ISSN 2229-5518

Adaptive Coupling of Heterogeneous Mobile Communications Networks

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Abstract-- Adaptive coupling is a new proposed integration mechanism that adaptively changes coupling level from loose to tight and to very tight according to networks' load status and delay constraints. Test results show that the adaptive coupling algorithm mitigates the problem of increased packet loss rate- due to load congestion- for the cases of tight and very tight coupling. In the same time it alleviates the problems of long delay and high dropping probability during vertical handover in the case of loose coupling.

Index Terms--Adaptive coupling; load congestion; packet loss rate; vertical handover delay; dropping probability.

1. Introduction

Based on the position of the integration point between heterogeneous networks, three[1] major coupling levels were classified in the literature [1]. The first is loose coupling where centralized billing and maintenance for different radio access technologies (RAT) is possible. Besides, the user enjoys a unique subscription if the network provider is the same for both networks where an interaction between the control planes of each RAT regarding the authentication procedure exists. In addition, loose coupling allows for the flexibility and independence of implementing individually different mechanisms within each network and eases the gradual deployment of one network with no or little modification on the other network(s). The main disadvantage of loose coupling is that vertical handover is not seamless; during the handover between two RATs, the service in progress has high probability to be dropped since the vertical (inter RATs) handover delay is significant.

The second coupling level is tight where tightly coupled networks require considerable effort in defining interfaces, protocols and mechanisms needed to support the necessary exchange of data and signaling between different RAT networks. The advantage of tight coupling is that it permits seamless and fast handover between RATs to take place. The provisioning of the service is more efficient and network selection is faster than in loose coupling. However, tight coupling suffers from potential of load congestion when one network full load is immersed on the other. The third coupling level is very tight coupling where the integration is built within the radio access network. Hence, the networks are able to perform a seamless and very fast vertical handover. As in tight coupling, very tight coupling requires new interface design to support the high level integration and necessary exchange of data and signaling between different RATs. Potential of load congestion is even higher than the case of very tight coupling.

This paper proposes a new coupling mechanism that adaptively changes coupling level according to networks' load status and delay constraints. The main goal of the adaptive coupling is to mitigate the problem of increased packet loss rate due to load congestion for the cases of tight and very tight coupling and in the same time alleviate the problem of vertical handover delay and dropping probability in the case of loose coupling. The paper is organized as follows: Section 2 introduces a literature review of the related work. Section 3 presents an integration architecture between 3GPP (UMTS) as wide area coverage cellular network and Mobile WIMAX as medium area wireless network. Different levels of coupling are shown depending on the point of integration. Section 3 illustrates in details the proposed adaptive coupling mechanism based on cost function evaluation with emphasis on coupling level selection criteria and decision key factors. Section 4 presents the adaptive coupling's considered scenario and simulation parameters and Section 5 shows the numerical results for the simulated algorithm. Finally, Section 6 concludes the paper.

[1] Open coupling is excluded since no real integration exists between different RATs with only a billing system being shared between them. Separate authentication procedures are used for each access networks and no vertical handovers take place; a current session in use will always be terminated as it hands over to a new RAT.

2. Related Work

Integrating and interworking heterogeneous cellular and wireless networks have been considered a hot area of research for the preparation of 4G systems. Seamless integration of the multiple 4G heterogeneous access technologies is needed to provide “Always Best Connectivity”, full broadband access, and perfect QoS. In [2], Yiping et al. proposed a new network selection scheme with vertical handover based on a Mobile IPv6. This scheme guaranteed always best connected services that both end-users and network operators would benefit from. F. Karam et al., in [3] proposed a solution for reducing handover latency in interworking WLAN, WIMAX and UMTS/LTE networks based on IEEE 802.21 Media Independent Handover (MIH). However, L. Nithyanandan and I. Parthiban in [4] managed to reduce handover latency- in interworking the aforementioned networks- by employing two mechanisms such as Neighbour Bandwidth Reservation and Gateway Relocation. In order to minimize data loss during vertical handovers, Song et al., in [5] proposed an innovative effective scheme, based on a new data forwarding function, for integration of WIMAX and 3GPP networks. Besides, Sun, Z. et al. in [6] proposed advanced centralized functional architectures- for integrating WIMAX and 3GPP networks- based on the Generic Link Layer (GLL) and the Multi-Radio Resource Management (MRRM) mechanisms. Meanwhile, Charles Sarraf et al., in [7] suggested a mechanism for mapping between the QoS of 3GPP UMTS and WiMAX in a tight coupling architecture specifically. Finally in [8], the author of this paper proposed two cost-based mechanisms of interworking between LTE and mobile WIMAX networks where numerical results showed a considerable enhancement in terms of blocking and dropping probabilities.

