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A Path Energy Control Technique for Energy Efficiency on Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) are being deployed in a wide range of application areas requiring high energetic efficiency to increase the application lifetime. Trading off power optimization and reliability has become one of the most significant concerns when dealing with modern systems based on WSNs to guarantee all nodes receive the transmitted data. This work presents a Path Energy Control Technique (PECT), which sets the transmission power of each node based on the path energy consumption. This setting blends three metrics: (i) Quality of the Path (QPth), (ii) Received Signal Strength Indicator (RSSI), and (iii) Data Packet Rate (DPR). Experimental results prove the efficacy of PECT in reducing the energy consumption up to 42% when compared to experiments with fixed transmission power, preserving the reliability of the data transmission.**

Keywords— WSN; transmission power; energy efficiency.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of communicating nodes, which contain sensing, data processing, and communication components, as well as battery power supply. Recent advances in wireless communication and electronic technology allow the development of small, low-cost, low-power and multifunctional sensor nodes [1]. Resources like processor, memory, and battery are restricted in sensor nodes since their replacement can be prohibitive in the hazardous and inaccessible areas where they are supposed to operate [2]. Nodes are likely to operate on limited battery life; power conservation is one of the most critical issues. Employing additional transmission power not only reduces the WSN lifetime but also introduces excessive interference. Thus, transmitting at the lowest possible power, while preserving the network connectivity and reliability has become an attractive strategy for saving energy in WSN [3]. Energy restrictions, limited computational and memory capacity introduce the challenge to create more efficient communication protocols for guaranteeing data delivery in WSNs since environment interferences can cause quality degradation [4][5].

The Data Packet Rate (DPR) affects the energy consumption of the communicating node since high rates may increase packet loss and augment the node's processing load, both impacting on the entire WSN energy consumption. This paper proposes the Path Energy Control Technique (PECT) to reduce the energy consumption by combining transmission power and path control. PECT selects the transmission power level of each communication using the Received Signal Strength Indicator (RSSI) feedback from the communication neighborhood and computes the Quality of the Path (QPth). PECT generates an efficient metric that manages the DPR, varying the traffic rates.

This paper (i) demonstrates the impact of DPR on the communication quality. Experimental results confirm that high DPR decreases the WSN efficiency and, consequently, increases its energy consumption; and (ii) shows that PECT guarantees efficiency while reducing the energy consumption on the data transmission, thus increasing the nodes lifetime.

The remaining of the paper is organized as follows. Section II compares works of energy optimization on WSNs with PECT. Section III presents PECT, detailing the used model as well as the proposed algorithm. Section IV describes the experimental results, detailing the simulation, the algorithm's test program, and the results. Finally, Section V shows the main conclusions.

II. RELATED WORK

Several works were proposed to optimize WSN energy. For instance, Lavratti et al. [6] proposed the Transmission Power Self-Optimization (TPSO), which depends on specific results provided by the coordinator to calculate this metric efficiently and it is applied to a single hop, whereas our technique may be used to multi-hop. Lin et al. [7] proposed the Adaptive Transmission Power Control (ATPC), which is a technique similar to PECT; both calculate new power settings based on a study of the signal interference. However, ATPC requires each node carries an inner table containing the RSSI of all network for data exchange implying extra memory and energy consumption, while our technique only requires the RSSI from the neighbor nodes. Kim and Kwon [8] introduced the Interference-aware Transmission Power Control (I-TPC), which is a technique that controls the power transmission and the RSSI providing comprehensive results, but implying high implementation complexity when compared to the PECT algorithm. PECT assures an efficient energy consumption based on a balanced tradeoff among node status, transmission power, as well as DPR.

