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Master’s Degree Thesis

An Enhanced Time Slot Allocation Scheme for Multi-Hop Concurrent Transmission with Multiple Directional Antennas

Graduate School of Chosun University

Department of Computer Engineering

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방향성 안테나 기반의 멀티홉 동시전송을 위한 타임 슬롯 할당 기법

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This thesis is dedicated to my parents for
their unparallel love, guidance and
support

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방향성 안테나를 활용하는 밀리미터파 기반 초고속 개인 영역 네트워크에 대한 관심이 증가하고 있다. 밀리미터파의 특성 및 다중 방향성 안테나를 사용하여 동일 지역 내에서 간섭현상 없이 동시 전송이 가능하다. 그러나 이러한 동시 전송을 극대화하기 위한 최적의 타임슬롯 할당은 NP-hard 문제로 실시간 스케쥴링이 매우 힘들다. 초고속 무선링크를 사용률을 증대시키기 위해 최적은 아니지만, 다중 홉 동시 전송 방법(MHCT)가 제안되었다. 이 논문에서는 다중 방향성 안테나를 이용하는 밀리미터파 기반의 통신을 위한 동시 전송 기법에 대한 분석 및 기존의 MHCT보다 향상된 방법인 EMHCT-E와 EMHCT-F를 제시한다. 이 방법들은 기존의 방법처럼 최적의 알고리즘은 아니지만 O(Nlog2N+N+1)의 계산 복잡도를 가지며, 기존의 방법에 비해 향상된 결과를

보여준다. 제안된 방법이 최적의 성능과 얼마만큼 차이가 나는지 비교를 위해 주어진 조건에서 최적의 성능을 water-filling을 이용하여 계산하였으며, 사용자 형평성 측면의 성능 비교도 수행하였다.

1. Introduction

Recently, the demand for high speed short range wireless networks (WPAN and WLAN) for home and office is increasing day by day. The advancement in multimedia applications such as High Definition Video TV and monitors, interactive gaming, large capacity file sharing devices such as Kiosk servers required ultra high speed wireless connection. To accomplish those needs, mmWave communication at 60GHz spectrum, becoming the most important candidate for front end technologies to fulfill the requirement of short range ultra high speed network applications.

1.1 *Standardization*

The mmWave communication with directional antennas at 60 GHz is adopted as the physical layer in the standardizations and specifications such as IEEE 802.15.3c [1] (WPAN) and IEEE 802.11 VHT [2] (WLAN) because the spectrum can achieve multi-gigabit link speed. IEEE 802.15.3c has low cost and low power consumption as compare to IEEE 802.11 VHT while both can provide Ultra high Data Rate of multi-Gbps. IEEE 802.15.3c WPAN is easy to install and easy to manage. It also has provision for Quality of Service (QoS) support and defines five usage models targeting variety of applications such as Wireless multimedia connectivity; High definition uncompressed streaming video, Interactive gaming, Video/audio distribution and High speed data transfer. VHT SG also dealing with issues of coexistence of various 60GHz technologies in same coverage area.

1.2 *Motivation*

mmWave communications at 60GHz spectrum has some unique characteristics. The signals at 60GHz have highest level of oxygen absorption property, which causes high level of propagation loss over distance. Thus, the transmission range of mmWave communication is usually much shorter than other wireless communications such as IEEE 802.11 and the link speed is drastically decreased over distance. The high level of path loss for long range wireless networks is a disadvantage but it become an advantage for WPAN and WLAN with directional antennas, in IEEE 802.15.3c WPAN a single PICONET can have 236 devices, because efficient space reuse of directional antenna under high degree of path loss environment is very high, since the overlapped region of transmission in localized region is very small as compare to omni-directional antennas. For instance, in a fully connected mesh topology such that all nodes in a localized region can communicate each other directly at a single hop distance. In case of omni-directional antenna a single transmission will block all other transmissions for the allocated transmission time, while in case of directional antenna with a high path loss factor each transmission occupies a small region and does not block all other transmissions in same localized region

These features make it possible for multiple users to coexist and can have *concurrent communication session* by scheduling to share the time slot allocations in same localized region using same radio frequency, the problem is *NP-Hard* [11]. Furthermore, reflection is more dominant than diffraction at receivers in high frequency band, leads to the need to maintain line-of-sight (LOS) to keep the high data rate. In order to keep a shorter distance and LOS between a transmitter and a receiver as much as possible, a relay node is introduced, which helps to achieve the high data rate between transmitter and receiver. To fully utilize the space reuse, previously a concurrent transmission among multiple transmitters and receivers are considered, which results in network level throughput increase, but still there is a room for improvement.

1.3 *Contributions*

We investigated the proposed scheme and found some possible improvements to further improve the network throughput. The previously proposed scheme creates the group of non-interfering transmissions for concurrent transmissions. However there is still a possibility to increase non-interfering transmissions within a group by considering inter-group collisions. Also few interfering transmissions can coexist with in a concurrent group with some conditions, such that no collision can take place. By considering inter-group collision and due to the coexistence of interfering transmissions, we get better network performance. We introduce “Concurrency Gain”, to find out theoretical bound of the network through, Concurrency Gain is used in capacity gaining water-filling algorithm, finally we gave “fairness” comparison of proposed schemes.

1.4 *Thesis Overview*

Chapter-2 briefly discuss the related work, in chapter-3 the problem statement has been explained in detail, chapter-4 is about explanation and analysis of *MHCT* scheme, chapter-5 proposed the enhanced versions *EMHCT-E* and *EMHCT-F* for concurrent transmission, chapter-6 explains the water filling algorithm, which is used to determine theoretical bound. Chapter-7 is about design considerations, the simulation parameters and performance metrics. The implementation of systems has been done in Matlab and C++. Chapter-7 also includes the water-filling comparison and various results and finally in conclusion section we concluded our work.

2. Related Work

2.1 *Spatial Reusability*

The spatial reusability is an important factor to increase the network capacity and performance. Due to the high path loss factor the important characteristic of spatial reusability is significantly high in 60GHz communication systems, which is the base for concurrent transmission. In [22] the spatial reusability aspect of 60-GHz wireless network is discussed in detail. The authors showed that in 60 GHz WPAN systems the possibility of spatial reusability is very high, which significantly improves the network performance. However the spatial reuse gain is generally dependent upon number of antennas, number of reflectors and frequency planning. [23] Showed that the performance of 60 GHz is highly dependent upon the obstructions between source and destination nodes. It is important to make sure 60 GHz network should operate in lightly obstructed environment. However due to spatial reusability property, network performance in highly congested situation is extensively high.

2.2 *Concurrent Transmission in mmWave WPANs*

To schedule the traffic for concurrent transmissions, different scheduling schemes have been proposed so far. Few of them targeting specific technologies for concurrency and some are giving general solution. The efficient mmWave medium access control (MAC) protocol is required for 60GHz technologies to support ultra high speed, which is still an open research issue [27]. Also 60GHz technologies are using directional antenna; hence modifications in MAC layer are vital to meet the issues stemmed due to the directional nature of the medium. Some Directional medium access control (MAC) related issues has been discussed for mmWave WPANs in the literature to deal with Multihop, concurrent and LOS based communication using directional antennas. [3] Proposed architecture for mmWave WPAN, where a relay node is selected when the LOS link between source and destination is blocked by moving. Without the relay, the transmission will be interrupted and the connectivity will experience serious link outage by moving obstacles. In [28] it is shown that LOS communication is very important in 60GHz systems because data rate of NLOS in same environment conditions drops by 1000 times. A modified MAC layer to deal with the directional nature of the medium is discussed in [29]. Specifically it is suggested that a node can also access channel without central controller, which means that beacon interval time is composition of both TDMA and CSMA/CA. The underutilization of MAC level channel capacity is discussed in [30]. Authors have also proposed a novel scheme to improve channel efficiency. In [31] TCP performance was checked for the MAC time allocation mechanism of IEEE 802.15.3. TCP performed well and achieves high throughput for high rate allocation, with appropriate selection of size of time slots. In [8] authors have investigated the effect of human mobility on the quality of 60GHz indoor channels. It is found that human activity has a very large scale effect on the quality of LOS channel. The disruption due to human activities can make a channel to be unavailable for duration up to 100ms. A site diversity technique by introducing relay nodes can be used to overcome on this problem of human obstruction. [4] and [5] developed an exclusive region (ER) based resource management scheme and analytically derived the optimal ER sizes to explore the spatial multiplexing gain of mmWave WPANs with directional antenna. [6] Tried to allow concurrent transmissions not causing interferences with each other to improve the network capacity. However, [6] is limited in terms of single hop or minimum hops relay for data transmission. In [15] Maximal Weighted Matching Scheduling (MWMS) algorithm is proposed for grouping the transmission requests for concurrent transmission. The algorithm removes profound interfering edges from the traffic graph to form groups of transmission which can transmit at acceptable interfering level. The algorithm also uses weight adjustment of transmission request to change the priorities for fairness. MWMS is investigated to check the effect of algorithm on overall energy consumption. The overall energy consumption is reduced due to making it possible to transmit in low interfering conditions. Concurrent transmission for multicast situation in multihop is discussed in [14].The problem of scheduling is first formulated as constraint and unconstraint optimization problems then some scheduling algorithms for concurrent transmission in rate adaptive multihop networks have been proposed in [13].Thus, [7] proposed a multi-hop concurrent transmission (*MHCT*) scheduling algorithm. The piconet controller (*PNC*) selects a *proper* number of relay nodes, to improve a single flow throughput between a transmitter and receiver based on a novel hop selection metric reflecting the degree of distribution of the traffic load across the network. The selection of relay nodes improves the throughput because the signal strength is highly dependent upon the distance between transmitter and receiver and also helps to avoid the NLOS problem caused by moving objects and human activity. To further improve the network performance, a multihop concurrent transmission (*MHCT*) scheme is used to allow non-interfering flows to concurrently transmit over an mmWave channel. By properly breaking one long-hop (i.e., low rate) transmission into multiple short hop (i.e., high rate) transmissions and allowing some noninterfering hops (including inner-flow hops and inter-flow hops) to concurrently transmit, the network capacity can be efficiently improved in terms of flow and network throughput. By carefully analyzing the work presented in [7] it is found that some improvement is possible to further increase the capacity of network by concurrent transmissions. The analysis work and enhanced algorithms are presented in chapter-5 of the thesis.

2.1.1 Additional applications of Concurrent transmission

The concurrent transmission for the WiMAX mesh network can improve the overall performance. A cross layer technique to fully exploit the benefits of concurrency at different layer in WiMAX mesh network is proposed in [24]. The concurrent transmission scheme has improved the network performance in terms of bandwidth efficiency and power controlling. The steered bean mmWave network provide ultra high data rate and its performance is very high is stationary environment, which make it a potential candidate to build wireless data centers with low cost, low power consumption and easy to install [25] which can replace messy wiring among different devices. Authors discussed the topology, routing protocols, fault tolerance and MAC layer implementation for the wireless data center. In [26] detail architecture for the wireless data centers using steering beams at high frequency is discussed and showed how to replace cross bar switches with wireless cross bar switching technique. A combination of wire & wireless can further improve the performance and significantly reduces the latency.

2.3 *Theoretical bound of Concurrent Transmission*

In order to calculate the optimum capacity gain, water-filling solution is well known algorithm to provide theoretical bound for the capacity gaining constrained optimization problem. In [16] water-filling solution for constrained optimization problems is discussed with a great detail. In terms of computational efficiency it is shown that water-filling solutions are best solution as compare to other numerical algorithm. Also Water-filling solution provides best practical solutions for most of the capacity achieving optimization problems.

In [17] the solution for power efficient resource allocation for TDMA in fading channel is given as water-filling solution. The time and bandwidth allocation among access points for load balancing is solved using water-filling algorithm [18]. In [19] the time slot allocation for multi users to maximize the network throughput with power constrained and minimum rate guarantee problem is solved using water-filling method. However most of the water-filling capacity achieving solutions considered power as a constrained variable and most of them provide very complicated problem specific solutions. A generalized and simple algorithm for water-filling problem is presented in [20]. The solution is provided under the constraint of power with objective of optimization of power transmission within a single frame. However, with minor changes and assumptions, solution can use for the theoretical bound for optimization of time allocation within a superframe, which described in detail in chapter-7.

3. Problem Description

3.1 *Notations*

- R_i = *i*-th Transmission Request.
- $n(i)$ = Time slots requirement by *i*-th Transmission Request.
- h_k^{Ri} = *k*-th Hop of *i*-th Transmission Request.
- $n(I,K)$ = Time slots requirement by *k*-th Hop of *i*-th Transmission Request.
- $d(i,j)$ = Distance between *i*–th and *j*-th node.
- $w(i,j)$ = Link weight between *i*–th and *j*-th node.
- $F(j)$ = Workload of *j*-th node.
- WT = Wireless terminal.
- G_i = *i*-th group of concurrent hop transmissions.
- $n(G_i)$ = Time slots requirement by *i*-th group G_i.
- $MAXSLOTS$ = Number time slots in superframe.
- N_slots = Available slots in superframe.

3.2 *Time slot allocation for concurrent transmission*

The time slot allocation for concurrent transmission can be considered as an optimization of packing problem. However the problem is different than Bin Packing or Strip Packing because in both cases width of Bin or Strip is fixed and variable size rectangular items are placed in such a way that in case of Bin Packing total volume consumption and in case of Strip Packing height of strip is to minimized. In time slot allocation for concurrent transmission problem, the items have variable width with interfering and conflict dimensions. The objective is to place these items (transmission requests) into variable size groups, such that

- Highest priority is given to the *transmission request* with highest *time slots requirement.*
- Two conflicting and interfering transmissions should not exist in the same group.

To achieve more densely populated groups the objective is to place items (transmission requests) into variable size groups, can further be enhanced, such that

- Two conflicting and interfering transmissions should not overlap in time dimension when they are in same group.

