Transmit Power Reduction ≠ Proportional Power Savings: Applicability of Transmit Power Control in Large-Scale Wireless Sensor Networks

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Abstract

This article argues that reducing transmit power at low-power RF transceivers does not lead to proportional energy savings. This is due to the fact that the baseline operations of low-power transceivers are already optimized for very low power consumption. The article then claims that typical transmit power control protocols discussed in the context of wireless sensor networks (WSNs) are tested in small-scale settings, and thus do not reflect the actual real-world large-scale WSN or IoT scenarios. The article also discusses how a joint transmit power and routing scheme can help in reducing the overhearing effects on the nodes that have significantly low available energy.

Introduction

Adjusting the radio transmission power of wireless IoT nodes can affect the energy consumption in a wireless network in a number of ways. Reducing the transmission power to the minimum level required to reach the receiver saves energy at the transmitting node due to reduction of the radiated signal energy. An additional benefit is the reduction of interference to neighboring nodes. Hence, transmission power control is commonly used in high-power wireless devices such as cellular phones and other systems where the transmitter dominates the energy usage.

On the other hand, in low-power devices such as wireless sensors or IoT devices, the energy used in radio transmission is small compared to that spent in the radio electronics (filter, modulator, demodulator, mixer, etc.), which does not depend on the transmission power. By extensively analyzing the commercially available low-power transceivers, I show that *reducing the transmission power only saves a small amount of energy at the transmitting node*. However, a joint network-wide transmission power control along with route adaptations can still provide significant energy savings in some nodes having critically low energy resources by reducing the amount of overhearing on them, which consumes a significant amount of energy. Notice that this article mainly focuses on wirelesss sensor networks (WSNs) with low data rate, and thus the effect of interference is not of primary interest.

The rest of the article is organized as follows. I summarize the effects of transmit power control in different low-power commercial radios, and why these radios do not achieve proportional reduction in current consumption by transmit power adaptation. I describe the potential of transmit power control in large-scale WSN scenarios. The article is then concluded.

Power Levels and Current Consumption of Typical Transceivers

Let us first study the power consumption of different transceivers available in the market. Table 1 shows the list of some commercial transceivers along with their product details. Figures 1–3 show the variation of current consumption at different power levels, which show that reducing the transmit power level does not lead to *proportional reduction in power/current consumption* of the transmitter.

Analysis of Current Consumption vs. Transmit Power

This phenomenon is analyzed in Figs. 1a–1e for sub-GHz RF transceivers. Figure 1a–b) show the characteristics of CC1000 radios, which are used by MICA2 and MICA2DOT sensor nodes. CC1000 radios @ 433 MHz consume 26.7 mA while transmitting at 10 dBm, and 6.9 mA at -20 dBm (i.e. a 75 percent reduction in current consumption for a three orders of magnitude reduction in transmit power level). At 868 MHz the radios sacrifice a 300× times reduction in transit power levels, to achieve a 66 percent reduction in current consumption. A similar phenomenon is noticed in CC1101 radios, where reducing the power level by more than four orders of magnitude, results in 65 percent reduction in current consumption. ON Semiconductor's AX5043 radios @868 MHz draw 54.6 mA @ 15 dBm and 7.5 mA @ 0 dBm, which results in ~86 percent reduction in current consumption, for 31× reduction in transmit power level. For Nordic nRF905 radios, a 26 percent reduction in current consumption leads to 63× reduction in power level.

Let us now study this phenomenon for transceivers that operate in gigahertz bands. Figures 1f and 2 show their characteristics. Operating at 2.4 GHz, CC2400 radios consume 19 mA at 0 dBm and 11 mA at –25 dBm, which leads to 42 percent of reduction in current consumption for 316× reduction in power level. CC2420 radios used by MICAz and TelosB sensor nodes consume 17.4 mA while transmitting at 0 dBm and 8.5 mA at –25 dBm [6], a 50 percent reduction in current consumption for more than 300× reduction in transmit power level. Similar behavior is also observed for CC2500 and CC2520 radios. AT86RF230 radios from Atmel consume 16.5 mA at 3 dBm and 9.5 mA at –17 dBm, which results in 42 percent reduction in current consumption for 100× reduction in power level. For ZL70250 radios, 75 percent reduction in current consumption leads to a sacrifice of 1000× reduction in transmit power level.

