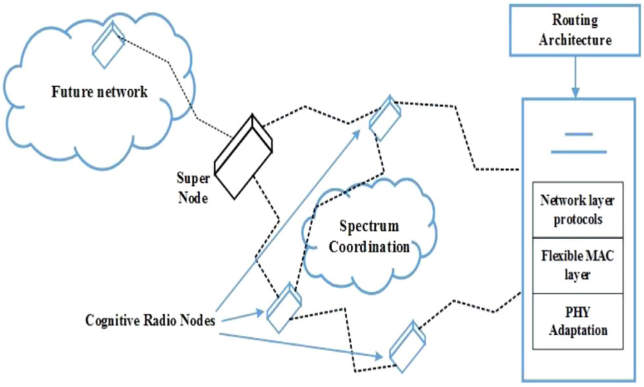

Fig. 1. Basic structure of CRN.

- **CR ad hoc access:** The ad hoc connection enables communication between the users on both the licensed and unlicensed frequency spectrum bands.
- **Primary network access:** The CR user can access the primary BS via the licensed bands by using adaptive Media Access Control (MAC) protocol.

Fig. 1 shows the CRN architecture. Wireless CRN is employed for the simultaneous communication of several users on a shared spectrum. It is also used to minimize the signal interference for licensed PUs and SUs in the similar frequency band range. The communication hierarchical architecture system considers the physical layer, media access layer and network layer. The CRN utilizes the similar spectrum frequency range for the recent communication system. The SUs search for the desired channels based on the bandwidth requirements. There is a need to find the alternative channels to sustain the traffic requirements of the network, during the addition of new PUs. However, the existing spectrum sensing and prediction-based sensing techniques consume more energy and exhibit low data transmission rate. This paper proposes an HMM-based channel selection framework to overcome the drawbacks of the existing approaches. The proposed approach achieves high transmission speed and low data loss, by obtaining the best-matched channel for the user. The main contributions of the proposed methodology are described as follows:

- Our channel selection framework minimizes the delay incurred during the channel selection, and optimizes the spectrum band range by using the time-slot based routing algorithm.
- The proposed framework is enhanced by implementing the routing algorithm along with the HMM.
- The channel estimation is applied for data transmission during the allocated scheduling time.
- For data transfer between nodes, the minimum time-slot consumption is achieved.

This paper is organized as follows. Section 2 reviews the existing works related to the spectrum sensing, channel allocation, and routing process in the wireless CRN. Section 3 explains the proposed HMM-based channel selection framework for optimal routing in the wireless CRN. Section 4 describes the performance evaluation results of the proposed method with the existing techniques. Section 5 presents a brief conclusion and future implementation of the proposed work.

2. Related work

This section reviews the relevant literature of the spectrum sensing, channel allocation, and routing process in the wireless CRN. Xing, Jing, Li, Huo, Cheng, and Znati [4] investigated the problem of optimal spectrum sensing interval for SUs. This approach was adaptive to the requirements of SUs and the network environment. By exploring the tradeoffs between the energy consumption and network throughput, the spectrum sensing interval was optimized using the energy-aware model. Due to the increase in the sensing interval, the network throughput was reduced. Amini and Dziong [5] presented an economic framework that incorporates the Call Admission Control (CAC) and routing and channel allocation in cognitive wireless mesh networks. The decomposed model permits for a decentralized channel allocation and the routing procedures. However, the proposed framework suffers due to the increase in the average rejection rate. Koroupi, Talebi, and Salehinejad [6] proposed an Ant Colony System (ACS) approach for spectrum allocation in the CRN. This approach was based on the Graph Coloring Problem (GCP). The running time and computation time of the proposed ACS approach were high.

Jia, Lin, Chen, Li, and Wang [7] discussed the joint channel and routing scheduling problem for wireless CR mesh networks. A mathematical model was developed along with a mixed integer non-linear programming formulation for optimizing the layers. To discover the globally optimal solution, an efficient nested optimization framework was introduced. This

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scheme achieved high network throughput by avoiding the network congestion. But, maximizing the number of channels will not improve the objective value significantly. Haghighat and Sadough [8] introduced the smart Primary User Emulation Attacker (PUEA) that transmits the fake signals in the absence of primary signal. This system could significantly reduce the performance of the sensing. Pradhan and Panda [9] introduced the Multi-Objective Cat Swarm Optimization (MOCSO) with the concept of fitness sharing. The proposed approach achieved a significant increase in the detection probability and effective reduction in the false alarm probability. Further, Cooperative Spectrum Sensing (CSS) can be extended with the distributed detection technique to enhance the sensing efficiency and reliability. But, the MOCSO approach requires more computational time.