If $n(i)$ represents the time slots requirement of i-th transmission request (R_i) for fixed amount of data encapsulated as frame payload and we assume N transmission requests are arrived at the *PNC* during the random access period. Let [R_i , $n(i)$] denote each transmission request with its arrival order. Then, Ri will be transformed into multihop transmissions according to the *MHCT* scheme. Let $\{[h_k^{Ri}, n(I,k)], k = 1, 2, \dots, m \text{ and } i = 1, 2, \dots, N \}$ denote the ordered sequence representing the multihop transmission for R_i. m will be a number between 1 and $n(n-1)/2$ where n is the number of WTs. For $h^{Ri}{}_j$ hop transmission, $n(I,J)$ represents required number of time slots. For example, the ordered sequence for $[R_1,n(1)]$ is $\{[h_1^{R1}, n(1,1)], [h_2^{R1}, n(1,2)], \dots, [h_k^{R1}, n(1,k)],\}$. Then the optimization problem of time slot allocation with in a superframe for concurrent transmission can be formulated as given below;

$$\max \sum_{i=1}^{n_f} R_i \tag{3.1}$$

Subject to,

$$\sum_{i=1}^{n_f} \sum_{k=1}^{n_h^i} n(i,k) < \ MAXSLOTS$$

$$\forall \ \ h_k^{Ri} \quad \{i = 1{,}2 \ldots.,n_f\},\{k = 1{,}2 \ldots.,n_h^i\} \tag{3.2}$$

MAXSLOTS represents the total number of time slots in a superframe. Minimization of time slots requirement of transmission request with fixed data payload means increasing the data rate.

To solve the problem, optimum result leads towards NP-hard [11] and no solution is possible in a polynomial time. Therefore instead of solving the problem for optimum result a sub optimum result is possible. But still we have to consider the simplicity of algorithm as much as possible because the decisions of scheduling would be carried out by PNC, which has limitation of computational power. The algorithm which we proposed has better sub optimum result with in a polynomial time computational complexity.

3.3 *Path Selection*

Although main optimization problem is related to scheduling of multihop transmission requests, but selection of path i-e conversion of direct transmissions into multihop transmissions is also has significant effect on flow throughput. Therefore it is also important to define how and when the path selection should be made. The path selection i-e conversion of direct transmission into multihop transmissions is based on the following hop selection metric used in [7].

$$w(i,j) = \frac{d^2(i,j)}{\overline{D^2}} + \frac{F(j)}{\overline{F}} \tag{3.3}$$

Where, $\overline{D^2}$ and $\overline{F}$ are the average link length square and average traffic loads of each *WT* respectively. $d^2(i, j)$ is the link length of link ($i \rightarrow j$) and $F(j)$ is the traffic load of WT_j.

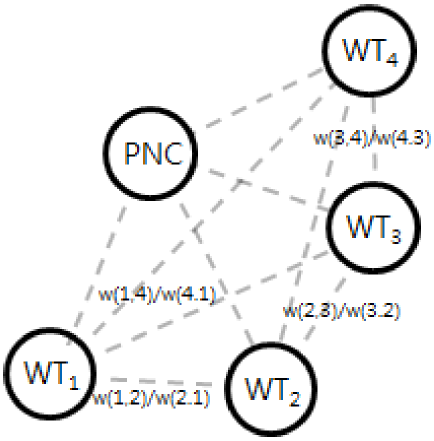

Figure 3- 1 Directinal complete graph of the network

The cost of each link is calculated by Eq. 3.3. The cost is very sensitive to the distance between *WTs* compared to the work load because the square operation on the distance. We omit the cost related to the *PNC* in Fig. 3-1.

To traverse the traffic flow on optimum path, and to boost the work load degree distribution across the network, path selection is not made at once. After scheduling of each non interfering group of hops with in a superframe, weighted graph is updated and next hop from requesting source node is recalculated for shortest path to destination.

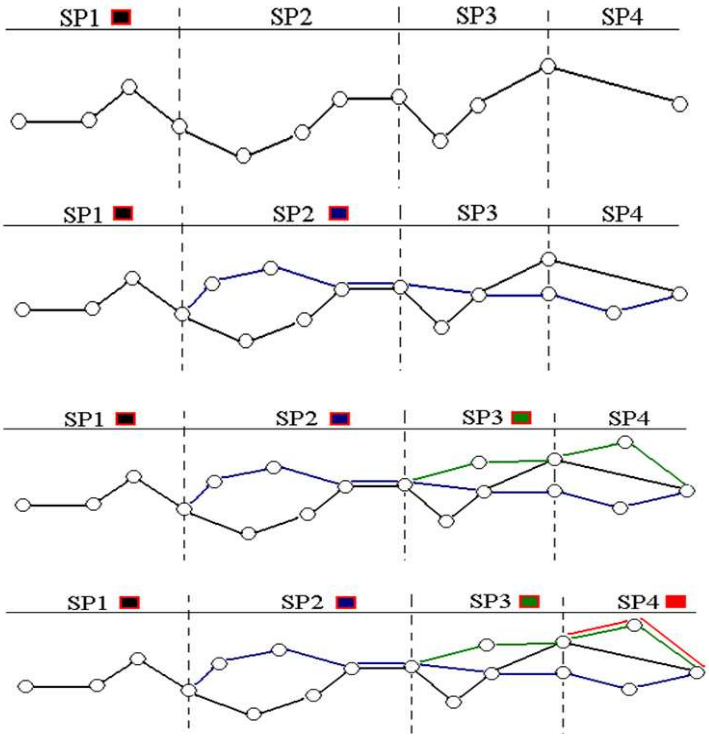

Figure 3- 2 Example of path selection decision

As shown in Fig. 3-2 at the beginning of superframe-1 (SP1) path from source to destination is calculated and represented by black lines, at the start of SP2 path from *current node* is calculated again and represented by blue lines in a similar way path is recalculated from current node until destination reaches. In static nodes positions path is still changing instantaneously because the path selection metric given in Eq. 3 is also dependent upon a dynamic factor of work load of nodes.

3.4 *Non-Interfering hop transmissions*

Transmission Conflict and signal interference (Collision) determine the Non-Interfering hop transmissions. In Fig. 3-3 there are 10 hop transmission requests [h_k^{Ri}, $n(I,k)$] among them 6 are scheduled for concurrent transmission as these are non-interfering hop transmissions. Request 4, 9, and 6 cannot be schedule in this group because one of the source or destination nodes is already scheduled for another hop transmission. The hop transmission number 7 is rejected because it has intolerable high level of signal interference from hop transmissions 1, 3 and 5.

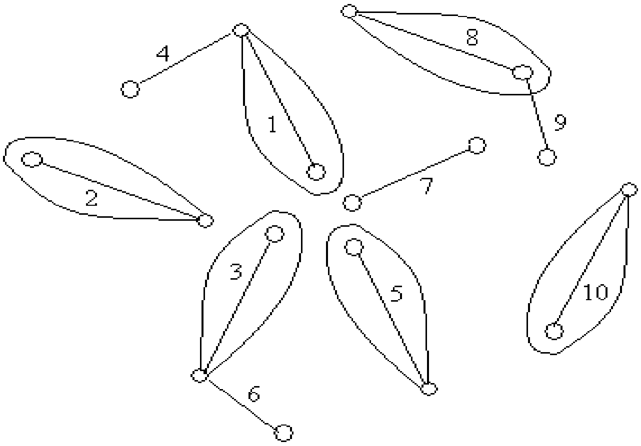

Figure 3- 3 Transmission Conflict (Collision) and signal interference, determine the non interfering hops

3.5 *Beam width and interference range*

The antenna beamwidth has significant impact on the probability of concurrent transmission i-e larger the antenna beamwidth lower the probability to find concurrent transmission, since with larger beamwidth each transmission occupies more coverage area and more likely to interfere other transmissions in same localized region, causing collision.

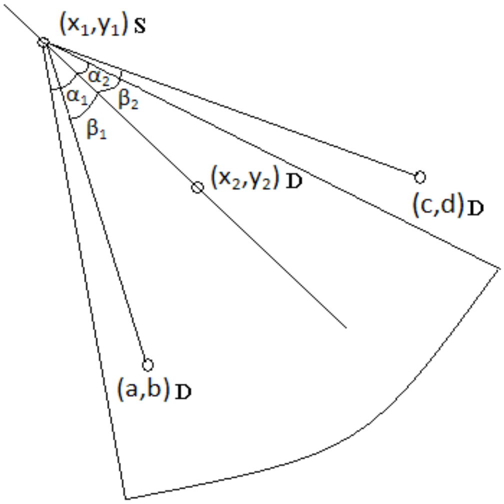

Figure 3- 4 Beam width and interference range

In Fig. 3-4 a transmission between source $(x_1,y_1)S$ and destination $(x_2,y_2)D$ is already scheduled. The angles α_1 and α_2 are calculated using basic trigonometric techniques ($\alpha_1 + \alpha_2$ = Beamwidth) these angles then used to determine the interference of this transmission with new transmission requests. For example two new transmission requests with destination *(a,b)D* and destination *(c,d)D* forms, angles of β_1 and β_2 with source $(x_1,y_1)S$. As $\alpha_1 > \beta_1$, therefore *(a,b)D* cannot be scheduled until *S-D* finishes but *(c,d)D* can be schedule concurrently with *S-D* because $\alpha_2 < \beta_2$.

4. Multihop Concurrent Transmission

The Multihop Concurrent Transmission (*MHCT*) scheme proposed in [7]. The main consideration of *MHCT* is to identify and group all non interfering hop transmissions into a single group such that the condition of coexistence of two or more hop transmissions of same collision (Transmission Conflict and interference) property in a same group should not occur.

4.1 *Multihop Transmission*

The MHT (Multihop Transmission) can be explained by using the following two examples.

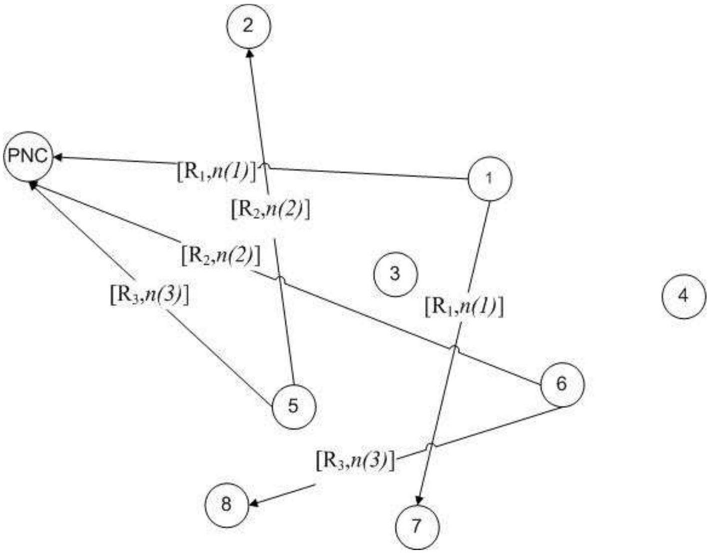

Figure 4- 1 Direct Transmission

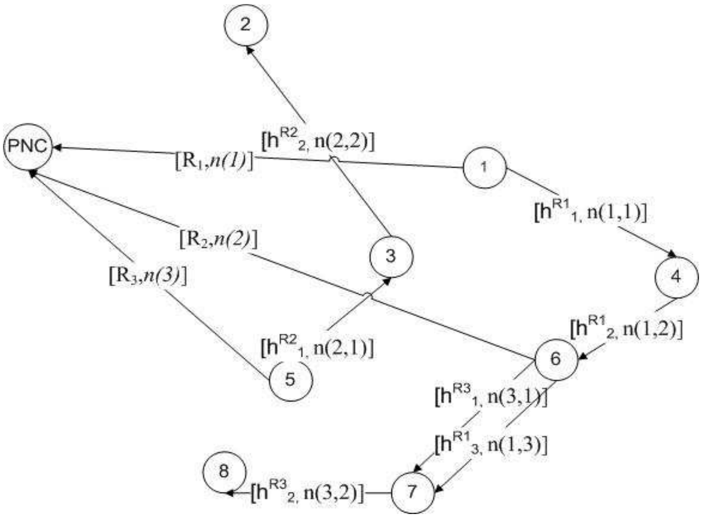

Figure 4- 2 Multihop Transmission.

Fig.4-1 and 4-2 depicts examples of direct single hop and multihop transmission. During random access period, the transmission requests *TREQ*{[R_1,*n(1)*], [R_2,*n(2)*] , [R_3,*n32)*] }of WT$_1$, WT$_5$ and WT$_6$ are arrived at the PNC. Then, *PNC* first tries to construct the directional complete graph of the network like Fig.2 based on the hop selection metric given in Eq. 3.

In Fig.4-1, the *PNC* will receive three transmission requests {[R_1, *n(1)*], [R_2,*n(2)*] , [R_3,*n32)*] }. The *PNC* will calculate the number of time slots for each hop transmission and allocate the estimated timeslots for each hop consecutively, at the beginning of transmission period. After finishing the first transmission request's scheduling, the second transmission request will be considered to be schedule and will schedule them one by one using simple TDMA without finding shortest path and concurrency.

In case of Fig. 4-2, the *PNC* will receive three transmission requests like the previous example. In the next step the *PNC* will to find the shortest path between the transmitter and the receiver. In case of the first transmission request in Fig.4-2, the *PNC* will chose the path from WT$_1$ to WT$_8$ for the data transmission and convert the [R_1,$n(1)$] into {[h_1^{R1} ,$n(1,1)$], [h_2^{R1} ,$n(1,2)$], [h_3^{R1},$n(1,3)$],} similarly [R_2,$n(2)$] converted into {[h_1^{R2} ,$n(2,1)$], [h_2^{R2} ,$n(2,2$]}and [R_3,$n32)$] is converted into {[h_1^{R3} ,$n(3,1)$], [h_2^{R3} ,$n(3,2$]}. Such that;

$$\sum_{i=1}^{3}\sum_{j=1}^{n_h^i}\left[h_j^{Ri}\,,n(i,j)\right] < \sum_{i=1}^{3}[R_i\,,n(i)] \tag{4.1}$$

Then *PNC* will schedule them one by one using simple TDMA without concurrency. The following algorithm is a concurrent transmission scheduling scheme proposed in [7] to further enhance the throughput by scheduling the hop transmissions concurrently.