III. THE PATH ENERGY CONTROL TECHNIQUE (PECT)

A WSN composed of a high quantity of nodes leads to a high data rate towards the Coordinator Node (CN), which may cause data packet loss and, consequently, increases the packet retransmissions. Figure 1 shows the effect of reception saturation for the CN throughout a simulation study (we employed all packets with 16-bytes size and 250 kpbs of transmission velocity). The efficiency indicates the ratio between the number of packets arriving at the CN and the number of packets supposed to arrive. Figure 1 depicts the communication efficiency as a relation of DPR and transmission power for six WSNs composed of 3, 4, 5, 6, 8 and 11 nodes. When increasing both the number of transmitting nodes and DPR (to more than 30 packets per second), the network efficiency suffers significantly. Thus, if the number of data packets created in a node exceeds this limit, the packets do not arrive at their destination and, the node waste retransmission energy. This fact grounds the technique proposed here since energy saving may be achieved at a DPR before the efficiency dropping point. Therefore, capturing these dropping points for each transmission power and each WSN, we defined the Energy Efficiency Operating Region (EEOR). PECT identifies the minimum energy necessary to send packets without

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affecting the reception quality into the EEOR, which means dealing with the tradeoff between the energy consumption and communication quality. Aiming to extract equations that are used by PECT algorithm for power transmission settings into the EEOR, we linearized the data acquired in the simulation study. This linearization performs a polygon partially represented on the top of Figure 1 and detailed in Figure 2.

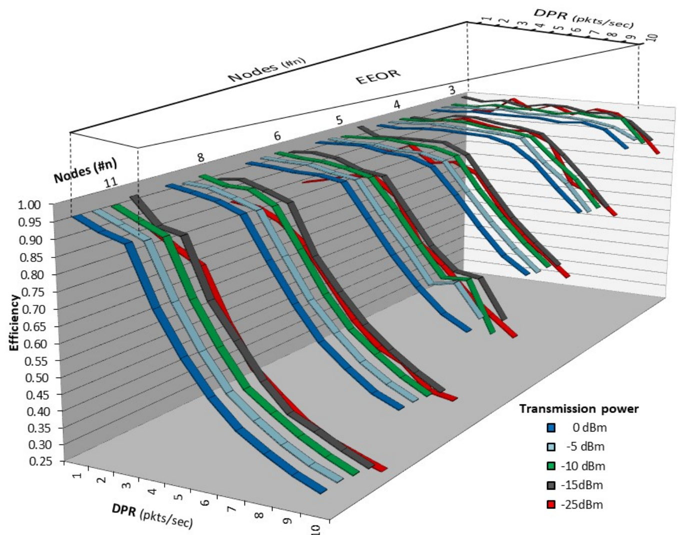


Figure 1. Relation between efficiency and data rate for some number of nodes and transmission power values. Additionally, a polygon representing a perspective of linearization of EEOR.

Figure 2 shows that we linearized EEOR to calculate the above-depicted efficiency, for using on the PECT flow.

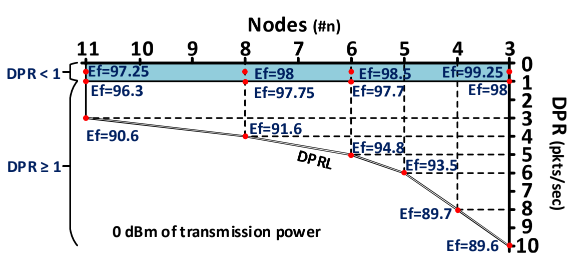


Figure 2. Linearization of EEOR extracted from the data depicted in Figure 1. Remark that the "Nodes (#n)" axis of Figure 1 is out of scale.

Equations 1 or 2 calculate the WSN efficiency (*Ef*) when the DPR < 1 packet/sec or DPR ≥ 1 packet/sec, respectively. Both equations approximate the values achieved by simulation using the method of least squares with a residual less than 2%, on average.

$$Ef = 100 - 0.25 \times \#n \tag{1}$$

$$Ef = 99.5 - 0.15 \times \#n - 0.28 \times \mathrm{DPR} - 0.2 \times \mathrm{DPR} \times \#n \tag{2}$$

Where: *#n* is the number of nodes sending packets. Likewise, if energy saving aspects would be considered in the equations, a lower number of sent packets would entail less energy consumption. Thus, less energy would be wasted due to the increased probability of all transmitted data packets arriving at their destination.

