行政院國家科學委員會補助專題研究計畫 □ 成果報告 ■期中進度報告

ZigBee 無線樹狀感測網路之初始化及通訊問題研究

計畫類別：■ 個別型計畫　　□ 整合型計畫
計畫編號：NSC 97－2221－E－009－142－MY3
執行期間： 2008 年 08 月 01 日　至　2009 年 07 月 31 日

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計畫參與人員：

成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

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中　華　民　國　98　年　06　月　27　日

中英文摘要

無線感測網路相關的研究議題得到許多研究單位及學者的關注，近年來ZigBee通訊協定被視為最適用於感測網路的通訊協定，本計畫將研究以ZigBee 樹狀網路為基礎之無線感測網路相關通訊協定，本計畫為三年之計畫，其目標主要包含三個面向：(1) ZigBee無線感測網路生成之研究，(2) ZigBee樹狀網路資料傳遞排程，(3) ZigBee基礎之長鏈狀網路研究。在第一年中，我們研究ZigBee感測網路的生成問題，在ZigBee規範中，一個節點加入到一個網路的條件為：該節點能找到一個父節點能夠給予該節點一ZigBee 網路位址，父節點們可利用ZigBee 所定義之分散式位址分配法來指定位址給子節點們，這一個位址指定方法相當簡單但是卻限制了一個節點最多可容忍之子節點個數以及整體網路的深度，我們觀察到如果使用ZigBee所定義之網路生成方式，會使得網路位址的使用率偏低，進而造成節點無法連上網路，因此在本計畫中，我們提出適用於ZigBee之網路生成方法，使得網路上的節點能夠自動組態並且形成一個可通訊之網路，並且提升網路位址使用率，降低網路中Orphan的數目。

關鍵字：圖形理論、IEEE 802.15.4、網路形成、孤兒問題、無線感測器網路、ZigBee

Recently, a lot of research works have been dedicated to the *wireless sensor networks (WSNs)* field. ZigBee is a communication standard which is considered to be suitable for WSNs. In this project, we discuss initialization and communication protocols for ZigBee tree-based WSNs. This project contains three research topics including 1) formation of a ZigBee-based WSN, 2) scheduling for ZigBee tree-based networks considering data flows, and 3) ZigBee-based long thin networks. In the first year, we discuss the ZigBee network formation problem. In ZigBee, a device is said to join a network if it can obtain a network address from a parent device. Devices calculate addresses for their child devices by a distributed address assignment scheme. This assignment is easy to implement, but it restricts the number of children of a device and the depth of the network. We observe that if one uses the random formation policy specified in ZigBee, the utilization of the address pool may be very low. Those devices that cannot receive network addresses will be isolated from the network and become orphan nodes. In this project, we propose network formation strategies to relieve the orphan problem.

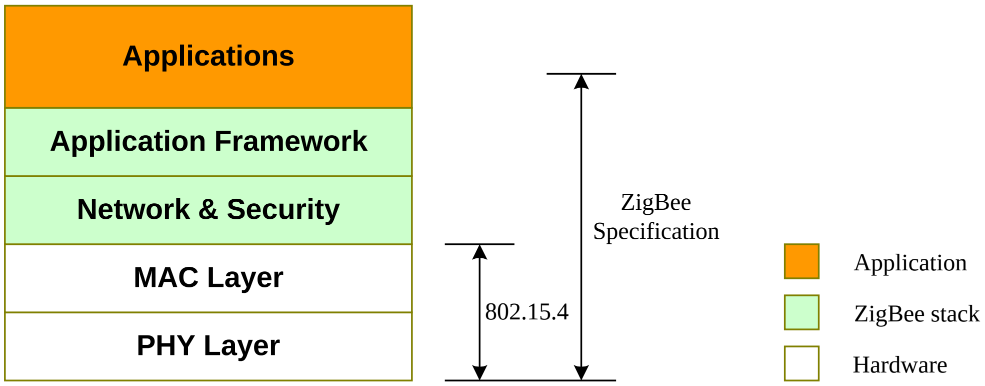
Keywords: graph theory, IEEE 802.15.4, network formation, orphan problem, wireless sensor network, ZigBee.

目錄

一、 前言

無線感測器網路 (wireless sensor network) 近年來被廣泛熱烈的討論，相關之研究議題包含許多方面，舉例來說，省電之MAC 協定 [1][2]、感測器之佈建議題 [3][4]、感測器覆蓋範圍 [5]、定位系統 [6] ...等等。而在應用層面，國內外均有許多研究成果，舉例來說，動物棲息地之生態監控 [7]，而 FirgBug 計畫 [8] 則是監控野外火災之發生，在 [9][10]，則是將無線感測器應用於導覽之方向。

近年來有相當多的無線感測網路平台被提出，例如：MICA [11]、Dust Network [12] 等，然而為了在不同的系統平台間相互傳遞資料封包，一個共通的通訊協定是必要的。在眾多無線接取協定中，ZigBee/IEEE 802.15.4 [13][14] 為一個專為無線感測網路所設計的通訊協定。IEEE 802.15 工作群組 (Working Group) 的第四任務群組 (Task Group 4, IEEE 802.15.4) 訂定一「低資料速率—無線個人區域網路 (Low Rate-Wireless Personal Area Network; LR-WPAN)」。該工作群組於 2000 年 12 月被批准成立，並且於 2003 年 10 月正式被 IEEE 批准而成為整個 IEEE 802.15.4 的標準。而適用於短距低速 率傳輸應用的通訊協定堆疊之上層部分，從網路層、應用程式界面 (Application Program Interface, API) 到應用層 (包含應用計畫檔 (Profile)) 部分則由 ZigBee 聯盟訂定標準，ZigBee 聯盟和 IEEE 共同研究合作將產生一個易於使用且標準化的無線網路平台，以適於無線監測和控制方面的應用。ZigBee 聯盟在 2006 年底公布第二版標準。下圖一為 ZigBee 與 IEEE 802.15.4 通訊協定堆疊之關係圖。



圖一、ZigBee/IEEE 802.15.4 協定堆疊

二、 背景知識

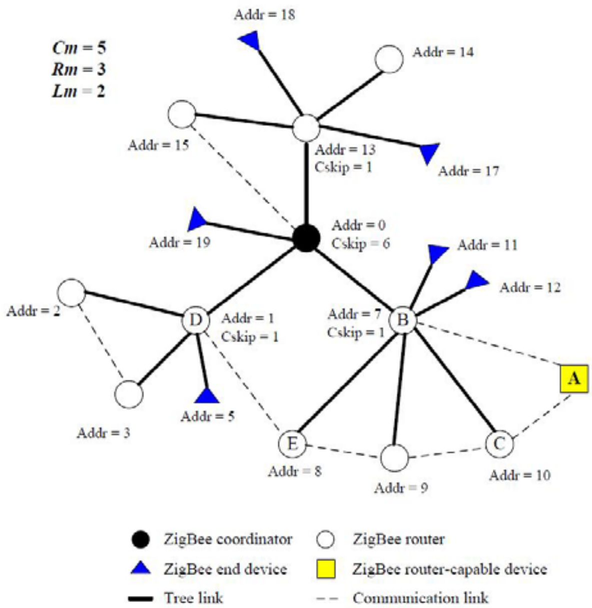
ZigBee 網路層協定中規範了一分散式網路位址分配演算法用以分配網路位址給加入該網路之裝置。當網路形成時，ZigBee 協調者先定義一 ZigBee 路由器最多可容許連線之裝置個數(Cm)以及最多的子 ZigBee 路由器的數量(Rm)，以及網路的深度(Lm)。ZigBee 規定 $Cm \geqq Rm$，因此一 ZigBee 路由器至少可供(Cm-Rm) ZigBee 終端設備連結上它。在此規範中，

裝置的網路位址是由其父節點 (Parent router) 所給定的。對 ZigBee 協調者而言，整個網路的位址空間被劃分成 Rm+1 塊，前 Rm 塊位址空間將會分配給其 Rm 個子路由器，而最後一部份則保留給與之連線之(Cm-Rm)個 ZigBee 終端設備。在此演算法中，ZigBee 路由器利用 Cm、Rm 和 Lm 來計算一個稱為 $Cskip$ 的參數，接著再利用 $Cskip$ 來計算其子路由器以及終

$$Cskip(d)=\begin{cases}1+Cm\cdot(Lm-d-1), & \text{if } Rm=1 \quad \text{(a)}\\ \dfrac{1+Cm-Rm-Cm\cdot Rm^{Lm-d-1}}{1-Rm}, & \text{Otherwise} \quad \text{(b)}\end{cases}$$

端設備的網路位址，假定一路由器位於網路的第 d 層，$Cskip$ 的數值可經由下式得到：

ZigBee 規範協調者位於深度 0，假設一路由器 x 位於深度 d 且一節點 y 為 x 的小孩，$Cskip(d)$ 則代表以 y 為根(Root)之 subtree (包括 y 自己)的最多可容納節點個數。位址的分配是由 ZigBee 協調者開始以及，ZigBee 協調者會先將自己的位址指定為 0 以及深度指定為 0，假設一個在深度 d 的父節點的位址已被指定為 $Aparent$，該父節點將指定他的第 n 個子路由器的位址為 $Aparent+(n-1)\times Cskip(d)+1$，並且指定他的第 n 個子終端設備的位址為 $Aparent+Rm\times Cskip(d)+n$。圖二中展示了一個位址分配的範例，在這範例中 ZigBee 協調者設定 Cm=5、Rm=3 以及 Lm=2，協調者的 $Cskip$ 值可由上式得知為 6。因此協調者的第一個到第三個子路由器的位址將分別被指定為 0+(1-1)×6+1=1、0+(2-1)×6+1=7 及 0+(3-1)×6+1=13，而協調者的子終端設備的位址將別為 0+3×6+1=19。值得注意的是，在 ZigBee 中，最多的網路位址容量為 2^{16}=65536。



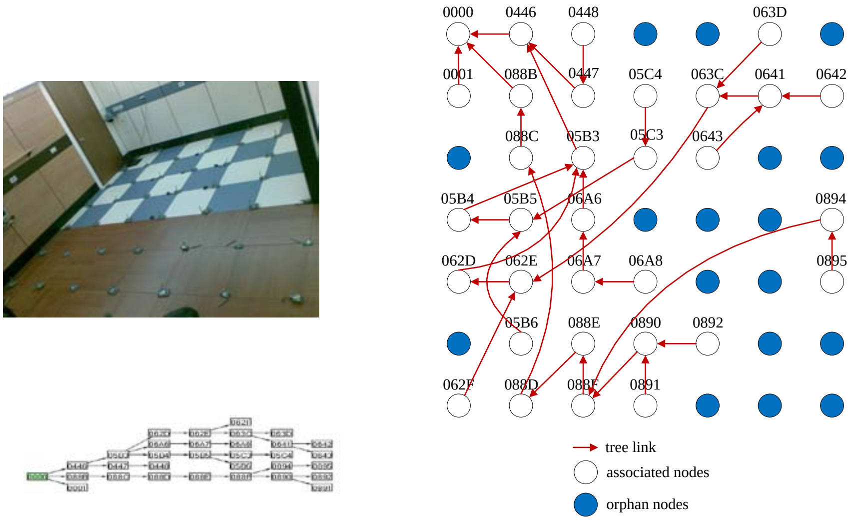
圖二、ZigBee 分散式位址分配範列

三、 研究目的

於 ZigBee 分散式位址分配演算法中，由於Cm、Rm 及Lm 的限制可以簡化網路位址分派的複雜度，但是這三個參數亦可能使得裝置無法加入此網路，即使還有父節點有剩餘的位址空間，甚至一個小型網路也有可能使得有孤兒節點(Orphan node)出現。舉例來說，

在圖二中，一個裝置A 有兩個可提供他連接之父節點 B 及 C，但是在圖二中，Router B 不能接受 A 因為它已經達到最大的容量(Cm=5)，而 Router C 也不能接受A，因為他的深度已經達到了最大深度(Lm=2)。由此我們可以得知裝置A 變成了一孤兒節點 (Orphan node)。

同時我們於 Jennic 平台上實作出 ZigBee 網路，使可進一步了解 Orphan 問題之嚴重性。如圖三所示，我們於一 360 cm x 360cm 之地板上，佈建 49 個 Jennic 感測器，每個感測節點天線傳輸功率為150 mW，於實測的過程中，我們不斷的改變(Rm, Lm)之數值，來觀察其Orphan數量的變化。由表格一可以清楚的發現，不管(Rm, Lm)如何的變化，於ZigBee形成的網路中，大約會存在有 30% ~ 70% 的Orphans，如表格一所示。而由此觀察也可發現，雖然較大之 Lm 可減少孤兒數量，但卻會導至更大的傳輸延遲時間。



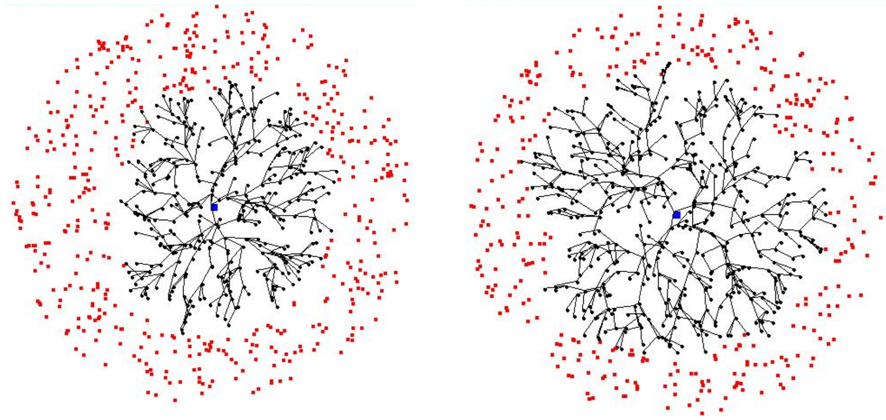
圖三、於Jennic平台上，ZigBee網路形成之實作

(Rm, Lm)	Orphans	Orphan Ratio	Delay
(6, 2)	35	71.4%	0.360 s
(5, 3)	31.4	64.1%	0.447 s
(4, 4)	30	61.2%	0.597 s
(3, 5)	21.2	43.3%	0.681 s
(2. 6)	27.8	56.7%	0.8125 s
(3, 7)	17.2	35.1%	0.991 s
(2, 8)	20.8	42.4%	1.197 s

