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Research Article

Topologies for Bluetooth Wireless Personal Area Network

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Abstract

The future standard for Personal Area network (PAN) is being promoted as being Bluetooth, one of the emerging technologies for short-range wireless communication. It could be utilized as an alternative to cables for data transmission between computers and the devices they are linked to by using short-range radio communications. The most optimal Bluetooth wireless local area network (BT-WLANs) topologies are the subject of this study. The investigation makes use of two optimization criteria. The first seeks to keep the network stable while reducing the average delay per packet. To shorten the computation time, a suboptimal criterion is derived from the optimal criterion. The second seeks to choose a network design that ensures the required throughput while reducing the traffic load on the most congested node.

Keywords: Personal Area Network (PAN); Bluetooth; Laptops

Introduction

A novel networking architecture is required for connecting information-intensive consumer devices like, PDAs, laptops and mobile phones [1]. The objective is to build a PAN which supports ad hoc, seamless data transfer between various devices of variable capacities without the use of cables, wired infrastructure, or manual configuration. The necessity for appropriate link-layer PAN technologies drove an industry group to develop and standardize Bluetooth version 1 of a low-power, short-range RF technology. The MAC protocol for Bluetooth is built on a centralized master-slave system rather than the distributed contention resolution found in conventional WLANs.

Bluetooth technology

In 2.4GHz frequency band, Bluetooth uses a pseudo-random frequency-hopping technique in which devices transmits for 625 µs on one frequency prior to switching to the next [2]. With no negative interference effects, such frequency hopping technique enables numerous Bluetooth communications to take place simultaneously within radio range of one another. There is one master and no more than seven slaves in a Bluetooth piconet. The master allots the slaves in the piconet transmission time slots, and consequently channel bandwidth. Only when a message from the master with its intended recipient was present in the preceding time slot does a slave send data. The Time-Division Duplex (TDD) protocol lies at the core of the Bluetooth MAC protocol. Numerous piconets could coexist and independently communicate in close proximity with little to no performance degradation since frequency-hopping allows for high density of communication devices. Bluetooth specification refers to interconnecting multiple piconets as a scatternet, yet doesn't include any instructions on how to do so.

The issue of choosing an optimal topology for BT-WPANs was addressed by Ajmone., *et al*. in 2006 [3]. An optimization method is used, and it depends on a model created from BT-WPAN-specific constraints. Zanella and Miorandi [4] looked into how a Bluetooth piconet's master selection affected its performance in 2002. The stability concerns were addressed, and both suboptimal and optimal selection criteria for master units were put forth. Numerical simulation was used to assess the performance increase compared to random choosing. Tan., *et al*. [5] concerns about internetworking ad hoc networks to create larger "scatternets" were resolved in 2002. To create scatternets, an effective online topology formation algorithm referred to as Tree Scatternet Formation (TSF) was created. TSF links nodes together in a tree topology to make packet routing and scheduling easier. Nodes can enter and exit arbitrarily, constructing the topology gradually and repairing partitions as they happen. The simulation results demonstrate that TSF provides an effective topology for packet forwarding and has reduced tree creation delay. A scatternet-route topology for multihop data transmissions in wireless ad hoc networks was put up by Liu., *et al*. in 2003 [6]. Both a scatternet-scheduling technique based on routes and the on-demand formation route of the scatternet route are discussed. The route discovery messages will be sent using an Extended Identification (EID) connectionless broadcast technique using the Bluetooth inquiry channel. The results of the simulation and performance analysis show that the scatternet-route structure is capable of achieving high network utilization and consistent route throughput.

Network topology

Piconets, which are often made up of a single master device and at least one slave device, are how Bluetooth devices are typically arranged in groups of (2-8) devices. A device can also belong to at least one piconet, either as a master of one piconet and a slave in another, or as a slave in both. With the use of such bridge devices, a scatternet can be created from piconets. The unlicensed Industrial Scientific Medical (ISM) frequency range, where Bluetooth operates, is frequently congested with signals from other devices such as baby monitors, microwave ovens, and garage door openers [1]. Each one of the Bluetooth piconets is synchronized to a particular frequency hopping pattern to assist Bluetooth devices in coexisting and stably functioning with other ISM devices. The pattern is specific to the piconet, cycling over 1600 distinct frequencies every second. Data packets are sent at a specific time period known as a frequency hop [7]. It is possible for a packet to span up to five time slots, in which case the frequency is constant during the transmission.