Figure 3 shows descending slopes regarding the energy consumption for systems with a decreasing quantity of transmitting nodes, even while using the same transmission power. Herewith, it is possible to assume the lower the set of nodes that transmit packets, the lower the probability of interference and, consequently, lower energy consumption. The data transmission rate of all nodes was set near the Data Packet Rate Limit (DPRL), which in our simulation study was about 30 packets/sec. Note that DPRL shows the number of packets per second in the CN, but the other nodes have a lower packet rate (e.g., with # n = 5, DPR is 6).

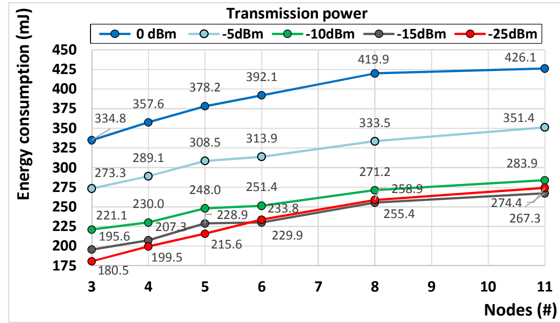


Figure 3. Transmission energy consumption.

In real scenarios, a significant number of packets do not reach the target node obliging nodes to transmit additional packets to compensate this loss, and we define *Ea* (additional energy in mJ) the energy spent to transmit these extra packets. Equation 3 calculates the Energy Consumption (*Ec*) (in mJ), which includes the minimum or initial energy consumption Ec_{min} (in mJ) and *Ea*.

$$Ec = Ea + Ec_{min} \tag{3}$$

Employing linear regression analysis, we achieve *Ea* and Ec_{min} in relation to #n and *Pd* (Power Dissipation, in mW) through the equations 4 and 5 with a residual less than 1%, on average.

$$Ea = 11.5 \times \#n \tag{4}$$

$$Ec_{min} = 5.43 \times Pd - 11.6 \tag{5}$$

Equation 6 computes *QPth*, which is the metric that defines the data path quality limited by DPRL. *QPth* is a part of the energy consumption added to the transmission packet to overcome the interference. We use *QPth* to reduce the overall *Ec* maintaining the efficiency. Thus, we multiply *Ea* by Ef_{min}, which is around of 90% and represents the minimum efficiency in the DPRL region; i.e., Ef_{min} represents the limit before the efficiency drops, and *Ef* is the efficiency computed by Equations 1 or 2.

$$QPth = \frac{1}{Ec} \times \frac{Ea \times Ef_{min}}{Ef} \tag{6}$$

Finally, Equation 7 expresses *QPth* applying on Equation 6 the equations 3, 4 and 5, and using $Ef_{min} = 0.9$.

$$QPth = \frac{10.35 \times \#n}{Ef \times (11.5 \times \#n + 5.43 \times Pd - 11.6)} \tag{7}$$

The transmission power is a parameter to be adjusted to assure the packets arrive at the destination. When the radio signal is transmitted, a part of the transmission power is wasted even without obstacles. The waste in power and data path measures result in the Path Loss (*Pl*) [4], which is the signal's power loss at CN. Let *Prx* be the receptor radio sensibility, and *RSSI* the Received Signal Strength Indicator (both in dBm), then Equation 8 describes *Pl*.

$$Pl = RSSI - Prx \tag{8}$$

Inequation I.1 shows that to perform a communication, the power radio transmission *Ptx* has to be greater than the sum of the radio receiving sensibility (*Prx*) with *Pl*.

$$Ptx - Prx - Pl \geq 0 \tag{I.1}$$

Table I shows the correlation between power dissipation (mW) and transmission power (dBm) of the transceiver used in experimental results with CC2420 of Texas Instrument [9].

TABLE I. POWER DISSIPATION AND TRANSMISSION POWER OF CC2420 [9].

TX_dBm	0	-1	-3	-5	-7	-10	-15	-25
Pd (mW)	57.42	55.18	50.69	46.20	42.24	36.30	32.67	29.04

We evaluated the behavior of the data packets using information about reception and transmission power, interference, and the path loss of these packets, with the goal of defining a satisfying *Pl* while maintaining a node with an efficiency of more than 90%. We used the simulator described in [10] configured to use the IEEE 802.15.4 protocol and the values described in Table I setting the transmission power to 0 dBm, -5 dBm, -10 dBm, -15 dBm, and -25 dBm, which enables to observe the behavior of data packets, as well as the behavior of *Pl* under the changing conditions. The interference value has to be lower; otherwise, the transmitting power needs to be increased. As a result, 20 dBm has been defined as a satisfying solution for each node to transmit data packets, without interference and with an efficiency metric higher than 90%.