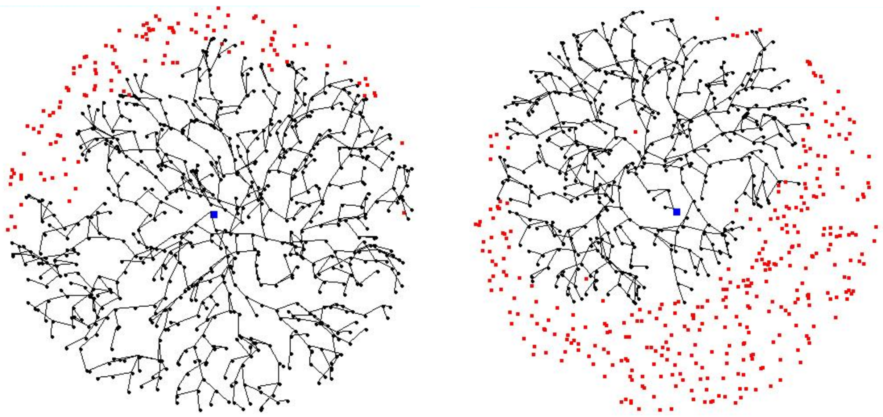
表格一、不同 (Rm, Lm) 之組合所造成之孤兒數及傳輸延遲時間

接著我們做了一個大型網路的實驗，如圖四所示，在這實驗中我們假設一個圓形網路，且其範圍半徑為 200 公尺，在這網路中任意的散佈 800 個 Router-capable 節點，而這些節點的傳輸半徑為 35 公尺，我們假設(Rm, Lm) = (4, 7), (3, 9), 以及(2, 15)，且 Rm = Cm，網路協調者被安排在網路的中心處，透過模擬我們得知如果使用 ZigBee 規範之網路生成方法，因為 圖四(b) 之 Lm 為 9 而 圖四(a) 之 Lm 為 7，所以圖四(a) 會造成較多之 orphan 數，但在圖的邊緣處，仍然有大量的網路節點無法正常的連上網路。利過圖四(c) Lm = 15，

可以發覺其 orphan 數大大的降低了，然而，在相同的參數設定下，圖四(d)卻造成了大量的網路節點形成孤兒，無法正常的連上網路，因此得知較大之 Lm 會造成較小之 Rm，因而可能反而會造成更多的節點無法連上網路，所以，透過簡單的參數調整，並無法解法 ZigBee 網路中所存在的 orphan problem。



(a) (b)



(c) (d)

圖四、ZigBee 網路形成大型網路的實驗，其中 (Rm, Lm) 分別為 (a) (4, 7), (b) (3, 9), 及 (c-d) (2, 15)。

同時，我們發現，一個較佳的網路生成方式可以改進上述之孤兒問題，以圖二為例，如果Router E變更連結至Router D，如此 Router B 變空出了一個空間可以給裝置 A 來連結上。因此在此計畫研究內容中，我們將考量 *Cm*、*Rm*、及 *Lm* 之限制，並且提出適用於 ZigBee 網路之網路生成演算法來改進孤兒問題。

四、 研究方法

ZigBee 網路生成問題定義

給予一個 ZigBee 網路，裡頭包含許多具 Router 能力的裝置(Router-capable device)以及許多終端節點(end device)，基於認為 Router-capable 裝置的能力較佳以及成本較高，我們將優先考慮讓 Router-capable 裝置可以連上網路，因此我們將 ZigBee 網路生成問題切割為兩個子題。在第一個子題中，我們只考慮 Router-capable 裝置，並且將這些點表示為一

個圖 *Gr*=(*Vr*, *Er*)，其中 *Vr* 為所有 Router-capable 裝置之集合，而 *Er* 為所有 *Vr* 中的無線連線，在給定 *Cm*、*Rm* 及 *Lm* 的條件下，第一個子題的目標為建構一棵樹來連接在 *Vr* 中的節點，並可以使得在 *Vr* 中所有的節點都能夠被連上所建構之樹上，而且該樹必須符合 ZigBee 對於樹狀結構廣度(*Rm*)及深度(*Lm*)之限制。

定義 給定一個圖 *Gr* = (*Vr*, *Er*), *Rm*, *Lm* 以及一個整個 *N*≦|*Vr*|，我們定義第一子題為：從 *Gr* 中建構一棵以協調者為根(Root)之樹*T*，此樹*T* 必須滿足 ZigBee 對於廣度及深度之限制 (Bounded-Degree-and-Depth Tree (BDDTF))且此樹必須至少包含N 個節點。

由文獻 [9] 中，我們可以知道分支度受限之展延樹(Degree-Constrained Spanning Tree)問題為一個困難之問題(NP-hard problem)，而且定義如下：

定義 給定一個圖 *Gc = (Vc, Ec),* 以及一個正整數 *Kc* ≦|*Vc*|, 則分支度受限之展延樹問題為能從 *Gc* 中找出一延展樹 *Tc*，使得在 *Tc* 中，沒有任一個 vertex 之分支度超過 *Kc*。

因此，本計畫定義了一個定理如下：

定理一 BDDTF 問題為一困難 (NP-Complete) 的問題。

接著我們定義第二子題，在第二子題中，我們將嘗試把所有終端設備連接到第一子題中所建構之樹中的Router 上，第二子題的目標為盡量使得網路上的終端設備盡量可以找到一個ZigBee 路由器來連接。為達到這一個目的，我們將這一個網路再次表示為一個圖 *Gd*=({*V'r*∪*Ve*}, *Ed*)，其中*V'r* 代表連接上第一個子題中所建構出之樹 *T* 的Router 們，*Ve* 代表所有終端設備，*Ed* 則表示所有*V'r* 與*Ve* 間的連線，每個屬於*V'r* 的節點*v* 可以接受 Cv≧(*Cm*-*Rm*)個終端設備，接著使用下列步驟將*Gd* 轉換成一個雙分圖(bipartite graph) *Gb*=({*V'br*∪*Vbe*}, *Ebd*)：

1. 對於每個屬於 *V'r* 的節點*v*，產生*Cv* 個節點*v1*, *v2*, …, *vCv* 於*V'br* 中。
2. 對於每個屬於 *Ve* 的節點*u*，產生一個節點*u* 於*Vbe* 中。
3. 對於每個在 *Ed* 中的連線(*v*, *u*)，其中*v*∈*V'r* 且*u*∈*Ve*，連接所有在rule 1 所產生的*Cv* 節點與在rule 2 中所產生的節點*u*，這些連線則形成*Ebd* 中的子集合。

在產生完 *Gb* 後，我們可以定義第二個子題如下

定義 給定一個圖 *Gb*，我們定義第二子題為：為找到中 *Gb* 最大的配對數(Maximum matching)。

ZigBee 網路生成問題之解決方案

在本計畫中，根據上面的分析與定義，我們將 ZigBee 網路中之 orphan problem 區分為

兩個子問題：分支度及深度受限之延展樹(bounded-degree-and-depth tree formation (BDDTF))問題及終端設備最大的配對數(end-device maximum matching(EDMM))問題。而於此兩個問題中，我們分別提出了集中式及分散式方法來降低 orphan 的數量。

BDDTF 集中式解決方案

對於第一個子題的解決方案概念為，我們先使用一個寬度優先的樹*T1* 來連結網路上的節點，接著我們在以由上到下(top-down)的方式來拜訪這樹上所有的節點，並且給予他們一個優先順序值(priority)，在給定完priority 後，我們將樹*T1* 給解散掉，然後在一句每個節點的優先順序重新建構一棵符合ZigBee 規範的樹*T*。給定*Rm* 及*Lm*，此方法的詳細步驟如下。

一、 將網路中所有的 Router-capable 裝置使用一個BFS 樹*T1* 連接起來

二、 接著我們由 *T1* 的根由上到下地來拜訪所有在*T1* 上的節點，當拜訪到一個位於深度*d* 的節點*v*，我們先計算節點*v* 的所有子孫節點個數，記錄為*D*(*v*)，以及與v 為同一層深度(*d*)與上一層深度(*d*-1)的鄰居節點個數，記錄為*N*(*v*)，接著我們給定節點*v* 一個優先順序值*p*(*v*)為

- 如果 *D*(*v*)不為零，則*p*(*v*)=*N*(*v*)/*D*(*v*)。
- 如果 *D*(*v*)等於零，則*p*(*v*)=*N*(*v*)

三、 解散 *T1*。

四、 接著我們以由上到下(top-down)之策略建構一個符合ZigBee 規範的樹*T*，其方式為，每一個已經連接上*T* 之節點*v*，可來找尋其鄰居中尚未連上*T* 的節點們，並且將那些節點依照其優先順序值由小到大來排序，節點*v* 接受至多排名*Rm* 小的節點們，並且指定他們為其子節點，以及他們的深度為*v* 的深度加一。這一個將節點連接上*T* 的動作將持續的進行直到達到最大深度*Lm* 或沒有節點可以連上為止。

BDDTF 分散式解決方案

由於集中式之解決方案通常需要大量的封包交換，以致於收集到足夠之資訊，通常不適用於無線感測器網路，因此，本計畫另設計一BDDTF分散式解決方案。本方法的精神為先執行一深度搜尋(depth-first search)後，再執行一寬度搜尋(breadth-first like search)。而深度搜尋之目的為建立出網路中最深、最長之骨幹(backbone)，並期望這此骨幹會通過網路中感測器密度最大之區域。接著再利用骨幹上之節點來執行寬度搜尋，來增進網路節點連接上網路之機率。此方法的詳細步驟如下。

1. (depth probing) 首先，ZigBee網路中之根(coordinator)會 flooding 一個 Probe 封包於整個網路中，並於 Probe 封包中記錄根之深度其為0，而每一個收到 Probe 封包之節點，會不斷地記錄此節點至根之最短路離，也就是最小之深度為何，並且記住自己的父親節點。
2. (probe response) 當執行完上述步驟後，每個節點會回報以自己為根之子樹之節點數量及子樹高度給節點之父親節點，同時，節點於自己的子節點中，選出一有最大深度之節點

為 tallest_child。

3. (backbone formation) 當整個網路之根節點收到所有子節點所回報之封包後，根節點會選擇出擁有最大高度之 Rm 個子節點為骨幹節點。因此，根節點會傳送 Backbone 封包來建立出整個 ZigBee 網路的骨幹，而當根之子節點收到此封包後，便會開始邀請自己的 tallest_child 加此骨幹，再藉由 tallest_child 進行進一步的邀請，完成骨幹的建立。
4. (BFS-like spanning) 當網路的骨幹形成後，網路之根節點便會開始廣播 beacon 封包來開始進行 association 的過程，而每個骨幹的節點收到 beacon 後，只能利用 association 程序來加入自己的父親節點，來形成網路。而網路中其他節點在進行 association 程序時，會告知自己的 association priority，而收到 association request 之節點便會依照此 priority 來邀請節點加入網路。

<u>EDMM 集中式解決方案</u>

如同本計畫用來定義 EDMM 問題之概念與方法，因此可知這是一個最大分配(maximum matching)的問題，因此，我們可以利用 maximum matching 演算法 [9] 來降低終端節點形成 orphan。而 maximum matching 演算法如下：

1. 首先，先利用貪婪式的方法，任意地尋找配對，也就是任意地將終端節點連至鄰居 Routers 中。
2. 利用深度搜尋法來找尋 alternating path，當找到 alternation path 後便可使多一個終端節點連上此網路，不斷的利用深度搜尋法，直到無法再找到 alternating path 時，便可找到 maximum matching。

<u>EDMM 分散式解決方案</u>

同樣地，因為集中式演算法不適用於無線感測器網路之中，因此，本研究另外提供了一個分散式演算法，而本研究所提供之方法類似於集中式演算法，先利用一貪婪式程序(greedy phase)，再利用探索式程序(probing phase)來找出更多的終端節點來加入網路。而此分散式配對演算法如下。

1. (greedy phase) 每一個 routing 會定期的廣播信標(beacon)封包來告知終端節點其是否仍可接受額外的子節點加入網路，因此每一個終端節點可記算出一 N 值來表示其有多少鄰居路由節點可以加入。而若 $N > 0$，則此終端節點便會試著發起結合(association)程序，而 Routers 簡單地接受擁有較小 N 值之終端節點加入。
2. (probing phase) 於貪婪程序結束後，每一個終端節點會重新計算其 N 值並廣播之，而每一個孤兒終端節點會發起一探索程序來減少孤兒數量，此程序如下。
   I. $N = 0$ 之孤兒終端節點會傳送一探索(Probe)封包給其任一鄰居路由節點 r。
   II. 當 r 收到探索封包時，若其存在一子終端節點 e’ 其 N ≧ 2，則 r 會轉送此探索封包給此節點 e’。
   III. 當 e’ 收到 r 之探索封包時，e’ 會試著結合上其他路由結點，若成功連上時，便傳送一 Probe_Ack 封包給 r，反之，則傳送一 Probe_Nack 給 r。
   IV. r 直接將 Probe_Ack 或 Probe_Nack 封包轉送給 e，而當 e 收到 Probe_Ack 時，便會連結上 r，反之，e 會尋找下一個鄰居節點，來發起探索程序。

五、 結果與討論

在本計畫中，探討 ZigBee 所設計之分散式位址分配演算法，由於 *Cm*、*Rm* 及 *Lm* 的限制可以簡化網路位址分派的複雜度，但是這三個參數亦可能使得裝置無法加入此網路，即使還有父節點有剩餘的位址空間，而造成了孤兒問題 (orphan problem)。同時，針對此問題，利用我們所提出的觀察，加上實測的結果，得知此問題並無法透過簡單的參數調整等方法來解決 orphan 的情形。因此，我們將此問題重新定義，並依照路由節點及終端節點兩種不同節點的特性，將此問題分成兩個子問題，分別為：分支度及深度受限之延展樹 (BDDTF) 問題及終端設備最大的配對數 (EDMM) 問題。同時，我們也證明了 BDDTF 為一個複雜的問題 (NP-Complete)，因為我們提供了一集中式的 BDDTF 演算法來降低孤兒之數量，而因應無感感測器硬體限制，也提供了一分散式演算法。而針對 EDMM 問題，本計畫證明了其為一最大分配 (maximum matching) 的問題，因此可以簡單的利用最大分配演算法來得到最佳解，也就是使得終端節點成為孤兒的情形最小。同樣地，我們也提供了一分散式的分配演算法，使得 ZigBee 網路可以利用較輕量 (lightweight) 的方式，使得網路位址可以最有效的應用，降低節點形成孤兒的機會。

- 赴國外出差或研習心得報告一份

所參與之研討會為「IEEE VTC 2009-Spring Conference」，其出國之報告書如附錄一

- 本計畫目前的研究成果為二篇論文如下：

附錄二：

M.-S. Pan, C.-H. Tsai, and Y.-C. Tseng, "The Orphan Problem in ZigBee Wireless Networks", IEEE Transactions on Mobile Computing, to appear. (SCI, EI).

