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Paper:

Enhanced Resource Allocation Algorithm for Heterogeneous Wireless Networks

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In heterogeneous wireless networks, service providers typically employ multiple radio access technologies to satisfy the requirements of quality of service (QoS) and improve the system performance. However, many challenges remain when using modern cellular mobile communications radio access technologies (e.g., wireless local area network, long-term evolution, and fifth generation), such as inefficient allocation and management of wireless network resources in heterogeneous wireless networks (HWNs). This problem is caused by the sharing of available resources by several users, random distribution of wireless channels, scarcity of wireless spectral resources, and dynamic behavior of generated traffic. Previously, resource allocation schemes have been proposed for HWNs. However, these schemes focus on resource allocation and management, whereas traffic class is not considered. Hence, these existing schemes significantly increase the end-to-end delay and packet loss, resulting in poor user QoS and network throughput in HWNs. Therefore, this study attempts to solve the identified problem by designing an enhanced resource allocation (ERA) algorithm to address the inefficient allocation of available resources vs. QoS challenges. Computer simulation was performed to evaluate the performance of the proposed ERA algorithm by comparing it with a joint power bandwidth allocation algorithm and a dynamic bandwidth allocation algorithm. On average, the proposed ERA algorithm demonstrates a 98.2% bandwidth allocation, 0.75 s end-to-end delay, 1.1% packet loss, and 98.9% improved throughput performance at a time interval of 100 s.

Keywords: enhanced resource allocation (ERA) algorithm, heterogeneous wireless networks (HWNs), quality of service (QoS), radio access technologies, wireless network resources

1. Introduction

Owing to the rapid development of wireless technology in recent years, multiple radio access technologies (RATs) have been investigated in wireless communication research. Networks with multiple RATs, where end-users transmit their data over multiple RATs simultaneously, are named as the multi-radio access system, which integrates RATs such as wireless local area networks, universal mobile telecommunication systems, long-term evolution, long-term-evolution advanced, worldwide interoperability for microwave access, and fifth generation as its subsystems. The coverage areas of these different wireless network access technologies in the same geographic area often overlap, resulting in the evolution of heterogeneous wireless networks (HWNs; see **Fig. 1**) [1–117]. Nonetheless, the allocation of available resources (bandwidth) in this type of network poses a significant challenge to telecom network operators in terms of satisfying the quality of service (QoS) requirements/criteria of various service traffic, namely real-time and non-real-time traffic [1–12, 17–117]. The problem is caused by the sharing of available resources by numerous users, random distribution of wireless channels, scarcity of wireless spectral resources, and dynamic behavior of generated traffic in HWNs [1–12, 17–117].

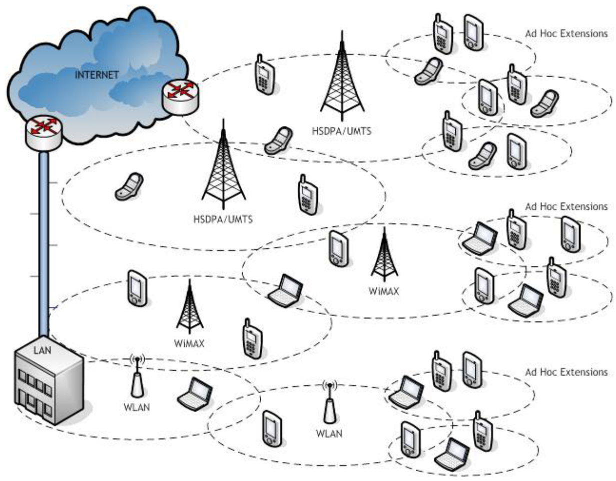

Fig. 1. Typical HWN architecture.

Previously, resource allocation schemes such as the dynamic bandwidth allocation (DBA) algorithm, static bandwidth allocation algorithm, and joint power band-

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width allocation (JPBA) algorithm have been proposed for HWNs [25–43]. However, these schemes focus on resource allocation and management, whereas traffic class is not considered [25–42]. Hence, these existing schemes significantly increase the end-to-end delay and packet loss because of inefficient bandwidth allocations in HWNs. This results in poor user QoSs and network throughputs in HWNs [1–12, 17–32, 78–117].

