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三维超宽带无线传感网的能耗界限*

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Energy Dissipation Bounds on Three Dimensional UWB Wireless Sensor Network

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Abstract: Considering a three dimensional TH-UWB wireless sensor network with n static identical randomly located sensor nodes in a sphere of volume normalized by one cubic meter, the formula for upper and lower bounds on the energy dissipation of some sensor node transmitting a data packet containing R bits to the sink node by multihop fashion are derived using Vapnik-Chervonenkis theory and Voroni tessellation covering sensor field. The main finding is that the upper and lower bounds on the energy dissipation are in inverse proportion to the node density n in the network. Thus, large-scale dense TH-UWB wireless sensor network is more preferable.
Key words: wireless sensor network; ultra wide band; energy dissipation

摘 要: 研究了 n 个静态节点随机分布在单位球上的三维超宽带无线传感网,利用 Vapnik-Chervonenkis 定理和 Voroni 棋盘格子覆盖传感区域,推导出了某个节点发射包含 R 比特的数据分组以多跳方式到达汇聚节点时的能量消耗上下界.研究表明,能量消耗的上下界与网络节点密度 n 成反比.因此,大规模密集超宽带无线传感网是更为可取的.
关键词: 无线传感网;超宽带;能量消耗
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1 Introduction

Recent developments in wireless technology have excited extensive research in wireless sensor networks. It can be implemented in a variety of applications, such as military, inventory tracking, consumer electronics, or fault detection[1]. These applications require low power dissipation, low cost and small size of sensor nodes. Therefore there has been significant interest in studying the minimization of the energy dissipation of wireless sensor

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networks. The thoughts of previous studies of the energy dissipation of wireless sensor networks were to propose energy-efficient algorithms and prove it by experimental simulation, and these studies mainly concentrated on the topology control, medium access, routing protocols, and data aggregation[2−6].

Thus, it is necessary and important to investigate the energy dissipation of wireless sensor networks in theory given a set of parameters. For example, studies on the asymptotic behavior of the energy dissipation with respect to the network size and volume provide insights pertinent to the network scalability and feasibility of deploying large-scale wireless sensor networks. The results with respect to the energy dissipation offers important guidance to research on the network management issues such as topology control, MAC and routing, data aggregation.

Ultra wide band (UWB) is a highly promising physical layer technology for wireless sensor networks due to its unique characteristics such as low power transmission, low cost and low complexity transceiver circuitry, noise-like signals, precise location capability, and resilient to Rayleigh fading from multipath interference. This paper considers the most common version of UWB based on the transmission of very short (picosecond) pulses emitted in periodic sequences, in an impulse radio fashion. Time hopping (TH) codes which introduce a variable delay on each transmitted pulse are used[7]. The impulse radio TH-UWB wireless sensor network will be considered in this paper.

Recently the capacities of UWB ad-hoc networks have been derived for various wireless ad-hoc networks[8,9], these results all demonstrate that the throughput for UWB ad hoc networks increases with node density.

Since energy dissipation is a critical concern in the design of wireless sensor networks, we study the asymptotic behavior of the energy dissipation of TH-UWB sensor network in this paper. To the best of our knowledge, the energy dissipation bounds on the three dimensional TH-UWB sensor network is not available in the literature.

This paper addresses the lower and upper bounds on the energy dissipation of the three dimensional TH-UWB wireless sensor network respectively. Such wireless sensor networks arise when the network consists of both terrestrial and satellite-based or aircraft-based communication links, or in building networks where sensor nodes are located on different floors, or in indoor networks where sensor nodes connected by Bluetooth.

The remainder of this paper is organized as follows. Section 2 presents system model, and the SINR and link's Shannon capacity of TH-UWB are given in Section 3. The lower bound and upper bounds on the energy dissipation of the three dimensional TH-UWB wireless sensor networks are derived respectively in Sections 4 and 5. Finally, Section 6 concludes the paper and also gives some future work.

2 System Model

In the three dimensional wireless sensor networks composed of n static sensor nodes and one sink node, these static sensor nodes are independent, identically distributed, and distributed uniformly in a sphere of volume normalized by *one* cubic meter. The n sensor nodes communicate over wireless channels and relay traffic each other. Each sensor node sends its acquired data to the sink node located at the center of the sphere.

