Module A

Project

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May 10, 2025

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Chapter 1

Literature Review

1.1 Heterogeneous Wireless Networks

Heterogeneous Wireless Networks (HWNs) combine different Radio Access Technologies (RATs) that coexist within the same geographical area, as depicted in Figure 1.1. These RATs interwork with one another to ensure that users always experience the best possible connection (ABC) [1]. These RATs include cellular networks (e.g., 3G, 4G, 5G) as well as non-cellular networks (e.g., Wi-Fi). They may provide the same or different network services, catering to users with diverse Quality of Service (QoS) requirements [2].

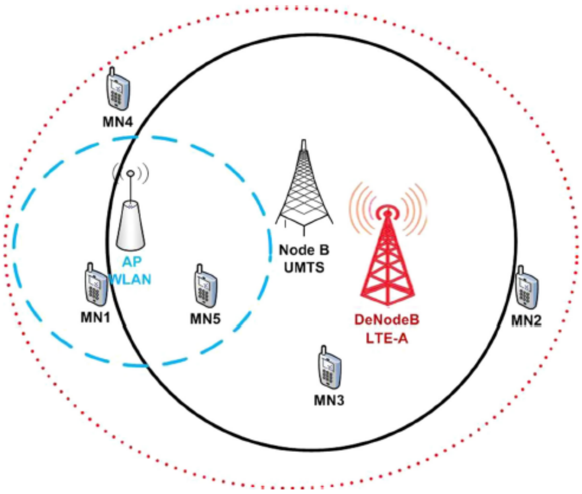

Figure 1.1: Example of Heterogeneous Wireless Networks

[2]

A key objective of HWNs is efficient radio resource utilization, achieved through Common Radio Resource Management (CRRM). CRMM enables coordinated resource allocation across different RATs, improving network efficiency, load balancing, and user connectivity [1].

The remainder of this literature review is structured as follows. Section 1.2 discusses the handover process in HWNs, including different types of handovers and their role in maintaining seamless connectivity. Section 1.3 explores Multi-Criteria Decision Making (MCDM) techniques, which are used to evaluate and select the most suitable network during handovers. Section 1.4 focuses on the Weighted Aggregated Sum Product Assessment (WASPAS) method, a hybrid MCDM approach that integrates WSM and WPM for improved decision-making in HWNs. Finally, Section 1.5 summarizes the key insights from this review.

1.2 Handover

Handover is the process of transferring a mobile user's service from one base station (BS) or access point (AP) to another, either within the same or across different technologies, ensuring seamless connectivity as users move between coverage zones [3].

There are two main types of handover: Horizontal Handover (HHO), which occurs within homogeneous networks where the technology remains consistent, and Vertical Handover (VHO), which is used in heterogeneous networks when the mobile node (MN) switches between different access technologies [3].

Handovers can be further categorized as either hard or soft, depending on the mobile node's (MN) connection to the base station (BS). A hard handover, also known as a break-before-make handover, takes place when the MN is connected to only one point of attachment (PoA) at a time during the handover process. In contrast, a soft handover, or make-before-break handover, occurs when the MN establishes a connection to the target PoA before disconnecting from the current PoA during the handover process in HWNs [4].

Chandrasekar et al. outline four key phases of handover: Handover Initiation, System Discovery, Handover Decision, and Handover Execution [3]. Obayiuwana et al. present a simplified model, as shown in Figure 1.2, that combines the first two phases into a single phase called Handover Information Gathering. This phase acts as a repository for newly available networks, gathering and evaluating the information needed to determine whether a handover should occur [2].

Figure 1.2: Simplified model of the Handover
[2]

The Handover Decision-Making phase plays a central role in determining whether the MN should stay on its current network or switch to a better one. This decision is made by evaluating multiple network alternatives using an MCDM algorithm, which considers necessary criteria for handover decision-making. The result is passed to the Handover Execution phase to carry out the transition. [2]

In HWNs, relying on single indicators is insufficient for triggering vertical handovers, as these networks involve diverse technologies with different performance standards. Therefore, HWNs require multiple decision indicators to effectively assess and trigger vertical handovers [2].

Handover decisions depend on multiple criteria, such as signal strength, bandwidth, and delay-MCDM techniques are essential for selecting the most suitable network. Section 1.3 introduces various MCDM techniques used in HWNs.

1.3 Multi-Criteria Decision Making (MCDM) Techniques

MCDM is a technique used to find the best possible choice when faced with decisions involving multiple factors or criteria. An MCDM problem can be mathematically be represented as a decision matrix, $D = (M \times N)$, where rows M represent alternatives and N represent criteria [2].

Commonly used MCDM techniques include Simple Additive Weighting (SAW), Multiplicative Exponent Weighting (MEW), Grey Relational Analysis (GRA), Analytic Hierarchy Process (AHP), ELimination Et Choix Traduisant la REalité (ELECTRE), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Distance to Ideal Alternatives (DIA), MULTIMOORA, VIKOR, and PROMETHEE [2].

Among these techniques, WASPAS offers a hybrid approach by combining WSM and WPM for improved decision-making. The next section, Section 1.4, provides a detailed explanation of the WASPAS technique.

1.4 Weighted Aggregated Sum Product Assessment (WASPAS)

WASPAS is a hybrid MCDM technique that integrates WSM and WPM, leveraging on the strengths of both techniques.

1.4.1 Weighted Sum Model (WSM)

WSM, also known as Simple Additive Weighing (SAW), is an MCDM technique that utilizes a weighted average approach to evaluate and rank alternatives based on multiple criteria. WSM determines the ranking of each alternative by multiplying the normalized criteria' values by the normalized weights of importance assigned by decision-makers. The ranking of alternatives is based on the total weighted sum, where the alternative with the highest weighted product performance score is considered the best. [2]

This technique follows the following key steps: [2][5]:

1. Construct a decision matrix D = (M× N) consisting of M alternatives and N criteria where benefit criteria contribute positively to performance.

