Necessary and Sufficient Girth Conditions for Tanner Graphs of Quasi-Cyclic LDPC Codes

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Abstract—This paper revisits the connection between the girth of a protograph-based LDPC code given by a parity-check matrix and the properties of powers of the product between the matrix and its transpose in order to obtain the necessary and sufficient conditions for a code to have given girth between 6 and 12, and to show how these conditions can be incorporated into simple algorithms to construct codes of that girth. To this end, we highlight the role that certain submatrices that appear in these products have in the construction of codes of desired girth. In particular, we show that imposing girth conditions on a parity-check matrix is equivalent to imposing conditions on a square submatrix obtained from it and we show how this equivalence is particularly strong for a protograph based parity-check matrix of variable node degree 2, where the cycles in its Tanner graph correspond one-to-one to the cycles in the Tanner graph of a square submatrix obtained by adding the permutation matrices (or products of these) in the composition of the parity-check matrix. We end the paper with exemplary constructions of codes with various girths and computer simulations. Although, we mostly assume the case of fully connected protographs of variable node degree 2 and 3, the results can be used for any parity-check matrix/protograph-based Tanner graph.

I. INTRODUCTION

Low-density parity-check (LDPC) codes, in particular quasi-cyclic LDPC (QC-LDPC) codes, are now found in many industry standards. One of the main advantages of QC-LDPC codes is that they can be described simply, and as such are attractive for implementation purposes since they can be encoded with low complexity using simple feedback shift-registers [1] and their structure leads to efficiencies in decoder design [2]. The performance of an LDPC code with parity-check matrix H depends on cycles in the associated Tanner graph, since cycles in the graph cause correlation during iterations of belief propagation decoding [3]. Moreover, these cycles form substructures found in the undesirable trapping and absorbing sets that create the error floor. Cycles have also been shown to decrease the upper bound on the minimum distance (see, e.g., [4]). Therefore, codes with large girth are desirable for good performance (large minimum distance and low error floor). Significant effort has been made to design QC-LDPC code matrices with large minimum distance and girth, see [5]–[10] and references therein.

In this paper, we will use some previous results by Mc-Gowan and Williamson [11] and the terminology introduced in Wu et al. [12] that elegantly relate the girth of H with the girth of $B_n(H) \triangleq \left(HH^{\mathsf{T}}\right)^{\lfloor n/2 \rfloor} H^{(n \bmod 2)}, n \geq 1$. We take

this connection in a new direction. Our purpose is to showcase certain submatrices of HH^{T} of importance when looking for cycles in the Tanner graph of H and thus to highlight the role that these matrices have in the construction of codes of desired girth. In particular, we show that the cycles in the Tanner graph of a $2N \times n_v N$ parity-check matrix H based on the $(2, n_v)$-regular fully connected (all-one) protograph, with lifting factor N, correspond one-to-one to the cycles in the Tanner graph of a $N \times N$ matrix, that we call C_{12}, obtained from H. Similarly, we show that imposing girth conditions on a $3N \times n_v N$ parity-check matrix is equivalent to imposing girth conditions on a $3N \times 3N$ submatrix of HH^{T}, which we call C_H. Although we mostly assume the case of an (n_c, n_v)-regular fully connected protograph, for $n_c = 2, 3$, the results can be used to analyze the girth of the Tanner graph of any parity-check matrix.

We use the results to construct codes of girth 6, 8, 10, and 12. We also show that, by following a two-step lifting procedure called pre-lifting [10], girth 12 codes can be pre-lifted in a deterministic way in order to obtain a girth 14 code and to increase the minimum distance. We conclude the paper with computer simulations of some of these codes, confirming the expected robust error control performance. We emphasize that we do not visit other constructions found in the literature because what we present is a unifying framework, in particular providing necessary and sufficient conditions for a given girth to be achieved, and thus all constructions must fit in this framework. The proposed algorithms to choose lifting exponents are extremely fast, in fact they can be evaluated by hand, and could display codes of a given girth for the smallest graph lifting factor N.

II. DEFINITIONS, NOTATIONS AND BACKGROUND

We use the following notation, for any positive integer L, $[L]$ denotes the set $\{1, 2, \ldots, L\}$. As usual, an LDPC code $\mathcal{C}$ is described as the null space of a parity-check matrix H to which we associate a Tanner graph [13] in the usual way. The girth $\mathrm{girth}(H)$ of a graph is the length of the shortest cycle in the graph.

A protograph [14], [15] is a small bipartite graph represented by a parity-check or *base* biadjacency matrix B with non-negative integer entries b_{ij}. The parity-check matrix H of a protograph-based LDPC block code can be created

by replacing each non-zero entry b_{ij} by a sum of b_{ij} non-overlapping $N \times N$ permutation matrices and a zero entry by the $N \times N$ all-zero matrix. Graphically, this operation is equivalent to taking an N-fold graph cover, or "lifting", of the protograph. We denote the $N \times N$ circulant permutation matrix where the entries of the $N \times N$ identity matrix I are shifted to the left by r positions modulo N as x^r.

