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ASYMMETRY IN OPTICAL WIRELESS LINKS

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Abstract: In this work we examine the bit error rate performance of IrDA links when influenced by physical layer and channel asymmetries. Physical layer asymmetries are possible due to component variations, ambient noise variations, and third party interference. We describe how such asymmetries cause differential link bit error rates, which in turn result in throughput degradation at the link and higher layers. We develop a model for the asymmetries incorporating PHY layer and LINK layer parameters. The condition for symmetry in optical wireless links is derived. We demonstrate that link layer throughput asymmetries are possible as a result of physical layer parameter asymmetries. The magnitude of such throughput asymmetries is calculated. Examples are analysed based on some typical user model environments where asymmetries may take place. Results based on a model of the IrDA protocol stack are given.

1. Introduction:

The development of optical wireless links into products such as portable computers, digital cameras and even wrist watches has been fuelled by low cost optical components, optoelectronic circuits, and very significantly by efforts towards forming industry standards. IrDA, (Infrared Data Association), is an industry organisation formed in 1993, [2], involving many major companies with business interests in computing, telecommunications and consumer electronic products. IrDA has developed standards for short range IR links and it is now widely used by computer manufacturers in products such as laptops, PCs, and printers, [3]. Numerous future products and service planned by telecommunication organisations, (e.g. optical wireless links to ISDN) and by consumer electronics organisations, (e.g. digital camera links and wristwatches) will make use of optical wireless links.

There has been increased research activity and international collaborations in establishing the IrDA standards. As a result, there are currently industry standards developed for IrDA SIR (serial Infrared) and IrDA FIR (Fast IR). These new standards for IR links have speeds of 115.2 kbit/s and 4 Mbit/s respectively. The VFIR (Very Fast IR) is an extension to 16 Mbit/s. The master slave point to point user model has recently been also been extended to cater for a pool of wireless connected users. The MAC layer protocols of CSMA/CD with RTS/CTS exchange is used as the basis for medium contention. This latter user model corresponds to the AIr (Advanced IR) standard proposal.

For any communication link and in particular wireless IR links directional asymmetries in the link performance are not desired. The user should not therefore be aware of any directional performance asymmetries inherent in the system and clearly good design should aim for reducing their effect.
We also suggest that asymmetries be examined at the product design stage and this work addresses this important aspect of optical wireless links.

2. Asymmetry of the IR Channel:

Asymmetry in the communication link between two users is not usually a desired effect [3]. We define asymmetry as the differential quality grade of the point to point link between two users in either direction. This implies that one of the directions is more vulnerable, degrades and may break down first. Asymmetries may be caused due to transmitter or receiver differences between the users, or channel spatial asymmetries, as will be illustrated later in this work.
The following definition of asymmetry is used, which relates to the maximum operational distance of a bi-directional optical wireless link. The link is asymmetric when the maximum distance (for the same link quality) from A to B is not the same as that of B to A.
We measure the quality of IrDA links normally by the IR physical-layer bit error rate, (BER).

A link is therefore asymmetric when the distance between directional links for the same link quality, or alternatively the corresponding link BER is a function of direction of transmission, for some specific alignment angles q, f in spherical polar co-ordinates.

$$d_{AB}(q_A, f_A) \neq d_{BA}(q_B, f_B)$$

Or ………………….(1)

$$BER_{AB}(q_A, f_A) \neq BER_{BA}(q_B, f_B)$$

This type of asymmetry is defined as directional asymmetry.

2.1 Directional Asymmetry:

In practice, component specification and manufacturing tolerances, ambient noise differences and third user interference, [1], [3] can result in link asymmetries. Component specification variation in products even from the same manufacturer, is possible. Specifically within the IrDA standard, there is a range of recommended component specification. It is therefore likely that products within the same or between different manufacturers would have varied performance.
For low cost fixed threshold receivers this component variation leads to receiver threshold and transmitter intensity differences leading to asymmetric bi-directional communication.

A second cause of directional asymmetric links is differential ambient light noise variation between the link receivers. Considering user A of a link is illuminated with a spotlight (the user is perhaps requiring artificial light to aid his working) causing additional noise at one of the receivers, in comparison to the ambient light noise in the receiver of user B.

Finally, third user interference results when a third transmitting user, unaware of an existing active IR link, is transmitting to one of the engaged users, with result to cause interference on the existing active link. The interference results in degradation of BER in one of the link directions. The strength of interference depends on the position of the interferer relative to the link. The deterioration of BER results also in link layer throughput detriment.

2.2 Spatial Asymmetry:

Third user interference may result in spatial as well as bi-directional asymmetries even in the scenario when all users are identical. When the spatial contour of equal BER is asymmetric about the optical link axis, then we have spatial asymmetry. In general, IR channel asymmetries, such as reflections from objects, walls and other surfaces may well result in spatially asymmetric interference. This is a likely occurrence in practice, especially in IR LAN environments, resulting in spatially asymmetric IR link BER and higher layer throughput patterns.

In this paper we first define the conditions which result in symmetric free space IR links, and show how the various link components affect the symmetry. We define and analyse the basic IR link and subsequently we also examine how third user interference results in asymmetries in IR links. Specific result are presented for IR links based on the IrDA standard.

2.3 Condition for channel symmetry

The systems assumed in this work are baseband direct detection systems in general of low cost.
The output of such a system is represented by:

$$Y(t) = rX(t) \otimes h(t) + N(t) \quad \text{...(2)}$$

The output signal $Y(t)$ is given by the convolution, ($\otimes$), of the transmitted signal $X(t)$, and $h(t)$ the channel impulse response, where $H(0) = \int_{-\infty}^{\infty} h(t)dt$ is the channel d.c. gain, with $N(t)$ the signal independent additive white Gaussian noise, of double-sided spectral density N_0, and r is the detector responsivity
The electrical signal to noise ratio at the receiver photodetector output is given by:

$$SNR = \frac{\left(rP_R\right)^2}{N_0 B} \quad \text{..(3)}$$

Where P_R is the average received optical power, and B is the receiver bandwidth.
By defining $P_R = T \times \Omega = T \times A_{eff} / d^2$, with d being the distance between the transmitter and receiver, T is the transmitter intensity in (W/Sr), and Ω, the transmitter solid angle, and A_{eff} the receiver effective area, we can deduce using the symmetry condition $SNR_{AB} = SNR_{BA}$, the following:

$$\boxed{\frac{T_A\sqrt{N_{0A}}}{r_A A_{Aeff}} = \frac{T_B\sqrt{N_{0B}}}{r_B A_{Beff}} = \text{C} \quad \text{constant}} \quad \text{........................(4)}$$

where A and B are the labels for users A and B respectively.