2. Calculate the normalized matrix, where each criterion is normalized based on maximum (for benefit criteria) or minimum values (for cost criteria).

   - For benefit criteria:
$$r_{i,j} = \frac{x_{i,j}}{x_j^{\max}} \tag{1.1}$$

   - For cost criteria:
$$r_{i,j} = \frac{x_j^{\min}}{x_{i,j}} \tag{1.2}$$

   where $x_j^{\max}$ and $x_j^{\min}$ are the maximum and minimum values of the jth criterion, respectively.

3. Calculate normalized weight vector using

$$\overline{W_j} = \frac{w_j}{\sum_{i=1}^{X} w_i} \tag{1.3}$$

4. Compute the WSM rank index by multiplying the normalized criteria values with corresponding normalized criterion weights.

$$Q_i^{(1)} = \sum_{j=1}^{n} \overline{w_j} \cdot r_{i,j} \tag{1.4}$$

5. Select the RAT with the highest WSM ranking index as the best alternative for the call.

1.4.2 Weighted Product Model (WPM)

WPM, also known as Multiplicative Exponent Weighting (MEW), is an MCDM technique used for ranking alternatives based on the weighted product of criteria [2][4]. WPW is mathematically similar to WSM but differs in its operations—while WSM relies on addition and multiplication, WPM uses multiplication and exponentiation [2][4]. This fundamental distinction gives MEW a nonlinear transformation characteristic, unlike the Weighted Sum Model (WSM), which remains linear [4].
WPM follows similar steps in determining the highest ranked network alternative, but the weights of the jth criteria are positive for the benefit criteria and negative for the cost criteria. The ranking index is computed as follows [2][5]:

$$Q_i^{(2)} = \prod_{j=1}^{n} r_{i,j}^{w_j} \tag{1.5}$$

Despite its advantages, MEW can exhibit ranking anomalies, particularly when lower-ranked alternatives are added or removed from the decision set. This occurs because MEW's exponential operation penalizes alternatives with lower criteria scores, which can significantly impact rankings [4].

WASPAS combines WSM and WPM as follows:

$$Q_i = \lambda Q_i^{(1)} + (1 - \lambda) Q_i^{(2)} \tag{1.6}$$

where $Q_i^{(1)}$ and $Q_i^{(2)}$ are ranking indices computed using WSM and WPM, respectively [5].
λ is an arbitrary value between 0 and 1 used by decision-makers to balance the contribution of WSM and WPM. When $\lambda = 0$, WASPAS is transformed to WPM, and when $\lambda = 1$, WASPAS is transformed to WSM [5].

1.5 Conclusion

In conclusion, this literature review has outlined key concepts related to Heterogeneous Wireless Networks, handover processes, and Multi-Criteria Decision Making techniques. The review highlighted the importance of efficient resource management in HWNs and the role of handovers in maintaining seamless connectivity. Furthermore, MCDM techniques, particularly WASPAS, which offers a balanced and efficient approach leveraging on the strengths of WSM and WPM, were discussed as useful tools for selecting the most suitable network alternative.

Chapter 2

RATs

Available RATs

Table 2.1 lists the available RATs

Available RATs
3G (UMTS)
WLAN (802.11n)
4G (LTE)

Table 2.1: Available Radio Access Technologies

Call(s) supported in each RAT

Each RAT supports different calls, as outlined in Table 2.2.

RAT	**Supported calls**
3G (UMTS)	Voice, Video Streaming, File Download
WLAN (802.11n)	VoIP, Video Streaming, File Download
4G (LTE)	Voice, Video Streaming, File Download

Table 2.2: Supported Services in Each RAT

RAT Selection Criteria

The selection of an appropriate RAT depends on several criteria, categorized as cost and benefit criteria:

- **Cost per Byte (%)** – Cost Criterion
- **Available Bandwidth (Mbps)** – Benefit Criterion
- **Delay (ms)** – Cost Criterion

Decision Matrix

The decision matrix values are adapted from [6]. According to Lahby et al. Cost per Byte is 'a measure of the operator's transport cost for a particular access network' [7].

	Cost per Byte (%)	Available Bandwidth (Mbps)	Delay (ms)
3G (UMTS)	60	2	50
WLAN (802.11n)	15	15	140
4G (LTE)	50	60	100

Table 2.3: Decision Matrix

User Weights

Users can assign a weight between 1 and 10 to each selection criterion, where:

- 1 represents the lowest priority
- 10 represents the highest priority

The set of possible weight values is:

$$W = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$$

Chapter 3

HWN Diagram

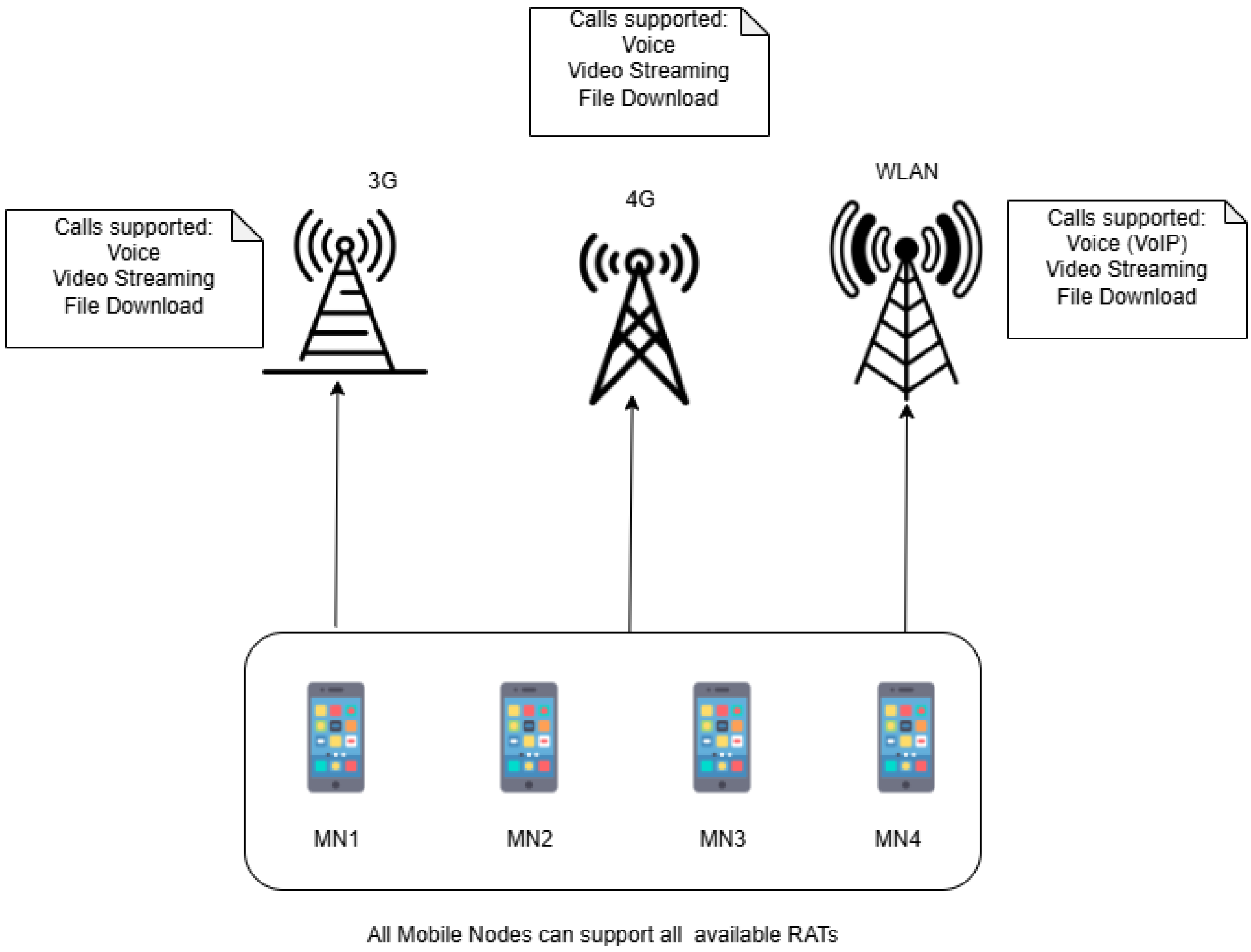

Figure 3.1: Illustration of Heterogeneous Wireless Network

Chapter 4

Flowchart

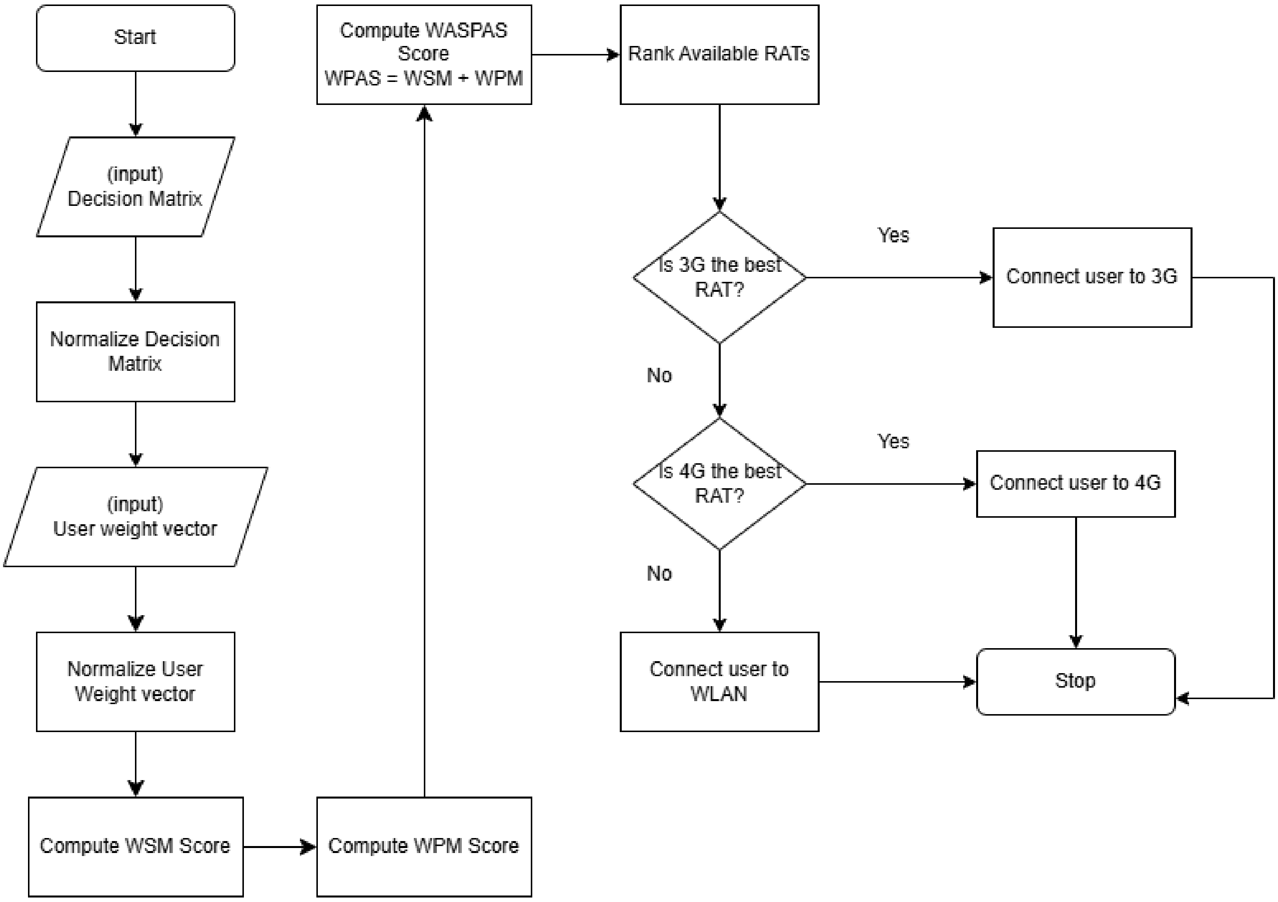

Figure 4.1: Flowchart

Chapter 5

Normalization

Decision Matrix (From Task 2)

The decision matrix values are adapted from [6].

