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Temperature MAC Plug-in for Large Scale WSN

Walid Bechkit *Member, IEEE*, Yacine Challal *Member, IEEE*, Abdelmalik Bachir, Abdelmadjid Bouabdallah *Member, IEEE*

Abstract—The quality of radio communication links decreases with high temperatures. In this paper, we investigate the effect of temperature on percolation-based connectivity in large scale wireless sensor networks and show that more energy can be saved by allowing some nodes to go to deep sleep mode when temperature decreases and links improve. We determine a closed-form formula for a threshold network density $\lambda^*(\tau) = \frac{C_0}{\pi R(\tau)^2}$ in function of temperature τ . Beyond $\lambda^*(\tau)$, the network percolates and guarantees connectivity. Based on this result, we propose a simple yet efficient Temperature-Aware MAC plugin (TA-MAC) that enables the underlying MAC protocol to dynamically adapt the network effective density to allow further energy savings while maintaining network connectivity. TA-MAC can be potentially used with any wireless MAC protocol. We carried out simulations and demonstrated that BMAC and SCP-MAC augmented with TA-MAC plugin allow a significant energy efficiency improvement.

Index Terms—Wireless Sensor Networks, Temperature Impact, Connectivity, Energy Saving.

I. INTRODUCTION

One of the important issues in WSN is network connectivity. Connectivity driven topology management has been widely investigated in the literature and a number of solutions have been proposed. Most of these solutions do not consider the impact of the atmospheric conditions such as temperature on the radio communication range. Temperature has been proven to significantly affect radio communication links negatively, as documented in the data sheets of low power radios [1], [2].

When temperature increases, both transmission power and sensitivity decrease which leads to the deterioration of wireless communication links thereby affecting the overall connectivity of the network [3]. As an example, a network designed to operate under typical conditions, i.e. a temperature of 25°C, will experience connectivity deterioration when temperature increases above 25°C. Conversely, when temperature decreases below 25°C, the radio link quality improves, the network becomes over-dimensioned and some nodes become less necessary for the network to remain connected. These nodes are able to go to deep sleep mode to save energy without affecting the connectivity of the network.

In this paper, we consider percolation-based connectivity and determine a closed-form formula for a threshold network density $\lambda^*(\tau) = \frac{C_0}{\pi R(\tau)^2}$ in function of temperature τ . Beyond $\lambda^*(\tau)$, the network percolates and guarantees connectivity. Based on this result, we propose a temperature-aware MAC

plugin that allows the underlying MAC protocol to dynamically adapt the network effective density to allow further energy savings while maintaining network connectivity. TA-MAC can be potentially used with any wireless MAC protocol.

This paper is organized as follows: in Section II we present an overview of the research carried out on percolation-based network connectivity. In Section III, we present a mathematical model for wireless links and connectivity conditions. In Section IV, we analyze and model the impact of temperature on the communication range of sensor nodes. Next, we propose in Section V a temperature-aware MAC plugin that allows the MAC protocol to minimize energy consumption while ensuring network connectivity under varying temperature conditions. In Section VI, we evaluate our solution according to various criteria including the mean power consumption and traffic load. We show that our temperature-aware MAC plugin allows saving significant amount of energy without affecting network connectivity. In section VII, we present our conclusions.

II. RELATED WORK

First, it is worthwhile to point out that the connectivity in WSN has been mainly studied from two sides: the *percolation-based connectivity* and the *full connectivity*. A fundamental result of the percolation theory is that a geometric graph induced by a Poisson Point Process with a constant density λ contains an infinite connected component with non-zero probability if and only if the density is higher than a critical value λ^* , we say then that the percolation occurs. In a network context, a node of this largest component can communicate with a high portion of the network. However, we may have many small disconnected components. The existence of an infinite connected component was considered sufficient in many research works, we refer to this paradigm as percolation-based connectivity. The full connectivity (resp. k -connectivity) on its turn guarantees that each pair of nodes can communicate with each others using at least one path (resp. k paths). The conditions of such connectivity were widely studied in the literature and a lot of relations were derived. As we consider large scale WSN, we will focus in what follows on solutions relying on percolation based connectivity.

