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A power-variation model for sensor node and the impact against life time of wireless sensor networks

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Abstract: Network protocols for wireless sensor networks should be evaluated in terms of life time in a whole system. There exists power variation node due to the manufacturing variation. In this paper, we develop a power model, in which we consider threshold-voltage variation. We implement it to QualNet in order to evaluate the impact against a life time. The simulation results show that the conventional model has overestimated the life time longer than our model when nodes are randomly deployed. In addition, the network life time is extended by 19.3% compared with the conventional model by an optimum deployment.

Keywords: wireless sensor networks, analytical modeling

Classification: Wireless circuits and devices

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1 Introduction

In wireless sensor networks (WSNs), expansion of network lifetime is one of the most important subjects. Network protocols for the WSNs such as media access control and routing should be evaluated in terms of life time in a whole system. Therefore, many researchers have implemented their proposed protocols into network simulators such as QualNet [1]. In their studies, all nodes have a same power performance. However in fact, there exists power variation node by node due to manufacturing variation, where only a few nodes with high power consumption may shorten the network life time. To the best of our knowledge, this aspect has not been addressed at all so far.

2 Sensor node architecture and power components

A sensor node chip is generally comprised of two blocks: a microprocessor and an RF part. The microprocessor can be further divided into logic circuits and memory. Hence, the sensor chip consists of three components. The logic circuits, memory, and RF part, however, have different characteristics in terms of power.

2.1 Dynamic Power in Logic Circuit

The logic circuits are comprised of digital circuits. Fig. 1 (a) represents a digital circuit, in which a dynamic power consumed by charge and discharge is dominant. The dynamic power (P_{dyn}) is proportional to the square of V_{dd}, and is given as follow [2]:

$$P_{dyn} = K_{dyn} V_{dd}^2, \tag{1}$$

where $K_{\mathrm{dyn}} = p_{\mathrm{a}} f_{\mathrm{op}} C_{\mathrm{total}}$. p_a is an average activation ratio (typically around 0.3), f_{op} is an operating frequency, and C_{total} is a total gate capacitance (+ other parasitic capacitance) in a circuit.

2.2 Leakage Power in Memory

In a static random access memory (SRAM), a dynamic power is small since only some memory cells are accessed. Leakage currents flow through the standby memory cells and bitlines as illustrated in Fig. 1 (b). Consequently,

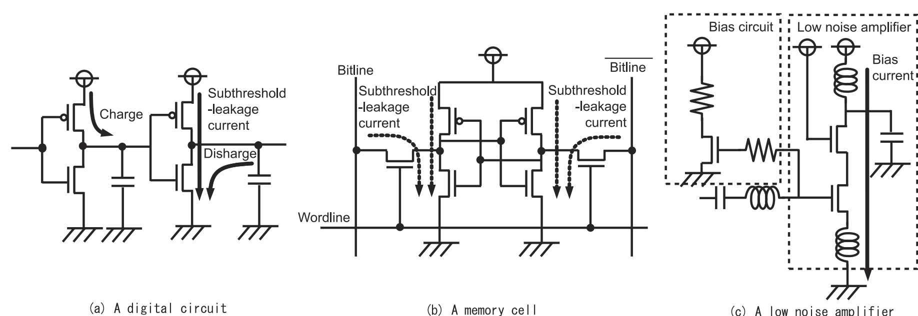

Fig. 1. power components of sensor node.

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the leakage power caused by the subthreshold-leakage currents becomes dominant in the SRAM. Other than the memory cells, the logic circuits, of course, draws other leakage current (see Fig. 1 (a)), however, the mechanism of the leakage current is the same. Even when a transistor is turned off and is in a subthreshold region, a subthreshold-leakage current flows through the transistor. The leakage power (P_{leak}) is expressed as follows [2]:

$$P_{\mathrm{leak}} = K_{\mathrm{leak}} V_{\mathrm{dd}} 10^{-\frac{V_{\mathrm{th}}}{s}} \tag{2}$$

where K_{leak} is a constant. V_{th} is a subthreshold voltage of a transistor. s is a subthreshold swing, and is about 0.1 V/decade in a recent process technology.

2.3 Analog Power in RF Part

An RF circuit is a kind of analog circuit. Fig. 1 (c) illustrates a low-noise amplifier. In the low-noise amplifier as well as other analog circuit, an amplifying transistor is biased to an intermediate voltage by a bias circuit and hence is in a saturation region, which means it always draws a bias current. The power caused by the bias current is dominant in the amplifier.

