An Efficient Method to Monitor Downlink Traffic for 4G and 5G Networks

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***Abstract*—This paper proposes a new scheme that allows the measurement of traffic loads of radio networks by decoding some information about the cell, such as downlink control information (DCI) broadcast on the physical downlink control channel (PDCCH). In the proposed scheme, a client decodes the entire DCI for all user equipments (UEs) with ongoing connections in a cell and extracts some information about the cell, such as the number of active UEs, the number of radio resources occupied, as well as the modulation and coding scheme used by each UE. Based on this information, mobile network carriers can measure exact traffic loads of cells preemptively without affecting ongoing connections. Contrary to an exhaustive searching scheme that attempts to decode DCI with all radio network temporary identifiers (RNTIs), the proposed scheme derives a small set of valid RNTIs by using an inverse function and attempts to decode DCI only with the valid RNTIs instead of the entire set of RNTIs. This reduction enables the client to recover the correct DCI with marginal computational complexity, which allows for real-time decoding of DCI. The simulation results show that the proposed scheme can significantly reduce the complexity required to decode the entire DCI in a cell, compared to the exhaustive searching scheme.**

***Index Terms*—Blind decoding, PDCCH, DCI, LTE**

I. Introduction

As high-quality multimedia streaming services are recently getting more popular, mobile data traffic has been sharply increasing [1]. Cellular network carriers utilize various advanced technologies such as multiple input and multiple output (MIMO) and small-cell networks to cope with the sharply increasing traffic by enhancing the spectral efficiency with limited radio spectra [2]–[5]. Despite the increasing spectral efficiency, extra radio spectra will be needed to increase the total capacity of mobile networks because the capacity of mobile networks grows with the amount of radio frequency. However, radio frequency is a limited resource and the deployment of additional networks over new radio frequency inevitably causes an enormous cost to mobile network carriers. The mobile network carriers always seek to evaluate an exact traffic load for their current networks before deploying additional networks over new radio frequency. An instantaneous traffic load for ongoing radio connections can be exactly estimated based on the information such as data rates and the amount of occupied radio resources. Unfortunately, however, current standards for long-term evolution (LTE) networks do not provide mobile network carriers with any indicator to measure the exact information for the whole ongoing radio connections, while they only allow a user equipment (UE) to measure radio frequency (RF)-related parameters such as received signal strength indicator (RSSI), reference signal received power (RSRP), and reference signal received quality (RSRQ) [6], [7]. Although a theoretical capacity of a point-to-point radio connection associated with an evolved nodeB (eNB) can be easily estimated from the RF parameters, a real data rate achievable in the radio connection is limited by the amount of available radio resources excluding the resources occupied by other connections in the associated eNB as well as the amount of data to transmit. In addition, it is also impossible to figure out the whole RF parameters for all ongoing connections at the same time. In LTE networks, an eNB assigns downlink resources to each UE and broadcasts the assignment information called downlink control information (DCI) on physical downlink control channel (PDCCH). A DCI for a UE contains the location of assigned resources and the information on modulations and coding schemes as well [8]–[11]. We can obtain the perfect information for all ongoing connections and estimate an exact traffic load of a cell without affecting the current connections only if we will be able to completely decode the whole DCI for all UEs on PDCCH [12]. An eNB scrambles each DCI with a target UE's unique radio network temporary identifier (RNTI) and the target UE can descramble the DCI with its own RNTI which has been already assigned by the eNB. If a client attempts to descramble all other UEs' DCI with all possible RNTIs, it will cause a tremendous complexity because 2^{16} RNTIs are available in each cell.

