Journal of Computational Analysis and Applications **VOL. 33, NO. 7, 2024**

10.48047/jocaaa.2024.33.07.37

Analyzing Power Consumption in Mobile Environments: Influence of Channel Capacity and Signal Bandwidth in Next-Generation Wireless Networks

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Abstract:- In today's digital age, wireless networking has become an integral part of everyday life, with uninterrupted connectivity playing a vital role in ensuring a smooth user experience. One of the most critical aspects affecting the performance of wireless networks is handover, especially when devices move between different network types. Among various factors influencing handover performance, mobility stands out as a major challenge. Since wireless devices operate on limited battery power, minimizing energy consumption—particularly in mobile environments—is key to improving network efficiency. This study explores how mobility, channel capacity, and signal bandwidth impact power consumption during vertical handovers between Wi-Fi and WiMAX networks. Simulations were carried out using two different types of wireless nodes, referred to as Type-I and Type-II, and their energy usage was evaluated at three voltage levels: charge voltage, nominal voltage, and cut-off voltage. Network performance was assessed based on key metrics such as throughput, packet delivery ratio, and residual energy. The results show that both node mobility and signal parameters like bandwidth and channel capacity significantly affect energy consumption. These findings offer meaningful direction for developing more energy-efficient handover strategies, supporting the broader goal of building greener and more sustainable next-generation wireless networks.

Keywords: - Wireless Networking, Mobile Environment, Power Consumption, Throughput, Packet Delivery Ratio, Residual Energy, Channel Capacity, Channel Bandwidth, Signal Bandwidth

Introduction

As technology continues to evolve at a rapid pace, wireless networking has become an essential part of our everyday lives. From smartphones and laptops to smart homes and IoT devices, people are increasingly relying on wireless communication to stay connected. However, with this growing dependency comes the challenge of maintaining high network performance while keeping energy consumption under control—especially in mobile environments where users and devices are constantly on the move.

One of the most critical stages in wireless communication is the handover process, which allows a device to switch its connection from one access point to another, either within the same technology or across different ones (such as Wi-Fi to WiMAX). Ensuring that this transition is smooth and uninterrupted is key to delivering a good user experience. But handovers are complex, and their performance can be affected by many factors—mobility being one of the most significant. When devices move quickly between coverage areas, issues like signal loss, interference, and the so-called "ping-pong" and "corner" effects can arise, disrupting the connection and draining battery life.

Since most wireless devices are battery-powered, managing energy consumption is a top priority. Reducing power usage during handovers not only extends device life but also improves overall

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network efficiency. This is where Green Networking comes into play—an approach focused on developing energy-aware technologies to make wireless networks more sustainable.

Two key technical factors that influence energy usage in these scenarios are channel capacity and signal bandwidth. Channel capacity determines how much data can be transmitted over a network, while signal and channel bandwidth relate to how efficiently that data is delivered. Variations in these parameters can significantly affect how much energy wireless devices use, especially during handoffs.

This paper presents a two-part study focused on energy efficiency in mobile wireless environments. First, it examines how mobility affects power consumption and network performance during handovers. Second, it analyzes the impact of channel capacity and signal bandwidth on energy usage. Simulations were conducted using two types of wireless nodes under varying voltage conditions. The network's performance was evaluated based on throughput, packet delivery ratio (PDR), and residual energy—all critical indicators of how well the network and devices perform.

The goal of this research is to provide insights that can help in designing more energy-efficient handover strategies for future wireless networks. The paper is structured as follows: Section 2 reviews related work on mobility models and their effects. Section 3 explains the methodology used for energy assessment. Section 4 describes the simulation setup, while Section 5 discusses the results. Finally, Section 6 concludes the study and outlines potential future directions.

Significance of Mobility and Channel Dynamics in Next-Generation Wireless Networks

Mobility has emerged as a critical factor influencing the performance of wireless networks, especially during handover scenarios. Due to the battery-constrained nature of wireless nodes, mobility adds to energy consumption and affects service continuity. Various studies have focused on addressing mobility-related challenges. Mobility models—classified as individual or group, and further divided into synthetic, trace-based, and hybrid models—have been widely used to simulate realistic movement patterns and their impact on network behavior [1–3]. Simulations over wireless ad hoc and sensor networks have shown that node movement, predefined pathways, and traffic models significantly affect performance metrics such as throughput and packet delivery ratio [4,5].

Several researchers have analyzed routing protocol behavior under varying mobility conditions. Studies show that factors like node density, speed variations, and security threats (e.g., black hole attacks) degrade network reliability and increase energy demands [6–13]. To improve realism and reduce implementation cost, adaptive models linking speed and direction history have been proposed.

