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An Investigation of Scheduling and Packet Reordering Algorithms for Bandwidth Aggregation in Heterogeneous Wireless Networks

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Abstract: Heterogeneous Wireless Network (HWN) is the next generation wireless communication system's platform where Internet services will be offered and delivered through multiple technologies like WiFi, WiMAX, GSM etc. There are some Internet applications that require high bandwidth and therefore, the bandwidth of an individual interface need to be aggregated to form a high speedy logical link. In this regard, some critical issues like packet loss, packet reordering and delay need to be addressed efficiently. This paper aims to investigate the common scheduling algorithms both adaptive and non-adaptive solutions that have been using in networking and communication field. Packet reordering is common in heterogeneous wireless network that has been evaluated briefly in reorder metrics analysis and reorder delay analysis sections. The challenges of packet reordering are also addressed in this paper. This paper gives a state-of-the-art knowledge of bandwidth aggregation and packet reordering in HWN and it is expected that this investigation will be a milestone for further research.

Key words: Packet reordering · Bandwidth aggregation · Heterogeneous wireless network · Scheduling algorithms · Logical links · Multi-paths

INTRODUCTION

Next generation wireless communication technology is expected to be heterogeneous consisting of several wireless technologies, namely; WiFi, WiMAX and GSM. It is also desired that most of the popular places would be overlapped by these technologies where an Multimode Device (MD) can use these technology simultaneously. These network technologies provide different range of bandwidths and every technology is operated independently. Therefore, aggregation of these different bandwidths into an MD can play an important role to enhance the performance of real-time applications. In a heterogeneous wireless network, a multi-interface enabled user can toggle among different Radio Access Technologies (RATs) and select the best suitable RATs for their applications [1, 2]. If there is no single RAT exists that does not have enough bandwidth to meet desired applications, multiple RATs can be selected and their bandwidth can be aggregated to create a single logical link that has enough bandwidth to serve the application [1]. In a HWN environment, a multimode device is connected with one default interface where two other interfaces are also available. If the default interface is unable to transmit the data, the available interfaces could make a logical link to transmit that data.

The concept is explained in figure 1 that default interface GSM is not capable to handle this data and therefore, make a logical link in cooperation with other interfaces as shown in dotted lines. Packet reordering over heterogeneous network leads to transmission delay as well as packet loss due to asymmetric link characteristics, fluctuation of wireless channels because of mobility and interference and inconsistent QoS provisioning [3].

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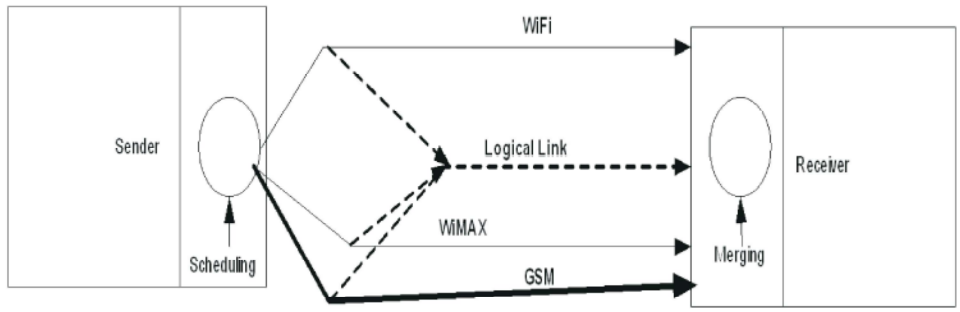

Fig. 1: Logical link in HWN

Bandwidth aggregation in heterogeneous wireless network has numerous benefits for real time applications. As there are multiple options are available, the transmitting traffic can be forwarded by choosing the optimum interfaces. Hence, this resource sharing increase the throughputs, enhance the packet delivery and reliability, maintain load balancing and reduce delay. However, there are still some challenges those need to be addressed in proper way. Packet reordering, packet scheduling and power consumption are the three most important issues in HWN. This research only addresses the details of packet reordering and scheduling while power consumption is not included the scope of this research.