附錄三：

M.-S. Pan and Y.-C. Tseng, “The Orphan Problem in ZigBee-based Wireless Sensor Networks”, ACM/IEEE Int'l Symp. on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2007.

- 計畫成果自評

第一年的主要工作目標有兩項：(1) ZigBee 網路生成之研究方法及問題定義，(2) 針對所定義之問題提出適切的解決方案。而在本計畫中，針對 ZigBee 網路生成問題，根據無線感測路由節點及終端節點不同之特性，將此生成問題分為 (1)滿足 ZigBee 對於廣度及深度之限制 (Bounded-Degree-and-Depth Tree (BDDTF))樹，及 (2) 最大的配對數問題。同時，我們提出了定理一來證明 BDDTF 為一個困難的問題，且證明了 EDMM 為一個最大配對數問題。

此外，分別針對 BDDTF 及 EDMM 問題，我們也分別提出了集中式及分散式演算法來解之，因此本研究可利用我們所提出之方法來降低 ZigBee 網路生成時，所造成的orphan數。

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附錄一

出國報告書

IEEE VTC 2009-Spring Conference

Barcelona, Spain, 2009/04/26~2009/04/29

出國報告書

撰寫時間： 2009 年 5 月 2 日

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出席國際會議名稱	IEEE VTC 2009-Spring Conference		
到達國家及地點	Barcelona, Spain (巴塞隆納，西班牙)		
出國期間	自 2009 年 4 月 26 日 迄 2009 年 4 月 29 日		

內容

議程為4/26 Workshop，4/27~29 Main Conference。本人參與該會議有以下三項任務：

1. 代表IEEE Vehicular Technology Society，台北分會成員列席Board of Government 會議。
2. 討論主辦VTC 2010-Spring在台北舉行之細 節。本會己經由台北分會爭取，並確定取得Board of Government同意在台北之舉辦權。本次出席之目的是和BoG討論舉辦之細節，以確定大會成功，並向本次與會人員宣傳明年台北舉辦之訊息。
3. 目前organizing committee訂定由吳靜雄教授和陳光禎教担任General Chairs，本人担任Vice General Chair。我們在大會晚宴中並向與會人員宣傳明年在台北舉辦之訊息

本會可謂一個極大型的國際會議，會中有來自多個國家，本人並藉此增廣見聞，同時吸收新知更，和同一領域之外國學者互相切磋討論。

附錄二

The Orphan Problem in ZigBee Wireless Networks

M.-S. Pan, C.-H. Tsai, and Y.-C. Tseng

IEEE Transactions on Mobile Computing, to appear. (SCI, EI).

The Orphan Problem in ZigBee Wireless Networks

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***Abstract*—ZigBee is a communication standard which is considered to be suitable for wireless sensor networks. In ZigBee, a device (with a permanent 64-bit MAC address) is said to join a network if it can successfully obtain a 16-bit network address from a parent device. Parent devices calculate addresses for their child devices by a distributed address assignment scheme. This assignment is easy to implement, but it restricts the number of children of a device and the depth of the network. We observe that the ZigBee address assignment policy is too conservative, thus usually making the utilization of the address pool poor. Those devices that can not receive network addresses will be isolated from the network and become *orphan* nodes. In this paper, we show that the *orphan problem* can be divided into two subproblems: the *bounded-degree-and-depth tree formation (BDDTF)* problem and the *end-device maximum matching (EDMM)* problem. We then propose algorithms to relieve the orphan problem. Our simulation results show that the proposed schemes can effectively reduce the number of orphan devices compared to the ZigBee strategy.**

***Index Terms*—graph theory, IEEE 802.15.4, network formation, orphan problem, wireless sensor network, ZigBee.**

I. INTRODUCTION

The recent progress of wireless communication and embedded micro-sensing MEMS technologies has made *wireless sensor networks (WSNs)* feasible. A lot of research works have been dedicated to this area, including energy-efficient MAC protocols [11][27], routing and transport protocols [8][13], self-organizing schemes [16][24], sensor deployment and coverage issues [14][22], and localization schemes [6][23]. Applications of WSNs include habitat monitoring [2], wildfire monitoring [1], mobile object tracking [21][25], and navigation [20][26].

Recently, several WSN platforms have been developed, such as MICA, MICAz, Imote2, TelosB [4], TI CC2431 [5], and Jennic JN5121 [3]. For interoperability purpose, most platforms have adopted ZigBee [29] as their communication protocols. ZigBee adopts IEEE 802.15.4 standard [15] as its physical and MAC protocols and solves the interoperability issues from the physical layer to the application layer.

ZigBee supports three kinds of network topologies, namely star, tree, and mesh networks. A *ZigBee coordinator* is responsible for initializing, maintaining, and controlling the network. In a star network, all devices have to directly connect to the coordinator. For tree and mesh networks, devices can communicate with each other in a multihop fashion. The network is formed by one ZigBee coordinator and multiple *ZigBee routers*. A device can join a network as an *end device* by associating with the coordinator or a router. Fig. 1 shows a ZigBee tree network.

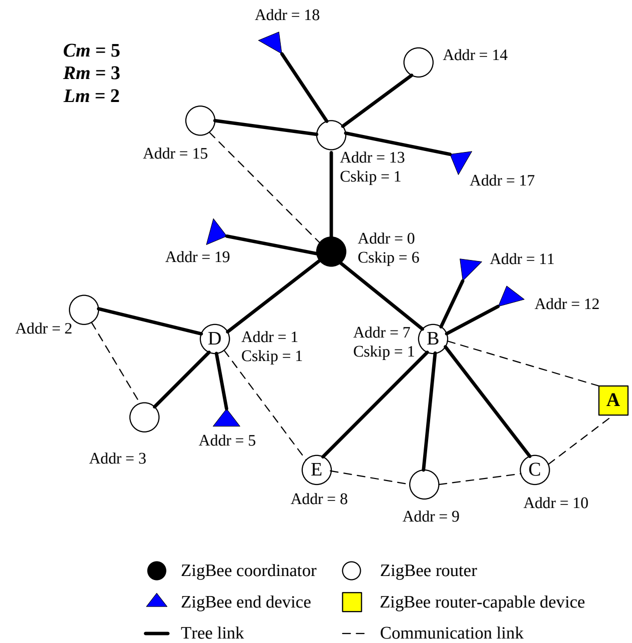

Fig. 1. An example ZigBee tree network.

In ZigBee, each node has a permanent 64-bit MAC address. A device is said to successfully join a network if it can obtain a 16-bit network address from the coordinator or a router. Using a short network address is for simplicity and for saving communication bandwidths. Before forming a network, the coordinator needs to decide three important system parameters: the maximum number of children of a router (Cm), the maximum number of child routers of a router (Rm), and the depth of the network (Lm). Note that a child of a router can be a router or an end device, so $Cm \geq Rm$. Given Cm, Rm and Lm, ZigBee has suggested a distributed address assignment scheme. While simple, the scheme may prohibit a node from accepting a child router/device as constrained by these parameters. We say that a node becomes an *orphan node* when it can not associate with any parent router but there are still unused address spaces remaining. We call this the *orphan problem*. For example, in Fig. 1, the router-capable device A has two potential parents B and C. Router B can not accept A as its child because it has reached its maximum capacity of $Cm = 5$ children. Router C can not accept A either because it has reached the maximum depth of $Lm = 2$. So A will become an orphan node. The orphan problem will worsen as

Manuscript received September 21, 2007; revised November 7, 2008.

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the network scares up. We will further support this claim in Section II-B through simulations and real experiments. The orphan problem can be relieved if proper actions are taken. For example, in Fig. 1, if router E is connected to router D, router B will have capacity to accept A.

Given Cm, Rm, and Lm, we show that the orphan problem can be divided into two subproblems: 1) connecting as many routers as possible to form a tree and 2) connecting as many end devices as possible to the above tree. The first subproblem involves the router-capable devices only and can be modeled as a *bounded-degree-and-depth tree formation (BDDTF)* problem. We prove that this subproblem is in fact NP-complete. The second subproblem needs to connect as many end devices to the above tree as possible constrained by router's capacities and can be modeled as an *end-device maximum matching (EDMM)* problem. We prove that the EDMM problem is computationally feasible and then exist an optimal algorithm to solve it. To summarize, our approach involves two stages. The first stage will try to relieve the BDDTF problem by connecting more routers. Based on the result, the second stage will be able to connect the largest number of end devices to the tree.

Several works have investigated the *bounded-degree spanning tree* problem. Reference [10] proposes polynomial-time graph algorithms when additional connectivity and maximum degree of a graph are given. However, the depth constraint is not considered. Reference [18] introduces an approximation algorithm, which can find a spanning tree with a maximum degree of $O(K+log|V|)$, where K is the degree constraint and V is the set of nodes in the graph. The result is not applicable to our case because it does not consider the depth constraint and the number of children of a node is not bounded. In [17], a polynomial time algorithm is proposed to construct a spanning tree with a bounded degree and a bounded diameter. However, this algorithm is designed for complete graphs, which is not the case in a ZigBee network. Also, these works are not tailored to ZigBee specifications. Some works have focused on address configuration. Reference [7] proposes a network address assignment scheme based on the address assignment rule for an n-dimensional hypercube. Interestingly, when the ZigBee network structure is close to an n-cube, this scheme can indeed reduce the waste of address space. However, in practice, a WSN is typically randomly deployed on a 2D plane, which is unlikely to be similar to a high-dimensional n-cube. In fact, the scheme still suffers from the compatibility issue when the n-cube is incomplete and the orphan problem may still exist. Besides, additional overhead will be incurred to ensure that no duplicate addresses are assigned to nodes. Reference [19] organizes a network into concentric tiers around the sink and does not employ unique per-node addressing. When transmitting, a node will randomly choose an identifier for one-hop routing. This scheme is address-light, but it is only suitable for reporting scenarios and can not support point-to-point routing. In [28], an adaptive block addressing scheme is introduced for network auto-configuration purpose. It takes into account the actual network topology and thus is fully topology-adaptive. However, because the size of the address pool allocated by the coordinator is depended on the topology, addition of new nodes can cause the whole network to conduct address update. Moreover, this scheme needs two phases to initialize its adaptive tree, which is different from the ZigBee association procedure and is thus not compatible with ZigBee.

The main contributions of this paper are threefold. First, this is the first work that points out the orphan problem in ZigBee wireless networks. Second, we show that the existence orphan is an inherent concern no matter how one sets the Cm, Rm, and Lm constraints. We verify this claim through different configurations and parameter settings. A larger Cm or Rm will impose more memory requirement on routers and packets, while a larger Lm will also induce longer network delays. Third, we connect the orphan problem to NP-complete and classical algorithms and then propose network formation heuristics that can effectively reduce the number of orphans with given Cm, Rm, and Lm.

The rest of this paper is organized as follows. Preliminaries are given in Section II. Section III and Section IV present our algorithms. Simulation results are given in Section V. Finally, Section VI concludes this paper.

II. PRELIMINARIES

A. Overview of IEEE 802.15.4 and ZigBee Standards

IEEE 802.15.4 [15] specifies the physical and data link protocols for *low-rate wireless personal area networks (LR-WPAN)*. In the physical layer, there are three frequency bands with 27 radio channels. Channel 0 ranges from 868.0 MHz to 868.6 MHz, which provides a data rate of 20 kbps. Channels 1 to 10 work from 902.0 MHz to 928.0 MHz and each channel provides a data rate of 40 kbps. Channels 11 to 26 are located from 2.4 GHz to 2.4835 GHz, each with a data rate of 250 kbps.

IEEE 802.15.4 devices are expected to have limited power, but need to operate for a longer period of time. Therefore, energy conservation is a critical issue. Devices are classified as *full function devices* (FFDs) and *reduced function devices* (RFDs). IEEE 802.15.4 supports star and peer-to-peer topologies. In each PAN, one device is designated as the *coordinator*, which is responsible for maintaining the network. A FFD has the capability of serving as a coordinator or associating with an existing coordinator/router and becoming a router. A RFD can only associate with a coordinator/router and can not have children.

According to ZigBee standard [29], a ZigBee network is formed by the following procedures. Devices that are coordinator-capable and do not currently join a network can be a candidate of a ZigBee coordinator. A device that desires to be a coordinator will scan all channels to find a suitable one. After selecting a channel, this device broadcasts a beacon containing a PAN identifier to initialize a PAN. A device that hears a beacon of an existing network can join this network by performing the association procedures and specifying its role, as a ZigBee router or an end device. If the device hears multiple beacons, it chooses the beacon sender with the smallest hop count to the coordinator. The beacon sender will determine whether to accept this device or not by considering its current capacity and its permitted association duration. If the device is successfully associated, the association response will contain a short 16-bit address for the request sender. This short address will be the network address for that device.