In [4], Godfrey and Ratajczak proposed Naps, a completely distributed topology control protocol for ad-hoc and sensor networks. Authors considered a network deployed according to an infinite Poisson Point Process (PPP) with a high density, they rely on the percolation-based connectivity and assumed the existence of a critical threshold λ^* such that for all density $\lambda > \lambda^*$, there is a non-zero probability that a particular node is in an infinite connected component. In Naps, each

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node waits for a random small amount of time and then starts its time period of length T . At the beginning of this period, it broadcasts a hello message to all its neighbors. If it receives more than c reply messages, it switches off its radio and go to sleep until the end of the period. Otherwise, it remains active for the whole period. The parameter c represents then a threshold value of the average node degree allowing the network connectivity based on percolation. Its value is computed depending on the target density λ^* .

In [5], authors propose a solution very similar to Naps [4] while relying also on the percolation-based connectivity. Authors propose that each node goes to sleep with a probability $\frac{\phi}{\langle N \rangle}$ at each round where $\langle N \rangle$ is the degree of the node. Using a degree-dependent dynamic site percolation process modeling, authors proved the existence of the constant ϕ ($2 < \phi < \infty$) such that the percolation occurs.

On another side, the effect of temperature has been validated independently by many researchers in the literature (e.g. [6] [7]). In [8] and [7], the authors studied through experiments the impact of the temperature on wireless communication links and data delivery performance in WSN outdoor deployments for industrial process. In [6], the authors separated the effect on the transmitter from the one on the receiver. However, the model they established only provides the reduction in link quality in function of the combined effects at both the transmitter and the receiver. A more accurate information about the effect of temperature on the radio transceivers can be directly obtained from radio circuits data sheets. The effect of temperature is also studied in [9].

As far as we can say, temperature impact on radio link quality has not been taken into consideration in designing MAC protocols for energy saving in low power networks while maintaining network connectivity. This is the aim of our solution that we present through the following sections.

III. SYSTEM MODEL

A. Wireless Network Model

We consider a wireless network where nodes are distributed according to a Poisson Point Process of constant spatial intensity λ in a surface \mathcal{A} . All nodes transmit with a full power P_t . The power of the signal emitted by Node i and received by Node j is $P_t L(d_{ij})$, where $L(\cdot)$ is the attenuation function in the wireless medium.

The uncoordinated nature of communication allows multiple transmitters to communicate at the same time, however, creates interference at all receivers. A common connection model in ad-hoc networks is the signal-to-interference noise ratio (SINR) model, where two nodes are connected if the SINR between them is greater than a threshold.

In other words node i can transmit data to node j if the signal received by j is strong enough, compared to noise. Formally, this condition is written as

$$SINR_{ij} = \frac{P_t L(d_{ij})}{N_0 + \gamma \sum_{k \neq i,j} P_t L(d_{kj})} \geq \beta \quad (1)$$

where N_0 is the power of the thermal background noise and β is the signal to noise ratio required for successful decoding.

The coefficient γ weights the effect of interferences, depending on the orthogonality between codes used during simultaneous transmissions. Without loss of generality, we will consider $L(d_{ij}) = ad_{ij}^{-b}$, where a and b are parameters that describe the wireless channel, b is usually called *path loss exponent*.

Using this transmission condition, the network can be modeled with a graph $G(N, E)$ where N is the set of nodes, and $E = (i, j) \in N \times N$, st. $SINR_{ij} \geq \beta$.

B. Radio Communication Range

We define the radio communication range R as the range that allows a successful transmission according to the condition in equation 1, in the absence of interference ($\gamma = 0$). In this case, if we neglect the thermal floor noise ($\gamma = 0$ and $N_0 = 0$) the successful transmission depends on the power of the received signal, referred to as P_r , which is equal to the power radiated by transmitter after attenuation:

$$\begin{aligned} P_r &= P_t L(d) \\ &= P_t a d^{-b} \end{aligned} \quad (2)$$

The minimum power of P_r that allows successful transmission is called sensitivity, and is referred to as P_s .

