Modeling and Evaluation of Bluetooth MAC Protocol

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Abstract – **The emergence of Bluetooth as a default radio interface allows handheld electronic devices to be instantly interconnected into ad hoc networks. These short range ad-hoc wireless networks, called piconets, operate in the unlicensed 2.45 Ghz ISM (Industrial-Scientific-Medical) band where up to eight devices may be used to configure single or overlapping piconets. This creates interference on the device from other devices operating in the same frequency band including microwaves and devices enabling various wireless LAN standards. This paper uses a signal capture model to study piconet MAC performance. Furthermore, simulations are used to validate the throughput obtained from this model. These results reveal important performance implications of the effect of inter-piconet interference on throughput.**

I. INTRODUCTION

Wires, wires, wires everywhere. Now it is possible to connect everything without any wire starting form phones, PDAs, and all PC devices. This is achieved by the emerging Bluetooth concept for building ad hoc wireless networks presented in February 1998 [1, 6, 10]. Bluetooth is an open specification technology for short-range wireless connectivity between electronic devices. It is proposed to be the IEEE 802.15 standard for personal area networks (PANs). In these networks, both synchronous traffic such as voice, and asynchronous data communications are supported.

This standard has the main advantage of establishing ad hoc networks, called piconets, reducing the need for wiring between personal devices such as computers, keyboards, printers, mobile phones, LANs, etc, within a small distance (up to 10m [10]), hence creating a new range of applications. Between two and up to eight devices form a piconet where access is coordinated by a master device through a polling scheme. A given device may take part in more than a piconet leading to configurations with overlapping piconets known as a scatternet (see Fig. 1). The Bluetooth design is such that interference is often the result of transmission in neighboring piconets since devices within the same piconet coordinate their medium access. Among other things, this work looks at the effect of such interference on piconet performance.

A large number of studies for wireless networks with random access, such as Slotted ALOHA [5], use the "capture" phenomenon [7, 8, 9]. Capture is defined as the receivers' ability to detect a signal in the presence of other interfering signals. This model is based on the concept that signal reception is possible as long as the signal to interference ratio (SIR) is above a given threshold, known as the *capture ratio*. This paper extends this study to Bluetooth networks where devices receive transmitted signals from different piconets with varying power levels. Mainly, this work presents an analytical model that determines the *normalized throughput*, or the number of correctly received packets per slot of the Bluetooth medium access protocol, and conducts simulations to validate the obtained results.

This paper is organized as follows. Section two introduces the Bluetooth architecture, with special emphasis on its medium access protocol. Next, sections three and four present the analytical model whereas section five discusses its main results. Sections six and seven describe the simulation model and its results respectively. Finally, section eight gives some final concluding remarks.

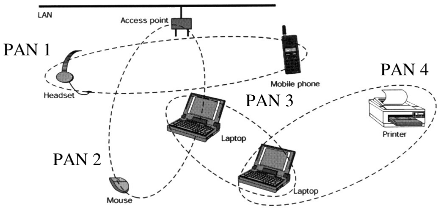

Fig. 1. Bluetooth Connectivity Model.

II. THE BLUETOOTH PROTOCOL ARCHITECTURE

Concerning the MAC, the basic Bluetooth protocol stack defines the following protocols:

- *Link Manager Protocol* (LMP) – Manages the link state and is also responsible for power control.
- *Logical Link Control and Adaptation Protocol (L2CAP)* – This is a data link level protocol. L2CAP is responsible for packet multiplexing, segmentation and reassembly as well as medium access control.

L2CAP, together with LMP, uses polling from a master device for medium access control. A device that is selected by the master may transmit whereas others must wait for their turn. Hence, collisions are avoided between devices within a single piconet. L2CAP adopts a channel communication model representing a data flow among remote devices. Such channels may be connection oriented or connectionless.

Definition of the Physical Link: The Bluetooth specification defines two distinct types of links for the support of voice and data applications, namely, SCO (*Synchronous connection-oriented*) and ACL (*Asynchronous connectionless*). Whereas the first link type supports point-to-point voice switched circuits, the latter supports symmetric as well as asymmetric data transmission.