Algorithm 1 Multihop Concurrent Transmission Scheduling Scheme

```
 BEGIN:
1:  PNC receives a request $h_j^{Ri}$ for n (I, J) time lots
2: for all non-empty group ($G_b$! = Null) do
3:     if $h_j^{Ri}$'s beam does not conflict with those of all existing hops in $G_b$ then
4:         if $h_j^{Ri}$ does not have shared nodes with other hops in $G_b$ then
5:             if $h_j^{Ri}$ requires extra slots, n (I, J) − n (b) > 0 then
6:                 if Available slots N_slots ≥ n (I, J) − n(b) then
7:                     Schedule $h_j^{Ri}$ in Group $G_b$;
8:                     Update $G_b = G_b U\{h_j^{Ri}\}$;
9:                     Update the available slots N = N − [n (I, J) −n (b)];
10:                    Update n (b) = n (I, J);
11:                    Update the allocated slots for $h_j^{Ri}$;
12:                    Sort all hops in the decreasing order of allocated slots.
13:                    go to END;
14:               else
15:                    go to line 26;
16:               end if
17:            else
18:               Schedule $h_j^{Ri}$ in Group $G_b$;
19:               Update $G_b = G_b \cup b;\{h_j^{Ri}\}$;
20:               Update the allocated slots for $h_j^{Ri}$;
21:               Sort all hops in the decreasing order of allocated slots.
22:               Go to END;
23:            end if
24:        end if
25:    end if
26:    Next Group;
27:  end for
28:  if Available slots N_slots≥n(I,J) then
29:      Start a new group G(k) = { $h_j^{Ri}$ };
30: else
31:      Reject request $h_j^{Ri}$ and release resources;
32: end if
END;
```

4.2 *Time slot Allocation Process in MHCT*

Once the direct transmissions converted into multihop transmissions, *PNC* allocates the time slots (calculated by Eq. 6.7) at the beginning of transmission period. The *PNC* sorts the hop transmission requests in decreasing order according to the number of time slots requirement *n(I,J)*, then it checks for the concurrent hop transmissions in *hop sequence* order of each transmission request and finally it will form groups G_i of hops which can transmit concurrently.

Initially, *PNC* receives multiple transmission requests R_1 *to* R_k. Each R_i is then converted to multiple hop transmissions. The set of $TREQ_1\{[h_1^{R1}, n(1,1)], [h_1^{R2}, n(2,1)], \ldots, [h_1^{Rk}, n(k,1)]\}$, represent the set of first hop transmission requests of multi-hop transmissions. All transmission requests in $TREQ_i$ are sorted in decreasing order and checked for concurrency to form a subset Group (G_1) of $TREQ_i$ which contains all first hop transmission requests that can be scheduled concurrently. In next step the set of $TREQ_2 = \{[h_2^{R1}, n(1,2)], [h_2^{R2}, n(2,2)], \ldots, [h_2^{Rk}, n(k,2)]\} \cup \{TREQ_1 - G_1\}$ representing the second hops transmission requests of multi-hop transmissions, along with remaining transmission requests from first hops, will be checked for concurrency and form next group of concurrent multi-hop transmissions, G_2. This is an iterative process which continues until one of the following two conditions satisfied.

1- $\sum_{i=1}^{n_g} n(G_i) < MAXSLOTS \quad \forall \quad G_i\{i = 1,2 \ldots., n_g\}$ (4.2)

2- All requests are scheduled.

Where $n(G_i)$ denotes the maximum number of time slots consumed by G_i and *MAXSLOTS* denote the total time slots in a single superframe. G_i and $TREQ_i$ has some relational properties given below.

- $G_i \subseteq TREQ_i$ (4.3)

- $G_i \cap G_j = \emptyset$ Where $i = 1,2,3.....n$ and $j=1,2,3...n$. and $i \neq j$. (4.4)

When condition "1" satisfied, the next hop to the latest successful scheduled hop of R_i is consider as initial hop to final destination node. In case next scheduling hop of R_i to be schedule in next superframe, *PNC* recalculate multi-hop transmissions from source node of current hop transmission to the initial hop to final destination node.

After finishing the scheduling of the last transmission request, we may obtain the transmission scheduling map such as Fig. 4-3.

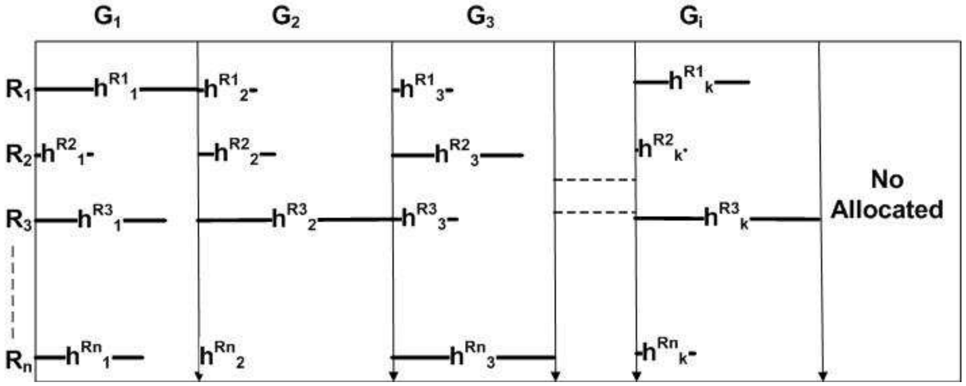

Figure 4- 3 An example of time slot allocation map of transmission period for concurrent transmission using *MHCT*

The allocation map made by Algorithm 1 indicates concurrent hop transmissions belong to each group and how many time slots each group consumes. Then total consumption of time slots are given below;

$$\sum_{i=1}^{n_g} n(G_i) \quad \forall \quad G_i\{i = 1,2 \ldots., n_g\} \tag{4.5}$$

Where $n(G_i)$ is equal to highest time slots required by a hop transmission in that group. This implies

$$\sum_{i=1\ MHCT}^{n_g} n(G_i) \ < \ \sum_{i=1}^{i}\sum_{k=1}^{n_h^i}\left[h_j^{Ri}, n(i,j)\right] \ < \ \sum_{i=1}^{i}[R_i, n(i)] \qquad (4.6)$$

The bandwidth efficiency is determined by Eq. 4.2. Higher bandwidth efficiency will be achieved with smaller value of Eq. 4.2, which is same as constraint of optimization problem discussed in chapter-3. If we carefully observe the map, we can find a margin to improve the efficiency with a little change to the allocation map.

4.3 *Algorithm Complexity*

To find out the worst case complexity of *MHCT*, we take some worst case considerations; if there are *N* numbers of traffic flows with maximum of *P* number of hops in a path. A path can have maximum of $P= n-1$ hops, where *n* is the total number of nodes. Then *MHCT* will have to schedule $N*(n-1)$ hops. For each hop scheduling request $[h_j^{Ri}, n(i,j)]$, in worst case *PNC* has to sort *N* elements. Similarly, For each hop scheduling request $[h_j^{Ri}, n(i,j)]$, in worst case *PNC* has to make *N* comparisons to check collision and finally one comparison is required to update current available time slots. So, in worst case of *MHCT PNC* has to perform sorting (merge sort with $O(NlogN)$ complexity) of *N* elements for $N*(n-1)$ number of times, has to make *N* number of comparisons (Linear comparison of all elements is linear search worst case complexity $O(N)$) for $N*(n-1)$ number of times and finally *1* comparison. It means to schedule one hop transmission *MHCT* has $O(Nlog_2N+N+1)$ computational complexity for *N* number of active traffic flows and *n* number of nodes. To schedule all the hop requests total time complexity is $O(N*(n-1)*(Nlog_2N+N+1))$.

5. Enhanced Multihop Concurrent Transmission

Algorithm 1 does not consider inter-collisions among groups but only considers intra-collisions within a group. The hop transmissions in a group are guaranteed to have no collision but hop transmissions between groups are not checked if they are interfered or not.

5.1 *Time slot Allocation Process in EMHCT-F/E*

To check the inter-group collision for each requested transmission request, we enhanced *MHCT* and proposed two versions *EMHCT-F* (Enhanced Multihop Concurrent Transmission-Fixed) and *EMHCT-E* (Enhanced Multihop Concurrent Transmission-Expandable). The main consideration of *EMHCT-F/E* is the identification and grouping of hop transmissions such that two or more conflicting/interfering hop transmissions can coexist in the same group if they fallow following conditions;

1- The conflicting and interfering transmissions should not overlap in time dimension when they are in same group.

2- They should fallow *hop sequence* order of each transmission.

3- In case of *EMHCT-F* the time slots requirement $n(I,J)$ should satisfy condition 'a' and in case of *EMHCT-E* the time slots requirement $n(I,J)$ should satisfy condition 'b'.

  a. $n(I,J)$ should be less than or equal to difference of largest time slots requirement of conflicting hop transmission and time slots requirement of the group $n(G)$.

    - $n(I,J) <= n(G) - max[n_c(I,J)]$

b. *n(I,J)* should be less than or equal to the sum of remaining time slots in the superframe and time slots requirement of the group *n(G).*

  - $n(I,J) <= N_{slots} + n(G) - max[n_c(I,J)]$

EMHCT-E and *EMHCT-F* both outperform each other based on beamwidth of antennas. For higher beamwidth each transmission occupies larger area, have a large interference dimension. Therefore, without altering the size of group, it becomes difficult to place new transmission request in already existing groups. The expansion of group which should satisfy the condition 3-b, increases the probability to place the new transmission request in existing groups. Hence *EMHCT-E* has better results as compare to *EMHCT-F* .But for smaller beamwidth each transmission occupies small area, have a small interference dimension. Therefore, without altering the size of group, we can place new transmission request in already existing groups, which should satisfy the condition 3-a. Hence *EMHCT-F* has better results as compare to *EMHCT-E*. In other words *EMHCT-F* tries to accept more fast transmission requests with small interfering range while *EMHCT-E* tends to accept slow transmission requests with large interfering range.

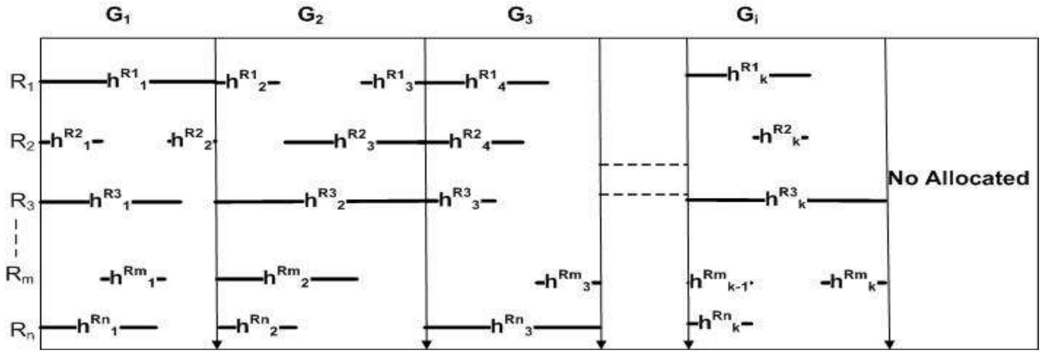

Figure 5- 1 An example of time slot allocation map of transmission period for concurrent transmission using *EMHCT-F/E*

In general pictorial form *EMHCT-E* and *EMHCT-F* both give the same time slot allocation map for concurrent transmission given in Fig. 5-1 but for specific situation allocation map for concurrent transmission for *EMHCT-E* and *EMHCT-F* can be different. The total consumption of time slots for *EMHCT-F/E* can also be represented by Eq. 4.5, but in *EMHCT-F/E* each group holds more hop transmission requests as compare to *MHCT*, hence number of groups will reduce for same hop transmission requests. The size of each group will also be almost same because the size of group determine by the priority scheme, which is same for *MHCT* and *EMHCT-F/E*. This implies

$$\sum_{i=1\;EMHCT-E/F}^{n_g} n(G_i) \;<\; \sum_{i=1\;MHCT}^{n_g} n(G_i)$$

$$< \sum_{i=1}^{i}\sum_{k=1}^{n_h^i}\left[h_j^{Ri}, n(i,j)\right] < \sum_{i=1}^{i}\left[R_i, n(i)\right] \qquad (5.1)$$

In *EMHCT-F/E* the relational properties of G_i and $TREQ_i$ are different and given below.

- $G_i \not\subset TREQ_i$ (5.2)

- $G_i \cap G_j \neq \emptyset$ Where $i = 1,2,3\ldots..n$ and $j=1,2\ ,3\ldots n$. and $i \neq j$. `(5.3)

In *EMHCT-F/E*, G_i can contain hop transmission requests from other $TREQ_j$. similarly two different groups can posses hop transmission requests of same collision properties.

In Fig. 5-1 hop transmission of h_2^{R2} in G_1 has interference with h_1^{Rm} and previous hop transmission of same transmission (h_1^{R2}) is also already exists in

G_1. Because *n(2,2)* is less then [*n(1,1)-(n(m,1)+n(2,1))*], h_2^{R2} is placed in G_1, such that it does not overlap with h_1^{Rm}. Similarly h_3^{R1} is placed in G_2 along with conflicting hop h_2^{Rm} and previous hop transmission of same transmission (h_2^{R1}) as it is satisfying all conditions to avoid the collision during concurrent transmissions.

5.2 *EMHCT-E/F Algorithm*

The Algorithm 2 and 3 are enhanced versions of concurrent transmission scheduling scheme which are considering inter-group and intra-group collisions to schedule hop transmission requests. A brief stepwise explanation is given below;

- STEP 1: Execute Algorithm 1 and obtain the time slot allocation map
- STEP 2: Sort the hop transmissions in every group with the number of allocated time slots in descending order
- STEP 3: Start span overlapping process from G_2 against G_1. After finishing the span overlapping between G_2 and G_1, apply the same procedure to G_3 against G_2 and so on. In case of G_2's span overlapping, start it from the first hop transmission of G_2, Check if this hop transmission or the span overlapping candidate causes a collision with the hop transmissions in G_1 one by one until meeting the hop transmission having a collision with each other or the hop transmission belonging to the same transmission request. If span overlapping candidate found few collisions or hop transmissions from same transmission request, in case of *EMHCT-F* it checks the conditions 1,2 and 3-a, while in case of *EMHCT-E* it checks the conditions 1,2 and 3-b.

