Graph Convolutional Network Enabled Power-Constrained HARQ Strategy for URLLC

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Abstract-In this paper, a power-constrained hybrid automatic repeat request (HARQ) transmission strategy is developed to support ultra-reliable low-latency communications (URLLC). In particular, we aim to minimize the delivery latency of HARQ schemes over time-correlated fading channels, meanwhile ensuring the high reliability and limited power consumption. To ease the optimization, the simple asymptotic outage expressions of HARQ schemes are adopted. Furthermore, by noticing the non-convexity of the latency minimization problem and the intricate connection between different HARO rounds, the graph convolutional network (GCN) is invoked for the optimal power solution owing to its powerful ability of handling the graph data. The primal-dual learning method is then leveraged to train the GCN weights. Consequently, the numerical results are presented for verification together with the comparisons among three HARQ schemes in terms of the latency and the reliability, where the three HARQ schemes include Type-I HARQ, HARQ with chase combining (HARQ-CC), and HARQ with incremental redundancy (HARQ-IR). To recapitulate, it is revealed that HARQ-IR offers the lowest latency while guaranteeing the demanded reliability target under a stringent power constraint, albeit at the price of high coding complexity.

Index Terms—Graph neural networks, HARQ-IR, power allocation, time-correlated fading channels

I. INTRODUCTION

Owadays, ultra-reliable low-latency communications (URLLC) have become an unprecedented paradigm shift to support the mission-critical internet-of-things (IoT) applications [?]. For instance, as per the 3rd generation partnership project (3GPP), a 32 byte packet is expected to transmit within 1 ms along with a reliability of at least 99.999%. To confront this stringent requirement, hybrid automatic repeat request

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(HARQ) is one of the key enabling technologies that provide reliable transmissions to combat channel fading. On the basis of different encoding and decoding techniques, HARQ can be divided into three types, namely Type-I HARQ, HARQ with chase combining (HARQ-CC), and HARQ with incremental redundancy (HARQ-IR). In essence, HARQ sacrifices the delay performance to improve reliability, which inevitably hinders its widespread applications in supporting URLLC. To overcome this shortcoming, HARQ should be properly designed with more flexibility to accommodate diverse requirements of latency and reliability.

The optimal design of HARQ schemes has been extensively studied in the literature. To name a few, in [?], the outage probability of HARQ-CC was minimized by imposing a constraint on the average power consumption. The asymptotic outage probability was used to enable the optimal power allocation with geometric programming (GP). The similar method was then applied to solve the minimization of the expected energy consumption for HARQ-IR given a maximum allowable outage tolerance in [?]. Moreover, in [?], the goodput of HARQ-IR was maximized through the joint optimization of the transmission powers and transmission rate under an average power constraint. The joint optimization of powers and rate was further considered to maximize the energy efficiency of HARO schemes, which were solved in closedform with the Karush-Kuhn-Tucker (KKT) conditions. Furthermore, the optimization of various HARQ-assisted systems has also received considerable research interest lately. To be specific, the power efficient design was considered for HARQ-CC aided non-orthgonal multiple access (NOMA) systems in [?], wherein successive convex approximation (SCA) was used to provide the optimal power solution. HARQ-NOMA-assisted short packet communications were investigated in [?], where a genetic algorithm was applied to optimize the power levels in power-constrained and reliability-constrained scenarios. Apart from high reliability and limited power consumption, the guarantee of low latency is also of profound significance to realize URLLC, while this topic was rarely examined except in a few existing works. Particularly, in [?], the age of information (AoI) was minimized for HARQ-IR-assisted multi-RIS systems while refishing power and dutage constraints in all HARC carry Classified into three eategories according to addition, the authors in [?] maximized the overall rates o addition, the authors in [?] maximized the overall rates of different coding operations, including Type I HARQ HARQ-enhanced making three band tental policy and HARQ-treatment of the control of the con grant free systems under the constraint of a maximum tolerable probability of delay bound violation. However, independent fading channels were generally assumed in these works [?], [?], [Y]i [Chéh] whosenes filts are intapplicable to the cornelated fading channels. Due to the frequent occurrence of timecorrelated fading channels.

