

Hybrid Distributed Iterative Capacity Allocation over Bluetooth Network

Son, L.T.; Schiøler, Henrik; Madsen, Ole Brun

Publication date:
2002

Document Version
Også kaldet Forlagets PDF

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Son, L. T., Schiøler, H., & Madsen, O. B. (2002). *Hybrid Distributed Iterative Capacity Allocation over Bluetooth Network*. <Forlag uden navn>.

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

HYBRID DISTRIBUTED ITERATIVE CAPACITY ALLOCATION OVER BLUETOOTH NETWORK

Le Thanh Son, Henrik Schiøler, Ole Brun Madsen

Distributed Real-Time Group, Department of Control Engineering

Aalborg University, Denmark

Email: lts,henrik,obm@control.auc.dk

Abstract—With the current development of mobile devices, short range wireless communications have become more and more popular, and many researches on short range wireless communications, such as Bluetooth, have gained special interests, in industry as well as in academy. This paper analyzes capacity allocation issues in Bluetooth network as convex optimization problem. We formulate the problem of maximizing of total network flows and minimizing the costs of flows. The hybrid distributed capacity allocation scheme is proposed as an approximated solution of the formulated problem that satisfies quality of service requirements and constraints in Bluetooth network, such as limited capacity, decentralized, frequent changes of topology and of capacities assigned to nodes in the network. The simulation shows that the performance of Bluetooth could be improved by applying the hybrid distributed iterative capacity allocation scheme.

Keywords Bluetooth, Scatternet, Capacity allocation, Network control, Congestion control, Capacity assignment

I. INTRODUCTION

Wireless short range technologies have recently attracted much attention both in public market and in industries. There are many researches on wireless short range communication, especially on Bluetooth. Bluetooth is a new radio technology that promises to be a very convenient, low cost solution for the interconnection of all kinds of mobile devices. Currently, Bluetooth Special Interest Group (SIG) [1] has defined a simple network topology, piconet, that only supports a limited number of devices and requires all devices to be in range. However, support of the more demanding multi-hop ad hoc network, which called scatternet, is not specified in detail yet. In this paper, we formulate an analytical model for the analysis of capacity allocation problem in Bluetooth network and propose the hybrid distributed iterative capacity allocation scheme for its approximated solution. Through simulation, it shows that the performance of Bluetooth could be improved by applying the hybrid distributed iterative capacity allocation scheme.

Bluetooth operates in the unlicensed ISM (Industrial-Scientific-Medical) band using a frequency hopping scheme. Bluetooth units are organized into *piconet*. There is one Bluetooth device in each piconet acting as master, which can have any number of slaves out of which up to seven can be active simultaneously. Master and slaves are allowed to send 1, 3 or 5 slot packets. Although Bluetooth can support on both voice and data traffics, in this paper we concentrate on the networks, in which only data links are used. Two or more piconets can form a *scatternet*, a true mobile ad hoc network,

in which a unit that can participate in multiple piconets is called bridge node.

There are many studies on Bluetooth scatternet, in both theoretical and practical aspects. Much attention has been given to polling and scheduling schemes for piconets and scatternet, respectively [7]. Some researches concentrate on scatternet topology and on the development of efficient scatternet formation algorithms [8]. However, issues of resource allocation are still opened. Zussman et al. [2] have studied on capacity assignment problem and proposed a heuristic algorithm, which has much lower complexity than that of the optimal algorithm and its performance is claimed to be close to that of the optimal algorithm.

In this paper, we study problem of resource allocations in Bluetooth network. It can be formulated as a convex optimization problem of maximization of total network flows and minimization of total cost of flows. The solution of optimization problem should satisfy constraints of Bluetooth network. It should be decentralized and has ability to response of frequent changes of topology and of capacities assigned to nodes in the network. We propose the hybrid distributed iterative capacity allocation scheme to address the problem requirements. The purpose of the distributed capacity allocation scheme is to get maximization of network flows, while minimizing the costs of satisfying Quality of Service (QoS) requirements. There is no prior assumption about the network.