With the rise of Green Networking, energy efficiency has become a priority. Research has focused on developing energy-aware architectures and frameworks to reduce power consumption at both the device and network levels [14–17]. These approaches aim to balance energy usage with performance, especially in mobile environments.

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In addition to mobility, channel capacity and signal bandwidth are key factors influencing network performance and energy consumption. Techniques based on the Effective Channel (EC) model have been proposed to enhance QoS in delay-sensitive applications [18], while time-varying channel behavior and noise have been addressed through statistical models and sampling theories [19–22]. Studies demonstrate that sub-Nyquist and non-uniform sampling methods can influence channel capacity without significantly increasing energy costs.

Antenna architecture and spectrum optimization also play a vital role in maximizing channel utilization [23, 24], and indoor communication challenges have been tackled using Optical Wireless Communication Systems (OWCS) [25].

Recent work has also emphasized the interdependence between power consumption and bandwidth efficiency. Controlled experiments have characterized energy usage across different mobility and channel conditions [26, 27], while hybrid systems combining CDMA and Spread Spectrum have shown improvements in energy and latency [28]. Trade-offs between energy and bandwidth efficiency have been explored using unified performance metrics [29, 30].

To meet increasing demand for high-speed, energy-efficient communication, millimeter-wave and sub-THz technologies have been proposed. These offer higher data rates with lower energy loss, although their performance is sensitive to channel attenuation [31]. Advanced resource allocation strategies have also been developed to enhance bandwidth and energy efficiency in heterogeneous small-cell networks [32, 33].

Energy Assessment Methodology:-

The energy assessment in this study follows a two-phase approach. In the first phase, **node mobility** is calculated based on two key velocity parameters: **node velocity** (the speed at which the node moves) and **frame velocity** (the speed of the reference frame in which the node resides). The **resultant velocity** derived from these defines the node's relative motion in the network.

Mobility is modeled with the node moving at a randomly selected speed within the range $[0,V_{max}]$, where V_{max} is the maximum velocity. Upon reaching a destination or changing direction, the node pauses for a duration T_{pause}. If $T_{pause} = 0$, the mobility is continuous. Over time, the **average velocity** is calculated as given in equation 1.

$$\textbf{Relative Velocity}(RV(i,j,t)) = (V_i(t) - V_j(t)) \qquad \textbf{(1)}$$

Node Mobility (N.M) can be expressed as average relative velocity over all node pairs (i,j) all over the time (T) as given in equation 2.

$$\textbf{N.M} = \frac{1}{i \times j} \sum_1^N \sum_1^N \frac{1}{T} \int_0^T RS(i,j,t)dt \qquad \textbf{(2)}$$

where N= Number of Nodes

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Similarly, the Frame Velocity (F.M) of reference frame with respect to the elements of the network can be calculated over the time (T). These two velocity components then combined to produce the resultant mobility of the nodes as depicted in equation 3.

$$R.M = \sqrt{N.M^2 + F.V^2} \tag{3}$$

Power Consumption Calculations:-

Based on mobility calculations, energy consumed by the nodes is calculated and calibrated to equivalent battery drainage. The steps followed in calculating the battery drainage of the nodes in mobile environment is briefly discussed as follows:-

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As the nodes are mobile, the energy of a node by virtue of its motion with respect to all the distinct node pairs (i,j) is calculated as Kinetic Energy (K.E) in joules as mentioned in equation 4.

$$\boldsymbol{KineticEnergy(K.E) = \frac{1}{2(i \times j)} m(R.M)^2} \tag{4}$$

The frictional losses caused due to air over a certain distance travelled can be calculated as represented in equation 5

$$FrictionalLoss = Airfrictionalforce(a) \times DistanceTravelled(d) \tag{5}$$

Considering the frictional losses, the energy possessed due to mobility of wireless nodes can be calculated as depicted in equation 6

$$\boldsymbol{MobilityEnergy(M.E) = FrictionalLoss + K.E} \tag{6}$$

The average mobility energy of a node under continuously varied mobile environment with respect to all the other node pairs can be calculated as mentioned in equation 7

$$\boldsymbol{M.E_{avg} = \frac{1}{n} \times \sum_{i=1}^{n} (M.E_i)} \tag{7}$$

Where n = Number of iterations

Considering the standard deviation factor in energy, the above equation of energy can be represented as equation 8 given below

$$\textbf{Standard Energy } \boldsymbol{(M.E_{std})} = \sqrt{\frac{1}{k-1} \times \sum_{i=1}^{k} (M.E_i - M.E_{avg})^2} \tag{8}$$