In this paper, we thus investigate how to decode the entire DCIs in a cell with an affordable complexity. Efficient designs and algorithms for DCI decoders were proposed to enable fast blind decoding process [13]. It was shown that the proposed parallel design can significantly reduce a processing time with a logic power consumption. However, it can be applied only when a receiver has the information of its valid RNTI, and it will still cause an excessive complexity to decode the entire DCI for all UEs without prior information of valid RNTIs. A new passive probing mechanism that enables a client to estimate the number of active UEs and their effective data

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rates in a cell by decoding DCI with no prior knowledge of valid RNTIs was proposed [7], [14]. It was assumed that valid RNTIs which were assigned to active UEs appear more frequently in a recent period of time, and the entire RNTIs can be thus classified into valid RNTIs and false RNTIs by observing their frequency of appearance during a certain time period. A RNTI of which the frequency of appearance exceeds a certain threshold value can be classified as a valid RNTI. However, not only does this approach cause estimation errors, but the probability of errors varies depending on given traffic patterns. We thus propose a simple scheme where a client, which can be a UE or a new type of equipment for measurement, can obtain the perfect information on active UEs including data rates and the amount of occupied radio resource without affecting ongoing communications by decoding the whole DCI on PDCCH without any decoding error. In the proposed scheme, we introduce an efficient method to calculate a set of candidate RNTIs for each control channel elements (CCE) chunk by using an inverse function. The client can attempt to decode each CCE chunk only with the set of candidate RNTIs. Thus, the complexity for decoding the whole DCI on PDCCH can be significantly reduced compared with a conventional scheme based on Brute-force searching. More specifically, our simulation results show that our proposed scheme only requires Viterbi decodings less than 20 when an eNB has 20 UEs and 80 CCEs, while the conventional scheme requires about 10^6 Viterbi decodings. The remain of this paper is organized as follows. Section II describes overall procedures of decoding DCI on PDCCH. The problem formulation of this paper and the proposed scheme are described in Section III. Our numerical results are shown in Section IV. Finally, the conclusions of this paper are drawn in Section V.

II. Overview of PDCCH procedures

In LTE networks, a PDCCH carries DCI messages such as resource allocations, modulation and coding schemes, and power-control commands. The processing of a DCI on the PDCCH is described in Fig. 1. A cyclic redundancy check (CRC) is attached to each DCI payload. An RNTI, which is the identity of a UE that has been temporarily assigned by an eNB and is only valid in the cell of the eNB, is embedded in the CRC calculation, but not explicitly transmitted for reducing the amount of bits to transmit on the PDCCH. Upon reception of the DCI, the UE will check the CRC using its RNTI. If the CRC-check succeeds, the DCI is declared to be correctly decoded and targeted to the UE [8], [9]. Otherwise, it will be ignored. For simple and efficient processing in UEs, DCI are mapped to resource elements of a PDCCH based on CCEs. The number of CCEs available for the PDCCH in a cell is determined by the size of the control region, which mainly depends on a cell bandwidth and can vary every subframe. A specific resource assignment on a PDCCH can be thus identified by the indices of the corresponding CCEs in the control region.

On the other hand, for a tradeoff between higher reliability and capacity, a channel condition between an eNB and a UE

