A Novel Piconet Coordinator Selection Method for IEEE802.15.3-Based WPAN

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Abstract- **Power awareness is an essential component of wireless personal area networks (WPANs), due to the limited energy stored in battery-operated equipment. Moreover, a WPAN has to deal with coexistence problems, since it may simultaneously operate over many types of network. Especially, when UWB, which is a candidate PHY technology for IEEE802.15.3-based WPANs, is applied, decreasing the transmission power is necessary to meet the Federal Communications Commission (FCC) regulation and diminish interference to other communication systems. In a WPAN, the Piconet coordinator (PNC) acts as an important role for central controller of the whole Piconet. As specified in the standard, IEEE802.15.3, the most capable device in a Piconet could be dynamically selected as the PNC in terms of the capacity of devices. However, the standard does not explicitly define the capacity function. In this paper, a novel PNC selection method, named Least Distance Square PNC (LDS-PNC) selection for IEEE 802.15.3-based WPANs is proposed. Using the proposed selection method, the transmission power can be lessened, and the interference area introduced by PNCs can be diminished as well. The simulation results show that it has power-saving and interference mitigation characteristics.**

Keywords: **WPAN, Ultra-wideband (UWB), Piconet Selection**

I. INTRODUCTION

The WPAN is of great importance to many industries and academics. Compared to other similar wireless networks, such as WLAN, and wireless cell network, the WPAN is operated within a smaller personal space, whose diameter is less than 10m, and higher data rate, which is more than 20Mbit/s. After establishing the strategic spectrum planning and appropriate regulation for ultra wide band (UWB) communication by FCC in 2002, UWB is regarded as a promising technology for physical layer implementation of short-range communications in WPANs. A new MAC protocol, IEEE 802.15.3 [1], was issued in September 2003, which is suitable for low power consumption and high data rate WPANs. Because of the reasonable power saving, power control management, QoS support, and security mechanisms in IEEE 802.15.3, it is also the potential MAC protocol for UWB communication [2]. Currently, most members of the IEEE 802.15.3 Working Group are supporting UWB as the technology of choice for the physical layer specification of IEEE 802.15.3.a.

An important issue for IEEE 802.15.3-based WPANs is that systems have to operate in the presence of other wireless networks, such as IEEE 802.11 WLAN, and other WPANs. The transmission power of WPAN devices should be well controlled and not exceed the limitation specified in FCC regulations. Moreover, like other portable wireless communication systems, energy consumption is still one of the key issues. In WPAN MAC of IEEE802.15.3, the PNC plays an important role, since it controls all the networking operations. As specified in the standard, the PNC device can be changed dynamically, so a good PNC selection method could improve the performance of a WPAN.

A lot of research effort has been expended in the area related to the physical layer technology of WPAN communication, such as UWB PHY technologies, which is a striking contrast to that in WPAN MAC layer. In this paper, focusing on the solution in MAC layer, a novel PNC selection method, called Least Distance Square PNC (LDS-PNC) selection is presented, to manage the critical interference mitigation and power-saving problems with only slight modification of the IEEE 802.15.3 standard.

The rest of this paper is organized as follows. Section 2 reviews the architecture of the Piconet and the IEEE 802.15.3 MAC protocol. Section 3 explains the proposed PNC selection method in detail. The simulation results, which validate the LDS-PNC selection algorithm, are presented and discussed in section 4. Finally, section 5 concludes the paper.

II. BACKGROUND

A. Piconet in IEEE802.15.3

The Piconet in IEEE 802.15.3 is an ad hoc data communication system, which is operated within a small area around person or object. Most of the communication devices are battery operated.

In a Piconet, the PNC is a "master" device, which centrally controls the whole Piconet. All other devices in a Piconet are called DEV. The PNC uses a beacon frame to manage QoS requirements, power-saving mode, and media access of whole Piconet. The PNC also classifies various packet transmissions, which are requested by the DEVs. Different packets have different priority levels for transmission. For instance, some command-data packets have higher priority to access the media.

If a PNC finds other devices are more capable than itself, it hands over the control of this Piconet to a more appropriate DEV. That means the Piconet in IEEE 802.15.3 has a dynamic membership, thus adapting to the dynamically changing environment and topology. Though the standard specifies the PNC handover mechanism, it does not detail PNC selection policies.

The authors of this paper are among the core members of the Mobile VCE working group.

