Flow Splitting for Multi-RAT Heterogeneous Networks

Xiao Ma, Min Sheng, *Member, IEEE*, and Yan Zhang

The State Key Lab of ISN, Xidian University, Xi'an, Shaanxi 710071, China
xiaoma@mail.xidian.edu.cn, msheng@mail.xidian.edu.cn, yzhang@xidian.edu.cn

Abstract—**With the development of heterogeneous networks, concurrent transmission of Multimode-User Equipment (MUE) within multiple Radio Access Technologies (RATs) can improve transmission reliability and boost system performance. In this paper, some novel splitting strategies combining with different queuing management architectures are presented to obtain the multi-radio transmission diversity gain effectively. Two-dimensional discrete-state continuous-time Markov process is used to analyze our strategies and closed-form solutions have been made. Simulation results demonstrate that our proposed flow splitting strategies utilize the system resources efficiently and outperform current strategies.**

Keywords-heterogeneous network; concurrent transmission; flow splitting

I. INTRODUCTION

As various wireless networks are gradually approaching the Shannon capacity, it's hard to improve the performance only by some complex signal processing technologies [1] in single RAT to satisfy the demand for high-definition (HD) traffic. Fortunately, the 4th Generation (4G) wireless communication system has led to a deployment of various RATs, such as cellular networks and WLAN, which form the heterogeneous wireless network environments. It's a common opinion that interworking of heterogeneous RATs is one of the best ways to improve network capacity and enhance Quality of Service (QoS) [2-3].

Nowadays, Multimode User Equipment (MUE) with several radio interfaces can connect with different heterogeneous access networks simultaneously. Therefore, concurrent transmission of MUE can achieve the double gain of transmission reliability and transmission rate. In this kind of concurrent transmission system, known as tight-coupling architecture[2] of heterogeneous networks, the MUE can not only realize seamless handover across diverse RATs, and more important is data flow can be split into different RATs to boost the system performance. As shown in Fig. 1, in the area overlapped by different RATs, MUE can access to both of the RATs simultaneous when neither RATs satisfy the requirements of MUE. In order to manage different RATs and execute flow splitting strategy effectively, a function entity called MRRM (Multi-radio Resources Management), connected with CN (Core Network), is introduced in [4-6]). Under this architecture, traffic flow is stored and split by MRRM. Each splitting flow is transmitted by different RATs, and reordered in MUE.

This paper is supported by NSFC (60972048，61172079), 973 Program (2009CB320404), TRAPOYT and 111 Project (B08038), PCSIRT(IRT0852), ISN01080301, National S&T Major Project (2011ZX03003-002-02and 2012ZX03002003).

As a promising approach, flow splitting for interworking heterogeneous wireless networks has been paid extensive attention. In [4], a multiradio access architecture has been provided and a Generic Link Layer (GLL) has been added to integrate different RATs. Radio resource management strategies have been described in [7-8]. Paper [5] shows the benefit of parallel transmission, and proposes a multiradio resource management strategy to achieve the maximum throughput of whole system by splitting the flow with the Fixed Probability (FP) corresponding to the throughput of each RAT. Paper [9] extends this problem to multi-user scenario which consists of foreground and background traffic, and exploits processor sharing (PS) queue to model the *N* multiple networks.

However, to our knowledge, none of the existing strategies have fully considered current RATs conditions to split traffic. In this paper, we propose some novel splitting strategies combination with different queuing management architectures. Based on the real-time state information, traffic flow is split into suitable RATs. Our schemes are more successful in keeping delay low with the same allowed traffic load.

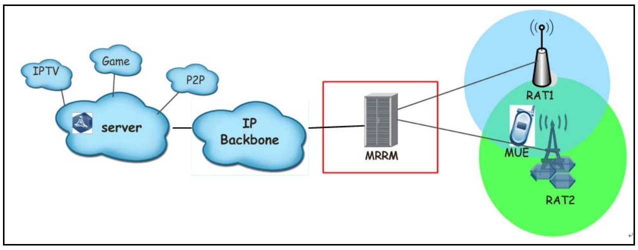

Figure 1. Concurrent use of multiple RATs in heterogeneous networks

The rest of the paper is organized as follows. In Section II, two queuing management architectures and three different kinds of splitting strategies are proposed. Simulation scenario and results are presented in Section III. Section IV reports some conclusions and future works.