We identify two metrics to adjust the power transmission appropriately: (a) the power required reaching the next destination and (b) the power necessary to overcome the losses of signal quality caused by interferences. The sum of these metrics is the deviation of the power radio transmission (Ptx_0) of the sensor node, which is expressed by Equation 9.

$$Ptx_0 = 20 \times (1 + QPth) + RSSI + Prx \tag{9}$$

When RSSI increases, the transmission power has to be increased. The same occurs when a higher *QPth* is desired; thus, it is necessary to transmit with more power to compensate the quality losses in the data path caused by the distinct interferences. Figure 4 shows the flow diagram of the proposed PECT. Observe that the first test concerns DPR, whose computation is defined according to the user's requirements, as long as the DPTL is respected.

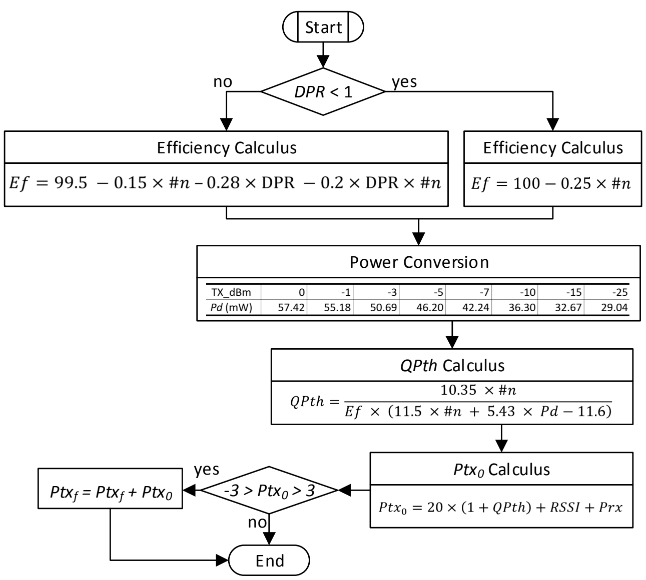


Figure 4. PECT flow diagram.

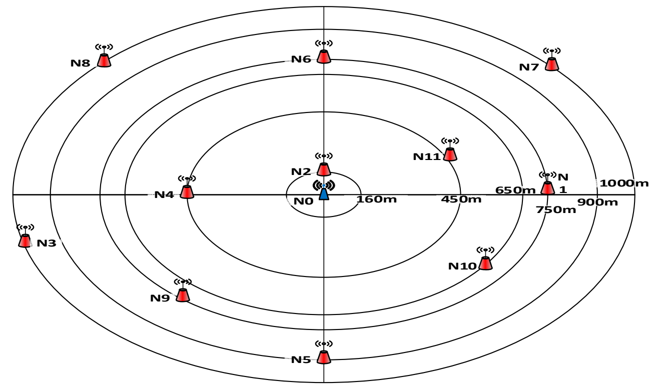
IV. EXPERIMENTAL RESULTS

We evaluate the impact of the energy consumed by message retransmission on the total energy consumption with the simulator. This section details the case study adopted during the experiments demonstrating the effectiveness of the PECT.

Figure 5 depicts the experimental setup, which a case study is based on a WSN composed of 11 nodes. All nodes start transmitting at the same time and continue sending packets to the coordinator (CN) during 50 seconds, and the coordinator receives the packets and responds with an acknowledgment to each node.