Bandwidth Aggregations: Heterogeneous Wireless Network (HWN) technologies like GSM, WiFi and WiMAX often integrated in a single MD to maximize network coverage areas using multiple Access Points (APs). It has been observed that the recent MDs have been equipped with multiple interface facilities. Therefore, the Internet Service Providers (ISPs) are looking into efficient solutions that can utilize multiple technologies at a time in a device. Radio Resource Management (RRM) approaches have been investigated in recent years considering composite capacity, QoS, handover and throughput in HWN [4]. A Joint RRM (JRRM) policy is proposed to study the computational cost when multiple RATs are aggregated in a mobile base station using linear programming techniques in HWN [5]. An improved scheduling algorithm has been designed for dynamic bandwidth aggregation of multiple interface enabled mobile devices where throughput has been improved compared to existing approaches [6]. An interface selection mechanism has been developed for bandwidth aggregation in HWN using multi-server scheduling scheme to prevent packet drop and delay [7]. To guarantee the improved QoS for the mission critical application transmission, a dynamic QoS negotiation scheme has proposed that allows users to dynamically negotiate the service levels required for their traffic and to reach them through one or more wireless interfaces [8]. This scheme shows significant improvement in terms of packet reordering delay and packet loss. Another QoS negotiation based scheme has been proposed for bandwidth aggregation to enhance the quality of real time applications over the heterogeneous wireless networks by reducing reordering delay and associated packet loss [9].

Solutions of Bandwidth Aggregations: The concept of bandwidth aggregation is relatively new and efficient solutions have been proposed by the researchers for last few years. Bandwidth aggregation that has been operated by varying traffic and wireless link conditions are termed as adaptive solution. Adaptive bandwidth aggregation utilizes wireless resources in dynamic way and efficient scheduling to achieve optimal throughput [1]. Bandwidth aggregation that has been operated based on constant link and traffic conditions are referred as non-adaptive solutions [1]. Non-adaptive bandwidth aggregation solutions may achieve lower performance gain particularly when the links and traffic are dynamics and changes over the time. Both adaptive and non-adaptive solutions can be designed and implemented at different layers of the network protocol stack in TCP/IP like application layer, transport layer, network layer and link layer [1]. This paper only addresses on the issues of network layer related bandwidth aggregation solutions.

Non-Adaptive Solutions: The Round Robin (RR) scheduler is known as a non-adaptive scheduling scheme which allows scheduling packets through multiple links.

The RR scheduling mechanism works in a cyclic manner and transfer packets of same flow and size to heterogeneous links. The RR scheduler is very simple whose computational complexity of O(1). On the other hand, in case of variable packets size and heterogeneous link rates, the RR scheduler's load balancing performance is too poor when a larger packet transmits through a low-bandwidth link than a high bandwidth path.

Weighted Round Robin (WRR) [10] and Surplus Round Robin (SRR) [11] are the enhancement of RR scheduler. These scheduling schemes allow packet transmission over multiple links with various transmission rates. A WRR supports normalized weight packets of the same flow to distribute through different paths. It transfers more packets to the receiver through a link with the larger weight in the scheduling round. A link weight depends on a link bandwidth function. Thus, WRR scheduler load balancing performance is better than simple RR scheduler but in the case of variable packets size, its load balancing performance can be poor and high packets reordering. SRR is the enhancement of WRR which is known as a practical scheduler. SRR is employed to disperse different size of packets through various heterogeneous capacities links. It is used mainly for load balancing efficiently over multiple links. In contrast, SRR cannot maintain the packets order of the flow in which packets transfer to the receiver. Hence, SRR packets ordering are too poor and it can affect the performance of real time applications and TCP. Although SRR depends on re-sequencing mechanism which is implemented at the receiver to re-arrange the original packets order, it may not appropriates for limited resources mobile terminals.