Let N_i denote the sensor node and its position. Let $P_{ti}\geq 0$ be the transmitting power of node N_i, and let $P_{rj}\geq 0$ be the receiving power of node N_j. For simplicity, assuming that it is a homogenous network, then $P_{ti}=P_t$, $P_{rj}=P_r$, $\forall i,j\in\{1,2,\ldots,n\}$.

The objective of this paper is to bound the energy dissipation $E(n)$ of the three dimensional TH-UWB wireless sensor network by a function of n, which is defined as the energy dissipation of some sensor node transmitting a data packet containing R bits to the sink node by multihop fashion. Since the underlying network is random, so is the energy dissipation. The energy dissipation bounds are derived to be certain functions with high probability (*w.h.p.*), i.e., with probability approaching 1 as the node density $n\rightarrow\infty$. As in Ref.[10], if there exist deterministic constants $c_1>c_0>0$ such that

$$\lim_{n\to\infty} \Pr(E(n) = c_0 f(n) \text{ is feasible}) < 1 \tag{1}$$

$$\lim_{n\to\infty} \Pr(E(n) = c_1 f(n) \text{ is feasible}) = 1 \tag{2}$$

If only Eq.(1) is satisfied, we say that the energy dissipation $E(n)$ is lower bounded by $\Omega(f(n))$; if only Eq.(2) is satisfied, we say that the energy dissipation $E(n)$ is upper bounded by $O(f(n))$.

3 SINR and Link's Shannon Capacity of TH-UWB

It is assumed that the communication channel is AWGN channel. The Gaussian noise power spectral density is η. Supposing the signal power decreases in proportion to the α order of the distance between the transmitter and receiver, and $\alpha>3$ is the distance loss exponent. The reason is that if $\alpha\le 3$, and nodes are uniform in space, then the interference level everywhere is unbounded as the number of nodes in the network increases.

All physical links are point-to-point. Each link is assumed to support a data rate corresponding to the Shannon capacity of that link.

Consider n nodes, binary pulse position modulation. The signal-to-interference and noise ratio (SINR) at the receiver N_j is the ratio of the received power by the total interference perceived by the receiver including the ambient AWGN noise and the transmissions of other links that occur at the same time. For TH-UWB, a receiver does not capture the full power of an interferer, but just a fraction that depends on the correlation of the spreading sequences of the sender and the interferer. The total noise at a receiver can thus be modeled as the sum of the ambient noise and the total interference multiplied by the orthogonality factor. Thus, SINR can be written as:

$$SINR = \frac{P_t h_{ij}}{\eta W + \sum_{k=1}^{M} a_k P_t h_{kj}} \tag{3}$$

where P_t is the transmit power of node N_i, h_{ij} is the signal power attenuation for the useful data, $h_{ij}=|N_i-N_j|^{-\alpha}$, and the distance $|N_i-N_j|$ is defined as the length of the segment connecting N_i and N_j, W is the signal bandwidth and M is the number of colliding data, supposing M nodes transmit data simultaneously and a_k is the orthogonality factor. For homogeneous network, $a_k=a$, $\forall k\in\{1,2,\ldots,n\}$.

The first term ηW of the denominator of SINR represents the ambient AWGN noise power, and the second term represents multiuser interference (MUI). If bandwidth is so large that the ambient AWGN noise power is markedly more than the MUI, then the MUI can be negligible with respect to the ambient AWGN noise. Accordingly, SINR can be simplified, i.e. $SINR=P_t h_{ij}/(\eta W)$.

According to Shannon capacity formula, each link's Shannon capacity C_{ij} is

$$C_{ij} = \lim_{W\to\infty} W\log(1+P_t h_{ij}/(\eta W)) = P_t h_{ij}/\eta \tag{4}$$

4 Lower Bound on Energy Dissipation

Radios of nodes typically have four power levels corresponding to the following states: transmitting, receiving, listening, and sleeping. In order to let the energy dissipation as small as possible, assuming if a sensor is not engaged in transmitting or receiving, it will keep sleep. Therefore, in this paper we only consider the consumed energy in the state of transmitting and receiving. We ignore the energy consumption in the sleeping state, because it is much smaller than the transmitting and receiving energy consumption.