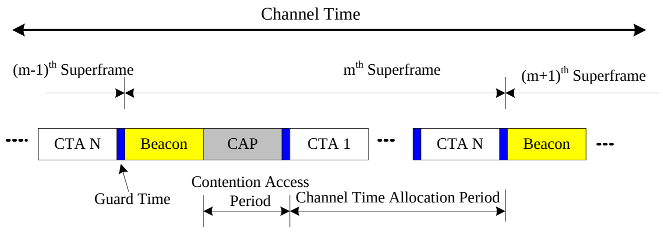


Fig. 1. The channel time and the superframe

B. Channel Access

In IEEE 802.15.3, the PNC globally controls channel access for each DEV. The channel time is divided into superframes. As illustrated in fig. 1, a superframe has three parts, Beacon, Contention Access Period (CAP), and Channel Time Allocation Period (CTAP). The CAP and the CTAP are optional periods. The allocation information about the CAP and the CTAP is indicated in the beacon.

The CAP is used for commands or non-stream data, which ensures a light traffic load. In a CAP, DEVs access the channel based on CSMA/CA. In order to minimize the collision, a DEV should wait for a random length of time at first, and then begin to transmit. When a DEV cannot receive an ACK after its sending a packet, it retransmits the packet, for up to 3 times [1].

The channel access in a CTAP is based on TDMA. The CTAP is divided into many Channel Time Allocations (CTAs) with fixed duration and start time. Each CTA is assigned to an individual DEV or a group DEVs. The location of each CTA and its duration is specified in the beacon by the PNC. The CTAP is designed for all kinds of data. A DEV makes a request of the PNC for a CTA in which to exchange data. Because the full duration of the CTA can be utilized by a DEV or a group of DEVs, successful transmission will result. The CTA can support bulk data (such as multi-Megabyte sized image files), and isochronous data (such as video stream) very well.

III. PICONET COODINATOR SELECTION METHOD

A. Motivation

In practice, a WPAN may experience spectrum overlapping and coexistence with other wireless networks, particularly, when UWB physical layer technology is applied. Minimizing the interference to other networks is one of the key problems in a WPAN. To meet the FCC regulations and afford a good quality signal, the transmission power of a device in a WPAN should be well controlled. On the other hand, it is well known that reducing the transmission power is also an important aspect for power saving in battery-operated wireless networks [3]. It is clear that reducing the transmission distance can decrease the transmission power required, due to the transmission power is strongly linked to the transmission distance. As described in [3], if $P_r(d_{i,j})$ is the desired receiving power level for a correctly decoded packet between device i and j, then the relationship of the transmission power $P_t(d_{i,j})$ and received power can be described by:

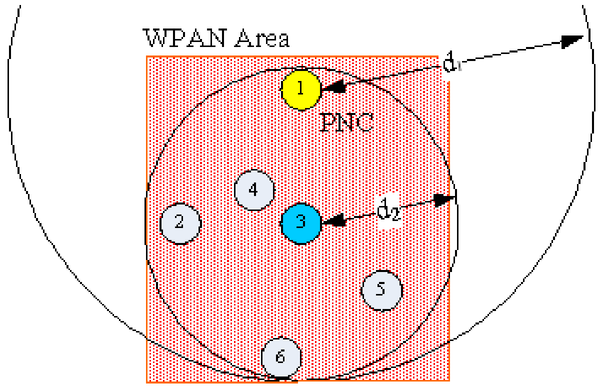


Fig. 2. Interference area introduced by different PNCs

$$P_r(d_{i,j}) = P_t(d_{i,j}) \cdot (\frac{\lambda}{4\pi d_{i,j}})^n \frac{G_t G_r}{L} \qquad (1)$$

where $d_{i,j}$ is the distance between transmitter i and receiver j, G_t and G_r are the antenna gains of the transmitter and receiver respectively, L is the system loss factor, n is the path loss exponent with a typical value between 2 and 4.

In terms of the standard, the most capable DEV may be dynamically selected as the PNC of a WPAN. Generally, the capability function, C_i, of a source limited DEV is determined by the transmission rate, memory capacity, CPU speed, residual energy, or other characteristics. The mechanism for defining the capability function has not explicitly specified by the standard.