The proposed enhanced resource allocation (ERA) algorithm attempts to solve the existing deficiency by providing an efficient bandwidth allocation solution that considers the QoS requirements of diverse service traffic in HWNs. The proposed ERA algorithm was designed by integrating the wavelet neural network prediction model and the max–min fairness (MMF) bandwidth allocation algorithm. This was performed to eliminate end-to-end delays and packet losses in HWNs, thereby improving the user QoS and network throughput in HWNs.

The remainder of the paper is organized as follows. In Section 2, we present the related studies. In Section 3, we present the design of the proposed ERA algorithm. The performance evaluation is presented in Section 4. Conclusions and future work are presented in Section 5.

2. Related Studies

In this section, we present previously proposed resource allocation algorithms for HWNs. In our discussions, we present the advantages of these existing algorithms. Thereafter, we discuss their disadvantages/limitations. [24-30, 43].

Bonani et al. [25] proposed a model and a simulation of flexible optical networks (FON's) spectrum-based partitioning as well as sharing approaches for providing various service requirements. The proposed bandwidth allocation model (BAM) solution adopts a different reservation strategy; consequently, the traffic demand would compete for assets within each specific class.

Callegati et al. [26] proposed and evaluated a reserve trunk plan for reducing the distortion of the spectrum. This approach focused on spectrum fragmentation and BAM-based allocation of resources centered on the use of networks between BAM models.

Hesselbach et al. [27] proposed a special resource allocation system for HWNs based on a revised Russian doll model (RDM). In a simple example, the authors tested the method proposed under different priority groups. The results show the improved performance afforded by the proposed system in terms of connection utilization and acceptance ratio compared with a maximum allocation model (MAM) and RDM.

The use of an RDM to allocate the bandwidth for an intra-optical network unit (ONU) in an Ethernet passive optical network (EPON) was proposed by Sadon et al. [28]. The designed model achieved superior performances in terms of bandwidth utilization, packet delay, and equality over two other dynamic hierarchical bandwidth algorithms. This is another example where BAMs can be used. The analogy with the proposed HWNs solution is unclear, but the reference indicates a different approach to implement BAMs in the optical domain.

Hence, Jiang et al. [34] hypothesized that the weight of two nodes connecting to a connection can be more accurately represented by the strength of the link. They suggested a betweenness-based bandwidth allocation strategy and demonstrated a better network performance effect.

In [34], the authors proposed an algorithm that dynamically allocates bandwidth to mobile notes. Their algorithm allowed the network to achieve maximum transportation efficiency by ensuring that their strategy was proportional to the queue length of the link output buffer per time stage. However, in rapidly changing networks, this competitive approach requires a strong prompt demand. Current studies focus on the infrastructure layer viewpoint, but network faults exist in the application process. Furthermore, we cannot explain the significance of each connection merely through the network structure. Therefore, the techniques above may not satisfy the requirements of multiple real-time applications.

Applications are important for fully utilizing the limited bandwidth resources for application requirements. Zhang et al. [35] discovered that different applications have different effects on network performance. Current static and dynamic allocation approaches typically involve application-generated traffic but disregard the application characteristic.

The DBA and JPBA algorithms in the EPON/passive optical network have been extensively studied [37, 38]. Usmani et al. [39] presented a comprehensive analysis of the throughput and delay output of various DBAs with different combinations of grant scheduling frameworks (i.e., offline, online, double step polling, ONU load status), grant sizing (i.e., limited, gated, set, excess distribution), and grant scheduling (i.e., the largest number of frames, shortest propagation lag, and shortest processing time). Knittle [40] presented a brief overview of various long-range passive optical network-dynamic bandwidth allocation (PON-DBA) schemes. However, these methods cannot be implemented directly in the next generation Ethernet passive optical network (NG-EPON) without considering the underlying real-time application requirements [41, 42]. In the NG-EPON (modified interleaved polling with adaptive cycle time (IPACT)), the legacy IPACT DBA can be introduced by assuming that all four wavelength channels are connected as one channel [37]. In a single license, a grant will be assigned to an ONU on all four wavelength channels. Hence, the available bandwidth is not used optimally as all wavelength channels are allocated regardless of whether the recorded bandwidth is small or large, owing to frame size mismatch and the inefficient use of the guard time. A water-filling algorithm based dynamic wavelength bandwidth allocation (WF-DBA) scheme was recently been suggested [14].

