PAPER

# Joint Control of Transmit Power and Frame Size for Energy-Optimized Data Transfer in Wireless Sensor Networks*

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**SUMMARY** Energy efficiency is one of the most important attributes in sensor network protocols. In sensor nodes, communication related activities consume the major share of battery energy. Therefore, judicious choice of transmit power and frame size are very important to maximize the energy efficiency and hence the lifetime of nodes. While there have been a few recent studies on transmit power control implementation in sensor nodes, **no report has thoroughly investigated** [Comment 9] transmit power control and the effect of its interplay with frame size on nodal energy saving.

In this paper, we report our implementation of automatic transmit power control in wireless sensor nodes based on open loop parameters – namely, link layer frame size, and close loop parameters – namely, number of consecutive positive acknowledgments and receive signal strength. Our extensive indoor and outdoor experimental results show that, for low to moderate transmission distances, transmit power control has the energy saving benefit, and the larger the frame size the more the energy saving. At a higher transmission distance or at a more error-prone communication scenario, transmit power control as well as a large frame size are detrimental to energy saving performance. The results from this study could be useful in deciding power control strategies and optimum frame length.

***key words:*** *implementation studies, automatic transmit power control, frame size control, open loop power control, close loop power control, minimum energy transmission*

## 1. Introduction and Motivation

A wireless sensor network (WSN) is an ad hoc network consisting of a large number of small sensor nodes deployed for unattended telemetry operations such as monitoring physical or environmental conditions, military applications, etc. A WSN may be deployed in an external environment or inside a building depending on the requirements. Sensor nodes gather mainly delay tolerant information from the surroundings and transfer it to a sink. This communication may occur via single hop or multi-hop routes through other sensor nodes. Each node has limited battery energy, and in many deployment scenarios it is quite difficult or impossible to **replenish the drained energy** [Comment 2]. So, to increase the nodal lifetime, efficient utilization of battery energy and low power network operation are highly desirable in a WSN. At the same time, while achieving energy efficiency, a high network performance must also be ensured.

The ways to reduce energy consumption of sensor nodes have been through *dynamic power management* (DPM) [1–3], wherein an active node tries to remain in a low power consuming state (e.g., sleep state) whenever its processor detects lack of useful nodal activity, and intelligently turns on and off the operating system to minimize the energy wastage. Such a DPM strategy is incorporated in the nodal hardware at the processor design stage, and it does not have anything to do with controlling the RF (radio frequency) output power in sync with the communication protocols and external environment.

Transmit power control (TPC) is naturally suggested in wireless network systems because successful communication with reduced power transmission *could* help nodal energy saving. There have been a significant volume of research literature on centrally coordinated as well as various distributed TPC protocols and the effects of power control on the network performance. (see, e.g., [4–8]). While the theoretical investigation on distributed power control strategies are very important – especially in a large network, implementation of TPC on the hardware platforms would enable realize ground reality specific relative merits among themselves as well as with respect to full power transmission. However, power controlled data transmission is not yet implemented in current day practice, and relatively fewer reported experimental works indicate that the implementation of even simple power control strategies are non-trivial.

**In current standard practice, besides fixed power transmission, link layer frame size is dictated by specific applications and the transport layer protocol used, irrespective of the dynamics of the physical channel state.** [Comment 3] We observe that, in most of the typical applications inter-nodal distance is sufficiently within a nodal communication range. Also, intuitively, frame error rate is a function of the frame size. Therefore, it makes logical sense to implement automatic TPC and frame size control (FSC) as a function of nodal surrounding and receiver's feedback, so that some nodal energy can be saved. Accordingly, there is

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Manuscript received March 17, 2010.

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[*] This research was supported by the Department of Science and Technology under the grant no. SR/S3/EECE/054/2007 and the Council of Scientific and Industrial Research under the grant no. 22/448/07/EMR-II.

DOI: 10.1587/trans.E0.??.1

a **need to be able to dynamically vary** [Comment 10] the transmit power of a node based on the external environment and also the packet size.

A few implementation studies of transmit power control were reported recently [9–14]. While the prior experimental studies laid an important basis of transmit power control implementation in sensor motes, effective energy saving per successful information unit transmission with different power control strategies as well as without power control has not been considered so far. Also, the relationship of energy saving, transmit power control, and link layer frame size was not studied earlier.

In this paper, we investigate the effective energy saving performance of two automatic transmit power control strategies, namely binary ACK (acknowledgment) based and receiver's signal quality information based approaches, on a Crossbow MICA2 platform operating at 915 MHz. We also study the effect of link layer frame size on nodal energy saving in sensor nodes. The key contributions of our experimental studies are: a) dynamic frame size control implementation as a power saving measure; b) implementation of optimized frame repeat window and transmit power adaptation; and c) investigation on the effect of joint transmit power and frame size control in a dynamically changing environment around a given transmitter-receiver pair to minimize the effective energy consumption.

Our results show that the effective energy saving via transmit power control is a function of transmitter-receiver distance, external environment like channel state, and link layer frame size. **In particular, we show that, a lesser (better) energy consumption per successful message unit is offered by a TPC up to a certain maximum distance, beyond which the full power transmission rather offers a lesser effective energy consumption. With variable sized frames we further demonstrate that the detrimental effect of large frame size in terms of increased energy consumption per successful message unit transmission is only apparent at a very large inter-nodal distance.** [Comment 1]

The remainder of the paper is organized as follows. Prior works on TPC implementation in wireless network nodes are surveyed in Section 2. The general strategy of the power control experiment and changes in the system functional modules are described in Section 3. Our TPC implementation strategy using open loop control is discussed in Section 4. Section 5 contains the close loop TPC implementation approaches. Field experiment results and discussions are presented in Section 6. The paper is concluded in Section 7.

## 2. Related work

There have been a significant number of prior and ongoing research works on transmit power control in wireless nodes and its various impacts. One aspect of research has been how a power control algorithm can be applied in a distributed coordination scenario and the impacts of cooperative or non-cooperative power control strategies on the network performance. Another line of work have been various power control and channelization strategies aiming at one or some of the performance criteria, such as, nodal energy saving, maximizing network life time, reducing multi-user interference, and increasing network throughput. However, all these works have been theoretical and network simulation based.