To calculate the corresponding battery drainage of the wireless nodes, the Kinetic Energy(K.E) in joules is then converted into Watt-hour and then to Ampere-hour according to equation 9 , equation 10, equation 11 and equation 12 as given below

$$\boldsymbol{M.E_{Wh}(avg) = M.E_{avg}/3600} \tag{9}$$

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$$\mathrm{M.E}_{(\mathrm{Wh})}(\mathrm{std}) = \mathrm{M.E}_{(\mathrm{std})}/3600 \qquad \textbf{(10)}$$

$$\mathrm{B.D}_{\mathrm{avg}} = \mathrm{M.E}_{\mathrm{Wh}}(\mathrm{avg})/\mathrm{Voltage} \qquad \textbf{(11)}$$

$$\boldsymbol{B.D_{std} = M.E_{Wh}(std)/Voltage} \qquad \textbf{(12)}$$

where
M.E (Wh) = Equivalent Energy in Watt-hour
B.D (Ah) = Equivalent Battery Drainage in Ampere-hour

When the effect of random influences is negligible and there are no random errors or disturbances during wireless communication, the channel is assumed to be noiseless. Under such conditions, for a data which is being represented using L signal levels, the relation between channel capacity (C) measured in bits per second (bps) and signal bandwidth (SB) measured in Hertz (Hz) is expressed by Nyquist Theorem[34][35] as stated in Equation 13.

$$C=2\times SB\times \log_2(L) \qquad \textbf{(13)}$$

If the size of data packet is n bytes and t_x is the transmission power in watts for one packet, then the total power consumed (P_1) in watts for transmission of one bit over the channel can be calculated as given in Equation 14.

$$P_1 = \frac{n\times 8}{t_x} \qquad \textbf{(14)}$$

For a given signal bandwidth (SB) in bits per second (bps), the total data (D_{total}) transmitted over the channel in a time period of T seconds and the power consumed (P_{BW}) in watts for transmitting D_{total} bits can be calculated as shown in Equation 15 and Equation 16.

$$D_{total} = T \times SB \qquad \textbf{(15)}$$

$$P_{BW} = P_1 \times D_{total} \qquad \textbf{(16)}$$

At a given voltage (V) in volts, the power consumed (P_{BW}) in watts is then calibrated into equivalent power (P_{BWh}) in Watt-hour (Wh) and equivalent power (P_{BAh}) in Ampere-hour (Ah) according to Equation 17 and Equation 18.

$$P_{BWh} = (P_{BW} \times \mathrm{T})/3600 \qquad \textbf{(17)}$$

$$P_{BAh} = P_{BWh} / \mathrm{V} \qquad \textbf{(18)}$$

B. Power Consumption in Noisy Channel

Considering the effect of noise in wireless networking, the relation between channel capacity (C) in bits per second and signal bandwidth (SB) in Hertz at a given Signal-to-Noise Ratio (SNR) can be calculated according to Shannon Hartley Theorem[36][37]as given in Equation 19.

$$C = SB\times \log_2 (1+SNR) \qquad \textbf{(19)}$$

Signal-to-Noise ratio can be expressed as ratio of signal power (S) in Watts and noise power (N) in Watts and therefore, the above equation can be expressed in terms of power consumed by the wireless nodes as shown in Equation 20 below.

$$C = SB \times \log_2(1+\frac{S}{N}) \qquad \textbf{(20)}$$

To consider different scenario causing noise in channel during wireless communications, for a given noise density i.e noise power per unit of bandwidth (N_0) in Watts/Hertz, Equation 20 can be redefined according to Additive White Guassian Noise (AWGN) model and is represented as Equation 21.

$$C = SB \times \log_2(1+\frac{P_S}{N_0 \times SB}) \qquad \textbf{(21)}$$

According to Shannon Hartley Theorem, when SNR becomes negative, the channel capacity becomes linear with respect to the bandwidth and logarithmic with respect to the power factor. This region is known as Bandwidth limited regime represented mathematically as given in Equation 22.

$$C \approx SB \times \log_2(\frac{P_S}{N_0 \times SB}) \qquad \textbf{(22)}$$

Similarly, when the SNR becomes positive, the channel capacity becomes insensitive to bandwidth and linear to the power factor. This region is known as Power limited regime as represented in Equation 23.

$$C \approx (\frac{P_S}{N_0 \times SB}) \log_2 e \qquad \textbf{(23)}$$

To calculate the overall power consumed by the wireless nodes due to the variation in channel capacity and signal bandwidth, the signal power (Ps) in watts can be calibrated into equivalent power P_{SWh}(in Watt-hour) and P_{SAh} (in Ampere-hour) for given time period (T) in seconds and voltage (V) in volts as given in Equation 24 and Equation 25.