II. FLOW SPLITTING STRATEGY

As mentioned above, in existing parallel transmission architectures, MRRM is only responsible for splitting flow. Traffic flow is stored in different RATs. While, in our work, splitting strategies have close relationship with queuing management, a unified queuing model is introduced in MRRM besides queuing in different RATs. Two categories and three different kinds of splitting strategies are proposed. The first category is queuing in different RATs, including Minimum Queuing Delay based splitting strategy (***MQD***) and Minimum

Queuing Length based splitting strategy (***MQL***). The second one is queued in MRRM, and a Unified Queuing Management based splitting strategy (***UQM***) is presented.

A. Minimum Queuing Delay Based Splitting Strategy

Consider the heterogeneous networks with n overlapped RATs $\{RAT_1, RAT_2, \cdots, RAT_n\}, n \geq 2$. Each RAT is entirely independent and no interference between them. Each arriving packet is assigned by MRRM to a RAT that currently has the minimum queuing delay, which is determined by the number of queuing packets and the average service rate of the RAT. After splitting, packets are buffered in RATs and waited to be transmitted to MUE.

Assuming packets arrive according to a Poisson process with rate λ, and the probability distribution of the service time of RAT_i is exponential with mean $1/\mu_i$. The number of packets queuing in system at time t is $N(t)$, $N(t) = \{N_{RAT_1}(t), N_{RAT_2}(t), \cdots, N_{RAT_n}(t) \mid t \geq 0, n \geq 2\}$ where $N_{RAT_i}(t)$ represents the number of packets queuing in RAT_i . Due to the memoryless property, $N(t)$ can be described as a discrete-state continuous-time Markov Chain, and the steady-state probability vector of $N(t)$ is $\pi = [\pi_{N(t)}]$ .Let $W_{RAT_i}(t) = N_{RAT_i}(t)/\mu_i$ denote the waiting time of packet in RAT_i at time *t*. For an arrival, the optimal RAT it will be split into based on ***MQD*** is determined by (1).

$$RAT_{opt} = \arg \min_{RAT_i \in \{RAT\}} \{W_{RAT_i}(t)\} \tag{1}$$

In this paper, we address two independent RATs. In this scenario, $N(t)$ can be described by a two-dimensional discrete-state continuous-time Markov Chain, as shown in Fig. 2. The *k* and *l* represent the buffer size of the two RATs. Here we assume that *k* and *l* are large enough so that there will be no packet overflow. At state (i, j) , a packet is assigned to RAT_1 and RAT_2 with probability $P_{i+1,j}$ and $Q_{i,j+1}$ respectively. $P_{i+1,j}$ and $Q_{i,j+1}$ can be determined by (2).

$$\begin{cases} P_{i+1,j} = 1, Q_{i,j+1} = 0, when(W_{RAT_1} \leq W_{RAT_2}) \\ P_{i+1,j} = 0, Q_{i,j+1} = 1, when(W_{RAT_1} > W_{RAT_2}) \end{cases} \tag{2}$$

As shown in Fig. 2, the state (i, j) can only goes to state $(i-1, j)$, $(i+1, j)$, $(i, j-1)$ or $(i, j+1)$. Thus this kind of two-dimensional Markov process is a birth-death process, and the steady-state probability vector $\Pi\{\pi_{i,j} \mid 0 \leq i \leq k, 0 \leq j \leq l\}$ of that can be efficiently found by algorithms such as matrix-geometric method (MGM) and matrix-analytic method (MAM) [11]. Then the average delay D between the time a packet entered MRRM and the time it arrives the MUE, can be calculated by (3), where $D_{i,j}$ is the delay of the packet spend in system at state (i, j) which means there were already *i* and *j* packets in RAT_1 and RAT_2 respectively.