The basic of the WF-DBA is to assign a bandwidth to a single ONU such that the bandwidth requirement of the ONU is satisfied, and the use of wavelengths converges to equity. The channels were sorted by the WF-DBA for their use. Next, a grant was issued on the least-used channel to suit the next least-used channel. For example, if the difference between the first two wavelength channels is greater than the ported bandwidth, a grant will be allocated to one channel only; otherwise, additional channels will be allocated based on the channel usage difference.

Therefore, according to the recorded bandwidth and the difference between the end times of the wavelength channels during the previous allocation, an ONU can be assigned a grant on multiple wavelength channels. For the WF-DBA, consider the situation in which all wavelength channels have the same termination time for the last allocation of bandwidth. If wavelength λ is maximum, then the ONU's total wavelengths are set at 4; subsequently, the WF-DBA will function as a modified IPACT and distribute grants across all four wavelength channels.

Therefore, once the wavelength channels' available times are equal, each next recorded bandwidth will be partitioned and granted equally across all wavelength channels. Such a situation can render all the wavelength channels busy for an equal and long time. Consequently, heavily loaded ONUs will be monopolized and other ONUs will be devoid of bandwidth. This inevitably increases the latency of the packet in the abovementioned ONUs. Even if λ max is set as 2, once all channels have the same starting time, the WF-DBA will assign two wavelength channels to the mobile nodes irrespective of the size of the recorded bandwidth.

Researchers have previously proposed and implemented bandwidth allocation algorithms. However, the previously proposed algorithms failed to forecast each mobile node's traffic type based on each mobile node's historical traffic information. In addition, these schemes focus on resource allocation and management, whereas traffic class is not considered. Hence, these previously proposed algorithms significantly increase the end-to-end delay and packet loss, resulting in poor user QoSs and network throughputs in HWNs.

Hence, we herein proposed a design for the ERA algorithm by integrating the wavelet neural network prediction model and the MMF bandwidth allocation algorithm. This was performed to efficiently allocate bandwidth. The proposed ERA algorithm minimalizes the end-to-end delay and packet loss, thereby improving the user QoS and network throughput in HWNs.

3. Design of ERA Algorithm

In HWNs, resource allocation must be effectively adapted to various traffic categories and their QoS criteria to improve network performance and user QoS. A wavelet neural network prediction model and an MMF bandwidth allocation algorithm were integrated to design the proposed ERA algorithm. The proposed ERA algorithm was designed to improve network performance and user QoS by allocating bandwidth efficiently, thereby minimalizing end-to-end delays and packet losses in HWNs.

3.1. Wavelet Neural Network Prediction Model

A wavelet neural network prediction model was used in this study to predict each mobile node's traffic type based on each mobile node's historical traffic information. Nonlinear sigmoid functions were replaced by a sequence of wavelet functions in the wavelet neural network prediction model. The wavelet neural network prediction model comprised an input layer, a hidden layer, and an output layer, where A_1, A_2, and 1 represent the number of neurons in the input layer, hidden layer, and output layer, respectively. We define the historical traffic y_i as the i-th input, and x_{ij} as the link weight connection between the i-th input layer node and j-th hidden layer node. x_{jk} is the link weight from a hidden layer node j to the output layer node k. To obtain the input of hidden layer node j, Eq. (1) is used.

$$H_{in}(j) = \sum_{i=1}^{A_1} x_{ij} y_i, \quad j = 1, 2, \ldots, A_2. \qquad (1)$$

To obtain the output of hidden layer node j, Eq. (2) is used.

$$H_{out}(j) = f\left(\frac{\sum_{i=1}^{A_1} x_{ij} y_i - u_j}{v_j}\right), \quad j = 1, 2, \ldots, A_2, \qquad (2)$$

where u_j and v_j are the dilation parameter and translation parameters of the j-th hidden units, respectively; f is the wavelet basis function $f(x) = \cos(1.75x)e^{-x^2/2}$. The output of the output layer is equal to the input of the output layer, i.e., $R_{out} = R_{in} = \sum_{j=1}^{A_2} x_{ij} H(j)$. $P(t)$ is denoted as the real output value of the t-th pattern. Eq. (3) defines the error function.

$$e = \frac{\sum_{t=1}^{N_t} (P(t) - w(t))^2}{2}, \qquad (3)$$

where N_t is the training group level. An iterative gradient-based approach was used to minimize the errors during the prediction process (see Eq. (4)).

$$x(s+1) = x(s) - \eta \Delta x = x(s) - \eta \frac{\partial e}{\partial x}, \qquad (4)$$

where η is a constant known as the learning rate. To obtain the corresponding derivatives, we used Eqs. (5) to (10).

