Chapter Three

Modeling of D2D Communication

Today and future wireless networks are facing one of their greatest limiting factors: interference. This is due to the unprecedented increase in the number of connected devices. Therefore, in order to meet the ever increasing demand for data rate and quality of services, more advanced techniques than what we have today are required to deal with interference [33].

D2D Communication using cellular network spectrum is an efficient way to handle the local traffic in a cost efficient manner. A D2D link is a direct connection from D2D transmitter (D2D Tx) to D2D receiver (D2D Rx) in spectrum managed by cellular network. There are several gains related to D2D communication underlying a cellular infrastructure, namely proximity gain of user equipment that allows high bit rate, low delays and low power consumptions, the reuse gain that concedes radio resources to be utilized by cellular and D2D links simultaneously, and finally hop gain that refers to applying an individual link in the D2D mode rather than using an uplink and a downlink resource when communicating via the BS in the cellular mode [34].

3.1 Path Loss Model

Path loss is the reduction (attenuation) in power density of an electromagnetic wave as it propagates through space. Path loss models describe the signal attenuation between a transmit and a receive antenna as a function of the propagation distance and other parameters. Path loss for a non-free space wireless environment, such as a path with obstructions consisting of buildings and trees, can be difficult to model. Different models have been developed to describe the propagation behavior in different conditions. Some models include many details of the terrain profile to estimate the signal attenuation, where as others just consider carrier frequency and distance travelled by the signal. Research on propagation models is an academic field of its own. For my research the log-distance path loss model is proposed. The log-distance path loss model is a radio propagation model that predicts the path loss a signal encounters inside a building or in densely populated areas over

distance. This model is widely used in literature because of its relative simplicity, the path loss for urban wireless environments are calculated as follows:

$$PL_{dB}(d) = PL_{FSdB}(d_0) + 10n \log_{10}(d/d_0) + X_{dB} \quad (3.1)$$

Where

$$PL_{FSdB}(d_0) = 20 \log_{10}(4\pi d_0 f/c) \quad (3.2)$$

$PL_{FSdB}(d_0)$ is the free space loss for a distance d_0 that is close to the transmitter, *n* is the path loss exponent, f is the frequency, c is the velocity of light and X_{dB} is a zero-mean Gaussian random variable representing the variations in the path loss caused by multiple reflections.

When the system parameters are fixed and the zero-mean Gaussian random variable neglected, equation (3.1) can be written as a function of the distance d:

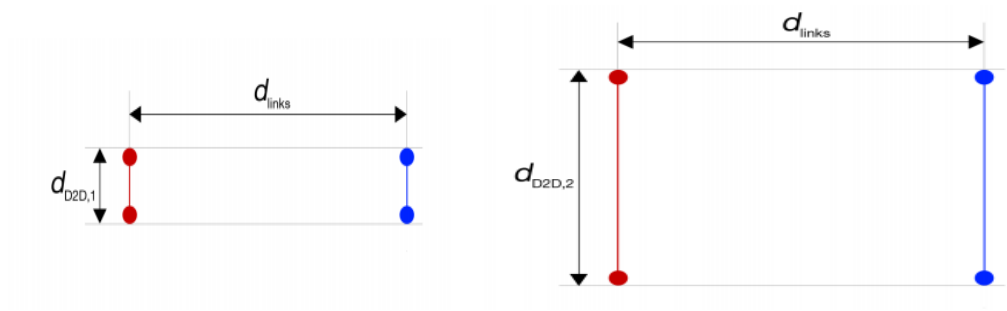
$$PL_{dB}(d) = 10n \log_{10}(d) + C \quad (3.3)$$

Where C is a constant which depends on the chosen system parameters. This path loss model is used in the rest of this work.

3.2 Minimum Distance Between Two D2D Links

The relation between the length of a D2D link and the distance between D2D links is illustrated in figure 3.1, in figure (3.1(a)), two D2D links are communicating over a distance of d_{D2D}, 1 and are separated from each other by a distance of d_{links}.

In figure (3.1(b)), the D2D link size is increased while the distance between the links remains the same. In the first case a better SINR will be experienced at the receivers than the latter case; to maintain the SINR at the same level, d_{links} would have to be larger as well.