On the other hand, a Nordic nRF52840 chip @2.4 GHz draws 4.8 mA at 0 dBm and 2.3 mA at –40 dBm [12] to achieve a 50 percent reduction in current consumption, the radio sacrifices a four orders of magnitude reduction in transmit

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Radio	Organization	Frequency	Power levels	Current consump. @ TX mode	Current consump. @ RX mode
CC1000 [1]	Texas Instruments	315/433/868/915 MHz	–20–10 dBm	6.8–26.7 mA	7.4–9.6 mA
CC1101 [2]	Texas Instruments	315/433/868/915 MHz	–30–12 dBm	11.9–33.4 mA	14.7 mA
AX5043 [3]	ON Semiconductor	27–1050 MHz	0–15 dBm	7.5–54.6 mA	6.5–9.5 mA
nRF905 [4]	Nordic Semiconductor	433/868/915 MHz	–10–10 dBm	11–30 mA	12.2–12.8 mA
CC2400 [5]	Texas Instruments	2.4 GHz	–25–0 dBm	11–19 mA	24 mA
CC2420 [5]	Texas Instruments	2.4 GHz	–25–0 dBm	8.5–17.4 mA	18.8 mA
CC2430 [6]	Texas Instruments	2.4 GHz	–25.2–0.6 dBm	18.3–32.4 mA	27 mA
CC2500 [7]	Texas Instruments	2400–2483.5 MHz	–55–1 dBm	8.4–21.5 mA	13.3 mA
CC2520 [8]	Texas Instruments	2.4 GHz	–18–5 dBm	16.2–33.6 mA	18.5 mA
AT86RF230 [9]	Atmel	2.4 GHz	–17–3 dBm	9.5–16.5 mA	15.5 mA
ZL70250 [10]	Atmel	868/915 MHz	–30–0 dBm	1.15–4.7 mA	1.9 mA
nRF52840 [11]	Nordic Semiconductor	2.4 GHz	–40–8 dBm	2.3–14.8 mA	4.6 mA
nRF24L01 [12]	Nordic Semiconductor	2.4–2.5 GHz	–18–0 dBm	7–11.3 mA	12.3 mA
nRFAP2 [13]	Nordic Semiconductor	2.4 GHz	–18–0 dBm	11–15 mA	17 mA

TABLE 1. List of transceivers.