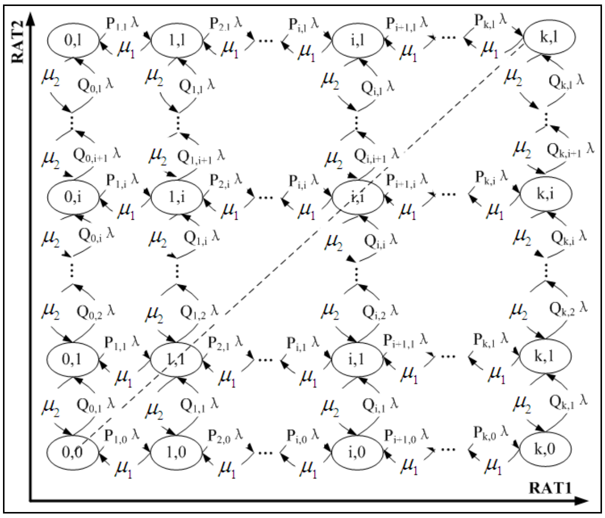

Figure 2. State transition diagram for ***MQD*** strategy in two RATs

$$\begin{cases} D = \sum_{i=0,j=0}^{i=k,j=l} \pi_{i,j} D_{i,j} \\ D_{i,j} = \begin{cases} (i/\mu_1) + 1/2\mu_1, when P_{i,j} = 1, Q_{i,j} = 0 \\ (j/\mu_2) + 1/2\mu_2, when P_{i,j} = 0, Q_{i,j} = 1 \end{cases} \end{cases} \tag{3}$$

Because ***MQD*** strategy considers both the system instantaneous state and the service rate of different RATs, the system behaves like an *M*/*M*/*n* queue system with heterogeneous nonshared servers, as shown in Fig.3. ***MQD*** strategy can obtain the joint scheduling gain of multi-queue, and gets a better performance than FP strategy, which worked as *n* separate *M*/*M*/1 queue.

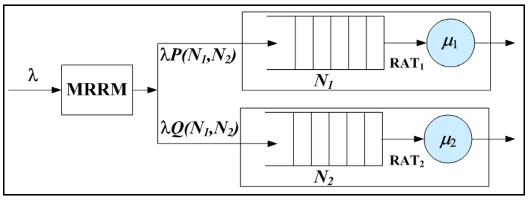

Figure 3. The queue system of ***MQD*** and ***MQL*** with *n*=2

B. Minimum Queuing Length Based Splitting Strategy

Without the RATs' resource information, ***MQD*** strategy becomes invalid. Hence, the minimum queue length (***MQL***) based splitting strategy, which only considers the number of waiting packets in RATs, is proposed in this section.

Each arriving packet of ***MQL*** is assigned to a RAT that currently has the smallest total backlog in packets. Consider the similar scenario mentioned in ***MQD*** strategy, the optimal RAT of ***MQL*** can be obtained by (4).

$$RAT_{opt} = \arg \min_{RAT_i \in \{RAT\}} \{N_{RAT_i}(t)\} \tag{4}$$

Coming back to the simplest heterogeneous network scenario with two independent RATs mentioned in section A.

$P_{i+1,j}$ and $Q_{i,j+1}$ can be conducted by (5). And the state-transition diagram can be simplified as Fig. 4.

$$\begin{cases} P_{i+1,j} = 1, Q_{i,j+1} = 0, when(N_{RAT_1}(t) < N_{RAT_2}(t)) \\ P_{i+1,j} = 0, Q_{i,j+1} = 1, when(N_{RAT_1}(t) > N_{RAT_2}(t)) \\ P_{i+1,j} = Q_{i,j+1} = 0.5, when(N_{RAT_1}(t) = N_{RAT_2}(t)) \end{cases} \quad (5)$$

Obviously, ***MQL*** strategy only uses the system state information, so the performance of ***MQL*** will be worse than that of ***MDQ*** strategy. However, ***MQL*** strategy still is an *M*/*M*/*n* queue system with heterogeneous nonshared servers, as shown in Fig.3， it outperforms FP strategy.

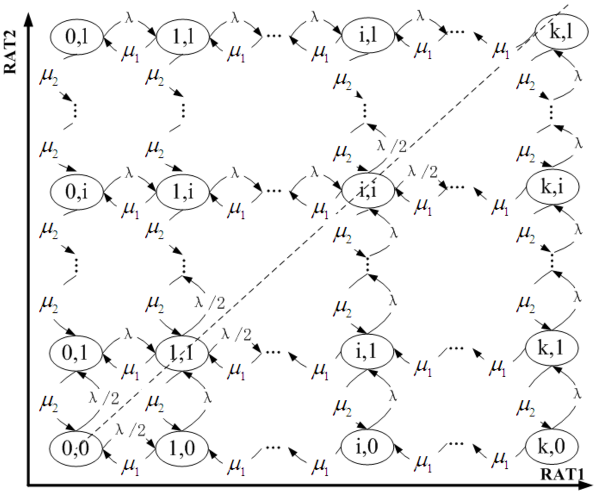

Figure 4. State transition diagram for ***MQL*** strategy in two RATs

C. *Unified Queuing Management Based Splitting Strategy*

Suppose packets are stored in MRRM before splitting, and there is no buffer in each RAT, a unified queuing management (***UQM***) based splitting strategy is presented.