The paper is structured as follows: Section 2 gives some descriptions about Bluetooth network model, capacity constraints and traffic model. In section 3, we formulate the convex optimization problem of capacity allocation in Bluetooth network. Section 4 features the hybrid distributed capacity allocation scheme. Section 5 contains some evaluations of the scheme. Section 6 illustrates some properties of the hybrid distributed capacity allocation scheme by presenting simulation results in basic scenarios. In section 7, some open issues are discussed. Finally, conclusion and future work are discussed in section 8.

II. BLUETOOTH NETWORK MODEL

Consider a Bluetooth network with a set of directional scatternet graph $G = (N, L, R)$, where N denotes the collection of Bluetooth nodes $\{1, 2, \dots, n\}$, which can be a master, a slave, or a bridge. The maximum capacity, C_i for the node i in the network with N nodes, is limited by network formation and hopping frequencies. In case of minimizing the number of

piconets, the maximum capacity C_i is bounded approximately following expression [4]:

$$C_i = \frac{\left(1 - \frac{1}{n_f}\right)^{2(\lceil \frac{N}{8} \rceil - 1)}}{\lceil \frac{N}{8} \rceil - 1} \quad (1)$$

where n_f is the number of frequencies in the hopping scheme. Each piconet has maximum possible nodes, i.e. 8 nodes, which consists of a master and 7 slaves. It is assumed that single slot packets and fully loaded piconets. In case that the number of piconets is maximized, which means the network contains only point-to-point piconets, the expression can be rewritten as [4]:

$$C_i = \left(1 - \frac{1}{n_f}\right)^{2(\lceil \frac{N}{2} \rceil - 1)} \quad (2)$$

The directional link connecting node i to node j is denoted by l_{ij} and the collection of directional links will be denoted by L . $Z(i)$ will denote the collection of node i 's neighbors. We denote by $L(U)$ ($U \subseteq N$) the collection of links collecting to nodes in U . Associated with each link l_{ij} has capacity c_{ij} . Let C_{ij} denote as the relative rate of c_{ij} and the maximal possible of a link, $0 \leq C_{ij} \leq 1$. From [2], the capacity of link should satisfy the following conditions:

$$\sum_{j \in Z(i)} C_{ij} \leq 1 \quad \forall i, j \in N \quad (3)$$

for bipartite graph, and:

$$\begin{aligned} \sum_{j \in Z(i)} C_{ij} &\leq 1 \\ \sum_{l_{ij} \in L(U)} C_{ij} &\leq \frac{|U| - 1}{2} \end{aligned} \quad (4)$$

$\forall i, j \in N, U \subseteq N, |U| \text{ odd}, |U| \geq 3$

for non-bipartite graph.

Let a route r be non-empty subset of L and R be the set of possible routes. We associate a traffic source with each route. Let source r generate traffic at rate x_r . The rate x_r is assumed to have a utilization function $U_r(x_r)$ to source r . Assume that $U_r(x_r)$ is a continuously differentiable, strictly concave, increasing function in the interval $(0, \infty)$.

III. CAPACITY ALLOCATION PROBLEM FORMULATION

In stable stationary state, the network flows come to the directional links should be equal or less than the link capacities, which are limited by capacities of nodes. It means that for any moderate initial condition, if $\sum_{r \in l_{ij}} x_r \leq c_{ij}$, $\forall i, j \in N$ and c_{ij} should satisfy condition expressed in inequalities 3 and 4, then the queue size, time delay, etc. will build up to an asymptotic average of $O(\cdot)$. Combining with conditions that node capacities in the Bluetooth network $G = (N, L, R)$ are constrained, and with assumption of utilization function $U_r(x_r)$ for source r mentioned in section 2, the optimal rate for the network flows that can be obtained by solving maximization problem [10], [13]:

Bluetooth network $G(N, L, R)$:

$$\begin{aligned} \max_{\{x_r\}} \quad & \sum_r \Delta_r U_r(x_r) \\ \text{subject to: } & \forall r \in R \end{aligned} \quad (5)$$

subject to: $\forall i, j \in N$

$$\begin{aligned} 0 \leq x_r &\leq c_{ij} | r \ni l_{ij} \\ \sum_{r \ni l_{ij}} x_r &\leq c_{ij} \\ \sum_{j \in Z(i)} c_{ij} &= C_i \end{aligned} \quad (6)$$

where capacity of link c_{ij} and capacity of node C_i must satisfy the constraints in expressions 3,4 and maximum constraints of node capacities. This optimization problem has a strictly concave objective function and the maximization is done over a finite set, so it has a unique solution.