$$\Delta x_{jk} = (R_{out} - P) \cdot H_{out}(j), \qquad (5)$$

$$\Delta x_{ik} = (R_{out} - P) \cdot x_{ij} \cdot \varphi \cdot \frac{1}{v_j}, \qquad (6)$$

$$\Delta u_{jk} = (R_{out} - P) \cdot x_{jk} \varphi \cdot \left(-\frac{1}{v_j},\right) \qquad (7)$$

$$\Delta v_j = (R_{out} - P) \cdot \varphi \cdot x_{jk} \cdot \frac{u_j - \left(\sum_{i=1}^{A_1} x_{ij} y_i - u_j\right)}{v_j^2}, \qquad (8)$$

$$\varphi = f' \frac{\sum_{i=1}^{A_1} x_{ij} y_i - u_j}{v_j}, \quad \ldots \ldots \ldots \ldots \quad (9)$$

$$f'(x) = -17.5\sin(1.75x)e^{-\frac{x^2}{2}} \\ -y\cos(1.75x)e^{-\frac{x^2}{2}} \quad \ldots \ldots \ldots \quad (10)$$

The learning process stops when the following conditions are satisfied: the prediction error exceeds a threshold (TH), or the number of iterations (NI) reaches the specified limit of 1000. Once the traffic forecast is completed, the bandwidth allocation proceeds.

3.2. Max–Min Fairness Bandwidth Allocation Algorithm

The MMF bandwidth allocation algorithm was used to allocate the bandwidth based on the predicted traffic type using the wavelet neural network prediction model. We used two types of traffic: real-time and non-real-time traffic. For real-time traffic, we used a packet size of 84480 bytes and 78022 bytes for online video conferencing and voice calls, respectively (see Eq. (10)). For non-real-time traffic, we used an FTP packet size of 500 bytes for email services (see Eq. (10)). In this study, real-time traffic was assigned a higher priority over non-real-time traffic. This was performed to reduce end-to-end delays and packet losses in HWNs.

$$\begin{cases} \text{If } PS_n \geq 78022, \\ \quad BW_H = \left[BW_{total} - \sum_i^N G_i^H \right] \\ \text{elseif } PS_n \leq 500, \\ \quad BW_L = \left[\frac{BW_{total} - BW_H}{\sum_i^N R_i^M} \right] \end{cases} \quad \ldots \ldots \quad (11)$$

3.3. ERA Algorithm Development

Algorithm 1 presents the developed ERA algorithm. Mobile speed (MS), latency (L), packet size (PS), packet loss (PL), and jitter (J) were used as input parameters to allocate the bandwidth (BW) efficiently in HWNs. Hence, the proposed algorithm minimized the end-to-end delays and packet losses. Consequently, the proposed ERA algorithm improved the throughput performance and user QoS in HWNs.

We present the flowchart of the proposed ERA algorithm in **Fig. 2**.

This section presents the development of the proposed ERA algorithm by integrating the wavelet neural network prediction model and the MMF bandwidth allocation algorithm to effectively allocate bandwidth in HWNs. Network Simulator-2 (NS-2) was applied to validate the efficiency of the proposed ERA algorithm, and the results are discussed in Section 4.

Algorithm 1 ERA algorithm

Input MS, L, PS, PL, J, PE, and NI
Process
While $PE > \frac{TH}{NI} > 1000$
If MS and $PS \neq 0$
  Do Eq. (1)
  Do Eq. (2)
  Do Eq. (3)
  Do Eq. (4)
  Do Eq. (5)
  Do Eq. (6)
  Do Eq. (7)
  Do Eq. (8)
  Do Eq. (9)
  Do Eq. (10)
  Do Eq. (11)
  If $PS_n \geq 78022$
    $BW_H = \left[BW_{total} - \sum_i^N G_i^H \right]$
  elseif $PS_n \leq 500$
    $BW_L = \left[\frac{BW_{total} - BW_H}{\sum_i^N R_i^M} \right]$
  End if
Output
Return $\frac{BW_H[\,]}{BW_L[\,]}$
End if
End while

4. Performance Evaluation

To validate the efficiency of the proposed ERA algorithm, the NS-2 version 35 computer simulation was applied in this study primarily because it presents a widespread simulation environment for network applications, traffic models, protocols, and different network types code [13–24, 118–123]. Furthermore, NS-2 is freely available on the Internet and is an open-source code software [13–24, 118–123]. Hence, this network simulator can be easily used in this study. NS-2 allows for add-ons and modification of protocols [13–23, 118–123]. In this study, we assume that each base station simulated encompasses a radius of 500 m. Furthermore, we assume that the IEEE 802.11 standard provides a 2 Mbps transmission rate in a 2.4 GHz band. **Table 1** lists the simulation parameters used in this study.