	Cost per Byte (%)	Available Bandwidth (Mbps)	Delay (ms)
3G (UMTS)	60	2	50
WLAN (802.11n)	15	15	140
4G (LTE)	50	60	100

Table 5.1: Decision Matrix

Normalization

Equations for normalizing the decision matrix:

- For a benefit criterion (higher is better):

$$r_{i,j} = \frac{x_{i,j}}{x_j^{\max}} \tag{5.1}$$

- For a cost criterion (lower is better):

$$r_{i,j} = \frac{x_j^{\min}}{x_{i,j}} \tag{5.2}$$

- where $x_j^{\max}$ and $x_j^{\min}$ are the maximum and minimum values of the jth criterion, respectively

Calculations:

	Cost per Byte (%)	Available Bandwidth (Mbps)	Delay (ms)
3G (UMTS)	$\frac{15}{60}$	$\frac{2}{60}$	$\frac{50}{50}$
WLAN (802.11n)	$\frac{15}{15}$	$\frac{15}{60}$	$\frac{50}{140}$
4G (LTE)	$\frac{15}{50}$	$\frac{60}{60}$	$\frac{50}{100}$

Table 5.2: Normalized Decision Matrix (Calculations)

Normalized Decision Matrix

	Cost per Byte (%)	Available Bandwidth (Mbps)	Delay (ms)
3G (UMTS)	0.25	0.0333	1
WLAN (802.11n)	1	0.25	0.3571
4G (LTE)	0.3	1	0.5

Table 5.3: Normalized Decision Matrix (Computed)

Chapter 6

Equations for Ranking Available RATs

The WASPAS score Q_i for the i-th RAT is computed as:

$$Q_i = \lambda Q_i^{(1)} + (1 - \lambda) Q_i^{(2)} \tag{6.1}$$

where:

- $Q_i^{(1)}$ is the score obtained using the Weighted Sum Model (WSM):

$$Q_i^{(1)} = \sum_{j=1}^{n} \overline{w_j} \cdot r_{i,j} \tag{6.2}$$

- $Q_i^{(2)}$ is the score obtained using the Weighted Product Model (WPM):

$$Q_i^{(2)} = \prod_{j=1}^{n} r_{i,j}^{\overline{w_j}} \tag{6.3}$$

- λ is a weighting factor balancing the contributions of WSM and WPM.
- $\overline{w_j}$ is the normalized weight assigned to the j-th criterion.
- $r_{i,j}$ is the normalized value of the j-th criterion for the i-th RAT.

The decision matrix values are normalized based on the type of criterion:

- For benefit criteria (higher is better):

$$r_{i,j} = \frac{x_{i,j}}{x_j^{\max}} \tag{6.4}$$

- For cost criteria (lower is better):

$$r_{i,j} = \frac{x_j^{\min}}{x_{i,j}} \tag{6.5}$$

where:

- $x_{i,j}$ represents the raw value of the j-th criterion for the i-th RAT.
- $x_j^{\max}$ and $x_j^{\min}$ denote the maximum and minimum values of the j-th criterion across all RATs, respectively.

Illustration

Consider a scenario where a user needs to choose among three RATs: 3G, 4G, and WLAN. The selection is based on the following criteria:

- **Cost per Byte (%)** – Cost Criterion
- **Available Bandwidth (Mbps)** – Benefit Criterion
- **Delay (ms)** – Cost Criterion

Decision Matrix (From Task 2)

The decision matrix values are adapted from [6].

	Cost per Byte (%)	Available Bandwidth (Mbps)	Delay (ms)
3G (UMTS)	60	2	50
WLAN (802.11n)	15	15	140
4G (LTE)	50	60	100

Table 6.1: Decision Matrix

Normalized Decision Matrix (From Task 5)

Normalization uses equations (6.4) and (6.5):

	Cost per Byte (%)	Available Bandwidth (Mbps)	Delay (ms)
3G (UMTS)	0.25	0.0333	1
WLAN (802.11n)	1	0.25	0.3571
4G (LTE)	0.3	1	0.5

Table 6.2: Normalized Decision Matrix (Computed)

User Weights

The user assigns the following weights to each criterion:

$$W = \{5, 9, 6\}$$

Normalized as:

$$\overline{w_1} = \frac{5}{5+9+6} = 0.25, \quad \overline{w_2} = \frac{9}{5+9+6} = 0.45, \quad \overline{w_3} = \frac{6}{5+9+6} = 0.30$$

Thus, the normalized weight vector is:

$$\overline{W} = \{0.25, 0.45, 0.30\}$$

Computation of WSM Scores

Using equation (6.2), the WSM score for each RAT is computed as follows:
For 3G (UMTS):

$$Q_1^{(1)} = (0.25 \times 0.25) + (0.45 \times 0.0333) + (0.30 \times 1) = 0.0625 + 0.014985 + 0.30 = \boxed{0.377485}$$

For WLAN (802.11n):

$$Q_2^{(1)} = (0.25 \times 1) + (0.45 \times 0.25) + (0.30 \times 0.3571) = 0.25 + 0.1125 + 0.10713 = \boxed{0.46963}$$

For 4G (LTE):

$$Q_3^{(1)} = (0.25 \times 0.3) + (0.45 \times 1) + (0.30 \times 0.5) = 0.075 + 0.45 + 0.15 = \boxed{0.675}$$