Beyond the theoretical and simulation studies, implementation of basic power control strategies in wireless nodes, namely, WLAN (wireless local area network) nodes and field sensor motes, has got some attention recently. In WLANs, power consumption measurements were conducted independently on Lucent 802.11 WaveLAN cards [15] and Cisco Aeronet 4800B PCMCIA 802.11 WLAN cards [16], where primarily transmit and receive power consumptions were considered and the effect of reduced power transmission on consumption was studied by *manually* controlling the transmit power. Also, in [17], the variation of input current drawn **at different transmit power levels** [Comment 11] was studied on 802.11 cards by *manually* altering the transmit power level. The utility of RSSI (receive signal strength indication) based fine grained transmit power control in WLAN nodes was studied by Srivastava *et al.* [12]. The authors concluded by indoor experiments that arbitrarily decided fine grained power levels may not be beneficial in terms of energy saving. They also proposed an on-line tunable granularity of power control depending on the work environment settings.

A few TPC implementations on wireless sensor motes were reported in recent past. Correia *et al.* [9] applied receiver's feedback to adjust (linearly increase or decrease) the transmitter's output power. In the iterative method, after every single reported failure power level is increased to the next discrete higher level, and after a few consecutive successes transmit power level is decreased to the next lower value. On the other hand, in attenuation based method, power control information (PCI) is piggybacked with the data and ACK frames. For every received ACK frame information, transmit power is adjusted. Both approaches showed improved delivery ratio with respect to a fixed power transmission, while the attenuation based method showing more fluctuations in the output power.

Lim and Wong [10] studied the relationship of transmit power, received signal RSS, and packet reception rate (PRR) on a Crossbow MICA2 platform at 315 MHz operating frequency [18]. Their results reiterate that besides RSS, the channel noise and interference significantly affects the PRR. **Their results also indicated**

**that, as the transmitter-receiver distance is increased and the signal transmission power is reduced, the channel between the transmitter and the receiver becomes increasingly asymmetric, i.e., the link error probability in the forward direction becomes different from that in the reverse direction.** [Comment 4]

Lin *et al.* [11] applied RSSI or LQI (link quality indication) based power controlled transmission on Crossbow MICAz motes, where the RSSI information to different neighbors are collected a priori via broadcast beaconing to its local neighbors. Through experiments they demonstrated that the RSSI/LQI information is sufficiently suitable for adaptation in TPC. During the actual data frame transmissions RSSI/LQI table is consulted to set an appropriate transmit power level.

Kim *et al.* [13] proposed an on-demand TPC approach which does not require to store in advance the LQI of all neighbors. Instead, from the initial data and ACK frames the transmit power level is gradually adjusted. This approach also allows to accommodate dynamic nature of wireless link quality, thereby avoiding the potential problem of using stale LQI information.

Park *et al.* [14] proposed three variants of power control algorithms, namely adaptive multiplicative increase and additive decrease (MIAD), packet error rate (PER) based, and simple channel model (SCM) based. As the control inputs, adaptive MIAD approach uses receiver threshold, desired PRR, current PRR, and RSSI; PER approach uses PRR and RSSI; SCM uses receiver threshold, desired PRR, and RSSI. The protocol performance was tested with respect to PRR and power saving factor per transmitted packet, where power saving factor was defined as the ratio of maximum transmit power and the average controlled (reduced) transmit power.

Overall, although some variants of TPC implementation have been reported in recent past, none have quantified the effective energy saving (i.e., energy consumption per successful Byte transfer) with or without power control under different channel conditions. Moreover, a study on the effect of distance and frame size on the optimum transmission power has not been reported.

## 3. General approach to implementation

Our experimental studies were carried out using MICA2 motes having extended communication range CC1000 RFIC operating at 915 MHz.

### 3.1 Experimental setup

Fig. 1 shows the experimental setup where there are two MICA2 (MTS400) motes communicating at 915 MHz band. TinyOS is the operating system used to handle the hardware. One of the motes connected to a computer through a gateway circuit receives the packets transmitted from another mote.

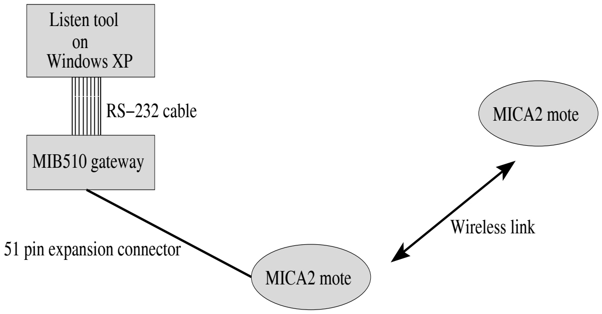

**Fig. 1** Experimental setup.

### 3.2 Software details

On the TinyOS platform, we have developed an application called `PowerControlM` for controlled power transmission of frames, and modified the TOSBase application for reporting the received frames. These applications communicate at 914.077 MHz which was ensured by setting the parameter in `MakeXbowlocal` module as:

$$\begin{aligned}\texttt{CFLAGS} &= \texttt{DCC1K\_DEFAULT\_FREQ}\\ &= \texttt{CC1K\_914\_077MHZ}\end{aligned}$$

#### 3.2.1 Power control application

The developed module (`PowerControlM`) transmits a random sized packet at a regular interval, say, every 10 ms, at a controlled power level as dictated by the look-up table (to be elaborated in Section 4). Its interaction with the other components is shown in Fig. 2. `PowerControlM` is connected to the following main components: `GenericComm`, `LedC`, `TimerC`, `CC1000ControlM`, and `RandomLFSR`. We have developed `RandomLFSR` module that generates a random number, which is taken by `GenericComm` as the payload size and transmitted periodically, with an interval