We use the elegant triangle operator introduced in [12] between any two non-negative integers e, f to define

$$d \triangleq e \triangle f \triangleq \begin{cases} 1 & \text{if } e \geq 2, f = 0 \\ 0 & \text{otherwise} \end{cases},$$

and between two $s \times t$ matrices $E = (e_{ij})_{s \times t}$ and $F = (f_{ij})_{s \times t}$ with non-negative integer entries to define the matrix $D = (d_{ij})_{s \times t} \triangleq E \triangle F$ entry-wise as $d_{ij} \triangleq e_{ij} \triangle f_{ij}$, for all $i \in [s], j \in [t]$.

The following theorem found in [11] and [12] describes an important connection between $\text{girth}(H)$ and matrices $B_n(H) \triangleq \left(HH^\mathsf{T} \right)^{\lfloor n/2 \rfloor} H^{(n \mod 2)}, n \geq 1$ and offers some insight on the inner structure of the Tanner graph which simplifies considerably the search for QC protograph-based codes with large girth and minimum distance.

Theorem 1. *([11] and [12]) A Tanner graph of an LDPC code with parity-check matrix H has $\text{girth}(H) > 2g$ if and only if $B_t(H) \triangle B_{t-2}(H) = 0, t = 2, 3, \ldots, g$.*

Lastly, we extend the theorem on cycles in all-one protographs from [10] that gives the algebraic conditions imposed by a cycle of length $2l$ in the Tanner graph of an all-one protograph to the more general case of any protograph.

Theorem 2. *Let $\mathcal{C}$ be a code described by a protograph-based parity-check matrix H where each (i, j) entry is the $N \times N$ zero matrix or a sum of non-overlapping $N \times N$ permutation matrices, denoted P_{ij}. Then, a $2l$-cycle in the Tanner graph of H exists if and only if there exists a sequence of permutation matrices $P_{i_0 j_0}, P_{i_1 j_0}, P_{i_1 j_1}, P_{i_2 j_1}, \ldots, P_{i_{l-1} j_{l-1}}, P_{i_0 j_{l-1}}$ (with no two equal adjacent permutations) such that $\left(P_{i_0 j_0} P_{i_1 j_0}^\mathsf{T} P_{i_1 j_1} P_{i_2 j_1}^\mathsf{T} \cdots P_{i_{l-1} j_{l-1}} P_{i_0 j_{l-1}}^\mathsf{T} + I \right) \triangle 0 \neq 0.[1]*

III. THE CASE OF A $(2, n_v)$-REGULAR PROTOGRAPH

We start the results of this paper with the case of $2 \times n_v$ base matrices because, although it has limited practical importance in its own, it becomes essential when seen as part of a larger protograph since each $n_c \times n_v$ base matrix of girth g, with $n_c \geq 2$, has $\binom{n_c}{2}$ $2 \times n_v$ base matrices that must have girth at least g.

Theorem 3. *Let P_i denote permutation matrices, $i \in [n_v]$, $n_v \geq 3$. Let $H = \begin{bmatrix} I & I & \cdots & I \\ P_1 & P_2 & \cdots & P_{n_v} \end{bmatrix}$ and $C_{21} = C_{12}^\mathsf{T} \triangleq \sum_{i=1}^{n_v} P_i$. Then $\text{girth}(H) = 2 \text{ girth}(C_{21})$.*

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[1] A $2l$-cycle in the Tanner graph of H is a lifted cycle of a $2l$-cycle in the protograph, i.e., it visits sequentially the groups of nodes of the same type in the lifted graph in the same order in which the cycle visits the nodes of the original protograph.

Proof: From Theorem 2, the Tanner graph associated with H has a cycle of length $2l$ if and only if there exist indices $i_1, i_2, \ldots, i_l \in \{1, \ldots, n_v\}$, such that $i_s \neq i_{s+1}$ and such that $IP_{i_1}^\mathsf{T} P_{i_2} I^\mathsf{T} IP_{i_3}^\mathsf{T} P_{i_4} I^\mathsf{T} \cdots P_{i_{l-1}}^\mathsf{T} P_{i_l} I^\mathsf{T} \triangle I \neq 0 \iff P_{i_1}^\mathsf{T} P_{i_2} P_{i_3}^\mathsf{T} P_{i_4} \cdots P_{i_{l-1}}^\mathsf{T} P_{i_l} \triangle I \neq 0$. Equivalently, there exist $m_1, m_2, \ldots, m_l$ such that $P_{i_1}(m_2, m_1) = P_{i_2}(m_2, m_3) = \cdots = P_{i_l}(m_l, m_1) = 1$, which is equivalent to having an l-cycle in C_{21}. ∎

Corollary 4. *Let P_i, Q_i be permutation matrices, $i \in [n_v]$, $n_v \geq 3$. Let $H = \begin{bmatrix} P_0 & P_1 & \cdots & P_{n_v} \\ Q_0 & Q_1 & \cdots & Q_{n_v} \end{bmatrix}$ and $C_{21} = C_{12}^\mathsf{T} \triangleq \sum_{i=1}^{n_v} P_i^\mathsf{T} Q_i$. Then $\text{girth}(H) = 2 \text{ girth}(C_{21})$.*

