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Optimal Huffman Coding Performance of Ad-Hoc Networks Based on Cross-Layer Design

RIDHIMA MEHTA
School of Computer and Systems Sciences
Jawaharlal Nehru University
New Delhi, 110067 India
E-mail: mehtar1989@gmail.com

Effective data compression and sustainable management of limited bandwidth are the fundamental challenges in the design of current ad-hoc wireless networks. Dynamic Huffman coding protocol with optimal prefix-free codewords assigned to network parameters through cross-layer methodology can considerably address these issues for performance enhancement in these networks. In this paper, the entropy based Huffman binary and ternary coding schemes are implemented with cross-layer design in mobile ad-hoc networks. This cross-layer approach for achieving higher adaptivity incorporated four layers of the traditional networking stack. The simulation results demonstrated the performance trade-off between throughput and coding metrics for the proposed cross-layer architecture. Moreover, our proposed model exhibits substantially higher compression ratio and coding efficiency than the other existing methods through the integration of this lossless coding protocol in the developed cross-layer framework.

Keywords: ad-hoc network, cross-layer design, Huffman coding, information rate, coding efficiency

1. INTRODUCTION

End-to-end reliable communication of data across multiple sessions is an important routing characteristic in ad-hoc networks without any fixed infrastructure. In addition, efficient compression of large amounts of text information and proficient utilization of scarce bandwidth are the key design characteristics of these networks. To resolve these issues, we implement the adaptive Huffman coding method through the adoption of cross-layer networking paradigm. Diversified parameters across different layers of the standard protocol stack can be optimized simultaneously through cross-layer information exchange [1]. This flexible interlayer networking principle can be efficiently exploited for performance enhancement in resource-restrained and autonomous ad-hoc networks with distributed cooperation among the nodes [2]. Also termed as variable-length coding, Huffman coding is a particular type of data compression technique for constructing source codes with minimal redundancy. The codes constructed are prefix-free codes such that no code is the prefix of another code. This prefix-specific property facilitates reversible data transformation which allows unique deciphering of the codes without information loss. Apart from this, Huffman coding is a statistical information retrieval technique in which shorter codes are assigned to more frequently occurring network symbols.

In this work, binary and ternary (non-binary) Huffman coding algorithms are applied to the transmission attempt probabilities of wireless nodes in the network. These proba-

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bility values are acquired by implementing cross-layer optimization across multiple layers in ad-hoc networking stack architecture. Concretely, cross-layer design among the Medium Access Control (MAC), network, transport and presentation layers of the traditional stack architecture is executed for the distributed and joint optimization of channel access control, multi-hop routing, rate control, and coding/data compression problems, respectively. Subsequently, several performance metrics relating to the employed coding schemes are measured and compared to evaluate the efficacy of the proposed cross-layer analysis modeling framework. The impact of the order of Huffman trees on network evaluation metrics such as achievable data-rates, coding efficiency, average codeword length, *etc.* is explored through extensive experimentation.

Table 1. A list of nomenclature showing all the variables used in the optimization model.

Symbol	Description
$\mathbb{S}$	Set of information source nodes
$\mathbb{K}$	Set of communication links
$\mathbb{V}$	Set of wireless nodes
$\boldsymbol{Z}$	Set of integers
$\mathbb{N}_v$	Set of neighbors of node $v \in \mathbb{V}$
O_v	Set of outgoing links from node $v \in \mathbb{V}$
r_s	Information rate of sourc $s \in \mathbb{S}$
ψ_s	Utility function associated with source $s \in \mathbb{S}$
ω_0	Maximum achievable data-rate
$H(s)$	Entropy rate of source $s \in \mathbb{S}$
$\pi_W(\cdot)$	Probability distribution of source information sequence W
p_k	Persistence probability of link $k \in \mathbb{K}$
δ_k	Data flow rate across link $k \in \mathbb{K}$
Ξ	Traffic routing matrix
Δ	Link flow rate vector
ζ	Session data-rate vector
Ω	Feasible set of source rates
τ	Number of iterations employed in CVX software

The remainder of the paper is structured in the following sections. Section 2 provides a brief overview of related work on the Huffman compression employed for general wireless systems over the previous years. Section 3 reviews the system model. Section 4 formulates the proposed optimization problem with the application of Huffman coding techniques based on the cross-layer principle. Implementation and simulation results are discussed in Section 5. Finally, Section 6 concludes the paper with future direction of research enhancement in the theme. Table 1 summarizes various symbols and variables deployed in the following sections together with their descriptions.