4.1 Total consumed energy

In order to obtain the total energy dissipation of the three dimensional TH-UWB sensor network when transporting a data packet containing R bits from one source node to the sink node, the energy consumption of one medial hop along the route must be first obtained.

Thus, the energy consumption of node N_i transmitting a packet containing R bits to its neighbor N_j is

$$E_{ij}=E_{ti}+E_{rj}=P_t\times R/C_{ij}+P_r\times R/C_{ij} \tag{5}$$

where E_{ti} and E_{rj} represent energy consumption for the i-th node transmission and j-th node reception respectively.

Supposing source node N_s wants to send a packet containing R bits to the sink node N_d using multihop fashion, the medial relay node N_i must send R bits data to its neighbor N_{i+1}. The energy dissipation $E_{i,i+1}$ can be written as follows.

$$\begin{aligned} E_{i,i+1} &= P_{ti}\times R/C_{i,i+1} + P_{r,i+1}\times R/C_{i,i+1} \\ &= P_t\times\frac{R}{P_t h_{i,i+1}/\eta} + P_r\times\frac{R}{P_t h_{i,i+1}/\eta} = \left(1+\frac{P_r}{P_t}\right)\times R\,|N_i-N_{i+1}|^{\alpha}\,\eta \end{aligned} \tag{6}$$

where $R/C_{i,i+1}$ represents the consumed time interval in which node N_i transmits R bits data to its neighbor node N_{i+1}.

Eq.(6) indicates that the smaller $|N_i-N_{i+1}|$ is, the smaller $E_{i,i+1}$ is. It implies that it will benefit to conserve energy of the node if the medial relay node N_i selects its closest neighbor as its next hop node N_{i+1}.

Therefore, the total energy dissipation $E_{tot}(n)$ when source node N_s transports R bits data to the sink node N_d is as follows.

$$E_{tot}=\sum_{i=0}^{X-1}E_{i,i+1}=\sum_{i=0}^{X-1}\left(\left(1+\frac{P_r}{P_t}\right)\times R\,|N_i-N_{i+1}|^{\alpha}\,\eta\right) \tag{7}$$

where X is the number of nodes from source sensor node N_s to the sink node, $N_0=N_s$, and $N_X=N_d$. Note that in most applications, the sink node is energy unconstrained, but for simplicity, the receiving energy dissipation of the sink node is included in Eq.(7).

4.2 Lower bound on the energy dissipation

Here we construct a Voronoi tessellation V_n of sphere S. Let $\{a_1,a_2,\ldots,a_p\}$ be a set of p points in sphere S. The Voronoi cell $V(a_i)$ is the set of all points which are closer to a_i than to any of the other a_j's, i.e.,

$$V(a_i):=\{x\in S: |x-a_i|=\min_{1\le j\le p}|x-a_j|\}\ ^{[10]}.$$

The tessellation has the following properties [11]:

(1) Every Voronoi cell V contains a ball of radius $\rho(n)$ and corresponding volume $100\log n/n$, i.e.,

$$4\pi\rho^3(n)/3=100\log n/n.$$

(2) Every Voronoi cell is fully contained within a ball of radius $2\rho(n)$.

Denote L_{sd} as the sum of the hop-lengths between the source N_s and the sink node N_d.

$$L_{sd}=\sum_{i=0}^{X-1}|N_i-N_{i+1}|\ge|N_s-N_d|=L_0 \tag{8}$$

Where L_0 is the straight line between the source node N_s and the sink node N_d.

The routing R_{sd} of source sink pair $N_s\rightarrow N_d$ is considered. Define a region $G(R_{sd})\subset S$ as follows.

$$\begin{aligned} &y\in G(R_{sd}) \text{ iff } \exists x\in R_{sd} \text{ s.t. } |x-y|\le 4\rho(n) \\ \text{and}\quad &z\in G(R_{sd}) \text{ iff } \exists x\in R_{sd} \text{ s.t. } |x-z|\le 4\rho(n) \end{aligned} \tag{9}$$

The $G(R_{sd})$ defines a coverage region around the route such that all cells intersecting the route have to be fully contained within this coverage region. Hence the total volume of the coverage region is

$$V(G(R_{sd}))=\frac{4\pi}{3}(4\rho(n))^3+\pi(4\rho(n))^2L_{sd}=\frac{6400\log n}{n}+\pi\left(16\left(\frac{3}{4\pi}\frac{100\log n}{n}\right)^{2/3}\right)L_{sd} \tag{10}$$