We may define the thresholds of the receivers of users A and B as R_A and R_B respectively, where $R = \frac{\sqrt{N_0}}{rA}$, A is the receivers area, for both users. We then derive from (4):

$$\boxed{T_A R_A \cos^m q_A \cos^n q_B = T_B R_B \cos^m q_B \cos^n q_A = \text{const}ant} \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

We assume all LEDs and photodiodes have radiation patterns of the form $\cos^m q$ and $\cos^n q$ respectively. We also assume that for every user, the transmitter LED and receiver photodiode axes are aligned. The corresponding misalignment angles between users are as shown in Figure 1.
Equations 4 and 5 may be thought of as the symmetry conditions for optical wireless links, [1].
In simple hard decision direct detection receivers therefore, it is important to ensure that the product of the transmitter intensity times the receiver threshold is kept constant, and the radiation lobe patterns of the transmitter and receiver are the same, (m=n). In this case the fact that the user misalignment angles are different, $q_A \neq q_B$, does not affect the link SNR differentially in direction. If the radiation patterns of the transmitter and receiver of the same user are different, $m \neq n$, then $q_A = q_B$ is necessary for symmetry.
In this case, the bi-directional link is said to be symmetric. This symmetry is at the physical layer, resulting from directional symmetry in SNR, and not necessarily at higher layers of the link, (LINK layer for example).

3. Basic IR system model

The effect of bit error rate asymmetries due to ambient noise and component specification variation is demonstrated next. We assume two IR users as shown in Figure 1. Assume no reflections from other objects, and that no other users are interfering in the transmissions. The analysis here assumes that all users are on the same plane for simplicity. Although this may not be true in practice, it is assumed here in order to simplify the otherwise very complex system of users and interferers in 3 dimensions.
IR users A and B are assumed linked and exchanging data. Figure 1 illustrates the physical parameters of the model. User A has transmitter Tx1 and receiver Rx1 and user B has Tx2 and Rx2. When A is transmitting to B, the link distance 'd' is related to the other system parameters, for NRZ data, by:

$$d = \sqrt{\frac{(m+1).P_{Tx1} A_r\, r\, .\cos^m q_A . \cos^n q_B}{4p \sqrt{2e(P_{B\_amb} + P_{Rx2})\, r\, .B.SNR}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where m and n are the Tx1 and Rx2 radiation pattern lobe index, B is the receiver bandwidth and A_r is the receiver area. We assume here normalised radiation patterns for the LEDs and photodetectors, of the form $\cos^m q_A$ and $\cos^n \theta_B$ respectively.

The transmitted, ambient and received optical powers are P_{Tx1}, P_{B_amb} and P_{Rx2} respectively. SNR is the signal to noise ratio, r is the detector responsivity, (in A/W), and 'e' is the electronic charge. Equation (6), describes the relation between the IR link distance and SNR which in turn is related to link Bit Error Rate, (BER), for fixed

ambient light noise and the other parameters. The established link between users A and B is symmetric about the connecting distance, d. Assuming the transmitting and receiving devices of users A and B are the same, or that the transceivers have the same parity, then the throughput is the same in both directions AB and BA. This results in symmetric bi-directional throughput, provided the ambient light noise is not asymmetric.
Hence the system SNR, BER and link layer throughput symmetries depend on ambient light, receiver bandwidth, transmitter power, receiver responsivity, receiver effective area, and transceiver lobe asymmetries.

Symmetry here implies that $d_{AB} = d_{BA}$ for the same BER and throughput.

Equation (6) also reveals that due to the multiplication of the parameters at the numerator and denominator, asymmetries due to individual parameters may cancel each other if in opposite direction, or indeed enhance when in the same direction.
It must also be pointed out that since the BER is directly related to throughput at higher layers, such as the IrDA IrLAP link layer, only when link layer parameters, (such as turnaround times and time-out times, window size etc), are also the same among different devices, is symmetry maintained at higher layers. We assume higher layers do not present any asymmetries themselves, hence we are calculating here the higher layer asymmetries induced due to physical layer asymmetries. [5].

4. Third user interference:

Channel asymmetries due to third user interference occur when a third user unaware of the existing transmission, interferes with the existing link. IrDA line of sight links are prone to this interference, since there is no inherent mechanism to avoid it.
This scenario is also equivalent to having a reflective surface nearby one of the transmitters, as shown in Figure 2, or alternatively when the reflecting surface is near both users and at the same time the user transmitter and receiver component radiation lobes differ. Reflections from a surface are equivalent to a virtual third user, transmitting interfering signals.
Throughout this analysis we assume that all users have transmitters of LEDs with radiation lobe index 'm', and photodiodes with receiving radiation pattern index 'n'.

Case A: **A**<← →**B**C

In order to model third user interference we use the user model, shown in Figure 3, where we assume the interfering user C is located on the same plane as users A and B. We also assume all users operate IrDA devices and that the ambient light background noise present is the same in the receivers of users A and B, in order to single out the third user interference effect.
The received signal of user A however, will arrive from both users B and C. The effect of transmissions from user C therefore is expected to cause degradation of link BA, due to interference on A. We assume C is located anywhere on the plane of AB, pointing towards A and C attempts to connect to A being unaware however of the existing link between BA. The link AB is unaffected by C. Asymmetry in link throughput between AB and BA would therefore occur due to transmissions from C towards A.

Specifically for IrDA links, under stable ambient light conditions, specified to have BER of $P_e = 10^{-9}$ at distance $d = \sqrt{\frac{T_B}{R_A}}$, when aligned, $q_A = q_B = 0$, we can derive the following expression for the bit error rate of link BA under the influence of interference from user C, [7].

$$P_{e_{BA}} = Q[\frac{6T_B \cos^n q_A \cos^m q_B}{R_A d^2} - \frac{6T_C \cos^m q_C \cos^n (q_A - q_1)}{r_2^2 R_A}] \text{……..(7)}$$

The BER for the link direction AB is given by:

$$P_{e_{AB}} = Q[\frac{6T_A \cos^m q_A \cos^n q_B}{R_B d^2}] \quad \text{………………………………...…..(8)}$$

Where R_A, R_B are receiver's A and B thresholds in W/m^2, T_A, T_B, T_C are transmit intensities of users A, B and interferer user C respectively in W/Sr, and Q is the complementary error function.