We denote $x_r f_r(\sum_{s: s \in l_{ij}} x_s)$ as the cost function assigned to each route $r \in R$ on the link $l_{ij} \in L$, $i, j \in N$ of the Bluetooth network G . The cost function $f_r(\sum_{s: s \in l_{ij}} x_s)$ can represent for the cost to get QoS requirements, which can be time delays, queueing sizes, etc., and assume it is continuous within stable limits of network. It is natural to define the cost of a flow x_r in G as:

$$\Phi_r(x_r) = \sum_{l_{ij} \in r} x_r f_r(\sum_{s \ni l_{ij}} x_s) \quad (7)$$

Only flows satisfying the capacity constraints will really be of interest and $f_r(\sum_{s: s \in l_{ij}} x_s)$ is closed proper convex and finite on c_{ij} , then:

$$\begin{aligned} \Phi_r(x_r) &\leq +\infty \quad \forall r \in R \\ \Leftrightarrow \sum_{s: s \in l_{ij}} x_s &\leq c_{ij} \quad \forall l_{ij} \in R, r \in R, i, j \in N \end{aligned} \quad (8)$$

By applying the feasible distribution theorem [9], it ensures the existence of at least one solution $x = (x_r, r \in R)$ that minimize the cost $\Phi = (\Phi_r(x_r), r \in R)$ satisfying the constraints 3,4.

We assume that searching the optimal rate of maximizing utilization function $U_r(x_r, r \in R)$ in (5,6) and the minimization requirement of the cost $\Phi = (\Phi_r(x_r), r \in R)$ in (7) represent the convex optimization problem. So the simultaneous capacity scheduling and allocation problem can be formulated as the following convex optimization problem:

Bluetooth network $G(N, L, R)$:

$$\max_{\{x_r\}} \sum_r \{\Delta_r U_r(x_r) - \beta \Phi_r(x_r)\} \quad (9)$$

subject to: $\forall i, j \in N, r \in R, l_{ij} \in L$

$$\begin{aligned} 0 \leq x_r &\leq c_{ij} | r \ni l_{ij} \\ \sum_{r \ni l_{ij}} x_r &\leq c_{ij} \\ \sum_{j \in Z(i)} c_{ij} &= C_i \end{aligned} \quad (10)$$

where Δ_r and β are constants that represent for trade-off of maximizing utilization function and minimizing the cost function.

In section 4, the hybrid distributed iterative capacity allocation scheme is introduced as an approximated solution of the convex optimization problem.

IV. HYBRID DISTRIBUTED ITERATIVE CAPACITY ALLOCATION SCHEME

The proposed hybrid distributed iterative capacity allocation scheme requires its own capacity partitions on each node of the Bluetooth network and it will try to divide network capacity to the links and to traffic sources in principles of maximizing the network flows and satisfying QoS requirements as formulated in the convex optimization problem in equations 9,10 . Each host node will inform other nodes on the route paths about estimated demand traffics, estimated permitted traffics to meet QoS requirements. The capacity of node in the network will be allocated to links controlled by the node and this allocation is based on the estimated demanded traffics outbound from the node. Allocations of link capacities are iterated on each link along the route paths. Resources of the link are divided to the longest route paths first and the unused resources will be allocated to the shortest route paths in the last iteration. These resource partitions will be combined with the estimated demand traffics, the estimated permitted traffics to meet QoS requirements and selected according to principles of satisfying QoS requirements and minimizing bandwidth. The process can be initiated by a node in the network when there is enough traffic change. It can also combine with routing discovery process, so that the capacity allocation is updated periodically.