(a) Short D2D links (b) long D2D links

Figure 3.1: Two D2D links of length d_{D2D}, 1, separated from by a distance of d_{links}

If the D2D link is larger, while the separation remains the same, more interference will be experienced at the receivers in (b).

The case in which two D2D links operating simultaneously are analyzed. In figure (3.2), suppose node i and node j from a D2D link, where node i is receiving data from node j. At the same time, node k is transmitting data to another node l. The SINR at node i will be

$$\text{SINR}i = \frac{PRij}{PRik + N} \tag{3.4}$$

Where P_{Rij} is the signal power received by node i from node j and P_{Rik} is the interference power received by node i from the interfering node k. For now we assume that there is no noise present. For simplicity reasons we proceed with notations in decibels. Hence equation (3.4) becomes

$$\text{SINR}_i = P_{Rij,} - P_{Rik} \tag{3.5}$$

Where

$$P_{Rij} = P_{Tj} - PL\ (d_{ij}) \tag{3.6}$$

And

$$P_{Rik} = P_{Tk} - PL\ (d_{ik}) \tag{3.7}$$

Where P_{Tj} and P_{Tk} is the power transmitted by node j and node k respectively, PL_{dB} (d) is the propagation loss of a signal travelling over a distance d. Therefore, in equation (6) d_{ij} is the length of the D2D link and in equation (3.7) d_{ik} is the distance between the receiver and the interferer. The propagation loss can be calculated using equation (3.1).

Using equations (3.6) and (3.7) in equation (3.5) it gives

$$SINR_i = P_{Tj} - PL(dij) - P_{Tk} + P_L(d_{ik}) \quad (3.8)$$

We assume that a D2D link has a maximum length of d_{D2Dmax} and all devices have a maximum transmit power P_{Tmax}. Suppose there is a minimum SINR requirement, stating that $SINR_{i,dB} \geq \Phi$ (dB). If the interfering node k is too close to the receiving node i, the SINR requirement will not be achievable and to guarantee a minimum SINR at node i, the minimum distance min (d_{ik}) between node i and k can be calculated, even if node j is transmitting at full power, i.e. when $P_{Tj} = P_{Tmax}$.

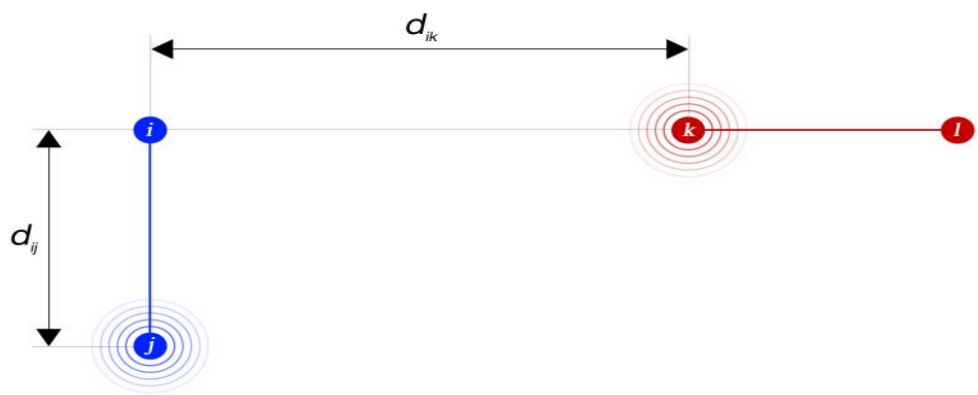


Figure 3.2: Node j is transmitting a signal to node i. Node k is interfering node i

We are interested in determining the minimum distance d_{min} between the receiving node i and the interfering node k, at which the SINR requirement can still be fulfilled, i.e. $\{d_{ik}=d_{min}\} \rightarrow \{\Phi \leq SINR_{i,dB}\}$. Hence equation (3.8) becomes

$$\Phi \leq SINR_i = P_{Tmax} - PL(dij) - P_{Tk} + PL(d_{min}) \quad (3.9)$$

In the worst case, the interferer is transmitting with full power, i.e. $P_{Tk} = P_{Tmax}$. In this case, $\Phi = SINR_{i, dB}$. Filling in these values in equation (3.9) gives.