The proposed ERA algorithm was compared with the JPBA and DBA algorithms. The JPBA algorithm was selected because it verifies the channel/link capacity and then assigns the bandwidth to that channel, whereas the DBA algorithm allocates bandwidth to mobile nodes dynamically without verifying the traffic type that a mobile node is transmitting at a specified time. In addition, both the JPBA and DBA algorithms have been previously tested in HWNs [25–43].

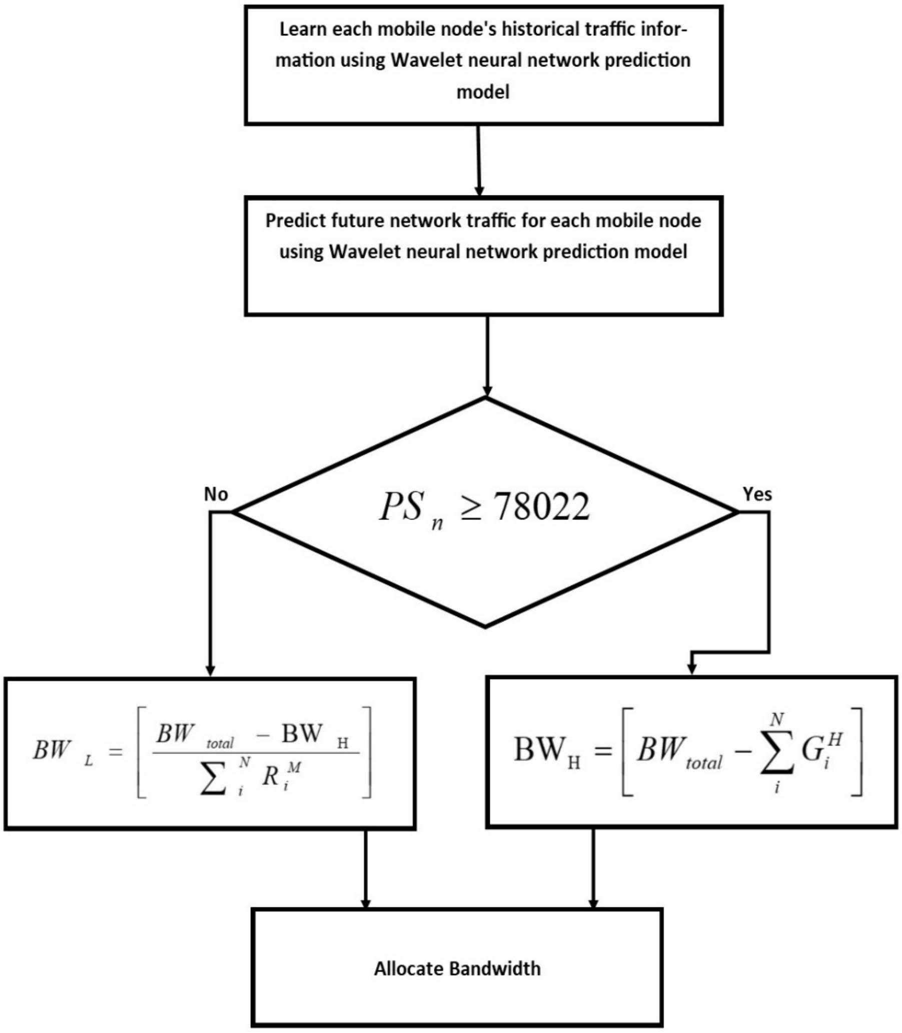

Fig. 2. ERA algorithm flowchart.

Table 1. Simulation parameters.