- STEP 4: if the lookup of STEP 3 finds the specific hop transmission satisfying the conditions, move the allocated time slots of the span overlapping candidate back to back at the end of the hop transmission before the specific hop transmission. Then, the next hop transmission of G_2 performs the same procedure of STEP 3. After finishing span overlapping of all hop transmissions in G_2, the hop transmissions of G_3 starts the span overlapping procedure as described in STEP 3 and STEP 4. The span overlapping procedure will continue until finishing the last group's span overlapping.

5.3 *Algorithm Complexity*

To find out the worst case complexity of *EMHCT-F/E* is same as *MHCT* except for scheduling of each hop, the number of comparisons in worst case is $N*(n-1)$. It means to schedule one hop transmission *EMHCT-F/E* has $O(N\log_2 N+(N*(n-1)+1)$ computational complexity for N number of active traffic flows and n number of nodes. To schedule all the hop requests total time complexity is $O(N*(n-1)*(N\log_2 N+(N*(n-1)+1))$.

Algorithm 2 EMHCT-F

```
BEGIN:
 1:  $PNC$ receives a request $h_j^{Ri}$ for n (I, J) time lots
 2: for all non-empty group ($G_b$! = Null) do
 3:     for all non-empty group ($G_i$! = Null) ,{i=1,2….b-1} do
 4:         if $h_j^{Ri}$'s beams conflict with few of existing hops in Gi or $h_j^{Ri}$ have shared nodes with other hops in Gi then
 5:             $G_c$ = Identify beam conflicting and shared nodes,     where $G_c \subseteq G_i$
 6:             n(c) = Maximum n in $G_c$
 7:             for all $h_j^{Ri}$ in $G_c$ do
 8:                 if n (I, J) ≤ n(i) - n(c)
 9:                     Update $G_i = G_i \cup$ i;{ $h_j^{Ri}$ }, position at n(c) and Go to END;
10:                 end if
11:             end for
12:         end if
13:     end for
14:     if $h_j^{Ri}$'s beam does not conflict with those of all existing hops in $G_b$ then
15:         if $h_j^{Ri}$ does not have shared nodes with other hops in $G_b$ then
16:             if $h_j^{Ri}$ requires extra slots, n (I, J) − n (b) > 0 then
18:                 if Available slots N_slots ≥ n (I, J) − n(b) then
19:                     Schedule $h_j^{Ri}$ in Group $G_b$;
20:                     Update $G_b = G_b$U{$h_j^{Ri}$};
21:                     Update the available slots N = N − [n (I, J) −n (b)];
22:                     Update n(b) = n (I, J);
23:                     Update the allocated slots for $h_j^{Ri}$;
24:                     Sort all hops in the decreasing order of allocated slots.
25:                     go to END;
26:                 else
27:                     go to line 38;
28:                 end if
29:             else
30:                 Schedule $h_j^{Ri}$ in Group $G_b$;
31:                 Update $G_b = G_b$ Ub;{ $h_j^{Ri}$ };
32:                 Update the allocated slots for $h_j^{Ri}$;
33:                 Sort all hops in the decreasing order of allocated slots.
34:                 Go to END;
35:             end if
36:         end if
37:     end if
38:     Next Group;
39: end for
40: if Available slots N_slots≥n(I,J) then
41:     Start a new group G(k) = { $h_j^{Ri}$ };
42: else
43:     Reject request $h_j^{Ri}$ and release resources;
44: end if END;
```

Algorithm 3 ***EMHCT-E***

```
BEGIN:
1:  $PNC$ receives a request $h_j^{Ri}$ for n (I, J) time lots
2: for all non-empty group ($G_b$! = Null) do
3:     for all non-empty group ($G_i$! = Null) ,{i=1,2….b-1} do
4:          if $h_j^{Ri}$'s beams conflict with few of existing hops in Gi or $h_j^{Ri}$ have shared nodes with other hops in Gi then
5:               $G_c$ = Identify beam conflicting and shared nodes,        where $G_c \subseteq G_i$
6:               n(c) = Maximum n in $G_c$
7:               for all $h_j^{Ri}$ in $G_c$ do
8:                   if n (I, J) ≤ n(i) - n(c)
9:                      Update $G_i = G_i \cup i;\{ h_j^{Ri} \}$, position at n(c) and Go to END;
10:                     else
11:                      if n(I, J) ≤ N_slots +n($G_i$)
12:                      Update $G_i = G_i \cup i;\{ h_j^{Ri} \}$, n($G_i$)=n(I, J) and Go to END;
13:                      end if
14:                  end if
15:              end for
16:         end if
17:     end for
18:         if $h_j^{Ri}$'s beam does not conflict with those of all existing hops in $G_b$ then
19:              if $h_j^{Ri}$ does not have shared nodes with other hops in $G_b$ then
20:                  if $h_j^{Ri}$ requires extra slots, n (I, J) − n (b) > 0 then
21:                      if Available slots N_slots ≥ n (I, J) − n(b) then
22:                          Schedule $h_j^{Ri}$ in Group $G_b$;
23:                          Update $G_b = G_b U\{h_j^{Ri}\}$;
24:                          Update the available slots N = N − [n (I, J) −n (b)];
25:                          Update n(b) = n (I, J);
26:                          Update the allocated slots for $h_j^{Ri}$;
27:                          Sort all hops in the decreasing order of allocated slots.
28:                          go to END;
29:                      else
30:                          go to line 41;
31:                      end if
32:                  else
33:                         Schedule $h_j^{Ri}$ in Group $G_b$;
34:                          Update $G_b = G_b \cup b;\{ h_j^{Ri} \}$;
35:                          Update the allocated slots for $h_j^{Ri}$;
36:                          Sort all hops in the decreasing order of allocated slots.
37:                          Go to END;
38:                  end if
39:              end if
40:          end if
41:         Next Group;
42:  end for
43:  if Available slots N_slots≥n(I,J) then
44:         Start a new group G(k) = { $h_j^{Ri}$ };
45: else
46:         Reject request $h_j^{Ri}$ and release resources;
47: end if  END;
```

6. Water-Filling

A generalized water-filling solution algorithms for a wide verity of family of water-filling solutions is presented in [20], in such a way to make the practical implementation simpler. If we reconsider our objective function of optimization problem and redefine according to the form of constraint optimization problem discussed in [20] then we can obtain water-filing result by using algorithm-3.

$$\max \sum_{i=1}^{n_f} \log\left(1 + R_i\, \rho_i\right)$$

Subject to,

$$\sum_{i=1}^{n_f} \sum_{k=1}^{n_h^i} n(i,k) < MAXSLOTS$$

$$\forall \;\; h_k^{Ri} \;\; \{i = 1,2 \ldots.,n_f\}, \{k = 1,2 \ldots.,n_h^i\}$$

$$n(i,k) > 0 \qquad\qquad \{\, i = 1,2 \ldots.,n_f\}, \{k = 1,2 \ldots.,n_h^i\} \qquad (6.1)$$

Given by

$$n(i,k) = (\mu - \rho_i^{-1})^{+} \qquad \{\, i = 1,2 \ldots.,n_f\}, \{k = 1,2 \ldots.,n_h^i\} \qquad (6.2)$$

Where $(\propto)^{+}$ selects the maximum value for *n(i,k)*, ρ is the concurrency gain for a transmission request, MAXSLOTS is the number of total slots in a superframe, *n(I,k)* is the time slots requirement by *i*-th transmission and *k*-th hop, *i*k* are the total hop transmission requests h_k^{Ri} and μ is the water level, which is chosen such that $\sum_{i=1}^{n_f} \sum_{k=1}^{n_h^i} n(i,k) = MAXSLOTS$. Water level depends upon the concurrency gain (ρ), it get high if concurrency gain (ρ) is low and it gets low if concurrency gain (ρ) is high. Which means that the hop transmission requests h_k^{Ri} will get higher data rate with low water level.

The constrained optimization problem in Eq. 6.2 is similar to the constrained optimization problem given in Eq. 3.1. The objective of our constrained optimization problem is to maximize R_i however in Eq. 6.2 objective is to maximize the log value of R_i with concurrency gain (ρ).

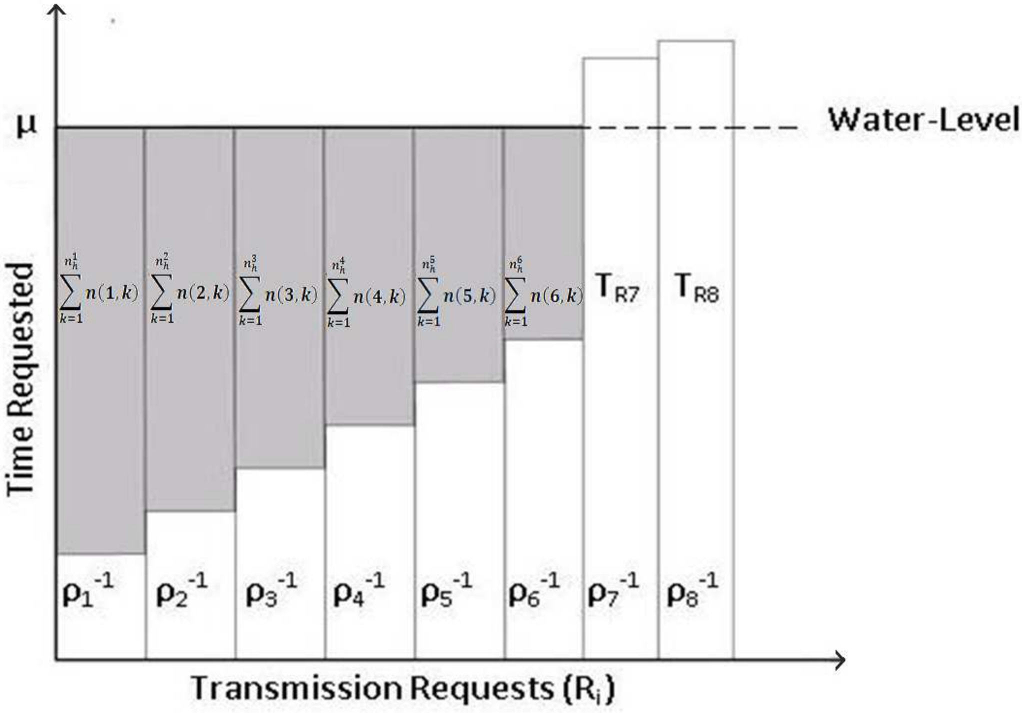

Figure 6- 1 Water-filling realization of problem given in Eq 6.1

The algorithm-3 [20] gives the water-filling solution for our constrained optimization problem with worst case complexity of *i*k* iterations. In algorithm-3 constraint function g satisfy the constraint condition i-e $g(\mu) = \sum_{i=1}^{n_f} \sum_{k=1}^{n_h^i} n(i,k)_\mu - MAXSLOTS$. this constraint function make the value of *n(i,k)* depends upon water level μ. In this way the hop transmission requests h_k^{Ri} with high concurrency gain (ρ) get more allocation of time resources.

Water-filling is a greedy solution of constrained optimization problem and allocate more resources to transmission request with high concurrency gain (ρ). This greedy approach increases the overall throughput of network to give an optimum result. We have compared the result of water-filling algorithm implementation with *MHCT* and EMHCT.

Algorithm 4 Water-filling solution

```
–

Input: Set of concurrency gain $\{(\rho)\}$ and constraint function $g$.
Output: Numerical solution $\{n(i,k)\}$ and water level.
    1. Set $\tilde{l} = i * k$, and sort the set $\{(\rho)\}$ such that $\rho_i$ are in decreasing order $\rho_{\tilde{l}}^{-1} > \rho_{\tilde{l}+1}^{-1}$ (define $\rho_{\tilde{l}}^{-1} = 0$)
    2. If $\rho_{\tilde{l}}$< $\rho_{\tilde{l}+1}$ and $g(\rho_{\tilde{l}})$ then accept and go to step 3. Otherwise, reject form new one by setting $\tilde{l} = \tilde{l} - 1$ and go to step 2.
    3. Find water level $\mu \in (\rho_{\tilde{l}}, \rho_{\widetilde{l+1}}) | g(\mu) = 0$, obtain numerical solution as,
       $n(i,k) = (\mu - \rho_{\tilde{l}}^{-1})^{+}$    $\{ i = 1,2 \ldots.,n_f\},\{k = 1,2 \ldots.,n_h^i\}$
    4. Undo sorting done at step 1 and finish.
```

7. System Design Simulation and Performance Evaluation

Considering an indoor WPAN consists of several wireless terminals (WTs) and a single PNC. Each of them is equipped with electrically steerable directional antennas, which means transmitters and receivers direct their beam toward each other for data transmission. All nodes are at single hop distance and making a fully connected mesh topology as shown in Fig. 3.1. The weighted graph has been created based on Eq.3.3. As the network size in WPAN is small, typically consists of single room and have low level of mobility, also we consider the traffic flows between the nodes within same PNC. So, we can assume that the PNC receives location information of each WT at the start of each superframe during random access period.

7.1 *mmWave Communication Rate and time slots calculation*

The indoor environment is less dynamic as compare to outdoor, so we can assume that channel conditions almost remain static for time duration of a superframe. In IEEE 802.15.3 throughput mainly depends upon scheduling scheme and least depends upon transmission power [13]. We can assume all nodes can transmit with maximum power.