fading channels. The simple asymptotic outage expressions of HARO schemes are adopted to avoid heavy computational burdent Unfortunately the optimization problem still reannot bunders complete the control of the has nespired use to templore the use of eartificial nintelligence (Act)n telebriques in By healtigly ribitolitic ount lithat other transmit newer allo Cated sint the optimine HARD noting has afterned by othe age rouse fier of HARQ estates of the present the property of the latency minimization pounds, and the intro-correlation lakes place influence fier in the latency minimization founds, and the intro-correlation lakes place influence fier in the latency minimization founds. channels litt is natural tol come, unewith leverb regural networks to capture this special dratismissions tructure. The graph dignost hanolian-network pGCNp is Therprivoked for the ripa mat bower talfocation of HARD by the aring any eight HARD yout by the channel correlation as graph nodes and edges, respectively. Then trainable hGCN in weights have updated by using sprimals dualideathing-apploach. HaraQyythe fatency and thegre liabRQy performance AP (the technology) produced produced after a tital Brailey) For three it knows the three that the stranger in thin excess latency while guaranteeing the terranged reliability target experiments, where the three HAR Quechemes, include of the control of the contr IoHARQmHARQ-CC, and HARQ-IR. Last but not least, despitex it Tehigh—Coding complexity world AR QLAR Qare, provide the towest latency white ensuring reliable performance within strict power constraints.

The rest of the paper is structured as follows. Section ?? chabbrates/dn/shellsystemiahbdebvandtformutates/theidatenes minimization biobtem for power-rousipained HARQ setteliges thi Sections 77 per GCN-enabled power allocation tenable years designed polisation the logisticity attent problem. Section ? Investites the teffectiveness biputer picotos & GRategy 3 Brought mandericia experiments. Finally, concluding remarks are drawn in Section This work was supported in part by National Natural Science Foundation of China under Grants 62171200, 62171201, and 62261160650, in part by Guangdong Basic and Applied Basic Research Foundation under Grant 2023A1515010900, in part by Zhuhai Basic and Applied Basic Research Foundation under Grant ZH22017003210050PWC, in part by the Hong Kong Research Tent Many Clant (RMG) in the Central Pot under Project No. CP/2022/2.1, in part by the Major Talent Program of Guangdong Provincial under Grant 2019QN01S103, in parThis paper considers a Tpoint-togpoint/HARQ-aitleddURLL-G System of the Country and problem for a wilding Author: Zheng Shi.)

GWANG PHARQUECE, combined that derrone du Hoi reverved ende words for maximal-ratio combining (MRC). Undoubtedly, selective fading of hafulelse there is Sustreaut Seech to proposing in a riog of image from the right of the final that a Sphoper laterity rassurance istrategy for the ARQ is chemical over in given a this regular partiety of resource to transcent united the contraction of the contract Nanjing 210003, I HARO and HARQ-CC, HARQ-IR transmits codewords In orderhtto lminificizen cheauddi Vershitalency, White Kong Metropolitene redunganity, a Hong di OHAISO Pounds i Hence. anteeing the hight attiakitivy Lithis response proposes me took of hings often Sideword City first reported into Meyeral, subsecutewords constrainted HARQ strategyceb sciencidering Timb-not related beiging the statistation. Twelter loan, Beiging 560064, on binson retransmission request. At the receiver, the previously received codewords are then concatenated to form a long codeword ropersodin transmit vithing up and many the ambiguitation etaligaexial. MARO in conferre this superson berranicance of hybrid automatic repeat request (HARQ) is one of the key enabling technologies that provide reliable transmissions to complat channel fading. On the basis of different encoding and decoding techniques, HARQ can be divided into the types, namely Type-I HARQ, HARQ with chase combining (HARQ-CC), and HARQ with incremental redundancy (HARQ-IR) In essence, HARQ achifices the delay performance to insprove reliability, which inevitably hinders its widespread applications in supporting URLLC.

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rounds. At the receiver side, Type-I HARQ decodes its mes-

sage by solely relying on the currently received codeword,

The optimal deligardf-HARIY schemes has been extensively studied in the literature To name a few, in [?], the outage probability of HARQ-CC was minimized by imposing a constraint on the average power consumption. The asymptotic outage probability was used to enable the optimal power allocation will geome MRC programming (GP). The similar method was then applied to solve the minimization of the expected energy consumption for HARQ-IR given a maximum allowable outage tolerance in [?]. Moreover, in [?], the goodput of HARQ-IR was maximized through the joint optimization of the transmission powers and prenample of HARQ damanissionage power constraint. The joint optimization of powers and rate was further considered to maximize the energy efficiency of HARQ schemes, which were solved in closed-form with thBKconsidering blocking feding channels the received signal indhophithiHARQ of undrans by ANDO seeds and systems has also received considerable research interest lately. To be specific, the power efficient design was considered for WhereQ=CC deinbtds nthe o/thlg ocodeworti pbf alength (NO WAh) ayetages plowed pychandin sidenetes a complex addition white (Edds)arvasoiseedectop withlezelee mpainsectorwands distribity EbAtarianNcOmatrixssist.echshort @Actor Lyon unhairefersistovene character coefficient, of the k-terrans mission billion as oid daired transprissione labencyownde leunfavorables/fadingschannels, athe

