# Analytical Comparison of MAC Schemes for Energy Harvesting - Wireless Sensor Networks

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***Abstract*—MAC protocols for multi-hop WSNs have to address the challenge of coordinating duty-cycling transmitters with duty-cycling receivers. All the suggested protocols can be classified into three basic paradigms: the synchronization, the preamble and the beaconing paradigm. In this paper, we discuss the suitability of the three paradigms in the context of Energy Harvesting - Wireless Sensor Networks (EH-WSNs) in which nodes are powered by energy that they harvest from their surrounding environment. The two suitable paradigms are modeled and compared to each other. The analysis indicates the specific conditions under which a scheme is more suitable than the other.**

***Index Terms*—Wireless sensor networks, Multiaccess communication**

## I. INTRODUCTION

Energy Harvesting - Wireless Sensor Networks (EH-WSNs) [10] are systems of networked sensing nodes that are powered by energy harvested from the surrounding environment. A key property of environmental energy sources is that the extracted energy varies in space and time. As an example, consider solar energy. The energy that can be harvested from the sun depends on various factors such as the time of the day, the weather conditions and the potential shadows. Yet, if the energy input is sufficient, a sensor node can be powered perpetually, thus reducing the costs and complexity of regular battery replacements.

In addition to the energy harvester, each node may also be equipped with an energy storage unit that acts as an energy buffer and stabilizes the energy input. If the energy that it is harvested is more than the energy that it is consumed - over a period of time that can be supported by the energy buffers - then the node operates at a sustainable state and effectively has a continuous lifetime. This state is defined in the literature as *Energy Neutral Operation (ENO)* [6]. Operating states where the harvested energy is much higher than the consumed energy are sustainable yet suboptimal, as the excess of energy is wasted instead of being used for increasing the performance of the system. The desired operating state is when the harvested energy is approximately equal to the consumed energy, since the system operates at a sustainable state while all the harvested energy is used to improve the system performance. Operating at this state, which is named in the literature as *ENO-Max* [15], constitutes a foundational goal of WSNs that are powered by energy harvesting.

Traditionally, the sensor nodes are cycling between activity and sleeping periods in order to save energy and survive with extreme low power resources. Duty cycling gives rise to a communication challenge for MAC (Medium Access Control) protocols that does not exist in typical wireless networks: a node with a packet to transmit to another node does not know whether the receiver is in an active state or in a sleeping state. In battery-powered WSNs, three basic paradigms have been proposed to solve this challenge: the synchronization, the preamble and the beaconing paradigm. In this paper, we present these three approaches and discuss their suitability in the context of an energy harvesting environment. On the basis of this discussion, we model and analytically compare two representative protocols of the two suitable approaches, in terms of energy consumption overhead and channel utilization overhead.

There are some related studies on MAC protocols for WSN environements. The authors of [4] studied several traditional MAC layer approaches in the context of EH-WSNs. Differently from this paper, they consider only the case of single-hop EH-WSNs, i.e. networks in which all the sensor nodes can directly communicate with the sink. In [7], the authors are modeling and analyzing several MAC protocols. However, they study does not include any protocol that follows the beaconing paradigm.

The remainder of the paper is organized as follows. In Sec. II, we present the three MAC schemes and evaluate their suitability in EH-WSNs. In Sec. III we provide a model of an arbitrary EH-WSN that the link layer communication is based on the respective suitable MAC schemes. Using the model, we compare these MAC approaches in terms of energy consumption overhead and channel utilization overhead. Sec. IV demonstrates the results of this comparison. Finally, Sec. V concludes the paper.

## II. BASIC MAC SCHEMES

Duty cycling gives rise to a communication challenge in the system, namely the transmitters do not trivially know if the receivers are awake and ready to receive the traffic or sleeping to save energy and recharge. Traditionally, MAC protocols for WSNs can be roughly categorized into two categories: synchronous and asynchronous ones.