Althunibat, Di Renzo, and Granelli [10] investigated the CSS effects on the energy consumption and feasible performance based on the limited time resources assumption. Once satisfying a detection probability threshold value, the optimal number of sensing users could increase the throughput and reduce the energy consumption. The increase in the number of users will lead to the increase in the energy consumption and decrease in the data transmission rate. El-Sherif and Mohamed [11] presented the problem of joint routing and spectrum allocation in multi-hop CRN. The system throughput was increased by using an optimal solution that determines the information about the route and spectrum allocation. This scheme guarantees high robustness for a set of routes and achieves a significant reduction in the time complexity. The improvement in the throughput rate becomes negligible when the selected hop is equal to the time complexity bound. Tumuluru, Wang, and Niyato [12] demonstrated the benefits of channel status prediction to the sensing operation of the spectrum. This system helps to enhance the utilization efficiency of the network and saves the sensing energy. It does not require apriori knowledge of the channel usage statistics. Also, the accuracy of the Multi-Layer Perceptron (MLP) and HMM prediction schemes was investigated. However, the performance of the MLP predictor was better than the HMM predictor.

Vadivelu, Sankaranarayanan, and Aswathy [13] presented a new high precision spectrum sensing approach for the CRN using HMM. Viterbi algorithm was employed in this approach for the HMM model. This scheme maximizes the network throughput and prediction accuracy. Mumey, Tang, Judson and Stevens [14] examined the problems of hard resource allocation in cognitive radio mesh networks. To increase the end-to-end path throughput, a set of available channels on each link was chosen for the channel selection problem. Anpalagan, Jaseemuddin, and Lee [15] presented a review of the resource allocation techniques in cooperative CRN. This scheme provides a better Quality-of-Service (QoS) guarantee and facilitates the usage of coexistence or cooperation spectrum-sharing scenarios.

Hasegawa, Hirai, Nagano, Harada, and Aihara [16] presented a novel optimization algorithm that avoids the exponential increase in the computational complexity of large-scale wireless networks. For varying number of cognitive users and frequencies, the total throughput was evaluated. Gavrilovska, Denkovski, Rakovic and Angjelichinoski [17] surveyed an extensive overview on the state-of-the-art advances in Cognitive-Medium Access Control (C-MAC) protocol. It highlighted the role of the regulative and standardization activities on the C-MAC cycle. Tachwali, Lo, Akyildi, and Agusti [18] introduced a novel resource allocation framework based on the minimization of bandwidth-power product. This metric was effective in evaluating the consumption rate of spectral resource in a CR environment. But, there is an increase in the bandwidth power product due to the rise in the number of supported beam forms.

Xu, Feng, Li, and Zhang [19] proposed a joint channel allocation and power control scheme. This scheme offered high flexibility and controllability in fairly allocating channels to the SUs, while achieving high throughput. Naeem, Illanko, Karmokar, Anpalagan, and Jaseemuddin [20] investigated the optimal power allocation of the cooperative CR network with the SUs outage. Further, it can increase the delay reduction mechanism and less energy improvement. The increase in the number of SUs will cause an effective reduction in the energy efficiency and increase in the transmission power in the outage constraint networks. Berangi, Saleem, Faulkner and Ahmed [21] investigated the performance of Time Division Duplex (TDD) operation inside a macrocell of a Cognitive Radio Femtocell Network (CRFN).

The existing spectrum sensing techniques require a control channel, system synchronization and suitable geographical spread of the cooperating nodes. The computational complexity of the existing channel allocation techniques is high. To overcome the issues in the existing approaches, this paper proposes an HMM-based channel selection framework for achieving optimal routing in the wireless CRN.