The achievable data rate according to Shannon theory is given by;

$$R = w * \log_2[1 + SNIR] \tag{7.1}$$

Where R is data rate and W is available bandwidth. In Additive white Gaussian noise (AWGN) channel SNR is given by;

$$SNIR = \frac{P_r}{(N_o + I) * W} \tag{7.2}$$

Where N_o is background noise, I is interference and P_r is received signal power. According to Friis free space equation, path loss between two isotropic antennas is given by;

$$L = \frac{(4\pi)^2 r^2}{\lambda^2 G_t G_r} \tag{7.3}$$

So, received signal power is given by;

$$P_r = \frac{P_t \lambda^2 G_t G_r}{(4\pi)^2 r^2} \tag{7.4}$$

Combining equation 1,2 and 4;

$$R = W \log_2 [1 + \frac{P_t G_t G_r \lambda^2}{16\pi^2 (N_o + I) W r^n}] \tag{7.5}$$

Where W is the system bandwidth, N_0 and I are the one side power spectral density of white Gaussian noise and interference respectively. P_t is transmission power, G_r and G_t are the antenna gain of receiver and the antenna gain of transmitter respectively, λ is the wavelength and r is the transmission distance between the transmitter and the receiver, n is the path loss exponent whose value is usually between 2 and 6 for indoor environment [8]. According to (1), we can easily understand R is very sensitive to r, large value of r means low data rate i-e smaller R.

Using Eq. 7.5 we calculate the channel capacity and time slots $n(I,J)$ requirement for a transmission request to deliver data to next hop destination.

To calculate the value of time slots $n(I,J)$ using Shannon formula. We first find out the channel capacity R by using the following modified version of Eq. 7.5;

$$R = W \log_2[1 + \frac{P_t G_t G_r \lambda^2}{16\pi^2(N_o + I * \boldsymbol{NF})W r^n}] \tag{7.6}$$

We introduce a new variable *NF* to adjust *SNR* according to active traffic flows. *NF* represents number of active flows within *G*. Due to concurrent transmission the value of I is very low but as number of active flows increases within *G,* the level of interference also increases.

Time slots required to send 10mb (Data payload) from $h_{k-1}^{R_m}$ to $h_k^{R_m}$ is given by,

$$n(I,J) = \frac{10/_R}{t_{ts}} \tag{7.7}$$

Where, t_{ts} is single time slot duration.

7.2 *Antenna Model*

For the antenna gain, an ideal “flat-top” model for directional antenna [7][10] is considered like the following equation,

$$g(\emptyset) = \begin{cases} 12, & |\emptyset| \le \frac{\Delta\emptyset}{2} \\ 0, & otherwise \end{cases} \tag{7.8}$$

Where $\Delta\varphi = 2\pi/N$ is the antenna beamwidth when every node is equipped with an antenna with N beams, each of which spans an angle of $2\pi/N$ radians. Thus, if a transmitter and a receiver are directed within the antenna beamwidth each other ($|\varphi|\le\Delta\varphi/2$), the antenna gains of transmitters and receivers, $G_t = G_r = 12dBi$ $G_t = G_r = 12dBi$ [10][12] and $G_t = G_r = 0$ outside. Therefore, in ideal antenna model discussed in [10], the interference outside the antenna beam is zero, while inside beam width is high enough to block other transmission. Also in LOS room case, mainly the received power is directed wave [9]. The following figure shows an example.

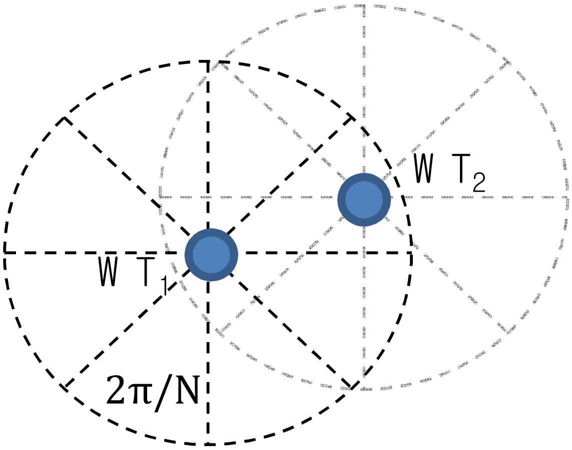

Figure 7- 1 An example of $G_t = Gr = 12$ between two nodes each of which lies within the beamwidths.

7.3 *Directional MAC Structure*

The IEEE 802.15.3 superframe structure in Fig. 7-2 is used for directional MAC.

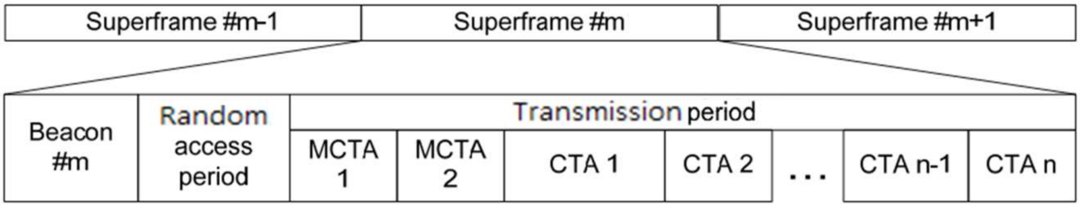

Figure 7- 2 IEEE 802.15.3 MAC.

Beacon period, random access period and transmission period is composing a single superframe. During a beacon period, a *PNC* sends all nodes a beacon frame for management information such as synchronization and scheduling information. The scheduling information message contains, the start time of the current transmission period and its duration, nodes concurrent scheduling information and direction information for steering beam. During the period followed by the beacon period, *WTs* having a data transmission are sending their transmission requests in random access manner. Only the transmission requests arrived at the *PNC* will be considered to be scheduled for the next transmission period. The transmission request also includes topology information to determine the transmitter's antenna direction and *WT's* load. During the transmission period or contention free period, only scheduled *WTs* are allowed to send their data during the allocated time slots, which is almost similar to TDMA.

7.4 *Priority Scheme*

During generation of $G_i s$ the highest priority is given to the $h_j^{R_i}$ with higher number of *n(I,J)* requirement, which means giving highest priority to low rate links. This scheme is adopted to achieve fairness.

7.5 *Simulation Settings*

Consider a room of 16x16 meter with 30 nodes randomly deployed at different locations. Each node has multiple antennas. The number of antennas depends upon the beamwidth we use.

$$No.of\ Antennas = \frac{360}{Beam\ width\ in\ degrees} \tag{7.9}$$

Table 1 Simulation parameters.

Parameters	Sign	Value
Bandwidth	W	7000MHz
Transmission Power	Pt	0.1 mW
Antenna gain of Transmitter and Receiver	Gt & Gr	12dBi
Background noise	No	-134dBm/MHz
Path loss exponent	n	3~6
Room size	X*Y	16x16
Number of Nodes	N	30
Antennas	18,8,4,2	count

802.15.3c operates with 9Ghz of bandwidth (57~66GHz), however in Korea, USA and Japan 7GHz of band is available and we considered 7GHz of bandwidth for our simulations. Rests of the parameters are selected according to the [7] and [13].

To get more accurate result, simulation is performed for different amount of data, for each traffic flow data is varying from 50~350mb. The frame payload is 10mb, which means during a single traffic flow session if source to destination 50mb of data has to be send, then it will consume 5 MAC frames. The frame size in terms of time slots requirement is variable, depending upon the channel condition and availability of multihope shortest path.

For each data set nodes are randomly deployed and simulated for different number of active traffic flows. The number of active traffic flows varying from

1~50 and for each simulation run, traffic flow pair selection, is also done randomly using 10 different seed values. In total for each Beam-Width selection, 700 simulations run were carried out; final result is taken by averaging all the simulation run for each beam-width selection. In our simulation the computational cost of antenna selection is not taken as a parameter. If we consider computational cost of antenna selection then there will be an upper bound of number of antennas to get highest throughput.

For water-filling simulation is carried out by taking the concurrency gain achieved by *EMHCT* with antenna beam of 45deg. Water-filling result also taken for the extreme values as well. Minimum concurrency gain is “1” while maximum concurrency gain is equal to the active number of traffic flows.

7.6 *Operational flow charts*

Fig. 7-3, 7-4 and 7-5 explain the operation of *PNC* during a single superframe for *MHCT*, *EMHCT-F* and *EMHCT-E* respectively. In BP, *PNC* broadcasts synchronization and scheduling information. During RAP, *PNC* receives transmission requests [R_i ,*n(i)*], from different nodes. After receiving the transmission requests [R_i ,*n(i)*] *PNC* updates the weighted graph and calculates the shortest multihop path between source and destination of each transmission requests [R_i ,*n(i)*]. Before creating the G_i*s*, priorities are assigned to the hop transmissions.

In case of *MHCT PNC* first make a check for available number of time slots (N_{slots}) in current superframe. If *n(i,j)* is less then available slots and group is empty then *PNC* will start new group. In case of non empty group, *PNC* will check interfering condition and feasibility in terms of extra time slots requirement to locate in current group. In case, available time slots in current group are less then requested time slots, *n(i,j)*. In case of non interference with members of current group, *PNC* still checks the feasibility in terms of extra time slots requirement to locate in current group. If newly coming non-interfering hop transmission $h_j^{R_i}$ cause's expansion in time slots requirement of current group or in case *PNC* started a new group, *PNC* updates the status of available time slots. *PNC* continues the process recursively until available slots reaches to zero or all requests get scheduled.

In case of *EMHCT-F PNC* checks the possibility to locate hop transmission $h_j^{R_i}$ in previously created group. First *PNC* compare the time requirement $n(i,j)$ by $h_j^{R_i}$ and size of group $n(G)$, if $n(i,j)<n(G)$, *PNC* identifies the group members having collision/interference with in coming hop transmission $h_j^{R_i}$, then *PNC* checks the feasibility of scheduling in terms of extra time slots requirement to schedule in group under checking. If *PNC* found that in coming hop transmission $h_j^{R_i}$ is satisfying all conditions, *PNC* schedules hop transmission $h_j^{R_i}$ in one of the already created groups. In case hop transmission $h_j^{R_i}$ is not satisfying the condition of concurrency within already created groups then *PNC* will fallow same steps like *MHCT* to locate in current group. *PNC* continues the process recursively until available slots reaches to zero or all requests get scheduled. Similarly for *EMHCT-E*, *PNC* perform almost same operation flow except that if possible, *PNC* allocate extra time slots for incoming non conflicting hop transmission $h_j^{R_i}$.