To reduce the interference introduced by PNC communication and save energy consumption within a Piconet, the distance between the PNC and other DEVs must be considered into the capability function, C_i, for the PNC selection method. For example, in fig. 2, the red rectangle defines a WPAN area. Assume that DEV 1 is chosen for the PNC. In this case, to cover all the DEVs, the PNC has to increase transmission power to satisfy the emission radius d_1. Compared with the PNC selection scheme which selects DEV 3 as the PNC, we can see that the interference area is reduced and less energy is consumed in the PNC and other remote DEVs, such as DEVs 5 and 6, who also require less power to successfully exchange information with the PNC. Generally, selecting a DEV, which has the least distance square, as the PNC can decrease the interference area and the extra transmission power introduced by the PNC.

However, from the point of view of improving the survivability of the whole WPAN, frequently selecting a PNC with low battery energy will easily lead to energy exhaustion in this PNC, thus resulting in network partitioning and topology instability [4-5]. Therefore, the residual energy should also be considered in PNC selection.

B. Details of LDS-PNC Selection

A PNC Selection Counter (PSC), which controls the frequency of the PNC selection operation, is configured to an initial value, *T*, when a PNC is selected. A PNC decreases its PSC until it reaches zero. The PNC selection routine is started by a PNC when either:

1. The PSC meets zero;

2. The PNC's residual battery energy meets the lower bound, E_L; or

3. The PNC needs to leave the Piconet.

To initiate the PNC selection process, the PNC attaches a PNC Selection Request (PSR) to the beacon frame and sends it to all the DEVs at the start of the superframe. When the DEVs receive the PSR, they will try to send a PSR-ACK packet back to the PNC as the acknowledgement. Each DEV attaches the value of its residual battery energy, E_i , and other characteristics, such as memory capacity, and CPU speed, to the PSR-ACK, and uses a maximum power level, $P_{\max}$, to send this packet during the CAP. Because the PSR-ACK is a small packet, it can be successfully transmitted by most DEVs within the CAP. For simplicity, if a DEV cannot successfully transmit a PSR-ACK within the CAP, for instance, because of severe access contention, this DEV will not try to send the PSR-ACK in other CAPs, which means that this DEV will be ignored in PNC selection.

All devices within the Piconet, including the PNC and DEVs, listen for this PSR-ACK. Since our algorithm just needs a rough value of the distance between two stations, the received signal strength of the PSR-ACK is measured to estimate the value of the distance. When DEV *i* receives DEV *j*'s PSR-ACK, it uses the equation (1), whose n is given by 2, to compute the distance between DEV *i* and *j*, $d_{i,j}$, as:

$$d_{i,j} = \lambda \sqrt{\frac{P_{\max} G_t G_r}{P_{r,i} L}} / 4\pi \qquad (2)$$

where $P_{r,i}$ is the received power lever measured by the station *i*. Assume there are *N+1* devices in the Piconet. The device, *i*, will record a set of the distances between other stations and itself, which can be depicted as:

$$D_i = \left\{ d_{i,j} \right\}; \qquad j = 0,1 \cdots N-1, N; \qquad j \neq i \qquad (3)$$

Then the average distance square of device *i*, among the distance set D_i can be calculated as:

$$E(D_i^2) = \frac{1}{N} \cdot \sum_{j=0,1,2,\cdots N;\, j \neq i} d_{i,j}^2 \qquad (4)$$

Generally, the PNC will consume more energy than normal DEVs, so it is necessary for a DEV to have enough battery energy to act as a PNC. Therefore, after receiving all the PSR-ACKs, the PNC tries to find a DEV set, R^*, in which the DEVs' residual battery energy is more than E_L. R^* can be defined as:

$$e(DEV_i) \geq E_L \qquad (\forall DEV_i \in R^*) \qquad (5)$$

where DEV_i is one of the DEVs in the set R^*, and $e(DEV_i)$ is its residual battery energy. This step prevents a centrally located device from being frequently chosen as a PNC without consideration of the residual energy. Without this criterion fast energy exhaustion in the PNC and network partitioning will result. In some cases, other QoS criteria, such as memory capacity, and CPU speed, may be considered in PNC selection. The capability function, $C(DEV_i)$ which includes these features, could be defined to find another set of DEVs, R^{**}, as:

$$C(DEV_i) \geq C_L \qquad (\forall DEV_i \in R^{**} \in R^*) \qquad (6)$$

where C_L is the lower bound of capability.