$$\Phi = P_{Tmax} - PL(dij) - P_{Tmax} + PL(d_{min})$$

$$= PL(d_{min}) - PL(dij) \quad (3.10)$$

Equation (3.3) can be used in equation (3.10) to calculate the path losses. This gives

$$\Phi = 10n \log_{10}(d_{min}) + C - (10n \log_{10}(dij) + C) \quad (3.11)$$

Cancelling out the constant C and rearranging gives us

$$d_{min} = [10^{\Phi/10n}]\, d_{ij} \quad (3.12)$$

This is the relation we were looking for. We can generalize equation (3.12) for any D2Dlink, replacing dij by d_{D2D}, the length of the D2D link. Thus

$$d_{min}(d_{D2D}) = [10^{\Phi/10n}]\, d_{D2Dmax} \quad (3.13)$$

Hence, when two links with node pairs i - j and k - l are operating at the same time, com municating independently from each other bi directionally, the following always holds:

$$\{\min(d_{ik}, d_{il}, d_{jk}, d_{jl}) \geq d_{min}(\max(d_{ij}, d_{kl}))\} \longrightarrow \{SINR_m \geq \Phi\}, \quad (3.14)$$

Where ***m*** can be any of the nodes {i, j, k, l} and d_{min} is calculated with equation (3.13). In the next paragraph we will extend this analysis for the case in which there are more than two D2D links operating simultaneously.

3.3 Minimum Distance Between D2D Links in a Cell using Log Distance Model

In this paragraph, we explain the model which has been used to derive an equation which describes a direct relation between the required minimum distance d_{min} between all D2D links operating simultaneously and the maximum length d_{D2Dmax} of a D2D link.

When all nodes are separated by at least d_{min}, a hexagonal grid is formed. This is shown in figure (3.3). The worst case in terms of interference is when the node in the center of the cell (green node) is in receiving mode while all other nodes are interferers (red nodes).

We would like to know how many nodes interfere on the receiving node in the center. This is equal to the number of nodes that fit in the cell minus the center node. As can be observed from figure (3.3), the interfering nodes are placed in hexagons around the receiver. The first three hexagons are shown in figure (3.4). On every hexagon, six interferers are placed. Hence the number of interfering nodes in a cell depends on the number of hexagons that fit in the cell. The length of the edges of a hexagon is equal to the distance of a node on that hexagon to the center of the cell; all nodes fulfill the requirement of being at least d_{min} an apart from each other.

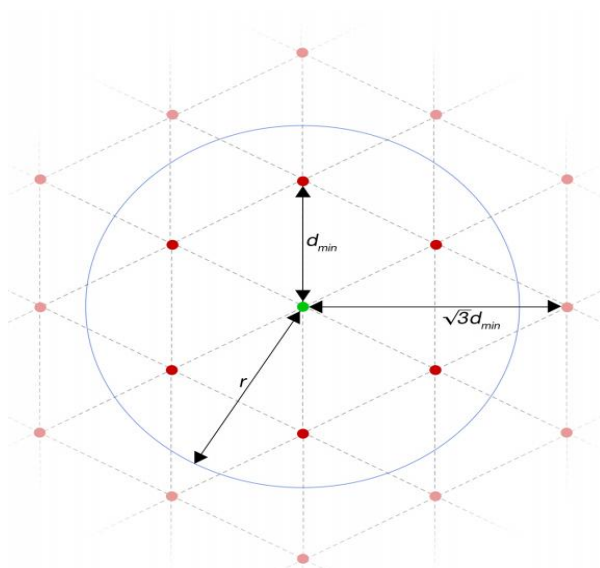


Figure 3.3: nodes position in the cell

Starting from the smallest hexagon, the length v_h of the edges of the hth hexagon is

$$v_h = \begin{cases} \frac{h+1}{2} d_{min}, & \text{if } h \text{ is odd} \\ \frac{h}{2}\sqrt{3} d_{min}, & \text{if } h \text{ is even} \end{cases} \tag{3.15}$$

We call the hth hexagon an odd or an even hexagon if h is odd or even respectively, and the first three hexagons on which the interferers around the center node are placed and shown below in figure 3.4.