$$P_{SWh} = (P_S \times T)/3600 \qquad \textbf{(24)}$$

$$P_{SAh} = P_{SWh} \,/\, V \qquad \textbf{(25)}$$

C. Cumulative Power Consumption in Noisy Channel

In noiseless channels, power consumption in watts due to signal bandwidth and channel capacity variations can be calculated individually under circumstances when signal bandwidth is lesser than channel capacity (P_{S1}) or under circumstances when signal bandwidth is equal to channel capacity (P_{S2}). To evaluate the overall power consumption of wireless nodes due to variation in channel capacity and signal bandwidth for noiseless channel, the average power ($P_{S(avg)}$)in watts can be calculated from the individual power (P_{Si}) for n iterations according to Equation 26 and Equation 27.

$$P_{S_i} = \frac{1}{2} \times \sum_{i=1}^{n}(P_{S_1} + P_{S_2}) \qquad \textbf{(26)}$$

$$P_{S(avg)} = \frac{1}{n} \times \sum_{i=1}^{n}(P_{S_i}) \qquad \textbf{(27)}$$

In view of the standard deviations, the standard power consumption $P_{S(std)}$(in watts) can be calculated according to Equation 28.

$$\textit{Standard Energy } (P_{S(std)}) = \sqrt{\frac{1}{k-1} \times \sum_{i=1}^{k}(P_{S_i} - P_{S(avg)})^2} \qquad \textbf{(28)}$$

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The average power consumption ($P_{S(avg)}$) can be calibrated to equivalent average power ($P_{SWh(avg)}$) in Watt-hour and equivalent average power ($P_{SAh(avg)}$) in Ampere-hour according to Equation 29 and Equation 30. The equivalent powers ($P_{SWh(avg)}$) and ($P_{SAh(avg)}$) can further be converted to standard values $P_{SWh(std)}$(in Watt-hour) and $P_{SAh(std)}$(in Ampere-hour) according to Equation 31 and Equation 32.

$$P_{SWh(avg)} = P_{S(avg)}/3600 \quad \textbf{(29)}$$

$$P_{SWh(std)} = P_{S(std)}/3600 \quad \textbf{(30)}$$

$$P_{SAh(avg)} = P_{SWh(avg)}/V \quad \textbf{(31)}$$

$$P_{SAh(std)} = P_{SWh(std)}/V \quad \textbf{(32)}$$

Experimental Setup:-

The simulation for this study was conducted using Network Simulator 2 (NS-2) to evaluate the impact of channel capacity and signal bandwidth on power consumption and network performance during a vertical handover scenario between WiFi (IEEE 802.11n) and WiMAX (IEEE 802.16) technologies. Two types of wireless nodes were used in the simulation: Type-I, equipped with a 3.7V 3500 mAh Li-ion battery, and Type-II, powered by a 14.8V 3500 mAh 4-cell Li-ion battery. The simulation setup was designed to observe how different battery capacities nodes namely charge voltage, nominal voltage and cut-off voltage and network parameters like throughput, packet delivery and residual energy influence energy usage during handoff events. The mobility of node iteratively varies with every simulation in the range of 10-100 m/sec by an interval of 10 m/sec. Similarly, the channel capacity and bandwidth of the channel varied in the range 10-100 Mbps at an increment of 10 Mbps per iteration. The overall simulation scenario is illustrated in Figure 1, and the detailed configuration and parameters are summarized in Table 1.