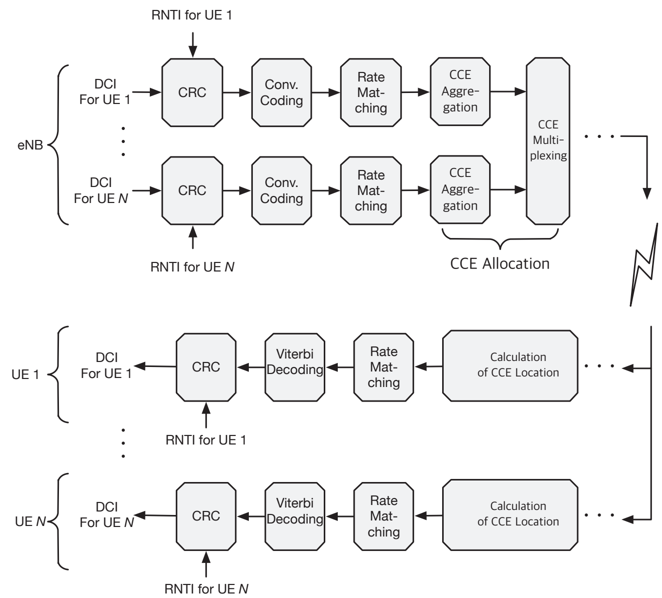

Fig. 1. Encoding and decoding procedures for PDCCH in LTE

determines the number of CCEs that is required for a DCI, which is referred to as the aggregation level. The higher the aggregation level used, the better the probability for the UE to successfully decode the DCI. As the CCEs for the DCI assigned to the UE vary and are not explicitly signalled, the UE should blindly determine the indices of the CCEs used for the DCI. To reduce the complexity of such process, certain restrictions on the aggregation of contiguous CCEs have been specified and search spaces are defined to limit the maximal number of blind decodings in UEs [8]–[10]. A search space is a set of candidate CCEs for a given aggregation level which a UE is supposed to attempt to decode. The whole control region is divided into common and UE-specific search spaces, and a UE thus monitors its UE-specific search spaces and common search spaces at the same time. In this paper, we only consider UE-specific search spaces because the complexity of blind decoding is mainly caused by UE-specific search spaces.

A. Encoding of DCI

Let $N_{\mathrm{CCE},k}$ be the total number of CCEs available at a subframe k. The available CCEs are indexed by i, $0 \le i \le N_{\mathrm{CCE},k} - 1$. α denotes an aggregation level for a DCI and $\alpha \in \mathbf{A}$, where $\mathbf{A} \triangleq \{1, 2, 4, 8\}$, and c denotes the number of candidate sets of CCEs that can be be assigned for a DCI and $c \in \mathbf{C}$, where $\mathbf{C} \triangleq \{6, 6, 2, 2\}$ [8]–[10]. For a given α, the value of c should be determined to satisfy $(\alpha, c) \in (\mathbf{A}, \mathbf{C})$, where $(\mathbf{A}, \mathbf{C}) \triangleq \{(1, 6), (2, 6), (4, 2), (8, 2)\}$ [8]–[10]. Given k, α, and c, the indices of α CCEs to be assigned for a DCI with RNTI r are determined by

$$z_k^r(j) = \alpha \left\{ (Y_k^r + m) \bmod \left\lfloor \frac{N_{\mathrm{CCE},k}}{\alpha} \right\rfloor \right\} + j, \quad 0 \le j \le (\alpha - 1), \tag{1}$$

where $0 \le m \le (c-1)$ and Y_k^r is defined by

$$Y_k^r = (A \cdot Y_{k-1}^r) \bmod D \text{ for } 0 \le k \le 9, \tag{2}$$

and $A = 39827$, $D = 65537$, and $Y_{-1}^r \triangleq r$ for $k = 0$ [9]. Y_k^r is only dependent on k and r.

B. Decoding of DCI

To decode a DCI transmitted by an eNB, a UE first calculates all candidate sets of CCEs based on (1) and (2). The UE can easily calculate $N_{\text{CCE},k}$ by using the information broadcast by the eNB and has a pre-assigned RNTI r. However, the UE is unaware of α and c that has been used to transmit the DCI by the eNB. Thus, the UE should consider all possible pairs of (α, c) in $(\mathbf{A}, \mathbf{C})$. For each candidate set of CCEs, the UE checks CRC with r. If the CRC check succeeds, the UE can decode the exact DCI. Otherwise, it repeats for the other sets of CCEs until the CRC check succeeds.

III. Problem Formulation and Proposed Scheme

In this paper, we investigate a passive probing problem where a client wants to estimates the traffic load of a cell by decoding the whole DCI transmitted to all UEs on a PDCCH in the cell and measuring the number of active UEs, the amount of occupied radio resource, and modulation and coding schemes. Contrary to a standardized LTE UE that only decodes its own DCI by using its known RNTI, the new client needs to decode the whole DCI for all UEs with no prior knowledge of valid RNTIs assigned in the cell. The client can thus attempt to decode all the DCI on a PDCCH by using the entire RNTIs exhaustively. The exhaustive decoding algorithm is described in Algorithm 1. $\mathbf{D}$ denotes a set indicating if each CCE has been already decoded and is defined as

$$\mathbf{D} \triangleq \{d_i | 1 \le i \le N_{\text{CCE},k}\}, \tag{3}$$

where

$$d_i = \begin{cases} 1, & \text{if the CCE } i \text{ has been decoded} \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

For each RNTI, the client carries out the same DCI decoding procedures for all possible candidate sets in $(\mathbf{A}, \mathbf{C})$ as in a standardized LTE UE. If a CRC check succeeds for a candidate set, the elements of a decoding vector $\mathbf{D}$ corresponding to the CCEs in the candidate set are set to 1. If any CCE of a candidate set has been already decoded successfully, the client can skip unnecessary decoding procedures on the candidate set because an eNB transmits all DCI orthogonally on a PDCCH without overlapping.