The previous equation (3) can be used to express the relation between the sensitivity P_s and the communications range R . We have:

$$P_s = a R^{-b} P_t \quad (4)$$

Thus, the radio communication range can be quantified according to the following equation:

$$R = \left(a \frac{P_t}{P_s} \right)^{1/b} \quad (5)$$

If we consider that our sensor network is deployed out-door, one of the most accurate model for the path loss is the two-ray ground propagation model. In the two ray ground model, the values of a and b are the following:

$$a = G_t G_r H_t^2 H_r^2 \quad (6)$$

$$b = 4 \quad (7)$$

where G_t (resp. G_r) is the antenna gain at the transmitter (resp. receiver), and H_t (resp. H_r) is the antenna height at the transmitter (resp. receiver).

C. Percolation condition under the physical model

Kleinrock and Silverster [10] studied the conditions to have an asymptotically connected network in radio networks. Authors assume that nodes are randomly distributed according to a Poisson Point Process (PPP) and found that the minimum required number of neighbors is equal to *six*, the 'magic number' as they called it. This 'magic number' was after that revised to *eight* in [11].

In [12] authors, proved that there is no magic number and that if the number of neighbors is constant the network will be disconnected when the region became large. They showed that for an infinite area there exists an infinite connected component (percolation) with non zero probability if the

number of neighbors $\pi R^2 \lambda > C_0$ for some critical value $2.198 < C_0 < 10.526$.

Following this condition, the minimum density required to induce network percolation is then given by :

$$\lambda^* = \frac{C_0}{\pi R^2} \quad (8)$$

The minimal density in equation 8 that induces network percolation has been derived for networks without interference ($\gamma = 0$). Dousse et al. have demonstrated in [13] that if a threshold density λ^* exists, with $\gamma = 0$ (no interference), so that $\forall \lambda \geq \lambda^*$ the network percolates, then under the generalized physical model with interferences, there exists $\gamma > 0$ such that the network percolates $\forall \lambda \geq \lambda^*$. In other words, if some threshold density λ^* induces network percolation under the simplified model ($\gamma = 0$, no interferences) then there exist some orthogonal coding through time or frequencies ($\gamma > 0$) such that the network percolation occurs also.

Following this result, we will consider λ^* in equation 8 as the critical value that induces network percolation under the generalized physical model.

IV. EFFECT OF TEMPERATURE

A. On Communication Range

There is increasing evidence that high temperature affects both the transmitter and the receiver. In [8] and [7], Boano et al. studied through experiments the impact of the temperature on wireless communication links and data delivery performance in WSN outdoor deployments for industrial process. In [6], the authors separated the effect on the transmitter from the one on the receiver. However, the model they established only provides the reduction in link quality in function of the combined effects at both the transmitter and the receiver. A more accurate information about the effect of temperature on the radio transceivers can be directly obtained from radio circuits data sheets. For instance, the data sheet of the widely used low-power radio CC2400 [1] provides quantitative information which shows that the values of P_s and P_t are not constants but are affected by temperature change. Therefore, we use the notation $P_t(\tau_t)$ (resp. $P_s(\tau_r)$) to express the variation of the transmission power (resp. sensitivity) in function of the temperature τ_t (resp. τ_r measured at the transmitter (resp. receiver). Consequently, the radio communication range is also affected by the temperature at the transmitter and the receiver. Therefore, we have:

$$R(\tau_t, \tau_r) = \left(a \frac{P_t(\tau_t)}{P_s(\tau_r)} \right)^{1/b} \quad (9)$$

The forms of the function $P_t(\tau)$ (resp. $P_s(\tau)$) depend on the radio chips. Some manufacturers provide data about this variation for some temperature values, e.g. CC2400 [1] and CC2530 [2]. A closed-form expression for $P_t(\tau_t)$ (resp. $P_s(\tau_r)$) is not provided. However, the data provided in the data sheet allows to use regression to find the closed polynomial representations for $P_t(\tau_t)$ and $P_s(\tau_r)$.