2. LITERATURE SURVEY

In this section, a qualitative review of the existing works that are related to our field of research study is presented. The authors in [3] executed Huffman coding and Space

Time Trellis coding techniques as a combination for simultaneous source channel coding for high data-rate wireless communications. It also provided the bit error rate analysis of unreliable wireless fading channels with interference and propagation loss. In a similar way, the implementation of Huffman coding scheme for modelling the source codes and Reed-Solomon coding system for representing the channel codes is designed to analyse the energy efficiency and error rate performance in wireless body area networks [4]. The entropy-based data compression technique is employed for the case of sensor nodes monitoring raw environmental data with low resolution [5]. This model based on the application of standard Huffman dictionary evaluated various coding related parameters for multiple temperature and relative humidity datasets. A novel Huffman encoding algorithm based on temporal data correlation for sensor networks is proposed in [6]. This algorithm improved power saving management through the communication of compressed sensor data, but it did not consider the limited capacity and throughput performance in wireless networks. Rao *et al.* [7] introduced Huffman coding based optimal path selection algorithm for wireless sensor networks. It aimed at providing quality of service support by reducing packet loss and energy utilization, but without concerning the capacity and channel access restrictions. Lossless data compression based on Huffman and run length coding techniques is used in [8] to achieve energy efficiency in wireless sensor networks. Recently, Yang *et al.* [9] presented coding optimization of text information in the context of wireless vehicular networks for real-time traffic control through Huffman encoding and neural network models. The authors in [10] proposed a modified Huffman coding algorithm to attain power efficiency and data security in the sensor networking paradigm. Work in [11] deployed rate control and opportunistic network coding for the data packets transportation across networks using the cross-layer framework.

In our previous work [12], a cross-layer iterative optimization algorithm is developed for ad-hoc networks with entropy-based data compression, bounded capacity and network flow validity restraints. This distributed algorithm [12] implemented the congestion control, transmission path selection, contention control and power control problems at the transport, network, MAC and physical layers, respectively. Furthermore, the dependency of Huffman protocol on compression window width is explored in [13] through the heuristic computation of coding efficiency bounds. Jang *et al.* [14] employed Huffman tree coding for long range communication in low speed wide area networks to address data compression and security issues. To implement low delay requirement and security mechanism in smart device applications with shared data, a novel encoding scheme based on Huffman compression is designed and implemented in [15]. An improved encryption method based on the application of Huffman tree mutations is introduced in [16] for compressed data transmission in multimedia networks. Likewise, the authors in [17, 18] used this coding technique for secure signal transfer through wireless data broadcasting networks with higher communication efficiency.

Despite these previous works, we focus on the combined and distributed optimal design of channel contention control, flow control, rate control and data compression problems encompassing four layers of the protocol stack. In the proposed work, n-ary adaptive Huffman coding algorithm is applied to the cross-layer design framework in wireless adhoc network. The developed cross-layer design architecture implemented with binary and ternary Huffman coding protocols is depicted in Fig. 1. This technique requires preliminary knowledge of the node persistence probabilities, which are optimally computed through cross-layer optimization. These probabilities dynamically change with the increasing number of nodes in the network. The designed cross-layering onto the protocol stack supported efficient multi-hop routing with optimal channel access and coding strategies. The contribution of this paper is twofold. Firstly, we perform cross-layer optimization across different layers of protocol stack. Secondly, the optimized node transmission attempt probabilities computed through cross-layer design are fed to the marginal source entropy rates to implement optimal Huffman binary and ternary coding protocols.

3. SYSTEM MODEL

Consider the communication topology of an ad-hoc wireless network modelled by an underlying connectivity graph with $|\mathbb{S}|$ source nodes and $|\mathbb{K}|$ links. Here, $|\cdot|$ is used to denote the cardinality of a particular set. Fig. 2 illustrates a sample ad-hoc network with random placement of nine wireless nodes. The end-to-end information flows across the four source-initiated communication sessions experimented in this network are enumerated in Table 2. The ordered pair (α, β) signifies the directed link $k \in \mathbb{K}$ between nodes α and β, $(\alpha, \beta \in \mathbb{V})$, where $\mathbb{V}$ is the set of all nodes in the network. In addition, suppose that O_v is the set of outgoing links from node v, and $\mathbb{N}_v$ is the set of neighboring nodes of node v such that $\mathbb{N}_v = \{w : (v, w) \in \mathbb{K}\}$.