Despite its simplicity, the exhaustive scheme in the Algorithm 1 causes a catastrophic complexity in the clients with a passive probing function because 2^{16} RNTIs are available in a cell [9]. It will be infeasible for the client to decode the whole DCI in real time. As shown in Algorithm 2, we thus propose a new algorithm to decrease the complexity to such a level that real-time decodings of the entire DCI are possible. In the proposed algorithm, a client first identifies whether each CCE is occupied by a DCI by detecting energy level in the CCE. If the energy level detected in the CCE exceeds a certain threshold, the CCE is declared to be occupied by a DCI. We assume a perfect energy detection without any error. Let N_{occ} denote the number of groups, where each group consists of contiguous CCEs. $\mathbf{I}_j$ denotes a set of indices for CCEs that are included in the j-th group, where $0 \le j \le N_{\text{occ}} - 1$. $l_j \triangleq |\mathbf{I}_j|$ and $1 \le l_j \le N_{\text{CCE}}$, where $l_j = N_{\text{CCE}}$ is valid only for $N_{\text{occ}} = 1$. Fig. 2 shows a simple example of CCE classification used in the proposed scheme with $N_{\text{occ}} = 4$.

Algorithm 1: Exhaustive decoding algorithm

Initialization:$\mathbf{D} = \emptyset$;
forall *RNTIs* r **do**
  Calculate Y_k^r from (2);
  forall $(\alpha, c) \in (\mathbf{A}, \mathbf{C})$ **do**
    Calculate CCE indices $z_k^r(0) \sim z_k^r(\alpha-1)$ from (1);
    if $\mathbf{D}[z_k^r(0)):z_k^r(\alpha-1)]$=**0** **then**
      Viterbi decoding;
      De-masking with RNTI;
      if *CRC Passed* **then**
        Decode DCI;
        $\mathbf{D}[z_k^r(0) : z_k^r(\alpha-1)] = \mathbf{1}$;
        Break;
      end
    end
  end
end

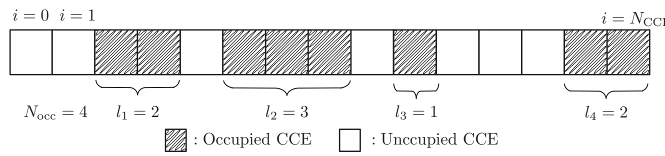

Fig. 2. An example of CCE classification used in the proposed scheme. $N_{\text{CCE}} = 15$, $N_{\text{occ}} = 4$, and $(l_1, l_2, l_3, l_4) = (2, 3, 1, 2)$. $\mathbf{I}_1 = \{2, 3\}$, $\mathbf{I}_2 = \{5, 6, 7\}$, $\mathbf{I}_3 = \{9\}$, and $\mathbf{I}_1 = \{13, 14\}$.

If $\mathbf{I}_j = \{i, i+1, \cdots, i+L-1\}$, we can obtain a set of all feasible aggregation levels, $\mathbf{X}$, for $\mathbf{I}_j$ satisfying

$$\mathbf{X} = \{x \in \mathbf{A} | (\mathbf{I}_j[0] \bmod x = 0) \cap (x \le l_j)\}, \tag{5}$$

where $\mathbf{I}_j[0] = i$ and $l_j = L$.