Furthermore, the ACL mode allows the use of 1, 3, and 5-slot data packets with the optional use of FEC (*Forward-Error Correction*). Table 1 presents the average transmission rates [6] using ACL links. These results where measured in ideal conditions without the presence of interference. In this table, DMx represents x-slot, FEC encoded data packets; DHx represents unprotected packets. This work mainly considers the use of ACL links since the L2CAP specification has been defined only for this link type [1, 10], and most data applications will use this kind of link.

TABLE 1 – THROUGHPUT (IN KBPS) USING ACL LINKS.

Type	Symmetric (Kbps)	Asymmetric (Kbps)	
DM1	108.0	108.8	108.8
DH1	172.8	172.8	172.8
DM3	256.0	384.0	54.4
DH3	384.0	576.0	86.4
DM5	286.7	477.8	36.3
DH5	432.6	721.0	57.6

III. MODEL ASSUMPTIONS

A simple model has been devised which takes into consideration an environment consisting of a set of independent piconets. As can be seen from [1], interference is likely to occur between a set of independent piconets once the clock settings are not synchronized and, thus, packets from neighboring piconets overlap. This paper gives special attention to this case, nevertheless it indicates the required changes in order to adapt it to the scatternet environment.

We assume that devices, from one or more piconets or a scatternet, are geographically distributed in a plane according to a Poisson process with λ stations/m^2 density. It is also assumed that a transmitting device is located at the center of an imaginary hexagonal cluster and operates using an omni-directional antenna. For mathematical convenience, the hexagonal area is normalized to π and the clusters are approximated by circles of unit radius.

L2CAP avoids packet collision within a piconet, but lack of synchronization among independent neighboring piconets conduces to packet overlapping within a time slot. The transmission power P_R, received by a receptor located at a distance r, is computed assuming a propagation model that takes into consideration signal attenuation, lognormal shadowing due to surface irregularities, and a η-th power loss law, where the propagation loss exponent, η, is around 4 [2]. As a result, the received signal P_R is given by [3]:

$$P_R = \alpha^2 e^{\xi} K r^{-\eta} P_T, \tag{1}$$

where α^2 is an exponentially distributed random variable with unit mean, ξ is a Gaussian random variable with zero mean and variance σ^2, Kr^{-n} refers to the power loss law, and P_T represents the transmitted power. The same signal propagation model is assumed for all devices. Since the lognormal attenuation variable ξ is given in dBs, the shadowing parameter, σ, is normally given in dB as well. Please note that the notation $\sigma = 0$ means that the lognormal attenuation in dB is Guassian with a null variance, in other words it is constant. This work uses a capture model which assumes that a receiver may correctly detect and receive a signal with power P_0 if: $\frac{P_0}{\sum_i P_i} > b$

where P_i represents interference resulting from the transmission of packets at piconet *i*, and *b* represents the capture threshold. Since the ISM band is an open one, other interference caused by non-Bluetooth devices is outside the scope of this study.

IV. THROUGHPUT ANALYSIS

In the following "0" and "*i*" refer to the expected and interference signals from piconet i ($i \neq 0$) respectively. According to the adopted capture model, the probability, P_S, that a transmitted packet by device "0" is successfully received when there are $\kappa \geq 1$ packet(s) (κ = n° of active piconets) is given by:

$$P_S = P\left[\frac{\alpha_0^2 e^{\xi_0} K r_0^{-\eta} P_T}{\sum_{i=1}^{\kappa} \alpha_i^2 e^{\xi_i} K r_i^{-n} P_T} > b\right], \tag{2}$$

Eq (2) assumes that piconets are independent from one another, which is the focus of this study. When considering scatternets, equation (5.148) from [11] may be applied with slight modifications to both the equation itself and to this model. The total offered load of new and retransmitted packets may be characterized with a distribution of density G packets per slot per cluster. Since P_S depends on user location, the transmitted packet density $g(r,\theta)rdrd\theta$ packets/slot in an area (r,θ) mainly depends on r and θ. Thus, the total traffic within a cluster is given by the sum:

$$G = \int_0^{2\pi} d\theta \int_0^1 r dr g(r,\theta). \tag{3}$$

Similarly, the throughput is given by:

$$S = \int_0^{2\pi} d\theta \int_0^1 r dr s(r,\theta), \tag{4}$$

where $s(r, \theta)$ is the throughput density. Next, the distribution of interference is examined. The probability of success P_S, in turn, depends on the $g(r, \theta)$ density law of the offered traffic. Even with the assumption that the device locations follow a Poisson distribution, $g(r, \theta)$ is not uniform as a result of the previous considerations. This introduces a high complexity level difficult to deal with in the analytical model. For simplicity, the following assumptions have been made:

I. Devices causing interference are uniformly distributed outside a piconet according to the Poisson spatial model;

II. Interfering transmissions are generated by devices independently of others and from slot to slot, in such a way that they collectively follow a Poisson model with G packets per slot per cluster;

III. The Variables α_i^2 and ξ_i are drawn independently at each transmission.

Assumption III is the result of considering attenuation conditions when using narrowband transmission independent from slot to slot [4]. The above considerations simplify the analysis as they ignore temporal and spatial correlation existing among transmitting devices. Consequently, the power interference distribution and the capture process only depend on G. The success probability P_S is obtained from (2), where κ is a random Poisson variable and r_i, $i = 1,...,\kappa$, are linearly distributed on the plane (i.e., user locations are uniformly distributed), according to assumptions I and II. At the end of the averaging process we obtain [12]:

$$P_S(G,r_0)=\int_{-\infty}^{\infty} d\xi \, \frac{e^{-\frac{\xi^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} e^{-GJ(\xi,r_0)}, \qquad (5)$$

where:

$$J(\xi,r_0)=\int_{-\infty}^{\infty} dx \frac{e^{-\frac{x^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma}\int_{1}^{\infty} \frac{2rdr}{1+b^{-1}e^{\xi-x}\left(\frac{r}{r_0}\right)^{\eta}}. \qquad (6)$$

The throughput is obtained by considering equilibrium between the newly generated traffic and the traffic that is successfully transmitted, i.e., $s(r)=P_S(G,r)g(r)$. (7)

Eq. (7) represents a generalization of eq. (37) in [5]. A simple solution is given when the throughput is uniform. In this case $s(r) \equiv s$ and $S = \pi s$, where π is the cluster area. By substituting $g(r)$ in (3) as obtained in (7) we have:

$$G=\int_{0}^{1}\frac{2\pi r dr s}{P_S(G,r)}, \qquad (8)$$

from which s may be derived resulting in the throughput as a function of G:

$$S(G)=\pi s = G\left(\int_{0}^{1}\frac{2rdr}{P_S(G,r)}\right)^{-1}. \qquad (9)$$

V. Model Analysis

The approximate analytical model presented in the previous section provides a quantitative performance evaluation of the Bluetooth medium access protocol. For this study, seven piconets have been considered ($\kappa = 7$).

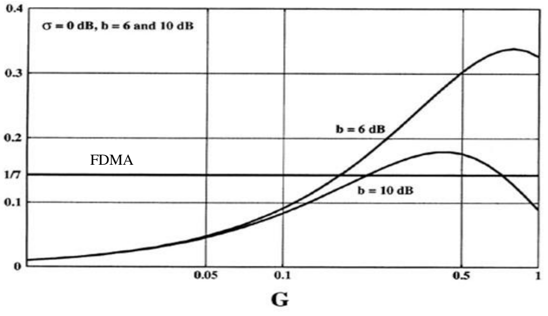

Fig. 2. Average Throughput per Piconet, S, vs. Offered load per Piconet, G; $\sigma = 0$ dB, $b = 6$ dB and $b = 10$dB.

Figs. 2 and 3 show the normalized throughput, S, versus the offered traffic G, with $\eta = 4$ using realistic [11] different capture and shadowing parameter values b and σ respectively. Note that the throughput for FDMA is included for comparison purposes only. In this system, the maximum throughput does not depend on G and is given as $S = 1/\kappa = 0.143$. The maximum offered traffic in a Bluetooth network is represented by $G = 1$ since there could be at most one packet transmission per slot per piconet.

In both scenarios, the maximum throughput for L2CAP is higher than that of FDMA and that it remains below 0.34 packets/slot. The figure also shows that throughput increases with the decrease of the capture threshold which is expected. A close look at the effect of the parameter σ, reflecting interference and the presence of obstacles, shows that throughput increases for lower values of σ as depicted in Figs. 2 and 3. For instance, Fig. 2 illustrates the situation with less obstacles and satisfactory signal propagation. Here, the normalized average throughput S leads to a maximum throughput around 746.64 Kbps (b = 6 dB) and 395.28 Kbps (b = 10 dB). Additionally, Fig. 3 describes a scenario with a higher number of obstacles and interference. Here, the normalized average throughput S limits the throughput to around 614.88 Kbps (b = 6 dB) and 351.36 Kbps (b = 10 dB).