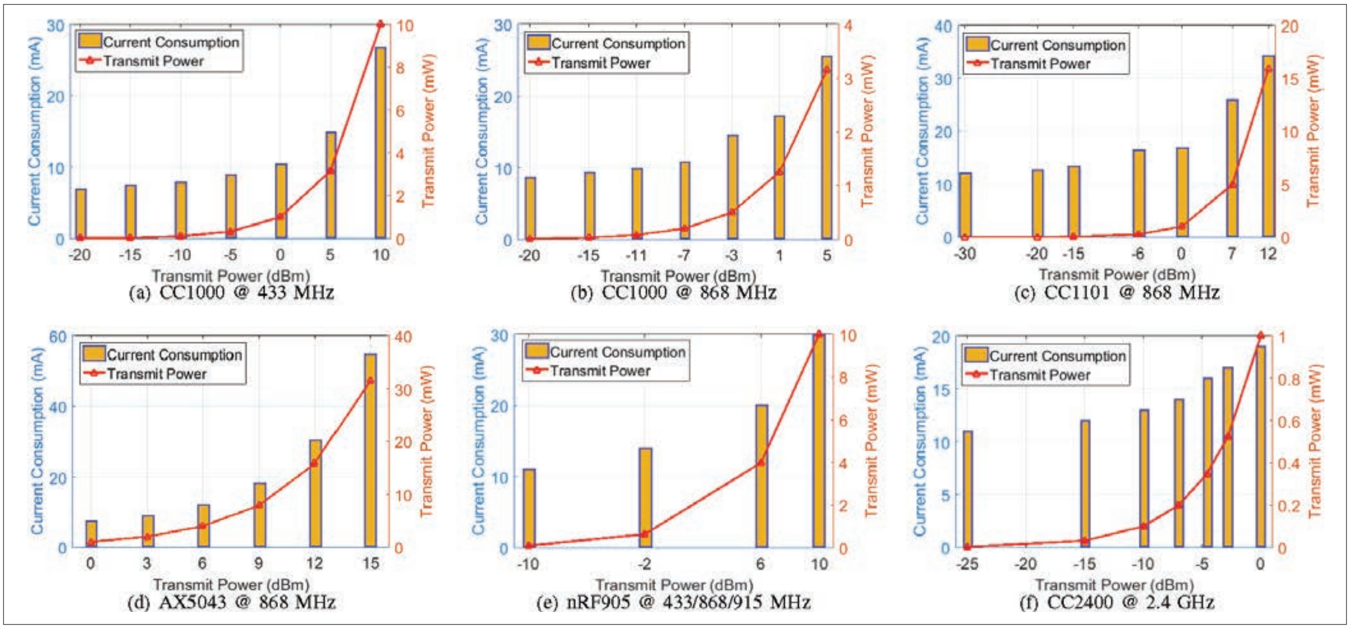

FIGURE 1. Current consumption at different transmit power levels for different transceiver platforms in MHz and GHz bands [1–5].

power levels. nRF24L01 radios consume 11.3 mA at 0 dBm and 7 mA at –18 dBm, 38 percent reduction in current draw for 63× reduction in power level. For nRFAP2 radios 26 percent reduction in current consumption leads to 63× reduction in power level. The characteristics of these Nordic platforms @2.4 GHz is depicted in Fig. 3.

Conceptual Reason behind the Phenomenon

Let us now discuss why transmit power reduction does not lead to proportionate power savings in low-power transceivers, as illustrated in Figs. 1–3. Figure 4 shows the conceptual block diagram for a typical transmitter. The key components of a transmitter are digital-to-analog converter (DAC), reconstruction filter, mixer, power amplifier (PA), and RF filter. The analog signal is first digitized by a DAC converter, passed through a reconstruction filter, and then through the mixer for frequency translation. This signal is then sent to a power amplifier, which boosts the signal power for reliable communication. Reference [15] has presented a comprehensive energy model for the RF front-end of a transmitter. The study also concluded that in a wireless transmitter, only the energy consumption of the power amplifier and the DAC is dependent on the transmit power level, whereas others are pretty constant irrespective of the power levels. The low-power wireless radios have a high overhead of energy consumption from these active circuit elements such as oscillators/frequency synthesizers and active mixers [16], which can consume up to a few tens of milliwatts. In fact, these active components together consume around 34–72 percent of the energy consumption for a transmitter [15]. Due to these active elements, the room for reducing the transceiver energy consumption by reducing the power level is quite limited. This justifies that these low power radios do not achieve proportional energy savings by dropping the power levels at the transmitters.