In [12], the practical measurements, using multiple heterogeneous interfaces simultaneously on packets re-arranging for quantify the impact of the scheduler. They display that the packets reordering is lower in common internet connection than multi links connection. After that they employ static packet scheduling mechanism to improve packet ordering and receive the advantages of multi links transmission. The proposed scheduling mechanism can assume about estimated selected paths delays before transfer the packets over the selected links. The main purpose of the proposed scheduler is to ensure the similar packets delays with the faster link and slower links and achieves least delay of the packets reordering. However, during the variable link conditions over the time the throughput degradation and packets reordering are higher compared to other static scheduling schemes.

The authors proposed a bandwidth aggregation mechanism which can be divided into two functional categories such as scheduling of packets partition and estimation of bandwidth in [13]. The estimated bandwidth converts the amount of traffic in bytes and transmits them over a link free of congestion. The packet partitioning scheduler determines the appropriate packets allocation through the links and ensures the efficient load balancing. The scheduling algorithm control a partition counter, where available bandwidth allows assigning a packet weight over a link determines to accept the amount of more bytes of the packets through a link.

Adaptive Solutions: The most significant and important network based adaptive bandwidth aggregation solution is Earliest Delivery Path First (EDPF) [14]. The aim of EDPF is to delivery packets over multiple available interfaces within the shortest time and in order delivery [1]. The key feature of EDPF is to dynamically estimate the delivery time of the next packet on the each link. Based on the shortest delivery time of each path, EDPF delivers the packet to that path. The shortest delivery time is estimated according to the following equation 1.

$$d_i^l = MAX(a_i + D_l, A_l) + \frac{L_i}{B_i} \tag{1}$$

Where d_i^l, a_i and L_i represent the estimated delivery time of packet *i* via path *l*, the arrival time of packet *i* at the network proxy and the length of packet *i*, respectively. D_l, A_l and B_l represent the delay from the proxy to the base station on path *l*, the time when path *l* is available for transmission and the bandwidth of path *l*, respectively. The first part of the equation establishes the time at which transmission can resume on path *l* and the second one returns the packet transmission time along the path. However, EDPF is not capable to utilize completely the bandwidth of the selected set of interfaces as it selects one interface at a time for the transmission of the packets during the transmission session. Moreover, it only considers path bandwidth and latency where packet loss rate is ignored [1]. An improved scheduling mechanism of EDPF is proposed that considers transmission rates and losses to estimate packet delivery time [15]. The packet delivery time can be estimated from equation 2.

$$d_i^l = D_l + d_l + \frac{L_i}{R_l(1-\alpha_l)} \quad (2)$$

Where D_l is the one way wire line delay in the core network of path l, d_l is the one way wireless delay on the path, R_l is the data rate of the wireless interface l, α_l is the packet loss rate on path l and L_i is the length of packet i. However, this scheme only considers losses due to wireless transmission errors avoiding losses that caused for congestion.

A time slot based EDPF (TS-EDPF) has been proposed for bandwidth aggregation in wireless network. According to this scheme, every terminal is assigned to time slot to access the wireless channel. For the accurate estimation of the delivery time of the next packets on the channel, the network proxy needs to know the start and end time slot that is assigned to the terminal. The delivery time can be estimated according to the equation 3.

$$d_i^l = g\left(f(MAX(a_i + D_l, A_l), l) + \frac{L_i}{B_l}, l\right) \quad (3)$$

Where f(y…) resolves the next transmission starting time slot at the base point on link *1* and g(y..) fix the returning time where the number of packets *i* transmission can be terminated. The packets transmission must be happened within the determined time slot that is defined by the functions. TS-EDPF packets losses and reordering delay is lower than EDPF. However, during the high congestion and wireless path losses EDPF cannot handle the cases effectively.