Experimental parameters	
Routing protocol	Link State Routing (LSR)
MAC protocol	IEEE 802.11
Propagation model	TwoRayGround
Mobility mode	Random waypoint
Queue type	Queue/DropTail/PriQueue
Number of nodes	15
Network bandwidth	20 Gbps
Simulation area	500 m × 500 m

4.1. Average Bandwidth Allocation

In a simulated HWN environment, the three algorithms were compared to determine the manner in which they allocate the available bandwidth to the mobile nodes. The proposed ERA, JPBA, and DBA algorithms allocated 98.2%, 82%, and 79% bandwidth, respectively (see **Fig. 3**).

The proposed ERA algorithm managed to correctly allocate a 98.2% bandwidth compared with the JPBA and DBA algorithms. This is primarily because the proposed ERA algorithm can forecast the traffic type that each mobile node is likely to process in the future based on the historical traffic information of that mobile node. The JPBA and DBA algorithms allocated the available bandwidth poorly primarily because both algorithms failed to predict the traffic type that mobile nodes are likely to process in the future.

4.2. Average End-to-End Delay

End-to-end delay or one-way delay refers to the time required for a packet to be transmitted across a network from the source to the destination. The average end-to-end delay was monitored for the three compared algorithms and the simulation results are presented in **Fig. 4**. The proposed ERA, JPBA, and DBA algorithms experienced average end-to-end delays of 0.75, 1.6, and 2.2 s, respectively, at a time interval of 100 s.

The proposed ERA algorithm experienced a shorter end-to-end delay predominantly because it can predict the

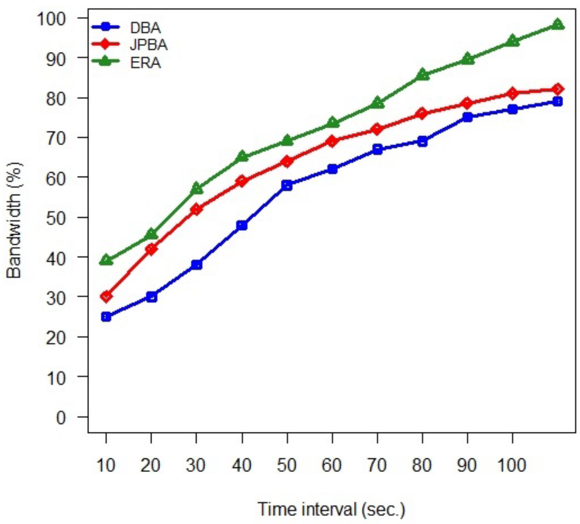

Fig. 3. Average bandwidth allocation.

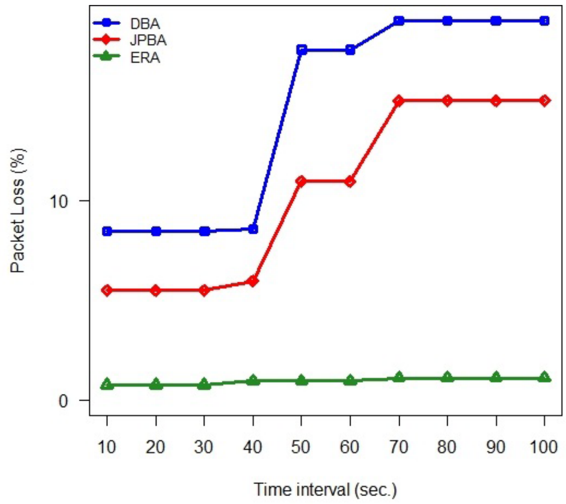

Fig. 5. Average packet loss.

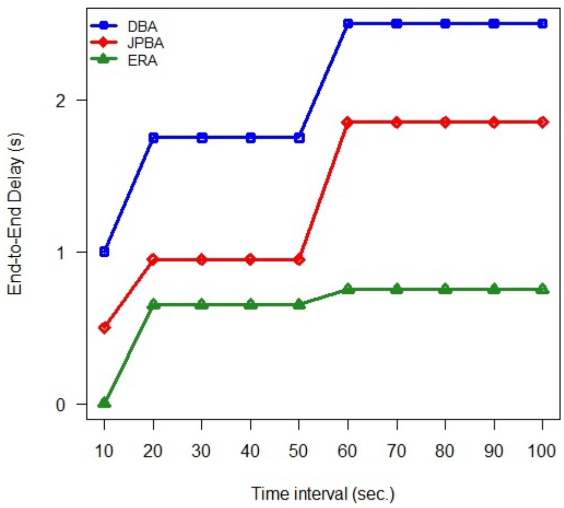

Fig. 4. Average end-to-end delay.