For each $\alpha \in \mathbf{X}$, the client carries out a Viterbi decoding for α CCEs from i to $(i + \alpha - 1)$, and finds the appropriate number of candidates, c, satisfying $(\alpha, c) \in (\mathbf{A}, \mathbf{C})$. For each candidate $m (0 \le m \le c-1)$, we need to calculate all possible RNTIs that might have been used in (1) for transmitting DCI to UEs. Toward this goal, we first derive $\hat{Y}_k^r$ satisfying (1) as follows:

$$(\hat{Y}_k^r + m) \bmod \left\lfloor \frac{N_{\text{CCE},k}}{\alpha} \right\rfloor = \frac{i - 0}{\alpha}, \tag{6}$$

where the first CCE index is only considered because the subsequent CCEs for a DCI can be easily found from the first

Algorithm 2: Proposed algorithm

Input: $\mathbf{I}_1, \cdots, \mathbf{I}_{N_{occ}}$;
for $0 \le j \le N_{occ} - 1$ **do**
  decCnt = 0;
  $l_j = |\mathbf{I}_j|$;
  $i = \mathbf{I}_j[0]$;
  while $decCnt < l_j$ **do**
    $\mathbf{X} = \{x | x \in \mathbf{A}, i \bmod x = 0$, and $x \le (l_j - decCnt)\}$;
    forall $\alpha \in \mathbf{X}$ **do**
      Viterbi decoding for α CCEs;
      Find an appropriate candidate set size c for α;
      for $m = 0$ *to* $(c-1)$ **do**
        forall $\{q\}$ *in* (8) **do**
          Calculate $\hat{Y_k^r}$ with q and (7);
          Find RNTI from $\hat{Y_k^r}$;
          De-masking with RNTI;
          if *CRC Passed* **then**
            Decode DCI;
            $decCnt = decCnt + \alpha$;
            $i = i + \alpha$;
            Break and Exit to **While**;
          end
        end
      end
    end
  end
end

CCE index and aggregation level, and thus $j = 0$ and $z_k^r(0)$ is replaced with i. $\hat{Y_k^r}$ in (6) can be rewritten as

$$\hat{Y_k^r} = \left\lfloor \frac{N_{\text{CCE},k}}{\alpha} \right\rfloor \times q + \frac{i}{\alpha} - m, \tag{7}$$

where q is a non-negative integer and can be limited by

$$\left(m - \frac{i}{\alpha}\right) \Big/ \left\lfloor \frac{N_{\text{CCE},k}}{\alpha} \right\rfloor \le q < \left(D + m - \frac{i}{\alpha}\right) \Big/ \left\lfloor \frac{N_{\text{CCE},k}}{\alpha} \right\rfloor \tag{8}$$

because $0 \le \hat{Y_k^r} < D$. Thus, the total number of candidate values for $\hat{Y_k^r}$ can be calculated as $\left\lfloor D \Big/ \left\lfloor \frac{N_{\text{CCE},k}}{\alpha} \right\rfloor \right\rfloor$. For each value of $\hat{Y_k^r}$, we can obtain a corresponding RNTI by using (2). If a CRC check succeeds, the client can decode a DCI in the α CCEs from i to $(i + \alpha - 1)$. Otherwise, the same procedure is repeated until the CRC check passes for another α, c, and q. The pseudocode for the proposed scheme is summarized in the Algorithm 2. Given $\hat{Y_k^r}$, we can calculate $\hat{Y_{k-1}^r}, \cdots, \hat{Y_{-1}^r}$ recursively based on (2). Then, $\hat{Y_{-1}^r}$ is the corresponding RNTI for the given $\hat{Y_k^r}$. This process can be easily implemented by a table-lookup method.

IV. Numerical Results

In this section, the performance of the proposed scheme is analyzed in terms of total number of CRC calculations and Viterbi decodings, and is compared with that of an exhaustive algorithm. In this paper, we only consider UE-specific searching spaces because the complexity caused by common searching spaces is marginal compared with that caused by UE-specific searching spaces. We assume that $N_{\text{CCE},k} = N_{\text{CCE}} \ \forall \ k$ and the number of DCI formats is one for a mathematical simplicity without the loss of generality. The value of α for each DCI is originally determined by a channel condition to enhance the probability of successful decoding with minimal resources. In this paper, α for each DCI is assumed to be uniformly distributed for simplicity. If all candidate sets for a UE have been occupied by other UEs' DCI, the UE's DCI is assumed to be discarded. In addition, we only consider a single-cell scenarios where there is no inter-cell interference.