Asymmetry in the probability of bit error rate is given by introducing the new symbol, **A<← →B**C representing a bi-directional link between fixed users A and B under the influence of a floating user C located next to B and influencing user A. This is simply given by:

$$\boxed{\textbf{A<← →B}\text{C}} = P_{e_{AB}} - P_{e_{BA}} \quad \text{………..……………………..(9)}$$

This asymmetry in BER also results in asymmetry in the link layer throughput. This will be illustrated with the specific IrLAP protocol throughput results, of the next section.

Case B:

A<← →>B
C<← →>D

In this case we examine two fixed bi-directional IrDA links A← →B and C← →D physically arranged at the corners of a rectangle. This represents two pairs of users sitting opposite on a table, exchanging data, as illustrated in Figure 4.

The notation **A<← →>B** **C<← →>D** represents fixed location users A,B,C, and D, with diagonal crosstalk.

In this case, assuming all users are identical, there is no asymmetry in BER. However, there will be a reduction of the 'cell' size, and the distance between the links is reduced to maintain the same BER.

The BER in both directions between A and B in this case is given as follows:

$$P_{e_{BA}} = Q\left[\frac{6T_B \cos^n q_A \cos^m q_B}{R_A d^2} - \frac{6T_D \cos^m (q \pm q_D) \cos^n (q \pm q_A)}{r^2 R_A}\right]$$

$$\ldots\ldots\ldots\ldots(10)$$

$$P_{e_{AB}} = Q\left[\frac{6T_A \cos^m q_A \cos^n q_B}{R_B d^2} - \frac{6T_C \cos^m (q \pm q_C) \cos^n (q \pm q_B)}{r^2 R_B}\right]$$

Any asymmetries in the components used in the IR links reflected in transmitter intensity or receiver threshold variations will cause asymmetric probability of errors, according to eqn. (10).

Case C:

A← →>C
B→

This notation represents two fixed position IrDA users A and B transmitting, and mobile user C receiving data from A but interfered by transmissions from user B. The parameters of the model for this case are shown in Figure 5.

This case is an example of not only directional (AC or CA), but also spatial asymmetry, depending on the position of user C on the user plane.
The BER of link AC, under the influence of interfering user B, and of link CA are given by:

$$P_{e_{AC}} = Q\left[\frac{6T_A \cos^m q_1}{R_C r_1^2} - \frac{6T_B \cos^m q_2 \cos^n f_1}{r_2^2 R_C}\right]$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(11)$$

$$P_{e_{CA}} = Q\left[\frac{6T_C \cos^n q_1}{R_A r_1^2}\right]$$

In this case we are assuming user C is aligned to user A for simplicity, but user A is pointing perpendicular to distance d.

The asymmetry in BER is therefore given by:

$$\boxed{\begin{array}{l}\mathbf{A}\leftarrow\ \rightarrow>\mathrm{C}\\ \mathbf{B}\rightarrow\end{array}} = P_{e_{AC}} - P_{e_{CA}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(12)$$

5. Results:

A<← →**B**C

5.1 Case A:

In order to demonstrate the effect of the interfering user C on the BER quality of link BA, we apply equation (7) above, for IrDA optical links. We assume an IrDA link between A and B fixed at a distance d= 1m, as shown in Figure 3. Users A and B are aligned, $q_A = q_B = 0$, and exchange data. User's C position is moving on the plane of AB but always keeping $q_C = 0$, but varying q_1, i.e. user C is aligned to link with user A and therefore interferes with the established link BA. The BER of link AB is unaffected from user C but the BER of link BA is in accordance to equation (7).
The results of the BER of link BA are shown in Figure 6. The contours show of the physical position of user C which results in a constant but reduced BER for link BA. It is clear that for a P_{eBA} of 10^{-8} user C should not approach user A to less than 3m along the $q_A = 0$ axis, and when it is at 1.5 m from A, the error rate is very poor, increasing to 10^{-4}. As user C is closer to the existing BA link, the P_{eBA} degrades, as shown in Figure 6, for BER of 10^{-8}, 10^{-6}, and 10^{-4}. The error rate of the fixed AB link is of course unaffected to a value of 10^{-9}. We have demonstrated that for the locations of user C in Figure 6, the link BER asymmetry is given by:

A<← →BC = 10^{-9}- 10^{-8} , 10^{-9}-10^{-6}, and 10^{-9}-10^{-4} respectively for the three contours of Figure 6. As discussed before, this kind of asymmetry is defined as directional asymmetry. For the above results we have assumed all transmitters to have output intensities of 40 mW/Sr, receiver threshold of 0.04 W/m^2, (within the range of typical IrDA values) and transmitter radiation patterns of m=20, and receivers of n=1.

Figure 7 shows contours of the location of user C for constant throughput for the IrDA IrLAP protocol for the link BA, that was shown in Figure 3.
In order to derive the throughput of link BA when user C is transmitting interfering signals towards user A, the derived probability of errors using the model described above was used, with a model of the IrLAP (link layer protocol), to produce normalised throughput results. The analysis of the IrLAP protocol is not presented here but an extensive analysis can be found in [5],[6]. For the position contours of user C shown in Figure 7, the BA IrLAP throughput decreases to 0.9, 0.5 and 0.2 respectively. In order to derive the throughput, we have used the above model for the physical as well as the link layers of IrDA. It is obvious that the throughput becomes negligible when the third user C, is as near as 1.5m along $q = 0$ in Figure 7.

5.2 Case B: **A<← →>B** **C<← →>D**

Two parallel fixed links AB and CD are represented in this case interfering diagonally, as shown in Figure 4. Assuming the individual link parameters are identical there will be no directional asymmetry, however the diagonal interference will influence and degrade the BER, according to equation (10).
Varying the distance 'l', (the distance between the parallel links), we have calculated the BER of the links AB and BA in Figure 8. The following link parameters were used: All transmitter intensities equal to 40mW/Sr, all receivers thresholds equal to 0.04 W/m^2, m=20 and n=1, and d varies from 1 to 1.3m.
The results show that significant BER degradation occurs when the distance 'l' is less than 0.6m.

Figure 9 shows the throughout of the IrLAP layer corresponding to the same parameters as that of Figure 8. The throughput degrades rapidly as the error rate deteriorates. For d=1.3m the throughout is near zero. The roll-off of the throughput due to cross interference is at longer adjacent link distances, l, as d increases and vice versa.

