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RESEARCH ARTICLE

A Comparison Between Neighbour Discovery Protocols in Low Duty-Cycled Wireless Sensor Networks

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Abstract— Wireless sensor networks are applied in a wide variety of applications, such as environment monitoring, target tracking and so on. Neighbour discovery process is an important component of wireless sensor network's access and basic communication. Duty-cycle based wireless sensor networks can save energy, but challenges the process of neighbour discovery. A comparison between neighbour discovery protocols in low duty-cycled wireless sensor networks is made and a classification of discovery protocols is proposed, i.e. random neighbour discovery and deterministic neighbour discovery. In particular, we analyze the deterministic neighbour discovery protocols in detailed. A qualitative comparison incorporating multiple criteria and a quantitative evaluation on energy efficiency are also included. Finally, the author indicates making full use of neighbour discovery protocol in real deployment is the key of future neighbour discovery protocol design.

Keywords —Wireless sensor network (WSN), duty cycle, neighbour discovery, asynchronous asymmetric, analysis of protocols

I. Introduction

Wireless sensor network(WSN)[1], as the name suggests, is a wireless network with spatially distributed autonomous low-power devices making use of sensors for data collection, processing, and transmission capacities. They are mainly used to collect and analyze physical or environmental conditions, including: habitat monitoring[2], target tracking[3], disaster relief[4], fire detection, environmental monitoring[5], urban sensing[6] and so on.

The energy problem has been plaguing the development of long-term unattended applications in wireless sensor networks. Nodes in WSN are generally energized by a battery whose energy is very limited. That the number of Nodes is very large and the distributed environment is very complex make it extremely difficult to replace or charge the battery. Therefore, energy consumption is a big issue in WSN. The study shows that most of the energy consumption of the sensor nodes is in idle listening phase[7]. Technology for the decrease of idle listening is mainly the duty cycle technology, which allows nodes alternately to be awake or asleep. While duty cycle technology greatly extends the life cycle of wireless sensor networks, it has brought new problems that is how do physical neighbour nodes, with such a low duty cycle, to achieve mutual logical discovery. Because the realization of low-energy working and neighbour discovery are mutually contradictory, one optimization often reduces another. A low duty cycled RF signal can achieve low power consumption but the transmission or reception delay will become high, and vice versa.

Conventional WSN neighbour discovery protocols cannot be applied to the low duty cycled wireless sensor networks. In this article, we review some researches on low duty cycled neighbour discovery protocol.

II. CONCEPT ANALYSIS

This section provides commonly used concepts in low duty cycled neighbour discovery protocols, including: time slot, discovery cycle, discovery latency, the worst-case discovery latency, duty cycle, symmetry, asymmetry.

Time slot, time is divided into intervals with equal size and each time interval is called a time slot. The concept of time slot reduces the difficulty of realizing the experiment and ensures that when the length of the time slot is greater than the total clock skew, it is possible to effectively overcome the impact of clock offset.

Discovery cycle, n time slots organize a discovery cycle. In a discovery cycle, nodes arrange their work status in accordance with a certain time slot schedules.

Discovery latency, the length of the time from the moment that two nodes within communication range of each other and start to work to the instant that they first discover each other.

The worst-case discovery latency, the longest latency of one node to discover all it's neighbourhood. It determines the minimum time that two nodes that within their communication range can discover each other.

Duty cycle, under duty cycle based WSN, nodes periodically alternate from working or sleeping status. The ratio between the duration of one node's working status and the total time length is called duty cycle. The smaller the duty cycle there is, the lower energy the node consumes.

Symmetry, the same scheduling of time slot sequence which represent the same duty cycle is called symmetry.

Asymmetry, the different scheduling of time slot sequence which represent the different duty cycle is called asymmetry.

III. NEIGHBOUR DISCOVERY PROTOCOLS IN LOW DUTY CYCLED WSN

In low duty-cycled wireless sensor networks, neighbour discovery protocols can be divided into two categories, one is random neighbour discovery protocols and the other is deterministic neighbour discovery protocols. Deterministic neighbour discovery protocols, based on their use of different mechanisms, can be divided into four categories: neighbour discovery based on the "more than half occupation", neighbour discovery based on quorum, neighbour discovery based on co-primes and neighbour discovery based on code. Classification results are shown in Fig. 1.