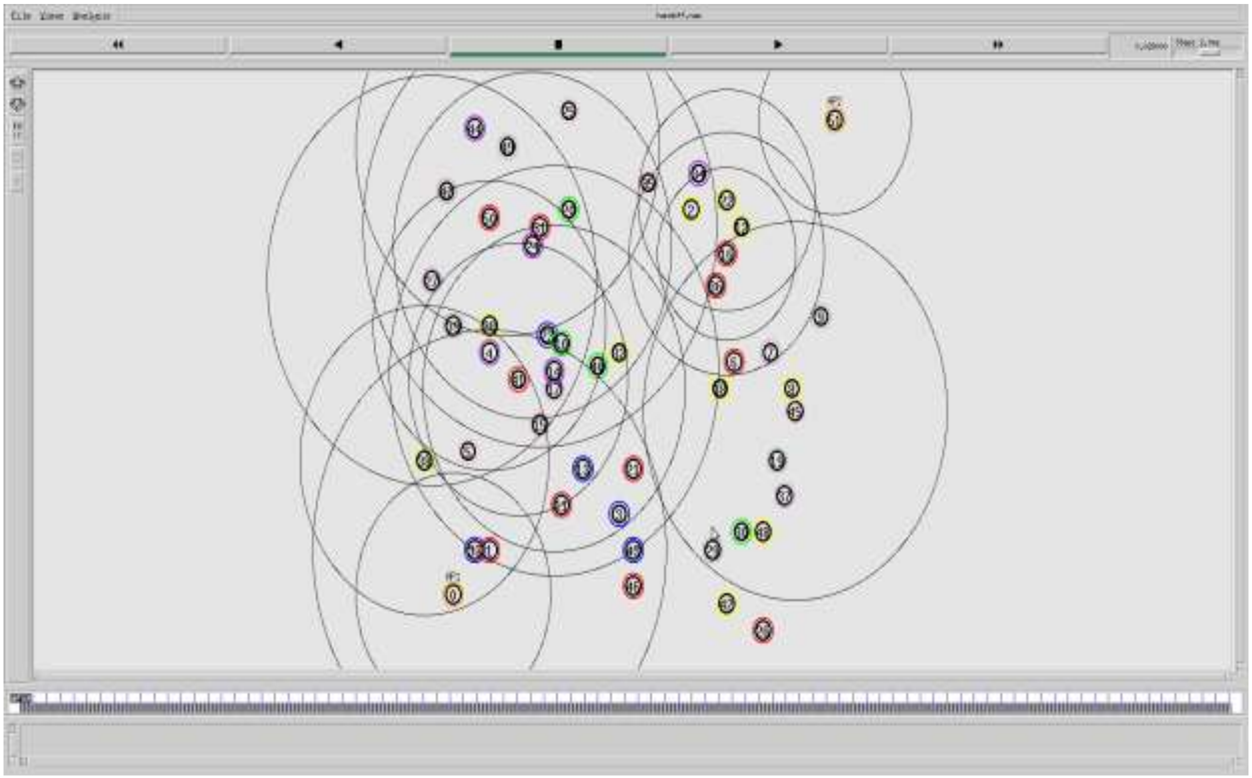

Figure.1. Simulation Scenario

Table 1. Simulation Parameters

Configuration	**Parametric Values**
Simulation Area	600 * 600
Access Points	2
Number of Nodes	50
Propagation Model	Two Ray Ground
Mobility Model	Random Waypoint
Traffic Type	CBR
Packet Size	1023 bytes
Channel Capacity	10-100 Mbps
Bandwidth	10-100 Mbps
Mobility	10-100 m/sec
Voltage Levels	4.2V, 3.7V and 3.2V

Result Analysis and Discussion:-

Power Consumption:-

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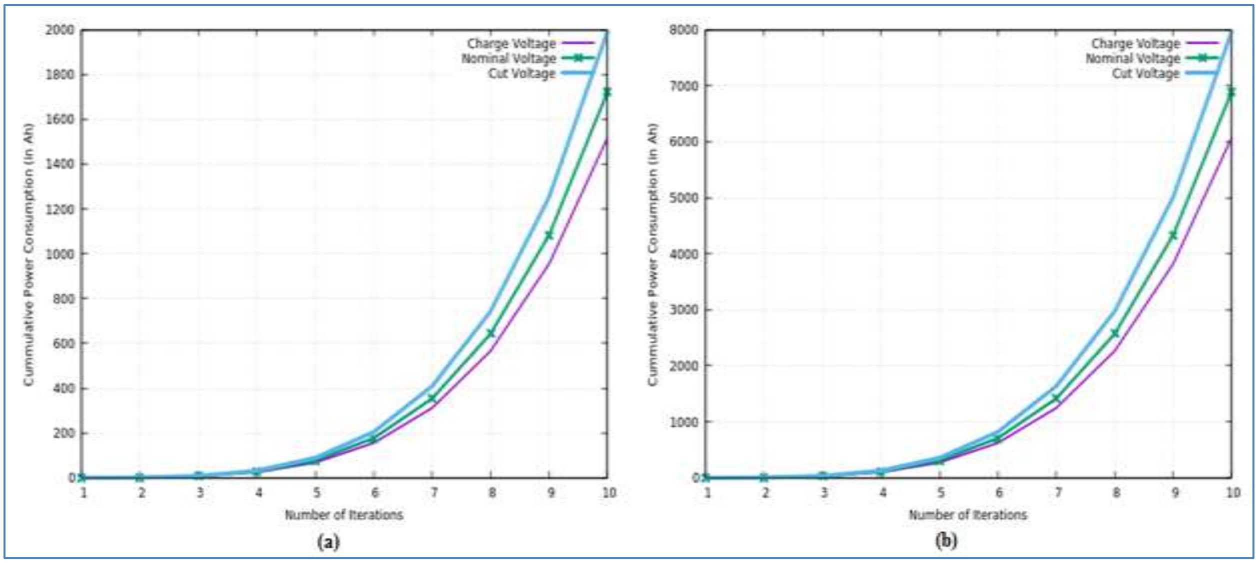

(a)

(b)

Figure.2. Cumulative power consumption. (a) For Type-I nodes. (b) For Type-II nodes.