3. HMM-based channel selection framework

This section describes the proposed HMM-based channel selection framework for optimal routing in the wireless cognitive radio networks. The major components of the proposed scheme are as follows:

- Network formation
- Channel allocation
- Channel estimation
- Routing mechanism

Initially, the network is formed along with the primary and the secondary users. The initial parameters such as the channel k-factor and the bandwidth are set to allocate the bandwidth. Then, the bandwidth is coordinated and segregated to access the channel. At that same time, the channels are estimated and are sensed to choose the optimal selection of

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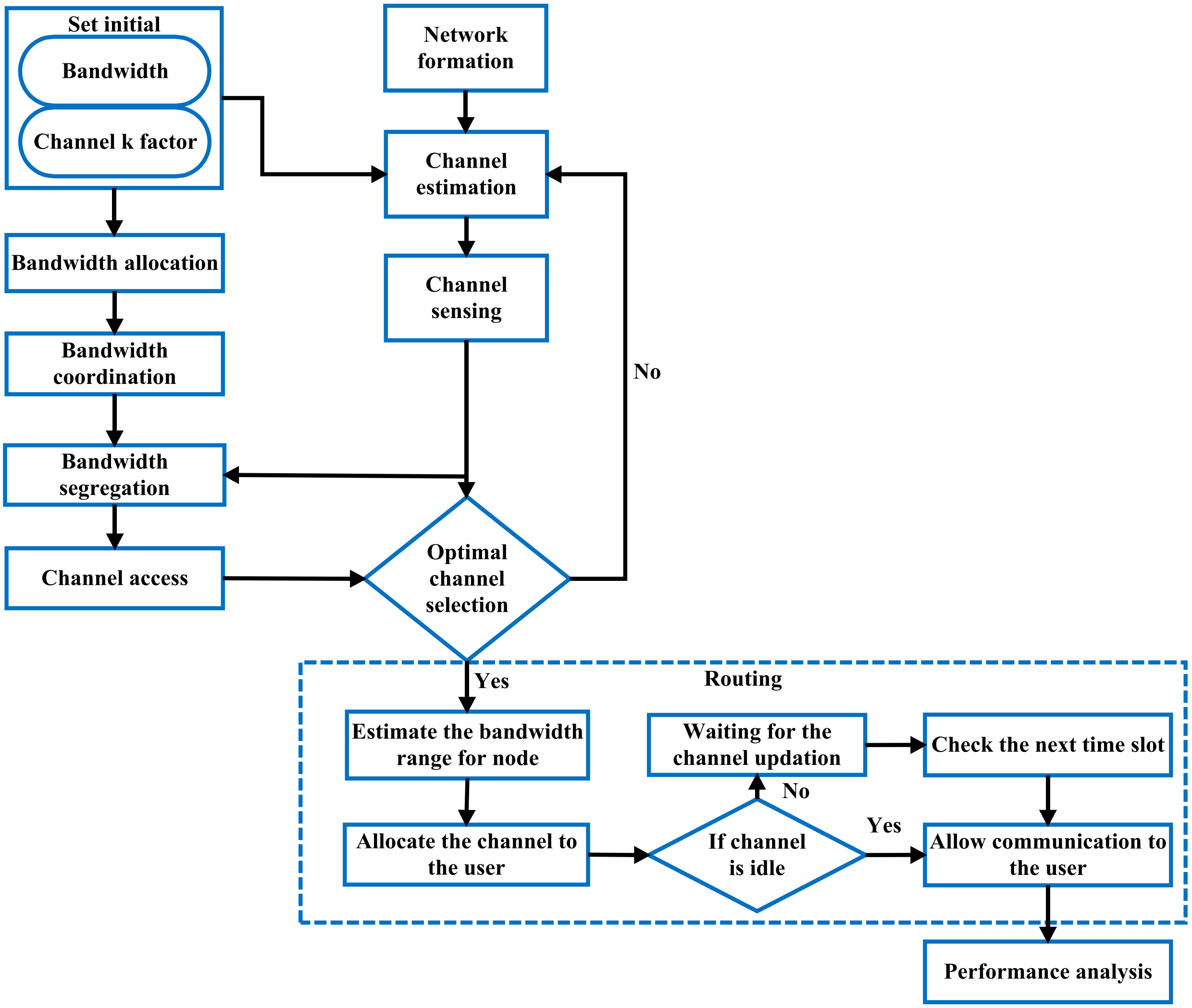

Fig. 2. Overall flow diagram of the proposed channel selection framework.

channels. To select the optimal channel, the HMM is employed. If it selects the optimal channel, the routing mechanism is selected along with the HMM framework. This system can estimate the range of bandwidth for the node and it further allocates the channel to the user. If the channel is in idle mode, it allows communication to the user. Otherwise, it waits for the channel updation and checks the next time slot. Fig. 2 illustrates the overall flow diagram of the proposed channel selection framework.