The packet-pair EDPF is the enhancement of EDPF for TCP applications (PET) in [16]. PET assumes the packets delivery time by transferring packet pairs at the receiver, which calculates the inter-arrival time using signaling acknowledgments (SIG-ACKs) to the proxy of the network. The proxy computes the bandwidth and delay on the link using inter-arrival information. After that, EDPF schedule and transfer the packets through the available links. The Buffer Management Policy (BMP) hides the remaining delay at the receiver from TCP and holds the order packets to convert them to reorder correctly for delivery over TCP. It is used as the comparison and timer based loss detection mechanisms. The timer-based technique employs a sequence number (N) to delivery packets with a timer. When expire the time N is not received by the receiver and it is considered that the packets lost.

The Effective Delay-Controlled Load Distribution (E-DCLD) which is known as a load distribution model and used for multilink packets transmission [17]. The main purpose of the model minimizes the latency difference among the links due to minimize the reordering of the packets to the receiver and load balancing efficiently over the links. This model can be divided into three different functional components: traffic splitter-which computes allocation ratios for the links, path selector- to select the correct path to deliver packets and load adapter- to assume end-to-end delay dynamically and rearrange the allocation ratios. However, the load distribution model did not consider wireless path and congestion losses.

The Dynamic Bandwidth Aggregation (DBA) scheduling mechanism [18] exists in the network proxy. The aim of this scheduling scheme enhances the network throughput delivering the same stream packets over the multiple paths. It can be divided into two categories: scheduling mechanism to calculate the least estimated departure time of the packets on every links and traffic monitor to observe the traffic through the wireless links and provide the suitable link information for the next packet at the DBA scheduler. However, the packet reordering is not well addressed in this mechanism.

The authors employed the Concurrent Multipath Transmission Scheme (CMTS) [19] which select a single application's to send over the multiple links. It optimizes the throughput if maintain the packets order correctly. This scheme mainly accomplishes the average available link delays artificially using faster path to schedule maximum packets. Let define the average interval time TIi to transmit over the faster link which is estimated and td end-to-end delay which is calculated between slow link and fast link. The number of the fast link packets is defined as

$$N_{fast} = \frac{t_d}{TI_i} + 1 \quad (4)$$

The total number of packets allocated to the paths in a scheduling round is given as

$$\sum_{i=1}^{N-1} N_{fast} + 1 \quad (5)$$

Where, the number of paths is denoted by N. However, the proposed scheme ignores the links losses and remaining packets reordering to the receiver.

In [20], the authors present a multipath proxy which stripes the same flow IP packets for heterogeneous links. If the traffic load balance over the links maintain efficiently then it ensures to receive the arrival packets in correct order. The proposed mechanism can be considered as the three different parts such as delay equalizer, packet scheduler and path monitor. The delay equalizer controls the buffer to schedule the packets to the fast link. The packet scheduler presents the allocation ratios of the traffic based on WRR and the path monitor maintain the previous two functions to update the network throughput and delay.

An analytical framework has been developed by [21] to distribute the traffic optimally through the multi links of the network. The traffic distribution is considered as the constrained optimization challenge. The purpose of the framework is to reduce the end-to-end path delay and the reordering delay as well. Let denote the r and s as the long term average rate and maximum burst size of the incoming traffic stream those are regulated by leacky bucket. The optimization problem can be solved by using closed-form solution which employs the maximum traffic distribution ratios that reduce the end-to-end paths delay and ensure the parameters of the leacky bucket. However, the proposed framework represents any scheme to dispatch the traffics from sender to receiver through the specific links orderly.