In context of information theory [19], the entropy of a communication link is interpreted as the expected number of bits required to encode data about link transmission attempt probability. Codewords are assigned to these network links with optimal length based on Huffman compression technique. The information rate r_s of a communication source $s \in \mathbb{S}$ is characterized by the maximal data-rate ω_0 achievable on the associated links and the entropy rate $H(s)$. For lossless data compression, the entropy encoded by the Huffman coding protocol is given as:

$$H(W) = \sum_l \pi_w(l) \log_2 \pi_w(l) \tag{1}$$

where $\pi_w(\cdot)$ is the probability distribution of the source information sequence. Each source node transfers information at a data-rate of r_s and consecutively acquires a utility of ψ_s. This utility is typically expressed as a continuous, monotonically increasing, strictly concave, and twice differentiable function of r_s.

Let us assume that random-access p-persistent algorithm is employed as the MAC layer protocol for wireless channel contention. In this mechanism, a node $v \in \mathbb{V}$ willing to transfer information contends for channel access with a probability $\sum_{k \in O_v} p_k$, where k is the set of outgoing links from the node v, and p_k is the persistence probability of link k. Additionally, assume that δ_k is the non-negative data flow rate across link k, that determines the routing of information over the network in accordance with a network layer routing algorithm.

We adopt a multi-commodity network flow model with several source-destination node pairs communicating simultaneously across point-to-point network links in multiple-hop fashion. Let $\Xi \in \boldsymbol{Z}^{|\mathbb{K}| \times |\mathbb{S}|}$ be the binary matrix characterizing the relationship between the end-to-end propagation of traffic flows and the link-centric data streams. Also, suppose that Δ is a $|\mathbb{K}| \times 1$ vector of non-negative link flow rates, and $\boldsymbol{\zeta}$ is an $|\mathbb{S}| \times 1$ vector of end-to-end data rates assigned to the network traffic flows from a source node to the destination of a particular data transmission session. Alternatively, $\Delta = [\delta_1, \delta_2, \ldots, \delta_{|\mathbb{K}|}]^T$, $\boldsymbol{\zeta} = [r_1, r_2, \ldots, r_{|\mathbb{S}|}]^T$.

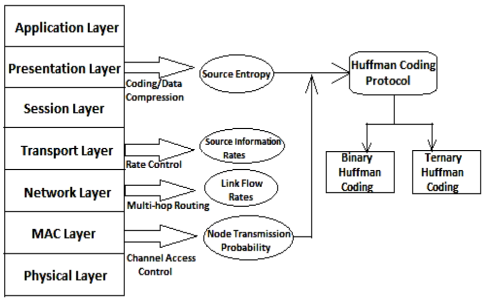


Fig. 1. Proposed cross-layer design architecture implemented with Huffman coding protocol.

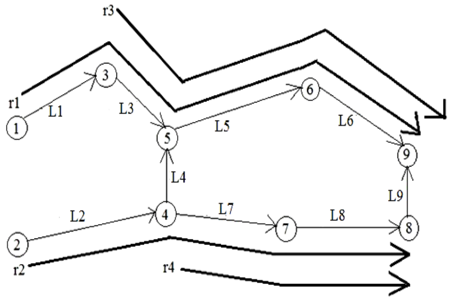


Fig. 2. Sample ad-hoc network with arbitrary topology comprising 4 sessions.

Table 2. Simulation information flows in sample topology of Fig. 2.