3. Integration Architecture and Coupling Levels

Figure 1 shows the an integration architecture between 3GPP (UMTS) [9] as wide area coverage cellular network and IEEE 802.16e Mobile WIMAX [10] as medium area wireless network. Different levels of coupling are shown depending on the point of integration: In the loose coupling, there is no direct link between the two radio access networks[11]. The gateways are mainly connected to IP-based internet backbone. In the tight coupling, there is direct link between the two radio access networks. The gateway of the WIMAX is connected to the UMTS core network whether at GGSN or more tightly at SGSN. In the very tight coupling, the integration point is at UMTS access network via the Radio Network Controller (RNC) [12].

ISSN 2229-5518

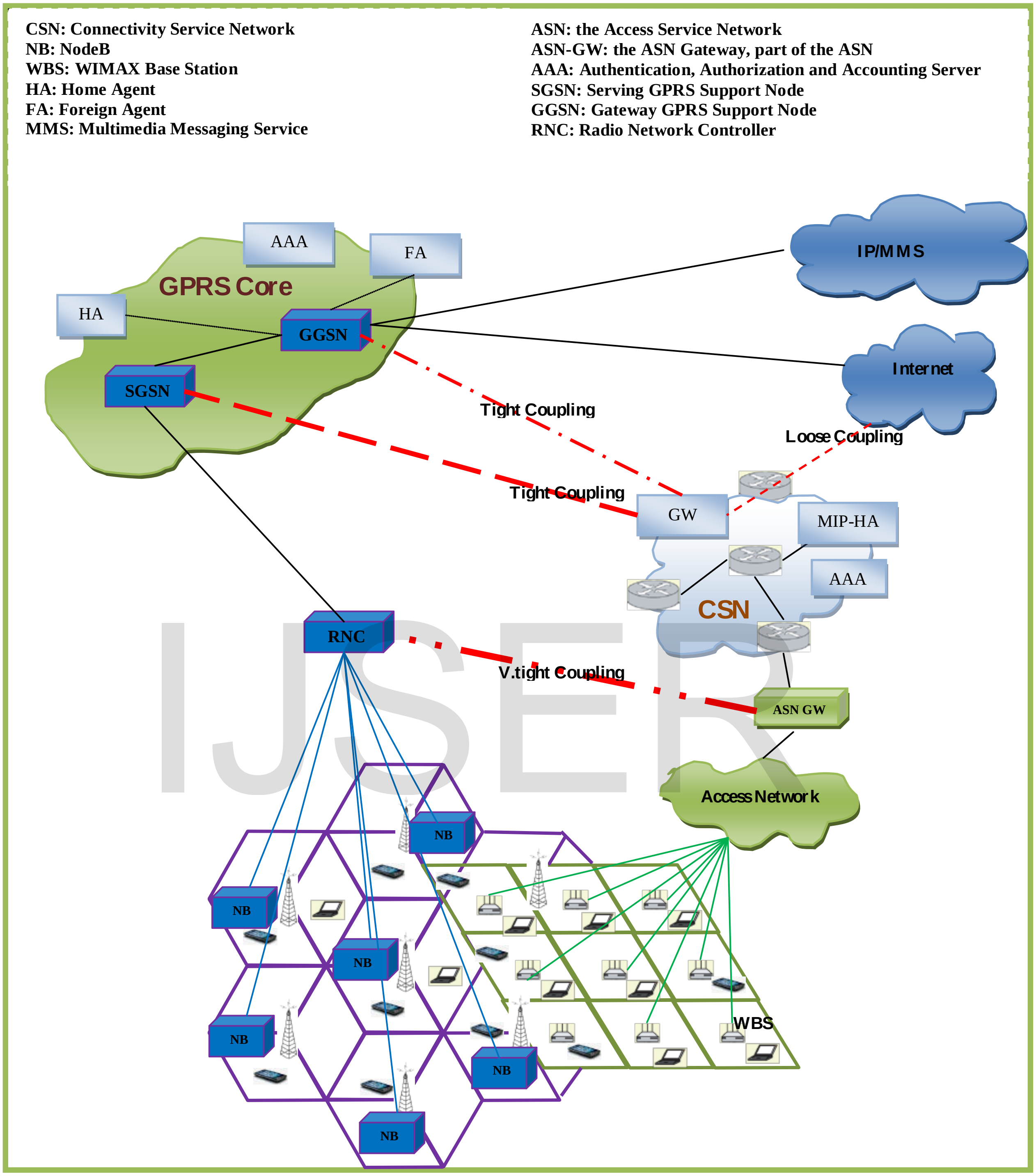

Figure 1: Mobile WiMAX and 3GPP UMTS Integration Architecture[2]

[2] All the WIMAX cells coexist within the UMTS coverage. It is not possible to show that in Figure 1 for convenient drawing!

4. Adaptive Coupling-Reconfigurable Integration

Adaptive coupling is a new proposed mechanism that adaptively changes coupling level from loose to tight and to very tight according to appropriate key factors such as networks' load status, delay constraints and application service.

4.1 Adaptive Coupling Mechanism

Figure 2 shows a flowchart of the proposed adaptive coupling mechanism where it starts with loose coupling as it allows for the flexibility and independence of implementing individually different mechanisms within each network. After waiting a predefined time (T_{-l}), the flowchart computes the average Vertical Handover (VHO) delay (VHO-delay) since the delay of handover process in loose coupling is the only critical key factor. If this value is lower than a predefined acceptable delay range upper threshold (D_{-upth}), loose coupling is maintained again for another time (T_{-l}). If it is higher, coupling is directly switched to the level tight.

Rather than looking after a single critical factor as the case of delay in loose coupling, in tight coupling many key factors count: load congestion, delay and application service. A Cost Function (CF) is preferable to balance the impact of these factors on the coupling switching decision. The proposed CF, illustrated in the next section, has three outputs states: stay in tight coupling, return to loose coupling or go to very tight coupling, Figure 2. If the output is to go to very tight coupling, then after waiting a predefined time (T_{-vt}), the cellular network load is computed since the load congestion in very tight coupling is the only critical factor.. If the actual cellular network load exceeds a predefined upper threshold ($Load_{-upth}$) then coupling state returns to tight coupling. If not it stays in very tight coupling states.