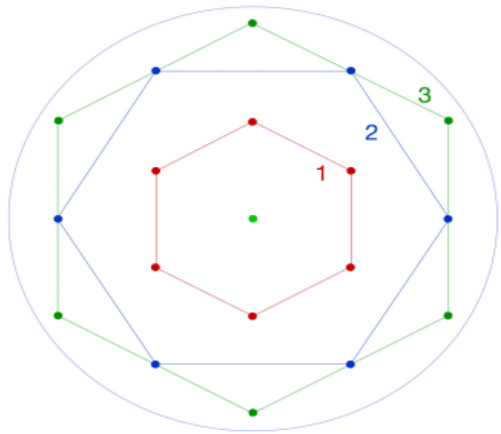


Figure 3.4: The modified model

The number of hexagons that fit in a cell is a function of the radius r of the cell and the minimum distance d_{min} between nodes. We can maximally fit $\frac{r}{dmin}$ odd hexagons and $\frac{r}{\sqrt{3}\,dmin}$ even hexagons in a cell with radius r. Hence the maximum number of interfering nodes according to the model illustrated in figure (3.3) is

$$N = 6\left[\frac{r}{dmin}\right] + 6\left[\frac{r}{\sqrt{3}dmin}\right] \tag{3.16}$$

When all interfering nodes transmit with the maximum power P_{Tmax}, an upper bound on the interference received by the node in the center of the cell can be calculated and is given by:

$$Imax = \sum_{i=1}^{A} \frac{PTmax}{PL(dA,i)} + \sum_{i=1}^{B} \frac{PTmax}{PL(dB,i)} \tag{3.17}$$

Where A and B are the total number of nodes on the odd and even hexagons respectively, i.e.

$$A = 6\left[\frac{r}{dmin}\right] \qquad \text{And} \qquad B = 6\left[\frac{r}{\sqrt{3}dmin}\right]$$

And PL (d) is the path loss as function of the distance d travelled by the signal as described in paragraph 3.2. As explained before, the distance from an interfering node to the center of the cell is

equal to the size of the vertices of the hexagon on which that interfering node is placed. The distances used in equation (3.17) are given by:

$$\mathrm{dA,i} = \left[\frac{i}{6}\right] dmin \quad \text{and} \quad \mathrm{dB,i} = \left[\frac{i}{6}\right] \sqrt{3}\, dmin \tag{3.18}$$

We simplify equation (3.17) by only taking the first hexagon ring of interfering nodes in account, i.e. A = 6 and B= 0. This simple model is illustrated in figure (3.5). From equation (3.18) we get

$$\mathrm{dA,i} = \mathrm{dmin} \tag{3.19}$$

And by combining equations (3.17) and (3.19) we find

$$Imax(dmin) = \sum_{i=1}^{6} \frac{PTmax}{PL(dmin)} = 6\frac{PTmax}{PL(dmin)} \tag{3.20}$$

Which in decibel notation is expressed as

$$\mathrm{Imax,dB(dmin)} = 10log10\left(6\,\frac{PTmax}{PL(dmin)}\right)$$

$$= P_{Tmax} - PL\,(d_{min}) + 10\log_{10}(6) \tag{3.21}$$

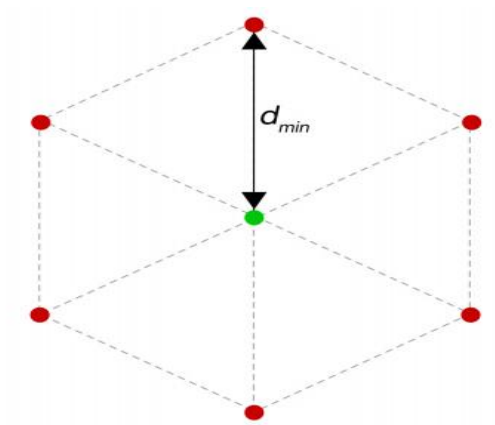


Figure 3.5: receiver node with interference nodes

For the calculation of the path loss, equation (3.3) is used with the parameter values shown in table (3.1), thus

$$PL(d) = 10n \log_{10}(d) + C \quad (3.22)$$

Table 3.1: Propagation Model Parameters

Parameter	Value
X_{dB}	0
d_0	1 (m)
f	2 (GHz)
c	3.10^8 (m/s)
n	Path lose exponent

By using equation 3.4 again

$$\text{SINR} = \frac{PR}{PR+N}$$

or in decibel notation

$$\text{SINR} = P_R - I_R - N$$

Where P_R is the received signal power, I_R is the received interference power and N is the noise. For now we take that N = 0. We assume that a D2D link has a maximum length of d_{D2Dmax} and the distance between all interfering nodes is at least d_{min}. Suppose there is a minimum SINR requirement, stating that SINR $\geq \varphi$ (dB). When the maximum interference is experienced by the receiver (i.e. $I_R = I_{max}$), we still want to achieve the minimum SINR requirement. Thus