Figure 1 illustrates the stages of the hybrid distributed iterative capacity allocation session with acceptance and blocking processes. The allocation process comprises three stages. In the first stage, nodes connecting to traffic sources estimate the demand traffics \hat{x}_r arriving from the sources and the permitted traffics \hat{x}_r^q that still satisfying QoS requirements. The \hat{x}_r and \hat{x}_r^q are predicted based on history records of packet arrivals from sources attached to the nodes and of QoS information updated periodically by nodes along the routes to the source nodes. The QoS information can be packet delays, packet losses, etc., for the sources. In a subsequent corrective step Δ_r^q , \hat{x}_r^q is increased or decreased according to QoS criteria being met or not, respectively. Each node will transmit the traffic estimations of the traffic sources attached to the node to other route nodes in probe messages. There are some approaches to assign link capacity [2]. However, in our scheme, the link capacity is allocated according to the outbound estimated demand traffics. Each node in the network will calculate and allocate its own capacity to the links that are under its control from the outbound estimated demand traffics and capacity of the node:

$$c_{ij} = \frac{\sum_{r:r \in l_{ij}} \hat{x}_r}{\sum_{r:r \in l_{is}, s \in Z(i)} \hat{x}_r} C_i \quad (11)$$

$$\forall i, j \in N, j \in Z(i), r \in R, l_{ij} \in L$$

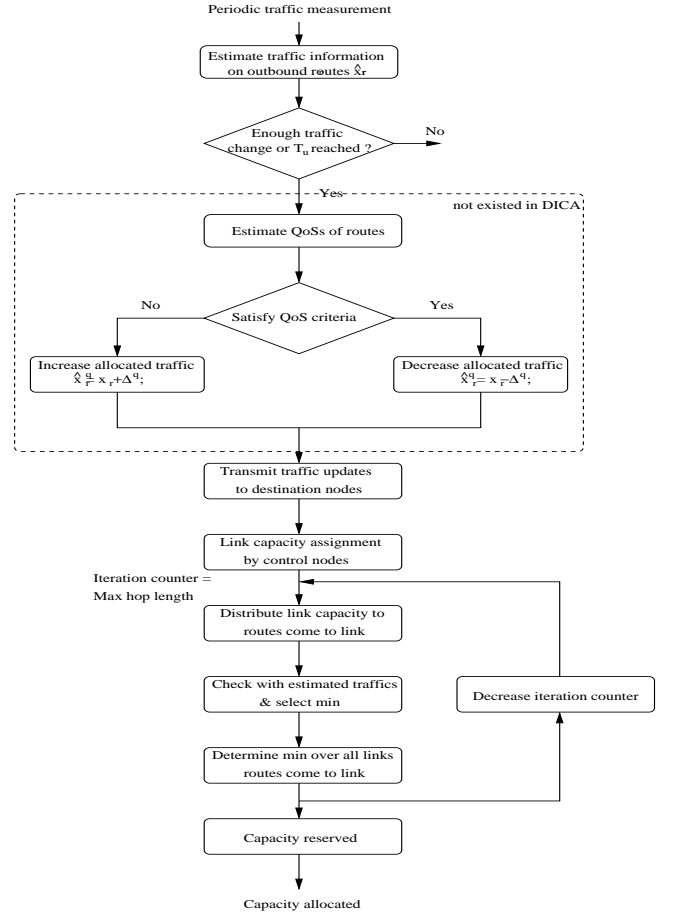


Fig. 1. Hybrid distributed iterative capacity allocation scheme in Bluetooth network

This stage can start when a node measures a significant traffic fluctuation or in a certain amount of time, and then making all nodes in network will transmit probe messages. The measurement is carried out in intervals T_m and the parameter T_u is the updating period. These parameters can be optimized for a specific traffic pattern to give the best information on the network transient behaviors. In this stage, it is assumed that each node has knowledge about the updated route paths in the links that it controls. In practice, this information can get from route discovery and network state updating.