The simulation results revealed that power consumption of wireless nodes increases exponentially with rising mobility and channel utilization. At charge voltage, the average battery drainage was 30.5 Ah for Type-I and 122.22 Ah for Type-II nodes; at nominal voltage, it rose to 34.68 Ah and 138.73 Ah respectively; and at cutoff voltage, it further increased to 40.10 Ah for Type-I and 160.41 Ah for Type-II nodes. In noiseless channels, as channel capacity increased, the average power consumption for Type-I nodes was 1,059.18 Ah and for Type-II nodes 4,236.73 Ah. In noisy channels, where signal bandwidth (SB) was less than channel capacity (C), average power consumption at charge voltage was approximately 4.75686×10^8 Ah for Type-I and 1.90252×10^9 Ah for Type-II; at nominal voltage, it increased to 5.27496×10^8 Ah and 2.06291×10^9 Ah; and at cutoff voltage, it peaked at 6.03813×10^8 Ah for Type-I and 2.56953×10^9 Ah for Type-II. These results affirm that both mobility and bandwidth utilization significantly impact energy consumption, with Type-II nodes consistently consuming more power than Type-I nodes across all scenarios. The variation of power consumption at different voltage levels can be graphically represented as Figure 2 (a) and (b).

Residual Energy:-

The study revealed that residual energy decreases exponentially and is inversely proportional to node mobility, as well as to increasing channel capacity and signal bandwidth. For mobility scenarios, the average residual energy at charge voltage was 3.480 Ah for Type-I and 13.980 Ah for Type-II nodes; at nominal voltage, it slightly decreased to 3.478 Ah and 13.978 Ah; and at cutoff voltage, to 3.474 Ah and 13.974 Ah respectively. In noiseless channels, with increasing channel capacity, the residual energy dropped further—averaging -1,055.01 Ah for Type-I and -4,222.72 Ah for Type-II nodes across the three voltage levels. For noisy channels, where signal bandwidth was less than the channel capacity, the average residual energy was approximately -4.75696×10^8 Ah, -5.27496×10^8 Ah, and -6.03813×10^8 Ah for Type-I and -1.90252×10^9 Ah, -2.06291×10^9 Ah, and -2.56953×10^9 Ah for Type-II nodes at charge, nominal, and cutoff voltages respectively. When signal bandwidth equaled channel capacity, residual energy declined further, averaging -5.86258×10^{48} Ah for Type-I and -2.34503×10^{49} Ah for Type-II nodes across all voltage levels. These findings confirm that higher mobility and greater bandwidth demands lead to significant energy depletion, with Type-II nodes exhibiting higher absolute energy loss due to their higher initial capacity. Figure 3 (a) and (b) represents the graphical representation of residual energy at different voltage levels.

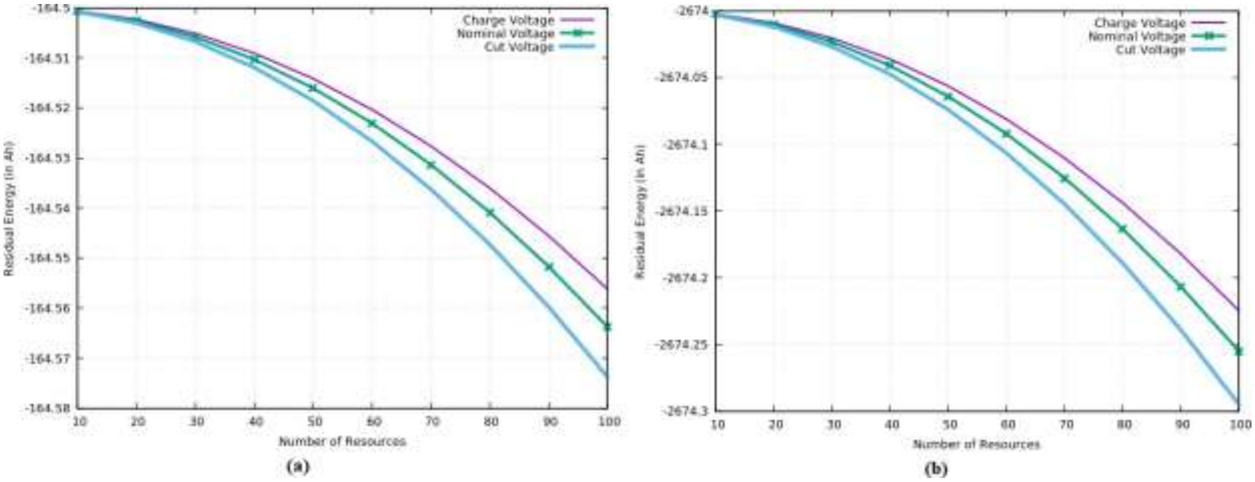

Figure.3. Cumulative Residual Energy. (a) For Type-I nodes. (b) For Type-II nodes