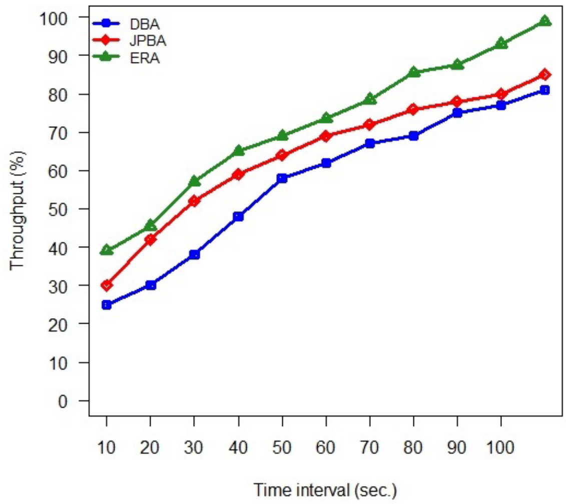

Fig. 6. Average throughput.

traffic type that each mobile node is likely to process in the future based on the historical traffic information of that mobile node. Consequently, the proposed ERA algorithm allocates a higher bandwidth to mobile nodes that are likely to process real-time traffic. This was performed to ensure that the end-to-end delay was reduced for real-time traffic in HWNs. The JPBA and DBA algorithms experienced lengthy average end-to-end delays primarily because both algorithms failed to predict the traffic type that mobile nodes are likely to process in the future. Hence, both algorithms failed to allocate bandwidth efficiently to mobile nodes that are likely to process real-time traffic.

4.3. Average Packet Loss

Packet loss occurs when one or more packets fail to reach its intended destination during packet transmission in any network type. For mobile nodes/users, packet loss manifests itself in the form of network disruption, slow service, and even total loss of network connectivity. Consequently, packet loss must be reduced in a network to provide a better user QoS and improve the throughput performance. In this study, the average packet loss was monitored for the three compared algorithms, and **Fig. 5** presents the simulation results.

The proposed ERA, JPBA, and DBA algorithms experienced average packet losses of 1.1%, 15%, and 19%, respectively, at a time interval of 100 s. The proposed ERA algorithm experienced a lower average packet loss primarily because the algorithm managed to allocate bandwidth efficiently. Both the JPBA and DBA algorithms experienced higher average packet losses predominantly because they failed to allocate bandwidth efficiently.

4.4. Average Throughput

The average network throughput was tracked and compared (as shown in **Fig. 6**) for the three compared algorithms. On average, the proposed ERA, JPBA, and DBA algorithms indicated throughout performances of 98.9%, 85%, and 81%, respectively, at a time interval of 100 s.

The proposed ERA algorithm showed a 98.9% throughput performance primarily because the algorithm managed to allocate the available bandwidth efficiently in HWNs. Hence, the proposed ERA algorithm minimized the packet loss and end-to-end delay in HWNs. This resulted in an improved throughput performance and user QoS. The JPBA and DBA algorithms demonstrated poor throughput performances predominantly they failed to efficiently allocate the available bandwidth in HWNs. Hence, these algorithms experienced higher packet losses and prolonged end-to-end delays in HWNs, resulting in poor user QoSs.

5. Conclusion and Future Work

An ERA algorithm was proposed herein; its design and development, which involved the integration of the wavelet neural network prediction model and the MMF bandwidth allocation algorithm to efficiently allocate the available bandwidth in HWNs, were presented. The integration was performed to eliminate packet losses and end-to-end delays. The proposed ERA algorithm improved the throughput performance and user QoS in HWNs. On average, the proposed ERA algorithm demonstrated a 98.2% bandwidth allocation, 0.75 s end-to-end delay, 1.1% packet loss, and 98.9% improved throughput performance at a time interval of 100 s. The proposed ERA algorithm allocated the available bandwidth correctly more effectively than the JPBA and DBA algorithms. This was because the proposed ERA algorithm can forecast the traffic type that each mobile node is likely to process in the future based on the historical traffic information of that mobile node. Future studies can include the implementation of security algorithms to secure packets transmitted in HWNs. Furthermore, the effectiveness of the proposed ERA algorithm can be evaluated in more complex network systems.

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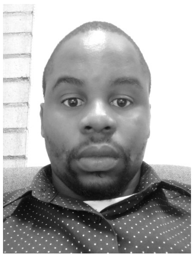

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