Fig. 3 shows the total numbers of Viterbi decodings required to decode the entire DCI. $N_{\text{CCE}} = 20, 40, \text{or } 80$, and the total number RNTIs available in a cell is 2^{16}. The exhaustive algorithm needs about 10^6 Viterbi decodings to decode the whole DCI, which is constant regardless of N_{CCE} and the number of users because it always attempts to decode DCI for all the RNTIs. On the other hand, it is shown that the proposed scheme significantly reduces the number of Viterbi decodings. For example, the proposed scheme only requires Viterbi decodings less than 20 when $N_{\text{CCE}} = 80$ and the number of users is 20. The number of Viterbi decodings slightly increases in the proposed scheme as the number of users increases because the number of DCI to be decoded increases. In addition, it also increases as N_{CCE} increases because the larger N_{CCE}, the higher the probability that a DCI can be assigned CCEs so that it will not be discarded.

Fig. 4 shows the total number of CRC checks required to decode the whole DCI. As in Fig. 3, it is also assumed that $N_{\text{CCE}} = 20, 40, \text{or } 80$, and the number of total RNTIs is 2^{16}. The exhaustive algorithm needs about 8.4×10^6 CRC checks to decode the whole DCI, which indicates that 8.4 CRC checks are needed for each Viterbi decoding on average. In addition, the number of CRC checks is also constant regardless of N_{CCE} and the number of users. On the other hand, the number of CRC checks for the proposed scheme increase as the number of users or N_{CCE} increases. For 20 users, the total CRC checks required for the proposed scheme are 1.6×10^6 for $N_{\text{CCE}} = 20$, 8.7×10^5 for $N_{\text{CCE}} = 40$, and 4.2×10^5 for $N_{\text{CCE}} = 80$, respectively.

V. Conclusions

In this paper, we studied how mobile network carriers decode the complete DCI without affecting current ongoing communications to measure a radio traffic load. In standardized LTE networks, an eNB scrambles a DCI with a target UE's RNTI and transmits it on a specific resource region selected out of multiple candidate regions. The target UE searches some sets of CCEs and attempts to blindly decode its DCI based on its own RNTI which has been already assigned by an eNB. Thus, decoding the whole DCI without prior knowledge of RNTIs for ongoing connections causes

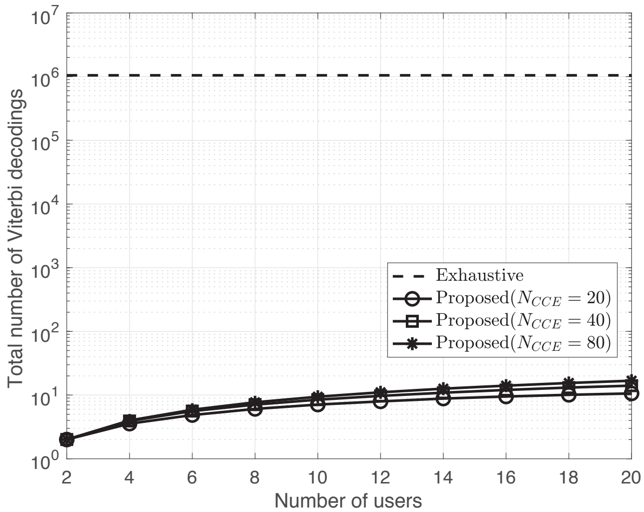

Fig. 3. The total number of Viterbi decodings. $N_{\text{CCE}} = 20, 40, \text{or } 80$, and the number of available RNTIs is 2^{16}.

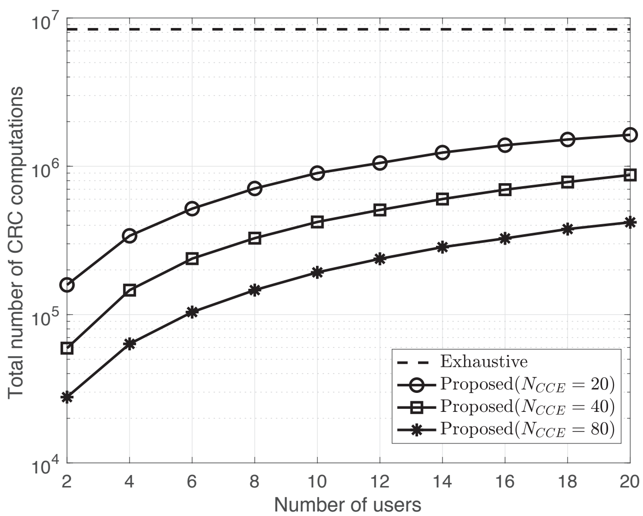

Fig. 4. The total number of CRC checks. $N_{\text{CCE}} = 20, 40, \text{or } 80$, and the number of available RNTIs is 2^{16} .