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In synchronization approaches, the nodes form virtual clusters that share a common sleeping schedule, effectively waking up simultaneously. On one hand, this approach has the overhead of keeping the nodes finely synchronized and establishing, maintaining and distributing sleeping schedules between the nodes. On the other hand, there are no additional overheads in the actual communication. This approach is intuitively unsuitable for EH-WSNs, as it cannot support *individual* duty cycles that are essential for adapting the energy consumption to the ambient energy that is available to each individual node. Consider that even if the system is tuned so that the node that has access to the least environmental energy operates in ENO state, then the other nodes will operate at suboptimal states where some of the harvested energy is wasted. Examples of MAC protocols based on synchronization are S-MAC [17], DSMAC [8], T-MAC [14], RMAC [2] and DW-MAC [11].

Even prior to EH-WSNs, the research community acknowledged the importance of decoupling the duty cycles of individual sensor nodes. Hence, several asynchronous approaches of communication have been proposed. The asynchronous approaches can be classified into two categories, namely the preamble and the beaconing approaches. In preamble approaches, the senders transmit a preamble lasting as long as the sleeping period of the receiver before the actual data transmission. The receiver periodically wakes up and if it detects the preamble, it stays awake waiting for the data transmission. There are two sources of overhead in this approach. First, the transmitter consumes energy transmitting the preamble for each packet transmission. Secondly, each node periodically needs to wake up and consume energy to listen the channel for preambles. Examples of MAC protocols based on the preamble approach are B-MAC [9], X-MAC [1] and WiseMAC [3].

In the alternative asynchronous approach, the communication is initiated by the receivers which periodically broadcast beacons that indicate their availability to receive data. Similarly to the preamble scheme, there are two sources of overhead in the beaconing approach. First, the transmitter consumes energy listening the channel for a beacon in each packet transmission. Secondly, each node periodically consumes energy to transmit the beacons. Examples of MAC protocols using the beaconing approach are RI-MAC [12], ODMAC [5] and the MAC protocol used by ORiNoCo [13]. Notice, that the energy consumption overheads of the two asynchronous approaches are inverted yet symmetrical.

Both asynchronous methods can effectively support individual duty cycles, which is a vital requirement for achieving the foundational goal of EH-WSNs, namely adaptively operating at a state which maximizes the performance while maintaining sustainable operation. Therefore, it becomes interesting to identify in which conditions the preamble or the beaconing approach is more suitable. The rest of the paper is focus on the comparison the two asynchronous MAC schemes. The beaconing protocols are represented by a basic version of ODMAC, in which the binding forwarding scheme is disactivated. ODMAC is a protocol designed for EH-WSNs. The preamble protocols are represented by a basic version of X-MAC. Instead of a long preamble, X-MAC is transmitting multiple short preambles that contain addressing information. The appropriate receiver is given with enough time to interrupt the series of short preambles with a special packet named *pre-ack* that indicates that it is ready to receive the data. The details of the two protocols can be found in [5] and [1] respectively.

Additionally, ODMAC incorporates an opportunistic forwarding scheme. Instead of waiting for a specific beacon, the ODMAC transmitter opportunistically forwards each frame to the owner of first beacon received as long as it is included in a list of appropriate forwarders, as specified by the routing protocol. We stress that although X-MAC does not incorporate such a forwarding scheme, it is able to support it; contrary to other preamble protocols, e.g. B-MAC. Focusing on a fair comparison on the actual overheads of the preamble and beaconing approach, we consider that X-MAC is also using the same opportunistic forwarding scheme. The symmetrical similarities of X-MAC and ODMAC are important for a fair comparison.

## III. MODELING ARBITRARY EH-WSN TOPOLOGIES

**Waiting Delay.** In ODMAC, a transmitter is listening to the channel waiting for an appropriate beacon for each packet it wants to transmit. In the case of X-MAC, it waits for an appropriate receiver to wake up and receive a short preamble. This *waiting delay* is on average equal on both protocols and can be modeled as follows.