In ZigBee, network addresses are assigned to devices by a distributed address assignment scheme. The coordinator determines Cm, Rm, and Lm. The coordinator and each router can have at most Rm child routers and at least $Cm - Rm$ child end devices. Devices' addresses are assigned in a top-down manner. For the coordinator, the whole address space is logically partitioned into $Rm+1$ blocks. The first Rm blocks are to be assigned to the coordinator's child routers and the last block is reserved for the coordinator's own child end devices. From Cm, Rm, and Lm, each node computes a parameter called $Cskip$ to derive the starting addresses of its children's address pools. The $Cskip$ for the coordinator or a router in depth d is defined as:

$$Cskip(d) = \begin{cases} 1 + Cm \times (Lm - d - 1) & \text{if } Rm = 1 \\ \frac{1 + Cm - Rm - Cm Rm^{Lm-d-1}}{1 - Rm} & \text{otherwise.} \end{cases} \quad (1)$$

The coordinator is said to be at depth 0; a node which is a child of another node at depth d is said to be at depth $d+1$. Address assignment begins from the ZigBee coordinator by assigning address 0 to itself. If a parent node at depth d has an address A_{parent}, the n-th child router is assigned to address $A_{parent} + (n-1) \times Cskip(d) + 1$ and n-th child end device is assigned to address $A_{parent} + Rm \times Cskip(d) + n$. An example of the address assignment is shown in Fig. 1. The $Cskip$ of the coordinator is obtained from Eq. (1) by setting $d = 0$, $Cm = 5$, $Rm = 3$, and $Lm = 2$. Then the child routers of the coordinator will be assigned to addresses $0+(1-1)\times 6+1 = 1$, $0+(2-1)\times 6+1 = 7$, $0+(3-1)\times 6+1 = 13$, etc. The address of the only child end device of coordinator is $0+3\times 6+1 = 19$. Note that, in ZigBee, the maximum network address capacity is $2^{16} = 65536$. This restricts that the coordinator can not decide the Cm, Rm, and Lm arbitrarily.

B. The Orphan Problem

By the above rules, the coordinator and routers can accept more routers and devices if they still have capacities. However, when a node can not join the network because all its neighbors have run out of their address capacities, we say the node has become an orphan. This situation may be relieved if there are remaining address spaces in other places of the network. Fig. 1 is a small-scale orphan problem. Here, we present some real implementation results of the ZigBee network formation procedure based on Jennic JN5121 [3]. Fig. 2 shows a deployment of 49 routers on a $360\ cm \times 360\ cm$ grid area. The grid size is $60\ cm \times 60\ cm$. Nodes' transmission power is set to $150\ mW$, which can reach a transmission range around 100 to $200\ cm$. For each combination of (Rm, Lm), we conduct five experiments and observe the average number of orphans and the average end-to-end delay from the deepest node to the coordinator. Table I shows our experimental results. We can see that regardless of different (Rm, Lm) combinations, there always exist $30\% \sim 70\%$ orphans. Although a smaller Rm can lead to fewer orphans, it also results in longer end-to-end delay.

TABLE I
THE PERCENTAGES OF ORPHANS AND END-TO-END DELAYS UNDER DIFFERENT COMBINATIONS OF (Rm, Lm) IN THE TEST SCENARIO OF FIG. 2.

(Rm, Lm)	Orphans	Orphan Ratio	Delay
(6, 2)	35	71.4%	0.360s
(5, 3)	31.4	64.1%	0.447s
(4, 4)	30	61.2%	0.597s
(3, 5)	21.2	43.3%	0.681s
(2, 6)	27.8	56.7%	0.8125s
(3, 7)	17.2	35.1%	0.991s
(2, 8)	20.8	42.4%	1.197s

Since it is infeasible to conduct large-scale real tests, we also use simulations to make more observations. In Fig. 3, 800 nodes are randomly deployed on a circular field with a radius of $230\ m$. Nodes' transmission range is $25\ m$. To reduce orphans, given an Rm, we will set Lm to the maximum possible value. So we set (Rm, Lm) = (4, 7), (3, 9), and (2, 15) (these Lm values are the maximum possible ones for the given Rm) and $Cm = Rm$ (which means no end devices). In Fig. 3(a), since $Lm = 7$, the network cannot grow too deep, so a lot of nodes are left as orphans. In Fig. 3(b), since a larger $Lm = 9$ is used, there are much fewer orphans. However, there are still a lot of nodes at the edge unable to connect to the network. In Fig. 3(c), with a larger $Lm = 15$, orphans are significantly reduced. However, with the same setting, Fig. 3(d) shows a more extreme case where all neighboring nodes of one of the coordinator's children have been associated with other routers, making it a leaf node. This actually wastes a lot of address spaces. A smaller Rm may result in a non-shortest path from a router to the coordinator, thus causing a longer transmission delay and even more orphans if their routing path lengths exceed the constraint of Lm. In fact, assuming $Cm = Rm$, a router at depth d serving as a leaf implies a loss of $\frac{1-Rm^{Lm-d+1}}{1-Rm}$ address spaces. This is why a larger part of the network at the lower right side is unable to join the network. Note that this could happen because the ZigBee tree formation is asynchronous and nodes will compete to connect to nearby routers. These observations motivate us to design our schemes by trying to maintain sufficient children for nodes nearby the coordinator.

While both routers and end devices may become orphans, there capabilities are different. A router may accept more routers/devices, while an end device cannot. Further, their address calculation rules are also different as reviewed in Section II-A. For these reasons, we divide the orphan problem into two subproblems: BDDTF and EDMM problems. In the first BDDTF problem, we consider only router-capable devices and model the network by a graph $G_r = (V_r, E_r)$, where V_r consists of all router-capable devices and the coordinator t and E_r contains all symmetric communication links between nodes in V_r. Given parameters Cm, Rm, and Lm such that $Cm \geq Rm$, the goal is to assign parent-child relationships to nodes such that as many vertices in V_r can join the network as

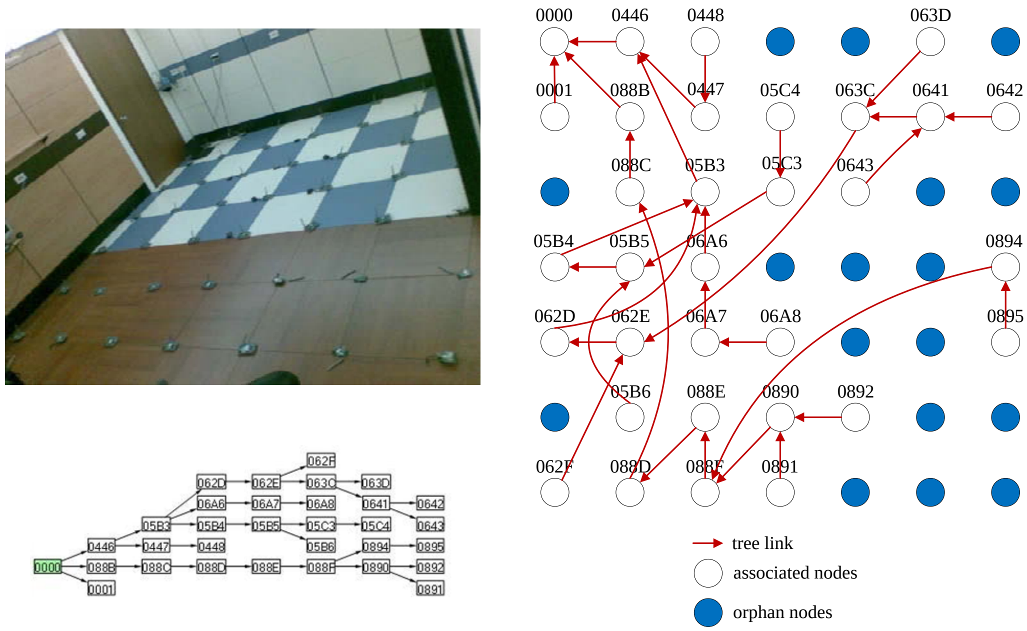


Fig. 2. A real-world ZigBee network formation example based on JN5121 in a 7x7 grid structure.

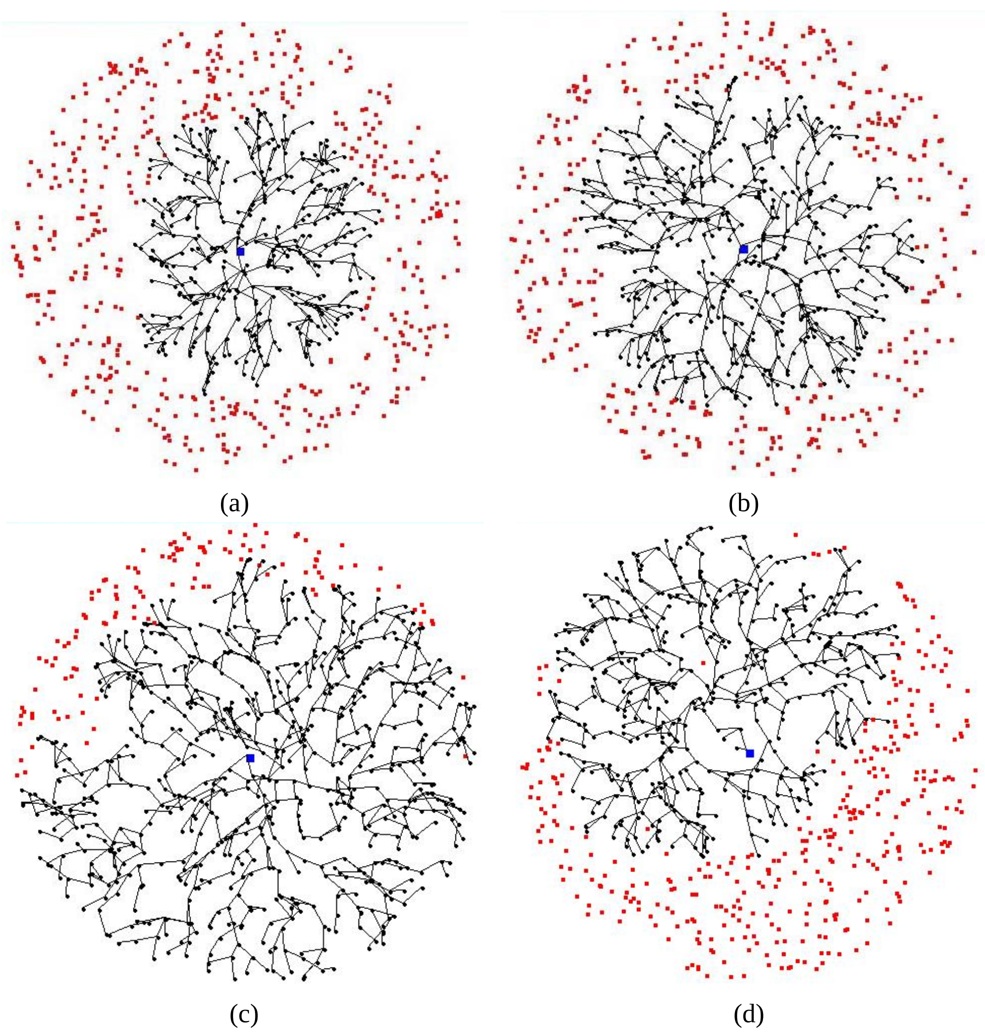


Fig. 3. ZigBee network formation examples with (Rm, Lm) equal to (a) (4, 7), (b) (3, 9), and (c-d) (2, 15). There are 461, 341, 120, and 351 orphan nodes, respectively.

possible. Below, we formulate this problem to a tree formation problem.

Definition 1: Given $G_r = (V_r, E_r)$, Rm, Lm, and an integer $N \leq |V_r|$, the *Bounded-Degree-and-Depth Tree Formation (BDDTF)* problem is to construct a tree T rooted at t from G_r such that T satisfies the ZigBee tree definition and T contains at least N nodes.

In [12], it is shown that the *Degree-Constrained Spanning Tree (DCST)* as defined below is NP-complete.

Definition 2: Given $G_c = (V_c, E_c)$ and a positive integer $K_c \leq |V_c|$, the *Degree-Constrained Spanning Tree (DCST)* problem is to find a spanning tree T_c from G_c such that no vertex in T_c has a degree larger than K_c.

Theorem 1: The BDDTF problem is NP-complete.

Proof: To prove that the BDDTF problem is NP-complete, we first show that the problem belongs to NP. Given a tree T in G_r, it is easy to check whether T satisfies the constraints of Rm and Lm and contains more than N nodes in polynomial time. Next, to prove that the BDDTF problem is NP-complete, we reduce the DCST problem to it. Let $G_c = (V_c, E_c)$ and integer K_c represent an arbitrary instance of the DCST problem. We can transform G_c to an instance of the BDDTF problem G_r by setting $V_r = V_c$, $E_r = E_c$, $N = |V_c|$, $Rm = K_c$, and $Lm \rightarrow \infty$ in polynomial time. We now claim that we can find a T_c for the DCST problem if and only if we can find a ZigBee-conformed tree T containing N nodes. To prove the *if* part, if there is a ZigBee-conformed tree T in G_r to connect $N = |V_c| = |V_r|$ nodes with parameters $Rm = K_c$ and $Lm \rightarrow \infty$, we can find a tree T_c in G_c to connect $N = |V_c|$ nodes as a spanning tree in G_c such that no vertex in T_c has a degree larger than K_c. Conversely, to prove the *only if* part, suppose that there is a spanning tree T_c to connect the nodes in G_c. Since $Rm = K_c$ and $Lm \rightarrow \infty$, there must exist a ZigBee-conformed tree $T = T_c$ in G_r containing $N = |V_c| \leq |V_r|$ nodes. So the theorem is proved. □

By Theorem 1, we can see that the first subproblem is intractable. Definition 1 and Theorem 1 imply the orphan problem is inevitable with any Rm and Lm. This also implies that there is no optimal decision for choosing Cm, Rm, and Lm to avoid the orphan problem.