If $R^* = \varnothing$ or $R^{**} = \varnothing$, a warning message will be sent to the application layer to make the user aware.

At the beginning of the next superframe, the PNC attaches all IDs of the DEVs in R^{**} and a Distance Report Request (DRR) in the beacon, and broadcasts it in its Piconet. To decrease energy consumed in transmission, just the DEVs, who are the member of R^{**}, and are specified in the beacon, listen for this DDR, and send DRR-ACK packets, enclosing the maximal distance square, $E(D_i^2)$, to the PNC during the following CAP. After receiving all the values of $E(D_i^2)$, the PNC will find an optimal DEV to replace itself. If the Least Distance Square PNC (LDS-PNC) selection metric is applied, the optimal DEV, DEV_{opt}, can be specified by:

$$E(D_{opt}^2) = \min_{\forall DEV_i \in R^{**}} E(D_i^2) \; (DEV_{opt} \in R^{**} \in R^*) \qquad (7)$$

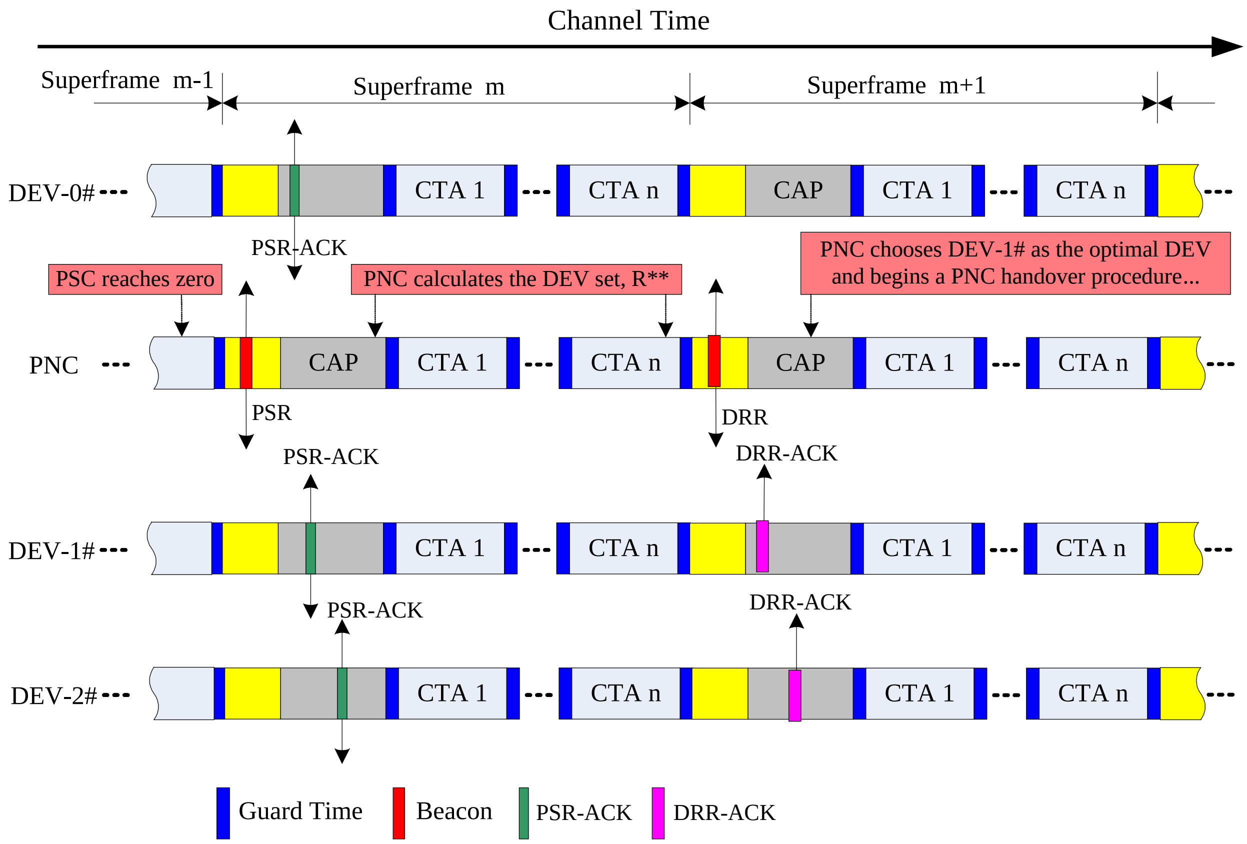


Fig. 3. PNC selection procedure

Then the current PNC will start a procedure to hand over control of this Piconet to the selected optimal DEV. When the selected optimal DEV becomes a PNC, it will also restart a PSC for the next PNC selection timer. The new PNC will transmit beacons and other control packets with a required transmission power level calculated through equation (1), given n=2:

$$P_t(d_{i,j}) = P_r^* \cdot (\frac{4\pi d_{\max}}{\lambda})^2 \frac{L}{G_t G_r} \quad (8)$$

where P_r^* is a required receiving power level for correctly decoding, and $d_{\max}$ is the maximal distance between the new PNC and other DEVs, which can be found in the distance set, D_i.

An example of the proposed PNC selection procedure is shown in fig. 3. When the PSC reaches zero, the PNC broadcasts a beacon with attached PSR information. During the following CAP, all the DEVs attach their features to their PSR-ACK packets and send them to the PNC. The remaining duration of the m^{th} superframe is enough for a PNC and DEVs to calculate the set R^{**}, and the distance square. In the next beacon window, the PNC sends the DDR information to the DEVs belonging to set R^{**} through beacon transmission. Then the DEVs (DEV-#1 and DEV-#2) in set R^{**} send the DDR-ACK to the PNC. Finally the PNC uses the distance information attached in DDR-ACK packets to choose the optimal DEV as the next PNC.

IV. Numerical Results

In this section, several examples are illustrated to show the performance of the proposed PNC selection method. In the simulation, all the devices are randomly located in the same coverage area so that they can communicate directly with each other. A real-time Variable Bit Rate (rt-VBR) MPEG4 traffic generator, introduced in [6] is implemented in the simulation. Table 1 shows some key parameters.

The energy consumption is estimated by the "first order radio" model discussed in [7]. This energy model can be described as follows:

$$\begin{aligned} E_{i\_tx} &= E_{tx} \times S_{tx} + \varepsilon_{amp} \times S_{tx} \times d_{i-j}^2 \\ E_{i\_rx} &= E_{rx} \times S_{rx} \end{aligned} \text{ (Joules)} \quad (9)$$

where E_{i_tx} is the energy consumed in transmission, and E_{i_rx} the energy consumed in reception for node *i*. E_{tx} and E_{rx} are the

TABLE I
Simulation Parameters

Parameters	Value
Superframe size	10ms
Mean offered load by rt-VBR	8Mbps
Simulation area	$10m \times 10m$
Total number of devices (including PNC)	5,10,15,20,25,30
PNC selection period	150ms
Channel Bit Rate	100Mbit/s
Packet deadline	33ms
Lower limitation of the residual energy in devices E_L	500Joul

radio transmitter and receiver operation energy dissipation per bit. We assume the node has some form of power control to achieve an acceptable signal-to-noise ratio. ε_{amp} is set to obtain the desired signal strength for transmissions to *j*. S_{tx} and S_{rx} are the transmitted packet size and the received packet size. $d_{i\text{-}j}$ is the distance between the source node *i* and the destination node *j*. In the simulation, $E_{tx}=E_{rx}=50nJ/bit$, $E_{amp}=100nJ/bit/m^2$. Each node is given an initial energy, calculated from a uniform PDF with the range $[1800J, 2000J]$.

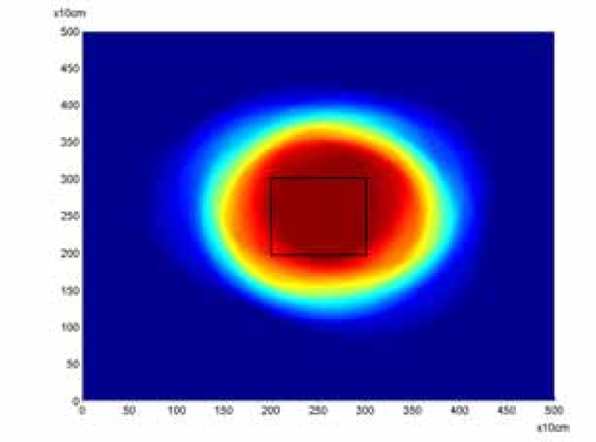
For validation of the PNC selection method, it is assumed that each device has same memory capability, CPU speed, and receiving/transmitting characteristics, which means $R^* = R^{**}$.