Computation of WPM Scores

Using equation (6.3), the WPM score for each RAT is computed as follows:
For 3G (UMTS):

$$Q_1^{(2)} = (0.25)^{0.25} \times (0.0333)^{0.45} \times (1)^{0.30} = 0.7071 \times 0.2223 \times 1 = \boxed{0.1572}$$

For WLAN (802.11n):

$$Q_2^{(2)} = (1)^{0.25} \times (0.25)^{0.45} \times (0.3571)^{0.30} = 1 \times 0.5946 \times 0.7282 = \boxed{0.4331}$$

For 4G (LTE):

$$Q_3^{(2)} = (0.3)^{0.25} \times (1)^{0.45} \times (0.5)^{0.30} = 0.7827 \times 1 \times 0.8123 = \boxed{0.6356}$$

Computation of WASPAS Scores

Using equation (6.1) and setting $\lambda = 0.5$ (i.e., equal contribution of WSM and WPM), the WASPAS score for each RAT is computed as follows:
For 3G (UMTS):

$$Q_1 = 0.5 \times 0.377485 + 0.5 \times 0.1572 = 0.1887425 + 0.0786 = \boxed{0.2673}$$

For WLAN (802.11n):

$$Q_2 = 0.5 \times 0.46963 + 0.5 \times 0.4331 = 0.234815 + 0.21655 = \boxed{0.4514}$$

For 4G (LTE):

$$Q_3 = 0.5 \times 0.675 + 0.5 \times 0.6356 = 0.3375 + 0.3178 = \boxed{0.6553}$$

Selection Decision

The RAT with the highest WASPAS score is **4G (LTE)** ($Q_3 = 0.6553$), and is therefore selected for new or vertical handoff calls.

Chapter 7

Effect of the Users' Weight Assigned to the Cost on RAT-Selection Decisions

Experimental Cases

To evaluate the effect of the users' weights assigned to Cost, four distinct weight cases were examined:

- Low priority range: $w_1 \in [1, 3]$
- Moderate priority range: $w_1 \in [4, 6]$
- High priority range: $w_1 \in [9, 10]$
- Full range (no priority): $w_1 \in [1, 10]$

Experimental Procedure

For each case, random user weights were generated for the three selection criteria, and the WASPAS scores for each RAT were computed based on these varying weight assignments. The RAT with the highest score was selected in each trial, and the selection frequency of the selected RAT was updated after each run.

The experiment was conducted over 1000 trials (250 trials for each case), and selection frequencies for each RAT under different weight levels for Price were recorded. Figure 7.1 illustrates the selection frequencies for 3G (UMTS), 4G (LTE), and WLAN (802.11n), demonstrating how RAT selection varies with changes in the weight assigned to Price while keeping the weights for other criteria at the full range

Results

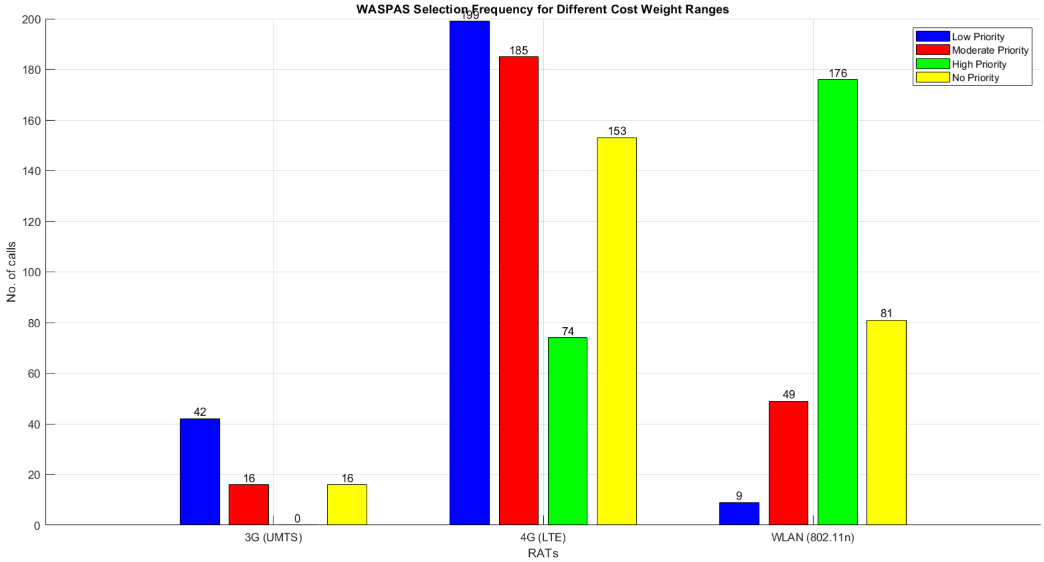

Figure 7.1: WASPAS Selection Frequency for Different Cost Weight Values.

Discussion of Results

When cost is assigned a low priority, 4G dominated, receiving 200 calls, followed by 3G with 42 calls and WLAN with 9 calls.

When the priority shifts to a moderate range, 4G remains the preferred choice with 185 calls followed by WLAN, increasing from 9 calls in the low priority range to 49. This increase reflects users' growing sensitivity to cost, as WLAN offers the lowest cost per byte (15%). 3G drops to 16 calls. This drop can be attributed to its poor cost-performance - combining the highest cost per byte (60%) with the lowest bandwidth (2Mbps), making it a less attractive choice.

When cost is highly prioritized, WLAN overwhelmingly dominates with 176 calls due to its lowest cost per byte (15%). In contrast, 4G drops to 74 calls, and 3G receives none.

Across the full range, 4G leads with 153 calls, followed by WLAN with 81 calls and 3G with 16 calls, illustrating the tradeoffs between bandwidth, cost and delay.

WLAN's dramatic increase with higher cost priority confirms the impact of its lowest cost advantage (15%). On the other hand, 4G's superior bandwidth (60 Mbps) makes it dominant when cost is less critical, despite its moderate 50% cost. 3G's combination of highest cost (60%) and lowest bandwidth (2 Mbps) explains its poor overall selection rate, even though it offers the lowest delay (50ms).