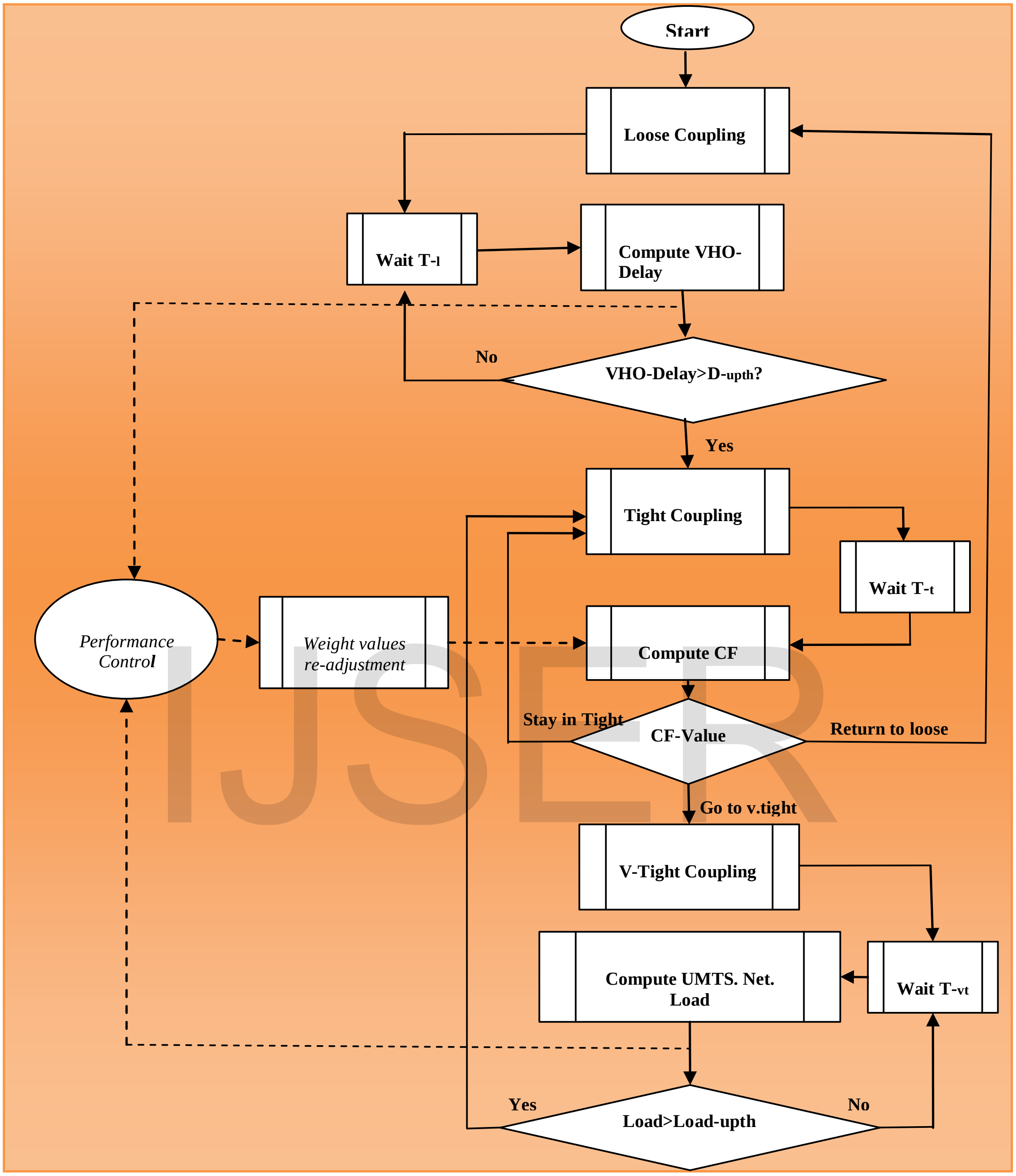

Figure 2: Adaptive coupling Flowchart

4.2 CF Evaluation

The CF, in general, is the summation of preference functions, each multiplied with a corresponding weight. The evaluation of preference functions recalls the need for pre-determined data and statistics for the probabilities of use of each criterion (or key factor). The purpose of the weights is to perform a balance between the different criteria (or key factors), represented by preference functions. For some reasons, a criterion can be more important than the other ones. These weights are pre-determined in order to meet the system optimization but can be re-adjusted if a particular situation claims it.

In this paper, an uncomplicated approach focuses on the weight values assigned to the key factors and gets rid of the need for pre-determined data and statistics.

$$C_f = \sum_i w_i p_i \qquad (1)$$

Where w_i are the weights corresponding to the preference p_i for a given factor *i* with $\sum_i w_i = 1$. Hence, the CF will no longer depend on preference functions and probabilities of use but depends only on some specified values depending on the available options, i.e. 0, 0.5 or 1, will be assigned for each preference function. In this scope, the value 0 defines the preference for loose coupling, 0.5 defines the preference for tight coupling and 1 for very tight, for example. The CF becomes a summation of weight values, each assigned to one of the key factors of the coupling selection process, multiplied with predefined values of preferences. The purpose of the weights is to perform a balance between the different factors where for some reasons, a factor can be more important than the other ones. Each weight takes a value from the range [0, 1] and the summation of all weight values should not exceed 1. Hence the value of the CF ranges from 0 to 1. These weights can be re-adjusted in order to meet performance optimization.