Let the state of ***UQM*** be $N(t)$, $N(t) = \{N_{RAT_1}(t), \cdots, N_{RAT_n}(t), N_{MRRM}(t) \mid t \geq 0, n \geq 2\}$, where $N_{RAT_i}(t)$ is the number of packet which is serving by RAT_i, so that $N_{RAT_i}(t)$ is either 0 or 1. $N_{MRRM}(t)$ is the number of packets queuing in MRRM. The same as section A, $N(t)$ can be described as a discrete-state continuous-time Markov Chain.

For the scenario of two independent RATs as mentioned above, the corresponding state transition diagram of the ***UQM*** strategy is shown in Fig. 5. There is no packet waiting to be transmitted in RATs. The parameters $P_{1,0}$ and $Q_{0,1}$ denote the packet allocating probability at state $(0,0,0)$, and can be conducted by (6).

$$\begin{cases} P_{1,0} = 1, Q_{0,1} = 0, when \mu_1 > \mu_2 \\ P_{1,0} = 0, Q_{0,1} = 1, when \mu_1 < \mu_2 \end{cases} \quad (6)$$

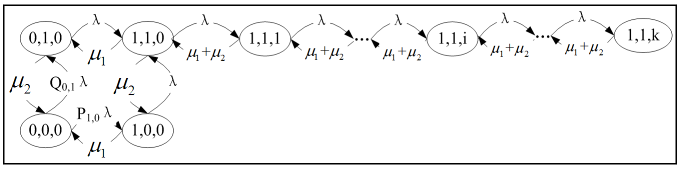

Figure 5. State transition diagram for ***UQM*** in two RATs

This kind of problem can be solved by method such as M/M/2 system with heterogeneous servers[12], and the steady-state probability vector of this Markov chain $\Pi\{\pi_{i,j,l} \mid 0 \leq i \leq 1, 0 \leq j \leq 1, 0 \leq l \leq k\}$ can be found easily. The average packet delay of this system can be calculated by (7).

$$\begin{cases} D = \sum_{i=0,j=0,l=0}^{i=1,j=1,l=k} \pi_{i,j,l} D_{i,j,l} \\ D_{i,j,l} = \{(l/(\mu_1+\mu_2)) + (3/(\mu_1+\mu_2)) \ when \ i = j = 1 \\ D_{0,0,0} = \begin{cases} 1/\mu_1 \ when \ \mu_1 > \mu_2 \\ 1/\mu_2 \ when \ \mu_1 < \mu_2 \end{cases} \\ D_{1,0,0} = 1/\mu_2 \\ D_{0,1,0} = 1/\mu_1 \end{cases} \quad (7)$$

UQM works as an *M*/*M*/*n* (as shown in Fig.6), and considers the resources of different RATs as a common resource pool, so that the maximum resource utility can be obtained.

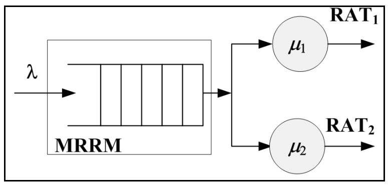

Figure 6. The queue system of ***UQM*** with n=2

III. SIMULATION AND RESULTS

In this section, we use OPNET simulator for our all simulation, and experiment with streaming application on a prototype scenario of the concurrent transmission architecture as the proof of concept to quantify the performance improvement of the novel splitting strategies over that of FP strategy.

A. *Parameter Setting*

We consider a heterogeneous wireless network overlapped by an IEEE 802.11g WLAN Access Point (AP) and a LTE eNodeB. A MUE in the overlap area can access to both of the AP and eNodeB simultaneously. Traffic will transmit to MUE through parallel links. The maximum WLAN channel rate is 54 Mbps, and the rate will automatically reduce to 18Mbps gradually when the MUE moved further away from the AP. And the equivalent data rate of LTE varies with the SNR which determine the MCS (modulation and coding scheme) used by MUE. We summarize the simulation parameters in the Table I. And the detail parameters selection criteria presented in Table

II. The definition of Load is $R_{request}/(T_{WLAN}+T_{LTE})$, where $R_{request}$ is the arrival rate requested by MUE, T_{WLAN} and T_{LTE} are the equivalent throughputs of WLAN and LTE respectively. And the service time of AP and eNodeB will be exponential distributed with the exponential packet size distribution [13-14].