In next stage, allocated resource on each link is divided to all route paths that come through the link. This partition is based on information about the estimated demand traffics, the estimated permitted traffics to meet QoS requirements for all route paths from the previous stage and capacity fraction from fair share capacity allocation approach. The fair share capacity allocation approach [12] is applied to get the maximum network flows and it is combined with the traffic demands, the permitted traffics to get the best use of the network capacity and to satisfy QoS requirements. In the first iteration, resources of the link are distributed to the route paths, so that the estimated Quality of Services (QoS) should not violate the QoS constraints. If any violation occurs, the link

capacity will be divided according to the saturation allocation. The amount portion $x_r^{l_{ij}}$ is the min value of \hat{x}_r^q , which is the capacity limit of the route path to meet the QoS constraints, the estimated demand \hat{x}_r and the divided fair share fraction:

$$x_r^{l_{ij}} = \min \left\{ \hat{x}_r, \hat{x}_r^q, \varepsilon \left(\frac{c_{ij} - \sum_{s: s \in l_{ij}} x_r^s}{1 + \varepsilon u} \right) \right\} \quad (12)$$

where the variable ε is to express the ideal QoS constraints tradeoff, e.g. throughput, delay, etc., x_r^s is the allocated capacity of the saturated route paths and u is the number of route paths of the link, which are not saturated before this iteration. The results are updated to traffic information messages. The process is iterated for successive links and the amount of available capacity is stored in the traffic information messages as they traverse through the links. At the end node, the saturation portion of the capacity for the route path can be determined by the minimum value of the stored $x_r^{l_{ij}}$ s all over the links:

$$x_r = \min_{l_{ij} \in r} \{x_r^{l_{ij}}\} \quad (13)$$

The results are sent back to the original source node. The allocation iterating is finite, because if there are r routes, they will be allocated after no more than r iterations.

In the last stage, the final capacities are reserved. As a result of the allocation processes, the route paths with longest hop lengths get capacities first and the shortest route paths take all left available capacities. However, the on-going connection is to be normally disconnected by depleted. The allocated capacities will adaptively approach to satisfy QoS demands and to make the best use of the network resources highlighted in the convex optimization problem in equations 9,10.

V. THE EVALUATION OF THE HYBRID DISTRIBUTED ITERATIVE CAPACITY ALLOCATION SCHEME

The performance evaluation of the proposed hybrid distributed iteration capacity allocation scheme (HDICA) addresses the following issues: the relationship between updating period and packet blocked probability, the ability to avoid congestion and the parameters affected to acceptance probabilities. It is also compared with distributed iteration capacity allocation scheme (DICA), i.e. the QoS criteria are not applied, and \hat{x}_r^q , which is represented for the permitted traffic to meet QoS criteria, does not appear in equation 12.

The network modeled in the section 2 is considered. When a Bluetooth packet from a source is supposed to arrive to a link on its route paths, it would be blocked if link is overloaded. In case that the arrival traffic is assumed to consist of a number of identical on-off sources with exponentially distributed *ON* and *OFF* periods, the packet blocked probability due to capacity c_{ij} of link l_{ij} exceeded can be estimated by the fluid-flow approximation for the k th interval, as:

$$p_b^{l_{ij}} = \frac{E[(\Lambda_{ij} - c_{ij})^+]}{E[\Lambda_{ij}]} \Big|_{l_{ij} \in L} \quad (14)$$

where Λ_{ij} is the aggregate load of the link l_{ij} during the updated period T_u and it depends on the established traffics x_r to the link during the k th interval:

$$\Lambda_{ij} = \frac{1}{T_u} \sum_k^{k+T_u-1} \sum_{r \in l_{ij}} x_r \quad (15)$$

The packet blocked probability estimation is accurate to a satisfactory degree if the sampling at the intervals of length T_u is long enough, which represents the dominant time-scale for the blocked process. In other words, it is an estimate of blocked packets based only on time-scale of T_u . Equation 14 then selects the dominant time-scale as the one giving worst packet blocked.

The efficiency of the hybrid distributed iterative capacity allocation approach is heavily dependent on the estimations of the demanded traffics of outbound traffic sources, and the permitted traffics to meet QoS requirements. By adaptively changing the permitted traffics, we can ensure that it will approach to satisfy the QoS demands. These estimations can be based on the past records that kept in the traffic histories. In next section, the performance evaluations and comparisons will be illustrated through simulation of a simple Bluetooth scatternet.