4.3 Coupling Level Selection and Decision key factors

The output of the CF ranges between 0 and 1 and provides the coupling preference i.e. the preference to a certain coupling level. The output of the CF determines the coupling preference according to the following rules:

$$\begin{aligned} 0 \le C_f \le 0.35 &\Rightarrow \text{Requests loose Coupling} \\ 0.35 < C_f \le 0.65 &\Rightarrow \text{Stays in tight coupling} \\ 0.65 < C_f \le 1 &\Rightarrow \text{Requests very tight Coupling} \end{aligned} \qquad (2)$$

The basic *Coupling Decision* key factors are defined as follows:

- **Vertical Handover Delay factor:** In coupling, vertical handover delay is significant while in tight (and very tight) coupling the delay is minimal. The total handover delay is the amount of time from when the mobile is disconnected from the old network to when the mobile receives the first packet from the new one. The delay required to complete a vertical handover is broken into the following components:
  - ✓ Discovery: is the component of delay where the mobile discovers that it must handover to a new network. The mobile is still connected to the old network during the time where it discovers that it can be connect to the new one.
  - ✓ Security procedure: including network access authentication
  - ✓ IP address acquisition and home agent (HA) registration: The delay due to Dynamic Host Configuration Protocol (DHCP), procedure enables the MN to obtain a new IP address via DHCP and to start IP connectivity with the new network.
  - ✓ Mobile IP (MIP) Delay: The MIP delay is the time required to perform the Mobile IP signaling procedure.
  - ✓ New path Delay: is the component of delay when the mobile informs the new network to start forwarding data to the mobile till the new network sends the first data packet to the mobile. This component is a function of the network latency and bandwidth.

The total handover delay is the sum of the above five delay components as follows:

$$\text{Total VHO Delay} = T_{\text{Discovery}} + T_{\text{Security}} + T_{\text{IP address acquisition}} + T_{\text{MIP}} + T_{\text{New path}} \qquad (3)$$

For MIPv6, IP address acquisition and security procedures are supported; the Return Routability (RR) procedure is used to support a secure communication between Mobile Node (MN) and Correspondent Node (CN). If TX-Y denotes the one way transmission delay between two nodes X and Y then the overall MIPv6 handover delay can be summarizes as [13]:

$$T_{\text{MIPv6}} = 2(2T_{\text{HA-MN}} + T_{\text{HA-CN}} + T_{\text{MN-CN}}) \qquad (4)$$

And the Total VHO delay becomes:

$$\begin{aligned} \text{Total VHO Delay} &= T_{\text{Discovery}} + T_{\text{MIPv6}} + T_{\text{New path}} \\ &= T_{\text{Discovery}} + 2(2T_{\text{HA-MN}} + T_{\text{HA-CN}} + T_{\text{MN-CN}}) + T_{\text{New path}} \end{aligned} \qquad (5)$$

- **Traffic load congestion factor**: In tight coupling, WIMAX full load is normally loaded in 3CPP cellular network yielding potential of load congestion. The problem is more severe in very tight while it does not exist in loose coupling. Typical effects include deterioration of quality of service; increased packet loss rate and high blocking probability, defined as follows:

- Packet loss rate (due to load congestion): the percentage of lost packets over the total number of transmitted packets.

- *Blocking probability*: the percentage of blocked users over the total number of connection trials.

The upper and down threshold limits of load congestion is based on the above two metrics; however in this paper's simulation tests, only packet loss rate factor will be used for simplicity.

- **Service application factor**: Due to QoS constraints, real-time application services, including conversational and streaming, could not assume long delay encountered in the case of loose coupling. Hence tight (and very tight) coupling is more suitable.

The CF is computed as follows:

$$C_f = \text{W\_Delay} * \text{Pref\_Delay} + \text{W\_Load\_Cong} * \text{Pref\_Load\_Cong} + \text{W\_Service\_App} * \text{Pref\_ Service\_App} \quad (6)$$

Where *W_Delay*, *W_Load_Cong* and *W_Service_App* represent the weight assigned to the delay factor, the Load congestion factor and the service application factor respectively while *Pref_ Delay*, *Pref_Load_Cong* and *Pref_Service_App* represent the preference to one of the three coupling levels. The preference functions are assigned 0 (preference to loose coupling) or 0.5 (preference to tight coupling) or 1 (preference to very tight coupling) according to the following criteria:

- ***Pref_ Delay*:** If the average delay exceeds the predefined acceptable delay range upper threshold (D_{-upth}), then *Pref_ Delay* is assigned 0 (privilege to returning to loose coupling), if it is below the delay range down threshold ($D_{-downth}$), it is assigned 1(privilege to switching to very tight coupling). If the average delay remains within the acceptable delay range; $D_{-downth}$ <=average VHO delay<= D_{-upth}, the *Pref_ Delay* is assigned 0.5 (privilege to staying in tight coupling).