Method

The problem under investigation is to find the optimal topology for a Bluetooth piconet with a priori known matrix. The optimization criterion is to select the identity (ID) of the master unit that yields the least average packet delay for a Bluetooth piconet when the end-to-end traffic matrix is known. The piconet topology can be defined as

B = (K, H, m) -----------(1)

In which K represent the total number of nodes (one active master and (K-1) slaves' nodes). Further, H is the traffic pattern matrix and m are the ID of the master node. The matrix H defines the end-to-end traffic pattern whose (i, j)-th entry, $h_{i\,j}$ represents the average packet rate generated by node i and directed to node j.

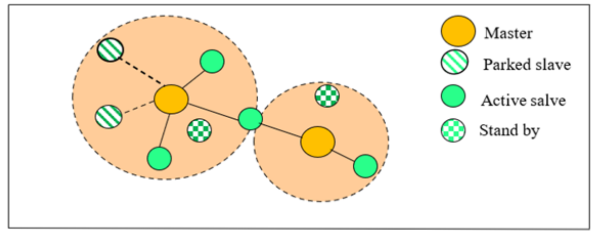

Figure 1: Bluetooth scatternet diagram.

Number of slaves nodes (K-1)	q_{max} (packet/s)	q_{max} (packet/slot)
1	800	0.5
2	400	0.25
3	266.6	0.1666
4	200	0.125
5	160	0.1
6	133.3	0.0833
7	114.285	0.0714

Table 1: Dependence of the maximum allowable effective packet rate with the number of slave nodes for ACL service.

For K-node network, the H matrix is K×K square matrix. Figure. 2 show a schematic diagram illustrating the elements of the matrix H corresponding to a packet generated at node 2 and directed to various nodes in a 6-node piconet topology. Recall that the communication between two slave nodes in a Bluetooth piconet occurs through the master node, therefore, the H matrix can be modified into another matrix Q whose (i,j)-th element, q_{ij} denotes the effective average packet rate from host i to host j without passing through any intermediate node. Thus

$q_{ij} = 0$ when $i, j \neq m$ ---------- (2)

Where m denotes the ID of the master node. Further, q_{ij} has a value greater than zero just if i = m or j = m

j = 0,…, K-1 ---------- (3)

i = 0,…, K-1 ---------- (4)

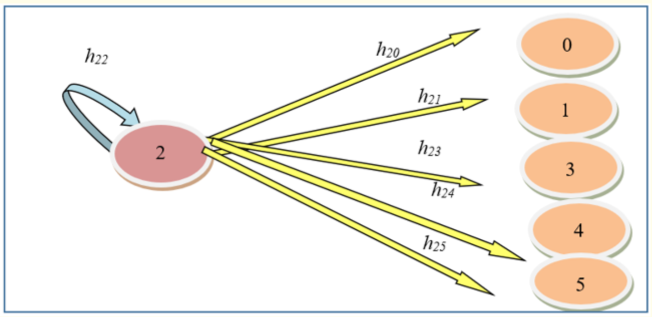

Figure 2: A schematic diagram which shows the elements of traffic pattern matrix corresponding to a packet generated at node 2 and directed to the 6 nodes in K= 6 topology

Equation 4 denotes the effective average packet rate from the master node m to a slave node j and it lumps all the communications from the (K-1) nodes to node j under observation, see Figure 3a Further q_{im} denotes the effective average packet rate from slave node i to the master node m and it lumps all the communication from node i to all the K nodes, see Figure 3b. The average delay for communication from the master to a slave node i is defined in Eq. 5. Similarly, the average delay for communication from a slave node i to the master node m is defined in Eq. 6.

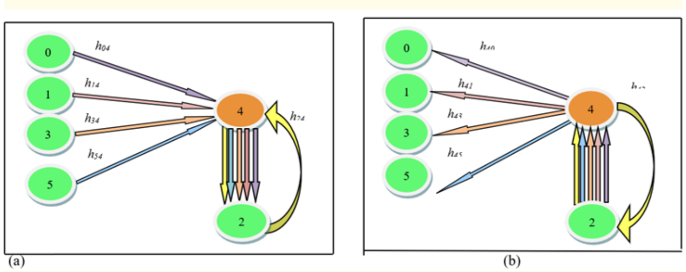

Figure 3: A 6-node Bluetooth piconet where node 4 is the master and node 2 is under observation (a) Traffic to node 2 (b) Traffic from node 2.