	Source Node	Destination Node	Routing Path
Information Stream 1	1	9	1-3-5-6-9
Information Stream 2	2	8	2-4-7-8
Information Stream 3	3	9	3-5-6-9
Information Stream 4	4	8	4-7-8

4. PROBLEM FORMULATION

The developed cross-layer design problem with mathematical formulation is given as the following non-linear and non-convex constrained optimization problem.

$$\text{maximize} \sum_{s=1}^{|\mathbb{S}|} \psi_s(r_s) \tag{2}$$

$$s.t.\ \delta_k \leq \omega_o p_k (1 - \textstyle\sum_{j \in O_\beta} p_j) \prod_{i \in (\mathbb{N}_\beta - \{\alpha\})} (1 - \textstyle\sum_{j \in O_i} p_j),\ \forall k \in \mathbb{K} \tag{3a}$$

$$\Xi \boldsymbol{\zeta} = \Delta \tag{3b}$$

$$r_s \geq H(s),\ \forall s \in \mathbb{S} \tag{3c}$$

$$0 \leq p_k \leq 1,\ \forall k \in \mathbb{K} \tag{3d}$$

$$\delta_k \geq 0,\ \forall k \in \mathbb{K} \tag{3e}$$

$$\boldsymbol{\zeta} \in \boldsymbol{\Omega} \tag{3f}$$

In the above optimization problem, the objective function defined in Eq. (2) models the maximization of the aggregated network utility over all the information sources. Theoretically, we consider the non-linear utility function $\psi_s(r_s) = \log(r_s)$. Assume that $\psi_s(r_s) \geq 0$, $\forall r_s \geq 0$, and its first partial derivative $\partial \psi_s / \partial r_s$ is well-defined and bounded function at r_s

= 0. In addition, since $(\partial^2 \psi_s/\partial r_s^2) < 0$, $\forall s \in \mathbb{S}$, the utility function is strictly concave with negative curvature. In the given set of constraints, the first constraint in Eq. (3a) represents the bandwidth control operation across each link $k \in \mathbb{K}$. The second constraint in Eq. (3b) enforces the link-oriented flow conservation system, which affirms that the total incoming traffic on an individual link is same as the total traffic emerging from that link. Eq. (3c) specifies the data compression restraint applied to each link k. This constraint ensures that different sequences of codewords with high correlation communicated by various sources have minimal redundancy of information. Eqs. (3d) and (3e) define the valid interval of values for all link transmission attempt probabilities and for all link flow rates, respectively. Finally, the polyhedral set $\mathbf{\Omega}$ in Eq. (3f) is used to specify the valid range for the source data-rate vector, $\boldsymbol{\zeta}$, *i.e.*, $\Omega = \{\zeta: r_s \le r_s^{\min}, r_s \ge r_s^{\max}, \forall s \in \mathbb{S}\}$.

The non-convexity of the aforementioned optimization problem stems from the non-convexity and non-separable programming conditions of the first constraint in Eq. (3a). However, the objective function involves maximization of a strictly concave logarithmic function over the information rates r_s. Besides, rest of the constraints in Eqs. (3b)-(3f) in the feasible region are linear and convex. To obtain a global optimal solution for the developed system with distributed implementation, it is necessary to transform the above non-convex problem into an equivalent convex optimization problem. This can be accomplished through the application of $\ln(\cdot)$ operator to the first constraint and the deployment of some supplemental variables which are given as follows: $r_s' = \ln r_s$, $r_s'^{\min} = \ln r_s^{\min}$, $r_s'^{\max} = \ln r_s^{\max}$, and $\delta_k' = \ln \delta_k$.

The reformulated optimization problem specified below is a convex programming problem since it incorporates maximization of a strictly concave criterion function subject to the convex feasible constraint set [20].

$$\text{maximize} \sum_{s=1}^{|\mathbb{S}|} \psi_s'(e^{r_s'}) \tag{4}$$

$$s.t.\ \ln(e^{\delta_k'}) \le \ln(\omega_o) + \ln(p_k) + \ln(1 - \textstyle\sum_{j \in O_\beta} p_j) + \textstyle\sum_{j \in (\mathbb{N}_\beta - \{\alpha\})} \ln(1 - \textstyle\sum_{j \in O_i} p_j),\ \forall k \in \mathbb{K} \tag{5a}$$