- **Pref_Load_Cong:** If the actual cellular network load exceeds a predefined upper threshold ($Load_{-upth}$) the Pref_Load_Cong is assigned 0 (privilege to returning to loose coupling) while If it is lower than the down threshold ($Load_{-downth}$) the Pref_Load_Cong is assigned 1 (privilege to switching to very tight coupling). If it remains within the acceptable load range, the Pref_Load_Cong is assigned 0.5 (privilege to staying in tight coupling).

- **Pref_Service_App:** If the majority of users are currently served with real time applications, the Pref_Service_App is assigned 1 (privilege to switching to very tight coupling) while If the minority of users are served with real time applications, the Pref_Service_App is assigned 0 (privilege to returning to loose coupling). However, if users are served with mixed of real and non real time applications, the Pref_Service_App is assigned 0.5 (privilege to staying in tight coupling).

4.4 Weight Values Re-adjustment and Performance Metrics

The value of weight assigned to each coupling level factor reflects the importance of this parameter in the decision process. This is generally measured by predefined performance metrics that used to re-adjust the weights in order to optimize coupling performance. Instead of equal weights assignment policy; 0.33 is given for each factor in a three factor CF, each factor could be assigned different weights from the possible [0, 1] values starting from 0 with a suitable step size. The re-adjustment of the weight values is carried out at a predefined time period.

To evaluate the performance of the coupling level decision process, the following metrics are defined:

- Packet Loss Rate: defined as the percentage of lost packets over the total number of transmitted packets.
- Dropping probability during VHO: defined as the percentage of dropped handovers over the number of handover trials.
- Vertical Handover Delay: defined as in Equation 5.

5. Adaptive Coupling's Considered Scenario and Simulation Parameters

The considered joint scenario represents the coexistence of the 3GPP (UMTS) macro deployment with an outdoor mobile WIMAX, see Figure 1. The 3GPP cellular layout considered for macro-cell system simulations consists of a hexagonal grid assuming 7 cell sites and three sectors per site with a total of 21 sectors. As far as the WIMAX case is concerned, the cell deployment consists of 9 omni-directional Base Stations placed in circular cells (rectangular cells are drawn in Figure 1 where WIMAX–UMTS are partially overlapped for convenience).

The developed software simulation platform- using an updated IST-FITNESS Simulation Platform (IST-2000-30116, 2003) [14] by C++ language and based on OPNET Modeler [15]- incorporates the appropriate functionalities to examine the proposed adaptive coupling algorithm taking into account networks' coexistence scenario and the simulation parameters listed in the following Tables from 1 to 4:

Table 1: Simulation parameters for the WIMAX-3GPP deployment scenario

Parameter	Value	Comments
Number of 3GPP cells	7	3-sectorized
Number of WIMAX cells	9	
Radius of 3GPP cells	1400m	
Radius of WIMAX cells	1000	
3GPP propagation model	$128.1+37.6\log_{10}d$ (dB)	d in (m)
WIMAX propagation model	L = 46.3 + 33.9log10(f) − 13.82log10(hB)− a(hR) + (44.9 − 6.55log10(hB))log10(D) + C	COST231 models [16],
Log-Normal Shadowing	10 dB	
Mobility for 3GPP	speed density function, range from 0 to 120 Km/h	As can be seen in Table 2
Mobility for WIMAX	speed density function, range from 0 to 100 Km/h	As can be seen in Table 3
antenna pattern (horizontal) for 3-sector cell sites	$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$	$\theta 3$ dB = 70◦ and Am = 20 dB.