Suppose that a node $i$ has to transmit one frame. This node may forward the frame to one of $n$ appropriate nodes. Each one of these nodes has a duty cycle period, $t_j$. We assume that the waiting time for the receiver to wake up follows a uniform distribution. The validity of this assumption depends on the randomization of the packet generation to avoid synchronizations. Let $X_j$ be the waiting time for the beacon of node $j$. Also let $x_j$ be the expected value of $X_j$. However, the node does not wait for a specific receiver. Instead, it forwards the frame to the node that wakes up first. Let $Y_i$ be the waiting time for the first appropriate node out of the $n$ potential next hops. Also let $y_i$ be the expected value of $Y_i$. Hence, $P(Y_i \le y_i) = 0.5$. Given that $X_J$ follows a uniform distribution, $P(X_j > y_i) = (t_j - y_i)/t_j$, the following equation gives us the expected *waiting delay*.

$$P(Y_i \le y_i) = 1 - \prod_{j=1}^{n} P(X_j > y_i) = 1 - \prod_{j=1}^{n} \frac{t_j - y_i}{t_j} \quad (1)$$

**Traffic Rate.** In ODMAC and the opportunistic extension of X-MAC, paths are opportunistically decided. Consider again that, a node may forward a frame to one of $n$ appropriate nodes. Each one of these nodes is expected to forward a portion of the node's packets, based on its beacon's period, $t_i$. The probability the packet will be forwarded by node $i$ is given by $p_i$ where the sum iterates over the nodes that are in the list of appropriate forwarders.

$$p_i = \frac{1}{t_i \sum\limits_{j=0}^{n} \frac{1}{t_j}} \tag{2}$$

The traffic a sensor needs to transmit ($r_i$) consists of the traffic it generates by sensing ($r_i^g$) and the traffic it forwards on behalf of other nodes ($r_i^f$). The traffic rate generated locally is equal to $r_i^g = 1/s_i$, where $s_i$ is the period of the sensing. In addition to that, every backward neighbor contributes with a part of its total traffic rate with respect to the probability of node $i$ being the actual forwarder (given by (2)). The latter is given by the following equation where the sum iterates over the nodes that have node $i$ in their list of appropriate forwarders.

$$r_i = \frac{1}{s_i} + \sum_{k=0}^{m} p_k r_k \quad \text{[1/sec]} \tag{3}$$

For the nodes that are in the outer layer of the network, Eq. (3) still applies with $m = 0$.

**Power Consumption Overhead.** We model only the power consumption overhead on the coordination process, as the rest of consumption sources are equal for both protocols.

In ODMAC, the total power consumed while waiting for an appropriate beacon ($P_i^w$) is given by the following formula where $P_r$ is the power consumed in reception, $y_i$ is the waiting time given by (1) and $r_i$ is given by (3).

$$P_i^w = P_r y_i r_i \quad \text{[W]} \tag{4}$$

The total power consumed for beaconing ($P_i^b$) is given by the following formula where $t_i$ is the beaconing period, the ratio of the beacon size ($L$) over the transmission rate ($R$) is the time required for a beacon transmission and $P_t^i$ is the power consumed while transmitting.

$$P_i^b = P_i^t \frac{1}{t_i} \frac{L}{R} \quad \text{[W]} \tag{5}$$

For the value of $P_i^t$, we use the power consumption model presented in [16]. In particular, the power consumed in transmission is given by the following formula where $P_i^{tx}$ is the selected power of the transmitted signal, $\eta$ is the drain efficiency and $P_{t0}$ is the power consumed in the circuits of the communication module constantly and independently of $P_i^{tx}$.

$$P_i^t = P_{t0} + \frac{P_i^{tx}}{\eta} \quad \text{[W]} \tag{6}$$

The sum of these sources of energy consumption gives the total power consumption overhead of node $i$ when running ODMAC.

$$P_i^{tot} = P_i^w + P_i^b \quad \text{[W]} \tag{7}$$

In X-MAC, the waiting time ($y_i$) is spent in looping between transmitting short preambles and listening for pre-acks. Thus, it is given by the following formula where $P_t^i$ is the power consumed in transmission given by (6), $P_r$ is the power consumed in reception, $y_i$ is the waiting time given by (1) and $r_i$ is given by (3).

$$P_i^w = \frac{1}{2} P_i^t y_i r_i + \frac{1}{2} P_r y_i r_i \quad \text{[W]} \tag{8}$$

In addition, for each forwarded packet, each node has to transmit a pre-ack packet before the actual packet transmission. The energy consumption of it is given by the following formula where $L$ is the pre-ack size and $R$ is the transmission rate.