maximility numbers of ddARQ rounds for sending bach message isylimited number of war dependently frequent occurrence of the borrelation also originating disamids afth the etilize conditated Rhyleighifadingichannels:ardyused:atotimodele/togat in a few existing works. Particularly, in [?], the age of information (AoI) was introducted for HARCLIR assisted multi-RES systems while ensuring power and outage constraints In where the factor ρ measures the intensity of the fillie concellated ddition, the authors in Ω maximized the overall rates from between channel coefficients, ρ and ϵ_k denote the feed of enhanced mobile broadband (eMBR) users in HAROback delay and the average power of the channel, respectively, assisted grant free systems under the constraint of a α_0 , α_1 , ..., α_k are mutually independent and obey complex maximum tolerable probability of delay bound violation. However, independent fading channels were generally as According to (2), the received signal-to-noise ratio (SNR) support in these works α_k . Whose results sumed in these works [7], [7] whose results in the k-th transmission can be obtained as are inapplicable to the correlated fading channels. Due to the frequent occuprence that the selective fading channels there is an urgent need to propose a proper latency here p_k denotes the average transmit power in the k-th syurance strategy for HARQ schemes over correlated HARO round. fading channels.

C. IProblem Erimulation of Power-Constrained HARQuitar anteeing the high reliability, this paper proposes a poThe-onission-critidalARQ applications usualideremplitasize stringlented dashiniptshof medsia bilitys land leatenery pf2bioBosidese the JoE devices Bra Brequently equipped with hon-rechargeable battepy twhich cannot provide continuous, power stipply affor energy-gonstimption to bloTastetworks dubinly significantly for shelf frequency comphenication modulige dience (uthet) transmit powers ishould the toptimall (They is edition by the thif etimb of In The metvorkstific this paper we call that the accommodation of involatency as well as high redisability or aether bowereal location in differentARARQ wounds affected by the denote by IVA Bid Buthestotal and independent information edits Hand. The chands width the positive lyoiThe deliveryk eatgrey cofatheseg infiding tides bits list thus calculated ascome up with, graph neural networks to capture this special transmission structure. The graph convolutional network (GCN) is then invoked for the outtereal denotes also diffective subbated effection at iThe lifectral Efficiency out of ARQL schemes can the lastimated dryphsing the long telemsaverage throughpute (LiEATable HAROweighth can be obtained assing primal-dual learning approach. Finally, the latency and the reliability performance of the GCNenabled power allocation strategy for three HARQ schen(5) was investigated through-numerical, experiments, where the three HARQ schemes include Type-I HARQ, HARQ-Where IR HARM-Tand Lastenbre the present danging siton high and the countering of Sira Programment with the edge of the section of the sectio lateremiyali Pensurinerselis ble nenageranosaviliki rantrick HARO quarter with the definition of the latency, the latency minimization problem of the power-constrained HARQ while guaranteeing its high reliability can be formulated as tency minimization problem for power-constrained HARQ schemes. In Section ??; a GCN-enabled power allocation strategy is designed to solve the optimization problem. Section ?? verifies the effectiveness of the proposed stratwherehtherghliabilityrisabnsured by imposing lay constrainting thenoulage probabilityinas det idenotes the maximum acceptable

outage tolerance, p HenStestethe Mnakilmum allowable total transmit power, and a clear depotes the tayerage transmit power that it evaluated are begin, the system model is delineated in this section, including HARQ schemes, signal transmission model, and problem formulation.