$$\Xi \boldsymbol{e}^{\zeta'} = \boldsymbol{e}^{\Delta'} \tag{5b}$$

$$e^{r_s'} \ge H(s),\ \forall s \in \mathbb{S} \tag{5c}$$

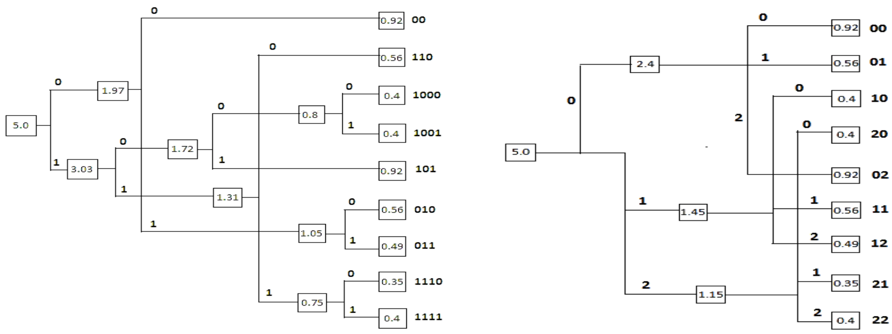
$$0 \le p_k \le 1,\ \forall k \in \mathbb{K} \tag{5d}$$

$$\boldsymbol{\zeta}' \in \boldsymbol{\Omega}' \tag{5e}$$

The computational polynomial-time complexity of the above optimization problem is evaluated as $O(3\tau(|\mathbb{S}| + |\mathbb{K}|))$, where τ is the number of iteration instances employed by the CVX solver [21] to achieve the evolved and improved global optimal solution. Further, Fig. 3 depicts the binary and ternary Huffman trees with variable-length codes assigned to leaves of the tree. These leaves correspond to the optimal values of node transmission attempt probabilities computed via the proposed cross-layer design in ad-hoc networks. Note that each branch is labelled with bits 0 and 1 in Huffman binary tree, while with trits 0, 1 and 2 in the Huffman ternary tree. Also, the ternary tree involves smaller number of internal nodes and shorter path length from root to the leaves, resulting in faster compression and more efficient coding, as is evident in the simulation results specified in the next section.

5. PERFORMANCE EVALUATION

This section verifies the performance of the proposed cross-layer coding techniques based on convex optimization theory. We consider dynamic Huffman coding schemes in which the codes adapt to the changes in network characteristics over time. In this work, the network size, *i.e.*, the total number of nodes in the wireless network is utilized as the varying attribute to experimentally compute and analyze different network service quality and coding metrics.



(a) (b)

Fig. 3. Huffman (a) binary and (b) ternary coding trees corresponding to the transmission attempt probabilities of different nodes in the sample ad-hoc network.

5.1 Simulation Environment

The proposed work is evaluated by conducting simulations in CVX software [21], which is the default MATLAB package employed for solving convex optimization problems. Specifically, the successive approximation technique is implemented in SDPT3 (version 4.0) solver of the CVX software for efficient handling and specification of the developed cross-layer scheme. We consider the random waypoint mobility model with Poisson distributed speed of movement and pause time of 100 ms. The imperative parameters and the respective values used in our simulation environment are summarized in Table 3.

Table 3. Basic simulation parameters.

Parameter	Value
Topographic Area	500m × 500m
Simulation Software	CVX
Channel Type	Wireless
Network Topology	Random
Number of Nodes	5 – 100
Node Mobility	Random Waypoint
Application Layer Protocol	CBR
Transport Layer Protocol	TCP
Network Layer Protocol	IP
MAC Layer Protocol	IEEE 802.11 DCF
Physical Layer Protocol	IEEE 802.11
Antenna Model	Omni-directional
Initial Information Rate	20 Kbps
Minimal Information Rate	5 Kbps
Maximal Information Rate	1200 Kbps

5.2 Simulation Results and Discussion

At this stage, distinctive coding and traffic capacity metrics are employed to evaluate the performance of the proposed cross-layer based Huffman coding methods. These metrics considered for simulation analysis include the link data-rate, average codeword length, coding efficiency, redundancy and source information rate. Fig. 4 shows the network data-rate for Huffman binary and ternary coding schemes implemented with the proposed cross-layer optimization formulation. For the investigated ad-hoc network comprising 50 nodes, the system data-rate achieved over the communication channel with binary coding is 568.2 Kbps, while that with ternary coding is 387.85 Kbps. Coding efficiency for both the coding techniques plotted in Fig. 5, is defined as the ratio of entropy to the expected codeword length. On an average, the Huffman ternary coding applied to presented cross-layer approach exhibits 36.33% higher coding efficiency than the binary coding counterpart, given the fact that ternary coding uses a larger set of symbols to compress the nodal information. The average codeword length acquired using the binary, ternary and optimal coding schemes is illustrated in Fig. 6. This coding metric is defined as the average number of *n*-ary digits per symbol for an *n*-ary Huffman code alphabet. It can be estimated that the average codeword lengths for the considered coding methods are 84.26, 58.243 and 56.45 respectively. Moreover, the average codeword length for ternary coding is approximately comparable to optimal coding method for all network sizes.