[22] propose an Adaptive Load Balancing Algorithm (ALBAM) that aims to achieve efficient utilization of the aggregated bandwidth capacity by reducing packet reordering. To select the best path for a packet, ALBAM lists all possible paths for incoming packets; each path is associated with a quality value defined by

$$S_i = Q_i + V_i^* \qquad (6)$$

Where Q_i is queuing delay experienced by a packet on path i and V_i is the weight parameter the path. The term V_i is used to configure traffic allocation ratios to conform to the desired application performance. When packets arrive, they are not scheduled immediately rather, they are temporarily buffered to create a time gap between consecutive packets; this helps to control the transmission order. When scheduling resumes, a packet

Table 1: Summary table of bandwidth aggregation solution

Approach		Advantages	Limitations
Non-adaptive	Round Robin (RR)	It is simple with less computational complexity for same size packets.	Poor performance for variable packet size over heterogeneous network.
	Weighted Round Robin (WRR)	WRR scheduler load balancing performance is better than simple RR scheduler.	Poor performance for variable packet size and high packet reordering.
	Surplus Round Robin (SRR)	SRR deals different size of packets over heterogeneous links.	SRR cannot maintain the packets order of the flow.
Adaptive	Earliest Delivery Path First (EDPF)	dynamically estimate the delivery time of the next packet on the each link.	It is not capable to utilize completely the bandwidth of the selected set of interfaces.
	A time slot based EDPF (TS-EDPF)	TS-EDPF packets losses and reordering delay is lower than EDPF.	during the high congestion and wireless path losses EDPF cannot handle the cases effectively.
	Packet-Pair EDPF for TCP applications (PET)	It is used as the comparison and timer based loss detection mechanisms.	When the timer expires, it is assumed that the packet was lost.
	Effective Delay-controlled Load Distribution (E-DCLD)	It minimizes the latency difference among the links by minimizing the reordering of the packets.	The load distribution model did not consider wireless path and congestion losses.
	Dynamic Bandwidth Aggregation (DBA)	It enhances the network throughput delivering the same stream packets over the multiple paths.	The packet reordering is not well addressed in this mechanism.
	Concurrent Multipath Transmission Scheme (CMTS)	It optimizes the throughput if maintain the packets order correctly.	The proposed scheme ignores the links losses and remaining packets reordering to the receiver.
	Adaptive Load Balancing Algorithm (ALBAM)	ALBAM reduces packet reordering and enhances throughput, even for TCP applications.	Its transmission buffers may introduce delays that may not be tolerated by real-time applications.

from the transmission buffer is allocated to a path that minimizes the quality value as defined by Eq. (8). To adapt to varying channel conditions, ALBAM monitors the paths and updates the quality value (S_i) periodically. ALBAM reduces packet reordering and enhances throughput, even for TCP applications. However, its use of transmission buffers to control the transmission order may introduce delays that may not be tolerated by real-time applications.

Packet Reordering: Packet reordering occurs when the order of packets of the same flow at the receiver is different from the order of the same packets at the sender [23]. Packet reordering in HWN can be caused for simultaneous transmission of the same flow through multiple interfaces those have different transmission delays and rate. Alternatively, it can be said that the sequence number of the arriving packet of a flow is lower than the sequence number of the consecutive packet that has already arrive at the receiver [1]. The concept of packet reordering among HWN is drawn in figure 2. Sender side apply proper scheduling algorithm to respective packets and forward the packets to suitable interfaces, namely; WiFi, WiMAX and GSM based on some parameters like availability, delay, jitter, etc. The receiver side merges and organizes all the packets according to the sequence number.

This packet reordering can degrade the quality of real-time applications. Transmission Control Protocol (TCP) also be affected by packet reordering [1] and it is not the best suitable for multi-interface handling. However, Stream Control Transmission Protocol (SCTP) is best suit for multiple interface dealing.