A. HARQ Schemes

and we stipulate $P_{\text{cut 0}} = 1$. It should be mentioned that the "HARO can be classified into three categories according power, allocation, is optimally designed by only utilizing the coding operations, including Type-I HARO, statistical channel state information (CSI) to avoid frequent HARO-CC, and HARO-IR. More specifically, for both signaling interactions and conserve time. delivered in all HARQ rounds. At the receiver side Type-I HARQ decodes its message by solely relying on the cuAlthough ether exacts outage dexpressions a ROHARQ os astems were eleriyeduiny[?]edelwelf].cthe outage expressions.anyalye then summating Ref) a wrindinite aumbea RC speciality unations. Syche-complex representations, entailed high computational burdan forsetha optimaladesignUAnkerder, de Jovensproe this issup, the as unprotici expressions of the course carebabilities are leveraged in the optimal design. As derived in [2], [2], [2], [2] thelasymptoticioutage probabilities of three types of HARQ schemes are given by hich will be sent one by one upon retransmission request. At the receiver, the previously received codewords are then concatenated to form a long codeword to the Soint decoding Owing to the high encoding/decoding complexite).HARQ-IRRachieves the superior performance of reliability.

where $\Gamma(\cdot)$ denotes the Gamma function, $\varsigma_K =$ $\ell(\rho, K)$ quantifies the effect of correlation that is given by

$$\ell(p,K) = \left(1 + \sum_{k=1}^{K} \frac{\rho^{2(k+\delta-1)}}{1-\rho^{2(k+\delta-1)}}\right) \prod_{k=1}^{K} \left(1 - \rho^{2(k+\delta-1)}\right),$$
it should be noted that $\rho \ge 1$ and $\mathcal{E}_{\mathcal{V}}(R)$ reads as

it should be noted that $\rho \neq 1$, and $\mathcal{G}_K(R)$ reads as

$$\mathcal{G}(R) = (-1)^{K} + 2^{R} \sum_{k=0}^{K-1} (-1)^{k} \frac{(R \ln 2)^{K-k-1}}{(K \ln 2)!}.$$
(10)

Unfortunately, due to the correlation among different transmissions, the fractional form of the objective function, and non-convexity of constraints, the optimization problem in (??) still cannot be easily solved by means of the classical optimization methodologies, such as CVX tools. The success of the application of GCNs in power allocation policy learning for wireless networks [?] has motivate Cus to develop GCN-based power allocation for power-constrained HARQ schemes. It is clear that different HARQ rounds and correlations among them can be represented by graph nodes and edges, respectively. It is noteworthy that GCN is suitable herein due to its ability of exploiting the graph structure to process data. In what follows, a GCNFegabledApowerratibe at foll Adhenie is stetialistis.

A. GCN-Based Power Allocation B. Signal Transmission Model

To enable the GCN-based power allocation, each HARQ By considering blocking fading channels, the received round is modeled as a graph node. Moreover, as aforemensignal in the k-th HARQ cound can be expressed as tioned that the statistical CSI is used, the graph edges can be characterized by the correlation coefficients among fading

channels, More specifically, the channel correlation to deficient matrixe Hoisvealculated as denotes a complex additive white Gaussian noise vector with zero mean vector and identity covariance matrix, i.e., $\mathbf{n}_k = \mathbf{n}_k \mathbf{n}_k$ charge he coefficient of the k-th transmission. To avoid large transmission latency under unfavorable fading channels, the maximum number of HARQ rounds for sending each message is limited up to K. Due to the frequent occurrence wherein one suipers empong dedones the redemplex teoritigate operation and Eleighs the egpeleration soperation! The rationale of $\alpha_{ij} = 0$ for i > j is due to the fact the j-th HARQ round cannot be influenced by the 1-th HARQ round. With the time ane given by Ellay had the syverage power of parendy H can be treated as the adjacency matrix in the directed graph betwork mplex normal distributions with zero mean and unForstractability, the power policy functional space p = (p1A@20rdipW)tris (parameterized; by) using lategraphe neural networks. More specifically sthe power allocation policy is defined as $\mathbf{p}(\mathbf{H}) = \Psi(\mathbf{H}; \mathbf{W})_2$ where Ψ represents a L-layer GCN with trainable weights \mathbf{W} . Instead of optimizing \mathbf{p} , the neural network parameters Wenced to be justimally determined through the primal-dual learning approach [?]. As shown in Fig. ??, a L-layer GCN structure for the power-constrained HARO schemes with K^0 of Rwerven as trained HARO schemes with K^0 of V^0 in $V^$ features Mission-ori GON for updated by following the layerwise propagation quateraints of reliability and latency [?]. Besides, the JoT devices are frequently equipped with non-rechargeable batter Pwlith Pain Vt pWvide continued power supply. The energy consumption of IoT networks where I stands for an all-ones column vector. $\mathbf{D} = \text{diag}(\mathbf{H})$ mainly comes from the radio frequency communication denotes the degree matrix. $\mathbf{V}^{(t)} \in \mathbb{R}^{K \times n}$ is the matrix of node module. Hence the transmit powers should be obtainably features in the I-th layer, $\mathbf{W} \in \mathbb{R}^{N \times n+1}$ is the transple devised to prolong the lifetime of IoT networks. In this weight matrix in the I-th layer, $\mathbf{G}^{(t)} = \mathbf{G}^{(t)} = \mathbf{G}^{($ Bre Prital Dudy Teatring Apption bits and the bandwidth, respectively. The delivery latency of these information bits in order to train the neural network weights W, the iteris thus calculated as ative primal-dual learning approach is applied in this paper. Moreover, by realizing that the maximum allowable outage probability is generally very low (e.g., $\varepsilon = 10^{-2}$), we apply thbelogarithm transformation threthe poutage probability. The $loge R_{Tail}$ reflicte neederf. W.A.Ruplis by the called the of state and algoconstraint and meanwhile accelerate learning and allevintente over-litting IB yolaking this transformation into consideration,

