

Energy-Efficient Hybrid Sensor Personalization Scheme for Wireless Sensor Networks

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Abstract. Sensor personalization is a form of device to device (D2D) communication in which user devices (UDs), such as smart phones and tablet PCs, directly communicate with various sensor devices (SDs) consisting of various sensors and communication modules. In this paper, we first introduce two widely used sensor personalization schemes named coordinator-based sensor personalization (CSP) and direct sensor personalization (DSP). Then, based on the advantages and disadvantages of the two schemes, we propose an energy-efficient hybrid sensor personalization (HSP) scheme that is more suitable for D2D communications in the domain of energy-limited wireless sensor networks (WSNs). Through analytical models, we show that the proposed HSP scheme outperforms other two schemes in terms of the energy consumption of network devices.

Keywords: Wireless sensor networks, Sensor personalization, Energy consumption, Device to device (D2D) communications.

1 Introduction

The recent development of technology for designing various wireless sensing systems has provided us with the capability to monitor and control all kinds of external environmental characteristics of our everyday lives ranging from room temperature [1, 2], personal health [3], to energy/utility usage [4, 5]. These systems, specifically, a form of wireless sensor networks (WSNs), are easily deployable in various settings and can provide users with information on the environment at a previously unreachable scale. In typical WSNs, a coordinator node manages sensor devices (SDs) that consists of application-targeted sensors and communication modules. In such systems users communicate with the coordinator to collect sensing data or control the SDs. Furthermore, recently, with the increasing interest in device to device (D2D) communications, various user devices (UDs) such as smart phones and tablet PCs hold the capability to directly access information from different forms of SDs directly. In this work, we define the process of associating SDs with UD for direct interaction as *sensor personalization*.

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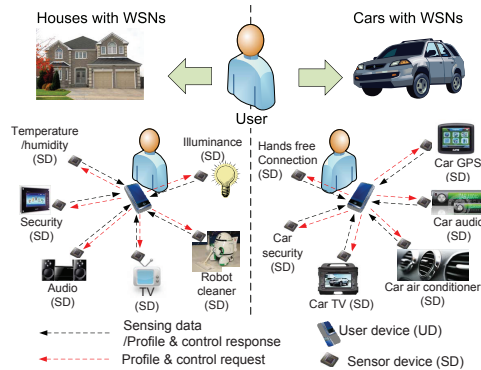


Fig. 1: Usage scenarios of sensor personalization for WSNs.

Fig. 1 shows usage scenarios of sensor personalization for WSNs. By personalizing the external SDs, UD_s can efficiently collect, manage and configure a network of SD_s so that they can meet the UD_s' application requirements. However, the process of sensor personalization can result in additional energy consumption at the power-constraint SD_s due to the increase in network control messages.

In this paper, we first introduce two traditional sensor personalization schemes named coordinator-based sensor personalization (CSP) and direct sensor personalization (DSP). These schemes are simple and are adaptable to various application scenarios. Then, based on preliminary studies on CSP and DSP, we propose an energy-efficient hybrid sensor personalization (HSP) scheme. Through analytical models, we show that the proposed HSP scheme outperforms other two schemes in terms of the energy consumption of network devices.

2 System Model

We consider a WSN topology in which K SD_s are deployed at random locations and N UD_s communicate with SD_s to gather the sensing data and control the SD_s wirelessly. Furthermore, a coordination device (CD) is installed as a sink node to manage sensor profiles collected by the SD_s and to relay control messages between the UD_s and SD_s. We assume that all devices are stationary and within a single-hop distance. Additionally, all devices share a single wireless channel while using carrier sense multiple access with collision avoidance (CSMA/CA). In the initial phase, UD_s or CD_s need to discover the SD_s and gather their sensor profiles. In doing so, the device that manages the SD_s (e.g., either UD_s or a CD depending on the scheme as presented later in Section 3) will first send a broadcast message to discover the surrounding SD_s. This broadcast message is 16 bytes in length and includes elements such as the source ID, destination ID, and sensing request conditions (e.g., which sensors should reply). Once this request is received at the SD_s, the SD_s will send a unicast response back to the source node and include its sensor profile in this message. The length of this response profile (to either the UD_s or the CD) is configured to be 64 bytes and this packet includes information such as source ID, destination ID, sensor types, the unit of sensing data, the min/max