TABLE I. THE PARAMETER VALUES FOR WLAN AND LTE

	Simulation Parameters	
	WLAN	***LTE***
bandwidth	20MHz	20MHz
standard	802.11g	Release 9
transmission rate	54-18Mbps (distance 10-50m)	100PRB×(40-140)Kbps (SNR3.8-16.2dB)

TABLE II. PARAMETERS SELECTION CRITERIA

LTE			WLAN	
SNR(dB)	**MCS**	**TBS_L2 (bit)**	**Distance (m)**	**Data rate (Mbps)**
$\gamma(t)\le 6.6$	12	39232	19	54
$6.6<\gamma(t)\le 9.9$	16	61664	23	48
$9.9<\gamma(t)\le 12.3$	19	73712	35	36
$12.3<\gamma(t)\le 16.2$	23	10184	42	24
$\gamma(t)>16.2$	28	149776	50	18

B. *Simulation Results for Single UE Scenario*

In this scenario, there is no competing MUE. In other word, all of the resources of both RATs can be used by the single user.

First, we consider the MUE near the AP and the SNR is higher than 16.2dB. The comparison of mean delay of different splitting strategies is shown in Fig. 7. The dotted lines are the theoretical value which calculated by the steady-state probability mentioned above, and the solid lines are the simulation value. The trajectory shows that the strategies presented in this paper have a much better performance than FP strategy, especially in the heavy load condition. The mean delay performances of different splitting strategies for parallel transmission are $D_{FP}>D_{MQL}>D_{MQD}>D_{UQM}$, which are consistent with our previous theoretical analysis.

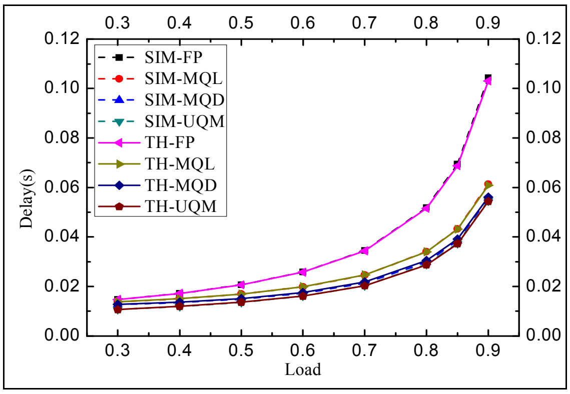

Figure 7. Value for mean delay comparison for different flow splitting strategies

The comparison of throughput for different flow splitting strategies is shown in Table III. Due to all the strategies are stable algorithms, the strategies proposed in this paper doesn't reduce the whole throughput of the system.

TABLE III. THE THROUGHPUT FOR DIFFERENT FLOW SPLITTING STRATEGIES

Load	Throughput(Mbps)			
	FP	***MQL***	***MQD***	***UQM***
0.3	58.2	58.1	58.1	58.2
0.4	77.6	77.6	77.6	77.5
0.5	97.2	97.1	97.1	97.0
0.6	116.6	116.5	116.66	116.31
0.7	136.0	135.7	136.1	135.8
0.8	155.5	155.5	155.3	155.2
0.9	174.8	174.8	174.7	174.7

Fig. 8 illustrates the mean delay of different RATs. The dotted and solid lines are the mean delay of WLAN and LTE respectively. Due to the lower transmission rate, the delay of WLAN has a smaller delay than that of LTE. With the increasing of load, the delay of ***MQD*** of WLAN increases much slower than that of other strategies, and the difference in delay between WLAN and LTE approximately approaches zero.

