in transmission with WOR or XMAC is less than that for the other protocols, because of the inter preamble-time expected for the reception of ACK-frames.

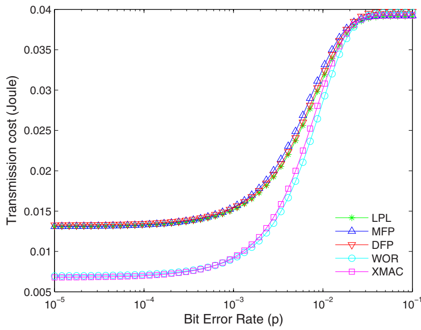

Fig. 4. Mean energy drained in transmission

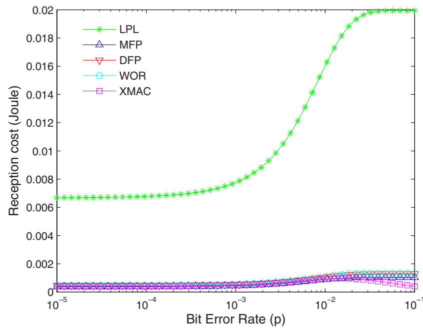

Fig. 5. Mean energy drained in reception

However, when the bit error rate is important (e.g. larger than 10^{-2}), all the protocols consume the same amount of energy in transmission, because receivers cannot correctly decode a preamble-frame and thus they do not interrupt the transmission of full-length preambles. Under high bit error rate all protocols use full-length preambles.

Fig. 5 presents the mean energy drained in reception. We can see that for LPL it is far larger than that drained in the case of the other protocols, because the preamble used by LPL does not carry any information on the forthcoming data transmission time, therefore, the receiver remains in active mode until it receives the data. WOR and DFP consume more energy in reception than MFP and XMAC, because the time needed to decide whether a preamble-frame is correctly received or not, is shorter in MFP and XMAC than in DFP and WOR. The same reason also makes the energy drained in receive mode in WOR larger than that of DFP, because of the inter WOR-frames expected in WOR.

We can also see that the energy drained in reception by MFP and XMAC decreases when the bit error rate is high (e.g. above 10^{-2}). For high bit error rates, a non-persistent receiver running XMAC or MFP does not correctly decode a preamble-frame, therefore, it does not wake up later to receive the forthcoming data frame. Note that this behavior of XMAC and MFP allows the receiver not to waste energy by waking up again to receive a data frame when the probability of reception is low. This results in a bell-like shape of the energy drained in reception for XMAC and MFP (cf. Fig. 5).

The energy drained by all protocols increases when the bit error rate is high, because of multiple retransmissions: each time a single transmission fails, the energy drained by the receiver increases as it wakes up again to receive retransmissions. We can see that the amount of energy drained by the receiver converges to an asymptotic value corresponding to the energy drained when all the retransmissions have been performed.

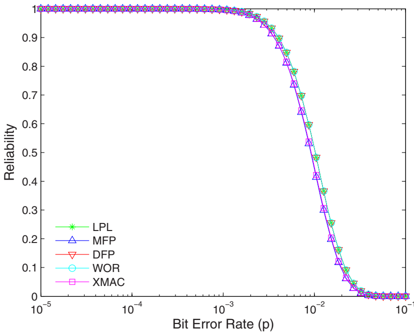

Fig. 6. Communication reliability

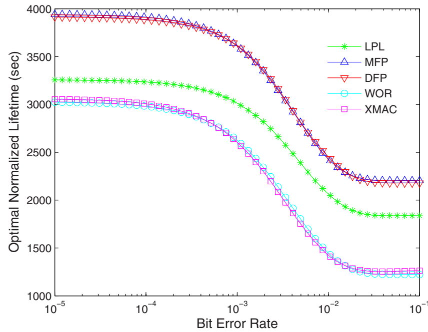

Fig. 7. Maximum Normalized Lifetime

5.2 Reliability and Optimal Normalized Lifetimes

Fig. 6 presents reliability, the probability of a successful transmission for different variants of protocols. It shows that reliability drastically decreases for bit error rates over 10^{-2}. We can also see that reliability of MFP and XMAC is very close and that of LPL, DFP, and WOR is the same, because successful transmission in the latter protocols depends only on the correct reception of a data frame. Note that LPL, DFP, and WOR are slightly more reliable than MFP and XMAC, because successful transmission does not depend on the correct reception of preamble frames.

Fig. 7 presents the optimal maximum lifetimes for each protocol variant for different bit error rates. The lifetimes are normalized, i.e. obtained with the initial energy of 1 Joule. Each point corresponds to the maximum lifetime obtained with the optimal value for T_{CI} and for traffic load of 1 message per minute. The lifetime takes into account the energy drained in sampling: we can see that MFP, DFP, and LPL have longer lifetimes than XMAC and WOR, because of the dominant energy drained in sampling.

6 Conclusions

In this paper, we have compared several representative protocols of preamble sampling schemes (LPL, MFP, DFP, XMAC, and WOR) with non-persistent receivers. Our goal was to take into account imperfect channel conditions as well as traffic load and find which protocol results in the longest network lifetime.

Although our analysis builds on a simple channel model (BSC), the numerical results provide an instructive insight into the main properties of preamble sampling protocols. In particular, our results show that the channel sampling costs have a significant impact on energy consumption along with retransmissions. Two preamble protocols (MFP and DFP) achieve the overall best performance.

If we consider the case of persistent receivers [2], i.e. receivers that keep receiving a preamble until it is correctly received or the channel is back to idle, our companion analysis of the same representative protocols (LPL, MFP, DFP, XMAC, and WOR) shows that there are not clear winners among them—different protocols perform better than the others for a given transmission error rate [2].

We can conclude that non-persistent access methods should be used over channels with high error rates. In such conditions, non-persistent methods save the energy of a node that does not continue to receive the preamble, because the probability of correct reception is low. On the opposite, persistent methods are better for channels with low error rates. In this case, persisting in preamble reception increases the probability of correct reception and thus saves the transmitter the cost of retransmitting.

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