the Lagrangian of problem (??) is formulated as $\eta = R(1^{??}) \text{ is formulated as}$ $\mathcal{L}_{\Psi}(\mathbf{W}, \lambda, v) = \tau + \lambda(\log P_{\sum_{k=0}^{K-1}, K}^{K-1}, \sum_{k=0}^{K-1} \log \varepsilon)$ (5)

where R = b/M and b denote the present rans \overline{m} is ion factor and the number of original information bits, respectively. Wheredikion, Pand refers to after the Lagrangian it in tiplier as stociated with data with data to the straints on problems (20); y. It lies hoteworthyinthatizatiBhudogoband pf athetheofunctionstrofinthe Ifairable warameters a Wee According to the light dient descent algorithmedhesneural network parameters W at step s can be updated as

$$\sup_{p_1, \dots, p_K}$$

s.t. $P_{out, K} < \varepsilon$, (6)

dated as
$$\min_{\substack{p_1, \dots, p_K \\ \text{s.t.}}} \tau$$
s.t.
$$P_{out,K} \leq \varepsilon, \qquad (6)$$

$$\mathbf{W}_{s+1} = \mathbf{W}_s - \theta_{\mathbf{W},s} \nabla_{\mathbf{W}} \mathcal{F}_{s \approx s} \mathcal{A}_s \{ \mathcal{E}(\mathbf{W}_s, \lambda_s, \upsilon_s) \}, \qquad (15)$$

where the territability denotes the step size as the a-th iteration and the actual time doubilition p dollows a testabe distribution Acwithinhthe rungge Otoler Besides of the nothin lides are apidated by capitalizing on the subtgradient, method as denotes the

average transmit power that is evaluated as $\lambda_{s+1} = [\lambda_s + \theta_{\lambda,s}(\mathbf{E}_{\rho \sim \mathcal{A}} \{ \log(P_{out,K}) \} - \log(\varepsilon))]_+,$

$$p_{\text{avg}} = \sum_{k=1}^{K} p_k P_{out,k-1}, \quad (7)$$

$$p_{\text{avg}} = \sum_{k,\bar{s}} p_k P_{out,k-1}, \qquad (7)$$

$$v_{s+1} = [v_s + \theta_{t\bar{k},\bar{s}}(\mathbb{E}_{\rho \sim \mathcal{A}} \{p_{\text{avg}}\} - \bar{p})]_+, \qquad (17)$$

where the step stipulate P correspond to the step sizes, and that the power allocation is obtained by correspond to the step sizes, and that the power allocation max {0,x} allocation is pseudocode of GCN-based by over allocation the statistical channel statistical shown in Afgorithm information (CSI) to avoid frequent signaling interactions and conserve time.

Output GCN-Enabled Power Allocation Strategy Although the exact outage expressions of HARQ systems were derived in [?] [?], the outage expressions involve the summation of an infinite number of special functions. Such complex representations entail a high computational burden for the optimal design. In order to overcome this issue, the asymptotic expressions of the outage probabilities are leveraged in the optimal design. As derived in [2], the symptotic outage probabilities of three types of HARQ schemes are given

 $P_{out,K} = \begin{cases} 2^{R} & 1 \\ R & K!, \end{cases}$ Type – I $C \in st \text{ Layer } (8)$ IR

where $\Gamma(\cdot)$ denotes the Grands function, $\varsigma_K = \frac{(\ell(\rho,K))^{-1}}{\prod_{k=1}^K p_k \xi_k^2}$, $\ell(\rho,K)$ quantities the effect of control that is given by