B. On Percolation

As shown in section IV-A, the transmission range is not fixed but changes according to temperature at the transmitter τ_t and temperature at the receiver τ_r . For the sake of simplicity, we consider that the network is deployed over homogeneous area in which the same temperature is measured at all the nodes, i.e. $\tau_t = \tau_r$. In this case, we use τ to refer to temperature. For simplicity, we use the notation $R(\tau)$ instead of $R(\tau_t, \tau_r)$. Similarly, the critical density that induces network percolation also depends on the temperature. Therefore, we have:

$$\lambda^*(\tau) = \frac{C_0}{\pi R(\tau)^2} \quad (10)$$

V. TEMPERATURE-AWARE MAC PLUGIN FOR ENERGY SAVING

In this section, we propose a simple yet efficient MAC plugin that adapts node's transceiver activity to ensure network connectivity while minimizing energy consumption, under varying temperature conditions. The underlying algorithm switches on and off nodes' transceivers in function of temperature. This algorithm guarantees that only those nodes that need to be on to ensure percolation and/or send data are operating. The others switch their transceivers off to save energy.

We use in what follows τ^+ to refer to the maximum temperature. To ensure connectivity in the worst case, the initial density of nodes should be equal to $\lambda_{\tau^+}^*$. We assume that $\mathcal{A}\lambda_{\tau^+}^*$ nodes are initially deployed over the deployment area \mathcal{A} following a Poisson Point Process. We assume also that nodes use the default transmission power level which is supposed to be the maximum transmission level (This is the case of most radio chips like CC2400, CC2420, CC1100, etc.). When the temperature τ is lower than τ^+ , a lower density is sufficient. We propose thus to put some nodes in sleep mode, and by doing so a sizable amount of energy can be saved.

We propose to calculate $\rho_\tau = \lambda_\tau^*/\lambda_{\tau^+}^*$ which represents the ratio of network density that is required to maintain connectivity when the temperature is τ compared to the initial deployment where the density is calculated according to the highest temperature. The value of ρ_τ also represents the number of nodes required to be on when temperature is equal to τ compared to that when temperature is equal to τ^+ .

By using equation (10), we obtain:

$$\rho_\tau = \frac{\lambda(\tau)}{\lambda(\tau^+)} \quad (11)$$

$$= \frac{C_0}{\pi R(\tau)^2} \times \frac{\pi R(\tau^+)^2}{C_0} \quad (12)$$

$$= \frac{R(\tau^+)^2}{R(\tau)^2} \quad (13)$$

The idea of our approach is then to keep the ratio of active nodes equal to ρ_τ at temperature τ . Note that, by selecting nodes which go off randomly, the distribution of the nodes which remain on maintains the same characteristics, i.e. distributed according to PPP (thanks to the thinning property of PPP). We also assume that each node is able to know its temperature (temperature sensor readings, extraction from log

files, computation, expectation, etc.). Our approach called TA-MAC relies on algorithm 1 that is executed by every node periodically (a predetermined period of time) without the need to exchange information with other nodes.

Algorithm 1: TA-MAC (Input: MAC protocol)

```

1 Obtain temperature  $\tau$  for the round:
2 Compute  $\rho_\tau$ 
3 if Node has data to send then
4   | Run underlying MAC protocol for the entire round
5 else
6   | Pick  $p$  a random value :  $p \in [0, 1]$ 
7   | if ( $p < \rho_\tau$ ) then
8     | Run underlying MAC protocol for the entire round
9   | else
10    | Off: go to sleep mode for the entire round
11  | end
12 end

```

VI. PERFORMANCE EVALUATION

In this section, we evaluate the energy efficiency of the proposed solution and compare it to existing MAC protocols that are not temperature-aware. First, we present the temperature model and the MAC protocols along with the energy model used in simulations. Next, we give and discuss the simulation results.