The minimum volume of a Voronoi cell is 100logn/n. Since the route can only intersect cells that are completely contained in $G(R_{sd})$, the number of such cells is upper bounded as:

$$N_{\max}^{cells}=\frac{V(G(R_{sd}))}{100\log n/n}=64+4\times 3^{2/3}\left(\frac{4\pi n}{100\log n}\right)^{1/3}L_{sd} \tag{11}$$

The Vapnik-Chervonekis theorem is applied to the tessellation of the network. The application of the Vapnik-Chervonekis theorem to the set of balls (contained in the cells) yields that the number of nodes per cell with high probability obeys 50log$n$≤$N(V)$≤150log$n$, which indicates that every cell V at least contains one node[11].

Thus, the maximum number of sensor nodes on the $G(R_{sd})$ is

$$N_{\max}^{nodes}\le 150\log n\times N_{\max}^{cells}\le k_1\log n+k_2L_{sd}\sqrt[3]{n(\log n)^2} \tag{12}$$

Where k_1 and k_2 are constants, with respect to n. And in the sequel, k_3, k_4, k_5, k_6, k_7 are all constants.

The lower bound on the total energy dissipation $E_{tot}(n)$ of carrying R bits data from source node N_s to the sink node N_d is

$$\begin{aligned}E_{tot}(n)&=\sum_{i=0}^{X-1}\left(1+\frac{P_r}{P_t}\right)R\eta\,|N_i-N_{i+1}|^{\alpha}\ge\left(1+\frac{P_r}{P_t}\right)R\eta N_{\max}^{nodes}\left(\frac{L_{sd}}{N_{\max}^{nodes}}\right)^{\alpha}\\&\ge\left(1+\frac{P_r}{P_t}\right)R\eta\frac{L_{sd}^{\alpha}}{(k_1\log n+k_2L_{sd}\sqrt[3]{n(\log n)^2})^{\alpha-1}}\end{aligned} \tag{13}$$

with high probability. Here, the concavity property of y^{α} is used.

Since as $n\to\infty$, $\log n<<\sqrt[3]{n(\log n)^2}$. $E_{tot}(n)$ can be written as follows.

$$E_{tot}(n)\ge\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}k_3(n(\log n)^2)^{-\frac{\alpha-1}{3}} \tag{14}$$

with high probability. Thus,

$$\lim_{n\to\infty}\Pr\left(E_{tot}(n)=\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}k_4\left(\frac{1}{n(\log n)^2}\right)^{\frac{\alpha-1}{3}}\text{ is feasible}\right)<1 \tag{15}$$

This proves the lower bound on energy dissipation is

$$E_{low-tot}(n)=\Omega\left(\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}\left(\frac{1}{n(\log n)^2}\right)^{\frac{\alpha-1}{3}}\right) \tag{16}$$

for $n\to\infty$, where $\alpha\ge3$.

Therefore, based on Eq.(16), we can conclude that if the node density n is increased, the lower bound of energy dissipation $E_{low\text{-}tot}(n)$ will be decreased. Thus, the large-scale dense UWB wireless sensor networks will be good to decrease energy dissipation.

5 Upper Bound on Energy Dissipation

According to Ref.[11], Pr(Every cell $V\in V_n$ contains a node)>1−50logn/n. Hence every cell in V_n contains at least one node to relay the traffic. Because every cell in the Voronoi tessellation is contained in a ball of radius $2\rho(n)$, the length of each hop to reach the next relay node is at most $8\rho(n)$, and accordingly, in this scenario $N_{\max}^{cells}$ is the maximum of relay nodes. Thus, the upper bound on the consumed energy $E_{tot}(n)$ of source node N_s sending R bits data to the sink N_d can be expressed as:

$$E_{tot}(n)=\sum_{i=0}^{X-1}\left(1+\frac{P_r}{P_t}\right)\times R\,|N_i-N_{i+1}|^{\alpha}\,\eta\le\left(1+\frac{P_r}{P_t}\right)\times R\eta N_{\max}^{cells}(8\rho(n))^{\alpha}$$
$$\le\left(1+\frac{P_r}{P_t}\right)R\eta\left(k_5\left(\frac{\log n}{n}\right)^{\frac{\alpha}{3}}+k_6L_{sd}\left(\frac{\log n}{n}\right)^{\frac{\alpha-1}{3}}\right) \quad (17)$$

with probability exceeding 1−50log$n$/n.