Table 2: Speed probability density function for 3GPP(UMTS)

Speed (Km/h)	0	1	3	8	10	20	30	50	70	80	100	120
Probability	3	4	5	7	9	10	11	13	17	10	9	2

Table 3: Speed probability density function for WIMAX

Speed (Km/h)	0	1	3	8	10	20	30	50	70	80	90	100
Probability	6	8	5	7	9	8	11	13	12	10	7	4

Table 4: Simulation parameters assumed for adaptive coupling algorithm

Parameter	Value	Comments
T_{-l}	3 s	
T_{-vt}	3 s	
T_{-t}	3 s	
D_{-upth}	20msec	
$D_{-downth}$	5msec	
$Load_{-upth}$	*Variable according to SNR*	*Based on Packet loss rate*
$Load_{-downth}$	*Variable according to SNR*	*Based on Packet loss rate*

6. Numerical result

Following are the numerical results for the simulated adaptive coupling algorithm:

6.1 Packet loss rate (due to load congestion):

Figure 3 shows the packet loss rate due to load congestion-for WIMAX downlink- when the adaptive coupling algorithm is employed. The packet loss rate is evaluated as a function of time for 60 seconds as real time simulation for three SNR values; 6, 18 and 30 dBs. It is easily shown that the curves jump from loose coupling's packet loss rate levels to tight and very tight levels and vice versa according to the adaptive mechanism where loss rates is inversely proportional to SNR.

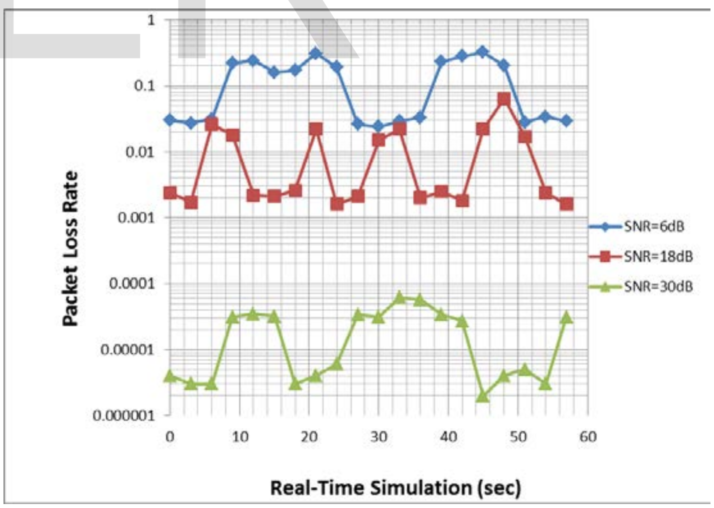

Figure 3: Adaptive Coupling- packet loss rate due to load congestion for WIMAX downlink

The average packet loss rates are calculated for various values of SNRs and redrawn in Figure 4 for all types of coupling levels; loose, adaptive, tight and very tight. Figure 4 shows the significant gain of decreasing packet loss rates, achieved by adaptive coupling algorithm as compared to tight and very tight coupling. Packet loss rates is reduced about 34% as compared to tight coupling and at least 50% as compared to very tight at low SNRs. At high SNRs the gains are more than 40% as compared to tight and more than 70% as compared to very tight. However, and as expected adaptive coupling is inferior to loose coupling in terms of packet loss rate due to load congestion as indicated by Figure B. So what is the benefit of the proposed adaptive algorithm? The answer is clarified in terms of reducing VHO delay and dropping probability of loose coupling in the next section.