The power levels of the simulator have been set using the PECT results. DPR has been calculated using DPRL and *#n*. The following fixed parameters have been used in the input function to evaluate the effectiveness of the PECT: *#n=11, DPR = 3, Ef = 90, Prx = -95dBm and Ptx = 0dBm.* If the calculation is executed using the values stated above, the PECT returns the final radio transmission power (Ptx_f), as illustrates Equation 10. It is possible to obtain each result of the equations comprising the PECT: efficiency, conversion, path quality, power difference as well as the Ptx_f.

$$Ptx_f = 0 + (-13\ dBm) = -13\ dBm \tag{10}$$



Nodes	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11
Distance (m)	750	160	1000	650	900	750	1000	1000	750	650	450
Path loss	56	40	59	54	58	56	59	59	56	54	46
Lane	4	1	6	3	5	4	6	6	4	3	2

Figure 5. Case study adopted.

The presentation of the experimental results is split into two phases: the first phase demonstrates the impact of the energy consumption of a sensor node, while the second phase evaluates the energy consumption of the proposed approach.

Two scenarios were considered during the first phase: (i) *Scenario1* - energy consumption related to the active CPU without data packet transmission; and (ii) *Scenario2* - energy consumption related to the data packet transmission.

For *Scenario1*, the energy consumption of an active CPU is shown to justify the DPRL. Table II presents the energy consumption from each part of a node including the active CPU. We observe the current required by CPU in Active mode is similar to the current of radio transmission at 0 dBm indicating the data packet processed and not transmitted wastes CPU time and energy. Consequently, the efficiency result beyond the DPRL dramatically increases the data packet loss during transmission and degrades the energy consumption performance.

TABLE II. ENERGY CONSUMPTION PARAMETERS.

Circuit	Mode	Current	Circuit	Mode	Current
CPU	Active	8.0 mA	Radio	Tx(-19 dBm)	5.2 mA
	Idle	3.2 mA		Tx(-15 dBm)	5.4 mA
	Power-down	103 µA		Tx(-8 dBm)	6.5 mA
	Power-save	110 µA		Tx(-5 dBm)	7.1 mA
	Standby	216 µA		Tx(0 dBm)	8.5 mA
EEprom	read	6.2 mA		Tx(+4 dBm)	11.6 mA
	write	18.4 mA		Tx(+6 dBm)	13.8 mA
Radio	Rx	7.0 mA		Tx(+8 dBm)	17.4 mA
	Tx(-20 dBm)	3.7 mA		Tx(+10 dBm)	21.5 mA

Scenario2 presents six different WSNs composed of 3, 4, 5, 6, 8 and 11 nodes that were analyzed while transmitting data during 50 seconds. Table III shows the data packet behavior varied according to *#n* and adopted *Ptx* (DPR multiplied by the number of nodes was fixed to DPRL). Observing the particular case, where the WSN is composed of 6 nodes (DPR = 5 packets/second), we identify the average number of packets received per node is 232, in 50 seconds of simulation. Note that the efficiency using PECT

reaches 92.8%, concerning the total number of 250 packets. We highlight the maximum power of 0 dBm results in an efficiency of 94.8% and 84.4% when using the minimum transmission power of -25 dBm. In fact, a decreasing number of nodes transmitting data packets increases the efficiency and thus, augments the performance.

TABLE III. AVERAGE OF DATA PACKET RECEPTION BY A NODE.

Average of data packet		Power (dBm)					PECT
		- 25	- 15	- 10	-5	0	
#n	11	115.4	131.6	133.7	134.6	136.0	129.2
	8	150.6	180.8	182.0	182.6	183.2	178.7
	6	211.0	231.0	233.5	235.5	237.0	232.0
	5	256.4	280.6	283.6	282.2	280.4	281.4
	4	318.5	333.7	334.0	337.0	333.2	335.0
	3	410.6	429.3	439.6	430.6	432.0	425.0

Figure 6 shows the PECT efficiency when using the proposed technique with other transmission power levels.

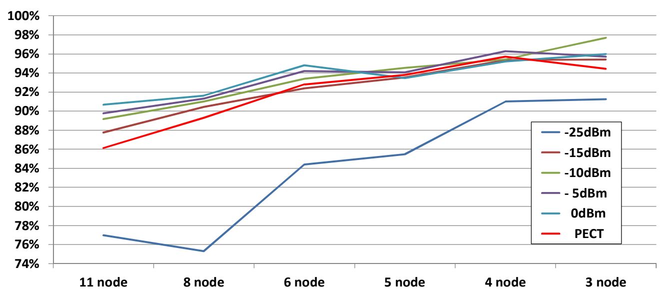


Figure 6. PECT efficiency regarding the percentage of received packets.