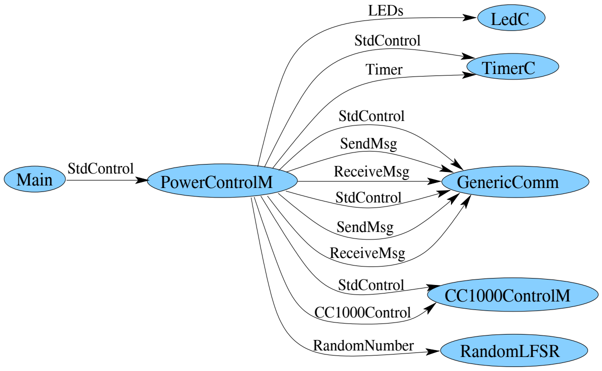

**Fig. 2** Component level view of power control application.

set by `TimerC`. For every frame sent, `LedC` is blinked. `CC1000ControlM` module was added that decides the RF power of the transmitted frame.

The `PowerControlM` module was further modified in the closed loop power control, depending on the chosen inputs for message transmission with controlled power and frame size.

### 3.2.2 TOSBase application

`TOSBaseM` is a TinyOS application that receives the frames through the radio channel and sends to MIB10 board which acts as a gateway to forward to the receiver-end computer via RS-232 Interface. Its component level interaction with the other modules is shown in Fig. 3. The modifications in this module allow display of received frames along with its error status in hex format. For closed loop power control purpose, it also generates an ACK for every received frame. The format of ACK was modified to accommodate the RSSI information along with the status if the received frame, which can be used at the transmitter to decide on a suitable power level for the subsequent frames.

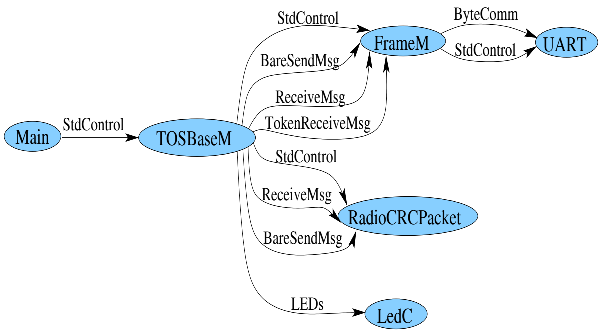

**Fig. 3** Component level view of TOSBase application.

Using the developed and modified functional modules, we conducted the experiments. To achieve the objective of energy efficiency through TPC and FSC, and thereby reducing the waste of network resource, we followed a modular approach. We divided the task into two steps namely, open loop power control (OLPC) and close loop power control (CLPC), which are explained in the following sections.

## 4. Implementation of open loop power control

In OLPC, the transmit power is varied without any knowledge of its external environment, including its desired receiver's state. That is, the transmitter does not use any feedback information from the receiver. The primary objective of this phase of experiment is to demonstrate that the transmitter node can *automatically* choose a transmit power as a function of some variable parameter, e.g., its internally-generated payload size. To this end, we note that for a given (fixed) wireless channel condition and transmitter-receiver distance, i.e., for a given bit error rate (BER) $p_b$, the frame error rate (FER) $p_f$ is a function of the frame length $L$ (bits). For simplicity of understanding, if we assume that all bit errors occur independently and at least one bit error in a frame leads to the frame error, then $p_b$ and $p_f$ are related as:

$$p_f = 1 - (1 - p_b)^L.$$

Thus, for a given $p_b$, a frame of length $L_1$ will be more error prone than a frame of smaller length $L_2$, i.e.,

$$p_{f_1} > p_{f_2}, \quad \text{if } L_1 > L_2.$$

It may be noted that the above simple BER-FER relationship does not hold in practical implementations because the frames are protected by CRC (cyclic redundancy check) bits, and in wireless channels bit errors generally occur in bursts.

To include the effect of frame size, for a certain fixed value of tolerable FER and a fixed distance to the receiver, we generated a look-up table of transmit power for different frame size. To this end, MICA2 motes offer 22 possible power setting ranging from $-20$ dBm to 5 dBm. For our OLPC experiment, we chose 8 discrete power levels. Table 1 shows the look-up table for a fixed distance of 10 meter in the laboratory room setting and a tolerable FER value 0.01 at the receiver. The table was generated by randomly transmitting 10,000 packets of payload size between 5 Bytes and 45 Bytes and identifying from a predefined set of discrete levels the minimum allowed transmit power that achieves the desired FER.

**Table 1** Look-up table of transmit power for different payload size

| Payload Size (Bytes) | Transmit Power (dBm) [Hex] |
|---|---|
| $5 - 10$ | $-11$ $[0 \times 08]$ |
| $11 - 15$ | $-09$ $[0 \times 0B]$ |
| $16 - 20$ | $-05$ $[0 \times 40]$ |
| $21 - 25$ | $-02$ $[0 \times 60]$ |
| $26 - 30$ | $0$ $[0 \times 80]$ |
| $31 - 35$ | $+02$ $[0 \times B0]$ |
| $36 - 40$ | $+03$ $[0 \times C0]$ |
| $41 - 45$ | $+05$ $[0 \times FF]$ |

After generating the look-up table, the frames were generated with a payload size randomly varying between 5 Bytes and 45 Bytes. It was then verified whether for every frame generated the transmitter sets a suitable transmit power using the look-up table. Table 2 shows some sample data of FER measurement using OLPC.

Thus, in this phase the transmitter's automatic power control capability was implemented, albeit for some arbitrarily chosen frame size. The same frame

**Table 2** Measured FER versus payload size.

| Payload Size (Bytes) | FER |
|---|---|
| 10 | 0.0092 |
| 21 | 0.0095 |
| Uniformly random in $[5,\ 45]$ | 0.0084 |

generation module was later used in the CLPC for generating frames of payload size varying between 30 Bytes and 240 Bytes, as allowed in the Crossbow motes [18]. However, the required power level (from the chosen 8 discrete values shown in Table 1) was chosen as per the receiver's feedback, as discussed in the next section.