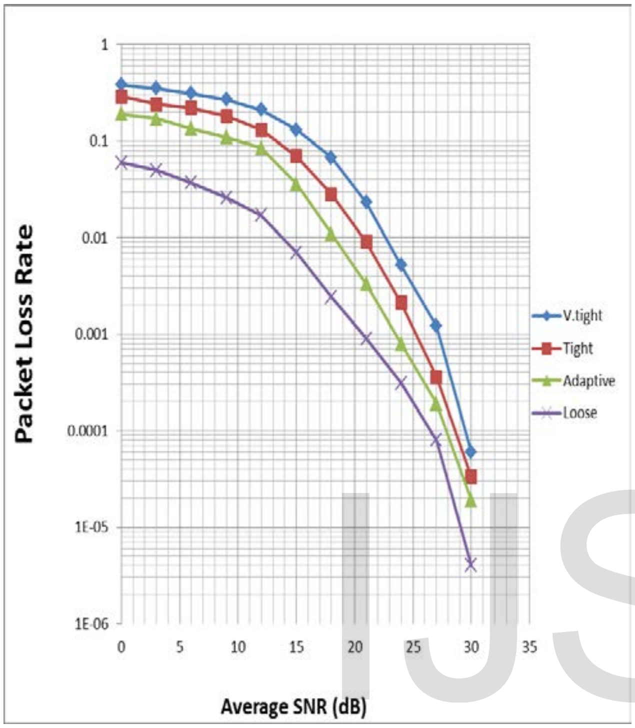

Figure 4: Packet Loss Rate due to load congestion for WIMAX downlink:

6.2 VHO Delay and Dropping probability

Figure 5 shows the average Vertical Handover Delay for all coupling levels. It is noticed that the adaptive coupling algorithm decreases the delay of loose coupling significantly; about 33%. However it is still more than the delay in both tight and very tight coupling as expected. Regarding the dropping probability during VHO, it can be seen from Figure 6 that the adaptive coupling algorithm decreases the dropping probability of loose coupling of about 43% while it is, again, more than the dropping probability in both tight and very tight coupling as expected.

Hence, the adaptive coupling algorithm mitigates the problem of increased packet loss rate due to load congestion for the cases of tight and very tight coupling and in the same time alleviates the problem of vertical handover delay and dropping probability in the case of loose coupling.

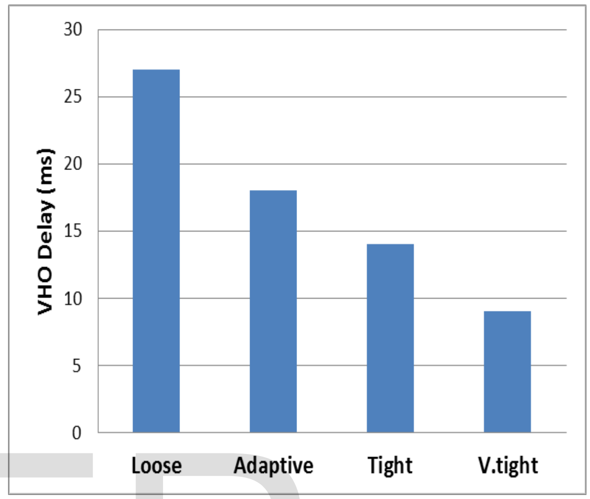

Figure 5: Average VHO Delay (from WIMAX to 3GPP) during 60sec simulation time.

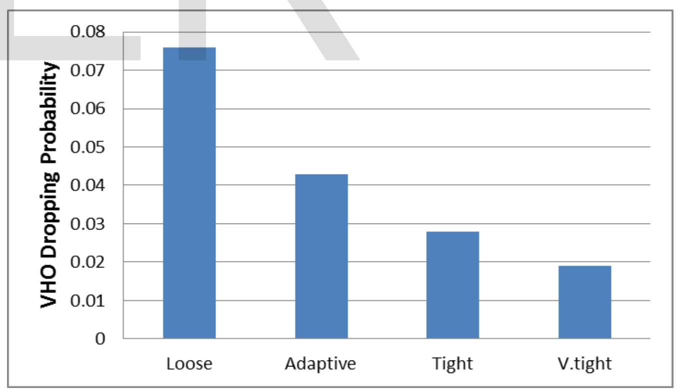

Figure 6: Dropping probability during VHO.

7. CONCLUSION

Numerical results show that the proposed adaptive coupling algorithm mitigates the problem of increased packet loss rate- due to load congestion- for the cases of tight and very tight coupling. Packet loss rates is reduced about 34% as compared to tight coupling and at least 50% as compared to very tight at low SNRs. At high SNRs the gains are more than 40% as compared to tight coupling and more than 70% as compared to very tight. Besides, adaptive coupling alleviates the problems of long delay and high dropping probability during vertical handover in the case of loose coupling. It decreases the delay of about 33% and the dropping probability of about 43%

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