$$\Phi \leq \text{SINR} = P_R - I_{max} \quad (3.23)$$

We want to find the d_{min} for which the SINR requirement can always be fulfilled, even when the paired transmitter and receiver are separated by the maximum D2D link length d_{D2Dmax}. In this worst case SINR= Φ and the transmitter transmits with maximum power P_{Tmax} , so that the received signal power will be

$$P_R = P_T - PL\,(d_{D2D})$$

$$= P_{TMAX} - PL\,(d_{D2Dmax}) \quad (3.24)$$

Using equations (3.23) and (3.24) we find that

$$\Phi = P_{Tmax} - PL\,(d_{D2Dmax}) - I_{max}\,(dmin) \quad (3.25)$$

Rewriting gives

$$I_{max}\,(d_{min}) = P_{Tmax} - PL\,(d_{D2Dmax}) - \Phi \quad (3.26)$$

Now equations (3.21) and (3.26) can be combined:

$$P_{Tmax} - PL\,(d_{min}) + 10\log_{10}(6) = P_{Tmax} - PL\,(d_{D2Dmax}) - \Phi \quad (3.27)$$

We can see that $P_{Tmax,\,dB}$ cancels out. Rewriting equation (3.27) gives

$$PL\,(dmin) = \Phi + PL\,(d_{D2Dmax}) + 10\log_{10}(6) \quad (3.28)$$

We can now use equation (3.3) to find the path losses and fill these in equation (3.28):

$$10n\log_{10}(d) + C = \Phi + 10\log_{10}(d_{D2Dmax}) + C + 10\log_{10}(6) \quad (3.29)$$

Cancelling out C and rewriting gives

$$dmin = \left[10^{\left(\frac{\Phi + 10\log10\,(6)}{10n}\right)}\right] dD2Dmax \quad (3.30)$$

3.4 Grouping of D2D Links

Equation (3.30) is derived to specify the minimum distance that must be maintained between links to guarantee a given SINR. Now we want to form groups of links which all fulfill the calculated minimum distance requirement with respect to each other so that all links in the same group may operate simultaneously while achieving a minimum SINR.

Groups of links are formed by using a distance criterium; only links that are separated from each other by a distance of at least d_{min} meters may belong to the same group, so that all links belonging to

the same group are separated by at least d_{min} meters. This is illustrated in figure (3.6). In this figure three links are shown. Suppose that $d < d_{min} < 2d$, so that the distance between the nodes of link 1 and 2 is less than d_{min}. From the distance criterium, it follows that link 1 and 2 may not belong to the same group. The same goes for link 2 and 3. Link 1 and 3 however, are separated by a distance larger than d_{min} and can therefore be placed in the same group.

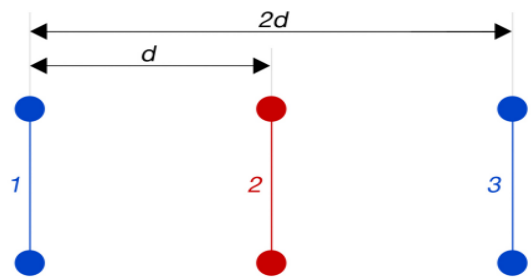


Figure 3.6: Grouping of D2D links with a distance criterium

Where d_{min} is the minimum distance criterium we derived in equation (3.30). If we do so, then all links belonging to the same group fulfill the minimum distance requirement. When all the links in a group and only the links of that group operate simultaneously, the minimum SINR used to calculate d_{min} is guaranteed for all links in that group.

3.4 Greedy Grouping Algorithm

A greedy algorithm is a mathematical process that looks for simple, easy-to-implement solutions to complex, multi-step problems by deciding which next step will provide the most obvious benefit [35].