The mobility prediction parameter directly proportional to the average entropy rate is plotted in Fig. 7 for varying network sizes. The expected value estimated for this parameter for the considered range of network nodes is 0.5153. Subsequently, Fig. 8 compares the redundancy of the two Huffman coding techniques. This redundancy metric is measured by the difference between the average codeword length and the entropy for a given probability distribution. For the investigated network topology with varying number of nodes, ternary coding method exemplifies 49.72% reduction in mean code redundancy as contrasted with binary coding. Finally, Fig. 9 depicts the evolution of the expected values of the source information rate with the network size. This rate is determined by the source entropy rate and the initial bit rate assigned to each communication source.

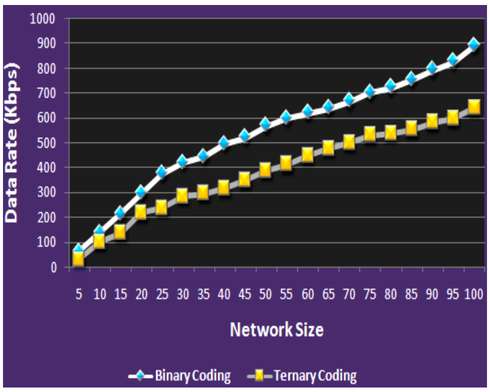


Fig. 4. Maximal data rate attained for binary and ternary coding with different network sizes.

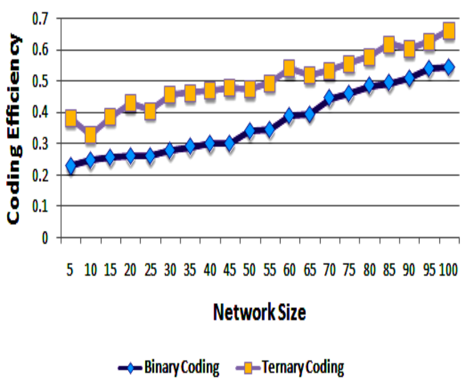


Fig. 5. Coding efficiency for binary and ternary coding schemes with varying network sizes.

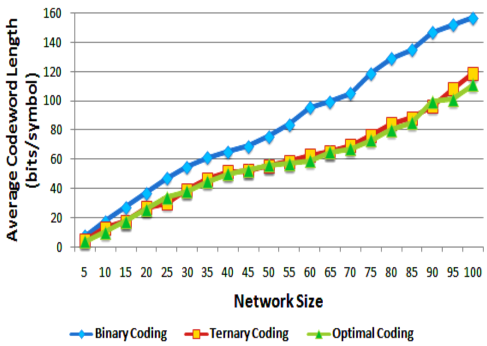


Fig. 6. Comparison of average codeword length for binary, ternary and optimal Huffman coding schemes.

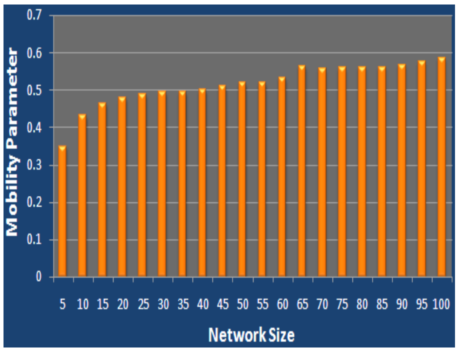


Fig. 7. Mobility parameter with varying network sizes.