After solving the BDDTF problem, we already have a tree T containing the coordinator and some routers. In the second EDMM subproblem, we will connect non-router-capable devices to the tree T constructed earlier following the ZigBee definition such that as many end devices are connected to T as possible. Toward this goal, we model the network by a bipartite graph $G_d = (\{\hat{V}_r \cup V_e\}, E_d)$, where $\hat{V}_r$ consists of the coordinator and all routers in T, excluding those at depth Lm (note that those at depth Lm are unable to accept more children), V_e consists of all end devices, and E_d contains all symmetric communication links between $\hat{V}_r$ and V_e. Each vertex $v \in \hat{V}_r$ can accept at most $C_v \geq (Cm - Rm)$ end devices. From G_d, we construct another bipartite graph $\tilde{G}_d = (\{\tilde{V}_r \cup \tilde{V}_e\}, \tilde{E}_d)$ as follows.

1) From each vertex $v \in \hat{V}_r$, generate C_v vertices v_1, v_2, ..., v_{C_v} in $\tilde{V}_r$.
2) From each vertex $u \in V_e$, generate a vertex u in $\tilde{V}_e$.
3) From each edge (v, u) in E_d, where $v \in \hat{V}_r$ and $u \in V_e$, connect each of the C_v vertices v_1, v_2, ..., v_{C_v} generated in rule 1 with the vertex u generated in rule 2. These edges form the set $\tilde{E}_d$.

Intuitively, we duplicate each $v \in \hat{V}_r$ into C_v vertices, and each edge $(v, u) \in E_d$ into C_v edges. These C_v vertices and C_v edges reflect the capability of router v to accept end devices. It is clear that $\tilde{G}_d$ is a bipartite graph with edges connecting vertices in $\tilde{V}_r$ and vertices in $\tilde{V}_e$ only. Since each vertex in $\tilde{V}_r$ is connected to at most one vertex in $\tilde{V}_e$, this translates the problem to a maximum matching problem as follows.

Definition 3: Given a graph $\tilde{G}_d = (\{\tilde{V}_r \cup \tilde{V}_e\}, \tilde{E}_d)$, the *End-Device Maximum Matching (EDMM)* problem is to find a maximum matching of $\tilde{G}_d$.

Given router tree T, the maximum matching problem in Definition 3 can be solvable in polynomial time [9]. Note that even with maximum matching, it does not guarantee that all end devices will be connected, so orphan end devices may still exist after solving the second subproblem. Below, we will propose several schemes for these two subproblems.

III. Algorithms for the BDDTF Problem

We propose two algorithms for the BDDTF problem. In our algorithms, we will repeatedly generate several BFS trees from G_r. For each tree being generated, we may decide to truncate some nodes if the tree is not conformed to the ZigBee definition. The truncation is done based on nodes' *association priorities* in the tree. Below, we show how such priorities are defined, given a BFS tree T in G_r:

- A node x has a higher priority than another node y if the subtree rooted at x in T has more nodes than the subtree rooted at y.
- If the subtrees rooted at nodes x and y have the same number of nodes, the one with less *potential parents* has a higher priority. A node regards a neighbor as a potential parent if this neighbor has a smaller hop count distance to the root in T than itself.

The above definitions are based on the considerations of address space utilization. The first rule is so defined because node x may have a better utilization. The second rule is so defined because a node with less potential parents is more likely to encounter difficulty when trying to attach to the network. For example, in Fig. 4, if $Rm = 3$, the coordinator will choose nodes A, B, and C as its child routers since they have larger subtrees. Similarly, B will choose D, E, and F as its child routers. However, if $Rm = 2$, the coordinator will choose A and B as its child routers. Further, B will choose D and E as its child routers. Node F is not selected because it has more (two) potential parents and thus has a higher probability to be connected in later stages of the formation.

A. Centralized Span-and-Prune Algorithm

Given a graph $G_r = (V_r, E_r)$, our goal is to find a tree $T = (V_T, E_T)$ from G_r conforming to the ZigBee tree definition.

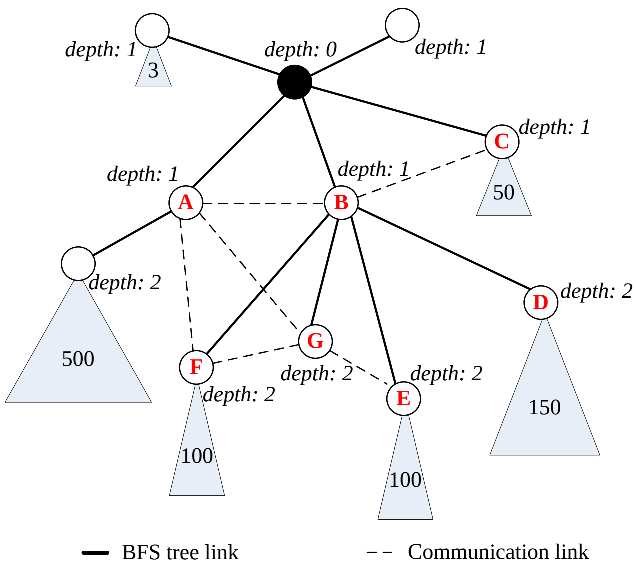


Fig. 4. Examples of priority assignment in our algorithm. (The numbers in triangles indicate sizes of the corresponding subtrees.)

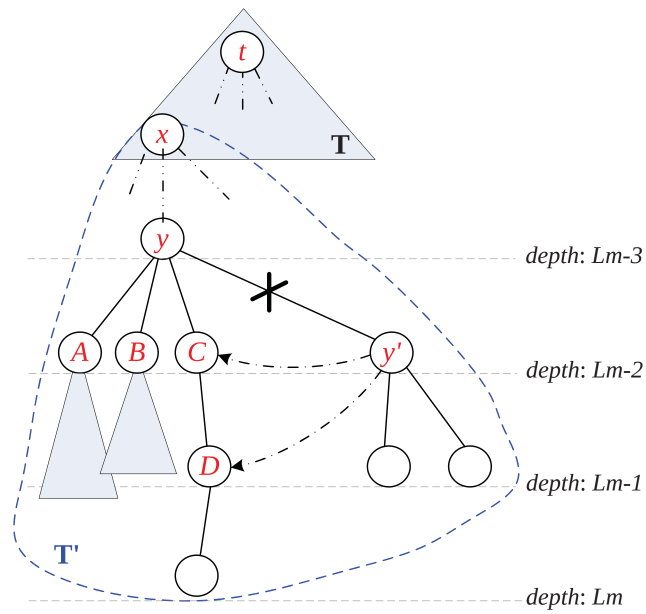


Fig. 5. An example of the Span-and-Prune algorithm.

The algorithm consists of a sequence of iterations. Initially, T contains only the coordinator t. Then in each iteration, there are two phases: *Span* and *Prune*. In the Span phase, we will pick a node in T, say x, and span from x a subtree T' to include as many nodes not yet in T as possible. Then we attach T' to T to form a larger tree. However, the new tree may not satisfy the ZigBee definition. So in the Prune phase, some of the newly added nodes in T' may be trimmed. The resulting tree is then passed to the next iteration for another Span and Prune phases. This is repeated until no more nodes can be added. Each node in the network will be spanned at most once. To keep track of the nodes yet to be spanned, a queue Q will be maintained. The algorithm is presented below.

1) Initially, let queue Q contains only one node t. Let the depth of t to zero. Also, let the initial tree $T = (\{t\}, \emptyset)$.
2) (*Span Phase*) Check if Q is empty. If so, the algorithm is terminated and T is the final ZigBee tree. Otherwise, let $x = \textit{dequeue}(Q)$ and construct a spanning tree T' from x as follows. Assuming the depth of x in T to be $\textit{depth}(x)$, we try to span a subtree from x with height not exceeding $Lm - \textit{depth}(x)$ in G_r in a breadth-first manner by including as many nodes in $V_r - V_T \cup \{x\}$ as possible. Let the resulting tree be T'.
3) (*Prune Phase*) Attach T' to T by joining node x. Still, name the new tree T. Since some of the nodes in T' may violate the Rm parameter, we traverse nodes in T' from x in a breadth-first manner to trim T.
   a) When visiting a node, say y, set y as "traversed" and check the number of children of y. If y has more than Rm children, we will compute their priorities based on T' (refer to the definitions of nodes' priorities in a tree given in the beginning of this section). Only the Rm highest prioritized children will remain in T, and the other children will be pruned from T.
   b) When each node, say y', that is pruned in step 3(a) or 3(b), let $\textit{tree}(y')$ be the pruned subtree rooted at y'. Since $\textit{tree}(y')$ is pruned, we will try to attach y' to another node n in T' if n satisfies the following conditions: 1) n is neighboring to y' but not a descendant of y', 2) n is not traversed yet, and 3) $\textit{depth}(n) + 1 + \textit{height}(\textit{tree}(y')) \leq Lm$. If so, we will connect the subtree $\textit{tree}(y')$ to node n. If there are multiple such candidates, the one with a lower depth is connected first. If no such node n can be found, y prunes all its children. Then for each pruned child, we recursively perform this step 3(b) to try to reconnect it to T'. This is repeated until no further reconnection is possible.
4) After the above pruning, call the resulting tree T. For nodes that are newly added into T in step 3, insert them into queue Q in such a way that nodes with lower depth values are inserted first (these nodes will go through Span and Prune phases again). Then, go back to step 2.

To summarize, step 3(a) is to prune those nodes violating the Rm constraint. In order to allow more vertices to join the network, step 3(b) tries to recursively reconnect those pruned subtrees to T'. Step 4 prepares newly joining nodes in Q for possible spanning in step 2.

Fig. 5 illustrates an example. When being traversed, y decides to prune y' and keep A, B, and C as children. Step 3(b) will try to reconnect y' to C or D, which are the neighbors of y' in T' and are not traversed. In this example, only C can be considered because connecting to D violates the depth constraint Lm.

The computational complexity of this algorithm is analyzed as follows. The iteration from step 2 to step 4 will be executed at most $|V_r|$ times. In each iteration, the complexity of constructing the tree T' in step 2 is $O(N^2)$, where $N = |V_r| - |V_T|$ is the number of nodes still not connected to T. Step 3 checks all nodes in T' and will be executed at most $O(N)$ times. For a run in Step 3 (assume visiting node y), the cost contains: 1) In step 3(a), y can use a linear search method to find Rm highest prioritized children and the computational cost is $O(D)$, where D is the degree of G_r. 2) Since the subtree size of y is at most $O(N)$ and a pruned node checks at most $O(D)$ neighbors to find its new parent, the cost of step 3(b) in a run is $O(ND)$. So, in one iteration, the time complexity of step 3 will be $O(N(D + ND)) = O(N^2D)$. Step 4 sorts new nodes of T according to their depth values, so the time complexity is $O(N^2)$. The complexity in each iteration is $O(N^2 + N^2D + N^2) = O(N^2D) = O(|V_r|^2D)$. Since there are at most $|V_r|$ iterations, the overall time complexity of this algorithm is $|V_r| \times O(|V_r|^2D) = O(|V_r|^3D)$. Although this complexity looks somewhat too high, we believe that using $|V_r|$ to bound N is too strong. Our experimental experience reveals that the value of N will degrade quickly because most nodes will be connected to the tree T after several iterations. So, the time complexity of an iteration is quite small in practice[1].

B. Distributed Depth-then-Breadth-Search Algorithm

The above Span-and-Prune algorithm is a centralized one. In this section, we present a distributed algorithm, which does a depth-first search followed by a breadth-first-like search. The depth-first search tries to form some long, thin backbones, which are likely to pass through high-node-density areas. Then from these backbones, we span the tree in a breadth-first-like manner. The algorithm is presented below.

1) (Depth Probing) Given a graph $G_r = (V_r, E_r)$, the coordinator t needs to probe the depth of the tree first. A Probe(*sender_addr*, *current_depth*, Lm) packet is used for this purpose. The Probe packets are flooded in a BFS-like manner, until a depth Lm is reached. Note that following the definition of ZigBee, before the final tree is determined, nodes will use their 64-bit MAC addresses to communicate with each other in this stage.
   This algorithm begins by the coordinator t flooding a Probe(*Addr*(t), 0, Lm) packet in the network, where *Addr*(t) is t's address. When a node v receives a Probe(*sender_addr*, *current_depth*, Lm) packet, it does the following:
   a) If this is the first time v receiving a Probe() packet, v sets its parent *par*(v) = *sender_addr* and its depth *depth*(v) = *current_depth* $+ 1$. If *depth*$(v) < Lm$, v rebroadcasts a Probe(*Addr*(v), *depth*(v), Lm) packet.
   b) If this is not the first time v receiving a Probe() packet, it checks if *depth*$(v) >$ *current_depth*$+1$ is true. If so, a shorter path leading to the coordinator is found. So v sets its parent *par*(v) = *sender_addr* and its depth *depth*(v) = *current_depth* $+ 1$. If *depth*$(v) < Lm$, v rebroadcasts a Probe(*Addr*(v), *depth*(v), Lm) packet.

   Note that to ensure reliability, a node may periodically rebroadcast its Probe() packet. And each node can know the number of its potential parents by the Probe() packet.
2) (Probe Response) After the above probing, a BFS-like tree is formed. Each node then reports to its parent a Report() packet containing (i) the size of the subtree rooted by itself and (ii) the height of the subtree rooted by itself. In addition, each node v will compute a *tallest_child*(v), which records the child of v whose subtree is the tallest among all child subtrees.
3) (Backbone Formation) After the coordinator t receives all its children's reports, it will choose at most Rm children with the larger subtree sizes as backbone nodes. This is done by sending a Backbone() message to each of the selected children. When a node v receiving a Backbone() message, it further invites its child with the tallest subtree, i.e., node *tallest_child*(v), into the backbone by sending a Backbone() packet to *tallest_child*(v). After this phase, t has constructed a backbone with up to Rm subtrees, each as a long, thin linear path.
4) (BFS-like Spanning) After the above backbone formation, the coordinator can broadcast beacons to start the network. A node can broadcast beacons only if it has successfully joined the network as a router (according to ZigBee, this is achieved by exchanging Association_Request and Association_Response with its parent). In our rule, a backbone node must associate to its parent on the backbone, and its parent must accept the request. For each non-backbone node, it will compete with each other in a distributed manner by its association priority, where the association priority is defined by the size of the subtree rooted by this node in the BFS-like tree formed in step 1. A non-backbone node sends its association requests by specifying its priority. A beacon sender should wait for association requests for a period of time and sorts the received requests by their priorities. Then the beacon sender can accept the higher-priority ones until its capacity (Rm) is full.