VI. SIMULATIONS

A. Simulation model

The Bluetooth network in consideration is a simple scatternet, as depicted in figure 2, which consists of two interconnected piconets. The piconet provides full-duplex transmission using time slots. The polling in Bluetooth piconet can be done in many different ways. The difference between the polling schemes is related to the order in which slaves are polled and the service disciplines used to serve a slave. In this simulation, we use the Fair Exhaustive Polling (FEP) [3] as the polling scheme in the piconets. The FEP gives high bandwidth efficiency with a fair allocation, while still being simplistic. Each piconet has a master and N slaves, $0 \leq N \leq 7$, and its traffic can be modeled as in [5]. The inter-piconet traffic is transferred through a bridge node (*S07/S17*). The modeled network uses asynchronous connectionless link (*ACL*). It is possible to send packets in multiple slots, which may be either 3 or 5 slots long. In this study, only the single slot data packet transmission between nodes in the modeled network is considered. Further, we assume that there is no transmission error and packet loss only occurs when the buffers are overflowed. Moreover, the piconets were assumed to be synchronized, which means there were no guard frames when the bridge node switches between the piconets.

The homogeneous traffics of packet arrivals can be modeled as Interrupted Bernoulli Process (IBP) sources [6]. The probability of transition between *ON* and *OFF* states could be characterized by p_{ON} and p_{OFF} . The packet arrivals are set to be aligned with the time slots in the modeled piconets.

The modeled scatternet uses the predictive inter-piconet scheduling [6], with the scheduled inter-connected window

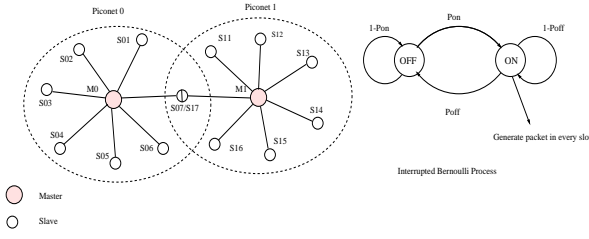


Fig. 2. The modeled Bluetooth scatternet with two inter-connected piconets and IBP traffic model

period T_s of the bridge node is set to 400 time slots and it is fairly allocated to the piconets, which the bridge node is connected to. The allocated active intervals of the bridge node on each piconet, which it belongs to, are dynamically varied depending on inter-piconet traffics and to/from the bridge node.

To verify working ability of the hybrid distributed iterative capacity allocation scheme in the Bluetooth modeled network, the output buffer sizes on each node are set to 40 packets, capacity of each node are set to C and it is the same for the nodes in the modeled network for a update period T_u . The increase/decrease step to adaptively change the permitted traffics to meet QoS requirement, i.e. packet losses, is set to 5 packets. The QoS parameter for each source route is γ , which can be 0.04 and 0.10. The simulation length is 10^6 time slots.

To estimate the demand traffics and the permitted traffics to meet requirement on packet losses on routes, several methods can be used, which possibly base on mathematical modeling of the estimated traffics. However, we use simple Levinson-Durbin algorithm, which is rather efficient to solve the Yule-Walker equation [14]:

$$R_X^{(M+1)} \begin{bmatrix} 1 \\ a_1^{(M)} \\ \vdots \\ a_M^{(M)} \end{bmatrix} = \begin{bmatrix} \alpha^{(M)} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (16)$$

where R_x is a $(M+1) \times (M+1)$ Hermitian Toeplitz matrix, $a^{(M)}$ is prediction coefficient and $\alpha^{(M)}$ is error variance. To simplify, the prediction order M was set to 2 and the record history of 3 previous measured data was applied.

B. Numeric results

Figure 3.b shows an example of capacity allocation for the links, which were controlled by the master $M0$, in case the hybrid distributed iterative capacity allocation scheme were applied. As mentioned in section 2, the capacities were allocated to links according to the demand traffics from traffic sources to the links. Higher traffic demand to a link means higher allocated capacity ratio to that link. It is natural that the capacities allocated to links that connect the node $S07/S17$, which is the bridge node, are much more higher than the links that connect to other nodes in the piconet. This is because of the homogeneous traffic sources and of higher inter-piconet traffic demand.