Chapter 8

Effect of the Users' Weight Assigned to the Available Bandwidth on RAT-Selection Decisions

This chapter evaluates the effect of the users' weight assigned to Available Bandwidth (in Mbps) on RAT-selection decisions for new or vertical handoff calls in a heterogeneous wireless network. WASPAS was used to compute RAT-selection scores, with varying importance levels assigned to Available Bandwidth while keeping the weights for the other criteria at their full range.

Experimental Cases

To evaluate the effect of the users' weights assigned to the available data rate, four distinct cases were examined:

- Low priority range: $w_2 \in [1, 3]$
- Moderate priority range: $w_2 \in [4, 6]$
- High priority range: $w_2 \in [9, 10]$
- Full range (no priority): $w_2 \in [1, 10]$

Experimental Procedure

For each case, random user weights were generated for the three selection criteria, and the WASPAS scores for each RAT were computed based on these varying weight assignments. The RAT with the highest score was selected in each trial, and the selection frequency of the selected RAT was updated after each run.

The experiment was conducted over 1000 trials (250 trials for each case), and selection frequencies for each RAT under different weight levels for available bandwidth were recorded. Figure 8.1 illustrates the selection frequencies for 3G (UMTS), 4G (LTE), and WLAN (802.11n), demonstrating how RAT selection varies with changes in the weight assigned to available bandwidth.

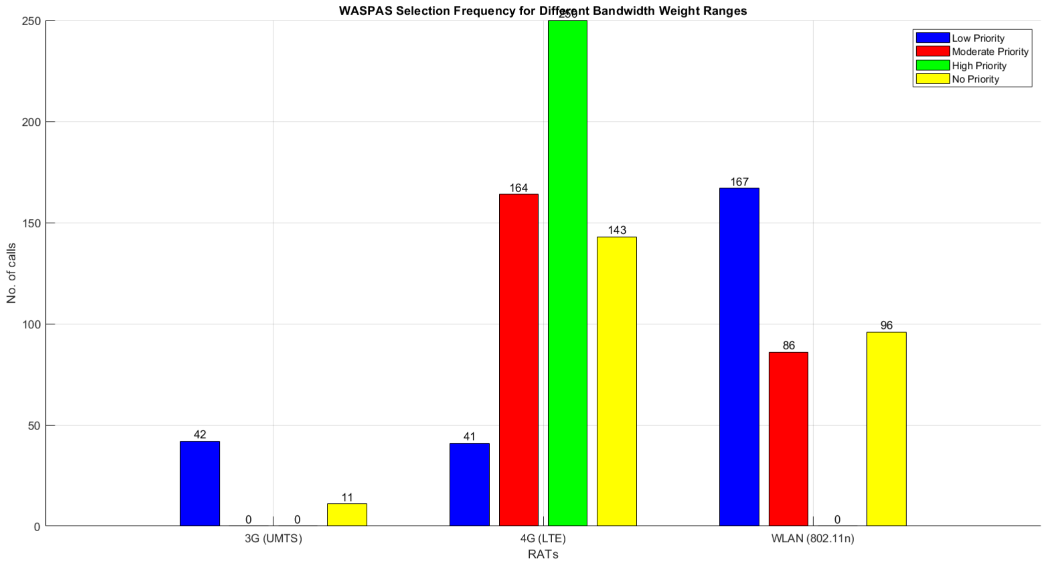

Figure 8.1: WASPAS Selection Frequency for Different Bandwidth Weight Values.

Results

Discussion of Results

When a low priority was assigned to bandwidth,WLAN dominates with 156 calls, followed by 3G with 50 calls, and 4G with 44 calls.

As the priority shifted to the moderate range, preference shifts significantly toward 4G, receiving 152 calls, while WLAN decreases to 98 calls. 3G receives no selections, highlighting its inadequate 2 Mbps bandwidth. This transition reflects a growing user preference for the higher data rates.

At the high priority range, 4G becomes overwhelmingly dominant (250 calls) due to its superior bandwidth (60 Mbps). WLAN receives no selections despite its cost advantage, and 3G remains at 0 calls, reflecting its severely limited bandwidth.

Across the full weight range, a moore balanced distribution emerges with 4G leading (152 calls) followed by WLAN (81) and minimal 3G (17), suggesting that when all factors are equally weighted, 4G's combination of high bandwidth and moderate cost provides the most balanced performance.

4G's dramatic increase with higher bandwidth priority confirms the impact of its superior bandwidth advantage (60 Mbps). WLAN's stronger performance when bandwidth is less critical reflects its excellent cost efficiency (15%) despite moderate bandwidth (15 Mbps). 3G's poor overall selection rate directly correlates with its severely limited bandwidth (2 Mbps), making it viable only when bandwidth is minimally prioritized.

Chapter 9

Effect of the Users' Weight Assigned to the Delay on RAT-Selection Decisions

This chapter evaluates the effect of the users' weight assigned to Delay (in milliseconds) on RAT-selection decisions for new or vertical handoff calls in a heterogeneous wireless network. WASPAS was used to compute RAT-selection scores, with varying importance levels assigned to Delay while keeping the weights for the other criteria at their full range.

Cases

To evaluate the effect of the users' weights assigned to delay, four distinct cases were examined:

- Low priority range: $w_3 \in [1, 3]$
- Moderate priority range: $w_3 \in [4, 6]$
- High priority range: $w_3 \in [9, 10]$
- Full range (no priority): $w_3 \in [1, 10]$

Experimental Procedure

For each case, random user weights were generated for the three selection criteria, and the WASPAS scores for each RAT were computed based on these varying weight assignments. The RAT with the highest score was selected in each trial, and the selection frequency of the selected RAT was updated after each run.

The experiment was conducted over 1000 trials (250 trials for each case), and selection frequencies for each RAT under different weight levels for delay were recorded. Figure 9.1 illustrates the selection frequencies for 3G, 4G, and WLAN, demonstrating how RAT selection varies with changes in the weight assigned to delay.