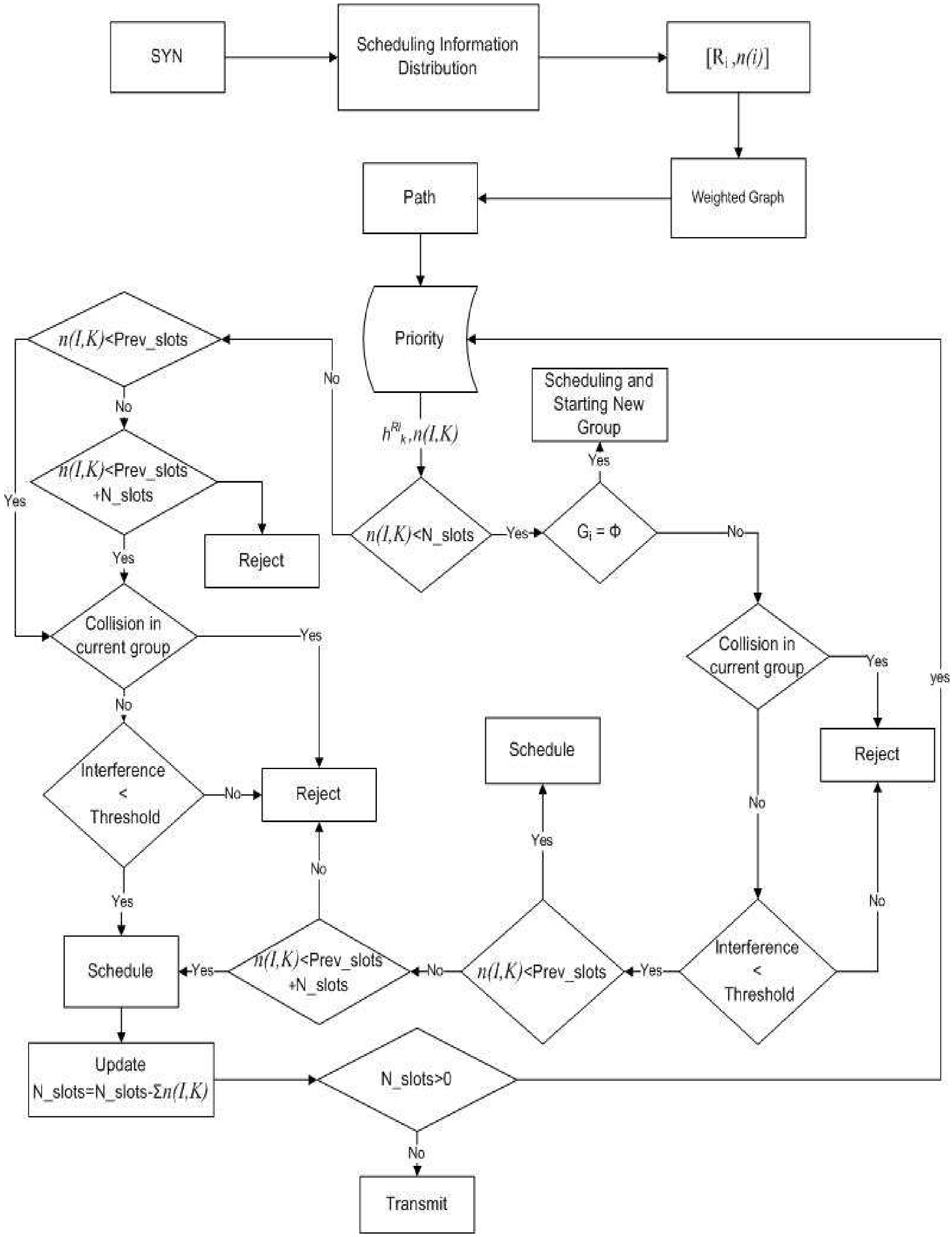

Figure 7- 3 Operational flow chart of *MHCT*

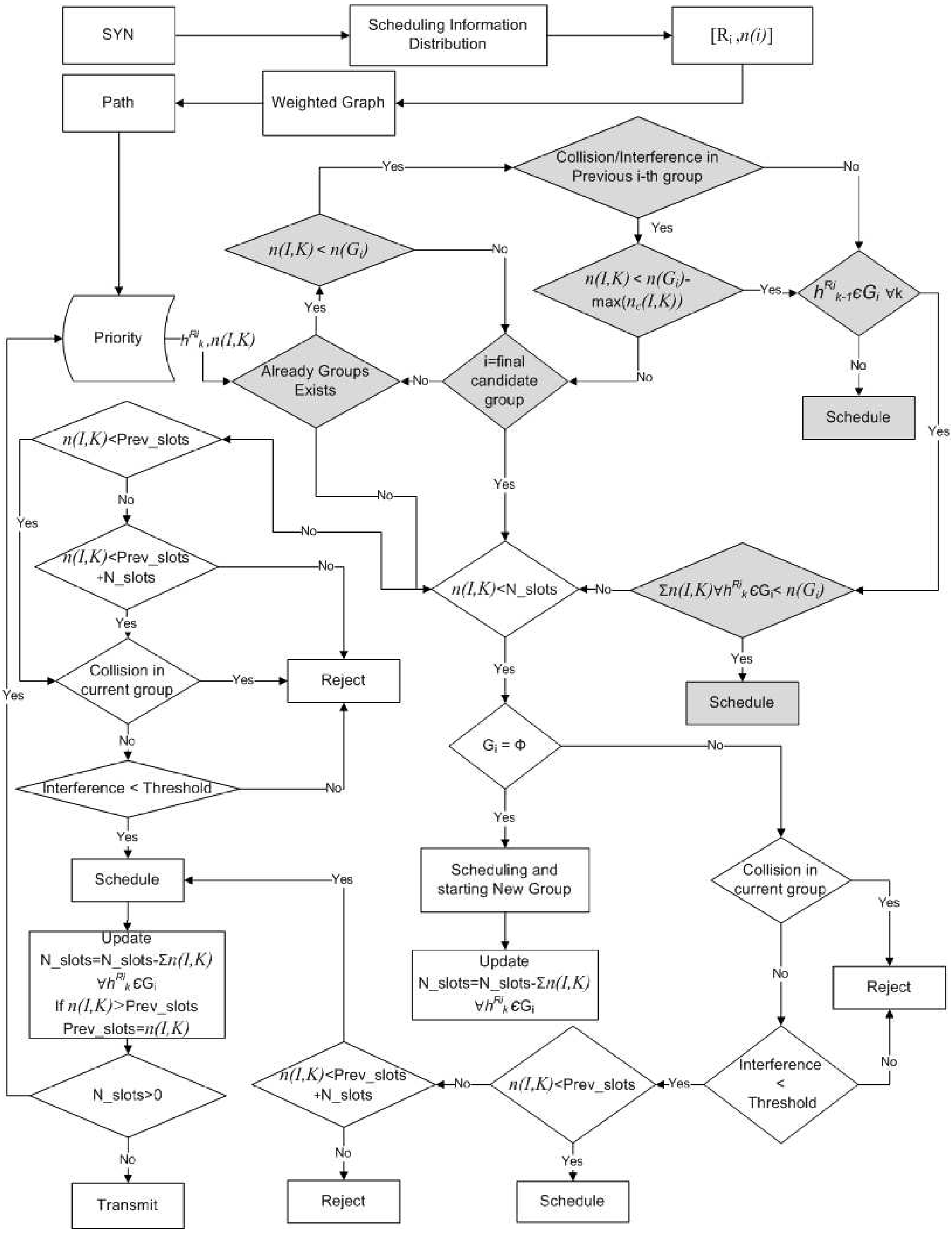

Figure 7- 4 Operational flow chart of EMHCT-F

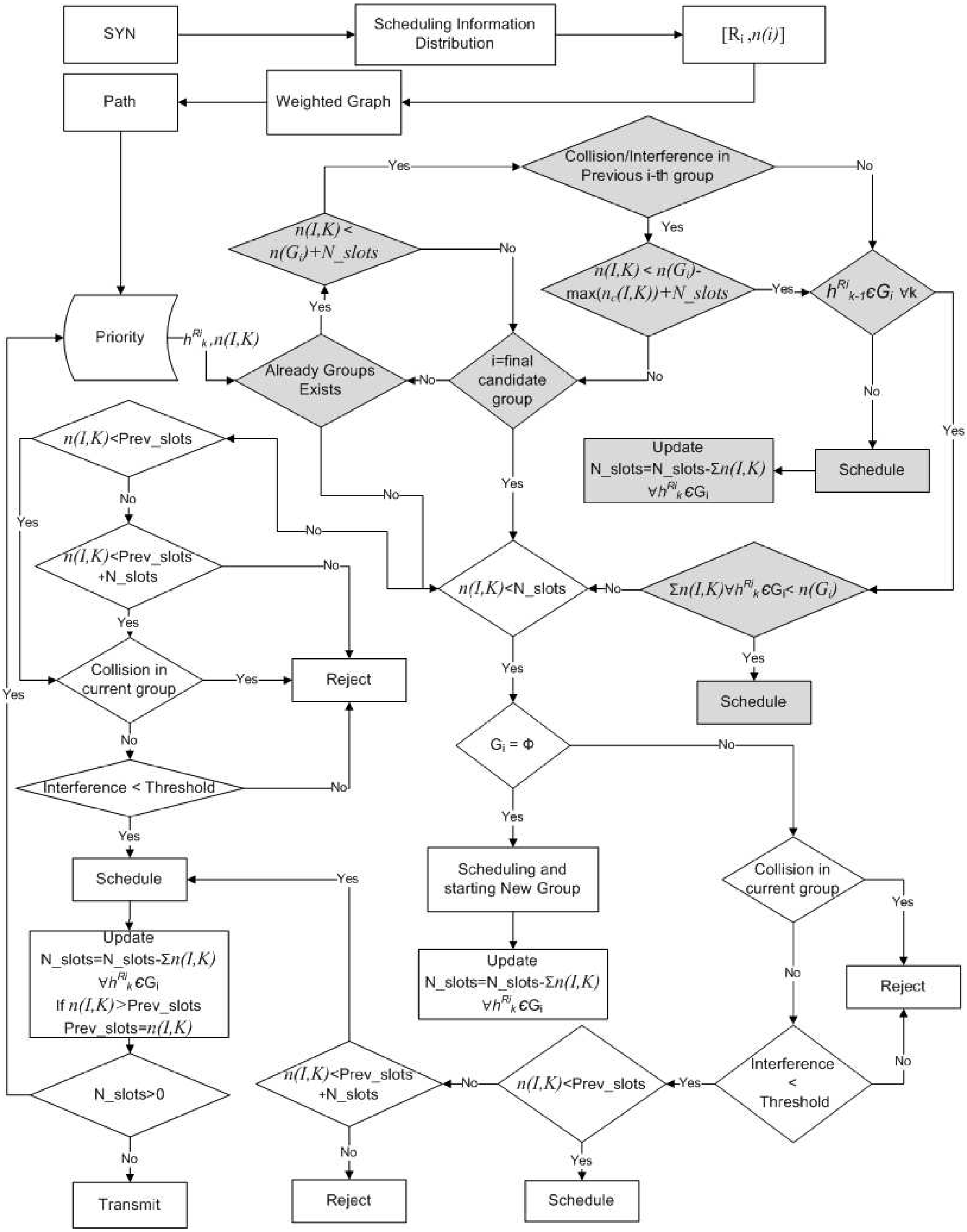

Figure 7- 5 Operational flow chart of EMHCT-E

7.7 *Performance parameters*

To compare and to measure the performance of our algorithm we considered following performance parameters.

7.7.1 **Throughput**

The sum data delivered across the network in unite time is known as network throughput. Network throughput is the widely used parameter to check performance of a given network. We calculated network throughput to check the bandwidth efficiency achievement across the network by using proposed algorithm.

7.7.2 **Fairness**

Usually a greedy network system which is designed to achieve higher network throughput leads to an unfair resource sharing. Hence from user perspective, few (with good channel conditions) get very high data rate and other users (with bad channel conditions) suffer from extreme low level of data rate. Our capacity gaining algorithm taking care of this problem and gives high throughput with acceptable fairness. We used Jain’s fairness index to measure the fairness of proposed systems.

7.7.3 **Concurrency gain**

Concurrency gain is a ratio between network throughput of EMHCT and direct transmission multiply by the time slots required for direct transmission. Concurrency gain is also used in water-filling algorithm to compare the optimum throughput of network under given conditions.

Concurrency gain is defined in Eq. 7.10.

$$\rho = n_d(i) * \frac{R_i^c}{R_i^d} \tag{7.10}$$

Where $n_d(i)$ is time slots requirement for direct transmission, R_i^c data rate achieved for concurrent scheduling and R_i^d is data rate achieved for direct transmission.

7.8 *Results*

Fig. 7-6 shows the throughput comparison of *MHCT* and proposed enhanced versions *EMHCT-F* and *EMHCT-E* with optimum result of water-filling solution for given concurrency gain (ρ) obtained from EMHCT-F. It clear that both *EMHCT-F* and *EMHCT-E* gives high throughput as compare to *MHCT* and both are better sub optimum solution.

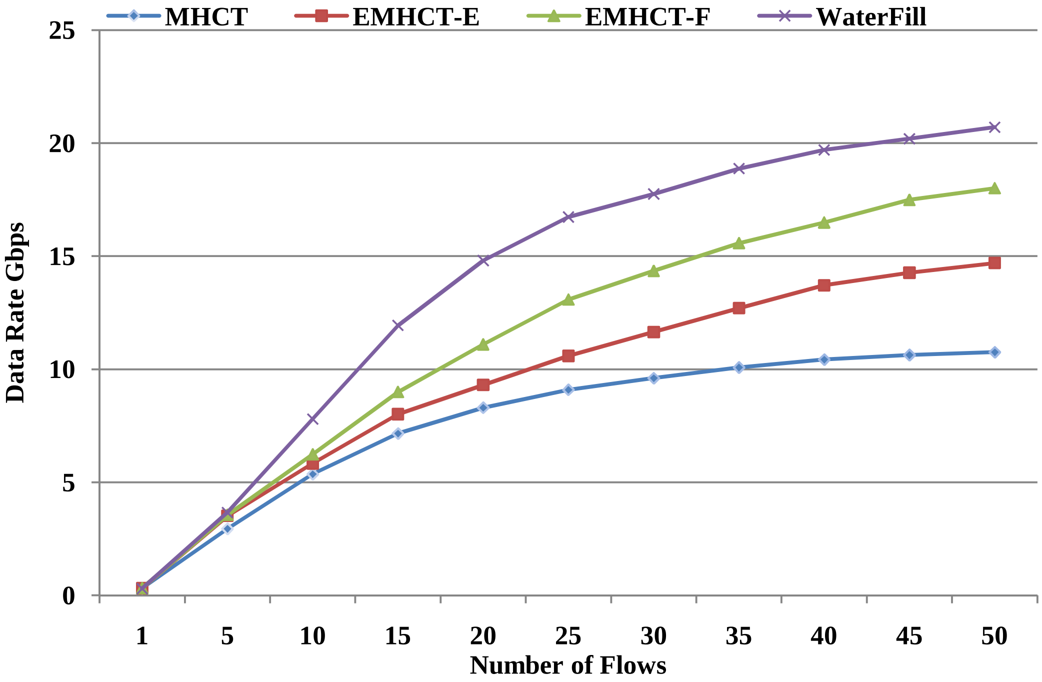

Figure 7- 6 Throughput MHCT, EMHCT-F/E and water-filling with concurrency gain (ρ)obtained from EMHCT-F

The concurrency gain (ρ) of *MHCT* , *EMHCT-F* and *EMHCT-E* is shown in Fig.7-7. *EMHCT-F* and *EMHCT-E* achieves higher concurrency gain as compare to *MHCT*. Which means, *EMHCT-E* /F can schedule higher number of transmissions for concurrently.

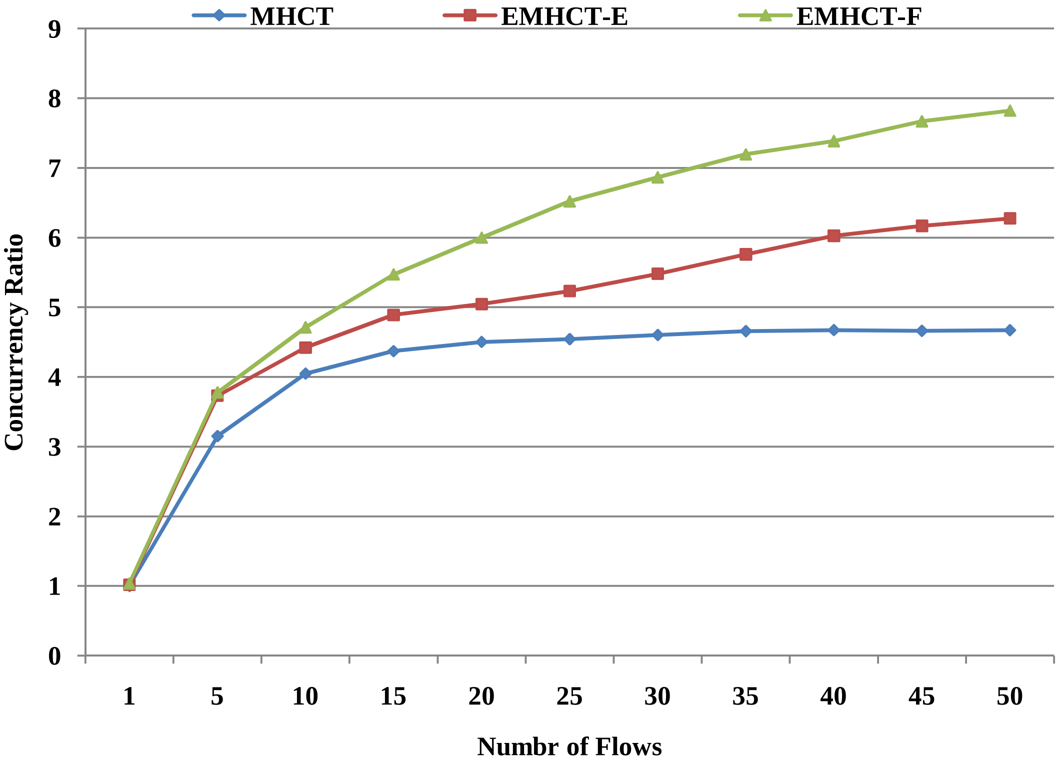

Figure 7- 7 Concurrency gain (ρ) MHCT and EMHCT-F/E

The optimum results for best condition along with optimum possible result for different antenna beam is given in Fig. 7-8 result for 20deg is obtained based on concurrency gain (ρ) of EMHCT-F, while for 180deg is obtained based on concurrency gain (ρ) of *EMHCT-E*. In best case concurrency gain (ρ) is equal to active number of flows and in worst case concurrency gain (ρ) is 1.