In an analog-circuit design, long-channel transistors are used to avoid the channel-length modulation effect, and to obtain the ideal saturation characteristics as expressed with the Shockley model. The analog power consumed by the bias current (Panalog) is given as follows [3]:

$$\begin{aligned} P_{\mathrm{analog}} &= K_{\mathrm{analog}} V_{\mathrm{dd}} V_{\mathrm{OD}}^{\alpha} \\ &= K_{\mathrm{analog}} V_{\mathrm{dd}} (V_{\mathrm{gs}} - V_{\mathrm{th}})^2 \end{aligned} \tag{3}$$

where K_{analog} is a constant. V_{OD} is called an overdrive voltage and is defined as $V_{gs} - V_{th}$. α is a velocity saturation index and is set to two for a long-channel transistor used in an analog-circuit design [4].

3 Threshold-voltage variation and power-variation model

The threshold-voltage variation has a standard distribution. In this paper, we set $\mu_{V_{th}}$ to 0.3 V supposing a low-power microprocessor, and infer that $\sigma_{V_{th}}$ is 0.025 V from an Intel's research [5]. $\sigma_{V_{th}}$ could become larger in a process technology that is not so recent as Intel.

3.1 Dynamic-power variation

If z is a function of V_{th} and is given by the following expression:

$$z = g(V_{\mathrm{th}}), \tag{4}$$

the standard deviation of $z(\sigma_z)$ can be derived with the first-order approximation as follows:

$$\sigma_z = |g'(\mu_{V_{\mathrm{th}}})| \sigma_{V_{\mathrm{th}}}. \tag{5}$$

Since the dynamic power is not a function of V_{th} as given in (1), the standard deviation of $P_{dyn}(\sigma_{P_{dyn}})$ becomes zero:

$$\sigma_{P_{\mathrm{dyn}}} = 0. \tag{6}$$

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3.2 Leakage-power variation

Unlike the dynamic power, the leakage power is varied by the threshold-voltage variation since it is a function of V_{th}. From (2), the standard deviation of the leakage power ($\sigma_{P_{leak}}$) is obtained by first-order approximation using tangent line at $\mu_{V_{th}}$ as follows:

$$\sigma_{P_{\rm leak}} = K_{\rm leak} V_{\rm dd} \frac{\ln 10}{s} 10^{-\frac{\mu_{V_{\rm th}}}{s}} \sigma_{V_{\rm th}} \tag{7}$$

3.3 Analog-power variation

Based on (3), the standard deviation of the analog power ($\sigma_{P_{analog}}$) is given as follows:

$$\sigma_{P_{\rm analog}} = 2K_{\rm analog} V_{\rm dd} (V_{\rm gs} - \mu_{V_{\rm th}}) \sigma_{V_{\rm th}} \tag{8}$$

3.4 Total-power variation

The abovementioned discussion leads the total-power variation to a standard-distribution model. We can approximately obtain the average value and standard deviation of the node power ($\mu_{P_{total}}$ and $\sigma_{P_{total}}$) from (1), (2), (3), and from (6), (7), (8), respectively:

$$\begin{aligned} \mu_{P_{\rm total}} = &K_{\rm dyn} V_{\rm dd}^2 \\ &+ K_{\rm leak} V_{\rm dd} 10^{-\frac{\mu_{V_{\rm th}}}{s}} \\ &+ K_{\rm analog} V_{\rm dd} (V_{\rm gs} - \mu_{V_{\rm th}})^2 \end{aligned} \tag{9}$$

$$\sigma_{P_{\rm total}} = \sigma_{P_{\rm dyn}} + \sigma_{P_{\rm leak}} + \sigma_{P_{\rm analog}} \tag{10}$$

The parameters in the expressions can be given by process engineer and circuit designers. Once the parameters are fixed, this model gives insight to the power distribution, and it can be more elaborate than the conventional model.

4 Verification with network simulator

4.1 Influence of node variation on WSN

In this section, we implement both the threshold-voltage variation (TV (Proposal)) model and the threshold-voltage constant (TC(conventional)) model to a network simulator, and investigate the impact of the power variation on system-level performance from the viewpoint of life time. The network simulator used is QualNet [1]. In a field of $100 \times 100\,m^2$, 256 sensor nodes are deployed at random, and a base station is placed in the center. We assume that the application is data gathering, where each sensor node transfers its sensed data to the base station every round which is set to 1,000 seconds. We define a life time as a duration for which a successful data received rate is 90% or more. The life time estimated by simulation is the averages of 50 trials.