5.3 Case C:

A← →>C
B→

Users A and C are linked together. However user A is fixed and C is portable and can be anywhere in the plane of A and B. A and C are not always aligned. User B is also transmitting and acts as interferer to user C. The user model is sketched in Figure 5. The BER of links AC and CA is given by equation (11), and the asymmetry by equation (12).
For the calculations, receiver C is moving but always pointing (alighned) to A. User B is transmitting in parallel to use A, as shown in Figure 5.
Figures 10 and 11show the position locii of C, for receiving constant BER data from A.
For Figure 10 users A,B, and C are all transmitting at 40mW/Sr, receiver thresholds equal to 0.04 W/m^2, m=20 and n=1, and the distance between A and B is 0.4m.
Similarly for figure 11, User A transmits at 40mW/Sr, user B at 100mW/Sr, receiver thresholds equal to 0.04 W/m^2, m=1 and n=1.
The spatial asymmetry of the position locii of C for BER better than 10^{-9}, (shaded area) 10^{-5}, (dotted contour) can be seen. When user B is not transmitting, the contour is symmetric, and the BER of AC is 10^{-9} (solid curve). See also [4].
The asymmetry is particularly pronounced when the sources of IR are of wide beamwidth, (fig.11).

Finally, we examine the asymmetries of the throughput at the IrLAP layer corresponding to the Figures 10 and 11.The link data rate is assumed to be 112.5kb/s. This is shown in Figures 12 and 13. Figure 12 shows the asymmetry of the throughput received by user C from A, and corresponds to the BER contours of Figure 10. Figure 13 also shows the asymmetry of the throughput received by user C from A, and corresponds to the BER contours of Figure 11.

6. Conclusion:

We have examined directional and spatial asymmetries in the BER of IrDA type links. Asymmetries in BER result in throughput asymmetries at link layer level and above. We derived a condition for symmetry of IR wireless links using hard threshold receivers, relating the transmitter intensities and receiver thresholds.

Asymmetries may be caused by component specification variation as well as variation in ambient light between the users, or other channel asymmetries such as reflections from nearby surfaces. Asymmetries may also be caused by reflections from walls as well as third user interference. We have modelled and derived formulae, which allow the calculation of those asymmetries. Asymmetric throughput is propagated to higher layers (LINK layer in this application) due to asymmetries at the physical layer. Even if the user transceivers are identical, it is possible to have asymmetries in link quality. This work allows designers to predict the level of asymmetry in BER and throughput in IR links, and how to reduce the undesirable effects of asymmetries in manufacturing.

The results indicate that unless neighbouring users are detected the effective useful area 'footprint' of the links are compromised and possibly distorted. A carrier sense method would be necessary in detecting the presence of neighbouring transmitters. A protocol capable from refraining users from causing interference to an existing link is necessary when multiple independent links are present in the same space.

Such a mechanism is in place in the Advanced IR MAC protocol, a more recent standard for multi-user IR wireless communication.

References:

[1]: Asymmetry of Free Space Optical Links: Anthony Boucouvalas, SPIE Proceedings on All Optical Communication Systems: Architecture, Control and Network Issues: Vol.2614, pp. 69-76, 25-26 Oct. 1995 Philadelphia, USA.

[2]: IrDA: For information contact IrDA administrator, PO Box 495, Brookdale, California 95007-0495, USA

[3]: The IrDA standards for high speed infrared communications, I. Millar, M. Beale, B. Donoghue, K. Lindstrom, and S. Williams: Hewlett Packard Journal, pp.10-17, February 1998.

[4]: Interference Induced IR Link Spatial Asymmetries, A.C. Boucouvalas, Jennifer Jerrams-Smith, and David Heathcote
Third Communication Networks Symposium, Manchester Metropolitan University, pp.214-219, 8-9th July 1996.

[5] IrLAP protocol performance analysis of IrDA wireless communications. A.C. Boucouvalas, P.Barker,
IEE, Electronics letters, Vol.34,no.25, pp.2380-2381,1998.

[6] Performance Modelling of the IrDA Infrared Wireless Communications Protocol. P.Barker, A.C. Boucouvalas,
to appear in International Journal of Communications.

[7] Asymmertic throughput in optical wireless Links.
A.C. Boucouvalas, P. Barker

2nd Electronic Circuits and Systems Conference, September 6-8, 1999, Bratislava, Slovakia, Sept. 6-8, 1999, pp. 129-134.

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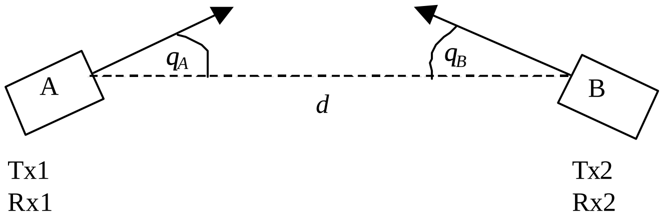

Figure 1: Two user IR link model. Tx1 and Rx2 are at a distance d apart, subtended by angles q_A, and q_B to d.

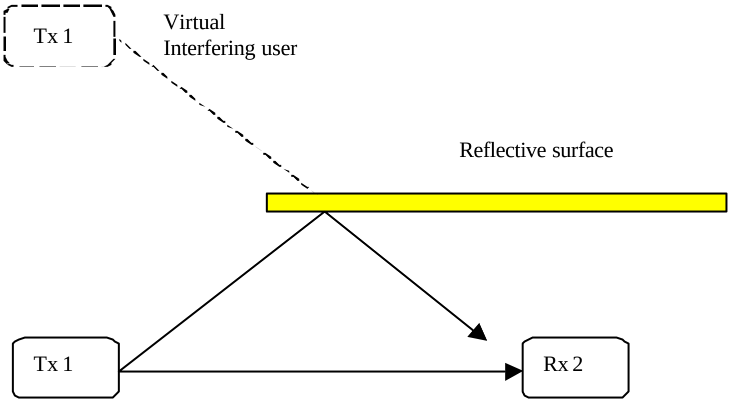

Figure 2: Third user interference as a result of reflection from a surface.