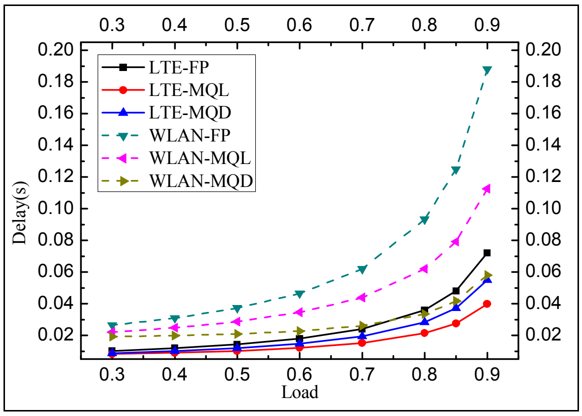

Figure 8. Value for mean delay of different RATs

The delay jitter is an important metric which can noticeably affect the quality of experience (QoE). Different from the single link system, the jitter in the parallel transmission system is mainly the variation in packet transit delay between different RATs. Fig.9 shows the mean delay jitter of different flow splitting strategies. It's worth noting that, with the increasing of load, the jitter of ***MQD*** is reduced. This phenomenon can be easily explained that the delay is mainly caused by the packets waiting in the RATs to be transmitted, and the ***MQD*** strategy allocates packet to RAT with a smaller delay, in other words, the delay of both RATs will be approximate equal when the system is in steady state. So, the heavier the load increases, the smaller the jitter reduces.

Then, we consider the MUE moving away from the AP and eNodeB, and the data rate rapidly decreases for increasing distances. Fig.10 shows the mean delay of MUE in different conditions. And the MUE requests a streaming application with an arriving rate of 50Mbps. The X axis represents the distance of MUE from the AP, and the Y axis represents the LTE downlink SNR of MUE. We can immediately observe that the splitting strategies proposed in this paper have a better performance than FP strategy in different conditions.

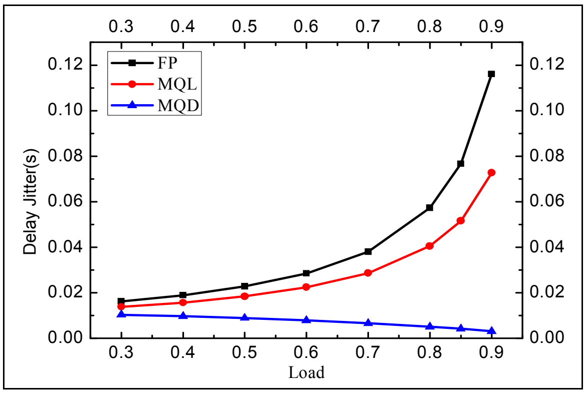

Figure 9. Value for mean delay jitter of different flow splitting strategies

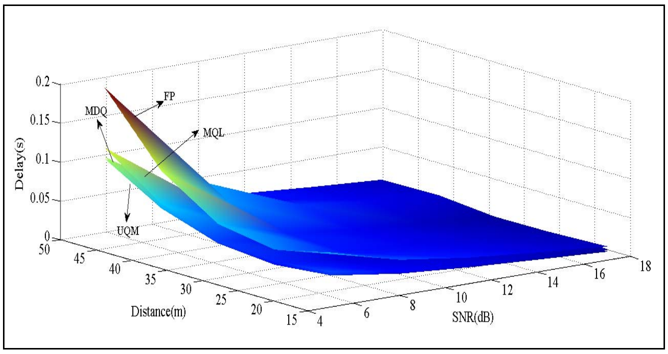

Figure 10. Value for mean delay of different data rate

C. *Simulation Results for Multi-UE Scenario*

In this scenario, there are 1-4 WiFi-only UEs which competing the shared WLAN channel with MUE and decreasing the equivalent data rate of MUE , and 3-6 LTE-only UEs which will occupy parts of the PRBs and reduce the number of PRBs available for MUE. Fig. 10 shows the mean delay of different flow splitting strategies. The x and y axial represent the equivalent transmit rate for WLAN and LTE-BS respectively. Figure 11 illustrates that the performance of flow splitting strategies are influenced by the difference between the transmit rates. When the difference of transmit rates is small, the performance improvement is getting better.

IV. CONCLUSION

In this paper, we address the problem to transmit the traffic over parallel links in heterogeneous wireless network. We proposed several novel flow splitting strategies to optimize the concurrent transmission system for peak performance by joint scheduling multi-RATs. Results demonstrated that the performance of heterogeneous network has been greatly improved. Future works will mainly focus on the multi-MUE scenario. The optimum resource allocation strategy must be proposed to identify how many and which MUEs should execute concurrent transmission.