A. Temperature model

We refer to the ERBS's model [14] as derived in [15] where the average normalized diurnal temperature variation is represented by:

$$\begin{aligned} \tau(y, m, t) = & \tau(y, m) + A_\tau(y, m) [0.4632 \cos(\gamma(t) - 3.805) \\ & + 0.0984 \cos(2\gamma(t) - 0.360) \\ & + 0.0168 \cos(3\gamma(t) - 0.822) \\ & + 0.0138 \cos(4\gamma(t) - 3.513)] \end{aligned}$$

where $\gamma(t) = 2\pi(t - 1)/24$; t is the time in hour; $\tau(y, m)$ is the daily monthly mean air temperature; and $A_\tau(y, m)$ is the monthly mean thermal amplitude in degrees Celsius [15]. For $\tau(y, m) = A_\tau(y, m) = 25^\circ\text{C}$, figure 2 top shows the temperature variation throughout the day (time in hours).

B. MAC protocols

In order to evaluate the efficiency of TA-MAC, we will consider two MAC protocols for WSN: BMAC [16] and SCP-MAC [17]. BMAC is one of the most deployed protocols in WSN as it is the default protocol in most of the sensor node prototypes (Micaz, Mica-2, etc.) that rely on the operating system TinyOs. BMAC achieves high energy savings through the use of preamble sampling technique (see [18] for a survey on these protocols) where nodes spend most of their time in sleep mode, but only wake up from time to time to check for incoming traffic. To make sure that a node does not miss

an incoming data packet, each node prepends its data packet transmission with a preamble that is long enough so that any potential receiver will wake up during the transmission of the preamble. When a node wakes up and detects a preamble being transmitted, it keeps receiving it until it decodes the data packet. A more advanced version of preamble sampling is SCP-MAC in which nodes synchronize on a common sleep/wake schedule to reduce the overhead of sending long preambles.

C. Energy consumption model

We propose to evaluate \mathcal{P} (Joules/s) the average power consumed by a node. The power \mathcal{P} depends on many parameters such as the energy consumption of the micro-controller and the radio. For the sake of conciseness and simplicity, we consider only the power consumed by the radio which is dominant. The energy consumed by the radio depends on the underlying MAC protocol.

We use the analytical model developed in [17] for the evaluation of the energy consumption of the BMAC [16] and SCP-MAC [17] protocols. We have:

$$\mathcal{P} = \mathcal{P}_{tx} + \mathcal{P}_{rx} + \mathcal{P}_{pl} \quad (14)$$

where \mathcal{P}_{tx} (resp. \mathcal{P}_{rx} , and \mathcal{P}_{pl}) is the average power drained in transmission (resp. reception and channel sampling). We evaluate the mean power consumption on the flooding; therefore, each node transmits one packet and receives $\eta(\tau)$ packets, where $\eta(\tau)$ is the number of neighbors. The average power drained during transmission (resp. reception and channel sampling) is:

$$\mathcal{P}_{tx} = (T_p + T_{data}) \cdot P_{tx} \cdot r_{data} \quad (15)$$

$$\mathcal{P}_{rx} = \eta(\tau) \cdot (T_p/2 + T_{data}) \cdot P_{rx} \cdot r_{data} \quad (16)$$

$$\mathcal{P}_{pl} = (T_{pl}/T_p) \cdot P_{pl} \quad (17)$$

where P_{tx} (resp. P_{rx} , and P_{pl}) is the power drained during the transmission (resp. reception and channel sampling). T_{data} is the transmission duration of one data packet, T_p is the channel sampling interval, T_{pl} is the duration of channel sampling, and r_{data} is the packet rate. We note that we assume that there are no transmission errors, and thus no retransmissions. We note that P_{pl} which is the power drained during the sampling of the channel can be considered to be equal to P_{rx} .

D. Simulation results

We conducted extensive simulations in order to evaluate the power consumption of our approach and compare it to MAC protocols that are not temperature-aware. We evaluate also the impact of our solution on the network connectivity. We give in Table I the common simulation parameters.