Results

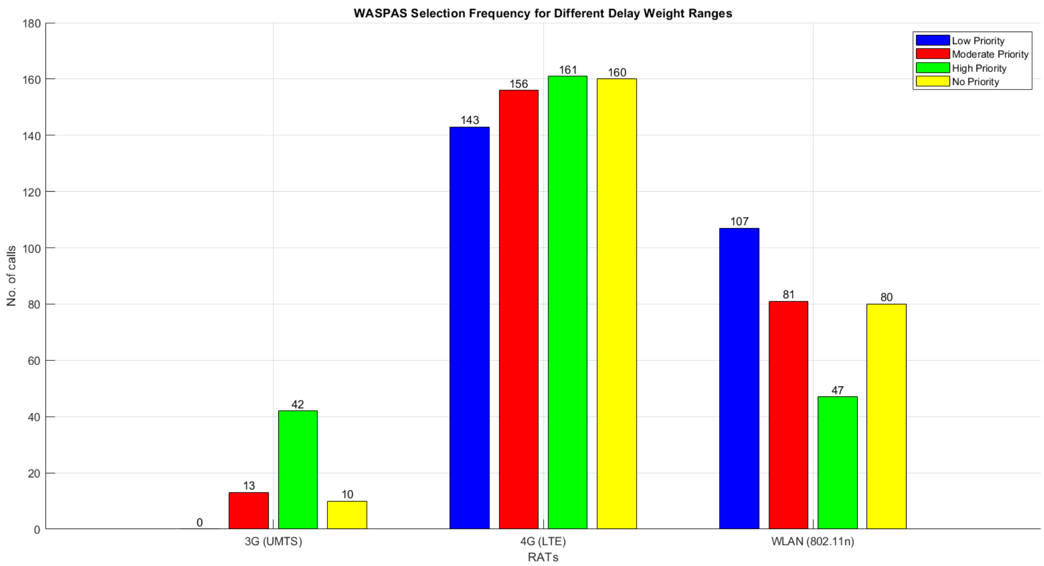

Figure 9.1: WASPAS Selection Frequency for Different Delay Weight Values.

Discussion of Results

When delay is assigned a low priority, 4G leads with 143 calls, followed by WLAN with 107 calls, while 3G receives none. This pattern suggests that when delay is less important, the combination of 4G's superior bandwidth (60 Mbps) and WLAN's lower cost (15%) are more influential factors.

As the priority shifts to a moderate range, 4G maintains dominance with 156 calls, while WLAN decreases to 81 calls. 3G shows an increase from no selection in the low priority range to 13 calls. The increase in 3G (UMTS) selection frequency compared to the low priority case indicates the influence of its low delay advantage.

When delay is highly prioritized, 4G remains dominant (161 calls), but 3G increases significantly to 42 calls due to its superior delay performance (50ms). WLAN drops to 47 calls, reflecting its disadvantage with the highest delay (140ms).

Across the full weight range, 4G maintains the highest selection frequency with 160 calls, followed by WLAN with 80 calls, and 3G with 10 calls. This overall distribution suggests that when considering all possible priority levels for delay, 4G remains the most frequently selected RAT.

Overall, 3G's increasing selection with higher delay priority directly reflects its superior delay advantage (50ms), though it never becomes dominant due to its other significant disadvantages (60%)cost, 2 Mbps bandwidth). 4G maintains strong performance across all delay priority levels due to its good balance of moderate delay (100ms), highest bandwidth (60 Mbps), and acceptable cost (50%). WLAN's declining performance as delay priority increases corresponds with its disadvantage in this category (140ms), despite having the lowest cost (15%). Notably, even at high delay priority, WLAN still maintains a moderate selection frequency (47 calls), suggesting that its cost advantage partially compensates for its delay disadvantage.

Chapter 10

Effect of the Proportion of the WSM and the WPM on RAT-Selection Decisions.

This chapter evaluates the effect of the weighting factor (λ) on RAT-selection decisions for new or vertical handoff calls in a heterogeneous wireless network. WASPAS combines the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) using λ, which determines the proportion of each technique.

Cases

To evaluate the effect of λ, five distinct cases were considered:

- $\lambda = 0$ (WPM only)
- $\lambda = 0.25$ (25% WSM, 75% WPM)
- $\lambda = 0.5$ (Balanced WSM and WPM)
- $\lambda = 0.75$ (75% WSM, 25% WPM)
- $\lambda = 1$ (WSM only)

Experimental Procedure

For each case, random user weights were generated for Price, Available Data Rate, and Delay. The WASPAS scores were computed for each RAT using different values of λ, and the RAT with the highest score was selected in each trial.

The experiment was conducted over 1000 trials (200 trials for each case), and the selection frequency of each RAT was recorded. Figure 10.1 presents the results, showing how the choice of λ influences RAT selection.