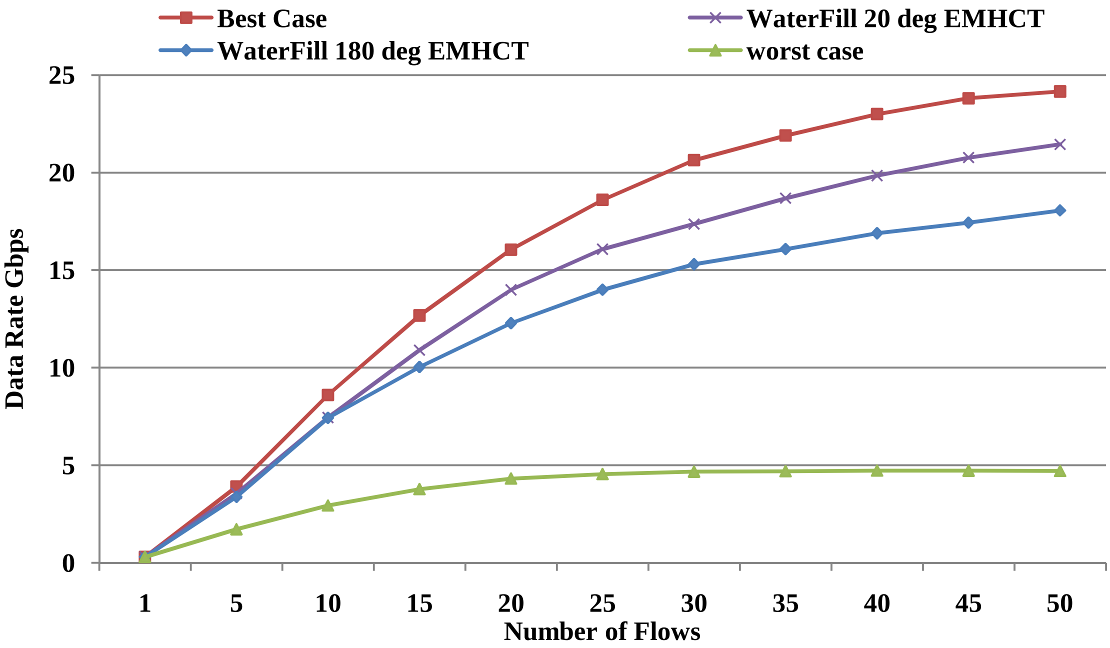

Figure 7- 8 **Water-filling throughput for extreme values of concurrency gain (ρ).**

Fig. 7-9 shows the comparasion of fairness (20deg of beamwitdth) of throughput per flow in *MHCT*, *EMHCT-F* and *EMHCT-E*. *EMHCT-F/E* has higher fairness, because in *EMHCT-F/E* on each allocation during span overlapping of groups once again highest priority is given to hop transmission request h_k^{Ri} with higher time slots *n(i,k)* requirement. Which further increase the chance of low rate traffic flow's hop transmission requests h_k^{Ri} to be scheduled, hence increasing the fairness.

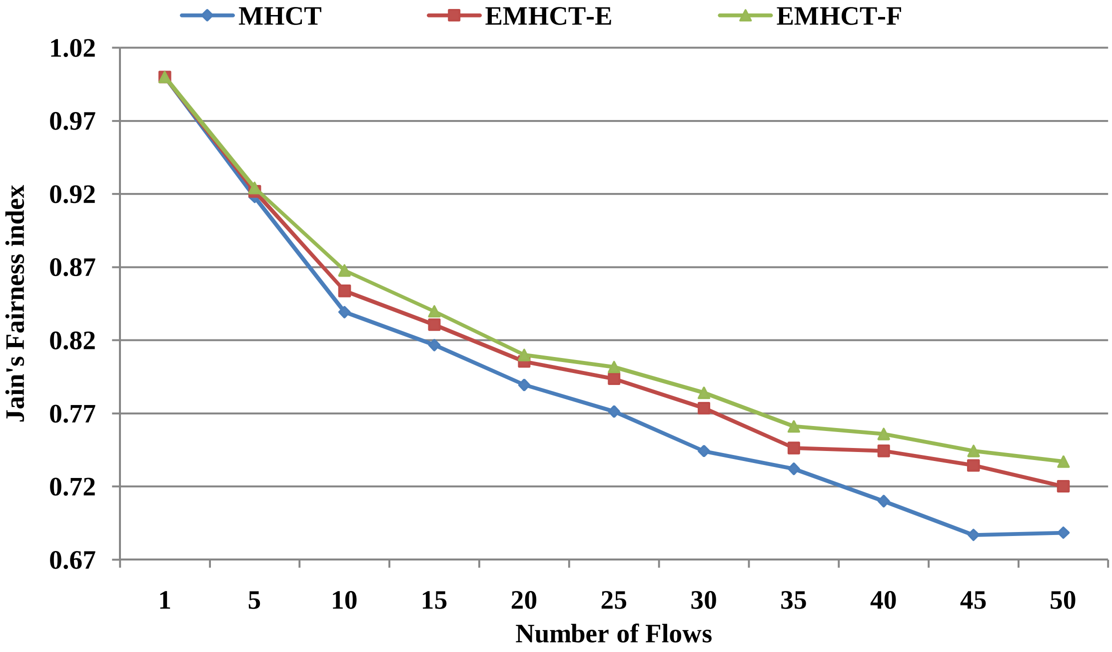

Figure 7- 9 Fairness MHCT vs EMHCT

The effect of beam width of antenna on amount of concurrent transmissions is significant. With narrow beamwidth the chance of concurrent transmission increases, hence network through put also increases. Fig. 7-10 to Fig. 7-13 shows the throughput comparison of *MHCT*, *EMHCT-F* and *EMHCT-E*, with different beamwidth selection. In all cases *EMHCT-F* and *EMHCT-E* performance is better than *MHCT*. *EMHCT-E* gives better throughput for large beamwidths but the increment in the performance with respect to reduction of beamwidth is slower as compare to *EMHCT-F*. Hence, *EMHCT-F* gives better performance for beamwidth lower than 45 deg. The reason of this behavior is obvious because *EMHCT-F* has a tendency to give more chance to the hop transmission request h_k^{Ri} with less time slots *n(i,k)* requirement. And for lower beamwidth, hop transmission request h_k^{Ri} with less time slots *n(i,k)* requirement get more chances because the probability of interference reduces. While *EMHCT-E* has a tendency to give more chance to the hop transmission request h_k^{Ri} with higher time slots *n(i,k)* requirement. For large beamwidth, the probability of interference increases and hop transmission requests h_k^{Ri} has less chance to be schedule in previous created group. However by expansion of group probability to schedule transmission requests h_k^{Ri} increases, which leads to a better performance.