Compared to the ZigBee protocol, this algorithm requires nodes to broadcast three extra packets (Probe(), Report(), and Backbone()). A Probe() packet needs to flood to the whole network and thus needs an efficient broadcast scheme (this is beyond the scope of this paper). Let n be the total number of nodes in the network. Below, we will show that the additional time and message complexity against to ZigBee are $O(Lm)$ and $O(n)$, respectively .

To see the additional time complexity, observe that the coordinator t will issue Probe() to check the depth of the tree and a node v will rebroadcast it only when *depth*$(v) < Lm$ or it can find a shorter path to t. So, the additional time complexity will be bounded by $O(Lm)$. In the process of finding the *tallest_child*, each node will report to its parent. Because the reporting is started from leaf nodes, the additional time complexity is also bounded by $O(Lm)$. Finally, the backbone formation will be triggered by t to construct a long, thin linear path. Again, the additional cost is $O(Lm)$. Overall, the additional time complexity of our algorithm against ZigBee

[1] By our simulation, in average, almost 75% of nodes can be connected to the tree T in first iteration. After second iteration, almost 88% of nodes can be connected to the tree T.

is bounded by $O(Lm)$.

To see the additional message complexity of our algorithm, observe that the probing step is similar to a BFS tree construction, so the message complexity is $O(n)$. In the step of finding *tallest_child*, because each node will only report to its parent once, the message cost is also $O(n)$. Finally, t will send Backbone() packets to its Rm selected children, who will further invite their children with the tallest subtrees. The cost is at most $O(Rm + Rm \times (Lm - 1))$. Overall, the additional message complexity against ZigBee is $O(n)$.

IV. Algorithms for the EDMM Problem

In Section II-B, we have formulated the EDMM problem as a maximum matching problem in a bipartite graph. It is already known that there exists optimal polynomial-time algorithms to solve this problem. Below, we show how to use the maximum matching algorithm in [9] to solve our problem. Recall that after connecting routers in the BDDTF problem, we will obtain a bipartite graph $\tilde{G}_d = (\{\tilde{V}_r \cup \tilde{V}_e, \tilde{E}_d\})$. From $\tilde{G}_d$, we can find a maximum matching as following.

1) Try a greedy approach by first matching those vertices with small degrees. We denote this matching edge set as M. Then, we transform the undirected graph $\tilde{G}_d$ to a directed graph $\tilde{G}_d{}'$ by directing the edges in M to point from $\tilde{V}_e$ to $\tilde{V}_r$ and directing the edges not in M to point from $\tilde{V}_r$ to $\tilde{V}_e$.
2) Apply a DFS search on $\tilde{G}_d{}'$ starting from any node of $\tilde{V}_r$. If $\tilde{G}_d{}'$ has any *alternating path* [9] P staring from $\tilde{V}_e$ and ending at $\tilde{V}_r$, we mark all edges of P belonging to M as not belonging to M, and vice versa. (It is easy to see that P must be of an odd length.) Then we reconstruct $\tilde{G}_d{}'$ based on the new M.
3) Repeat step 2 until each node in $\tilde{V}_r$ has been searched once. Then the final M is a maximum matching of $\tilde{G}_d$.

As shown in [9], the complexity of the above procedure is $O((|\tilde{V}_r|)(|\tilde{V}_r| + |\tilde{V}_e| + |\tilde{E}_d|))$.

The above algorithm is a centralized one. In practice, we need a distributed algorithm to allow routers to connect end devices in a decentralized way. Below, we present a distributed algorithm, which has a *greedy phase* followed by a *probing phase*. In the greedy phase, the routers will accept end devices which have less potential associable routers. Then, each orphan router will try to probe a 3-hop alternating path P as discussed above to relieve its orphan situation. The probing process can be executed before a timer T_{probe} expires. After T_{probe} expires, an end device can not change its parent.

1) (Greedy phase) Each router will periodically broadcast beacon packets with a reserve bit to indicate whether it still has capacity to accept more end devices. Each end device e will overhear beacons from routers and, based on these beacons, compute the number N_e of its neighbor routers with their reserve bits on. In the case of $N_e = 0$, e is a potential orphan. If $N_e > 0$, e will try to perform the association procedure by providing its N_e value to routers. Routers simply accept as many end devices as possible with smaller N_e first (intuitively, a smaller N_e means less potential parents).
2) (Probing phase) After the greedy phase, each associated end device will broadcast its new N_e value (note that this value counts its parent as well as those neighboring routers which still have remaining capacities). For an orphan end device e (with $N_e = 0$), it can try to resolve its situation as follows:
   a) A Probe() packet[2] can be sent by e to any neighboring router r.
   b) When r receives the Probe() from e, r can check if it has a child end device e' such that $N_{e'} \geq 2$. If so, r will send a Probe() packet to e' to ask e' to switch to another router.
   c) On reception of r's Probe(), e' will try to associate with another router other than its current one. If it succeeds, a Probe_Ack() will be returned to r; otherwise, a Probe_Nack() will be returned.
   d) When r receives the result from e', a Probe_Ack() or a Probe_Nack() will be returned to e accordingly. In the former case, e will associate with r. In the latter case, e will try another router by going back to step (a), until timer T_{probe} expires.

The above protocol allows an orphan to probe 3-hop paths. It is not hard to extend this protocol to allow probing longer paths at higher costs (we leave it to the audience). Next, we analyze the additional time and message complexity required for this protocol against the original ZigBee. The additional time complexity will be bounded by $O(T_{probe})$. The additional message complexity is incurred by the *probing phase*. Our protocol has a progressive property because each probe may reduce one orphan end device. So the extra cost will be bounded by a polynomial function of the number of end devices. If longer alternating paths are explored, the cost will be higher. However, one may use the timer T_{probe} to bound the cost.

V. Simulation Results

A simulator has been implemented based on Java. First, we compare our Span-and-Prune algorithm (SP) and Depth-then-Breadth-Search algorithm (DBS) against the ZigBee algorithm (ZB) in their capabilities to relieve the BDDTF problem under random and regular node deployment. Next, through varying the combinations of Cm, Rm, and Lm, we further show the superiority of SP and DBS even under different node density environment. We also investigate in more details the advantage of the backbone probing in our DBS scheme. Finally, we will show the performance of our distributed EDMM scheme to connect end devices.

A) Random vs. Regular Networks: In Fig. 6, we test a $90°$-sector area with a radius of $200\ m$ and with 400 randomly deployed router-capable nodes each with a transmission range of $32\ m$. We set $Cm = Rm = 2$ and $Lm = 8$. ZB, SP, and DBS algorithms incur 110.2, 13.7, and 37.9 orphan routers, respectively, in average. DBS only incurs slightly more orphans than the centralized SP does. In particular, we see that both SP and DBS may leave some nodes nearby the

[2] This Probe() should be distinguished from the Probe() in Section III-B.

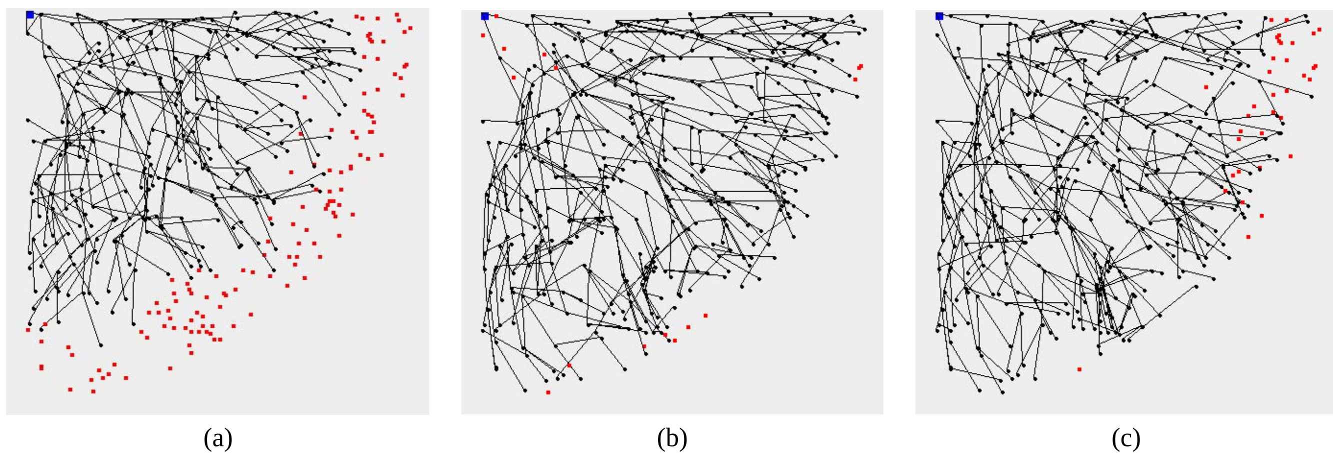


Fig. 6. Network formation results in a 90°-sector area by (a) ZB, (b) SP, and (c) DBS.

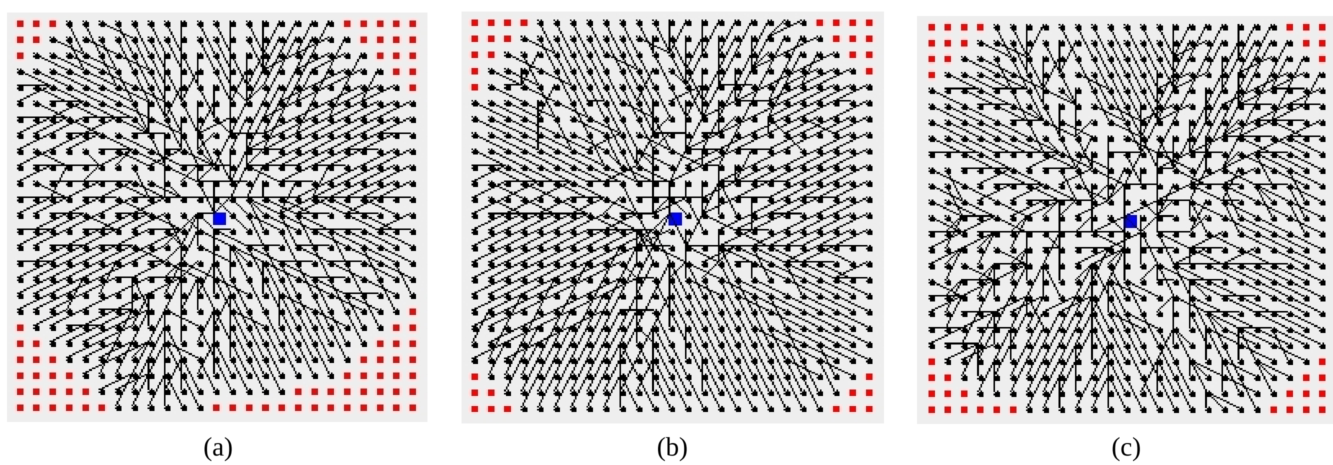


Fig. 7. Network formation results in a 25×25 grid area by (a) ZB, (b) SP, and (c) DBS.

coordinator unconnected due to the Rm constraint but can reach farther nodes. Fig. 7 considers a 25×25 regular grid with a grid distance of $10\ m$. Nodes' transmission distances are $23\ m$. We set $Cm = Rm = 4$ and $Lm = 7$. In this case, ZB, SP, and DBS incur 70.2, 37.2, and 40.4 orphan routers, respectively. ZB performs the worst. DBS performs closely to the centralized SP.

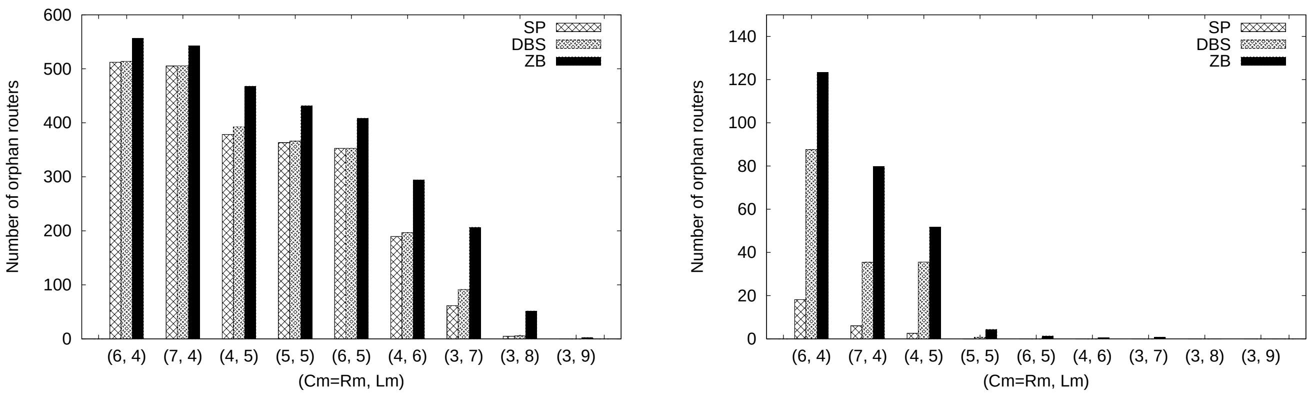
B) Impact of Link Density on the BDDTF Problem: We simulate 800 randomly distributed router-capable devices in a circular region with a radius of $200\ m$ with the coordinator at the center. We restrict $Cm = Rm$ and vary Rm and Lm to observe the number of orphan routers. Table II shows the address spaces of different combinations of Cm, Rm, and Lm, which can clearly accommodate much more than 800 nodes ideally. We set nodes' transmission ranges to $35\ m$ and $60\ m$. Since the network area and the number of nodes are fixed, a larger transmission range actually means denser links among neighboring nodes. As Fig. 8 shows, denser links do lead to much less orphans. However, transmission range depends on hardware features as well as deployment needs, which are sometime uncontrollable. In addition, we see that in all cases, SP performs the best, followed by DBS and then ZB.