1) *Impact of temperature on power consumption:* In this subsection, we compare power consumption when varying temperature from -20°C to $+80^\circ\text{C}$. We plot in Figure 1 the impact of temperature on power consumption per node when

TABLE I
SUMMARIZE OF THE SIMULATION PARAMETERS

CC2400 radio	V	3 v
	I_{rx}	24mA
	I_{tx}	19mA
	data rate	250 kbps
Radio propagation (TRG)	H_r	1.5m
	H_t	1.5m
	G_r	1
	G_t	1
MAC Layer	r_{data}	(1/300)Packet/s
	T_{data}	50Bytes \times 32 \cdot 10 ⁻⁶ s/Byte
	T_p	200 \cdot 10 ⁻³ s
	T_{pl}	2.5 \cdot 10 ⁻³ s

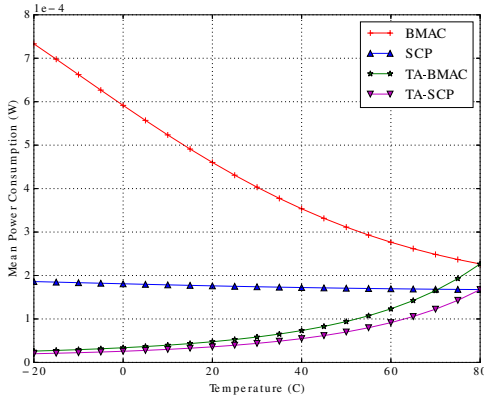


Fig. 1. Impact of Temperature on Power Consumption

using BMAC and SCP-MAC as MAC protocols and when using the same protocols augmented with TA-MAC algorithm.

The figure shows that TA-MAC approach presents a significant improvement in terms of power consumption compared to MAC protocols without temperature awareness. This is due to the proposed temperature-aware sleep scheduling. Indeed, at each round a fraction of nodes $(1 - \rho_\tau)$ turn their radio off which allows to save a significant amount of energy.

2) *Average power consumption*: In this subsection, we compare the average power consumption per node when using BMAC and SCP-MAC as MAC protocols and when using the same protocols augmented with our Temperature-Aware MAC approach. We recall that nodes are initially deployed considering the highest possible temperature (with a density equal to $\lambda_{\tau+}$).

The mean power consumption when a given node is on is given in Eq. (14) and we assume that the power consumption when the node is off is equal to zero. Indeed, as explained before, the most important amount of energy is consumed by the radio and the power consumption can be negligible whenever nodes turn their radios off. We plot in Figure 2 the obtained results when considering the CC2400 radio chips and the two ray ground model (parameters are given in Table I).

Figure 2 shows that by using the basic MAC protocols where nodes do not use temperature aware energy saving,

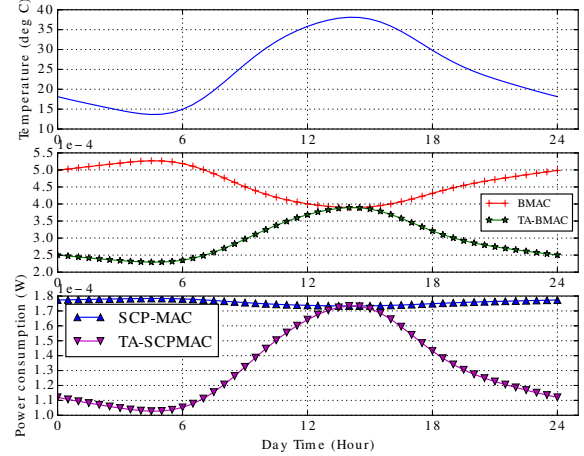


Fig. 2. Top: Temperature variations. Bottom: Mean power consumption per node

the average power consumption increases when the temperature decreases and vice versa. Indeed, when the temperature decreases the communication range becomes higher and the number of potential neighbors of each node increases which increases the power drained by the data reception.