Reasons of Packet Reordering: Packet reordering is one of the challenging issues to design bandwidth aggregation in HWN. It has been observed that packet reordering in a single TCP link is rare event and the incident happen not more than 3% [24]. However, packet reordering occur more than 30% in heterogeneous wireless network when packets are being transmitted through multiple paths [25]. There could be many reasons for packet reordering those are not limited to these reasons [26]. (I) In heterogeneous wireless network where bandwidth aggregations is applied [27, 12], (ii) when an earlier packet is placed in a longer queue and later packet in a shorter queue, (iii) retransmission on wireless links and due to TCP, (iv) giving lower priority and providing placement in different queues, (v) route fluttering and (vi) during the handoff session of a mobile node. Packet reordering affects both TCP and UDP significantly. In the case of TCP, when packets go out of order in forward path then receiver may consider packets as lost that reduces congestion window and increases number of retransmission [28-30]. In the case of UDP, particularly for real time applications, reordered packets arrives after the elapse of playback time is considered as lost that degrades the quality of the applications. To resolve this problem the out-of-sequence packets are buffered until they can be played back in sequence to the application and this process consumes more wireless resources [28]. Therefore, many updated hardware and routers have been introduced to minimize the packet reordering [31]. For example, these types of hardware include input buffer to ensure that packets from the same flow are forwarded to the same processing element [32] or output buffers to ensure that packets from a flow are released from the router in more or less the same order in which they arrive at the router [33]. These two mechanisms that involves tracking packet flows best suit and packet reordering can be mitigated within the routers. However, these two mechanisms are not well suited for route fluttering and not scalable to handle increased number of packet flow [34, 35]. Moreover, it is also found that video traffic over UDP perform poorly and high packet reordering has been noticed [36]. Therefore, a scalable, robust, efficient packet reordering mechanism has to be designed for homogeneous as well as

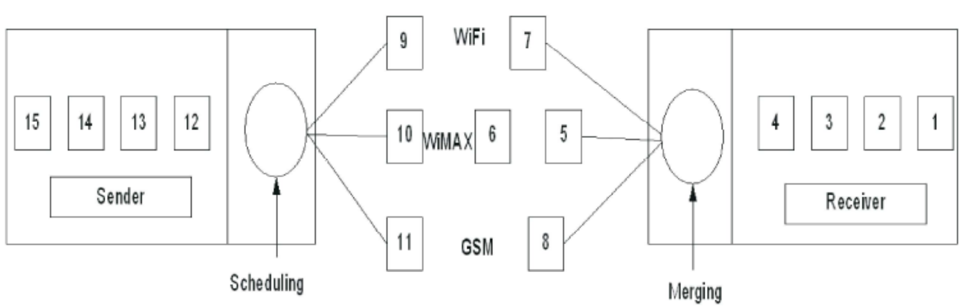

Fig. 2: Packet Reordering in HWN

heterogeneous wireless network. Packet reordering is most important for bandwidth aggregation in heterogeneous wireless network. There are some criteria are listed for developing packet reordering mechanism namely; simplicity, orthogonality, differentiability, usefulness, evaluation of complexity, robustness, broader applicability [28].

Packet Reordering over a Single Path: Packet reordering is relatively low over a single path. Packet reordering can be occurred in traditional TCP/UPD for many reasons like multipath routing, route fluttering and retransmissions [37]. It leads unnecessary packet retransmissions and therefore creates congestion over the network. It has been noticed that the packet transmission over UDP at high rate is more when packet size is smaller due to short inter spacing time from sender side [38]. It has been also observed that packet reordering happen at different rates in different paths with the probability when same UDP packets are transmitted.

Packet Reordering over Multiple Paths: Packet reordering is a common phenomenon in heterogeneous wireless network when packets of same application are being transmitted via multiple paths. These packets have to be reordered at the receiver buffer that causes excessive delay and degrades the quality of service of real-time services [25]. Initially, large buffer scheme was proposed to avoid the packet loss at the receiver but that is not efficient solution as it increases delay and cost of the network [12]. A multilink proxy based architecture has been developed that splits traffic onto different paths [16]. A Multipath Transmission Control Scheme (MTCS) combines bandwidths of available interfaces and schedules the packets for real time applications in heterogeneous environment [39]. A Grouping-based Multipath Selection (GMS) mechanism is developed to avoid underlying shared bottlenecks between topologically joint paths [40]. The simulation results of GMS shows better than other existing multiple path solution. A scheduling mechanism is proposed for interactive multimedia transmission over heterogeneous wireless network [41].