an excessive complexity to a client because 2^{16} RNTIs are available in a cell. We thus proposed an efficient scheme which can decode the entire DCI for all UEs with no prior knowledge of RNTIs for the UEs. The proposed scheme can calculate candidate RNTIs for each CCE chunk occupied by DCI by using an inverse function. Thus, it can significantly reduce the complexity with no estimation errors by attempting to decode each CCE chunk only with the valid RNTIs, contrary to an exhaustive scheme which attempts to decode DCI with the whole RNTIs. Our numerical analysis and extensive simulation results revealed that the proposed scheme requires much less Viterbi decodings and CRC checks to decode the whole DCI than the exhaustive algorithm. More specifically, the proposed scheme only requires Viterbi decodings less than 20 while the exhaustive algorithm requires about 10^6 Viterbi decodings.

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REFERENCES

[1] Cisco, Cisco visual networking index: Forecast and methodology, 2016–2021, White Paper, Sep. 2017. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.html

[2] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta,"Massive MIMO for next generation wireless systems," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[3] Young-Han Nam, Boon Loong Ng, Krishna Sayana, Yang Li, Jianzhong Zhang, Younsun Kim, and Juho Lee,"Full-dimension MIMO (FD-MIMO) for next generation cellular technology," *IEEE Communications Magazine*, vol. 51, no. 6, pp. 172–179, Jun. 2013.

[4] X. Ge, J. Yang, H. Gharavi, and Y. Sun,"Energy Efficiency Challenges of 5G Small Cell Networks," *IEEE Communications Magazine,* vol. 55, no. 5, pp. 184–191, May 2017.

[5] M. Golam Kibria, K. Nguyen, G. Porto Villardi, K. Ishizu and F. Kojima,"Next Generation New Radio Small Cell Enhancement: Architectural Options, Functionality and Performance Aspects," *IEEE Wireless Communications,* pp. 1– 9, Apr. 2018.

[6] 3GPP TS 36.214 v8.8.0, 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA) Physical Layer Measurements.

[7] R. Falkenberg, C. Ide, and C. Wietfeld, "Client-Based Control Channel Analysis for Connectivity Estimation in LTE Networks," 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall), Montreal, QC, pp. 1–6, 2016.

[8] 3GPP TS 36.212 v8.8.0, 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA) Multiplexing and Channel Coding.

[9] 3GPP TS 36.213 v8.8.0, 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA) Physical Layer Procedures.

[10] E. Dahlman, S. Parkvall, J. Skold, and P. Beming, *4G: LTE/LTE-Advanced for Mobile Broadband,* 2nd Edition, Elsevier, Oct. 2014

[11] X. Chen, W. Yang, C. Xu, and Y. I. Kim,"RNTI Allocation Schemes for User Equipments in LTE System," 2012 8th International Conference on Wireless Communications, Networking and Mobile Computing, Shanghai, pp. 1–4, 2012.

[12] Keysight Technologies, "89600 WLA Software Technical Overview," [Online]. Available: http://literature.cdn.keysight.com/litweb/pdf/5990-9178EN.pdf

[13] Mohamed S. Abo Zeid, Khaled M. Elsayed, Mohamed E. Nasr, and Salah El Deen A. Khamis, "Efficient Design and Implementation of LTE Downlink Control Information Decoder," *International Journal of Computer Theory and Engineering*, vol. 6, no. 2, pp. 160–169, Apr. 2014.

[14] R. Falkenberg, K. Heimann and C. Wietfeld,"Discover Your Competition in LTE: Client-Based Passive Data Rate Prediction by Machine Learning," 2017 IEEE Global Communications Conference, Singapore, pp. 1–7, 2017.