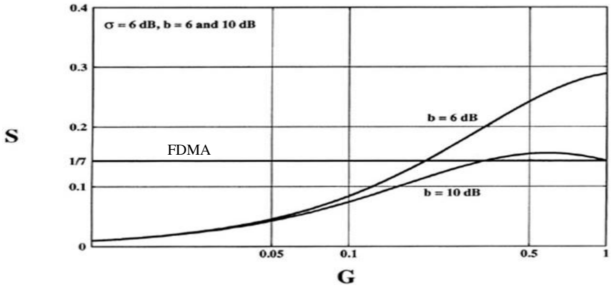

Fig. 3. Average Piconet Throughput, S, vs. Offered load per Piconet, G; $\sigma = 6$ dB, $b = 6$ dB and $b = 10$dB.

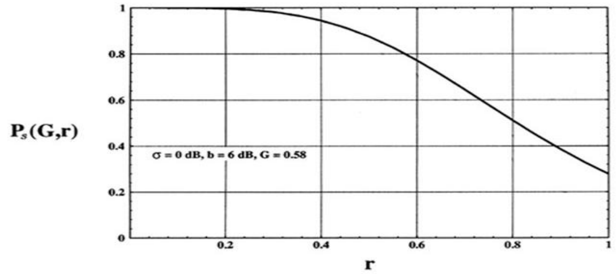

Fig. 4. Success Probability $P_s(G, r)$, vs. Distance r, for $\sigma = 0$ dB, $b = 6$ dB, and Intensity of Interfering Traffic $G = 0.58$.

This important result helps in determining the quality of service that applications should expect given the capture threshold. Furthermore, system performance may be evaluated in environments with varying interference.

Another crucial factor in determining a successful packet reception is the distance, r, between a transmitter and a receiver. Fig. 4 illustrates better the relationship among these parameters. Here, P_s is shown for varying r where interfering traffic from other piconets has been adjusted independently to $G = 0.58$ packets/slot/piconet, for $\sigma = 0$ dB and $b = 6$ dB.

Finally, Fig. 5 shows the behavior of P_s when varying r for $G = 0.43$, corresponding to $S = 0.28$ as previously presented in Fig. 2. When considering constant throughput $s(r)=s$, the corresponding curve $g(r)$ is inversely proportional to the one shown, see (7).

VI. SIMULATION MODEL

The simulation model and its L2CAP performance results are presented in the following two sections. The model implements the basic functionality of the Baseband, LMP and L2CAP layers using the NS-2 (*Network Sumulator - 2*). Classes like *BT_Baseband*, *BT_DRRScheduler*, *BT_LMP*, *BT_L2CAP*, *BT_Classifier*, *BT_Node*, *BT_Piconet*, etc, were implemented according to [1].

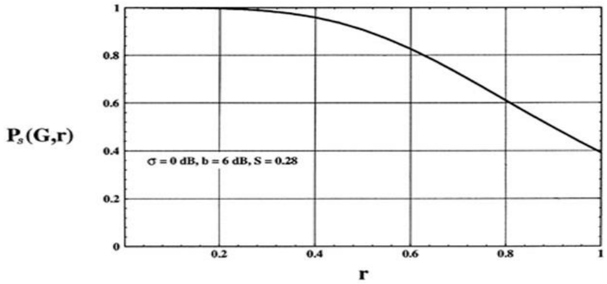

Fig. 5. Success Probability $P_s(G, r)$ vs. Distance r, using throughput S=0.28, for σ = 0dB, b = 6dB. Interfering Traffic G = 0.43pkts/slot/piconet.

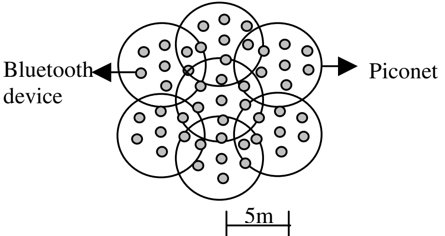

Fig. 6. Topology used in the simulation.