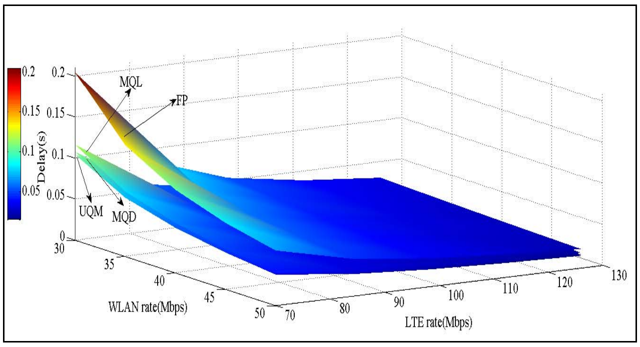

Figure 11. Value for mean delay comparison for different splitting strategies

REFERENCES

[1] Cox. D.; "Fundamental limitations on increasing data rate in wireless systems," Communications Magazine, IEEE , vol.46, no.12, pp.16-17, December 2008.

[2] Ferrus. R.; Sallent. O.; Agusti. R.; "Interworking in heterogeneous wireless networks: Comprehensive framework and future trends," Wireless Communications, IEEE , vol.17, no.2, pp.22-31, April 2010.

[3] Ahmavaara. K.; Haverinen. H.; Pichna. R.; "Interworking architecture between 3GPP and WLAN systems," Communications Magazine, IEEE , vol.41, no.11, pp. 74- 81, Nov. 2003.

[4] Dimou. K.; Agero. R.; Bortnik. M.; Karimi. R.; Koudouridis. G.P.; Kaminski. S.; Lederer. H.; Sachs. J.; , "Generic link layer: a solution for multi-radio transmission diversity in communication networks beyond 3G," Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd , vol.3, no., pp. 1672- 1676, 25-28 Sept., 2005.

[5] Alessandro Bazzi, Gianni Pasolini, and Oreste Andrisano, "Multiradio Resource Management: Parallel Transmission for Higher Throughput?," EURASIP Journal on Advances in Signal Processing, vol. 2008, Article ID 763264, 9 pages, 2008.

[6] Jijun Luo; Mukerjee. R.; Dillinger. M.; Mohyeldin. E.; Schulz. E.; , "Investigation of radio resource scheduling in WLANs coupled with 3G cellular network," Communications Magazine, IEEE , vol.41, no.6, pp. 108- 115, June 2003

[7] Taddia. C.; Mazzini. G.; "Per-packet allocation strategies for heterogeneous multichannel wireless networks," Wireless Networks, Communications and Mobile Computing, 2005 International Conference on , vol.1, no., pp. 158- 162 vol.1, 13-16 June 2005.

[8] D. Niyato and E. Hossain. "A noncooperative game-theoretic framework for radio resource management in 4G heteroge-neous wireless acces networks. " IEEE Trans, on Mob. Computing, 7(3):332-345, Mar. 2008.

[9] Gerard Hoekstra, Rob van der Mei, Yoni Nazarathy and Bert Zwart, "Optimal File Splitting for Wireless Networks with Concurrent Access," Network Control and Optimization Third Euro-NF Conference, NET-COOP 2009 Eindhoven, The Netherlands, November 23-25, 2009 Proceedings.

[10] Yuan-Chieh Chow; Kohler, W.H.; "Models for Dynamic Load Balancing in a Heterogeneous Multiple Processor System," Computers, IEEE Transactions on , vol.C-28, no.5, pp.354-361, May 1979.

[11] G. Bolch, S. Greiner, H. de Meer, and K.S. Trivedi, "Queueing Networks and Markov Chains, Modeling and Performance Evaluation with Computer Science Applications. " John Wiley & Sons, 1998.

[12] D. Bertsekas and R. Gallager, "Data Networks, " 1987. :Prentice-Hall.

[13] Bobarshad. H.; Shikh-Bahaei. M.; "M/M/1 Queuing Model for Adaptive Cross-Layer Error Protection in WLANs," Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE , vol., no., pp.1-6, 5-8 April 2009

[14] Namakoye. J.; Van Olst. R.; "Performance evaluation of a voice call handover scheme between LTE and UMTS," AFRICON, 2011 , vol., no., pp.1-5, 13-15 Sept. 2011