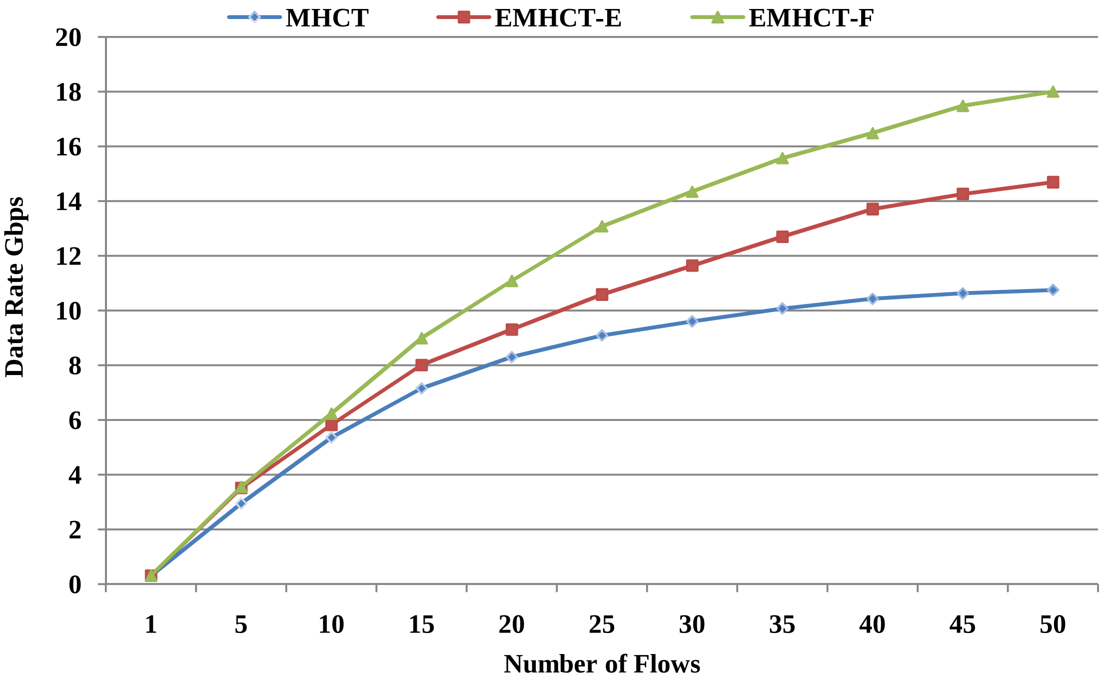

Figure 7- 10 Throughput of MHCT and EMHCT-F/E for 20deg Beam-widths

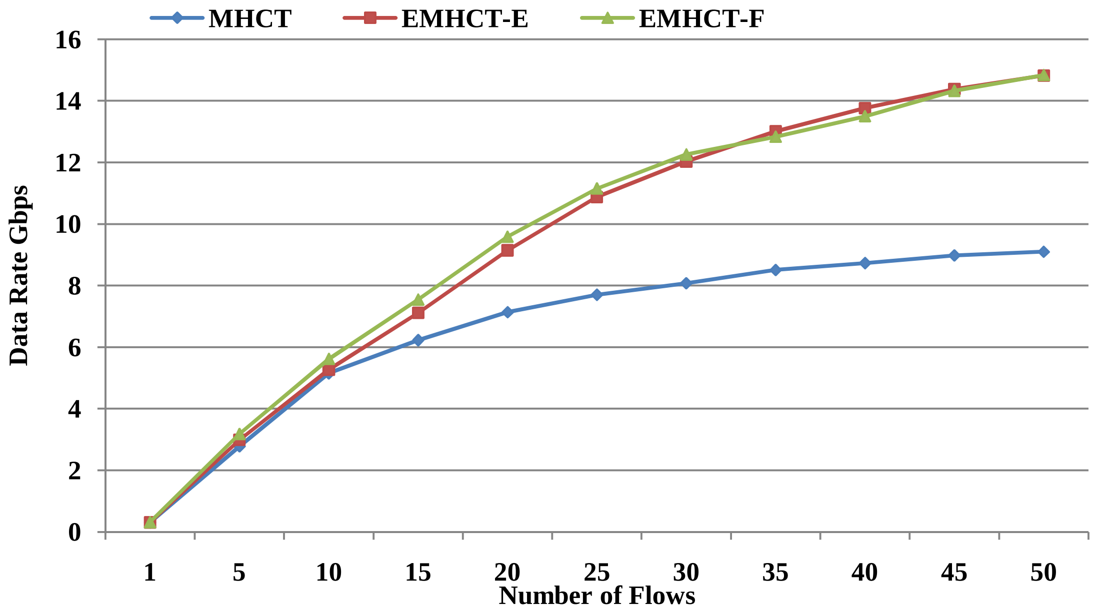

Figure 7- 11 **Throughput of *MHCT* and *EMHCT-F/E* for 45deg Beam-widths**

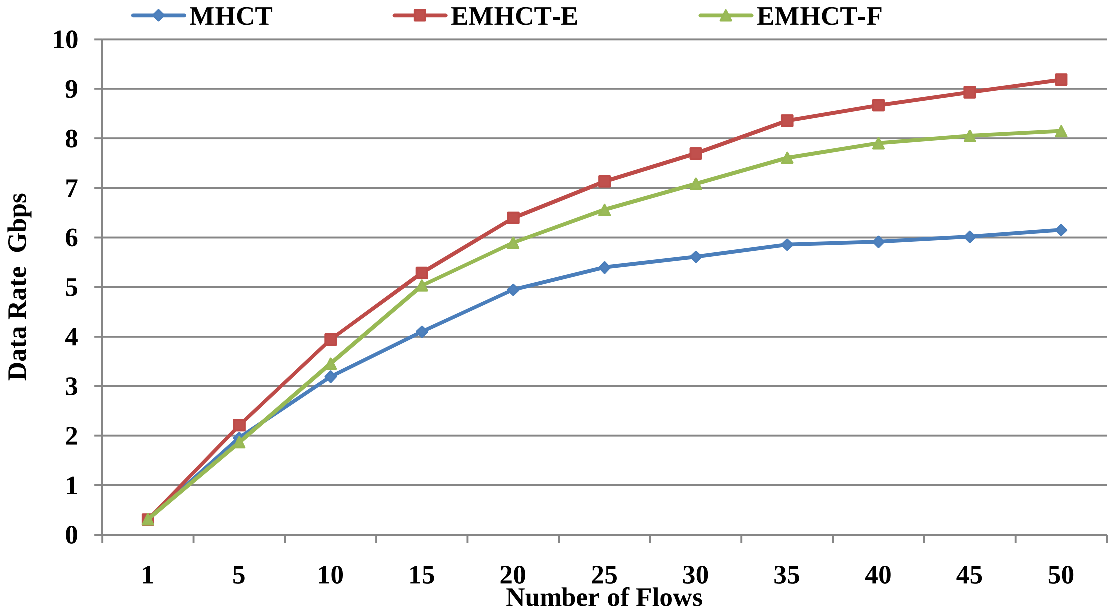

Figure 7- 12 **Throughput of MHCT and EMHCT-F/E for 90deg Beam-widths**

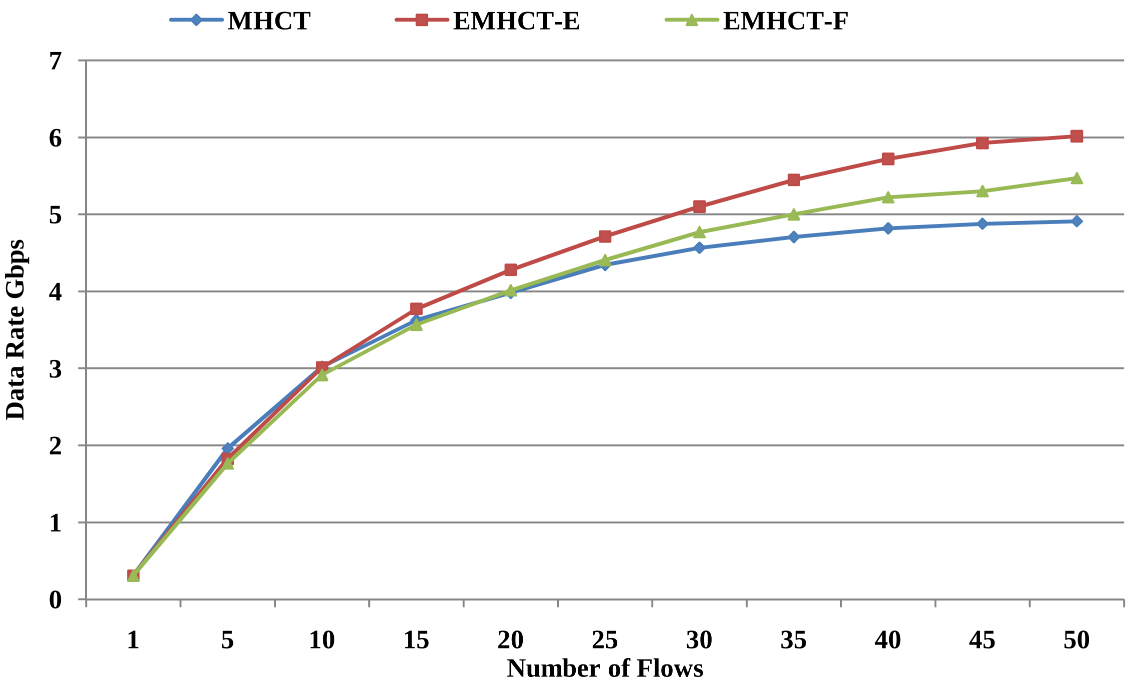

Figure 7- 13 Throughput of MHCT and EMHCT-F/E for 180deg Beam-widths

Conclusion

This thesis analyzed the process of multi-hop concurrent transmission for mmWave communication at 60GHz, considering WPAN in single room. We showed that it's a capacity achieving NP-hard constrained optimization problem, which can be resolve for sub optimum result with P-time complexity.

On the basis of analysis of proposed algorithm in [7] it is found that there is a margin to be improved if we consider the collision relations between hop transmissions in the previous groups. Thus, for better bandwidth efficiency, we have proposed two versions of span overlapping scheme to reduce the total number of allocated time slots in transmission period for a given transmission requests. Also we implicitly showed by simulation result that span overlapping is beneficial. The performance of *MHCT*, *EMHCT-E* and *EMHCT-F* also compared with the water-filling solution of NP-hard constrained optimization problem. *EMHCT-E* and *EMHCT-F* both outperform each other for different beamwidth selection. From the performance comparison of *EMHCT-F/E* and ideal curve of water-filling, it is clear that there is a possibility for additional improvement.

Besides further improvement of scheduling algorithm the throughput can also be increased by some other techniques. For instance the performance is also highly dependent upon the nodes density in a localized region, because high density leads to reduce the average distance between nodes. However we can predict that, the performance will keeps increasing until the average distance between nodes approaches to radioactive near field.

MHCT, *EMHCT-E* and *EMHCT-F* all scheduling schemes give an acceptable fairness index, because three of them gives high priority to the transmission request with high time slots requirement. This selection criterion not only ensures the high fairness but also make it possible to create groups with large number of transmissions, leading to high throughput. If we reverse the priority then for each transmission request the size of group should be expended, which makes the problem more complex, in case we restrict the expansion then it leads to a larger number of small groups.

References

[1]. IEEE 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c (TG3c) .[Online]. Available: http://www.ieee802.org/15/pub/TG3c.html.

[2]. IEEE 802.11 VHT Study Group. Available: http://www.ieee802.org/ 11/Reports/vht_update.htm.

[3]. S. Singh, F. Ziliotto, U. Madhow, E.M. Belding, M.J.W. Rodwell, “Millimeter Wave WPAN: Cross-Layer Modeling and Multihop Architecture,” in Proc. IEEE INFOCOM’07, May 2007, pp.2336-2240.

[4]. L. X. Cai, L. Cai, X. Shen, and J. W. Mark, “REX: a Randomized EXclusive Region based Scheduling Scheme for mmWave WPANs with Directional Antenna,” IEEE Trans. Wireless Commun., Vol. 9, No. 1, pp. 113-121, 2010.

[5]. L. X. Cai, L. Cai, X. Shen, and J. W. Mark, “Spatial Multiplexing Capacity Analysis of mmWave WPANs with Directional Antenna”, in Proc.IEEE GLOBECOM’07, Novermber 2007, pp.4744-4748.

[6]. J. Wang, R.Venkatesha Prasad, I.G.M.M. Niemegeers, “Enabling Multihop on mm Wave WPANs,” in IEEE ISWCS’08, October 2008, pp.371-375.

[7]. J. Qiao, L.X. Cai, X. Shen, “Multi-Hop Concurrent Transmission in Millimeter Wave WPANs with Directional Antenna,” in Proc. IEEE ICC’10, May 2010, pp.1-5.

[8]. S. Collonge, G. Zaharia, and G. El Zein, “Influence of the Human Activity on the Propagation Characteristics of 60 GHz Indoor

Channels”, IEEE Transactions on Wireless Ccommunications, VOL.3, NO. 6, November 2004.

[9]. S. Y. Geng, J. Kivinen, X. W. Zhao, P. Vainikainen, “Millimeter-Wave Propagation Channel Characterization for Short-Range Wireless Communications,” IEEE Trans. Veh. Technol., vol.58, no.1, pp.3-13, Jan. 2009.

[10]. R. Mudumbai, S. Singh, U. Madhow, “Medium Access Control for 60 GHz Outdoor Mesh Networks with Highly Directional Links,” in Proc.IEEE INFOCOM’09, April 2009, pp. 2871-2875.

[11]. Lin X. Cai, Lin Cai, Xuemin Shen and Jon W. Mark, “REX: A Randomized EXclusive Region Based Scheduling Scheme for mmWave WPANs with Directional Antenna”, IEEE Transactions on Wireless Ccommunications, VOL. 9, NO. 1, January 2010.

[12]. ,” High Gain Active Microstrip Antenna for 60-GHz WLAN/WPAN Applications”,

[13]. Z. Yang and L. Cai and Wu-Sheng Lu, “Practical Scheduling Algorithms for Concurrent Transmissions in Rate-adaptive Wireless Networks”, in Proc.IEEE INFOCOM’10, March 2010.

[14]. Z. Liu, M. Yang, H. Dai and J.Dai, “Concurrent Transmission Scheduling for Multi-hop Multicast in Wireless Mesh Networks”, in Proc. IEEE WiCOM’08, October 2008.

[15]. J. Shen, I. Nikolaidis and J. J. Harms, “Energy–Efficient Multi–Hop Scheduling for Multi–Rate 802.15.3 WPANs”, in Proc.IEEE ICC’07, June 2007, pp. 4824 - 4830.

[16]. Wei Yu, “Competition and Cooperatuion in Multi-User Communication Environments”, PhD thesis, Stanford University, USA, June 2002.

[17]. X. Wang, .and G. B. Giannakis, “Power-Efficient Resource Allocation for Time-Division Multiple Access Over Fading Channels”, IEEE Transactions on Information theory, VOL. 54, NO. 3, March 2008.

[18]. J. K. Chen, T. S. Rappaport and G.de Veciana, “Iterative Water-filling for Load-balancing in Wireless LAN or Microcellular Networks”, in Proc. IEEE VTC’06, May 2006. .

[19]. N. H. Lee, K. C. Hwang, S. Bahk, and K. Bok Lee, “Optimal Time slot Allocation for Multi-user Wireless Networks”, Wireless Communications and Networking Conference, 2004. WCNC. 2004 IEEE.

[20]. D. P. Palomarand J. R. Fonollosa, “Practical Algorithms for a Family of Waterfilling Solutions”, IEEE Transactions on Signal Processing, VOL.53, NO. 2, February 2005.

[21]. K. Liu, L. Cai, . and X. Shen, “Exclusive-Region Based Scheduling Algorithms for UWB WPAN”, IEEE Transactions on Wireless Communications, VOL. 7, NO. 3, March 2008.

[22]. M. Park, and P. Gopalakrishnan,” Analysis on Spatial Reuse and Interference in 60-GHz Wireless Networks”, IEEE Journal on Selected Areas in Communications, VOL. 27, NO. 8, October 2009.

[23]. M. Park, C. Cordeiro, E. Perahia, and L. L. Yang, “Millimeter-Wave Multi-Gigabit WLAN: Challenges and Feasibility”, in IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications, 2008.

[24]. Y. Jiao, M. Ma, Q. Yu, K. Yi and Y. Ma,"Cross-layer Concurrent Transmission Scheduling in WiMAX Mesh Networks",IEEE International Conference on Communication Systems (ICCS), 2010.

[25]. J. Shin, E. G. Sirer, H. Weatherspoon and D. Kirovski ,"On the Feasibility of Completely Wireless Data Centers",Cornell University Library, http://hdl.handle.net/1813/22846.

[26]. Y. Katayama, K.Takano, Y. Kohda, N. Ohba and D. Nakano, “Wireless Data Center Networking with Steered-Beam mmWave Links”, in Proc. IEEE WCNC 2011.

[27]. Robert C. Daniels, James N. Murdock, dore S. Rappaport, and Robert W. Heath, Jr.,"60 GHz Wireless: Up Close and Personal", IEEE Microwave Magzine, December 2010.

[28]. Shankar, N., Cordeiro, C., et. al., “MAC Channel Access in 60GHz,” IEEE 802.11-09/572r0, May 2009, https://mentor.ieee.org/802.11/dcn/09/11-09-0572-00-00ad-60GHz-MAC_Channel_Access.ppt.

[29]. E. Perahia, C. Cordeiro, M. Park, and L. L. Yang," IEEE 802.11ad: Defining the Next Generation Multi-Gbps Wi-Fi",in Proc. IEEE CCNC 2010.

[30]. S. Mehta and K. S. Kwak, “Performance Improving Schemes for mm Wave WPAN MAC Protocol”, in Proc. IEEE ICACT 2009.

[31]. Kwan-Wu Chin and D. Lowe, “A Simulation Study of TCP over the IEEE 802.15.3MAC”, Proceedings of the IEEE Conference on Local Computer Networks 30th Anniversary, LCN 2005.

Abstract

An Enhanced Time Slot Allocation Scheme for Multi-Hop Concurrent Transmission with Multiple Directional Antennas

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A high speed wireless personal area networks (WPANs) using millimeter wave (mmWave) with directional antenna are gaining increased interests. Due to some special characteristics of mmWave ,the use of *multiple directional antennas* make it possible to find non interfering transmissions in a localized region. The problem of finding an optimum time allocation for concurrent transmissions is an NP-hard problem. To maximize the utilization of high speed links, a suboptimum multi-hop concurrent transmission (*MHCT*) scheme e proposed. In this thesis, the analysis/design and implementation of concurrent transmission in mmWave communication system with multiple antennas has been carried out. We analyzed the *MHCT* scheme and found some possible improvements. On the basis of our analysis, we have proposed two enhanced versions of multi-hop concurrent transmission schemes (*EMHCT-E* and *EMHCT-F*). These schemes are also sub optimum solution for the NP-hard problem of time allocation for concurrent transmissions. However, both schemes can solve the concurrent transmission problem in P-time at the cost of $O(N\log_2 N+N+1)$ computational complexity, with significant improvement in

throughput and fairness as compare to *MHCT*. The simulations were carried out for a different number of antenna selections. Optimum results using water-filling model were taken for comparison with *MHCT* and *EMHCTE/F*. Finally fairness of schemes was calculated.

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논문제목	한글 : 방향성 안테나 기반의 멀티홉 동시전송을 위한 타임 슬롯 할당 기법 영어 : An Enhanced Time Slot Allocation Scheme for Multi-Hop Concurrent Transmission with Multiple Directional Antennas				

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

- 다 음 -

1. 저작물의 DB구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함
2. 위의 목적을 위하여 필요한 범위 내에서의 편집·형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포·전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5년으로 하고, 기간종료 3개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 또는 출판을 허락을 하였을 경우에는 1개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물의 이용허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음
7. 소속대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송·출력을 허락함.

동의여부 : 동의(○) 반대( )

2012년 5월 10일

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