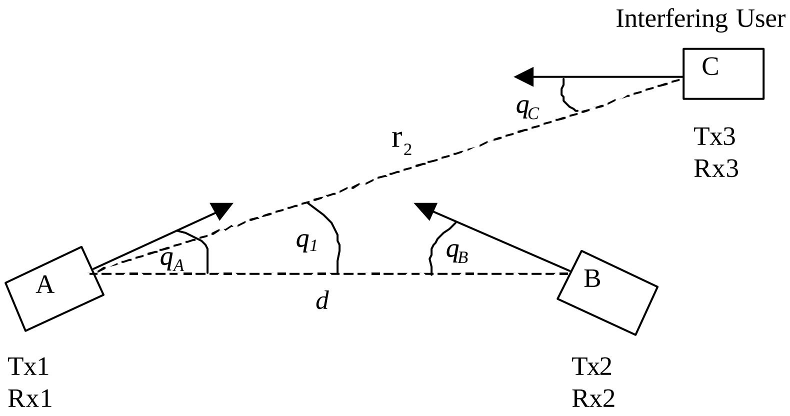

Figure 3: Interference by user C: User A is linked to B. user C interferes with A.

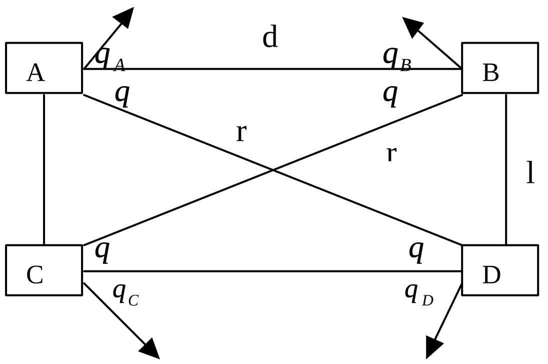

Figure 4: Parallel link interference: User A and B are interfering with users C and D, diagonal crosstalk.

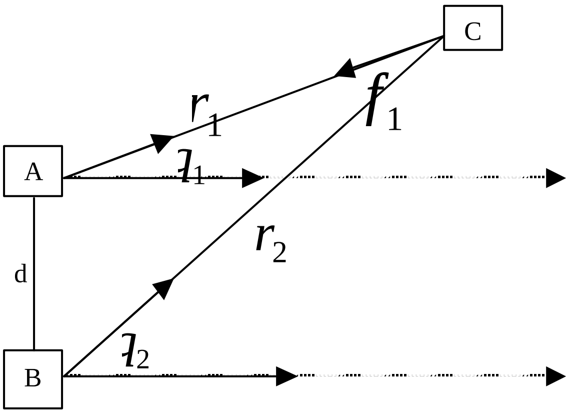

Figure 5: Users A and C are linked. User C is moving on the plane but interfered by fixed user B. Users A and B are aligned and radiate normal to direction d .

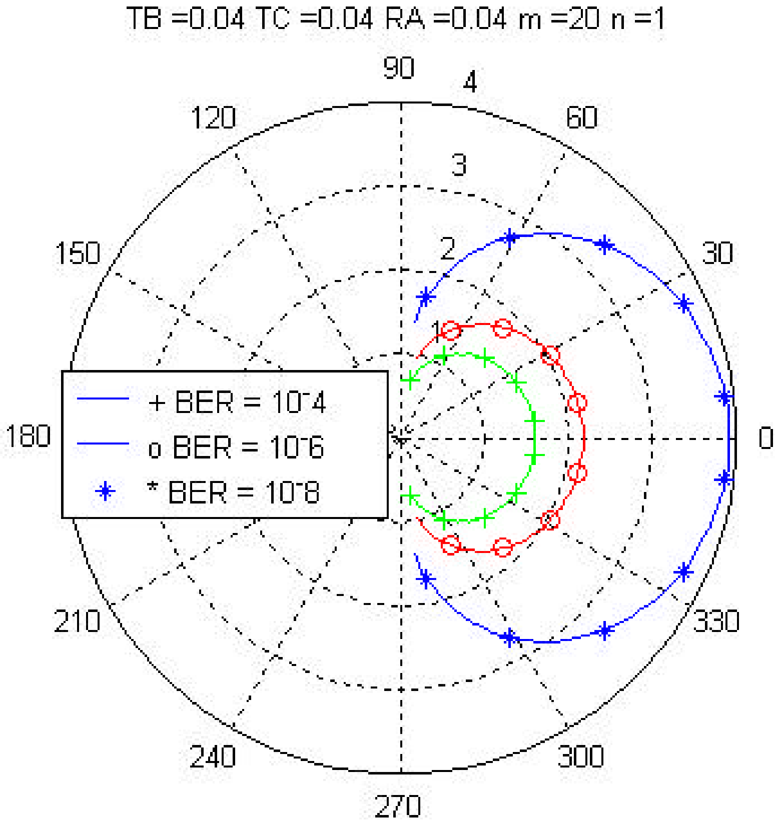

Figure 6: Third user interference: Contours of position of C for constant BER of link BA when interfering user C, of intensity 40mW/Sr is aimed and interferes with user A. The contours indicate the minimum distance user C is allowed to approach user A for various BER values of link BA.

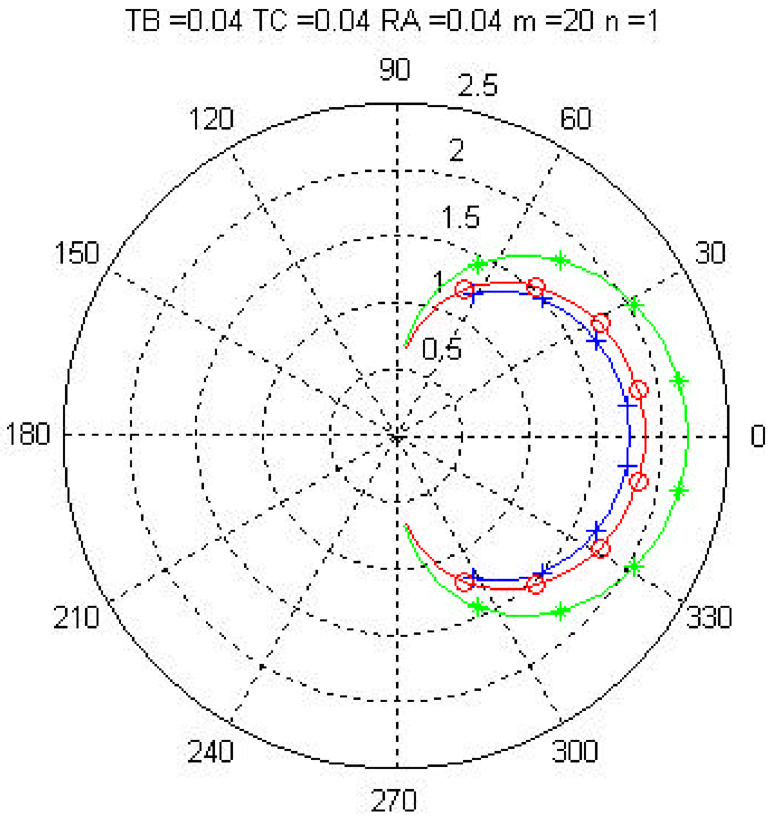

Figure 7: Third user interference: Contours of position of C for constant IrLAP throughput of link BA when interfering user C, of intensity 40mW/Sr is aimed and interferes with user A. The contours indicate the minimum distance user C is allowed to approach user A for various throughput values of link BA.