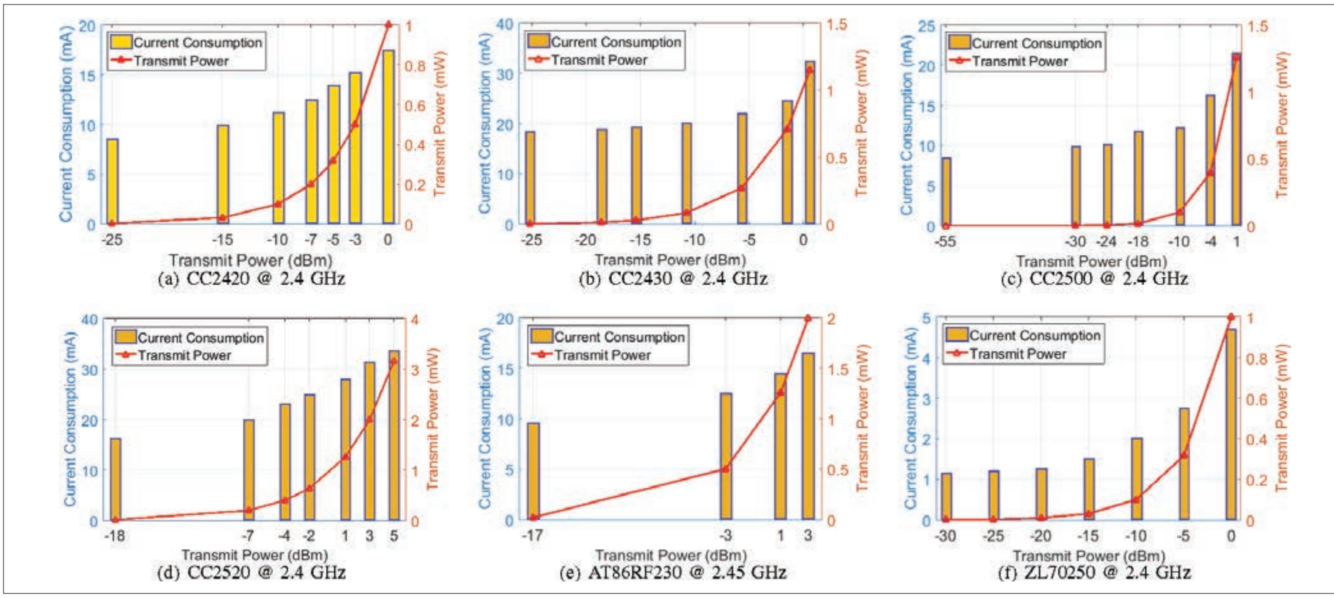

FIGURE 2. Current consumption at different transmit power levels for different transceiver platforms in GHz band [6–11].

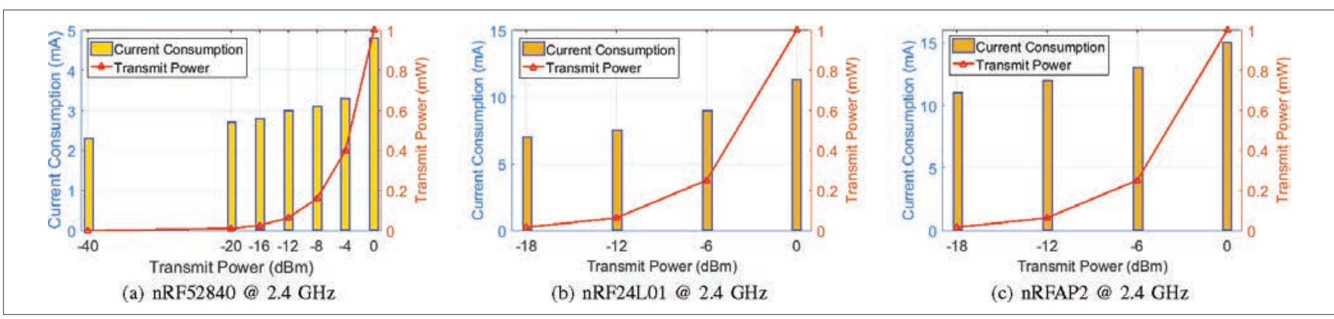

FIGURE 3. Current consumption at different transmit power levels for Nordic nRF52840, nRF24L01, and nRFAP2 platforms [12–14].

Use of Transmit Power Control

Transmit Power Control and Related Literature

Transmit power control has been studied extensively in the related literature for energy conservation. In [17] the authors have proposed an adaptive transmit power control scheme that finds the minimum transmission power at each link to provide a good link quality. It uses feedback-based power control to dynamically maintain individual link quality over time. The authors have shown experimentally on 43 MICAz sensor nodes that the scheme consumes 53.6 percent of the transmission energy as compared to the maximum power solution. However, the experimentation has been conducted in an area of 15 × 15 m^2, and deploying 43 nodes within this area means the distance within the neighboring nodes is within a few meters. Because of these short links, many nodes have managed to reduce their power levels close to the minimum level. Such a reduction can be possible only with *short* wireless links of a few meters. But this level of improvement cannot be achieved in a wide-area sensor network, where nodes are separated by several tens of meters.

A similar study was conducted in [18] on 50 sensor nodes, where the distance between the nodes and the sink is at most 50 meters, which is reachable by just one hop with the highest power level (the transmission range with the highest transmit power is assumed to be 82.92 m in this article). On this network topology the authors showed that by reducing the power level of the nodes to an optimal level, the network lifetime can be extended by up to 43 percent. In a large sensor network, the sink is generally not reachable within one hop, even at the highest power level. Thus, the level of improvement shown in such literature is achieved in the *optimistic* scenario, but do not reflect the realistic scenario of a large network.

In [19, 20] the authors achieved energy-efficient transmit power control in the context of body area networks. As the body area networks are limited to within a few meters, such an improvement is achievable. However, this improvement does not reflect the effect of power control in large environments.