## 5. Implementation of closed loop power control

In this phase, transmission power of the transmitter was automated based on *dynamically changing* the distance and the external environment. Unlike the open loop method, here the transmitter gets feedback from its receiver about the reception quality (in terms of binary ACK or RSSI) and accordingly sets its transmission power for the subsequent frames.

A half-duplex communication between the transmitter and receiver is established using stop-and-wait protocol, where it is implicitly assumed that the sensor application is delay tolerant. To successfully transmit a frame of a given size, the frame is simply retransmitted until it is correctly received. The following performance criteria were used:

*Definition 1:* The network performance criteria is measured as *frame throughput*, defined as the probability of successful transmission of a frame.

Note that, if the frame size is varied, the defined throughput measure does not quantify the superiority of a transmission protocol with respect to its energy efficiency. It is thus an interim performance measure.

***Definition 2:*** **To quantify the delay tradeoff associated with power control irrespective of frame size, the actual information delivery rate is measured as *link layer goodput* (in bps), defined as the rate at which a protocol can successfully deliver the information bits to the receiver.**

**Let the transmission rate of the radio transmitter be $R$ bps, data frame length be $D$ Bytes, ACK frame length be $A$ Bytes, and $p_s$ be the success probability in each attempt. With unlimited number of retries and ignoring the delays due to signal propagation and additional waiting for timeout, the time taken to complete a successful data frame transmission is: $\frac{8(D+A)}{Rp_s}$. With the payload size of $P$ Bytes in a data frame, the goodput is: $\frac{PRp_s}{8(D+A)}$.**

**Note that, the goodput measure inherently accounts for the retransmissions due to loss of frames. However, a higher goodput performance does not imply a higher energy saving.**

***Definition 3:*** **The energy saving measure is defined as the total energy consumed at the transmitter-receiver pair per *successful* payload Byte (excluding header and CRC bits) – called *energy per successful payload Byte* (EPSPB), which accounts for the consumption due to retransmissions and idle listening.**

**Denote $V$ as the operating voltage of the sensor nodes, and $I_t$ and $I_r$, respectively, as the transmit and receive current consumptions, where $I_t$ can vary at different transmit power. Following the notations for goodput expression, the EPSPB is: $\frac{8(D+A)}{PRp_s} \cdot V\left(I_t + I_r\right)$.**

**The EPSPB uniquely determines the energy saving quality of a transmission protocol, which can be used to compare the protocol performance at any frame size.** [Comment 1]

### 5.1 Effect of a chosen power control Algorithm

We have implemented and studied the energy saving performance of three link layer transmission protocols with varying frame size: full power transmission, automatic TPC with binary ACK (modified PCI approach in [9]) – called Linear Increase and Linear Decrease (LILD) algorithm, and automatic TPC with RSSI feedback ( [9, 11, 13]) with optimized waiting parameters – called attenuation method. Close loop performance of the implemented protocols were observed in different external environments and by varying internodal distance. Note that, while the basic close loop power control approaches adopted here were studied earlier, our contribution has been to implement them in dynamic receiver conditions, tuning the parameters for improved energy saving performance, and evaluating their relative merits in terms of energy saving performance with different frame length.

### 5.1.1 Full power transmission

This algorithm does not use power control. The only implementation issues here are to generate frames of variable size and effecting the stop-and-wait protocol. In this mode of transmission, the transmitter transmits a frame with maximum power and waits for an ACK. In case of an unsuccessful transmission, the frame is retransmitted after a timeout, and the process is repeated until an ACK is received. A successful transmission is followed by the next frame transmission.

### 5.1.2 Attenuation based power control

In this algorithm the transmitter sets a transmission power for the next frame by observing the RSSI value from the receiver (achieved by modifying the TOSBase application), such that a desired signal strength at the receiver is maintained. In our experiment, by trials we chose $-85$ dBm as the receive threshold that offers about $1\%$ FER. If the RSSI is less than the threshold value, the transmission power is increased to the next discrete level. To reduce a fluctuating error performance, instead of changing the power at the first instance of reported reduced RSSI (as done in [9]), the transmitter waits for 3 consecutive such instances.

#### 5.1.3 LILD approach

It is a heuristic algorithm which dynamically changes the transmission power depending on successful reception of previous frames. In this approach, the RSSI information is ignored; rather the number of successive positive/negative ACKs is used to decide on the future transmit signal strength. As in case of attenuation based method, to avoid ping pong effect in power controlled transmission, we chose 10 number of consecutive successful transmission of frames to decrease the transmit power by one level. To effect quick error recovery, a single failure of frame delivery results in increasing the transmit power by one level.

### 5.2 Effect of frame size

Since, for a given transmit power, frame error loosely depends on frame size, an optimal value frame size may offer a better energy saving measure. Thus, for a fixed distance between the transmitter and receiver and a fixed BER value, an optimal frame size may give better network performance in terms of energy consumption. Accordingly, the effect of frame size was studied in all three power control transmission protocols.

## 6. Results and discussion

We performed the experiments in indoor as well as outdoor environments. For studying the effect of frame size on **EPSPB**, the total payload size was kept constant at 8000 Bytes. Accordingly, the number of frames to be delivered varied depending on the payload size per frame. Readings were taken at different distances and with different payload size. Each experiment was repeated three times and average of them were taken.