-*- Throughput = 0.9

-o- Throughput = 0.5

-+- Throughput = 0.2

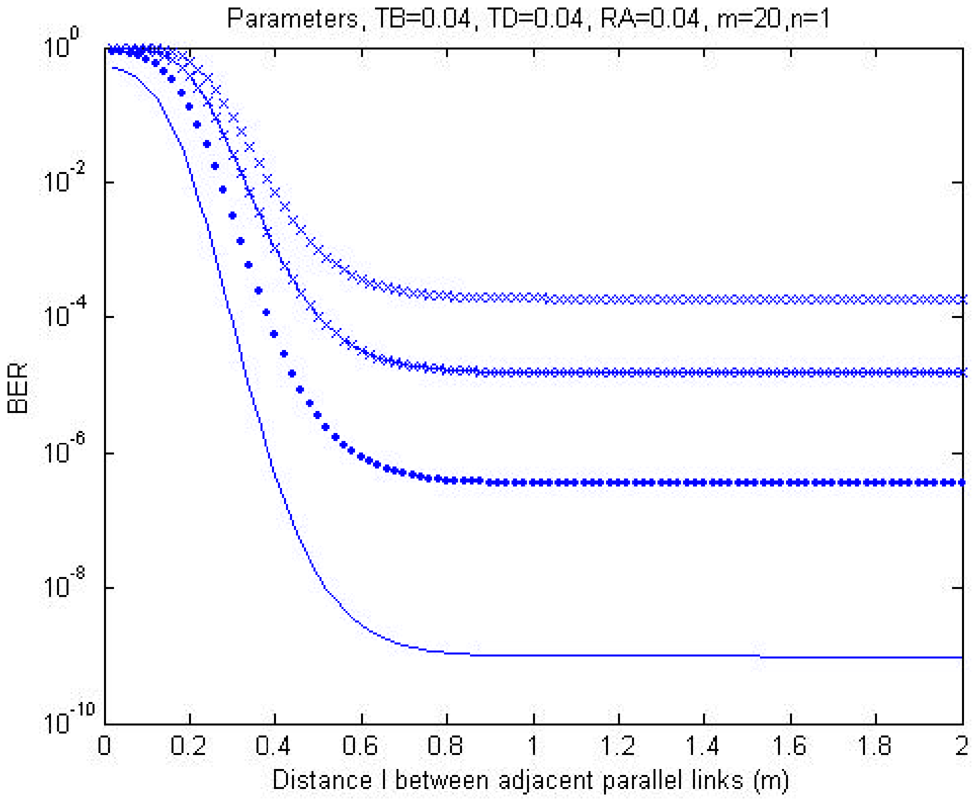

Figure 8: BER of bi-directional link AB when the distance 'l' between the link AB and an identical link of interfering users set C and D (located as shown in Fig. 4), is varying; 'd' is the distance between AB.

______	d=1
. . . .	d=1.1
-x-x-x-x-x-	d=1.2
x x x x x	d=1.3

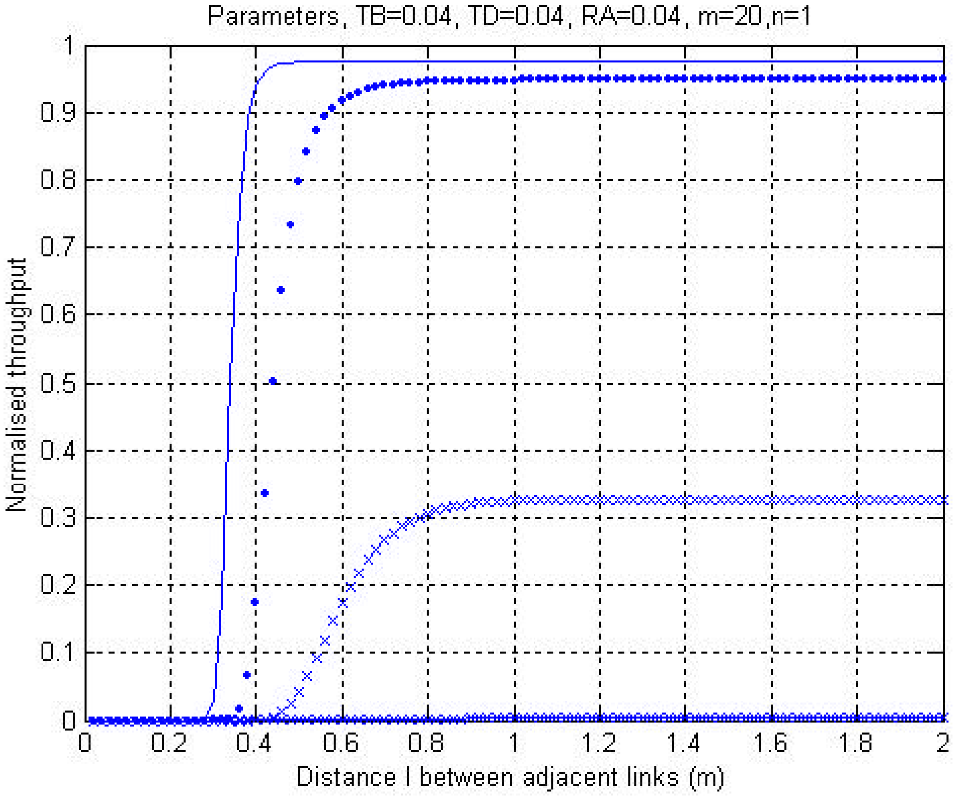

Figure 9: IrLAP throughput of bi-directional link AB when the distance 'l' between the link AB and an identical link of interfering users set C and D (located as shown in Fig. 4), is varying; 'd' is the distance between AB.