How Can Power Control Help Large WSNs?

A natural question immediately follows from the previous findings: how can the transmit power control then be used in large wireless sensor networks? Notice that in low-power radios, the current consumption in receive mode is comparable to the transmit mode[1], as observed from Table 1. For example, CC2420 radios consume at most 17.4 mA in transmit mode and 18.8 mA in receive mode. From these values, one can observe that power control can still be useful to reduce *overhearing* on the sensor nodes whose energy is critically low. Field research has shown that overhearing is the key factor that leads to energy wastage in mesh sensor networks [21, 22], where a data packet transmitted to a specific neighboring node is also received (or overheard) by all other unintended neighbors of the transmitting node before being discarded. Notice that overhearing is the critical energy consuming factor, due to the *receive mode current consumption*. Thus, overhearing causes transmissions from one node to affect the energy consumption of its neighbors, especially in the case of asynchronous sensor networks.[2] Cooperative power control (CPC) can alleviate this

[1] This is somewhat different when computed for high-power wireless devices where the energy usage for RF transmissions dominate over that used for receiving and electronics.

[2] Note that overhearing can also be eliminated by applying scheduling schemes, where nodes maintain non-overlapping transmission schedules. However, that requires time synchronization among the nodes.

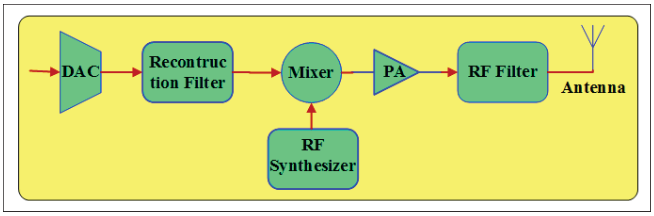

FIGURE 4. Illustration of a conceptual transmitter architecture [15].

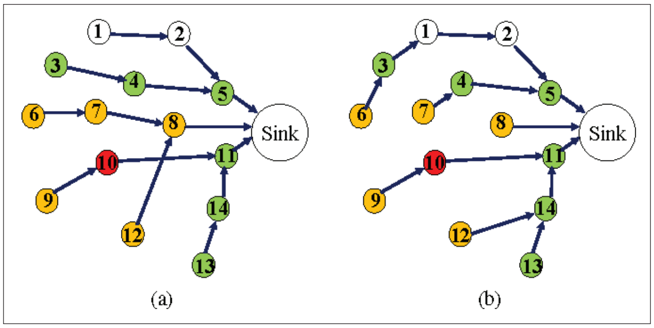

FIGURE 5. Illustration of the benefits of power control: a) before; b) after adaptation. The energy-critical node is marked in red. Here the yellow nodes are the strong overhearers, whereas the green nodes are weak overhearers of the energy-critical node.

Var	Values	Var	Values	Var	Values	Var	Values
I_{Br}	20 mA	T_{Br}	140 ms	I_{Dr}	20 mA	T_{Dr}	140 ms
I_P	20 mA	T_P	3 ms	I_S	7.5 mA	T_S	112 ms

Var	Values	Var	Values
I_{Bt}, I_{Dt}	17.4 mA (0 dBm), 16.5 mA (–1 dBm), 15.2 mA (–3 dBm), 13.9 mA (–5 dBm), 12.5 mA (–7 dBm), 11.2 mA (–10 dBm), 9.9 mA (–15 dBm), 8.5 mA (–25 dBm)	T_{Bt}, T_{Dt}	140 ms

TABLE 2. Different parameters for MICAz.

issue, where the nodes can adapt their behavior to help support the energy budgets of their *energy-critical neighbors*.

An illustrative example of CPC is shown in Fig. 5, where the red node is assumed to be energy-critical. The *strong* overhearers can reduce their transmit power, as well as routes (e.g., nodes 6, 7, 12) to avoid causing overhearing of the critical node. Notice that in Fig. 5b the nodes have adopted power control in conjunction to route adaptation. Because of this reason, the traffic of node 6 is not going through nodes 7 and 8, which are also strong overhearers of the red node. Similarly, the *weak* overhearers (e.g., green nodes) can also reduce their transmit power as well as routes to:
- Reduce the overhearing effects on the red node
- Forward their traffic away from the red node (as done by node 3), which also reduces overhearing on the critical node

Notice that in wide area sensor networks, some of these overhearers may not be able to reduce their transmit power significantly (as discussed earlier), but their cumulative effect of transmit power reduction may result in a significant amount of overhearing reduction on an energy-critical node. In fact, for some weak interferers, a small reduction in transmit power may completely avoid causing overhearing to the critical nodes. At the same time, the joint use of power control along with route adaptation (i.e., forwarding the traffic away from the critical nodes) can significantly reduce the overhearing effects on the critical nodes; a detailed protocol is discussed in [23].