Network Topology: The topology adopted reflects a real Bluetooth configuration [6], namely, an office environment with different devices communicating concurrently within piconets. This work gives special consideration to interference among piconets since these are limited to eight devices including the master. Fig. 6 shows the topology used in the simulations where seven piconets have been defined with control over their interference. For illustration purposes, piconets are assumed to be circles with 4m radius where Bluetooth devices are distributed with a density of one device per 4m2. For simplicity, the devices are assumed to remain within the same piconet during the simulation, although these may freely move within their piconet. Moreover, in order to determine the maximum throughput, it has been assumed that higher layers always have data to transmit. ACL connections are modeled using a Poisson arrival process.

VII. DISCUSSION OF THE SIMULATION RESULTS

Validating the Analytical Model: Initially, the simulation results are compared to those from the adopted analytical model. Figs. 7 and 8 show the results obtained through simulation under the same conditions and input parameters. Although at a lower scale, the simulation results behave the same way as those from the analytical model. A lower throughput is obtained since the Bluetooth error recovery messages at the link level were not considered. Only data packets have been effectively computed. Table 2 compares the approximated throughput values obtained for the adopted network when varying interference and capture threshold levels using both simulation and analytical approaches.

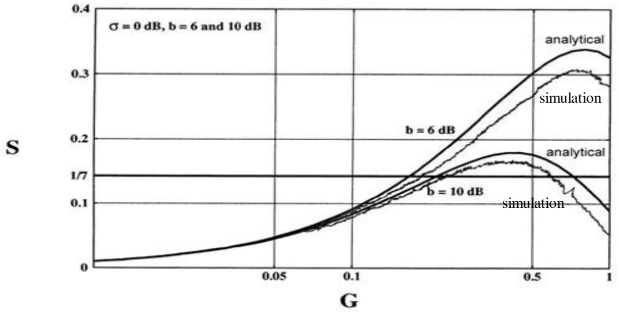

Fig. 7. Average Throughput per Piconet, S, vs. Piconet Offered Load, G; Analytical and Simulation Results for σ = 0dB.

TABLE 2 – THROUGHPUT (IN KBPS) FOR ANALYTICAL AND SIMULATION MODELS.

	Analytical Model	Simulation
σ = 0 e b = 6 dB	746.64	680.76
σ = 0 e b = 10 dB	395.28	373.32
σ = 6 e b = 6 dB	614.88	570.96
σ = 6 e b = 10 dB	351.36	329.40

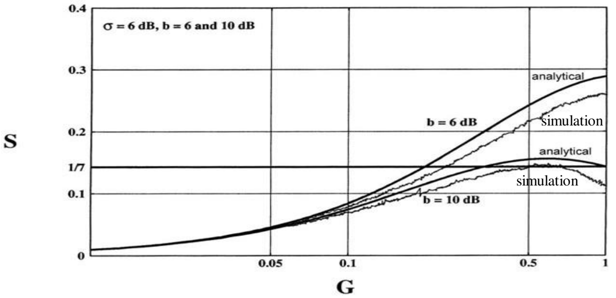

Fig. 8. Average Throughput per Piconet, S, vs. offered Piconet load, G; Analytical and Simulation Results for σ = 6dB.

Next, the probability that a packet is successfully received as a function of the distance r between transmitter and receiver is analyzed. Similar conditions to those from the analytical environment have been maintained in this simulation study. For example, traffic interference, from other piconets, has been independently adjusted to $G = 0.58$ packet/slot/piconet, for $\sigma = 0$ dB and $b = 6$ dB. Fig. 9 compares simulation and analytical results showing compatible trends. Finally, Fig. 10 depicts the behavior of P_s versus r for $G = 0.43$, where the results present compatible trends. The differences between the curves in Figs. 9 and 10 are due to the higher interfering traffic, G, in Fig. 9.

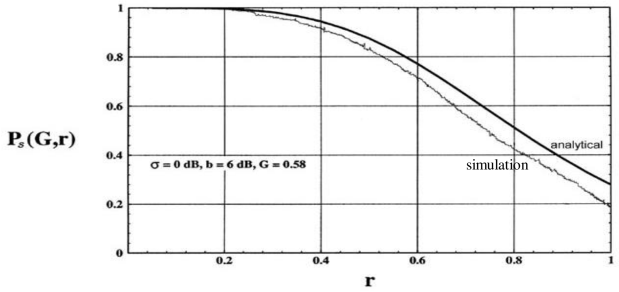

Fig. 9. Success Probability $P_s(G, r)$, vs. Distance r; Analytical and Simulation Results for Traffic Interference $G = 0.58$.