3.1. Network formation

In this module, the node formation is performed in the form of several numbers of PUs and SUs. In the proposed system, four PUs and two SUs for each PU are initialized. These users are randomly placed within the coverage area. In this formation, each SU can communicate with PU to transfer the data on the licensed and unlicensed frequency usage.

3.2. Channel allocation

The Rayleigh channel is implemented to transfer the message to the receiving node. There are various channels employed in the existing systems like Rician, Nakagami channel, etc. Among these channels, Rayleigh channel is better to transfer the data packet in terms of high frequency. The Rayleigh channel distribution is estimated by using Eq. (1). Normally, the adaptive white Gaussian noise is added to the channel for transmitting the data signal. Based on the bandwidth requirements of the user, the number of channels is initialized.

The Rayleigh distribution is given as

$$\text{Rayleigh}, \quad H = \frac{1}{\sqrt{2}} * (G) \tag{1}$$

The Gaussian Random Variable G is defined as

$$G = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-a)^2}{2*\sigma^2}} \tag{2}$$

Where x - Distribution for ‘N’ number of samples

a – Mean of distribution
σ – SD of distribution

Rayleigh channel is the Gaussian distribution channel having zero mean value and unit variance. The antenna parameter A is obtained from the convoluted values of the output signal from the transmitting antenna. It is estimated based on the channel coefficient and input sample data as given below

$$A(\mathrm{j}) = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=0}^{\mathrm{N}-1} \mathrm{h(i)x(i)e}^{\left(-\mathrm{j}\frac{(2\pi)}{\mathrm{N}}\mathrm{ij}\right)} \tag{3}$$

Where $x(i)$ – Input sample data.

$h(i)$ – Channel coefficient.
N – Number of samples.
j – Index of the symbol.

3.3. Channel estimation

Furthermore, the channel parameters are extracted to find out the matching of the channel frequency usage, along with the frequency of the node. The channel estimation and channel segregation are done by using the enhanced HMM process as mentioned below.

The weight of the channel is estimated to determine whether the bandwidth of the channel lies within a specific range and noise level of the channel is low. The weight of the channel is computed as an exponential value as given below

$$W(i,n) = \frac{1}{N} \sum_{j=1}^{N-1} e^{-j\left(\frac{2\pi}{N}\right)(i-j)n} * X(j) \tag{4}$$

Where, $X(j)$ – Sub-carriers of the transmitted signal. The matrix representation of the weight of the channel and noise term is given as

$$\begin{pmatrix} Y(S(1)) \\ \vdots \\ Y(S(N)) \end{pmatrix} = \begin{pmatrix} W(S(1),0) & \dots & W(S(1),N-1) \\ \vdots & \ddots & \vdots \\ W(S(N),0) & \dots & W(S(N),N-1) \end{pmatrix} h + \begin{pmatrix} Z(S(1)) \\ \vdots \\ Z(S(N)) \end{pmatrix} \tag{5}$$

The vector form of the above equation can be represented as,

$$Y = Wh + Z \tag{6}$$

Where ‘Z’ is the noise term. From this ‘Y’ sequence, the optimal fitness value is extracted from the Enhanced HMM from the output of probability sequence, ‘O’ and ‘N’ represents the number of channels. If the probability value is high, the channel is selected. The probability value is estimated based on the state transition probabilities and emission probabilities.

$$O_N = \sum_{i=1}^{N} \sum_{j=1}^{N} Y(i) a_{ij} b_j (W(j+1)) h(j) \tag{7}$$

From this selected index, ‘S’ is estimated as,

$$S = \begin{Bmatrix} index(O_N) & O_N \geq Avg.(O_N) \\ 0 & Else \end{Bmatrix} \tag{8}$$