$$P_i^{pa} = P_i^t \frac{L}{R} r_i^f \quad \text{[W]} \tag{9}$$

Lastly, each node needs to periodically listen the channel for short preambles. A receiver may start listening while a transmitter is waiting for a pre-ack. Hence, for receiving the short preamble in the worst case scenario, the nodes listen the channel for twice the duration of its transmission. Thus, the energy consumption for periodic listening is given by the following formula where $t_i$ is the cycle period, the ratio of the preamble size ($L$) over the transmission rate ($R$) is the time required for a preamble transmission and $P_r$ is the power consumed while receiving.

$$P_i^l = 2 P_r \frac{1}{t_i} \frac{L}{R} \quad \text{[W]} \tag{10}$$

The sum of these sources of energy consumption gives the total power consumption overhead of node $i$ when running X-MAC.

$$P_i^{tot} = P_i^w + P_i^{pa} + P_i^l \quad \text{[W]} \tag{11}$$

**Channel Utilization Overhead.** Channel utilization overhead indirectly approximates the amount of interference each protocol is responsible for and refers to the percentage of time a node transmits overhead data, namely beacons for ODMAC and short preambles and pre-acks for X-MAC.

In ODMAC, channel utilization overhead is caused by beacon transmissions. Hence, it is approximated by:

$$I_i = \frac{1}{t_i} \frac{L}{R} \tag{12}$$

In X-MAC, channel utilization overhead is caused by the transmission of short preambles and pre-acks.

$$I_i = \frac{1}{2} y_i r_i + \frac{L}{R} (r_i - \frac{1}{s_i}) \tag{13}$$

Obvisously, the channel utilization overhead does not necessarily translates to performance degradation due to collisions, as both protocols can support and do incorporate collision avoidance mechanisms. Nevertheless, the higher this metric is, the more probable is for a node to find the channel occupied while attempting to transmit.

**Transmission Range.** The transmission range model is based on the link budget formula. $P_i^{rx}$ is signal's power at the receiver in $dBm$, $P_i^{tx}$ is the power of the transmitted signal in $dBm$, $G^{tx}$ and $G^{rx}$ are the antenna gains at the transmitter and receiver in $dBi$, respectively, and $PL_i$ is the signal attenuation over the path, i.e. path loss, in $dB$. We consider the antenna gains to be the same at all nodes.

$$P_i^{rx} = P_i^{tx} + G^{tx} + G^{rx} - PL_i \quad [\text{dBm}] \qquad (14)$$

The free space path loss at a distance $d_i$ is given by the following equation, where $f$ is the frequency of the signal (MHz) and $e$ is the loss exponent.

$$PL_i = 20\log(f) - 27.55 + 10\log(d_i^e) \quad [\text{dBm}] \qquad (15)$$

If we equate $P_i^{rx}$ to the receiver's sensitivity threshold, we get the transmission range, $d_i$, of node $i$.

**Arbitrary Topologies.** Given an arbitrary set of nodes, with either predefined or random positions in $A \times A$ field, and a set of input parameters for each one of them, we can approximate the respective overheads of the two protocols.

## IV. ANALYTICAL COMPARISON

Table I provides the values of some parameters of the model. The parameters suppose using the CC1000 transceivers [16]. We consider 10 random topologies of 50 nodes that generate traffic once every $50s$. These values are used for all the nodes unless stated otherwise. Based on these parameters, the transmission range is approximately 105 meters. The sink node is placed in position $(0, 0)$. The list of appropriate forwarders includes all the nodes that are one hop closer to the sink. Lastly, we consider the worst case scenario (low energy input) where all the nodes operate at the maximum duty cycle period, $t_{max}$.