The second phase of experimental results evaluated the PECT energy consumption. Table IV summarizes the energy of the data packet transmissions The DPR of PECT was set near to the DPRL. The yellow cells represent the minimum energy consumption during simulation and the gray cells the maximum energy. The results obtained by the proposed algorithm are highlighted in blue. Analyzing the behavior of the PECT regarding energy consumption, one can observe that its results are close to the minimum consumption of all quantities of nodes evaluated in this paper. In the analysis of energy consumption performance, the PECT yields good results and, in some situations, saves 40% of energy more than a system using a fixed transmission power. Note that the energy consumption of PECT follows the same constant descending behavior for the data sets related to the WSNs transmitting at 0 dBm, -5 dBm, -10 dBm, -15 dBm, as well as -25 dBm, respectively. It starts at 0.273 J and arrives at 0.193 J when the *#n* is reduced to 3 nodes. These results enable to state that the energy savings may reach up to 42%.

TABLE IV. ENERGY CONSUMPTION OF THE TRANSMISSION.

Energy (J)		Power (dBm)					PECT
		0	-5	-10	-15	-25	
#n (nodes)	11	0.4261326	0.3513710	0.2839251	0.2672930	0.2743594	0.2732760
	8	0.4199369	0.3335261	0.2712230	0.2554190	0.2589229	0.2593790
	6	0.3921217	0.3139173	0.2514375	0.2299160	0.2338307	0.2394850
	5	0.3781713	0.3084656	0.2480082	0.2288530	0.2156329	0.2324220
	4	0.3575773	0.2891056	0.2299943	0.2073290	0.1995277	0.2105150
	3	0.3348260	0.2732510	0.2211320	0.1956290	0.1805120	0.1936860

The results in Table V have been obtained using a WSN composed of 11 nodes and a DPR fixed at 1 packet/sec. Table V shows the energy savings may reach up to 36% and, in some cases, the PECT achieves the minimum energy consumption using the least transmission power. Thus, PECT can reduce energy consumption, maintaining a satisfying efficiency of 90%, or even more while sending data packets.

TABLE V. COMPARISON OF ENERGY CONSUMPTION.

#n	DPR	Major (0dBm)	Minor (-15dBm)	PECT	Saving from (0dBm)	Loss from (-15dBm)
11	DPRL	0.426132	0.267293	0.273276	35.9%	2.2%
	1 pkt/s	0.163601	0.106744	0.110090	32.7%	3.1%
8	DPRL	0.419936	0.255419	0.255419	39.2%	0.0%
	1 pkt/s	0.121962	0.076555	0.079557	34.8%	3.9%
6	DPRL	0.392121	0.229916	0.239485	38.9%	4.2%
	1 pkt/s	0.089205	0.056661	0.056661	36.5%	0.0%
5	DPRL	0.378171	0.215632	0.232422	38.5%	7.8%
	1 pkt/s	0.073924	0.047721	0.047721	35.4%	0.0%
4	DPRL	0.357573	0.199527	0.210515	41.1%	5.5%
	1 pkt/s	0.057130	0.037032	0.037082	35.1%	0.1%
3	DPRL	0.334826	0.180512	0.193686	42.2%	7.3%
	1 pkt/s	0.042333	0.026690	0.026690	37.0%	0.0%

V. FINAL CONSIDERATIONS

This paper presented a novel algorithm named PECT for reducing energy consumption on WSN. The influence of the interference caused by the sensor nodes in the network, as well as the PECT efficiency has been analyzed. Based on the RSSI information of a neighbor node and the amount of perturbation caused by the nodes, PECT can calculate, with good approximation, the power associated with each path among nodes and with a reasonable compromise to reduce energy consumption. The results obtained from the simulations demonstrated that the adoption of PECT enables to reduce the energy consumption up to 42% when compared to a WSN that adopts a fixed transmission power.

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