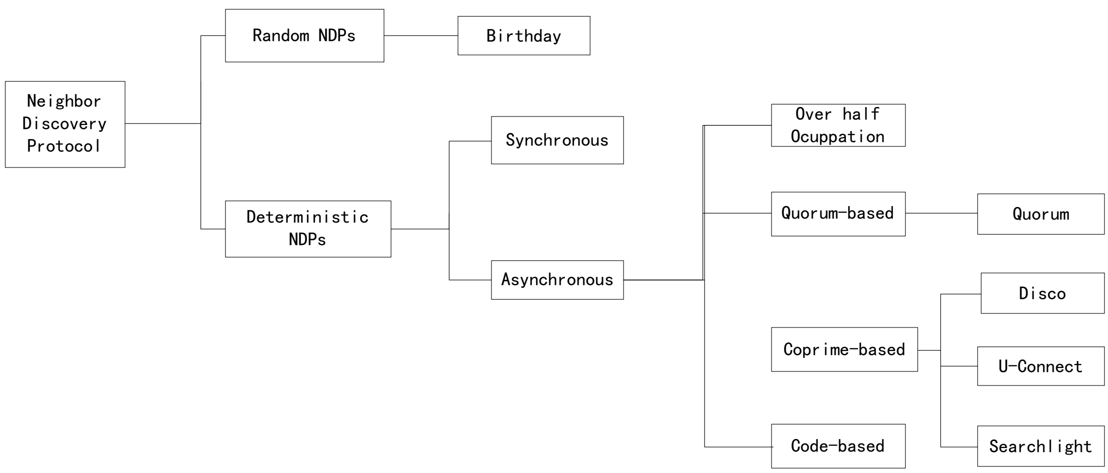

Fig. 2 classification of neighbour discovery protocols in low duty-cycled WSN

A. Random neighbour discovery protocols

While keeping the nodes from high consumption of energy, random neighbour discovery protocols commit to discovering neighbours with high probability.

Mcglynn and Borbash proposed "Birthday protocol" [8]for asynchronous neighbour discovery in static wireless sensor network. They consider a long time of nodes deployment process and problems of discovery after deployment. Nodes are set to three different states: listening, transmitting and idle. Each state corresponds to a possibility. They make use of the birthday paradox principle to choose a probability of the state for the current time slot which result in a high chance to discover neighbours in a consecutive time slots.

B. Deterministic neighbour discovery protocol

Deterministic neighbour discovery protocol can ensure neighbour discovery within a certain period of time.

1) *Neighbour discovery based on the "more than half occupation"[9]:* The most direct neighbour discovery protocol is to keep the node be awake during at least half of the time slots to ensure discovery in one time cycle. For example, for each period of time containing n time slots, the front $\lceil (n+1)/2 \rceil$ time slots are awake and the rest of the time slots are in a dormant state.

Two nodes in this mode, in the absence of time offset, will be able to ensure the realization of neighbour discovery. In addition, this approach ensures discovery within one time period which is very excellent from the perspective of discovery latency.

2) *Neighbour discovery based on quorum:* Tseng et al. [10]proposed a neighbour discovery protocol based on quorum within a multi-hop self-organized network. Time is allocated into a series of beacon intervals and m2 consecutive intervals form a group. M is a global variable which is the same in all nodes. These m2 time intervals are arranged as a 2-dimensional m x m array and each host can pick one row and one column of entries as awake intervals to transmit or receive signal frames. In every m2 time intervals, there are 2m-1 awake time slots. Because m is a global variable that all nodes share, it is a limit for quorum-based neighbour discovery protocols.

3) *Neighbour discovery based on co-primes:* Dutta and Culler proposed "Disco"[11] protocol for handling asynchronous neighbour discovery problem. According to the Chinese remainder theorem, node selects two prime numbers and the sum of their reciprocal is equal to the value of its duty cycle. Every node has a local counter and its value plus one when one time slot passes. When its value is a multiple of any of the selected prime numbers, the node keeps awake for a duration of one time slot. And the remaining slots keep dormant. The worst-case discovery latency is the product of two selected prime numbers. The author suggest that we should choose balanced prime numbers under symmetric condition (to meet duty cycle condition, the node choose two primes of the smallest difference), and we should choose unbalanced prime numbers under asymmetric condition (to meet duty cycle condition, the node choose two primes of the biggest difference).

U-Connect protocol[12] selects a prime number q as its basic working period, which is different from Disco who uses two prime numbers. It builds an array of q × q in T consecutive slots, and randomly select one column and half of a row, i.e. there is one awake slot every p time slots and (p+2)/2 awake slots every p^2 slots. U-connect protocol combines the Chinese remainder theorem and Quorum thinking.