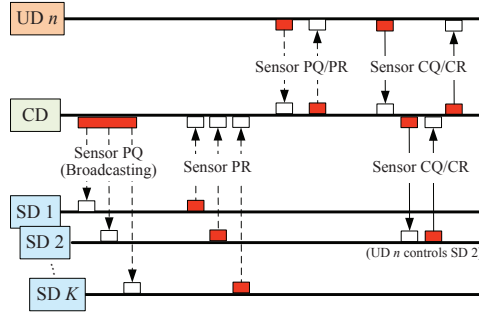


Fig. 2: Coordinator-based sensor personalization (CSP) scheme.

values of the sensing information, and a list of supported services. Given a 250 Kbps link (e.g., IEEE 802.15.4 [6]), these packets each require transmission times of 0.512 msec, and 2.04 msec, respectively.

Once the SDs are registered in a UD or CD, the next step is to collect their sensing information. This process also takes place in a request-and-response form of message exchange. We configure a packet with a length of 16 bytes for the data/control request packet (from the UD/CD to the SD) and the response message which includes the sensing details is 42 bytes. These packets represent an air time of 0.512 msec and 1.344 msec each. We also assume that a single clear channel assessment (CCA) check takes 0.581 msec equaling to 6.39×10^{-5} mA/msec of energy. Lastly, we assume that all devices in the model are battery operated with equal energy consumption for packet transmissions and receptions.

3 Sensor Personalization Schemes for WSNs

In this section, we introduce two conventional sensor personalization schemes, i.e., CSP and DSP. Then, based on their strengths and drawbacks, we propose the HSP scheme.

3.1 Coordinator-based sensor personalization (CSP)

Fig. 2 shows the procedure of the CSP scheme. Notice that the CSP heavily involves the use of a CD. Most IEEE 802.15.4-based WSNs require a coordinator to manage the network (e.g., root of a collection tree network or the central node in a star topology network), which maintains details for each SD under its hierarchy [6]. As Fig.2, the advantage of the CSP scheme is that UDs *only* communicate with the CD single-hop; thus, allowing the networking protocol to be simple. In this type of configuration UDs will simply access the CDs to collect sensor information. Furthermore, the CD can efficiently manage the sensor resources in the network. On the other hand, the disadvantage of CSP is that the CD becomes a single point of traffic concentration; therefore, it can suffer from communication overhead as the number of interacting UDs increases and also can cause critical outcomes if the CD fails during the communication process.

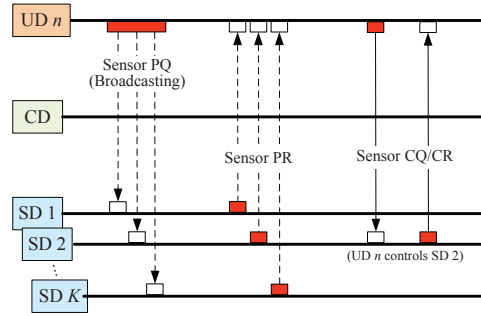


Fig. 3: Direct sensor personalization (DSP) scheme.

3.2 Direct sensor personalization (DSP)

Fig. 3 illustrates the procedure of the DSP scheme. In contrast to the CSP scheme, DSP does not use a CD but rather the SDs and UDs communicate directly with each other using the wireless medium as shown in Fig. 3 [7]. While this allows the system architecture to be simple and it also reduces the number of overall packet transmissions, the management and control process of the sensor resources becomes a distributed process. As a result, the advantage of this scheme is that the number of sensor control request (CQ)/control response (CR) messages decreases compared to the CSP scheme. On the other hand, the disadvantage is that the SDs will be requested to exchange a large number of sensor profile request (PQ)/profile response (PR) messages as the number of UDs increases since each UD will require a unique pairing with each SDs.