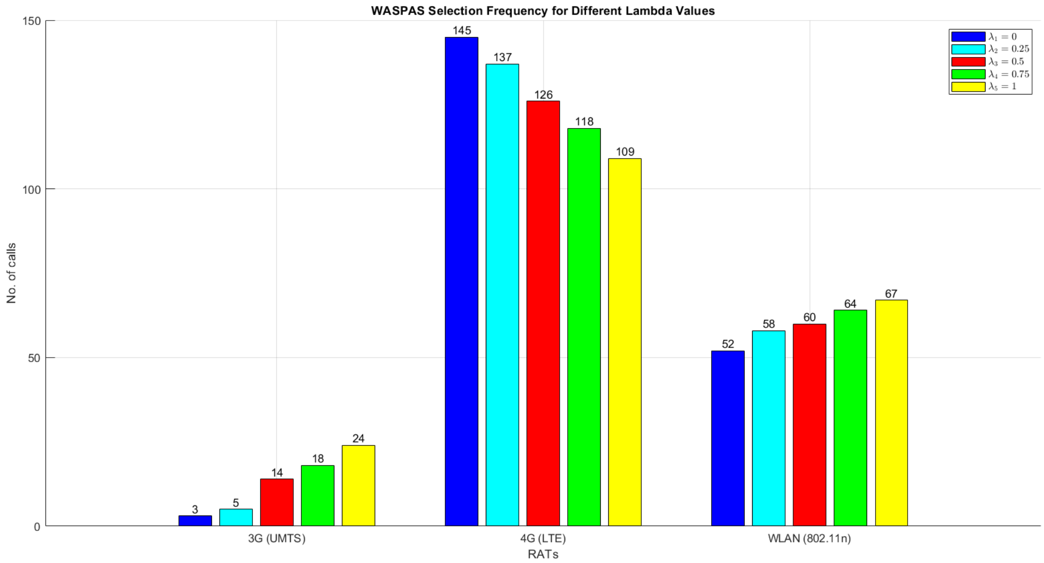

Figure 10.1: WASPAS Selection Frequency for Different Lambda Values.

Results

Discussion of Results

Figure 10.1 illustrates how RAT selection patterns shift as λ increases from 0 (pure Weighted Sum Model) to 1 (pure Weighted Product Model).

At $\lambda = 0$, 4G dominates with 145 calls, followed by WLAN with 52 calls, while 3G receives only 3 calls. This indicates that under a pure WSM approach, 4G (LTE) emerges as the preferred network option.

As λ increases to 0.25, shifting slightly toward WPM, 4G remains dominant but decreases to 137 calls, while 3G receives 5 calls and WLAN increases to 58 calls. This shows that even a small contribution from the WPM component begins to shift preferences.

At $\lambda = 0.5$, where WSM and WPM are equally weighted, 4G remains dominant but shows a decline to 126 calls, followed by WLAN with 60 calls and 3G with 14 calls received.

With $\lambda = 0.75$, moving predominantly toward WPM, 4G further declines to 118 calls, while WLAN increases to 64 calls and 3G to 18 calls.

Finally, at $\lambda = 1$ (pure WPM), 4G remains dominant with 109 calls, but the gap narrows significantly with WLAN at 67 calls, and 3G at 24 calls, illustrating a more balanced distribution across all λ values.

As λ increases, shifting from WSM to WPM, 4G's dominance steadily decreases while both WLAN and 3G gain selection frequency. This shows that WPM tends to penalize 4G's cost disadvantage more than WSM. Notably, 3G's significant increase in selection frequency (from 3 to 24 calls) as λ moves from 0 to 1, indicating that its low delay advantage (50ms) receives more weight under multiplicative methodology despite its high cost (60%) and low bandwidth (2 Mbps).

Chapter 11

Summary of the Key Findings of the Project

The project evaluated the effect of user-assigned weights on four key factors (Cost, **Available Bandwidth**, **Delay**, and the **WASPAS weighting factor,** λ) on Radio Access Technology (RAT) selection decisions in heterogeneous wireless networks. The key findings are summarized as follows:

When Cost was assigned a low priority, 4G was the most preferred RAT with 200 calls. As the priority for Cost increased to a moderate level, 4G remained dominant with 185 calls, while WLAN's selection frequency increased to 49, reflecting users' growing sensitivity to cost. When Cost was highly prioritized, WLAN overwhelmingly dominated with 176 calls due to its lowest cost per byte, while 3 G received none because of its poor cost-performance. Across the full range, when no priorities were assigned, 4G remained the preferred option with 153 calls.

WLAN's increased selection frequency under high cost priority highlights its low-cost advantage. 4G remained dominant when cost was less critical due to its high bandwidth (60 Mbps) and moderate cost (50%). 3G's poor performance can be attributed to its high cost and limited bandwidth, despite offering the best delay (50 ms).

When bandwidth was assigned a low priority, WLAN was preferred with 156 calls, followed by 3G (50) and 4G (44). This indicates that when bandwidth is not critical, WLAN's cost-effectiveness and 3G's low delay become more influential. As bandwidth priority increased to moderate, preference shifted significantly to 4G with 152 calls. WLAN declined to 98 calls, and 3G was not selected, indicating its bandwidth limitations (2 Mbps). At high bandwidth priority, 4G overwhelmingly dominated with 250 calls, while WLAN and 3G received none, highlighting a strong preference for high bandwidth. Across all priority levels, 4G led with 152 calls, followed by WLAN (81) and 3G (17).

When delay was assigned a low priority, 4G led with 143 calls, followed by WLAN (107), while 3G received none. This reflects the greater importance of bandwidth and cost when delay is less critical. At moderate delay priority, 4G maintained dominance with 156 calls. WLAN dropped to 81, while 3G increased to 13 calls, indicating the influence of its superior delay performance. When delay was highly prioritized, 4G remained in the lead with 161 calls. 3G increased to 42 calls due to its low delay (50 ms), while WLAN dropped to 47 calls due to its delay disadvantage (140 ms). Across all delay weight levels, 4G had the highest selection frequency (160), followed by WLAN (80) and 3G (10). 3G saw improved selection only under high delay priority, but its overall limitations in cost and bandwidth prevented it from becoming a dominant choice. WLAN's decline in performance at high delay weights confirmed the influence of its high latency, despite its low cost.

As λ increased, shifting from WSM to WPM, 4G's dominance steadily decreased from 145 to 109, while both WLAN and 3G saw consistent gains in selection frequency. This pattern highlights how WPM increasingly favours low-delay and low-cost options, with 3G benefiting from its 50 ms delay, despite its high cost and low bandwidth.

In conclusion, 4G emerged as the most balanced and frequently selected RAT due to its high bandwidth (60 Mbps), moderate cost (50%), and moderate delay (100 ms). WLAN became dominant in scenarios prioritizing cost or under high λ values due to its low cost (15%), despite its poor delay performance. 3G only gained some preference when delay was highly prioritized, but its high cost and poor bandwidth limited its overall attractiveness.

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