Searchlight[13] explores another neighbour discovery protocol by leveraging constant offset between periodic awake slots. There are two awake slots in a cycle of t slots. The first one(index from 0) which is always awake is called anchor slot. The other awake slot, called the probe slot, traverses from position 1 to $\lfloor t/2 \rfloor$ across $\lfloor t/2 \rfloor$ cycles (i.e. a period).

4) *Neighbour discovery based on code:* Meng and Wu[14] proposed a model of time slot either. Because of the energy limitation, every node performs based on duty cycle. Every time slot is coded as binary 0 or 1.When node is awake, the time slot is coded as binary 1 and when node is dormant, the time slot is coded as binary 0.By this means, time slot is coded. On this basis, the author derives the optimal objective function and obtains its extremum, achieving the optimal energy efficient "coding" scheme, i.e. the corresponding time slot sequence.

IV. Analysis and comparison between neighbour discovery PROTOCOLS in low duty cycled wireless sensor networks

A. protocol analysis

In Birthday protocol, node transmit/receive or sleep at each time slot with different possibilities. Considering the probabilistic nature of this approach this scheme achieves good performance in the average case. And since there is no limit on the length of time slot, it is allowable for asymmetric operation. However, the main drawback of Birthday protocol is that it cannot provide a worst-case latency bound and lead to a long-tail effect which is the common shortage of random neighbour discovery protocols.

In quorum protocol, time is divided into m^2 consecutive slots, arranging as a $m \times m$ array. Each node picks one column and one row. This pattern of slot schedule ensures that no matter which row or column is chosen, any two nodes can have at least two time slots overlapped. Quorum-based protocols provide a reasonable bound for the worst-case discovery latency. But compared with random protocols, it performs worse in the average case. Because m is a global variable, the origin quorum protocol can only support symmetric duty cycle operation. Lai et al. gives an improvement for asymmetric duty cycle operation when there are two different schedules in the total network. But only two duty cycle scheme cannot meet the requirement of real environment.

Compared with quorum, prime-based schemes can support asymmetric neighbour discovery when they choose different prime pairs.

In Disco, node chooses a pair of primes and the sum of their reciprocal equals the target duty cycle. When the counter is a multiple of either prime, the node turns awake. This schedule provides a deterministic discovery latency which is better than Quorum and Birthday protocols in the asymmetric duty cycle case. However, there exists a key problem that we can select primes for symmetric case or primes for asymmetric case, but we cannot select primes that are suitable for both cases. If we choose the same unbalanced pair of primes for the nodes, the worst-case latency will be very large.

In U-Connect protocol, the author proposed “energy-latency” target used to evaluate the efficiency of asynchronous neighbour discovery. With theoretical analysis, we can see that U-Connect is a 1.5-approximation protocol while Quorum and Disco are both 2-approximation protocol. U-Connect protocol performs better than Disco and Quorum in the symmetric duty cycle case.

Though these deterministic neighbour discovery protocols have good performance in the worst-case latency and co-prime based protocols improve the latency boundary, they perform worse than Birthday protocol in the average case.

By adopting a systematic approach that has both deterministic and probabilistic components, Searchlight achieves average-case performance comparable to the probabilistic protocols and significantly improves worst-case bound for symmetric operation in comparison to the above deterministic protocols.

In code-based protocol, the author build a difference set coding in the symmetric duty cycle and build a difference set coding in the asymmetric duty cycle case. They both take advantage of the non-aligned awake time slot and derive a smaller latency boundary. It reduces 50% latency boundary in symmetric case and it reduces 30% latency boundary in asymmetric case.

B. Performance comparison

One of the most important targets in neighbour discovery protocols is to ensure that for a given time limit L, any two nodes can discover each other within one-hop communication range. Different algorithms pay differently for these targets. One of the costs is the energy consumption. And this merit is mainly evaluated by the smallest duty cycle. Obviously, to achieve the same worst-case duty cycle, the smaller duty cycle there is, the higher performance there is.

1) *Best case*： The article[15] has a detailed theoretical discussion about the optimal condition for neighbour discovery algorithm. When the given time limitation is L = k2+k+1, the optimal condition for neighbour discovery is to choose k+1 awake time slots in L time intervals. But k is must a prime or a power of a prime. So for a given worst-case discovery latency, the node’s duty cycle is LDC = (k+1)/(k2+k+1) = $\left(\sqrt{L-3/4}+1/2\right)/L$.

2) *Quorum neighbour discovery protocol*: Quorum can ensure a discovery in the range of physical radiation in two consecutive period of T time slots under symmetric environment. The worst-case discovery latency L=T and the number of each row and column is m = $\sqrt{T}$.