TABLE I
VALUES OF MODEL PARAMETERS

| | | | | | |
|---|---|---|---|---|---|
| $L$ | 100 Bytes | $G$ | 0 dBi | $P^{tx}$ | 10 dBm |
| $L_b$ | 2 Bytes | $e$ | 4 | $\eta$ | 0.157 |
| $R$ | 256 Kbps | $P^{rx}$ | $-96$ dBm | $P^{t0}$ | 15.9 mW |
| $f$ | 433 MHz | $A$ | 300 m | $P^{r0}$ | 22.2 mW |

**Basic Comparison.** Fig. 1 depicts the average power consumption overhead of the two protocols for different values of the maximum duty cycle period, $t_{max}$, given a sensing period of $S = 25$ seconds. Generally, the beaconing scheme (*BCN*) performs better at large duty cycling periods, while the preamble scheme (*PRE*) performs better at low periods. Both schemes have a operating point where the energy consumption overhead is minimized. The results suggest that the beaconing protocol can be configured to consume less energy than the preamble protocol. Moreover, the minimum of the preamble scheme appears for lower values of $t_{max}$, indicating shorter delays. Hence, beaconing is more suitable in cases where either the harvested energy is relatively low or the delay is not a performance priority and the excess of harvested energy should be used elsewhere (e.g. throughput or security). On the other hand, preambles perform better in case of delay-sensitive applications in environments with high energy availability.

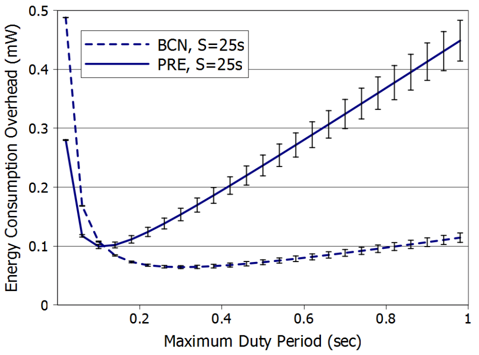

Fig. 1. Power Consumption Overhead.

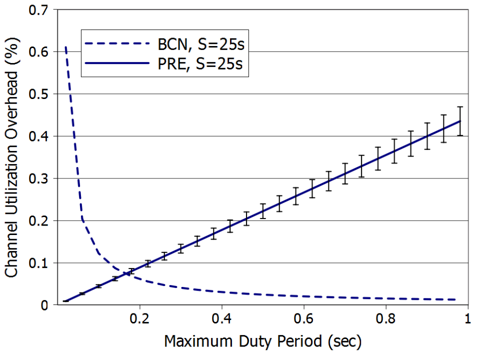

Fig. 2. Channel Utilization Overhead.

Fig. 2 shows the average channel utilization overhead, which is the percentage of time a node transmits overhead data. In low duty cycle periods, the preamble scheme performs better due to the frequent beacon transmissions. The opposite applies for high duty cycle periods where the overhead is exponentially decreased as the beaconing period is increasing. This gives an estimation of the created interference. The error bars in the figures indicate the 90% confidence intervals for the average overheads over the 10 random topologies. We can observe that the beaconing scheme is less dependent on the topology.

The next figures show the influence of different values of the system parameters on the MAC schemes.

**Sensing Period.** Fig. 3 depicts the average power consumption overhead of the two protocols for different values of the sensing period ($S$). Decreasing the sensing period, the minimum consumption point decreases and moves towards higher duty cycle periods for both protocols. The trends that describe their relative performance remain the same to Fig. 1. Fig. 4 depicts that increasing the sensing period improves the channel utilization overhead of the preamble scheme. The result is intuitive as the main source of this overhead is the preambles that depends on the amount of data the network generates.

**Beacon/Preamble Size.** Fig. 5 depicts the average power consumption overhead of the two protocols for different values of the beacon and preamble size, respectively. Since they are carrying addressing information, their size highly depends on the size of the network. We can observe that at the lower duty cycle periods, the smaller the beacon/preamble size the better performance of both protocols. However, smaller beacons/preambles decrease the relative

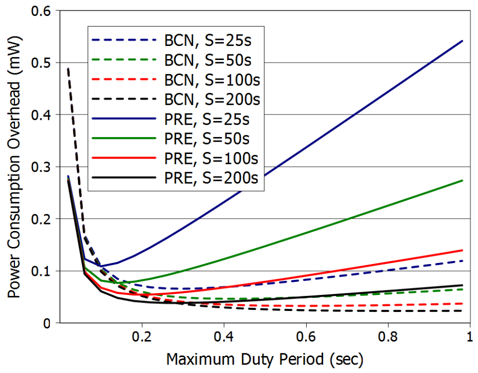

Fig. 3. Power Consumption Overhead for Various Sensing Periods.