A. Interference area introduced by PNC communication:

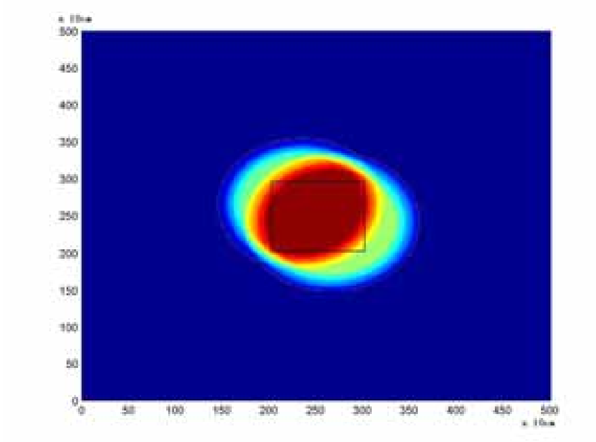
Generally, a DEV, which is selected as a PNC, has smaller distance square, and will be located in the central area of the Piconet. On the other hand, the proposed method utilizes an estimated distance to control the transmission power level of the PNC, thus the area occupied by the PNC communication radiation and the battery energy consumed in the PNC could be diminished. Fig. 4 shows the coverage of PNC communication in the normal IEEE802.15.3-based WPAN and the proposed PNC selection methods. In the simulation, 10 devices (1 PNC, 9 DEVs) are randomly located in a $10m \times 10m$ area, which is indicated by the black frame in fig. 4. The warm colour area means this area has been covered by the PNC's transmission for a high percentage of time. It is clear that using the proposed PNC selection method can decrease the coverage area of the PNC radiation, which means less interference to neighbouring networks and energy saving for the PNC.

B. Average residual energy in each device:

To measure the power-saving features of the proposed PNC selection algorithm, the average battery energy of 10 devices, including 1 PNC and 9 DEVs, is measured in a 4-hour simulation. The measured values are normalized by the initial battery energy in each device. Fig. 5 compares the results of the LDS-PNC selection method against the normal IEEE802.15.3 mechanism. Because the transmission power is decreased through avoiding long transmission paths, more energy is saved when using LDS-PNC selection. For example, the devices in the piconet employing LDS-PNC selection survive 1 hour longer than the devices in the normal IEEE802.15.3 WPAN when 50% of the initial battery energy is used.



(a) Normal selection method



(b) LDS

Fig. 4. Interference area introduced by PNC communication

C. PNC survival probability:

When E_L is configured to zero, which means the PNC selection method does not consider the residual energy in the selection, the central DEVs will have a high probability of being selected as the PNC. However, frequently selecting DEVs with small distance square will easily lead to energy exhaustion of these devices, thus resulting in network partitioning and topology instability. Fig. 6 compares the PNC survival probability of the proposed LDS, LDS without the lower limitation of residual energy, and the normal IEEE802.15.3-based WPAN PNC selection. It is obvious that the proposed PNC selection method can prolong the lifetime of PNCs in WPANs.

D. Percentage of energy consumption for PNC selection:

The drawback of the proposed PNC selection method is that it may result in more packet exchange, which is produced by PSR, PSR-ACK, DRR, and DRR-ACK packets. The energy used for receiving and transmitting these packets is the majority