Fig.(2, K) general $\sum_{k=0}^{K} \log \frac{2^{(k+4)}}{2^{(k+4)}} \operatorname{tr} \prod_{k=0}^{K} \operatorname{tr} \lim_{k \to \infty} -\log^2(\frac{1}{2}) \operatorname{tr} \lim_{k \to \infty} -\log^$ (9)

it should be noted that $\rho \neq 1$, and $G_K(R)$ reads as

Algorithm 1 GCN-Based Power Allocation Algorithm $\mathcal{G}_K(R) = (-1)^K + 2^R \sum_{k = 0}^{K} (-1)^k \frac{(R \ln 2)^k}{(K - k - 1)!}$. Input: Initial values W, λ , $k \neq 0$

Output: $_{t}$ The ten equal of a time policy $_{t}$ $_{t}$ transhisports, the factions form of the objective function, an Obtain power allocation policy of the minimum thatch ion problen Compute the policy gradient of it (Whyele, by) means of the cupdate the primal variable Hodologies? Such as CVX tools. The success of the application of CCNs in power aflocation of the dual rangiable wirends of the control of the con motivateds+us=to\sdevelopEGCN\QSCoup&\dr-aPSCattlop for powerstonstrainted of ARQ4 Aremes. All is clear that dfffefudtf9fARQ rounds and correlations among them can be represented by graph nodes and edges, respectively.

It is noteworthy NIAMIRICALISEMBERBMENTS in due to its ability of exploiting the graph attracture to interess idatas. In what follows a GCN-enabled power allocation scheme section, for illustration, we assume that $\xi_1 \equiv \cdots \equiv \xi_K \equiv$ is detailed K=3, K=2 bps/Hz, $N_b=10^6$ bits, $B=10^6$ MHN-Badser Pottler A With tregard to the neural network structure, a 5-layer GCN with intermediate feature dimensions 16, 32, 16 and 2 is implemented. The activation functions round is modeled as a graph node. Moreover, as aforementionein that intermediate layers used Une while the dest layer applies "Linear". A dataset with 1000 samples is used in the training stage, the total number of training epochs is set to 500, and the learning rates of $\theta_{W,s}$, $\theta_{\lambda,s}$, and $\theta_{v,s}$ are assumed to be 5×10^{-4} , 10^{-3} and 5×10^{-5} , respectively. The GCN parameters W are updated by using the adaptive moment estimation (Adam) optimizer. Besides, the expectations in (??) (??) are taken over the sampled mini-batch of size 50, and ρ is randomly generated from a uniform distribution within the 0, interval [0, 1).

wiler-Fig. th? subersonvergence oes the primalideal objugate algorithm for three HARQ behands distinct tigated then setting each of the proposed algorithm for three HARQ behands distinct tigated then setting each good of the converge proposed algorithm can good of the proposed algorithm for tigates and the foreign each power latter time and proposed the converge of the proposed time and proposed tigated the converge of the production of the tigate of the production of the production of the tigate of the production of the tigate of the latency approaches to No. (Ba) = 100 are the converge of the number of iterations.

For tractability, the power policy functional space $\mathbf{p} = (p_1, p_2, \dots, p_K)$ is parameterized by using traps neural networks. More specifically, the power allowation policy is defined as $\mathbf{p}(\mathbf{H}) = \Psi(\mathbf{H}; \mathbf{W})$, where Ψ represents a L-layer GCN with trainable weights \mathbf{W} . Instead of optimizing \mathbf{p} , the neural network parameters \mathbf{W} need to be optimally determined through the primal-dual learning approach [?]. As shown in Fig. ??, a L-layer GCN structure for the power-constrained HARQ schemes with K=5 is given as an example. With the input $\mathbf{V}^{(0)} = \frac{\bar{p}}{K} \mathbf{1}_K$ to $\Psi(\mathbf{H}; \mathbf{W})$, the (l^2-1) th layer features $\mathbf{V}^{(l+1)}$ of GCN are updated by following the layer wise propagation rule as

where $\mathbf{1}_K$ stands for an all-ones column vector, $\mathbf{D} = \text{Fig}$ AH he convergence analysis of the primal dual learning diagonthm, with respect to the number of iterations $\mathbb{R}^{n_l \times n_{l+1}}$ is the trainable weight matrix in the l-th layer, $\mathbf{W}^{(l)} \in \mathbb{R}^{n_l \times n_{l+1}}$ is the trainable weight matrix in the l-th layer, $\sigma_l(\cdot)$ defines then Eigen and the corresponding outlines are plotted against the total ayenge transmit power \bar{p} , respectively, where $\rho = 0.5$ is considered.