The effectiveness of CPC is experimentally validated on a testbed of 25 MICAz sensor nodes in Fig. 6. These nodes are programmed using TinyOS [24] and deployed on the rooftop of an academic building at the University of North Carolina (UNC) Charlotte, as shown in Fig. 6a. To imitate a real multi-hop WSN environment, the power level of the radios are varied between –1 dBm and –13.4 dBm, which results in a multihop scenario even without any power adaptation. The nodes send data packets and beacon packets with an interval of 1 minute and 5 minutes, respectively. Notice that *the beacon messages are sent using the highest power so that all neighboring nodes can receive them*. Two sensor nodes are made to be energy-critical, as their energy availability is assumed to be significantly lower as compared to others. Initially, all nodes start with their maximum transmit power level of –1 dBm. Over time, the non-energy-critical nodes gradually reduce their transmit power levels, along with adapting their routes to avoid overhearing caused to the energy-critical nodes. The experiment is run for six hours. Figure 6b illustrates the variation of overhearing on the critical nodes over the period of six hours; the figure clearly shows that immediately after deployment, the overhearing on the critical nodes is significantly high. However, the amount of overhearing at the critical nodes is reduced by up to 75 percent because of the network-wide power control and route adaptations.

Let us now demonstrate how these overhearing reductions are reflected in the reduction of current consumption of these two critical nodes. For measuring the current consumption of a sensor node we use the experimentally developed model described in [22], which is expressed as

$$I = \underbrace{I_{Bt}T_{Bt}/T_B}_{\text{Beacon transmission}} + \underbrace{MI_{Dt}T_{Dt}}_{\text{Data transmission}} + \underbrace{NI_{Br}T_{Br}/T_B}_{\text{Beacon reception}} + \underbrace{OI_{Dr}T_{Dr}}_{\text{Overhearing}} + \underbrace{FI_{Dt}T_{Dt}}_{\text{Forwarding}} + \underbrace{I_ST_S/T_D}_{\text{Sensing}} + \underbrace{\eta_P I_P T_P}_{\text{Processing}} \quad (1)$$

where I_X and T_X represent the current drawn and the duration, respectively, of event x; transmission/reception of beacons is denoted by B_t/B_r, data transmit/receive is denoted by D_t/D_r, and processing and sensing are denoted as P and S, respectively. The beacons and data packets are transmitted at an interval of T_B and T_D, respectively. We assume that the overhearing and forwarding rates of the sensor nodes are denoted by O and F, respectively. N is the number of neighbors of the sensor node. M is the rate at which a sensor node transmits its own packets.

The sensor nodes use the *LowPowerListening* (*LPL*) scheme [25], where they wake up η_P times in a second to check whether the channel is busy or not, which we define as the *processing* task. If the channel is idle, they go back to sleep; otherwise, they stay on until the end of the ongoing transmission. η_P is set to 8 for the experiment.

The current consumptions of all the events are recorded experimentally and are listed in Table 2.[3] The current consumption in different power levels ranging from 0 dBm to –25 dBm are also shown in Table 2. With these parameters, Fig. 6c shows the corresponding reduction in current consumption of the two critical nodes over six hours. Similar to Fig. 6b, the current consumptions of these two nodes are quite high when the experiment starts, but gradually become lower over time. From Fig. 6c, we can observe that due to the joint transmission power control and route adaptation of the non-critical nodes, the current consumption of the critical nodes reduces by up to 40–45 percent.

Conclusion

This article has discussed the feasibility of transmit power control, which is an important design problem for applications in large-scale wireless sensor networks. The corresponding design

[3] Note that the manufacturer's datasheet reports the current consumption of a MICAz mote at 0 dBm to be 17.4 mA and 19.7 mA in transmit and receive modes, respectively [26]. However, for our performance evaluations we assume the measured values of 20 mA for these two modes, which is a close approximation.