C) Impact of Rm and Lm on the BDDTF Problem: The above Fig. 8 indicates that increasing Lm can more effectively reduce orphan routers as opposed to increasing Rm. In Fig. 9, we further fix Lm and vary Rm to conduct our tests. We see that the orphan situation can benefit less by enlarging Rm under low link density. However, as the link density is higher, enlarging Rm is still quite effective. This is because a higher link density will allow a node to have more potential children. Our scheme can save space for Rm and thus allow a larger space for Lm. For example, in Fig. 8(a), SP incurs nearly the same number of orphan routers in the (3, 7) case (resp., the (3, 8) case) as ZB does in the (3, 8) case (resp., the (3, 9) case). In Fig. 9(b), SP incurs nearly the same number of orphan routers when $Rm = 6$ as ZB does when $Rm = 11$. Saving the space for Rm can allow a larger Lm, which can in turn relieve the orphan problem. This shows the benefit of our SP scheme.

D) Impact of the Backbone Formation in DBS: In DBS, there is a backbone formation to choose subtrees of larger sizes. We modify DBS to a DBS-NB (NB = non-backbone) scheme, which works similar to DBS but does not form backbones as in DBS (i.e., all nodes in step 4 are considered as non-backbone ones). The results are in Fig. 10, which clearly shows the importance of the formation process.

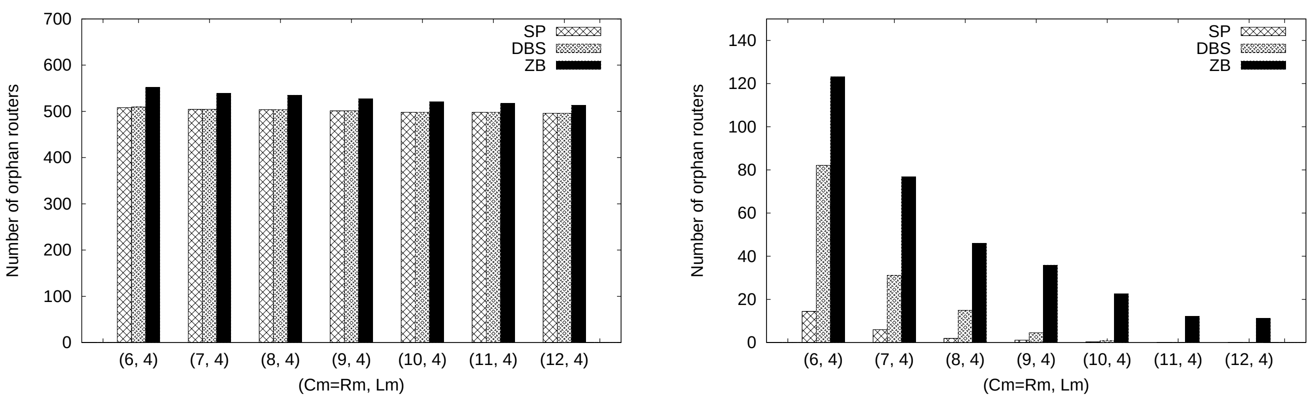
TABLE II
IDEAL ADDRESS SPACES OF VARIOUS COMBINATIONS OF Rm AND Lm ($Cm = Rm$).

$(Cm = Rm, Lm)$	(3, 7)	(3, 8)	(3, 9)	(4, 6)	(4, 5)	(5, 5)	(6, 5)
Total address spaces	3280	9841	29524	5461	1365	3906	9331
$(Cm = Rm, Lm)$	(6, 4)	(7, 4)	(8, 4)	(9, 4)	(10, 4)	(11, 4)	(12, 4)
Total address spaces	1555	2801	4681	7381	11111	16105	22621



(a) (b)

Fig. 8. Comparison on the number of orphan routers when the transmission range is (a) 35 m and (b) 60 m.



(a) (b)

Fig. 9. Comparison on the number of orphan routers by fixing Lm and varying Rm when the transmission range is (a) 35 m and (b) 60 m.

E) The EDMM Problem: In these experiments, we simulate the networks with both routers and end devices. We randomly place 800 routers and 8000 end devices in a circular area of radius 200 m with the coordinator at the center. Routers' transmission ranges are 35 m, and end devices' are 15 to 30 m. An end device can only associate to a router located within its transmission range. We set $Cm = 15$, $Rm = 3$, and $Lm = 8$. We use SP to connect routers and then apply the centralized maximum matching scheme (Max-Match), our distributed matching scheme (Dis-Match), or ZigBee (ZB) to connect end devices. In all cases of end devices' transmission ranges, Fig. 11 shows that Dis-Match can significantly reduce orphan end devices as opposed to ZB, and perform quite close to Max-Match.

VI. CONCLUSIONS

In this paper, we have identified a new orphan problem in ZigBee-based wireless sensor networks. We show that the problem is non-trivial because a device is not guaranteed to join a network even if there are remaining address spaces in other places of the network. We model this orphan problem as two subproblems, namely the BDDTF problem and the EDMM problem. We prove that the BDDTF problem is NP-complete and propose a two-stage network formation policy, which can effectively relieve the orphan problem. Compared to the network formation scheme defined in ZigBee, our algorithms can significantly reduce the number of orphan routers. Contrarily and interestingly, we show that the EDMM

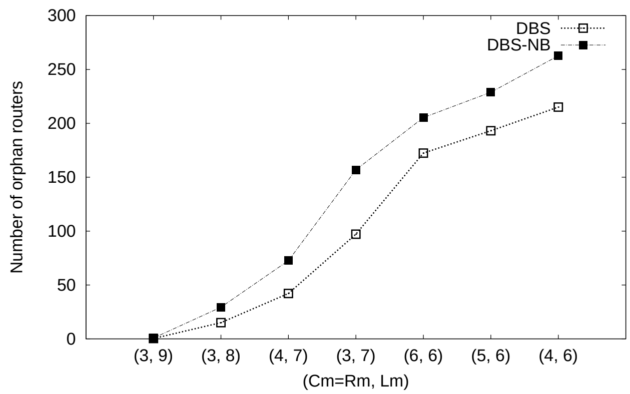


Fig. 10. Comparison of DBS and DBS-NB schemes (800 routers; a circular sensing field of a radius of 200 m; nodes' transmission range 35 m).

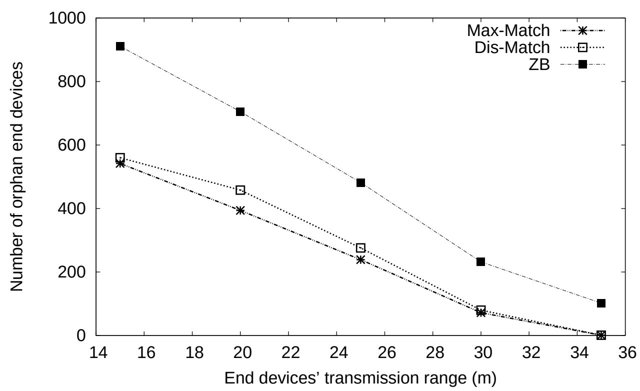


Fig. 11. Comparison on the number of orphan end devices at various transmission ranges.

problem is solvable in an optimal way in polynomial time by a centralized algorithm and propose a distributed matching algorithm. Our simulations also show that our distributed algorithm performs quiet closely to the maximum matching algorithm. These results are expected to significantly enhance the connectivity of ZigBee networks.

ACKNOWLEDGMENT

Y.-C. Tseng's research is co-sponsored by MoE ATU Plan, by NSC grants 95-2221-E-009-058-MY3, 96-2218-E-009-004, 97-3114-E-009-001, 97-2221-E-009-142-MY3, and 97-2218-E-009-026, by MOEA under grant 94-EC-17-A-04-S1-044, by ITRI, Taiwan, and by III, Taiwan.

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附錄三

The Orphan Problem in ZigBee-Based Wireless Sensor Networks

M.-S. Pan and Y.-C. Tseng

ACM/IEEE Int'l Symp. on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2007.

The Orphan Problem in ZigBee-based Wireless Sensor Networks

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ABSTRACT

ZigBee is a standard which is considered to be suitable for wireless sensor networks. In ZigBee, a device is said to join a network if it can obtain a network address from a parent device. Devices calculate addresses for their child devices by a distributed address assignment scheme. This assignment is easy to implement, but it restricts the number of children of a device and the depth of the network. We observe that if one uses the random formation policy specified in ZigBee, the utilization of the address pool will be very low. Those devices that can not receive network addresses will be isolated from the network and become *orphan* nodes. In this paper, we model the *orphan problem* by two subproblems: the *bounded-degree-and-depth tree formation (BDDTF)* problem and the *end-device maximum matching (EDMM)* problem. We then present solutions to these problems. The results can be applied to network formation in ZigBee networks.

Categories and Subject Descriptors

C.2.1 [**[Computer-Communication Networks**]: Network Architecture and Design—*Distributed networks, Wireless communication*; G.2.2 [**Discrete Mathematics**]: Graph Theory

General Terms

Algorithms, Design, Theory.

Keywords

graph theory, IEEE 802.15.4, orphan problem, wireless sensor network, ZigBee.

1. INTRODUCTION

The recent progress of wireless communication and embedded micro-sensing MEMS technologies has made *wireless sensor networks (WSNs)* more attractive. A lot of research works have been dedicated to this area. Recently, several WSN platforms have been developed. For interoperability among different systems, standards

MSWIM'07, October 22-26, 2007, Chania, Crete Island, Greece.

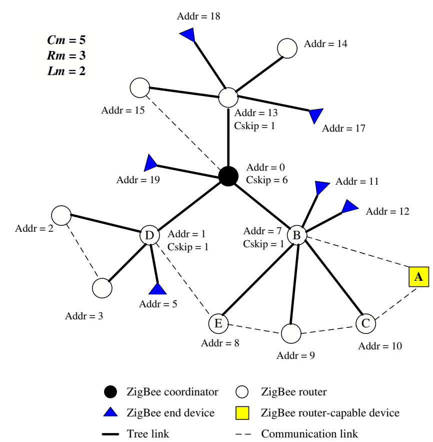

Figure 1: An example ZigBee tree network.

such as ZigBee [4] have been developed. In the ZigBee protocol stack, physical and MAC layer protocols are adopted from the IEEE 802.15.4 standard [3]. ZigBee solves interoperability issues from the physical layer to the application layer.

ZigBee supports three kinds of networks, namely star, tree, and mesh networks. A *ZigBee coordinator* is responsible for initializing, maintaining, and controlling the network. A star network has a coordinator with devices directly connecting to the coordinator. For tree and mesh networks, devices can communicate with each other in a multihop fashion. The network is formed by one ZigBee coordinator and multiple *ZigBee routers*. A device can join a network as an *end devices* by the associating with the coordinator or a router. Fig. 1 shows a ZigBee tree network.

In ZigBee, a device is said to join a network successfully if it can obtain a network address from the coordinator or a router. Before forming a network, the coordinator determines the maximum number of children of a router (Cm), the maximum number of child routers of a router (Rm), and the depth of the network (Lm). Note that a child of a router can be a router or an end device, so $Cm \geq Rm$. ZigBee specifies a distributed address assignment using parameters Cm, Rm, and Lm to calculate nodes' network addresses. While these parameters facilitate address assignment, they also prohibit a node from joining a network. We say that a node becomes an *orphan node* when it can not associate with the network but there are unused address spaces. We call this the *orphan problem*. For example, in Fig. 1, the router-capable device A has two potential parents B and C. Router B can not accept A as its child because it has reached its maximum capacity of $Cm = 5$

children. Router C can not accept A either because it has reached the maximum depth of $Lm = 2$. So A will become an orphan node.

Given Cm, Rm, and Lm, we model the orphan problem by two subproblems. The first considers router-capable devices only. We model this subproblem as a *bounded-degree-and-depth tree formation (BDDTF)* problem, which discusses how to include as many routers as possible into a tree with a bounded degree and depth. We show that this subproblem is NP-complete. After connecting routers, end devices are connected to routers. We model this as an *end-device maximum matching (EDMM)* problem. Based on the above model, we design a two-stage network formation policy to relieve the orphan problem. The first stage algorithm is designed for the BDDTF problem and the goal is to connect as many routers as possible. And then, based on the result of the first stage, the second stage algorithm, which is designed for the EDMM problem, is used to reduce the number of orphan end devices. For example, the orphan problem in Fig. 1 can be relieved if router E is connected to router D, so router B has capacity to accept A.

It is possible that the orphan problem can be relieved trivially by enlarging Cm, Rm, or Lm. In practice, the devices capabilities and application demands of this network should be carefully deliberated before doing so. Large Cm or Rm values cause that routers need more memory spaces to store the information of their child devices. And a large Lm value induces longer network delay. Besides, in theory, it can not be guaranteed that there are no orphan devices with any given Cm, Rm, and Lm (This will be shown in Section 2.2). Based on above discussions, we claim that enlarging Cm, Rm, or Lm is not a good solution for solving the orphan problem. The simulation results show that the proposed network formation strategies can effectively reduce the number of orphan devices without enlarging Cm, Rm, or Lm.

The rest of this paper is organized as follows. Preliminaries are given in Section 2. Section 3 presents our algorithms. Simulation results are given in Section 4. Finally, Section 5 concludes this paper.

2. PRELIMINARIES

2.1 ZigBee Address Assignment

In ZigBee, network addresses are assigned to devices by a distributed address assignment scheme. After forming a network, the ZigBee coordinator determines the maximum number of children (Cm) of a ZigBee router, the maximum number of child routers (Rm) of a parent node, and the depth of the network (Lm). Note that $Cm \geq Rm$. The basic idea of the assignment is that for the coordinator, the whole address space is logically partitioned into $Rm+1$ blocks. The first Rm blocks are to be assigned to the coordinator's child routers and the last block is reversed for $(Cm-Rm)$ child end devices. The coordinator computes a $Cskip$ value by Cm, Rm, and Lm to represent the size of first Rm address blocks. For the coordinator's child routers, they also logically partition its own address block into $Rm + 1$ blocks and compute their $Cskip$ values. An example of the address assignment is shown in Fig. 1. Note that, in ZigBee, the maximum network address capacity is $2^{16} = 65536$, so the coordinator can not decide the Cm, Rm, and Lm arbitrarily.