On the other hand, the figure shows clearly that the TA-MAC algorithm outperforms the other approaches thanks to sleep scheduling. When the temperature decreases, the communication range becomes higher which reduces the fraction of nodes required to guarantee the network percolation. This allows to save more energy since more nodes will turn off their radios. The results show that the TA-MAC algorithm allows to save a sizeable amount of energy which ranges from 0% when the temperature is maximum to about 50% (for BMAC) and 40% (for SCP-MAC) when the temperature is minimum.

3) *Impact of data rate on energy savings*: In Figure 3, we study the effect of traffic load variations on the mean power consumption of our Temperature MAC Plugin. We show that there is a significant difference between BMAC and SCP-MAC without our Temperature MAC Plugin and the same protocols with the Plugin. The difference in energy consumption is particularly high with BMAC because nodes running BMAC use long preambles and thus consume more energy than those running SCP-MAC in which nodes spend more time in sleep mode. Therefore, the effect of using Temperature MAC Plugin is less visible with MAC protocols having a very high sleep mode ratio and in lighter traffic loads.

4) *Impact of Check Interval variation*: In Figure 4, we vary the check interval (T_p) and plot the induced mean power consumption. For BMAC, we notice that there is an optimal value (0.075s for the configuration setup we used) for the check interval where the mean power consumption is minimized (Note that BMAC has a limited duty cycle [16] because longer check intervals involve longer preamble transmissions and result in higher energy consumption. Therefore, the amount of energy savings that can be achieved with BMAC is limited). For values smaller than 0.075s more energy is

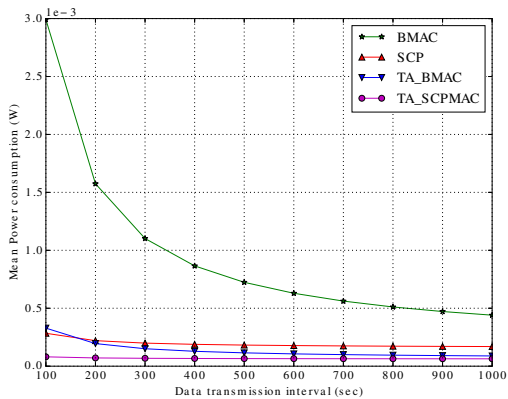


Fig. 3. Energy savings with respect to data rate

consumed because nodes spend more time in checking the channel waiting for incoming data. Smaller check intervals are only interesting for delay constrained applications. However, we notice that the optimal value for the check interval with TA-BMAC is significantly larger than that of BMAC which offers the possibility of using higher duty cycles thereby allowing higher amounts of energy savings. The reason why TA-BMAC has a higher check interval is because it has smaller number of neighbors which limits the amount of energy spent at the reception side. Also, with TA-BMAC, nodes that are not selected to continue to operate normally, will go into deep sleep mode where they do not transmit packets, which results in lesser energy spent in transmission (particularly the long preamble). For SCP, there is no limitation for the check interval and the energy consumption continues to decrease when the check interval increases. The same behavior is observed with TA-SCP.

VII. CONCLUSION

In this paper, we proposed a temperature-aware MAC plugin that can be used with potentially all existing WSN MAC protocols to make them even more energy efficient in environment where temperature variations are frequent and significant. We have shown that TA-MAC is relatively simple to implement and provides substantial benefits for large scale networks by adapting node's transceiver activity to ensure percolation-based connectivity under varying temperature conditions.

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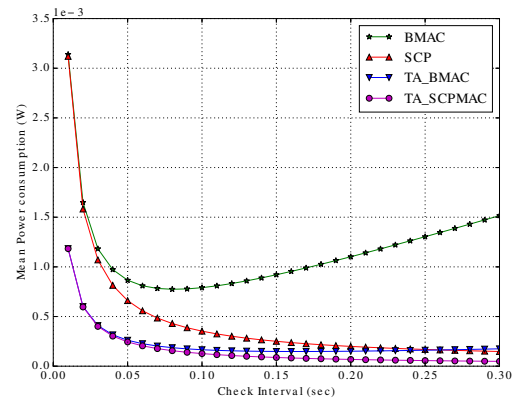


Fig. 4. Energy savings in function of check interval

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