The average delay from a slave node i to a slave node j could be calculated as

$\tau(i,j) = \tau_0 (i,m)+\tau_0 (m,j)$ --------- (5)

The average delay a packet undergoes in the network (could be expressed in the following way:

$$\tau_d = \sum_{i=0}^{K-1} \sum_{j=0}^{K-1} \frac{h_{ij}\,\tau(i,j)}{R}$$ -----------(6)

Here R is the total offered traffic and it can be expressed as

$$R = T \sum_{ij} h_{ij}$$ -----------(7)

$$\tau_d = \frac{1}{R} \sum_{i=0}^{K-1} \sum_{j=0}^{K-1} h_{ij} \left[\tau_0(i,m) + \tau_0(m,j)\right]$$

$$\tau_d = \frac{1}{R} \left[\sum_{i=0}^{K-1} \tau_0(i,m) \sum_{j=0}^{K-1} h_{ij} + \sum_{j=0}^{K-1} \tau_0(m,j) \sum_{i=0}^{K-1} h_{ij}\right]$$

$$\tau_d = \frac{1}{R} \left[\sum_{i \neq m} q_{im}\, \tau_0(i,m) + \sum_{j \neq m} q_{mj}\, \tau_0(m,j)\right]$$ -----------(8)

The optimum criterion used here can be stated as follows. Choose the ID of the master node for minimizing the average packet delay for a given traffic matrix **H**. Mathematically one can write

$$m = \arg \min_{i=0,\dots,k-1} \tau_d(i)$$ -----------(9)

One can also use another criterion to optimize the design of Bluetooth piconet topology. The goal is to maintain the system as far away from the stability limit as possible [4]. This criterion gives slightly higher value of compared with the optimum criterion stated above. Therefore, this new criterion is called here a suboptimal criterion. This criterion works as follows

The total offered traffic is calculated using Eq. 10 The effective offered traffic is defined as

$R_{eff} = T[\sum_i \sum_j q_{ij}]$ ----------(10)

Substituting Eq. 2.10 into Eq. 2.11

$$R_{eff} = 2R - \sum_{n=0}^{k-1} h_{n,m} + h_{m.n}$$ ------------(11)

The master ID in the suboptimal criterion is chosen such as to minimize the offered traffic R_{eff}

$m = \arg \min R_{eff}$ ---------(12)

Note that the R_{eff} is minimized when $(\sum_{n=0}^{k-1} h_{n,m} + h_{m.n})$ aximized (see Eq. 11). Therefore, the suboptimal criterion master ID is

$$m = \arg \max_{i=0,\ldots,k-1} \left(\sum_{n=0}^{k-1} h_{n.i} + h_{i,n}\right) \quad \text{---------(13)}$$

Our simulation results reveal that the suboptimal criterion needs less computational time than the optimal criterion.

Simulation Results

Simulation results are obtained using MATLAB (version 7) environment programs are written to characterize both optimal and suboptimal topologies.

Tables 2 through 5 shows, respectively, the dependence of the average packet delay τ_d on total offered traffic R for 5-,6-,7- and 8-node piconets. The ID of the master node is also specified for each value of the total offered traffic. Each table contains two parts; part (a) corresponds to the optimal criterion and part (b) corresponds to the suboptimal criterion. The results are also plotted in Figure 4 a-d. Investigating the results in these tables and figures reveals the following findings.

- Both optimal and suboptimal criteria offer almost identical results when R is less than 0.35 and this effect is almost more pronounced in the case when the number of nodes K increases. For example, consider the case of R = 0.3. The optimal criterion gives τ_d = 20.05, 25.87, 34.39 and 41.88 ms when K = 5, 6, 7, and 8, respectively. These values are to be compared with 25.23, 29.62, 35.64 and 45.07, respectively, when the suboptimal criteria are used.
- The difference between the average packet delays predicted by optimal and suboptimal criterion $\Delta\tau_d$ increases as R increases. For example, $\Delta\tau_d$ is equal to 5.18, 3.39, 1.25 and 3.19 ms when K = 5, 6, 7, and 8, respectively, with R = 0.3. Increasing R to 0.5 yields $\Delta\tau_d$ = 29.43, 100.69, 84.15 and 81.69 ms, respectively.
- The master ID may be the same or not for optimal and suboptimal criterion.
- The ratio R_{eff}/R is independent of R and it equal to 1.04, 1.02, 1.3 and 1.4 when K = 5, 6, 7 and 8, respectively.