______ d=1
. . . . d=1.1
x x x x x d=1.2
-x-x-x-x- d=1.3

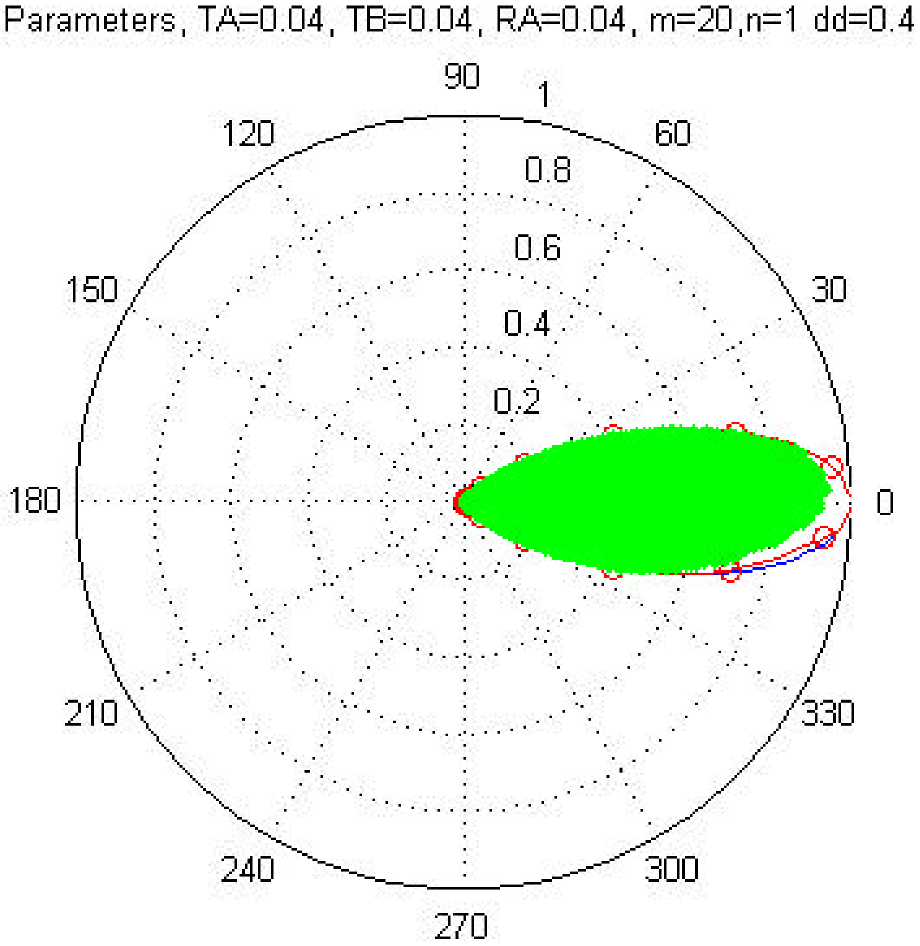

Figure 10: Position loci of user C (fig. 5), in order that C receives equal BER form A.
BER better than 10^{-9}, (shaded area), for link AC.
---o--- BER $=10^{-5}$ for link AC, with interference from B
_____ BER = 10^{-9} for link AC without interference from B.

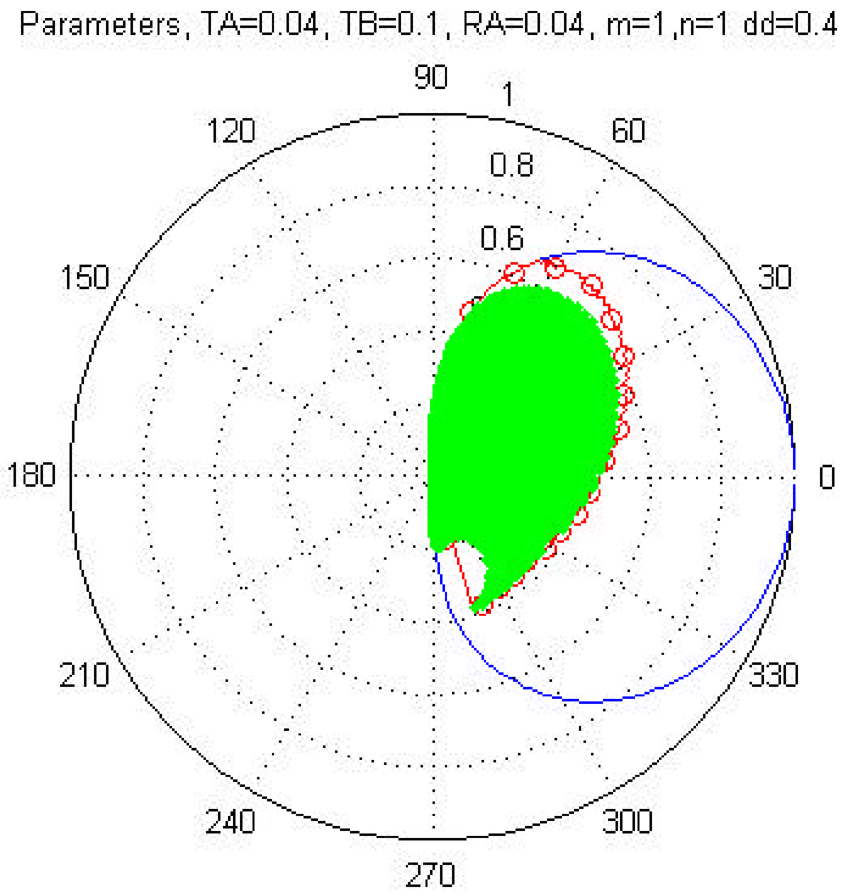

Figure 11: Position loci of user C (fig. 5), in order that C receives equal BER form A. (Interfering user B is of stronger intensity and transceiver lobes wider).

BER better than 10^{-9} , (shaded area), for link AC, with interferer.

-o-o- BER $=10^{-5}$ for link AC with interferer.