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Procedure for Enhanced HMM Process

```
State Sequence Variables: $X_1 \ldots X_T$.
// 'X' denotes the sequence arrangement of the channel array upto 'T' number of channels.
Output Sequence Variables: $O_1 \ldots O_T$
// 'O' denotes output sequence label to select channel number to transmit the data packet.
Set of Hidden States ($S_1 \ldots S_N$)
Output Alphabet ($K_1 \ldots K_M$)
Initial State Probabilities ($\pi_1 \ldots \pi_N$)
    $\pi_I = p(X_1 = S_i),\ i = 1, \ldots, N$
State Transition Probabilities ($a_{ij}$) $i,j \in \{1,\ldots,N\}$
    $a_{ij} = p(X_{t+1}|X_t),\ t = 1, \ldots, T$
Emission Probabilities ($b_{ij}$) $i \in \{1,\ldots,N\}, j \in \{1,\ldots,M\}$
$b_{ij} = p(X_{t+1} = S_i|X_t = S_j),\ t = 1,\ldots,T$
```

In the HMM process, the channel values such as K-factor, Sigma, and alpha values are passed initially. From these parameters, the correlation matching for each row value of each channel matrix is extracted. According to the correlation factor, the sample weight value for each iteration of randomized particle value is updated. Then, the condition in which the present state is greater than the flag array condition of sampled weight updation is checked. Moreover, the index value matched with the channel limitation for the given number of the sequence is extracted. This sequence gives the log-likelihood value of the given channel matrix condition.

3.4. Routing mechanism

After the channel selection, the optimal routing mechanism is selected. Time-slot based routing process is introduced in the proposed system. The input considered for this process is the channel label. It is checked whether the channel is in the idle state or not, for the number of time slots along with the length of the selected channel index. If the condition is said to be true, then the matching channel is checked for the node and data transmission through the channel is performed. Otherwise, it waits for the next time slot.

Time Slot based Routing Mechanism

```
Input: Channel Label
Output: Index of node to transmit
// S – Selected channel index.
For $t = 1$ to number of time slot
  For $i = 1$ to length of 'S'
    If ith channel == idle, then
      Check matching channel for node and transmit data;
    Else
      Waiting for next time slot;
    End loop;
  End loop;
Demodulate the received packet;
Reconstruct Frames;
Reconstruct message bit;
End loop;
```

At last, the received packets are demodulated, and the frames are constructed. Also, the message bits are reconstructed to obtain the index of the node to transmit. The advantages of the proposed system are:

- Minimization of the frame losses and execution time.
- Repetition of the process is avoided.

The HMM optimization gives the result of best fitness value based on the probability of channel parameters. Our proposed HMM optimization enables best selection of the channel for the PUs and SUs. From the Emission Probabilities (bij) of the HMM, the probability of the best features of the channel is obtained. From this, the index of the best feature of the channel is extracted to obtain the channel selection result from the HMM.

4. Performance analysis

This section analyzes the performance of the proposed system with various existing techniques by using the performance metrics such as run time, energy consumption per bit of traffic, end-to-end throughput, average end-to-end delay, and bandwidth-power product. In this analysis, the number of users/nodes is 7, the number of channels is 8, the cognitive radio is 4, and the relay networks are 4.

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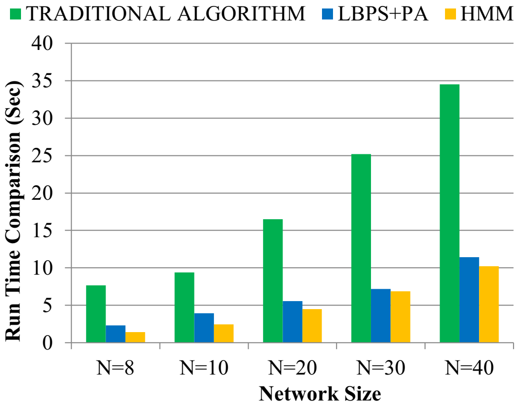

Fig. 3. Comparison of the running time with respect to the network size.

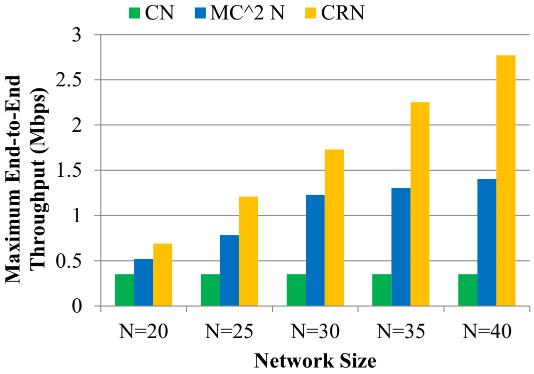

Fig. 4. Maximum end-to-end throughput analysis with respect to the network size.