3.3 Proposed hybrid sensor personalization (HSP)

Fig. 4 shows the procedure of the proposed HSP scheme. Based on the advantages and disadvantages of the CSP and DSP schemes, in HSP, we take the best of the two schemes to minimize the energy consumption. We note that we are especially interested in reducing the power usage at the SDs since these are the devices that would require the longest lifetimes. In combining CSP and DSP, the HSP scheme uses the CD for exchanging the summary of sensor profiles (e.g., similar to the CSP) and allows UDs to communicate with SDs directly to reduce the number of sensor CQ/CR messages (e.g., similar to the DSP). The procedure of the HSP scheme is as below.

- a) The CD first performs a search for SDs to collect SD profiles by broadcasting a sensor PQ message.
- b) Then, each SD sends back a sensor PR message with its profile information.
- c) The CD keeps the summary of SD profiles and the CD sends it back using a sensor PR message when UDs send the CD a sensor PQ message.
- d) The UDs select an SD from which it will collect sensing data or control the SD and directly send the SD a sensor CQ message.
- e) Finally, the SD sends back a sensor CR message to reply the sensor CQ message.

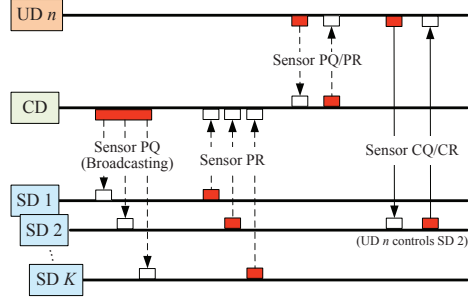


Fig. 4: Proposed hybrid sensor personalization (HSP) scheme.

The outcome of this hybrid scheme is that the HSP scheme not only has the benefit of the CSP scheme to manage the sensor resources and decrease the number of sensor PQ/PR messages by using a coordinator, but also takes the strengths of the DSP scheme to reduce the number of sensor CQ/CR messages.

4 Analytical Modeling and Performance Evaluation

In this section, we introduce our analytical model for computing the energy consumption of the sensor personalization schemes detailed in Section 3 and evaluate the performance in terms of energy consumption of the network devices.

4.1 Analytical Modeling

We denote the transmission time (e.g., duration) for sensor PQ and PR packets as T_{PQ} and T_{PR} , respectively. Furthermore, we define T_{CQ} and T_{CR} to be the transmission times for the sensor CQ and CR packets, respectively. Lastly, T_C is defined as the time required for performing a radio carrier sensing (here, we adopt T_{CCA} in [8] for T_C) and E_{TR} is defined as the energy used for transmitting or receiving a packet.

We first compute the packet arrival rates for each of the CSP, DSP, and HSP schemes, λ_{CSP} , λ_{DSP} , and λ_{HSP} , to obtain the values required for computing N_C . Then, λ_{HSP} , λ_{CSP} , and λ_{DSP} can be expressed as,

$$\lambda_{CSP} = \frac{\alpha T_{CSP}}{T_{CSP} + T_{DSP} + T_{HSP}}, \quad (1)$$

$$\lambda_{DSP} = \frac{\alpha T_{DSP}}{T_{CSP} + T_{DSP} + T_{HSP}}, \quad (2)$$

$$\lambda_{HSP} = \frac{\alpha T_{HSP}}{T_{CSP} + T_{DSP} + T_{HSP}}, \quad (3)$$

where α is a constant value to obtain the packet arrival rate per msec and T_{CSP} , T_{DSP} and T_{HSP} can be expressed as

$$T_{CSP} = N(T_{PG} + T_{PQ} + T_{PR} + 3T_C + 2R(T_{CQ} + T_{CR} + 2T_C)) + (K-1)(T_{PG} + T_C), \quad (4)$$

$$T_{DSP} = N(T_{PQ} + T_{PR} + 2T_C + R(T_{CQ} + T_{CR} + 2T_C)) + (K-1)(T_{PQ} + T_C), \quad (5)$$

$$T_{HSP} = N(T_{PG} + T_{PQ} + T_{PR} + 3T_C + R(T_{CQ} + T_{CR} + 2T_C)) + (K-1)(T_{PG} + T_C). \quad (6)$$

Table 1: System parameters.