Packet Reordering Metrics

Reorder Density (RD): Several metrics have been proposed to quantify, namely; Reorder Density (RD) and Reorder Buffer-occupancy Density (RBD) are considered informative and useful metrics [42]. RD can be termed as the distribution of displacement of packets from the original positions where an early packet represents as negative displacement and a late packet corresponds to positive displacement. It has been normalized to the number of packets in the original sequence. RD has been shown an important metric to provide inclusive information of packet reordering of IP packets [1]. The concept of RD can be well understood from following explanation [42].

Consider a sequence of packets (1,2…N) transmitted over a network. A Receiver Index (RI) (1,2…) is assigned to each packet as it arrives at the destination. Lost and duplicate packets are not included in the RI. If the RI assigned to packet m is (m + d_m), with $d_m \neq 0$, then packet reorder event has occurred and this event is denoted by r(m, d_m). When packet reorder does not occur then the sequence number of the packet and the RI are the same, i.e., $d_m = 0$ for each packet. A packet can be considered as late if $d_m > 0$ and early if $d_m < 0$. Therefore, the sequence of packet reordering R represents by the union of reorder events, R.

$$R = \bigcup \left\{ r\left(m, d_m\right) \mid d_m \neq 0 \right\} \quad (7)$$

RD is defined as the histogram of d_m values, normalized with respect to the total number of packets, which has been adjusted for losses and duplicates. Fig. 3 illustrates the sequence, assigned receive_index values and displacements, as well as the corresponding reorder set and RD for a sequence. In this example, packet 6 and packet 3 are displaced by one and two unit from its positions, thus the density components are 1/8 and 2/8 respectively. Packet 7 and packet 5 are early by one and two position respectively with the RD 1/8 and 2/8. Finally, the RD for zero is 4/8.

Arrived Sequence	1	2	5	4	3	7	6	8
Receive Index	1	2	3	4	5	6	7	8
Displacement	0	0	-2	0	2	-1	1	0
R = {(3, 2), (5, -2), (6, 1), (7, -1)}								
RD[0] = 4/8, RD[1] = 1/8, RD[-1] = 1/8, RD[2] = 1/8, RD[-2] = 1/8								

Fig. 3: Reorder Displacement (RD) calculation

Arrive Sequence	1	2	3	4	7	5	6	8
Expected	1	2	3	4	5	6	7	8
Buffer-occupancy	0	0	0	0	1	1	0	0
RBD[0] = 6/8, RBD[1] = 2/8								

Fig. 4: Reorder Buffer-occupancy Density (RBD) calculation

Reorder Buffer-occupancy Density (RBD): RBD is the normalized buffer that allow to recovery from out-of-order delivery of the packets. If the arrival packet is early than expected then it can be added in the hypothetical buffer until it can be released in order [42]. After arrival of each packet the occupancy of buffer is used as the measure of reordering.

For the sequence (1, 2, 3, 4, 7, 5, 6, 8), shown in Fig. 4, the buffer- occupancy when the packet with the sequence number 7 arrives is 1 because it arrived when 5 was being expected. The buffer occupancy remains 1, when the packet 5 arrives.

Analysis of Packet Reordering Delay: In wireless communication system, two types of delay can be occurred, namely; fixed or propagation and variable or queuing delay. Consider D_p^m and Q_p^m are propagation and queuing delay respectively and overall delay, $d_p^{(m)}$ can be denoted as shown in equation (8) where *m* represents the packets that has been transmitted over path *p*.

$$d_p^{(m)} = D_p^m + Q_p^m \tag{8}$$

In a heterogeneous wireless network, packets *m* are being transmitted over multiple paths, for example two paths are considered in this case *i* and *j*. The delay of packet reordering can be measured from the equation (9) [43].

$$\Delta_{i,j}^{(m)} = d_i^{(m-1)} - d_j^m \tag{9}$$

for $\forall\ i \neq j$

$\left|\Delta_{i,j}^{(m)}\right|$ is the most desirable value that needs to be minimized for real-time applications.