The node status in Disco can be reflected as:

$$\psi_g(i,\mathrm{t}) = \begin{cases} 1, if\,[t]_{\sqrt{L}} = c\ or\ r \le \dfrac{[t]_L}{\sqrt{L}} < r+1 \\ 0,\ \ else \end{cases}$$

In the equation, $[\mathrm{t}]_{\sqrt{T}}$ means t mode $\sqrt{T}$.

For a given worst-case discovery latency L, the duty cycle in Quorum is $\mathrm{LDC}_g = \left(2\sqrt{L}-1\right)/L.$

3) *Disco neighbour discovery protocol*: In Disco, each node chooses two different primes p_1 and p^2 as its waking cycle, i.e. the node will be awake for one slot duration at every multiple of p_1 and p_2. Based on Chinese remainder theorem, the worst-case discovery latency S=$p_1 \times p_2$ in symmetric condition. The node status in Disco can be reflected as:

$$\psi_d(i,t) = \begin{cases} 1, if\,[t]_{p_1} = 0\ or\ [t]_{p_2} = 0 \\ 0,\ \ else \end{cases}$$

For a given worst-case discovery latency L, the duty cycle in Disco is:

$$\mathrm{LDC_{disco}} = \frac{1}{p_1 p_2}\sum_{i=0}^{p_1 p_2} \psi_d(i,\mathrm{t}) = \frac{p_1 - p_2 - 1}{p_1 p_2} \ge \frac{2\sqrt{p_1 p_2} - 1}{p_1 p_2} = \frac{2\sqrt{L}-1}{L}$$

4) U-Connect neighbour discovery protocol

For a given time limitation S=p_2, U-Connect choose the awake time slots based on two cycles. The first cycle is to wake for one slot every p slots and the second cycle is to wake up for p/2 consecutive slots after the schedule of the first cycle. Every two nodes in T=p x p time slots must be able to discover each other in the symmetric wireless sensor network. Let L be the worst-case discovery latency. L=T and p= $\sqrt{T}$ and the node status in U-Connect can be reflected as:

$$\psi_u(i,\mathrm{t}) = \begin{cases} 1, if\,[t]_p = 0\ or\ 0 \le [t]_{p^2} < (p+1)/2 \\ 0,\ \ else \end{cases}$$

For a given worst-case discovery latency L, the duty cycle in U-Connect is:

$$\mathrm{LDC}_u = \frac{1}{p^2}\sum_{i=0}^{p^2-1} \psi_u(i,t) = \frac{\frac{p}{2}+p}{p^2} = \frac{3p}{2p^2} = \frac{3\sqrt{L}}{2L}$$

5) Code-based neighbour discovery protocol

In this protocol, the length of coding is limited to n and the time slot offset is δ. The duty cycle of this protocol is:

$$\mathrm{LDC}_u = (1+\delta)\frac{1}{\sqrt{2L}}$$

It can achieve high energy efficiency and reduce the latency of neighbour discovery obviously.

C. Improvement direction of neighbour discovery protocols in low duty cycled wireless sensor networks

Neighbour discovery protocols in low duty cycled wireless sensor networks have four basic requirements. First, distribution. While centralized services can provide much of the support, but it must be limited in the connection between nodes and central server and it will bring big discovery latency and energy consumption. Second, asynchronous. The need to synchronize between nodes, like GPS, may introduce high energy consumption and reduce the lifetime of battery. Third, deterministic. Random methods may lead to random length of discovery latency. In this case, a node may lose the chance to interact with other neighbour nodes. Fourth, symmetric and asymmetric duty cycle. Different nodes may have different tasks and remain with different battery life, so they choose different duty cycles in the discovery process. Therefore, nodes must rely on distributed asynchronous neighbour discovery method and each node ought to have independent deterministic active-sleep pattern.

After the above analysis, to meet the four requirements is a prerequisite for real applications. Currently, neighbour discovery protocol proposed for WSN is not mature. Though these protocols can achieve good performance in theoretical analysis, they need adjustment in real deployment because of a series of factors, for example, the node density of the deployment region, the size of time slot, whether the node is moving or not.

Therefore, that how to build a more robust neighbour discovery protocol in the real environment should get more attention. To study the NDPs together with actual platform has a greater significance.

V. CONCLUSION

Neighbour discovery protocol is an important part of a wireless sensor network research. In this paper, we introduce different classification of representative NDPs in accordance with different mechanisms. By analyzing the wireless sensor network neighbour discovery research status and application of the agreement, the current neighbour discovery protocols in WSN is deficient in practical applications where should be improved greatly.

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