Parameter	Value
Transmitting and receiving power per packet (E_{TR})	6.39×10^{-5} mA/msec [9]
Transmission airtime for Sensor PQ and CQ (T_{PQ}, T_{CQ})	0.512msec
Transmission airtime for Sensor PR (T_{PR})	2.04msec
Transmission airtime for Sensor CR (T_{CR})	1.344msec
Maximum number of CCAs (N_C)	4 [6]
Period for performing CCA (T_C)	0.581msec [6, 9]
α for the packet arrival rate per msec	10^{-4}

Next, we present the energy consumption of the CSP, DSP, and HSP schemes, E_{HSP} , E_{DSP} , and E_{CSP} . We denote by R the number of control messages between the UDs and SDs. E_{CSP} , E_{DSP} , and E_{HSP} can be expressed as

$$E_{CSP} = 2(E_{SD} + N((T_{PQ} + T_{PR} + T_C N_C) + R(T_{CQ} + T_{CR} + T_C N_C))E_{TR} - K T_{PQ} E_{TR} / NR) + (T_{PQ} + T_C N_C) E_{TR}, \quad (7)$$

$$E_{DSP} = 2(E_{SD} - (N - 1)(T_{PQ} + T_C N_C) E_{TR}), \quad (8)$$

$$E_{HSP} = 2(E_{SD} + N(T_{PQ} + T_{PR} + T_C N_C) E_{TR} - K T_{PQ} E_{TR} / NR) + (T_{PQ} + T_C N_C) E_{TR}, \quad (9)$$

where E_{SD} is the energy consumption of the SDs and E_{SD} can be expressed

$$E_{SD} = \begin{cases} K(T_{PQ} + T_{PR} + T_C N_C) E_{TR} / NR & \text{for CSP and HSP} \\ + NR(T_{CQ} + T_{CR} + T_C N_C) E_{TR} & \\ N(K(T_{PQ} + T_{PR} + T_C N_C) E_{TR} & \text{for DSP.} \\ + R(T_{CQ} + T_{CR} + T_C N_C) E_{TR}) & \end{cases} \quad (10)$$

We point out that the current overall energy consumption E_β ($\beta = \text{CSP, DSP, HSP}$) for each scheme per millisecond (mA/msec) is bounded as below, given that the worst-case scenario is a fully saturated wireless channel.

$$0 \leq E_\beta \leq \frac{E_\beta}{1 - \lambda_\beta T_\beta}, \quad (11)$$

where $1 < \lambda_\beta < 1/T_\beta$ and β is one of CSP, DSP, and HSP. Then, the overall energy consumption is sum of the energy consumption of all devices according to the packet exchanges between UDs and SDs.

4.2 Performance Evaluation

We now investigate the performance of the proposed HSP scheme in terms of the energy consumption for SDs (since SDs are devices deployed in the field and are typically battery operated) and the resulting system as a whole using MATLAB simulations. Furthermore, we compare the proposed HSP scheme with the CSP and DSP schemes with respect to varying numbers of SDs, UDs, and control messages (K , N , and R). The key parameters are listed in Table 1.

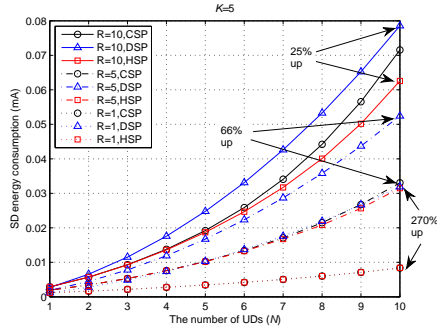
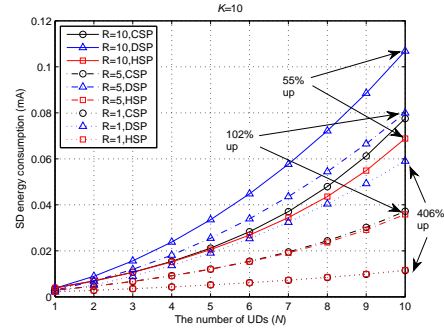
(a) $K=5$ (b) $K=10$