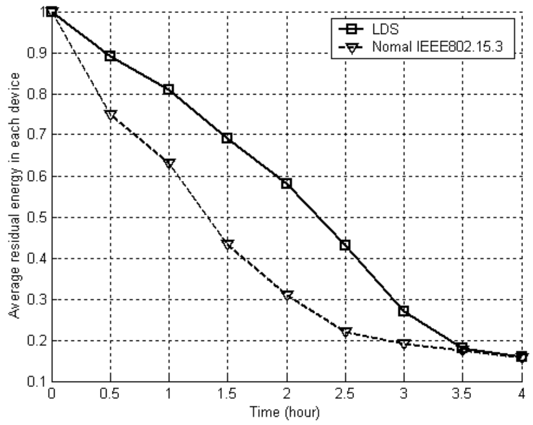


Fig. 5. Average residual energy in each device

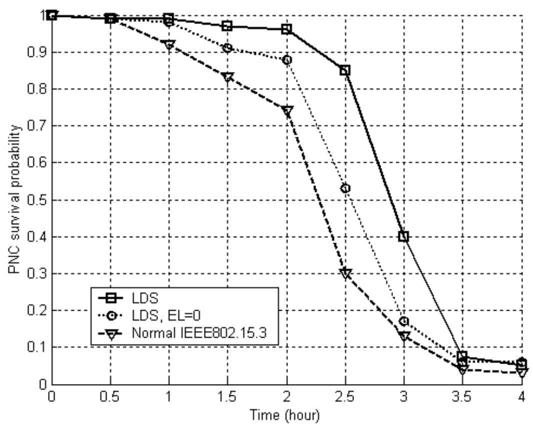


Fig. 6. PNC survival probability

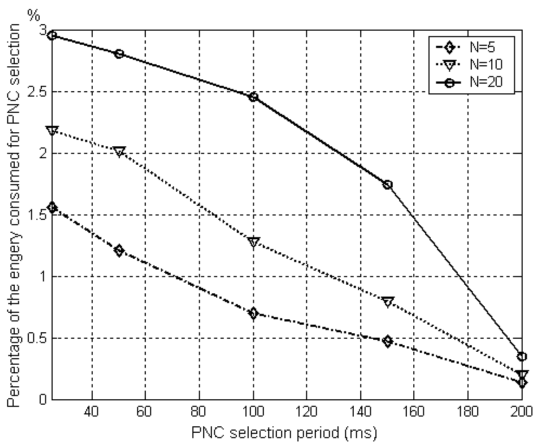


Fig. 7. Percentage of the energy consumed by PNC selection mechanism vs. different PNC selection period

of energy consumption for the PNC selection mechanism. Depicted in fig. 7, the percentage of the energy consumption for PNC selection mechanism is strongly linked to the PNC selection period and the number of devices, *N*. A short PNC selection period can help the algorithm accurately obtain the change of the devices' status, but this will result in frequent transmission of the control packets, whose tradeoff should be considered carefully in real systems. However, because the control packets are very small, and the beacon frames are also used for PNC selection, the additional energy consumption for the PNC selection method is very small. For instance, when the selection period is *150ms*, the average energy consumed for the PNC selection is less than 1.75% of the total energy consumption.

V. CONCLUSION

Power awareness is an essential component of WPANs, due to limited energy stored in battery-operated devices. Moreover, a WPAN has to deal with coexistence problems, since it may be simultaneously operating with other types of networks. Especially, when UWB, which is a candidate PHY technology for IEEE802.15.3-based WPANs, is applied, decreasing the transmission power is necessary to meet the FCC regulations and diminish interference to other communication systems. In this paper, a novel PNC selection method for IEEE 802.15.3-based WPANs is proposed. In this method, a universal distance estimation method is used to help the PNC selection. Using the proposed PNC selection method, the transmission power can be lessened, and the interference area introduced by PNCs can be diminished as well. The simulation results validate that this method has power-saving and interference mitigation characteristics.

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REFERENCES

[1] LAN MAN Standards Committee of the IEEE Computer Society, "IEEE Std 802.15.3 – 2003, Wireless LAN medium Access Control (MAC) specifications," IEEE, 2003

[2] M. Z. Win, and R. A. Scholtz, "Impulse Radio: How It Works," IEEE Communications Letters, Vol. 2, No. 2, Feb. 1998

[3] I. Stojmenovic and X. Lin, "Power-aware Localized Routing in Wireless Networks", IEEE Transactions on Parallel and Distributed Systems, Vol. 12, Issue: 11, Nov. 2001, pp. 1122-1133

[4] R. C. Shah, and J. M. Rabaey, "Energy Aware Routing for Low Energy Ad Hoc Sensor Networks," Wireless Communications and Networking Conference, 2002, WCNC2002, IEEE, vol.1, 17-21 March 2002, pp.350 – 355

[5] Y. Zhou, D. I. Laurenson, S. McLaughlin, "High Survival Probability Routing in Power-Aware Mobile Ad Hoc Network," IEE Electronics Letters, Vol. 40, No. 22, 28th Oct. 2004, pp.1424-1426

[6] http://www.sce.carleton.ca/~amatrawy/mpeg4/

[7] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," In Proc. Hawaii International Conference on System Sicence, 2000, vol. 2,pp.10