Throughput:-

The study observed a decline in node throughput with increased mobility. At charge voltage, the average throughput was 149.295 Kbps for Type-I nodes and 349.295 Kbps for Type-II nodes; at nominal voltage, it dropped to 139.295 Kbps and 339.295 Kbps respectively; and further decreased to 129.295 Kbps and 329.295 Kbps at cutoff voltage. Throughput improved with increased channel capacity, especially in a noiseless environment, where average throughput values were 51.495 Mbps, 50.495 Mbps, and 49.495 Mbps for Type-I, and 53.495 Mbps, 51.995 Mbps, and 50.495 Mbps for Type-II at charge, nominal, and cutoff voltages respectively. In contrast, under noisy conditions, the average throughput values declined to 46.594 Mbps, 41.095 Mbps, and 35.595 Mbps for Type-I and 49.095 Mbps, 43.595 Mbps, and 38.095 Mbps for Type-II at the corresponding voltage levels. The variation of throughput for different voltage levels is represented in the Figure4 (a) and (b) below

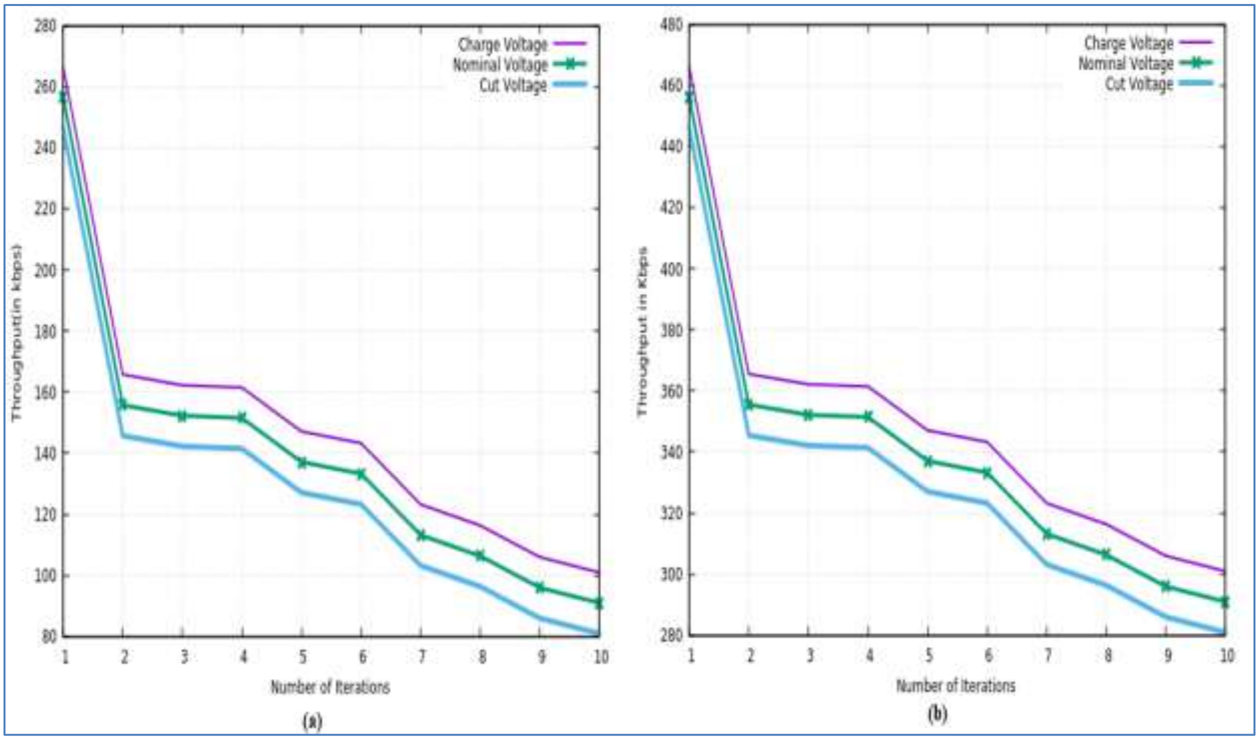

Figure.4. Variation of Throughput. (a) For Type-I nodes. (b) For Type-II nodes

Packet Delivery Ratio (PDR):-

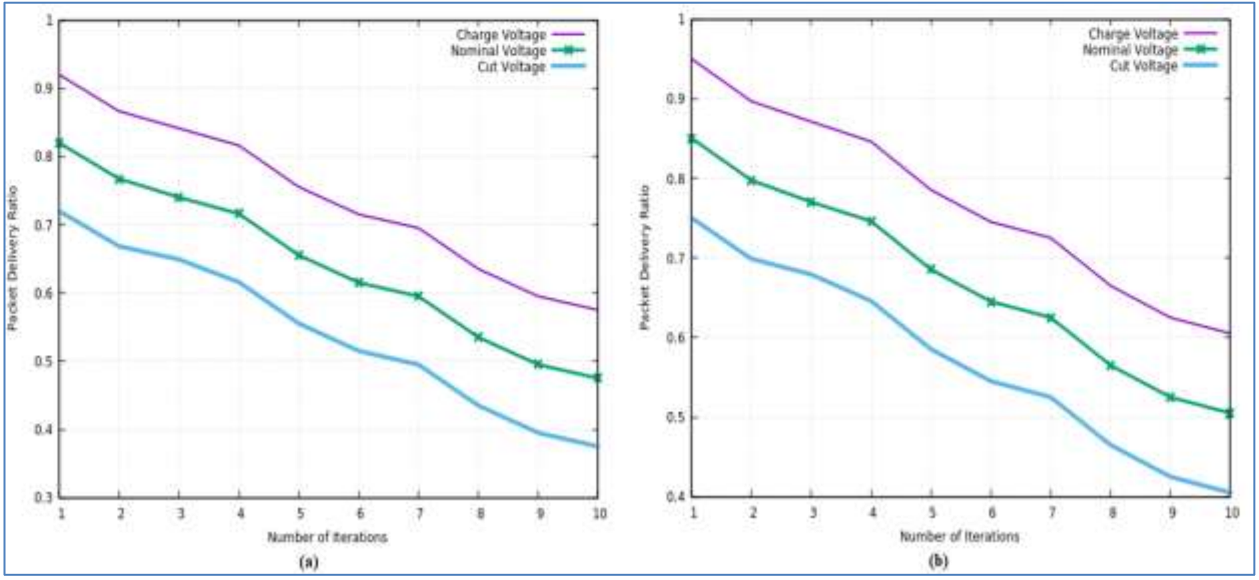

Figure.5. Variation of Packet Delivery Ratio. (a) For Type-I nodes. (b) For Type-II nodes

The simulation results indicated that the Packet Delivery Ratio (PDR) decreases with increasing node mobility. At charge voltage, the average PDR was 0.75 for Type-I nodes and 0.78 for Type-II nodes; at nominal voltage, it declined to 0.65 and 0.68 respectively; and at cutoff voltage, it further dropped to 0.55 for Type-I and 0.58 for Type-II nodes. PDR was observed to increase with channel capacity in both noiseless and noisy environments. In a noiseless channel, the average