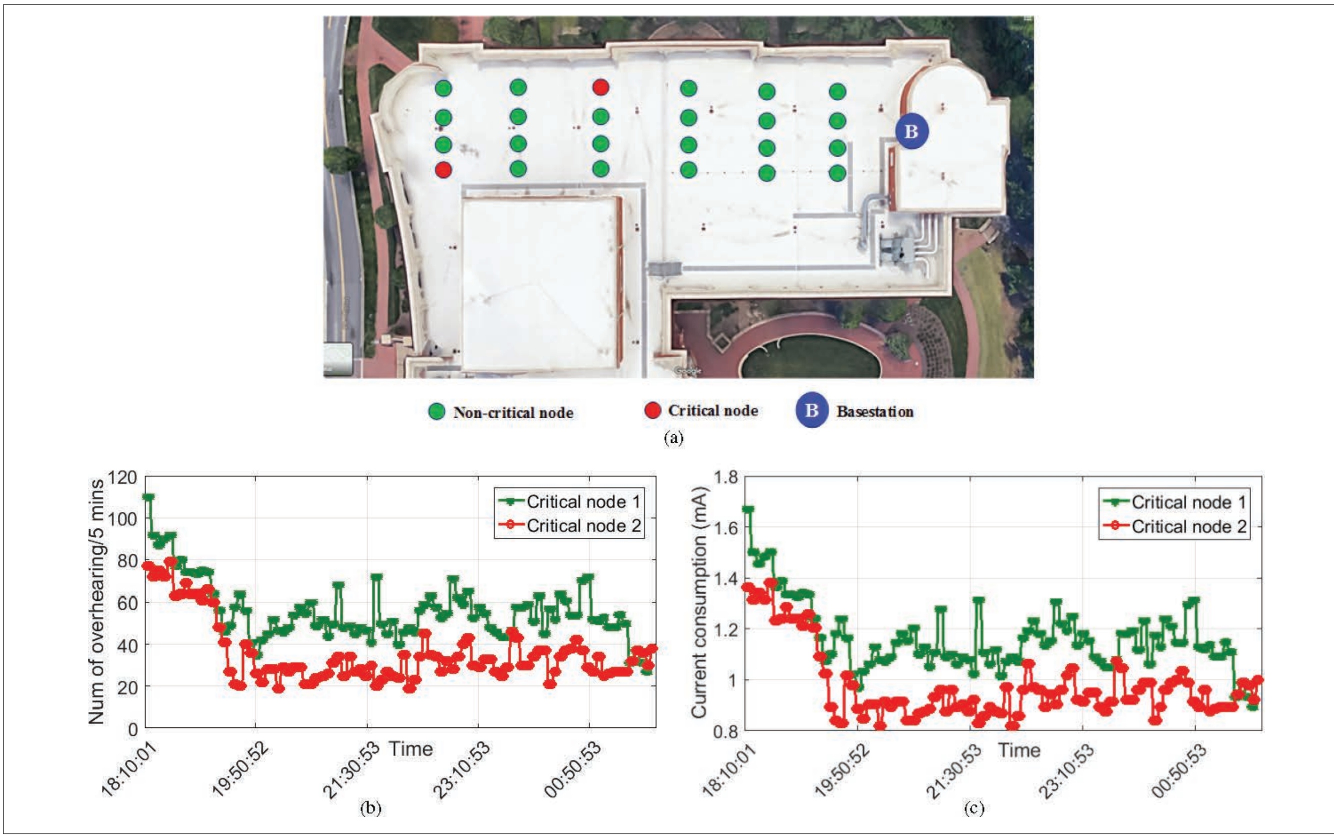

FIGURE 6. The effect of CPC is tested on: a) a 25-node wireless sensor network testbed; b) the number of packets overheard by the two critical nodes; c) their corresponding current consumption over time.

issues and problem characteristics are obtained from an extensive set of commercial radios used in WSN scenarios. This article has claimed that transmit power control does not reflect in proportional improvement in energy efficiency in a practical setting of large-scale WSNs. The article has also discussed how power control can be exploited for cooperative power control and route adaptation to alleviate the overhearing problem, which is a key issue in large-scale wireless sensor networks.

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Biography

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