We first show the frame error performance without and with power control. **Then the goodput performance is shown as a delay measure of the link-layer transmission process. Finally, the EPSPB performance and time response plots are presented, to evaluate the energy saving performance of the transmission protocols.** [Comment 1]

**To compute the goodput, note that, the transmission rate of MICA2 motes operating at 915 MHz is** $38.4$ **kbps. The header length of a data packet is 5 Bytes and the CRC is 2 Bytes long. Thus, for a payload of size** $P$ **Bytes, the link layer data frame length is** $(P{+}7)$ **Bytes. The ACK frame size is 6 Bytes, which can ensure binary as well as analog (RSSI) feedback from the receiver. Since the transmitter-receiver distance is short (maximum up to 270 m, as found in our experiments) and the transmission rate is low, the propagation delay is negligible compared to the data/ACK transmission delay, and hence it is ignored in computing the goodput. The receiver acknowledges immediately after receiving a packet, and the timeout for retransmission is set nearly as the sum of data and ACK transmission times. Accordingly, the time spent in one frame transmission attempt is the sum of data and ACK transmission delays.**

**To compute the EPSPB, the operating voltage** $(V)$ **was taken** $3$ **Volts, as the nodes are run by two AA batteries. The current consumption values at receive mode and transmit mode at various power levels were taken from the Crossbow MICA2 data sheet [19].** [Comment 1]

### 6.1 Indoor performance

For indoor experiments we placed two motes in a long corridor, with a fixed height of 110 cm from ground level so as to have a line-of-sight between the two motes.

#### 6.1.1 Frame error performance

Figs. 4 to 6 show that, expectedly the frame error performance with full power point-to-point transmission is the best (which may not necessarily be true in a general network environment, in presence of other interfering transmitters). **On the other hand, between the two power control methods, the attenuation based method performs poorer than the LILD beyond a very short distance.** [Comment 5]

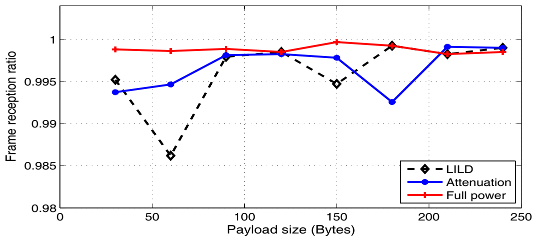

**Fig. 4** Indoor: Frame error performance versus payload size. Transmitter-receiver distance 5 m.

While the frame error rate is indicative of retransmission requirements, a related but closer measure of delay performance is goodput. In the following, we

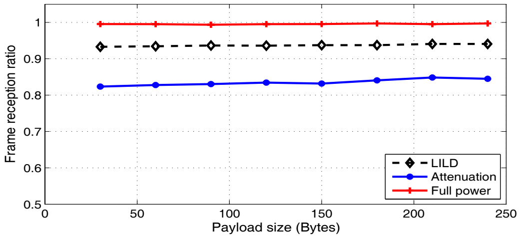

**Fig. 5** Indoor: Frame error performance versus payload size. Transmitter-receiver distance 100 m.

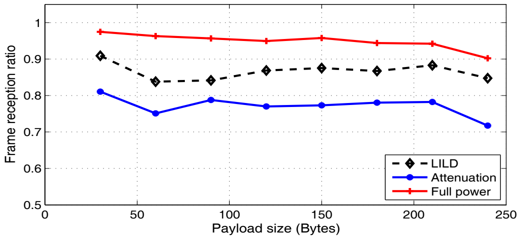

**Fig. 6** Indoor: Frame error performance versus payload size. Transmitter-receiver distance 270 m.

present the relative results on link layer goodput performance.

### 6.1.2 Link layer goodput performance

**Figs. 7 to 9 show the relative goodput performance versus payload size in the indoor environment.**

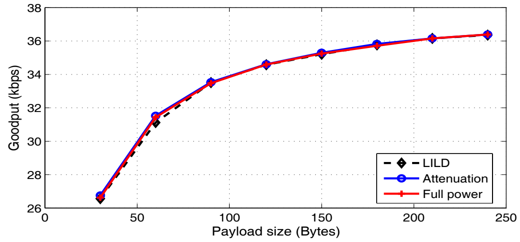

**Fig. 7** Indoor: Link layer goodput versus payload size. Transmitter-receiver distance 5 m.

**As observed in the frame error performance results (Figs. 4 to 6), at very low transmitter-receiver distance, the relative goodput performances are nearly identical. At higher distances, full power transmission offers a rather better performance, as also anticipated from the frame reception ratio plots. In all cases, at a small payload size the overhead being high, the payload bit transfer rate is low - even though the frame reception ratio is high. Again at very large payload size, a lower frame delivery success rate pulls down the goodput.** [Comment 1, 8(b)]

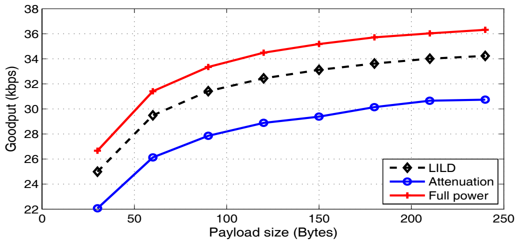

**Fig. 8** Indoor: Link layer goodput versus payload size. Transmitter-receiver distance 100 m.

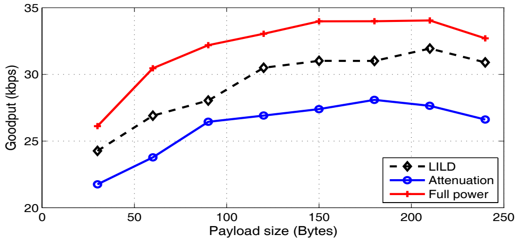

**Fig. 9** Indoor: Link layer goodput versus payload size. Transmitter-receiver distance 270 m.

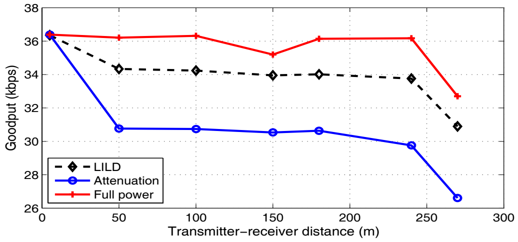

**Fig. 10** Indoor: Link layer goodput versus transmitter-receiver distance. Payload size 240 Bytes.

**The effect of transmitter-receiver distance on the goodput performance is further demonstrated in Fig. 10, which shows that, the performance decreases as the distance increases. At a very low distance, since power control plays very little role, all approaches have nearly the same goodput performance. With the power control comes into effect at a moderate distance, a higher frame loss rate causes a lesser goodput compared to fixed power transmissions.** [Comment 1]

In telemetric sensor network applications possibly a more important performance parameter is average energy spent per successful information unit transmission, which is studied next.