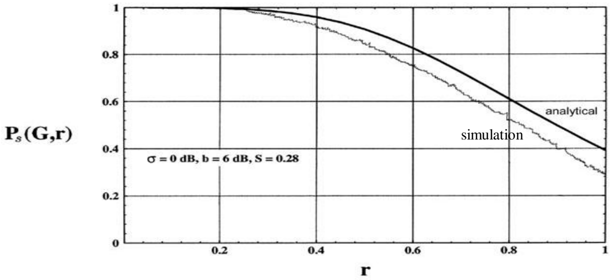

Fig. 10. Success Probability $P_s(G, r)$, vs. Distance r; Analytical and Simulation Results for constant throughput $S = 0.28$ and Interfering Traffic $G = 0.43$ pkts/slot/piconet.

Performance of DHx ACL Links: It is expected that most existing IP-based packet data transfer applications would be mapped using connectionless unreliable Bluetooth ACL links of type DHx. Therefore, their throughput, including in the presence of interference, are analyzed. Fig. 11 shows the average data throughput over DHx ACL links when using 1-slot, 3-slot and 5-slot data packets without interference. As expected, DH5 ACL links offer higher channel utilization than the two others. Overall, higher throughput is achieved compared when using DH1 and DH3. On the one hand, Fig. 11 also shows the relative inefficiency of DH1 ACL links and how these fail to take advantage of the channel. On the other hand, there is little performance difference between DH3 and DH5 ACL links although it may be decisive to applications requiring quality of service. Fig. 12 illustrates similar results now with the presence of interference. Note that this has a considerable influence on performance. In all scenarios, the fall in throughput is considered to be sizable. Table 3 provides a summary of DHx ACL throughput values with and without interference. These are compared with those from Table 1 in ideal conditions. A quick analysis shows that Table 3 analytical results are in line with the simulation ones obtained in Table 1 especially when there is no interference. A lower throughput is due to interference, highlighting the need to tailor applications to these working conditions.

VIII. CONCLUSION

The Bluetooth technology represents an attractive approach to enable short distance connectivity. This work presented the evaluation of the Bluetooth MAC, called L2CAP. L2CAP has been shown to offer good performance guarantees when compared to other access techniques such as FDMA. L2CAP performance has been evaluated using an analytical model and then validated through simulations. The results obtained are relevant for the use of piconets and the study of their interference and limitations on throughput.

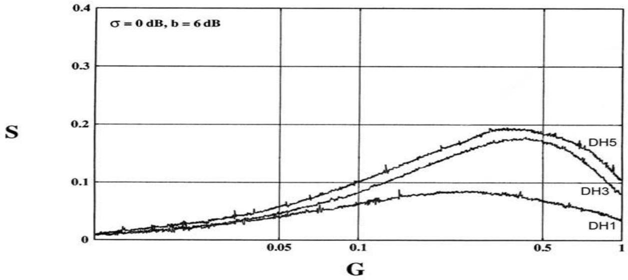

Fig. 11. DHX ACL Channel Throughput without Interference.

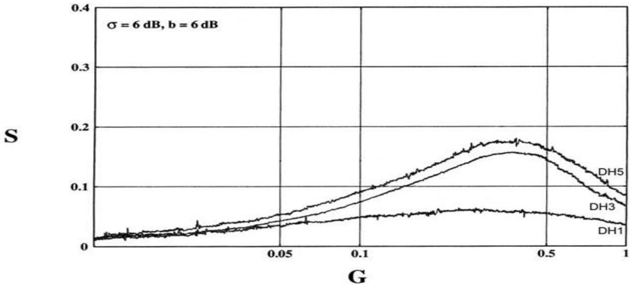

Fig. 12. DHX ACL Channel Throughput with Interference.

TABLE 3 – DHx THROUGHPUT WITH/WITHOUT INTERFERENCE (IN KBPS).

	Ideal Conditions	Without Interference	With Interference
DH1	172.80	166.66	120.78
DH3	384.00	373.32	329.40
DH5	432.60	417.24	373.32

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