A greedy algorithm is an algorithm that follows the problem solving heuristic of making the locally optimal choice at each stage, with the hope of finding a global optimum. In many problems, a greedy strategy does not in general produce an optimal solution, but nonetheless a greedy heuristic may yield locally optimal solutions that approximate a global optimal solution in a reasonable time [36].

To draw the graph edges, the distance criterium d_{min} must be given as input. From the graph we construct an adjacency matrix. This matrix is used in the greedy grouping algorithm.

As an example, we can show what groups are formed out of ten links with a link length of 300 meters, randomly placed in a cell with a radius of 1000 meters. From equation (3.30) we calculate that for a target SINR of 6 dBs and path exponent n = 4, the distance requirement d_{min} =663.2 meters. The links are shown in figure (7). Every color represents a group, so that links of the same color belong to the same group. The figure shows that five groups are created to accommodate all ten links.

The histogram in figure (8) shows how many links are placed in every group. It can be seen that the number of members in a group is not equally divided; the first group accommodates three links, while the second, third and fourth group accommodate two links per group. The last group is created for only one link. From the algorithm, it is expected that the first groups usually contain more members compared to the last groups. This is because we specified in the algorithm to try to place links in a group which is as low numbered as possible, and the Links of the same color belong to the same group.

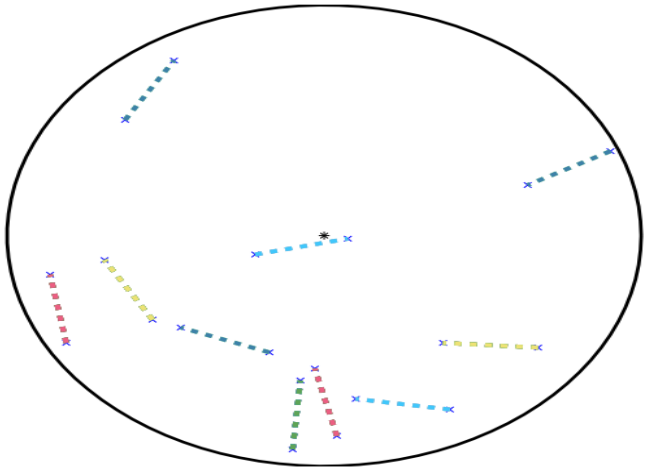


Figure 3.7: ten links grouped with the greedy grouping algorithm

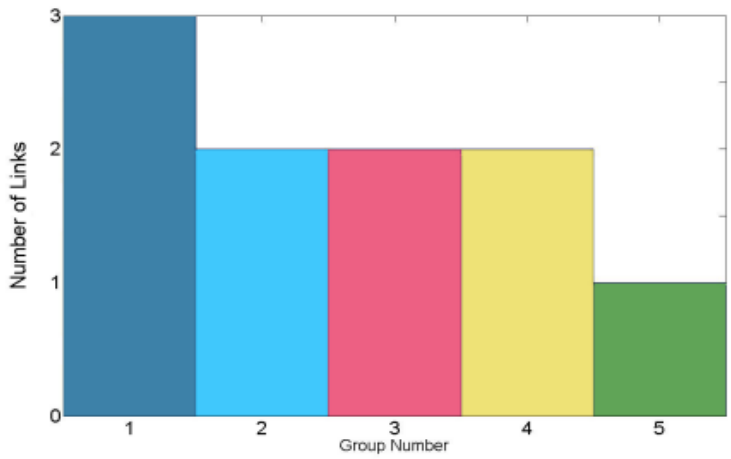


Figure 3.8: Histogram showing the number of links per group

The above figure resulting from the greedy grouping algorithm of the links shown in figure (3.7), the bar colors correspond with the group colors shown in figure (3.7).

The unequal distribution may seem unfair, because links in a crowded group will experience more interference than links in a less filled group. Nonetheless, the greedy grouping algorithm is well suited to be used with our first distance model described in paragraph (3.4). Then the distance criterium d_{min} is given by equation (3.32), with our first distance model, a minimum SINR is guaranteed if the corresponding minimum distance requirement is fulfilled, which is always the case with the links in groups formed with the greedy grouping algorithm.