Conclusions

Optimal topologies for BT-WPANs have been investigated. Two optimization criteria have been used in the analysis. The first seeks to keep the network stable while reducing the average delay per

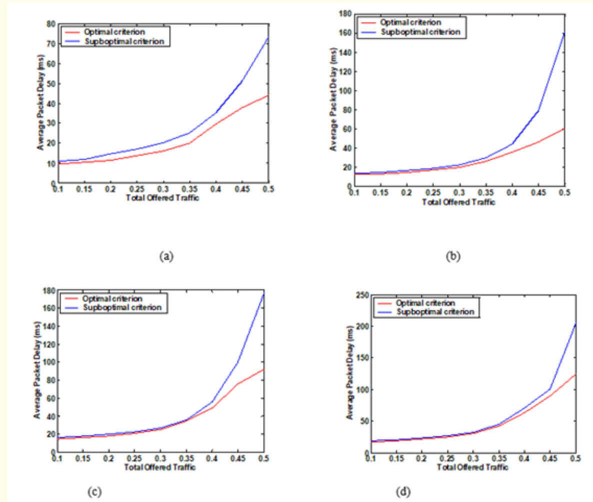

Figure 4: Variation of the average packet delay obtained by using the optimal criterion and suboptimal criterion with total offered traffic for (a) 5-node piconet (b) 6-node piconet (c)7-node piconet (d) 8-node piconet.

Optimal criterion

Total offered traffic R	Average packet delay τ_d (ms)	Master ID m
0.1	9.52	1
0.15	10.42	1
0.2	11.46	2
0.25	13.60	5
0.3	16.03	1
0.35	20.05	2
0.4	29.61	3
0.45	37.85	2
0.5	44.07	5

Suboptimal criterion

Total offered traffic R	Effective total offered traffic R_{eff}	Average packet delay τ_d (ms)	Master ID m
0.1	0.10	10.77	4
0.15	0.16	11.76	5
0.2	0.21	14.64	2
0.25	0.26	16.92	5

0.3	0.31	20.22	1
0.35	0.36	25.23	2
0.4	0.42	35.10	5
0.45	0.47	51.22	5
0.5	0.52	73.5	5

Table 2: Dependence of the average packet delay and master ID on total offered traffic for a 5-node piconet using optimal criteria (a) and suboptimal criteria (b).

Total offered traffic R	Average packet delay τ_d (ms)	Master ID m
0.1	12.13	1
0.15	13.03	1
0.2	14.52	3
0.25	16.90	1
0.3	19.50	6
0.35	25.87	2
0.4	35.28	2
0.45	46.29	5
0.5	60.50	6

Optimal criterion

Total offered traffic R	Effective total offered traffic R_{eff}	Average packet delay τ_d (ms)	Master ID m
0.1	0.12	13.34	6
0.15	0.18	14.56	3
0.2	0.24	16.36	6
0.25	0.30	18.61	4
0.3	0.36	22.48	6
0.35	0.42	29.62	5
0.4	0.48	43.72	6
0.45	0.54	78.80	3
0.5	0.60	161.19	6

Suboptimal criterion

Table 3: Dependence of the average packet delay and master ID on total offered traffic for a 6-node piconet using optimal criteria (a) and suboptimal criteria (b).

Total offered traffic R	Average packet delay τ_d (ms)	Master ID m
0.1	14.33	1
0.15	16.00	6
0.2	17.65	1
0.25	20.70	1
0.3	25.16	2
0.35	34.40	6
0.4	48.93	5
0.45	75.58	7
0.5	92.04	Any node (1-6)

Optimal criterion

Suboptimal criterion

Total offered traffic R	Effective total offered traffic R_{eff}	Average packet delay τ_d (ms)	Master ID m
0.1	0.13	15.86	1
0.15	0.20	17.60	4
0.2	0.26	19.78	6
0.25	0.32	22.60	1
0.3	0.39	26.61	4
0.35	0.46	35.64	5
0.4	0.52	55.67	2
0.45	0.59	99.60	3
0.5	0.65	176.55	7

Table 4: Dependence of the average packet delay and master ID on total offered traffic for a 7-node piconet using optimal criteria (a) and suboptimal criteria (b).

Total offered traffic R	Average packet delay τ_d (ms)	Master ID m
0.1	16.76	1
0.15	18.73	1
0.2	21.22	1
0.25	24.74	1
0.3	30.01	1
0.35	41.88	4
0.4	63.16	3
0.45	89.28	3
0.5	124.32	7

Optimal criterion

Suboptimal criterion

Total offered traffic R	Effective total offered traffic R_{eff}	Average packet delay τ_d (ms)	Master ID m
0.1	0.14	18.47	8
0.15	0.20	20.27	6
0.2	0.28	23.04	3
0.25	0.35	26.49	2
0.3	0.42	31.84	6
0.35	0.49	45.07	5
0.4	0.56	70.33	6
0.45	0.63	100.51	6
0.5	0.70	205.92	6

Table 5: Dependence of the average packet delay and master ID on total offered traffic for an 8-node piconet using optimal criteria (a) and suboptimal criteria (b).

packet. A suboptimal criterion has been also deduced from this optimal criterion to reduce the computation time. The second seeks to choose a network topology that ensures the needed throughput while reducing the traffic load on the most congested node.

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