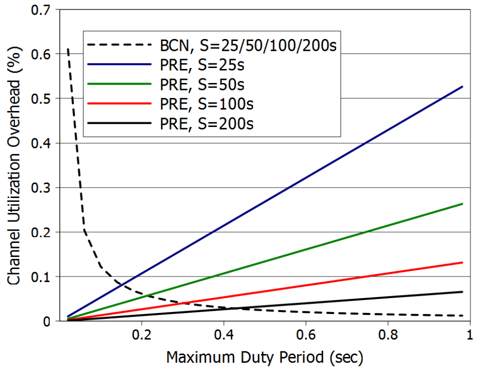

Fig. 4. Channel Utilization Overhead for Various Sensing Periods.

difference between the MAC schemes reducing the local dominance of the preamble scheme. At higher duty cycle periods the influence of the beacon / preamble size is less significant. Same conclusion applies to the channel utilization overhead (Figure 6).

**Transmission Rate.** The influence of the transmission rate on the protocols' overheads (Figures 7 and 8) is similar to the beacon / preamble size. In particular, as we increase the transmission rate the energy consumption of both protocols is improved. Furthermore, the improvement for the beaconing scheme is higher than the preamble scheme.

**Power Consumption for Receiving.** In Fig. 9 we evaluate the power consumption overhead for different values of the receiving power costs. We observe that the influence of the receiving power costs is similar for both schemes at high duty cycle periods. On the other hand, when the duty cycle period is low, higher listening costs increase the energy consumption of the preamble scheme while the beaconing scheme remains unaffected.

**Network Density.** Next, we investigate the effects of the network density on the performance of the two MAC schemes. In particular, 50 to 200 nodes are placed in the same area. Fig. 10 depicts the power consumption overhead. Network density has insignificant influence on the power consumption overhead for low duty cycling periods. However, the overhead decreases for both protocols at higher cycling periods. Moreover, the improvement for

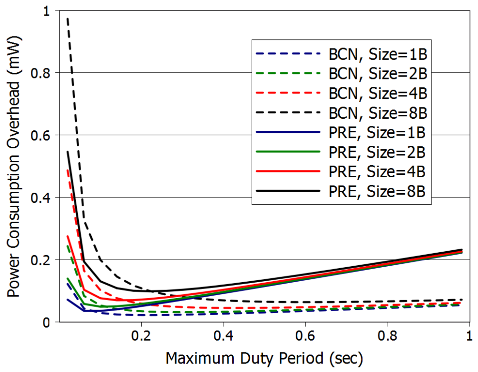

Fig. 5. Power Consumption Overhead for Various Beacon / Preamble Sizes.

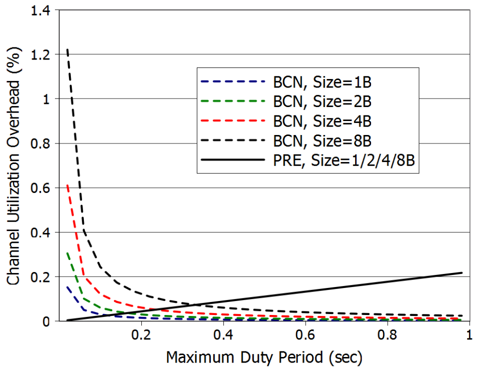

Fig. 6. Channel Utilization Overhead for Various Beacon / Preamble Sizes.

the preamble scheme is higher than the beaconing scheme. Same applies for the channel utilization overhead (Fig. 11). This is caused by the opportunistic forwarding scheme, which we consider X-MAC also incorporates.

## V. CONCLUSIONS

Medium Access Control protocols for multi-hop WSNs are following one of three basic schemes for coordinating the transmitter with the receiver, namely synchronization, preamble and beaconing. In this paper, we investigate which one of them is more appropriate in WSNs that are powered by energy that they harvest from their surrounding environment. Synchronization approaches are unsuitable, as they require synchronized duty cycles. Environmental power sources provide energy that varies continuously over time and space. This makes individual and decoupled duty cycles vital for adapting the energy consumption to the harvested energy and providing sustainable operation.