______ BER= 10^{-9} for link AC without interference from B.

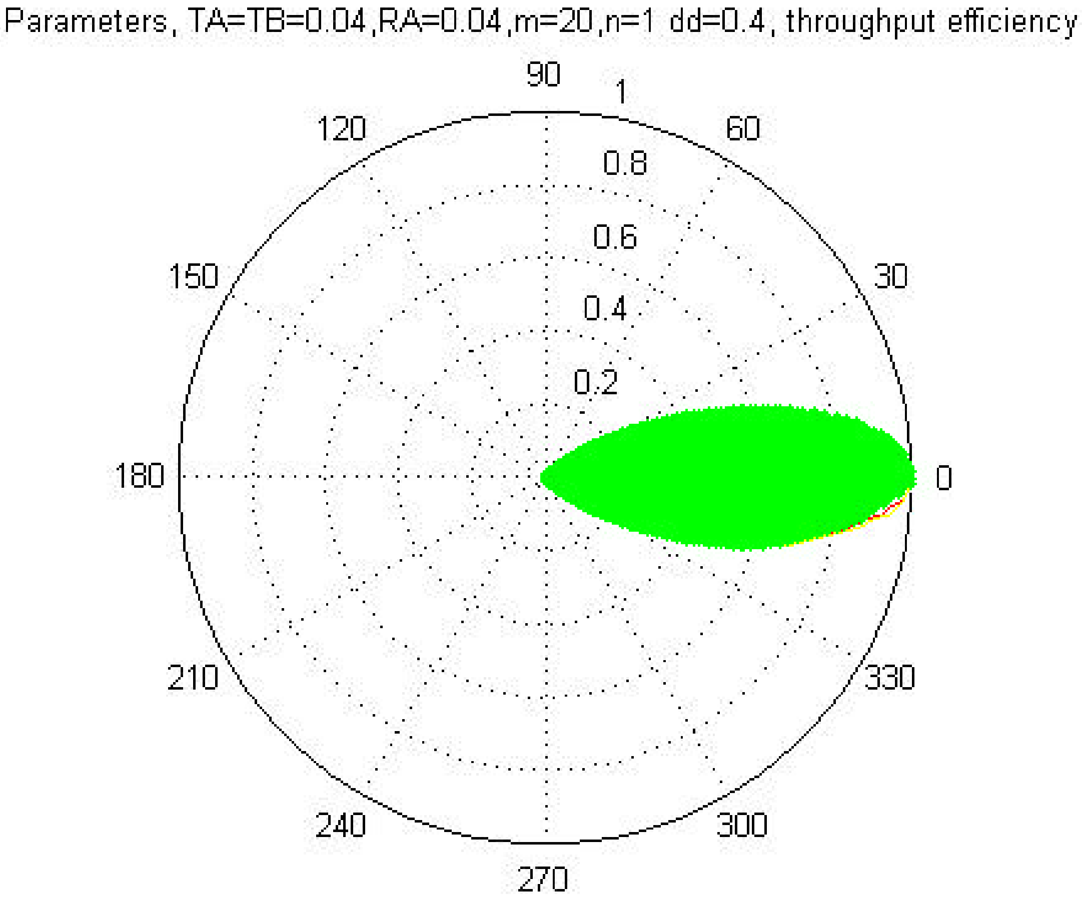

Figure 12:
Position loci of user C (fig. 5), in order that C receives equal IrLAP layer throughput form A.
Link layer throughput better than 0.9 , (shaded area), for link AC.
_____ (red), throughput efficiency = 0.5

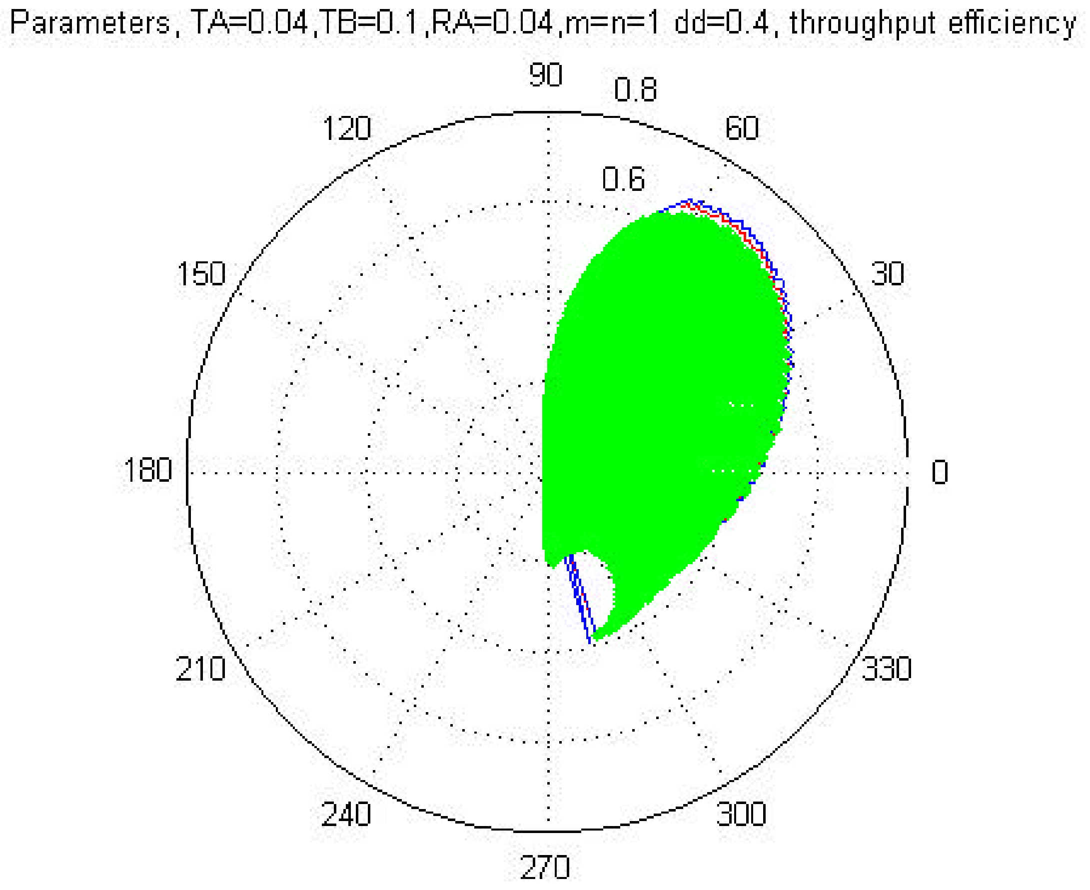

Figure 13: Position loci of user C (fig. 5), in order that C receives equal IrLAP layer throughput form A. (Interfering user B is of stronger intensity and transceiver lobes wider).

Link layer throughput better than 0.9 , (shaded area), for link AC.

___(blue, outer line) throughput = 0.2
___(red, inner line) throughout =0.5