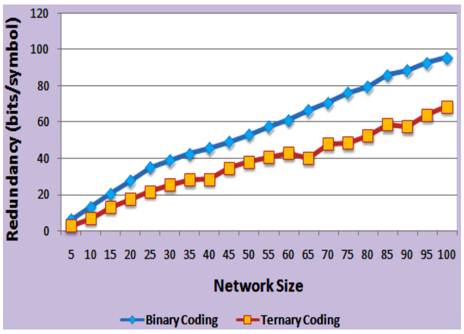


Fig. 8. Redundancy for binary and ternary cod-Ing schemes with varying network sizes.

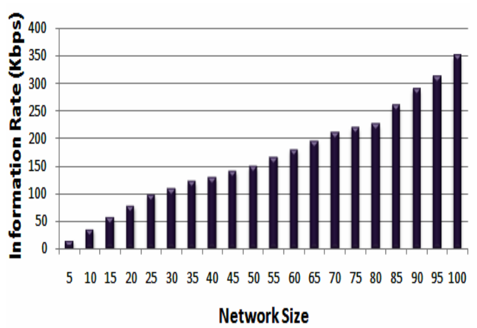


Fig. 9. Minimal required information rate for different network sizes.

These simulation experiment results demonstrate the comparative trade-off between achievable throughput and coding efficiency for the employed Huffman coding cross-layer models. Observe that the binary coding strategy with higher data-rates corroborates lower coding efficiency. This is attributed to the increased length of codewords for each node and more code redundancy accomplished with the binary codes as compared to the ternary codes. In general, as *n* increases for *n*-ary Huffman coding implementation of the presented cross-layer formulation, the coding efficiency performance increases whereas the throughput decreases.

Further, we compare the performance of the proposed coding models comprising of network size of 30 with previously existing related works [8-10] by analyzing the throughput, compression ratio, average codeword length and coding efficiency as shown in Table 4. Although these earlier works implemented Huffman coding techniques for performance improvement in wireless networks, they did not exploit the cross-layer modeling paradigm with conflicting resource constraints and data coding requirements. Contrary to this, we employ cross-layer design methodology encompassing four layers of the conventional protocol stack structure to attain performance gains. Both the proposed models in our work perform better than the previous methods in terms of obtaining significantly higher throughput by up to 90.53%, fast compression ratio by more than 88%, and approximately 62%

increased coding efficiency. They also outperformed the existing methods with essentially 69.4% reduction in the expected compressed length of nodal probabilities.

Table 4. Performance comparison of proposed models with existing works [8-10].

	Throughput (Kbps)	Compression Ratio (%)	Average Code-word Length (bits)	Coding Efficiency (%)
Proposed Binary Coding Model	425.4	332.65	56.4	27.25
Proposed Ternary Coding Model	276.2	458.4	38.7	44.56
Model in [8]	93	51	114.7	18.35
Model in [9]	40.28	54.15	126.5	16.9
Model in [10]	172	72.03	92.45	19.86

6. CONCLUSIONS

This paper presented a lossless adaptive binary and ternary Huffman coding techniques applied to the ad-hoc networks implemented with cross-layer design architecture. The simulation trade-off between network data-rate and coding efficiency metrics is established through the analysis of applied cross-layer design for the general n-ary Huffman algorithm. Finally, the performance comparison between the proposed work and the previously existing models is evaluated in terms of networking service and compression quality metrics. For the investigated network of size 30, our proposed model demonstrated higher compression ratio by up to 89% and coding efficiency by around 62% than the other existing methods.

The effect of other significant network performance issues such as power limitations, channel errors and expected end-to-end delay constraints on the proposed work can be investigated in future. The proposed model can be extended to consider the impact of source information rates and link flow rates on the optimal Huffman coding procedure with augmented complexity. Moreover, to implement general and practical wireless network scenarios, the future directions may consider the implementation of non-deterministic and time-varying unreliable channel characteristics in the developed cross-layer system model.

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Ridhima Mehta received her Ph.D. degree in Computer Science and Technology from School of Computer and Systems Sciences, Jawaharlal Nehru University (JNU), New Delhi, India in December 2018. She received the M.Tech degree in Computer Science and Technology from JNU in 2013, and the B.Tech. degree from the Department of Computer Science and Engineering, Indira Gandhi Delhi Technical University for Women (IGDTUW), New Delhi, India in 2011. Her areas of interest include computer networks, ad-hoc networks, cross-layer design, machine learning, and convex optimization.