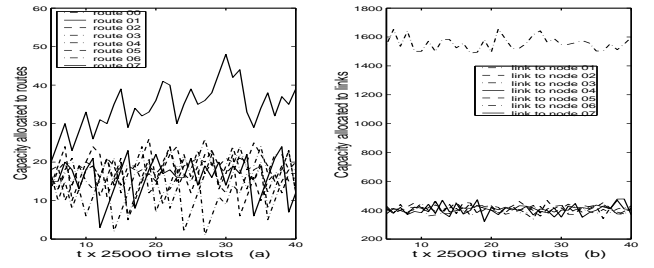


Fig. 3. Transient behavior of Bluetooth scatternet, with hybrid distributed iterative capacity allocation: an example of capacity allocations for routes and for links controlled by master

The allocated capacity of link was divided to the routes, which were passed through the link, and results are illustrated in figure 3.a. It shows an example of capacity allocated to the traffic sources, which were accompanied by the routes and attached to a node in the modeled network. The capacity allocation to the traffic source depends on available capacity of links that its route comes through, the estimated traffic demand and the estimated permitted traffic to meet QoS requirement (packet losses). Figure 4 shows the modeled network performance, when the hybrid distributed iterative capacity allocation (HDICA) and the non hybrid distributed iterative capacity allocation (DICA) were applied, when traffic intensity was increased. The latter did not use QoS oriented capacity allocation and the QoS requirement criteria, i.e. \hat{x}_T^q does not appear in equation 12. The packet loss probability (fig.4.a), when the HDICA was used, is much more lower than when the DICA was used. It indicates the QoS oriented capacity allocation scheme reduces packet losses. Furthermore, the figure also shows that the QoS criteria γ and the updating period T_u affect to the packet loss performance. Lower γ or longer T_u means lower packet loss probability. Figure 4.b shows performance of the modeled network, in terms of packet blocked percentage, when increasing the network traffic intensity. From the figure, the HDICA blocks more packets entering to the network than the DICA. And similarly, the QoS criteria γ and the updating period T_u also affect to the packet loss performance. When the traffic intensity is very low, the percentage of the block packets with the HDICA application is kept high, because of the high prediction errors of the Levinson-Durbin recursion, which was used for traffic and QoS estimations in the HDICA. In the very low traffics, the uncorrelation of the measured demand traffic and the feedback packet losses are significantly increased, the spectral flatness is inversely decreased. It means higher prediction errors.

Figures 4.c and 4.d compare performance of the modeled network in terms of profitability and process gain ratios, when the hybrid distributed iterative capacity allocation and the non hybrid distributed iterative capacity allocation schemes were applied. It also illustrates the modeled network performance for different QoS requirements (packet loss) γ and updating periods T_u . The profitability is the ratio between the handled traffic without overhead and the traffic admitted to the network. When increasing traffic intensity, the profitability is kept

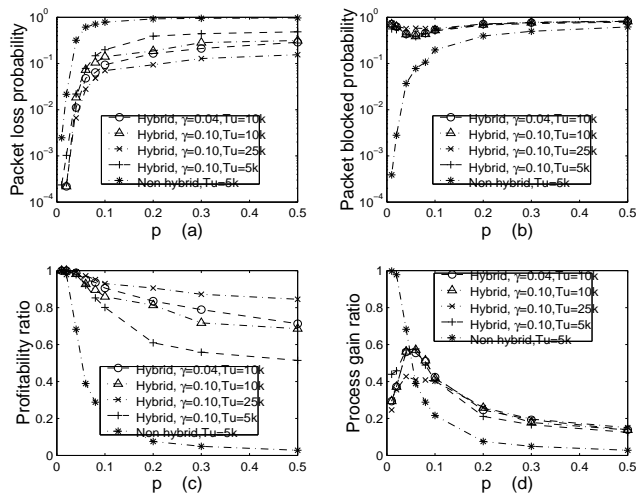


Fig. 4. Performance of Bluetooth scatternet, comparison of hybrid and non hybrid distributed iterative capacity allocations

higher in case of the hybrid distributed capacity allocation. More restricted packet loss requirement or longer update period also help to maintain high profitability.

Process gain comparison is depicted in figure 4.d. The process gain ratio is defined by ratio of the handled traffic, without overhead, and the arrival traffic. The increment of traffic intensity of the nodes in the modeled network is followed by the decrement of process gain. However, at very low traffic intensity, due to high prediction errors, which is caused by low correlationness and spectral flatness, the working ability of the hybrid distributed iterative capacity allocation scheme is poor. The process gain for the hybrid distributed iterative capacity allocation scheme is higher than for the non hybrid distributed iterative capacity allocation scheme. It means higher throughput. More restricted packet loss requirement and longer updating period also reduce process gain.