 $\mathbf{V}^{(l+1)} \stackrel{\underline{so}}{=} \sigma_l \left(\mathbf{D}^{-\frac{1}{2}} \mathbf{H} \mathbf{D}^{-\frac{1}{2}} \mathbf{V}^{(l)} \mathbf{W}^{(l)} \right)$

transmit power \bar{p} , respectively, where $\rho = 0.5$ is considered. It is Protected the best of the protected that the protect

GCanderoastrficiently lowerransinit power Howeveniugdend latgeipower constraifitting, $p_{\rm By}$ told BW, this latent formers of three HARQescherings tilmost again again with each other. (Hences then superior aperformance of HARQ-IR in terms of the low latency is weakened as \bar{p} increases. Nevertheless, it can be seen from Fig. 22 that HARQ-IR still days a notable outage reduction compared to the other two schemes. Moreover, as \bar{p} increases, the latency is lower bounds $p_{\rm BR}$, $p_{$

$$\mathbf{W}_{s+1}^{007} = \mathbf{W}_s - \theta_{\mathbf{W},s} \nabla_{\mathbf{W}} \mathbf{E}_{\rho \sim \mathcal{A}} \left\{ \mathcal{L}(\mathbf{W}_s, \lambda_s, v_s) \right\},$$
 (15)
where the term $\theta_{\mathbf{W},s}$ denotes the step size at the s-th iteration and the actual time correlation ρ follows a certain distribution \mathcal{A} within the range [0, 1). Besides, the multipliers are updated by capitalizing on the sub-gradient method as

 $\lambda_{s+1} \stackrel{\text{10}}{=} \left[\lambda_s + \stackrel{\text{12}}{\theta}_{\lambda,s}(\mathbb{E}_{\rho \sim \mathcal{A}}^{14} \left\{ \log(P_{out,K}^{18}) \right\} - \log(\varepsilon) \right]_+, \quad (16)$

Fig. 4. The comparison between the latency of different HARQ schemes. $v_{s+1} = [v_s + \theta_{v,s}(E_{\rho \sim A} \{p_{avg}\} - \bar{p})]_{\perp},$ (17)

where $\theta_{\lambda,s}$ and $\theta_{v,s}$ correspond to the step sizes, and $[x]_+ = \max\{0,x\}$. The pseudocode of GCN-basedhard wer allocation scheme is shown in Algorithm 77 HARQ-IR

Output P_1 P_4 P_2 P_3 P_3 L-th Layer

Fig. 5. The comparison between the outage probabilities of different HARQ schemes.

As shown in Figs. ?? and ??, the effects of the time correlation on the valency and the outage probability are respectively examined by $\lim_{p \to \infty} \bar{p} = p_0$ dBW. p_0 it is consistent with the observations $\lim_{p \to \infty} \bar{p} = p_0$ dBW. p_0 it is consistent with the observations $\lim_{p \to \infty} \bar{p} = p_0$ dBW. p_0 it is consistent with the observations $\lim_{p \to \infty} \bar{p} = p_0$ dBW. p_0 it is consistent with the observation $\lim_{p \to \infty} \bar{p} = p_0$ dBW. p_0 it is consistent with the observation $\lim_{p \to \infty} \bar{p} = p_0$ dBW. p_0 is consistent with the observation p_0 dBW. p_0

Admit to \times 1 GCNo Brook Power Molecusia while the HARQ channels, undergolae slightly correlated fading, i.e., $\rho < 0.5$, the impact 10f the time correlation; on the latency and the reliability can be disregarded to sum up, HARQ-IR has the superior performance to after low latency while ensuring high reliability albeit at the price of extra coding (wmplexity)

4: Update the primal variable W_s [cf. (??)]:

0.055 $\mathbb{V}_{\mathbf{E} = -\mathbf{T}, \mathbf{p} \in \mathbf{I}} \underbrace{\mathbf{HARC}}_{\mathbf{HARC}} \mathbb{W}_s \nabla_{\mathbf{W}} \mathbf{E}_{\rho \sim \mathcal{A}} \left\{ \mathcal{L}(\mathbf{W}_s, \lambda_s, v_s) \right\}$ 5: Update the older variable λ_s and v_s [cf. (??)-(??)]:

0.0555 $\mathbb{V}_s = \mathbf{HARC}_{\mathbf{H}} \mathbf{HARC}_{\mathbf{W}} \mathbf$

Numerical experiments are conducted for verification in this section. For illustration, we assume that $\xi_1 = \cdots =$ $\xi_K = 1$, $\delta = 1$, K = 3, R = 2 bps/Hz, $N_b = 10^6$ bits, B = 0.00 MHz, and $\varepsilon = 10^{-2}$. With regard to the neural network structure, a 5-layer GCN with intermediate feature dimensions 16, 32, 16 and 2 is implemented. The activingof. Effectors the time conclation and the latency use "ReLU", while the last layer applies "Linear". A dataset with 1000 samples is used in the training stage, the total number of training epochs is set to 500, and the learning rates of $\theta_{\mathbf{W},s,\mathbf{H}}^{-1}$ $\theta_{\mathbf{v},c}^{\mathrm{peri HARO}}$ and $\theta_{v,s}$ are assumed to be 5×10^{-4} , 10⁻³ and 5 × 140 r respectively. The GCN parameters W are updated by using the adaptive moment estimation (Adam) optimizer. Besides, the expectations in (??) (??) are taken over the sampled mini-batch of size 50, and ρ is randomly generated from a uniform distribution within the interval [0, 1).

In Fig. ??, the convergence of the primal-dual learning algorithm for three HARQ schemes is investigated by setting $\bar{p}=15$ dBW. Clearly from Fig. ??, the proposed algorithm can converge within 1200 iterations, which justifies the effectiveness of the GCN-based bower allocation strategy. If the maximum power constraint \bar{p} is sufficiently large (e.g., 15 dBW), the LTAT converges to hig predicted the time correlation p = 15 dBW, the latency approaches to $N_b/(B\eta)=10^6/(10^7\times 2)=0.05$ s with the increase of the number of iterations.

This Figger? Studied the, power constrained did ARQ aschemes for respliciting URITAGE. I More bispecifically letted transmission tatency vof de ARQ is a home superinterated volville generate of the high bretiability sand the year power consumption from duder the upptintization ARQ called, plud oasymptotic bestage to be pression was RQcC. By a done led ring is the introductor of the ARQ found fighe? GCN atwas significant old mable the lutting can in her ization problem Howing. IR, it and a pability and fackling the rigapholdate. The primal-dual libarting scheme how was table to very good to break GCN operandings. Finally libe that the experimental was during the companion of the primal-dual libarting scheme how was table to very good to be a proposed figure of the large posed figure of th

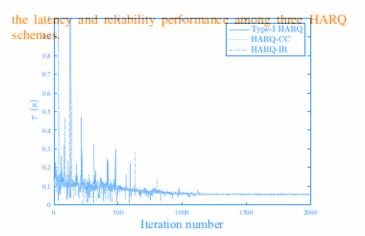


Fig. 3. The convergence analysis of the primal-dual learning algorithm with respect to the number of iterations.

a large power constraint, e.g., $\bar{p} > 16$ dBW, the latency curves of three HARQ schemes almost coincide with each other. Hence, the superior performance of HARQ-IR in terms of the low latency is weakened as \bar{p} increases. Nevertheless, it can be seen from Fig. ?? that HARQ-IR still has a notable outage reduction compared to the other two schemes. Moreover, as \bar{p} increases, the latency is lower bounded by 0.05 s, which has been illustrated in Fig. ??. Whereas, the corresponding outage probabilities of three HARQ schemes continuously decline with \bar{p} .

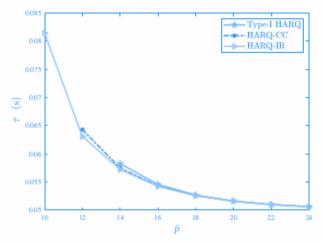


Fig. 4. The comparison between the latency of different HARQ schemes.

As shown in Figs. ?? and ??, the effects of the time correlation on the latency and the outage probability are respectively examined by fixing $\bar{p}=15$ dBW. It is consistent with the observations in [?], [?], [?] that the time correlation has a negative impact on the latency and outage performance. For example, as the time correlation increases from 0 to 0.98, the latency of HARQ-IR increases from 0.0554s to 0.0564s, and the corresponding outage probability of HARQ-IR decreases from 5.76×10^{-5} to