4.1. Run time comparison

The run time is defined as the overall execution time of the algorithm. Fig. 3 shows the comparison results of the run time of the existing algorithm such as Simplex method implemented in C Programming (CPLEX), decomposition scheme, i.e., Link-Band Pair Selection (LBPS) plus Power Allocation (PA) (LBPS plus PA) [22], and the proposed technique. It is the total running time of solving Pricing Problem (PP) until an optimal result for Master Problem (MP) is obtained. The running time needed by the proposed system is lower than the other two techniques. From the graph, it is obvious that the proposed scheme outperforms the traditional algorithm and the decomposition technique.

4.2. End-to-end throughput vs. network size

The end-to-end throughput (TH) is defined as the ratio of the number of frames delivered and run time, in Mbps.

$$TH = \frac{\omega}{T_R} \tag{9}$$

Where, ω is the Number of Frames delivery, and T_R is the run time.

The maximum end-to-end throughput in Fig. 4 under four various network architectures are [23]:

- Single-radio single-channel single-hop traditional cellular network,
- Single-radio single-channel multi-hop cellular network,
- Single-radio single-channel multi-hop cognitive cellular network, and
- Multi-radio Multi-channel multi-hop cognitive cellular network.

Particularly, these architectures mention the current typical Cellular Network (CN). This scheme indicates that it cannot fully support all the demands of data traffic. It increases the spectrum spatial reuse and adaptivity of link rate. Maximum End-to-End throughput of the CRN is compared with the Cellular Network (CN) and multihop cognitive cellular network (MC^2 N). From Fig. 4, it is clearly evident that the proposed scheme achieves maximum end-to-end throughput than the other methods [23]. The end-to-end throughput of the CRN increases with the increase in the network size.

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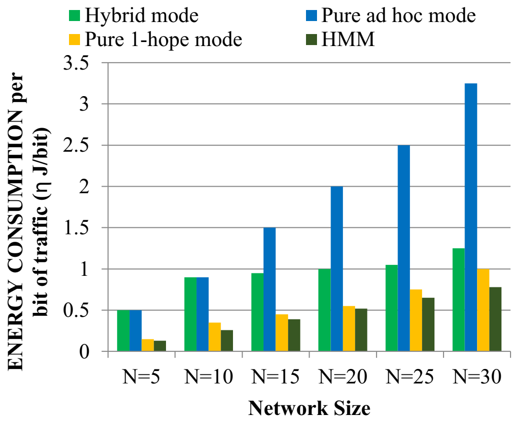

Fig. 5. Energy consumption per bit of traffic with respect to the network size.

4.3. *Energy consumption per bit of traffic vs. network size*

The energy consumption is performed along with the transmission energy and reception energy, per bit of traffic. The proposed scheme is compared with the hybrid mode, pure ad hoc mode, and pure one-hop mode [22]. It is estimated by dividing the total power consumption by the maximum end-to-end throughput achieved. Energy consumption at mobile users is considered as more critical in wireless networks. It is given as

$$E = m * S + b \tag{10}$$

Where, ‘E’ is the energy consumption in Joules, ‘m’ is number of present activate node, ‘S’ is the size of frames and ‘b’ is the fixed cost of node.

Therefore, Fig. 5 shows the energy consumption per bit of traffic for all users, when N ranges from 5 to 30. The energy per bit consumed in the proposed scheme is the lowest than the other schemes since the transmission energy of users is 0. It is clearly evident that given the same N, the users consume much more energy per bit in the other existing schemes. Apart from the existing techniques such as hybrid mode, pure ad hoc mode, pure 1-hope mode, the proposed methodology achieves a significant reduction in the energy consumption than the existing schemes.

4.4. *Bandwidth-power product*

The power product is defined as the ratio of the characteristics of the transmitting and receiving antennas and transmission range.

$$P_x = A/d \tag{11}$$

Where ‘A’ is the characteristics of the transmitting and receiving antennas and ‘d’ is the Transmission range.