Since as $n\to\infty$, $\left(\frac{\log n}{n}\right)^{\frac{\alpha-1}{3}}>>\left(\frac{\log n}{n}\right)^{\frac{\alpha}{3}}$. Thus, we have

$$\lim_{n\to\infty}\Pr\left(E_{tot}(n)=\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}k_7\left(\frac{\log n}{n}\right)^{\frac{\alpha-1}{3}}\text{ is feasible}\right)=1 \quad (18)$$

Hence the upper bound is

$$E_{upp-tot}(n)=O\left(\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}\left(\frac{\log n}{n}\right)^{\frac{\alpha-1}{3}}\right) \quad (19)$$

for $n\to\infty$, where $\alpha\ge3$.

When the node density n is increased, the upper bound of energy dissipation $E_{upp\text{-}tot}(n)$ will be decreased too.

6 Conclusion and Future Work

In this paper, we investigate the energy dissipation of the three dimensional TH-UWB wireless sensor network. It is shown that for such a static TH-UWB sensor network, consisting of n randomly distributed identical nodes in a sphere of volume normalized by *one* cubic meter and transporting R bits data from some node N_s to the sink node N_d, the lower bound on energy dissipation is $\Omega\left(\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}\left(\frac{1}{n(\log n)^2}\right)^{\frac{\alpha-1}{3}}\right)$, and the upper bound is $O\left(\left(1+\frac{P_r}{P_t}\right)R\eta L_{sd}\left(\frac{\log n}{n}\right)^{\frac{\alpha-1}{3}}\right)$. In order to decrease energy dissipation, designer may employ large-scale dense TH-UWB wireless sensor network.

Performing simulations to assess how tight the bound on energy dissipation will be done in the further research, and the energy dissipations of the multicast and mobile network are also the subject of future work.

References:

[1] Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E. A survey on sensor networks. IEEE Communications Magazine, 2002,40(8): 102−114.

[2] Younis O, Fahmy S. HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. IEEE Trans. on Mobile Computing, 2004,3(4):366−379.

[3] Ye W, Heidemann J, Estrin D. An energy-efficient MAC protocol for wireless sensor networks. In: Proc. of the 21st Int'l Annual Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM 2002). New York: IEEE Computer Society, 2002. 1567−1576.

[4] Shah R, Rabaey J. Energy aware routing for low energy ad hoc sensor networks. In: Proc. of the IEEE Wireless Communications and Networking Conf. Orlando: IEEE Communications Society, 2002. 350−355.

[5] Xu Y, Heidemann J, Estrin D. Geography-Informed energy conservation for ad hoc routing. In: Proc. of the 7th Annual ACM/IEEE Int'l Conf. on Mobile Computing and Networking. Rome: ACM Press, 2001. 70−84.

[6] Madden S, Franklin M, Hellerstein J, Hong W. TAG: A tiny aggregation service for ad hoc sensor networks. In: Proc. of the 5th Symp. on Operating Systems Design and Implementation. Boston: ACM Press, 2002. 131−146.

[7] Win M, Scholtz R. Ultra-Wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications. IEEE Trans. on Communications, 2000,48(4):679−691.

[8] Negi R, Rajeswaran A. Capacity of power constrained ad-hoc networks. In: Proc. of the IEEE INFOCOM 2004. IEEE, 2004. 443−453.

[9] Zhang F, Kang X. Throughput capacity of UWB ad-hoc networks with infrastructure support. In: Proc. of the 1st Int'l Conf. on Wireless Algorithms, Systems, and Applications. Berlin: Springer-Verlag, 2006. 252−263.

[10] Gupta P, Kumar PR. The capacity of wireless networks. IEEE Trans. on Information Theory, 2000,46(2):338−404.

[11] Gupta P, Kumar PR. Internets in the sky: The capacity of three dimensional wireless networks. Communications in Information and Systems, 2001,1(1):33−49.

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