### 6.1.3 Effective energy consumption per unit success

Figs. 11 to 13 show how the frame size affects the effective energy consumption. Observe that, up to a moderately large distance increasing the payload size from 30

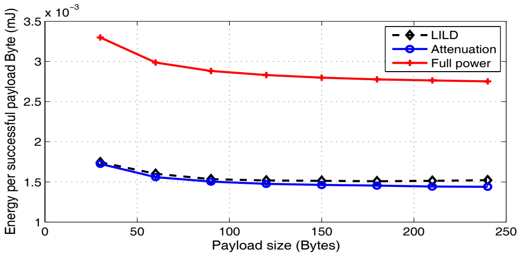

**Fig. 11** Indoor: **EPSPB** versus payload size. Transmitter-receiver distance 5 m.

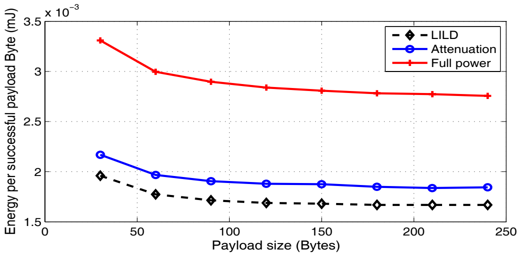

**Fig. 12** Indoor: **EPSPB** versus payload size. Transmitter-receiver distance 100 m.

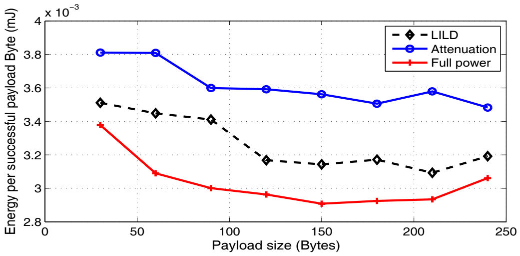

**Fig. 13** Indoor: **EPSPB** versus payload size. Transmitter-receiver distance 270 m.

Bytes to 240 Bytes has an effect of decreased **EPSPB** in all the three methods. At very short distances, attenuation based power control algorithm performs better. But at longer distances attenuation method becomes more error prone because RSSI based power control becomes less reliable, and hence it requires frequent retransmissions. At moderate distances, LILD method performs better among the three. The Full power algorithm gives the worst result in all cases except at a very long distance (270 m), where it outperforms the other two algorithms as they consume more energy due to retransmissions. It is also observed that at very long distances, the optimum payload size (210 Bytes) is quite higher than the default maximum payload size (128 Bytes).

A cross-examination of the results in Figs. 7 to 9 reveal that, although the reception quality and correspondingly the goodput with full power transmission is always better, unless the transmitter-receiver distance is very large, effective energy requirement per successful transmission with full power transmission is higher than the power controlled transmission approaches.

Fig 14 shows the effect of distance on the **EPSPB**. With full power transmission, the consumption is nearly steady, which is quite intuitive as it uses maximum transmission power and the number of retransmissions are nearly the same expect at a very long transmitter-receiver distance. The results indicate that, at moderate transmitter-receiver distances LILD is effectively more energy efficient. These results also demonstrate that, at very high distance or in a much error prone situation, full power transmission offers overall more energy saving.

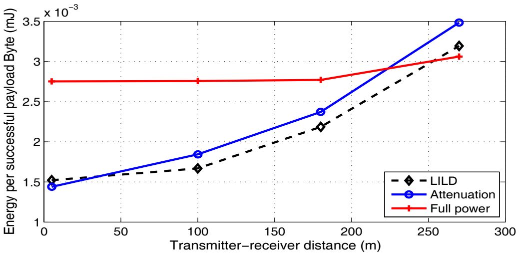

**Fig. 14** Indoor: **EPSPB** versus transmitter-receiver distance. Payload size 240 Bytes.

### 6.1.4 Time response

As observed in Fig. 15, LILD has a poorer performance over the attenuation method in terms of stability, although LILD offers lesser effective energy consumption with respect to the attenuation algorithm.

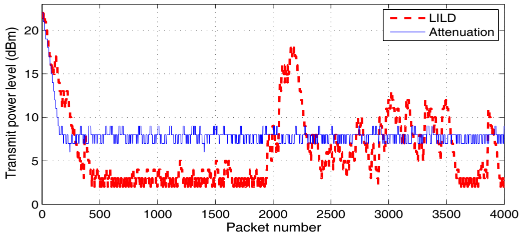

**Fig. 15** Indoor: Time response for a receiver distance 50 m and payload size 30 Bytes.

A similar fluctuating performance trend with LILD is observed with a different payload size (90 Bytes) and at a larger distance (180 m), as depicted in Fig. 16. It can be additionally noted that, average power used per *transmitted* frame in **LILD is a little higher than** [Comment 6] that of the attenuation based method.

**Thus, despite the fact that the energy consumption per unit success in LILD method is lower (see Figs. 12 and 13), with respect to stability, even in a static environment, the inherent property of LILD**

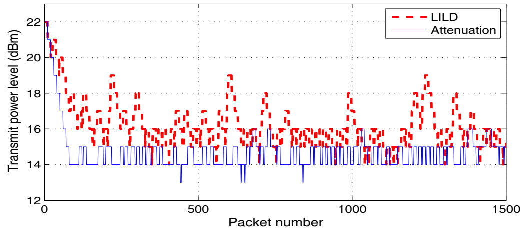

**Fig. 16** Indoor: Time response for a receiver distance of 180 m and payload size of 90 Bytes

**does not allow the transmitter to settle at an optimum transmit power. This implies that, in a network, the interference scenario at the neighboring nodes will be continually changing even if the status of the communicating node pairs do not change, thereby leading to more unpredictable packet errors than that in the attenuation method.** [Comment 7]

### 6.2 Outdoor performance

For the outdoor measurements, we set up experiments in an open sports field. The readings were taken at night times so as to minimize the fluctuations due to human and other moving obstacles. In the outdoor setting, the maximum transmission distance was found to be about 90 m with a high FER (up to 30%). All the experiments of indoor were repeated for outdoor case also, but only limited results are shown to avoid repetition. Since, as in the indoor environment, the FER performance is accounted in the link layer goodput performance, the goodput versus payload size plots are omitted. Moreover, the transmit power fluctuations with time in the outdoor setting has a similar trend as in the indoor, and hence the time response plots are also omitted here.