Fig. 5: Energy consumption of SDs

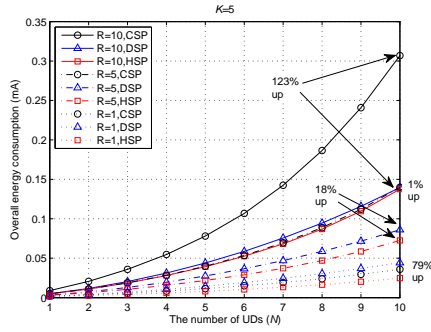
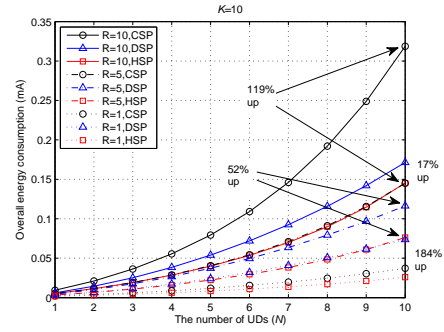
(a) $K=5$ (b) $K=10$

Fig. 6: Overall energy consumption

Fig. 5 presents the results of the SDs' energy consumption with $K=5$ and 10 as the number of UDs increase. Overall, the SD energy consumption increases as N , R , and K increases together. In Fig. 5-(a) and (b), the DSP scheme always shows worse performance than the others because the number of sensor PQ/PR message exchanges increase rapidly with increasing K . Quantitatively speaking, in Fig. 5-(a), the HSP scheme improves the DSP scheme by $\sim 270\%$, $\sim 66\%$, and $\sim 25\%$, respectively, when $R=1$, 5, and 10. In this configuration, the CSP scheme shows the same or worse performance when compared to the HSP scheme. Furthermore, in Fig. 5-(b), we can notice that the HSP scheme improves the DSP scheme by $\sim 406\%$, $\sim 102\%$, and $\sim 55\%$ for $R=1$, 5, and 10, respectively. As a result, the proposed HSP scheme shows better performance in terms of for SD energy consumption than the CSP and DSP schemes.

Fig. 6 describes the results of *overall* energy consumption of the system with $K=5$ and 10 as the number of UDs increase. As the number of SDs increase, the HSP scheme outperforms other two schemes due to the number of PQ/PR message exchanges increasing rapidly. Specifically, in Fig. 6-(a), the HSP scheme improves the DSP scheme by 79%, 18%, and 1%, respectively, when $R=1$, 5, and 10. Additionally, the HSP scheme always shows better performance than the CSP scheme (e.g., 123% better when $R=10$). Finally, in Fig. 6-(b), the HSP scheme has better performance than

the DSP scheme by $\sim 184\%$, $\sim 52\%$, and $\sim 17\%$, respectively, when $R=1, 5$, and 10 . Another finding we see here is that the HSP scheme always performs better than the CSP scheme in all cases (e.g., 119% up when $R=10$). As a result, the proposed HSP scheme outperforms the CSP and DSP schemes in terms of energy efficiency for network devices and the energy consumption gradually grows as the number of SDs increase in the network.

5 Conclusion

In this paper, we first defined a new concept of sensor management method, i.e., sensor personalization, for WSNs and then proposed an energy-efficient sensor personalization scheme named HSP based on the advantages and disadvantages of the CSP and DSP schemes. Through analytical models, we evaluate the energy consumption of network devices and show that the proposed HSP scheme outperforms other two schemes in terms of the energy consumptions of SDs and total network devices for packet exchanges. For future work, we plan to study a dynamic sensor personalization scheme with transmission power control for WSNs.

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