Fig. 2 shows the characteristics of the successful data received rates in cases of the TV and TC power models. The average power of a microprocessor ($\mu_{P_{dyn}} + \mu_{P_{leak}}$) and an RF part ($\mu_{P_{analog}}$) are set to the same for both power

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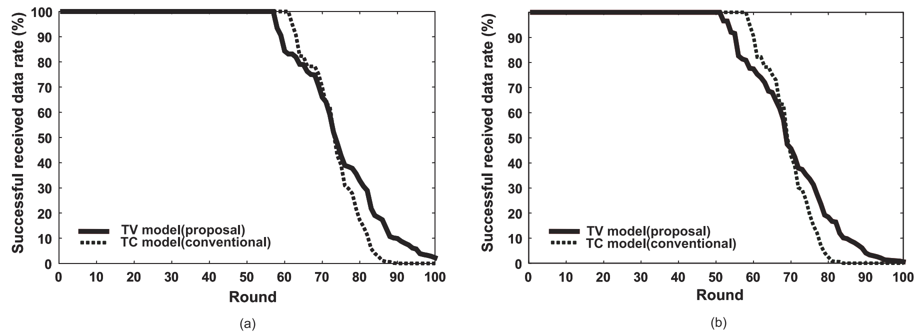

Fig. 2. Successful data received rates in the case of (a)$\mu P_{dyn} + \mu P_{leak} : \mu P_{analog} = 0.5 : 0.5$, and (b)$\mu P_{dyn} + \mu P_{leak} : \mu P_{analog} = 0.9 : 0.1$.

models in Fig. 2 (a). In Fig. 2 (b), the ratio of the microprocessor power to the RF power is 0.9:0.1. In a future sensor node, a microprocessor power may increase in order to handle encryption/decryption, and Fig. 2 (b) predicts such a case.

We observe that the proposed TV model results in a shorter lifetime than the conventional TC model by 10.8% in Fig. 2 (b) because in the TV model, some nodes have inefficient power performances. This fact can make the network vulnerable. By contrast, this effect is not involved in the TC model. This is the reason why the figures show that the TC model indicates the optimistic results compared with the TV model. By comparison between Figs. 2 (a) and (b), we find that the successful received data rate shown in Fig. 2 (b) starts to drop earlier than that in Fig. 2 (a). This implies that the microprocessor power is distributed more widely than the RF power.

4.2 Optimum deployment of sensor nodes

The optimum deployment of sensor nodes with the power variation maximizes its life time in WSNs. The nodes near a base station very often communicate

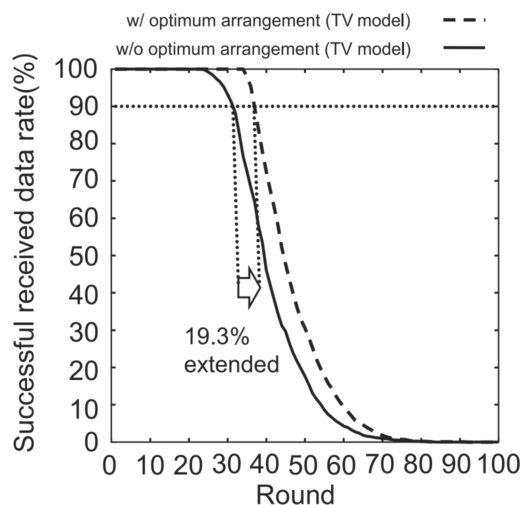

Fig. 3. Lifetime at the optimum deployment in the case of $\mu P_{dyn} + \mu P_{leak} : \mu P_{analog} = 0.9 : 0.1$.

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to relay packets from other nodes, and consume more power than ones away from the base station [6]. Fortunately, we can infer a mean threshold voltage in a chip from a leakage test (I_{DDQ} test) in a burn-in phase, and thus can sort node chips into some bins. It is preferable that low-power nodes are deployed near the base station, and high-power ones are disposed away from the base station. We demonstrate the network simulation result of this optimum deployment in Fig. 3. The network life time is extended by 19.3%, and it can be said that this optimum deployment exploits the power variation well.

5 Conclusion

In this paper, we developed a power model considering manufacturing variation of a threshold voltage in a microprocessor and an RF part, which we named the TV model. We implemented the model to QualNet, and the simulation results showed that the conventional model which we call the TC power model optimistically estimated a network life time longer than our proposed TV model by 10.8%. We have also demonstrated that the optimum deployment of sensor nodes with the power variation extends the network life time by 19.3% compared to the case of the conventional TC model.

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