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PDR for Type-I nodes was 0.7812, 0.6812, and 0.5812, and for Type-II nodes, it was 0.8812, 0.7812, and 0.6812 at charge, nominal, and cutoff voltages respectively. Under noisy channel conditions, the PDR was 0.7326, 0.6326, and 0.5326 for Type-I, and 0.8326, 0.7326, and 0.6326 for Type-II nodes across the same voltage levels. The variation of packet delivery ratio is depicted in Figure 5 (a) and (b).

Conclusion:-

This paper evaluated the impact of node mobility, channel capacity, and signal bandwidth on power consumption and network performance in a vertical handover scenario between WiFi and WiMAX technologies using Type-I and Type-II wireless nodes at three voltage levels (charge, nominal, and cutoff). Results showed that power consumption increased and residual energy decreased with higher mobility and greater channel capacity or signal bandwidth, particularly under noisy conditions. On average, mobility simulations yielded a power consumption of 87.77 Ah, residual energy of 8.73 Ah, throughput of 239.3 Kbps, and PDR of 0.665. In channel-based simulations, average throughput and PDR were higher in noiseless channels (51.25 Mbps and 0.7312) compared to noisy channels (42.34 Mbps and 0.6826), while average power consumption was significantly higher under noisy conditions. Type-II nodes consistently outperformed Type-I nodes in network performance but consumed more power. The study concludes that optimal performance and energy efficiency can be achieved by operating nodes at low to moderate mobility levels and within charge to nominal voltage ranges, offering insights for developing sustainable Green Networking solutions.

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