Fig. 6 depicts the impact of a number of users on the bandwidth-power product utilization using Bandwidth-Power Product Minimization (BPPM) algorithm and Power Minimization (PM) algorithm [24]. The required data rate per user is 100 Kbps. The graph shows the reduction of bandwidth-power product utilization using proposed system, when compared to the BPPM and utilization of PM. The bandwidth power product of the proposed approach increases gradually for the data rate of 100 Kbps, with respect to the increase in the number of users.

4.5. *Average end-to-end delay*

The end-to-end delay is the total amount of the delay incurred during the transmission of a packet through the different nodes from a source node to the destination node. The average end-to-end delay for the packets of data stream ‘F’ is given by

$$D_F = \sum_{v \in v_F} D_v^F \tag{12}$$

Where v_f is the set of nodes that constitute the transmission routes for the packets of the data stream. D_v^F is estimated as,

$$D_v^F = T(v) \tag{13}$$

Here ‘T’ represents time taken for packet transmission. The delay rate can be varied for the probability of channel as,

$$D_v^F = \frac{T(v)}{P} \tag{14}$$

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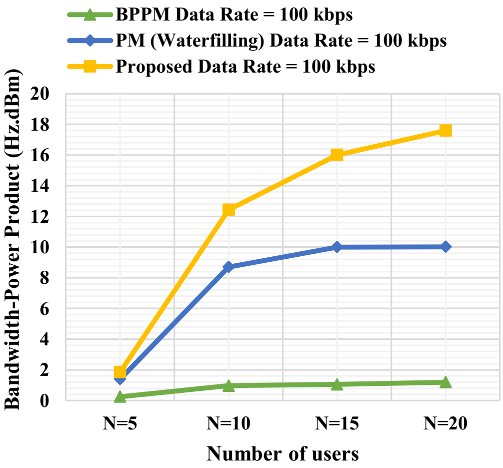

Fig. 6. Bandwidth-Power product with respect to the number of users.

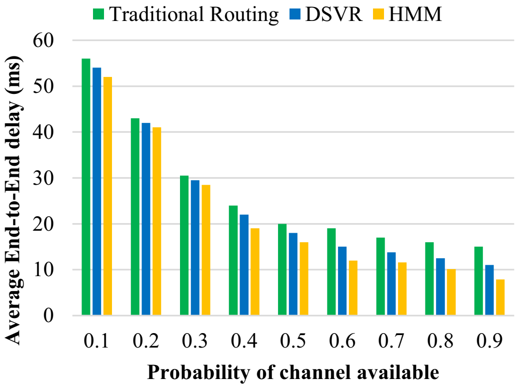

Fig. 7. Average end-to-end delay with respect to the probability of channel available.

Where ‘P’ represents the probability of channel. Since the delay rate is inversely proportional to the probability of channel, it decreases with the increase in ‘P’ value.

From Fig. 7, it can be concluded that the average end-to-end delay of the proposed HMM approach is lower than the Dynamic Spectrum Variation real-time (DSVR) algorithm and the traditional routing algorithm [25]. Due to the time-slot based routing, the average end-to-end delay decreases with respect to the increase in the availability of the channels. From the performance analysis results, it is concluded that the proposed approach achieves maximum end-to-end throughput and bandwidth-power product, and lower running time, energy consumption per bit of traffic, and low average end-to-end delay.

5. Conclusion and future work

In the proposed work, we implement an optimized and efficient routing algorithm in CRN. This process estimates the channel selection by using HMM-based approach. From the optimization result, maximum probability of the channel usage is obtained based on the channel parameters and its features. According to the maximum probability of the channel usage, the PU and SU channels are estimated based on the channel scheduling and routing process. During the routing process, the maximum probability of the channel is considered as PU. The index related to the probability matched to its channel usage is considered as the SU. Then, it is allocated to the users according to the channel state. In our proposed work, the best channel is chosen among the idle channels based on the HMM-based channel estimation method. The selected channel is allocated to the user. Also, it has minimum packet loss and bandwidth loss than the existing algorithms. The proposed approach achieves signification reduction in the data loss and increase in the transmission speed, by obtaining the best matched channel for the user. In future, we implement power optimization technique through the cluster formation with scheduling of the frame transmission and channel sensing parameters. This optimization technique will reduce the complexity of the present work and achieve better performance in terms of parameters such as delay rate, transmission time, and scheduling time allocation.

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