By the ZigBee formation, each device tries to find a parent with a smaller depth value. By such formation, some devices may not be able to join the network even if there are remaining address spaces. Fig. 1 is a small-scale example. Here, we present a large-scale simulation result in a circular field of a radius 200 m and a coordinator at the center. There are 800 router-capable devices randomly deployed in the network. The transmission range of nodes is set to 35 m. We set $Cm = Rm = 3$ and $Lm = 7$, which implies that this network can accommodate up to 3280 routers. Our simulation result shows that, in average, more than 25% of devices (about 207.45 devices) will become orphan nodes. Fig. 2 shows one simulation scenario, where many devices near the network boundary can not join the network. We see that some devices near the center do not have any child, which means that the address spaces are underutilized.

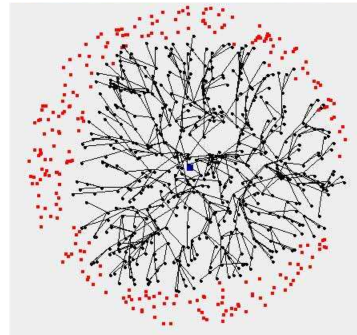

Figure 2: A ZigBee network formation example. Isolated dots are orphan nodes.

2.2 Problem Definitions

Given a sensor network, we model the orphan problem by two subproblems. In the first problem, we consider only router-capable devices and model the network by a graph $G_r = (V_r, E_r)$, where V_r consists of all router-capable devices and the coordinator t and E_r contains all symmetric communication links between nodes in V_r. We are also given parameters Cm, Rm, and Lm such that $Cm \geq Rm$. The goal is to assign parent-child relationships to nodes such that as many vertices in V_r can join the network as possible. Below, we translate the subproblem to a tree formation problem.

DEFINITION 1. *Given $G_r = (V_r, E_r)$, Rm, Lm, and an integer $N \leq |V_r|$, the* Bounded-Degree-and-Depth Tree Formation (BDDTF) *problem is to construct a tree T rooted at t from G_r such that T satisfies the ZigBee tree definition and T contains at least N nodes.*

In [2], it is shown that the *Degree-Constrained Spanning Tree (DCST)* as defined below is NP-complete.

DEFINITION 2. *Given $G = (V, E)$ and a positive integer $K \leq |V|$, the* Degree-Constrained Spanning Tree (DCST) *problem is to find a spanning tree T of G such that no vertex in T has a degree larger than K.*

THEOREM 1. *The BDDTF problem is NP-complete.*

PROOF. 1) Given a tree T in G_r, we can check if T satisfies the constraints of Rm and Lm and if T contains more than N nodes in polynomial time. 2) The DCST problem can be reduced to a special case of the BDDTF problem when $Rm = K$, $Lm \to \infty$, and $N = |V_r|$. □

In the second subproblem, we will connect non-router-capable devices to the tree T constructed earlier such that the ZigBee definition is followed and as many end devices are connected to T as possible. Toward this goal, we model the sensor network by a graph $G_d = (\{\hat{V}_r \cup V_e\}, E_d)$, where $\hat{V}_r$ consists of all routers in T formed in the first stage, V_e consists of all end devices, and E_d contains all symmetric communication links between $\hat{V}_r$ and V_e. Each vertex $v \in \hat{V}_r$ can accept at most $C_v \geq (Cm - Rm)$ end devices. From G_d, we construct a bipartite graph $\tilde{G}_d = (\{\tilde{V}_r \cup \tilde{V}_e\}, \tilde{E}_d)$ as follows.

1. From each vertex $v \in \hat{V}_r$, generate C_v vertices v_1, v_2, ..., v_{C_v} in $\tilde{V}_r$.
2. From each vertex $u \in V_e$, generate a vertex u in $\tilde{V}_e$.
3. From each edge (v, u) in E_d, where $v \in \hat{V}_r$ and $u \in V_e$, connect each of the C_v vertices v_1, v_2, ..., v_{C_v} generated in rule 1 with the vertex u generated in rule 2. These edges form the set $\tilde{E}_d$.

It is clear that $\tilde{G}_d$ is a bipartite graph with edges connecting vertices in $\tilde{V}_r$ and vertices in $\tilde{V}_e$ only. Intuitively, we duplicate each $v \in \hat{V}_r$ by C_v vertices. Then we enforce each vertex in $\tilde{V}_r$ to be connected to at most one vertex in $\tilde{V}_e$. This translates the problem to a maximum matching problem in graph $\tilde{G}_d$.

DEFINITION 3. *Given a graph* $\tilde{G}_d = (\{\tilde{V}_r \cup \tilde{V}_e\}, \tilde{E}_d)$*, the* End-Device Maximum Matching (EDMM) *problem is to find a maximum matching of* $\tilde{G}_d$.

From Theorem 1, we can know that, in theory, we can not guarantee there are no orphan routers or there are only fixed number of orphan routers with any given Rm and Lm. Definition 3 implies that we can know the number of orphan end devices when we are given $\tilde{G}_d$. In sum, we can not decide if there are orphan devices with any given Cm, Rm, and Lm.

3. THE PROPOSED ALGORITHM

3.1 The Algorithm for the BDDTF Problem

Given a graph $G_r = (V_r, E_r)$, our goal is to find a tree $T = (V_T, E_T)$ from G_r which satisfies the ZigBee tree definition. We propose an algorithm to reduce orphan routers in ZigBee networks. In our algorithm, we decide to connect or disconnect a node according to its *association priority*. The priority assignment is based on forming BFS trees from G_r. Although a formed BFS tree may not satisfy the definition of ZigBee, we can still assign priorities to nodes with respect to the BFS tree. The priority rules are defined as follows:

- A node x has a higher priority than another node y if the subtree rooted at x (in the BFS tree) has more nodes than the subtree rooted at y.
- If the subtrees rooted at nodes x and y have the same number of nodes, the one with a less number of potential parents has a higher priority. A node takes a tree neighbor as its potential parent if this neighbor has a smaller hop count distance to the root of the BFS tree than its.

The above definitions are based on the considerations of address space utilization. The first rule is so defined because node x has a better utilization. The second rule is so defined because a node with less potential parents may encounter difficulty to attach to the network.

The algorithm consists of a sequence of iterations. Initially, T contains only the coordinator t. Then in each iteration, there are two phases: Span and Prune. In the Span phase, we will pick a node in T, say x, and span from x a subtree T' to include as many nodes not in the tree T as possible. Then we attach T' to T to form a larger tree. However, the new tree may not satisfy the ZigBee definition. So in the Prune phase, some of the newly added nodes in T' may be trimmed. The resulting tree is then passed to the next iteration for another Span and Prune phases. This is repeated until no more nodes can be added. Each node in T will be spanned at most once. To keep track of the nodes yet to be spanned, a queue Q will be maintained. The algorithm is presented below.

1. Initially, let queue Q contains only one node t and set the depth of t to be zero. Also, let the initial tree $T = \{\{t\}, \emptyset\}$.
2. (Span Phase) Check if Q is empty. If so, the algorithm is terminated and T is the final ZigBee tree. Otherwise, let $x = \textit{dequeue}(Q)$ and construct a spanning tree T' from x as follows. Assuming the depth of x in T is $\textit{depth}(x)$, we try to span a tree with height not exceed $Lm - \textit{depth}(x)$ in G_r in a breadth-first manner by including as many nodes in the set $V_r - V_T \cup \{x\}$ as possible. The resulting tree is called T'.
3. (Prune Phase) Attach T' to T by joining node x. Still, name the new tree T. Since some of the nodes in T' may violate the Rm parameter, we traverse nodes in T' from x in a top-down manner to trim T.
   (a) When visiting a node, say y, we set y is traversed and then we check the number of children of y. If the number of children is greater than Rm, we will compute their priorities based on T' (refer to the definitions of nodes' priorities in a tree given in the beginning of this section). Only the Rm highest prioritized children will remain in T, and the other children will be pruned from T.
   (b) When a node, say y, is pruned, the whole subtree rooted at y is pruned. Node y checks if it has any neighbor n in T' which satisfies 1) n is not y's descendants, 2) n is not traversed, and 3) $\textit{depth}(n)+1$ plus subtree height of v does not exceed Lm. If so, we will connect the subtree to node n. If there are multiple such candidates, the one with lower depth value is connected first. If y has no such neighbor, y prunes its children and excludes itself from T'. The nodes pruned by y do this procedure to find their new parents.
4. After the above pruning, call the resulting tree T. For nodes that are newly added into T in this iteration, insert them into queue Q in such a way that nodes with lower depth values are inserted first (these nodes will go through Span and Prune phases again). Then, go back to Step 2.

Note that, in Step 3.a, if a node has more than Rm child nodes, some of its child nodes will be pruned according to the designed rules. In order to allow more vertices can connect to the tree T, in Step 3.b a pruned node tries to find a neighbor with a lower depth value as its new parent. Step 4 uses the similar concept to decide the sequence the nodes in Q. The node, which locates near to t, can be extracted from Q earlier; thus, more nodes can be connected to the tree T. Step 3.b can guarantee loop-free because a pruned node does not choose any of its descendants as its new parent.

3.2 The Algorithm for the EDMM Problem

Given a $\tilde{G}_d = (\{\tilde{V}_r \cup \tilde{V}_e, \tilde{E}_d\})$, a solution for the EDMM problem can be obtained by applying a bipartite maximum matching algorithm in [1].

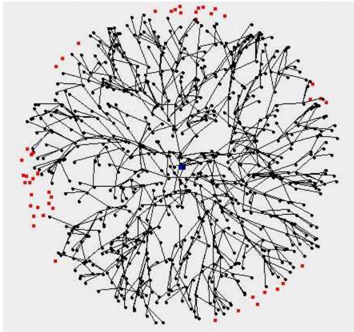

Figure 3: A network formation result when using the proposed SP algorithm for the BDDTF problem.

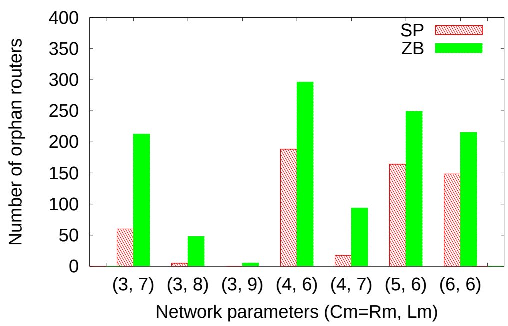

Figure 4: Simulation results on the number of orphan routers.

4. SIMULATION RESULTS

In this section, we first simulate the network that uses the same settings as the ones in Section 2.1. We use the proposed algorithm, denote as SP, for the BDDTF problem to form the network. Fig. 3 shows one simulation result. Compare to Fig. 2, we can see that the proposed SP algorithm can effectively reduce the number of orphan routers.

Next, we consider there are only router-capable devices randomly distributed in a circular region. And a coordinator is placed at the center of the network. We set the number of router-capable devices to 800, the network radius to $200\ m$, and the transmission range of devices to $35\ m$. Here, we set $Cm = Rm$ and vary Rm and Lm to observe the number of orphan routers. Fig. 4 shows the results. We can observe that, under the same Rm and Lm, SP always outperforms ZB, which means that the address utilization of SP is better than that of ZB. We can also observe that the SP can effectively reduce orphan routers with a smaller Rm or Lm. For example, the number of orphan routers of SP with $Rm = 3$ and $Lm = 7$ (or $Lm = 8$) are nearly the same as the number of orphan routers of ZB with $Rm = 3$ and $Lm = 8$ (or $Lm = 9$).

Next, we simulate the networks that contain both router-capable devices and end devices. We place 800 routers in a circular network with network radius $200\ m$. The coordinator is located at the center of the network. The transmission range of routers are $35\ m$. We randomly place 8000 end devices in this network. In this simulation, end devices have smaller transmission ranges than routers. An end device can only associate to a router located within its transmission range. We set $Cm = 15$, $Rm = 3$, and $Lm = 9$.

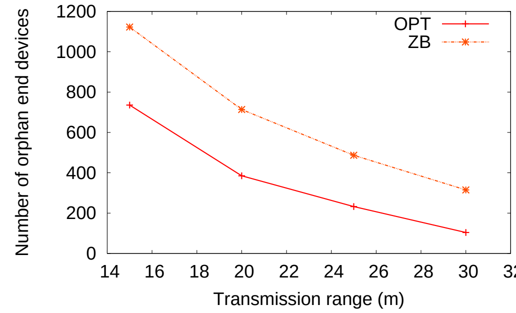

Figure 5: Simulation results on the number of orphan end devices.

The proposed SP algorithm is used to connect router-capable devices. According to Fig. 4, almost all router-capable devices can join the network. Then we compare the proposed algorithm, denote as OPT, for the EDMM problem with the ZB. Fig. 5 shows the simulation results when the transmission ranges of end devices are varied. We can see that if end devices have larger transmission ranges, the number of orphan end devices will be decreased. Compare to ZB, the proposed algorithm can effectively reduce the number of orphan end devices.

5. CONCLUSIONS

In this paper, we discuss the orphan problem in ZigBee-based wireless sensor networks. We model this orphan problem by two subproblems. Firstly, we define a bounded-delay-and-depth tree formation (BDDTF) problem to consider only router-capable devices. We prove that the BDDTF problem is NP-complete. Secondly, we define an end-device maximum matching (EDMM) problem to consider end devices. We propose network formation strategies to relieve the orphan problem. Simulation results indicate that our algorithms can effectively reduce the number of orphan devices.

6. ACKNOWLEDGEMENTS

Yu-Chee Tseng's research is co-sponsored by Taiwan MoE ATU Program, by NSC grants 93-2752-E-007-001-PAE, 96-2623-7-009-002-ET, 95-2221-E-009-058-MY3, 95-2221-E-009-060-MY3, 95-2219-E-009-007, 95-2218-E-009-209, and 94-2219-E-007-009, by Realtek Semiconductor Corp., by MOEA under grant number 94-EC-17-A-04-S1-044, by ITRI, Taiwan, by Microsoft Corp., and by Intel Corp.

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