In this paper, we modeled and compared two representative protocols from the two asynchronous schemes. The analytical results suggest that the beaconing paradigm can be tuned to consume less energy. As a result, it is more suitable in cases of limited environmental energy and the cases that the application requires the system to operate at the duty cycle that provides the minimum energy consumption (e.g. applications that have throughput or security as priority performance metrics). On the other hand, the preamble paradigm can provide better performance

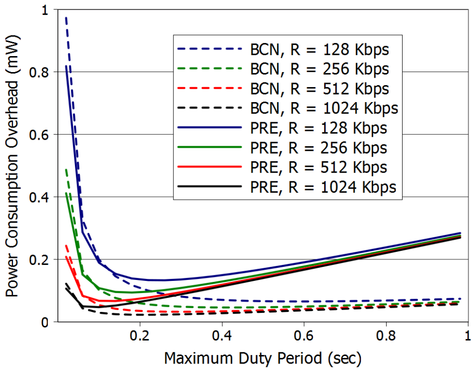

Fig. 7. Power Consumption Overhead for Various Transmission Rates.

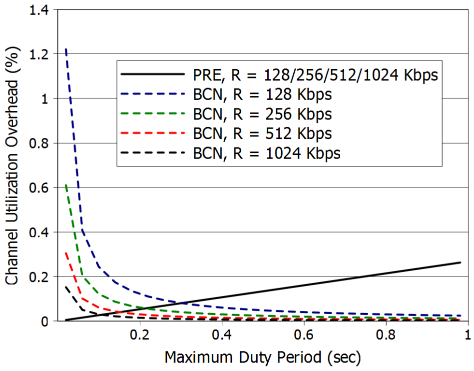

Fig. 8. Channel Utilization Overhead for Various Transmission Rates.

for delay-sensitive applications in environments where the energy input is sufficiently enough to allow the system to operate at duty cycles that consume more energy. Despite the fact that adjusting several parameters of the system can increase or decrease the performance of the two paradigms, the main trends remain the same.

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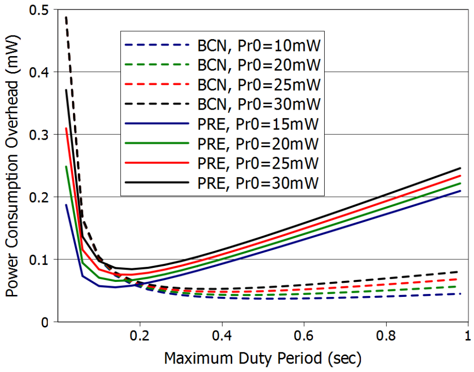

Fig. 9. Power Consumption Overhead for Various Receiving Power Costs.

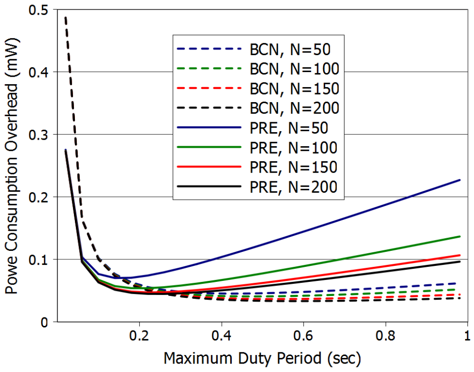

Fig. 10. Power Consumption Overhead for Different Network Densities.

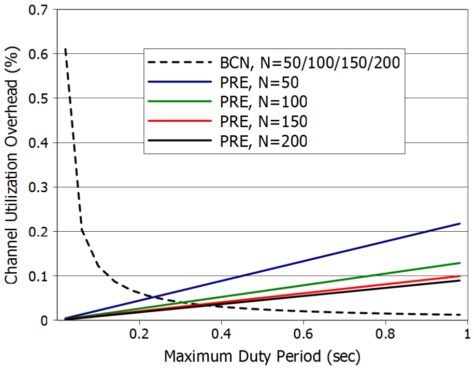

Fig. 11. Channel Utilization Overhead for Different Network Densities.

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