In heterogeneous environment, packet reordering occur due to packet splitting and path switching into available interfaces based on the probabilistic measurements [43]. The probability of packet reordering, π_r can be measured from the equation (10) [43, 44]

$$\pi_r = \pi_s \sum_{i\in P} \sum_{j\in P} \phi_{i,j}^{(m)} \Omega(\Delta_{i,j}^{(m)}) \tag{10}$$

Where π_s is the probability of overall splitting of packets and $\phi_{i,j}^{(m)}$ is the probability of the path switching from path *I* to path *j* and P is the parallel paths. This indicates that *(m-1)*th packet will be transmitted through path *I* and *m*th packet will be forwarded via path *j*. $\Omega(\Delta_{i,j}^{(m)})$ represents the conditional probability of packet reordering when the path is switching from *i* to *j* that is the function of $\Delta_{i,j}^{(m)}$ which has been shown in equation (2). It can be said that, if $\Delta_{i,j}^{(m)} > 0$ then $\Omega(\Delta_{i,j}^{(m)}) > 0$ indicates that packet reordering risk is exist. Otherwise, if $\Omega(\Delta_{i,j}^{(m)}) = 0$, packet reordering will never happen. The smaller value of $\left|\Delta_{i,j}^{(m)}\right|$ is the smaller risk of packet reordering.

Challenges of Packet Reordering: In HWN, packet reordering can occur due to lateness, displacement and buffer occupancy.

Packet Reordering in Terms of Lateness: It is expected that transmission of placket must be in order at the receiver end. Transmission through a single interface, packet reordering is very few. However, it has been observed that packet reordering more in HWN. Generally, there is no packet reordering observed when send rate is very low in any interface but reordering happen about 50% while the sending rate increases. The average one way delay is measured 80ms over HSPA and 44ms on WiFi networks [45].

Packet Reordering in Terms of Displacement: Packet displacement is an entity that provides detailed distribution about a received packet how far it is displaced from their original position. If the packet arrives early with compared to expected time is marked as negative displacement and reach late considered as positive displacement. This displacement or reorder density (RD) has been demonstrated to provide comprehensive information about the amount of packet reordering [1].

It has observed that some packets have displaced at most 300 positions from their original location and only 2% packet are received as expected while the majority of the packets are displaced by three positions [45-48]. If three or more positive displacement positions found, TCP has to retransmit the presumably lost packet and additionally reduces its send rate.

Packet Reordering in Terms of Buffer Occupancy: Buffer occupancy is required to restore in-order of packet sequence. It can be said that buffer occupancy is not utilized when bit rate is set low it is mostly occupied for high speed packet transmission. It is especially important for predicting the amount of buffer space required to correct packet reordering.

Simulation Tools: A simulator executes a model that is represented by a computer program and gives useful information about the behaviour and performance of the model. It provides the users with the ability to define arbitrary network topologies including mobile nodes, links, attach applications, queues on each node and connectors, etc. A number of simulation software are being using in the networking field for evaluating the performance of the model, namely; OPNET, NS-2, OMNeT++ and QualNet are widely-used and popular among network oriented industries and researchers. Only few simulation tools support the bandwidth aggregation mechanism as it is relatively new in research area. NS-2 is the common and widely used simulation tool that has been mentioned in many literatures as it is freely available. On the other hand, OPNET is a commercial but effective tool for developing bandwidth aggregation models.

CONCLUSION

Efficient scheduling and packet reordering algorithms are the effective tools that can improve the quality of HWN. The advantages and limitations of scheduling algorithms are investigated for further research. Packet reordering metrics and delays are analyzed to develop a noble packet reordering algorithm in further research works. The challenges of packet reordering and useful simulation tools are mentioned in this research as a future guideline of the research. It is expected that future work of this research will be carried in terms of analytical and simulated based on the guideline from this paper.

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