VII. OPEN ISSUES

There are still many open issues to the hybrid distributed iterative capacity allocation scheme. The main open issues we study are following:

- The scheme uses a lot of messages to exchange information between nodes in the Bluetooth network. It burdens to the system and requires complicated message handling.
- The mobility of Bluetooth nodes, dynamic network topology can subject to changes of routing algorithm and of capacity allocated to the nodes in the network. It also requires special message handling. It should have further investigation and improvements on the hybrid distributed iterative capacity allocation scheme to cope with these issues.
- The simulation showed the need of a good predictor. More efficient and sophisticated prediction algorithms should be investigated to improve the working ability of the allocation scheme.

- It indicates the application of the dynamic alternative routing schemes and the adaptive capacity allocations, network topology could enhance the performance of Bluetooth network.

VIII. CONCLUSION AND FUTURE DEVELOPMENT

We have considered the problem of optimal resource allocation for Bluetooth network. The network resource allocation problem is optimized through capacity constraints on the total traffic supported on individual Bluetooth nodes. We formulated the allocation problem as a convex optimization problem, in which the total network flows and the costs of the flows to get the QoS requirements are concave function of the associated resource variables.

We also developed the hybrid distributed iterative capacity allocation scheme. The allocation scheme tries to get maximum network flows while satisfying QoS requirements. The scheme uses iteration cycle and QoS requirements to the traffic sources to reallocate the capacity. The computations needed are simple but the complexity is instead moved to the management of control messages. The simulations showed the working ability of Bluetooth network could be improved by applying the hybrid distributed capacity allocation scheme. Some open research issues were discussed and it requests further research.

REFERENCES

- [1] Bluetooth Special Interest Group, *Specification of Bluetooth System*,
- [2] G. Zussman, A. Segall, *Capacity Assignment in Bluetooth Scatternets: Analysis and Algorithms*, in Proceedings of IFIP-TC6 Networking 2002, LNCS Vol. 2345, May 2002.
- [3] N. Johansson, U. Korner and P. Johansson, *Performance Evaluation of Scheduling Algorithms for Bluetooth*, Proc. of IFIP TC6 Fifth International Conference on Broadband Communications '99, Hongkong, November 1999.
- [4] P. Johansson et al. *Inter-piconet communication in Bluetooth networks*, November 2000.
- [5] H. Schiøler, J.D. Nielsen, O.B. Madsen and S. Le Thanh, *Communicating cooperative robots*,
- [6] S.T. Le, H. Schiøler, O.B. Madsen, *Predictive scheduling approach in Inter-piconet Communications*, Proc. WPMC'01, Aalborg, September 2001.
- [7] S. Baatz et al. *Bluetooth scatternet: An Enhanced Adaptive Scheduling Scheme*, Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM 2002, New York, June 2002. Texas, USA, November 2001.
- [8] S. Basagni, C. Petrioli, *A Scatternet Formation Protocol for Ad Hoc Networks of Bluetooth Devices*, IEEE Vehicular Technology Conference Spring 2002, Vol. 1, pp. 424-428.
- [9] R.T. Rockafellar, *Network Flows and Monotropic Optimization*, John Wiley & Sons, 1984.
- [10] S. Kunniyur and R. Srikant, *A time-scale decomposition approach to adaptive ECN marking*, to appear in the IEEE Transactions on Automatic Control, Anchorage, Alaska, 2001.
- [11] Harold J. Kushner, *Heavy Traffic Analysis of Controlled Queueing and Communication Networks*, Springer -Verlag, 2001.
- [12] J. M. Jaffe, *Bottleneck Flow Control*, IEEE Trans. on Commun. vol. 29, no.7, pp. 954-962, 1981.
- [13] L. D. Berkovitz, *Convexity and Optimization in R^n* , John Wiley & Sons, 2001.
- [14] M. H. Hayes, *Statistical Digital Signal Processing and Modeling*, John Wiley & Sons, 1999.