### 6.2.1 Frame error performance

Figs. 17 and 18 show the frame error performance without and with power control methods at different receiver distances. The performance of attenuation method is observed to deteriorate with increased distance, although it is better than the LILD method at a low distance. The other observations from indoor measurements also apply here.

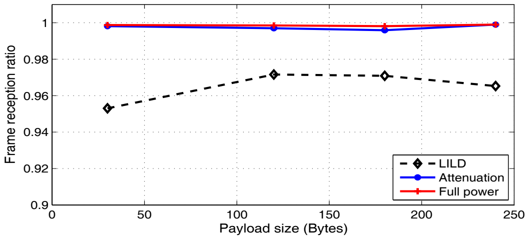

**Fig. 17** Outdoor: Frame error performance versus payload size. Transmitter-receiver distance 5 m.

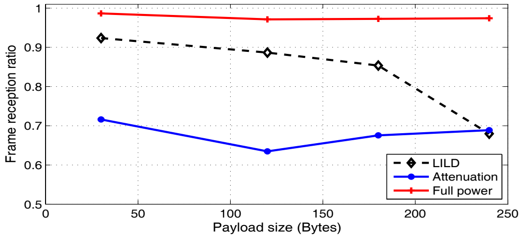

**Fig. 18** Outdoor: Frame error performance versus payload size. Transmitter-receiver distance 70 m.

### 6.2.2 Link layer goodput performance

**The goodput versus transmitter-receiver distance shows that, although at a low distance the attenuation method performs a little better than LILD, as the distance increases, it deteriorates fast. Also, the full power transmission has a higher goodput.** [Comment 1]

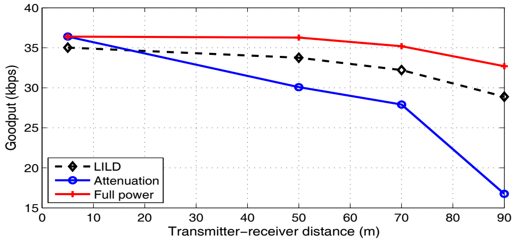

**Fig. 19** Outdoor: Goodput performance versus receiver distance. Payload size 240 Bytes.

As in the indoor studies, below we now look into the energy saving performance.

### 6.2.3 Effective energy consumption per unit success

As shown in Figs. 20 and 21, the effect of payload size has been similar as in the indoor setting, except that LILD performs better until a large payload size. As noted in Fig. 17, although at a lower receiver distance LILD has a higher frame error rate, Fig. 20 indicates that its energy saving performance is equally good as the attenuation method.

Overall, we observe that for smaller distances irrespective of the environment, the optimal payload size is 240 Bytes, which is the maximum size possible for MICA2 motes and it is certainly higher than the default maximum payload size (128 Bytes). At higher distances

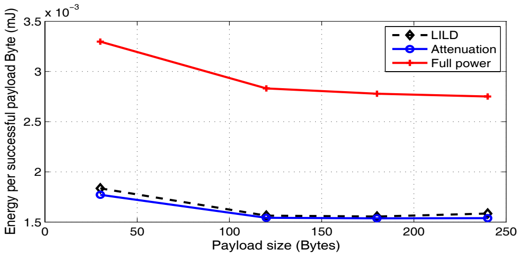

**Fig. 20** Outdoor: **EPSPB** versus payload size for a transmitter-receiver distance 5 m.

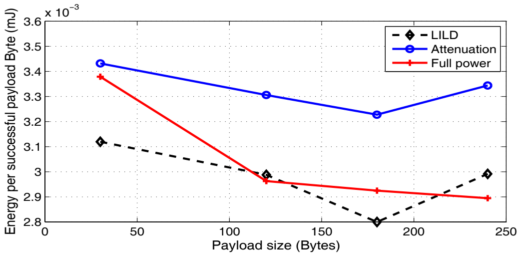

**Fig. 21** Outdoor: **EPSPB** versus payload size for a transmitter-receiver distance 70 m.

the optimum payload size found to be 180 Bytes, which is slightly lesser than the maximum value.

The effect of transmission-receiver distance on the power control performance is severe. As shown in Fig. 22, beyond a moderate distance of about 60 m, power control algorithms has so high failure rates that the overall energy consumption with power control schemes supersede that with no power control.

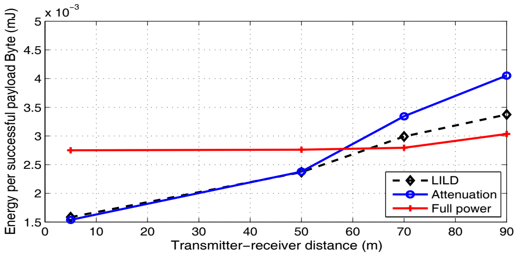

**Fig. 22** Outdoor: **EPSPB** versus receiver distance. Payload size 240 Bytes.

### 6.3 Remarks

**For implementation of automatic joint TPC and FSC in sensor nodes, similar to the discrete transmit power levels, a table of possible link-layer payload size can be incorporated at the PowerControlM module of the transmitter. For a given transmitter-receiver setting, the TPC and FSC can be implemented in two stages. Since TPC has a higher influence on nodal energy saving (EPSPB), with a nominal frame size and optimum transmit power level can be first decided. The nominal frame size can be programmed depending on the working environment of the sensors. For example, as noted from our experimental findings, in the indoor environment, the optimum payload size is about 210 Bytes, whereas that in the outdoor setting is about 180 Bytes. After the initial transient phase of power control, further tuning on the optimum frame size can be performed. In a mobile environment, given the automated TPC and FSC capabilities, the transmitter would automatically reconfigure itself to a new transmit power and frame size as the working environment changes.** [Comment 8(a)]

## 7. Conclusion

In this work, our aim was **to study experimentally the effective energy consumption properties of wireless sensor nodes with and without** [Comment 12(a)] transmit power control and at different payload size. Our experimentations on Crossbow MICA2 platform have shown that the nodal energy consumption not only depends on the transmitter-receiver distance but also on the surrounding environments and frame size.