3.5 Flow Chart

This flow chart explain the simulation stage of calculating the minimum distance with greedy grouping algorithm for all scenarios

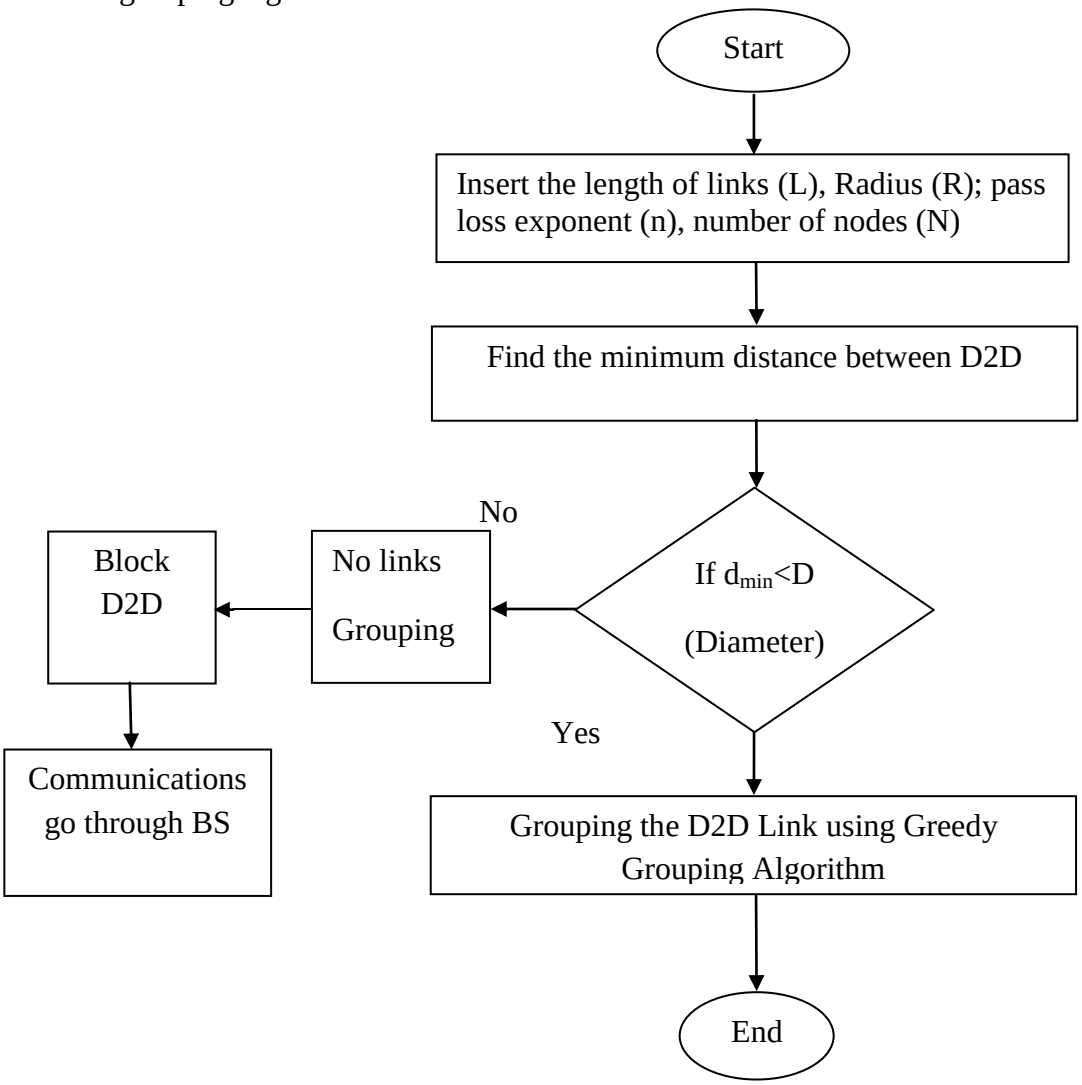


Figure 3.9: Flowchart of minimum distance d_{min} with greedy grouping algorithm

3.6 Assumptions

1- No shadow or the Gaussian mean zero XdB is neglected.

2- The cell shape is hexagon.

The simulation applies to the different area scenarios by using the parameters in the table 3.2 and the results are compared and analyzed.

Table 3.2: Pass Loss exponent for different environments.

Environment	Pass Loss Exponent (n)
Free Space	2
Urban Area	2.7 to 3.5
Suburban Area	3 to 5
Indoor (Line of Sight)	1.6 to 1.8