**Our studies on goodput performance indicated that, full power transmission always offers a higher goodput, albeit generally at the cost of more energy consumption per unit success. In other words, controlled power transmissions offer the benefit of lesser effective energy consumption, but with a delay tradeoff.**

We have also shown that, beyond a short transmitter-receiver distance, receiver's binary acknowledgement based power control strategy outperforms the RSSI based power control in terms of energy consumption per successful unit payload. However, the binary acknowledgment based approach has a higher variability in transmit power level. Our results also indicated that, at a very large distance it is rather energy efficient to transmit at full power.

Further, we have demonstrated that, although the frame error rate slightly increases with the increased frame size, up to a moderately large distance the effective energy saving is still high with the largest possible payload size, which is 240 Bytes in MICA2 motes. At a large distance, **a payload size slightly smaller than the maximum** [Comment 12(b)] offers a higher energy saving. Specifically, in an indoor environment the optimum payload size is found to be 210 Bytes and in an outdoor setting it is 180 Bytes – both of which are higher than the default maximum payload size in MICA2 motes.

The results from this study could be useful in deciding power control strategies and optimum frame length.

## Acknowledgment

The authors wish to thank the reviewers for their insightful comments which has helped improving the clarity and quality of presentation of the paper.

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### References

[1] T. Simunic, L. Benini, P. Glynn, and G.D. Micheli, “Dynamic power management for portable systems,” Proc. ACM MOBICOM, Boston, MA, USA, Aug. 2000.

[2] A. Sinha and A. Chandrakasan, “Dynamic power management in wireless sensor networks,” IEEE Design and Test of Computers, Mar./Apr. 2001.

[3] M. Seok, S. Hanson, Y.S. Lin, Z. Foo, D. Kim, Y. Lee, N. Liu, D. Sylvester, and D. Blaauw, “The Phoenix processor: A 30pW platform for sensor applications,” Proc. IEEE Symp. VLSI Citcuits, Honolulu, HI, USA, pp.188–189, June 2008.

[4] J.P. Monks, V. Bharghavan, and W.M.W. Hwu, “A power controlled multiple access protocol for wireless packet networks,” Proc. IEEE INFOCOM, Anchorage, AK, USA, pp.219–228, Apr. 2001.

[5] E.S. Jung and N.H. Vaidya, “A power control MAC protocol for ad hoc networks,” Proc. ACM MOBICOM, Atlanta, GA, USA, pp.36–47, Sept. 2002.

[6] S.J. Park and R. Sivakumar, “Load-sensitive transmission power control in wireless ad hoc networks,” Proc. IEEE GLOBECOM, Taipei, Taiwan, ROC, Nov. 2002.

[7] A. Muqattash and M. Krunz, “Power control dual channel (pcdc) medium access protocol for wireless ad hoc networks,” Proc. IEEE INFOCOM, San Fransisco, CA, USA, April 2003.

[8] S. De, K. Egoh, and G. Dosi, “A receiver initiated power control multi-access protocol in wireless ad hoc networks,” Proc. IEEE Sarnoff Symp., Princeton, NJ, USA, May 2007.

[9] L.H.A. Correia, D.F. Macedo, D.A.C. Silva, A.L. dos Santos, A.A.F. Loureiro, and J.M.S. Nogueira, “Transmission power control in MAC protocols for Wireless Sensor Networks,” Proc. ACM MSWiM, Montreal, Qubec, Canada, Nov. 2005.

[10] J.C. Lim and K.D. Wong, “Exploring possibilities for rss-adaptive power control in mica2-based wireless sensor networks,” Proc. IEEE ICARCV, Singapore, Dec. 2006.

[11] S. Lin, J. Zhang, G. Zhou, L. Gu, T. He, and J.A. Stankovic, “ATPC: Adaptive transmission power control for wireless sensor networks,” Proc. ACM SenSys, Boulder, CO, USA, Nov. 2006.

[12] V. Srivastava, D. Agrawal, A. Mishra, S. Banerjee, and T. Nadeem, “Understanding the limitations of transmit power control for indoor WLANs,” Proc. ACM IMC, Hong Kong, China, Oct. 2007.

[13] J. Kim, S. Chang, and Y. Kwon, “ODTPC: On-demand transmission power control for wireless sensor networks,” Proc. Information Networking, ICOIN, Jan. 2008.

[14] P.G. Park, C. Fischione, and K.H. Johansson, “Experimental evaluation of power control algorithms for wireless sensor networks,” Proc. 17th World Congress IFAC, Seoul, Korea, July 2008.

[15] L.M. Feeney and M. Nilsson, “Investigating the energy consumption of a wireless network interface in an ad hoc networking environment,” Proc. IEEE INFOCOM, Anchorage, AK, USA, pp.1548–1557, Apr. 2001.

[16] B. Burns and J.P. Ebert, “Power consumption, throughput, and packet error measurements of an IEEE 802.11 WLAN interface,” Tech. Rep. TKN-01-007, Technical University of Berlin, Berlin,

Aug. 2001.
[17] A. Sheth and R. Han, "An implementation of transmit power control in 802.11b wireless networks," Tech. Rep. CU-CS-934-02, Dept. of CS, Univ. Colodaro, Boulder, CO, Aug. 2002.
[18] Crossbow Inc., Motes, smart dust sensors, wireless sensor networks, 2006.
[19] Crossbow Inc., MPR-MIB Users Manual, rev. A, June 2007.