Proof: The graph of H is equivalent to the graph of the matrix $\begin{bmatrix} I & I & \cdots & I \\ P_0^\mathsf{T} Q_0 & P_1^\mathsf{T} Q_1 & \cdots & P_n^\mathsf{T} Q_n \end{bmatrix}$ which, based on Theorem 3 has twice the girth of C_{21}. ∎

Example 5. To insure that the matrix $H = \begin{bmatrix} I & I & I \\ I & P_2 & P_3 \end{bmatrix}$ of size $2N \times 3N$ has girth 8 we only need to choose matrices P_2, P_3 such that the matrix $I + P_2 + P_3$ has entries 0 or 1, while in order for H to have girth 12, we need to choose P_2, P_3 such that the girth of $I + P_2 + P_3$ has girth 6. For example, the 7×7 parity-check matrix of the cyclic projective code given by the parity-check polynomial matrix $1 + x + x^3$ has girth 6 giving a 14×21 matrix H with girth 12. Since the girth of $I + P_2 + P_3$ cannot exceed the upper bound 6 if P_2, P_3 are circulant, we need to take them non-circulant to obtain a larger girth. The matrix H with

$$P_2 = \begin{bmatrix} x & 0 & 0 \\ 0 & x^{13} & 0 \\ 0 & 0 & x^7 \end{bmatrix} \text{ and } P_3 = \begin{bmatrix} 0 & x & 0 \\ 0 & 0 & x^2 \\ x & 0 & 0 \end{bmatrix}$$

has girth 8 for a circulant size $N = 7$, girth 10 for $N = 11$, and girth 12 for $N = 31$. Therefore, the modulo 31 polynomial matrix (or the $6 \cdot 31 \times 9 \cdot 31$ scalar parity-check matrix) constructed with these matrices P_2, P_3 has girth 24. ∎

IV. THE CASE OF A $(3, n_v)$-REGULAR PROTOGRAPH

We now provide results for the case of a general $3 \times n_v$ base matrix. These results will be used in Section V to form simple constructive algorithms.

Theorem 6. *Let H define the $3N \times n_v N$ parity-check matrix of a protograph-based LDPC code such that: $P_1 = Q_1 = I$ and*

$$H = \begin{bmatrix} I & I & \cdots & I \\ P_1 & P_2 & \cdots & P_{n_v} \\ Q_1 & Q_2 & \cdots & Q_{n_v} \end{bmatrix}, C_H \triangleq \begin{bmatrix} 0 & C_{12} & C_{13} \\ C_{21} & 0 & C_{23} \\ C_{31} & C_{32} & 0 \end{bmatrix}$$

$$C_{12} = C_{21}^\mathsf{T} \triangleq \sum_{j=1}^{n_v} P_j^\mathsf{T}, C_{13} = C_{31}^\mathsf{T} \triangleq \sum_{j=1}^{n_v} Q_j^\mathsf{T},$$

$$C_{23} = C_{32}^\mathsf{T} \triangleq \sum_{j=1}^{n_v} P_j Q_j^\mathsf{T}.$$

Then the following equivalences hold.

1) $\text{girth}(H) > 4 \Leftrightarrow \text{girth}(C_{ij}) > 2 \Leftrightarrow C_H \triangle 0 = 0$;
2) $\text{girth}(H) > 6 \Leftrightarrow C_H \triangle 0 = 0$ *and* $C_H H \triangle H = 0$;
3) $\text{girth}(H) > 8 \Leftrightarrow \text{girth}(C_H) = 6 \Leftrightarrow C_H^2 \triangle I = 0$;
4) $\text{girth}(H) > 10 \Leftrightarrow \begin{cases} \text{girth}(C_H) = 6 \\ C_H^2 H \triangle (H + C_H H) = 0 \end{cases}$;
5) $\text{girth}(H) > 12 \Leftrightarrow \begin{cases} \text{girth}(C_H) = 6 \\ C_H^3 \triangle (I + C_H + C_H^2) = 0 \end{cases}$.

   Proof: Note that

$$B_2(H) = HH^\mathsf{T} = n_v I + C_H, \quad B_3(H) = n_v H + C_H H,$$
$$B_4(H) = (n_v I + C_H)^2, B_5(H) = (n_v I + C_H)^2 H,$$
$$B_6(H) = (n_v I + C_H)^3, \text{ etc..}$$

Then 1) $B_2(H) \triangle I = 0 \Leftrightarrow C_H \triangle 0 = 0$;
2) $B_3(H) \triangle B_1(H) = 0 \Leftrightarrow C_H H \triangle H = 0$;
3) $B_4(H) \triangle B_2(H) = 0 \Leftrightarrow (n_v I + C_H)^2 \triangle (n_v I + C_H) = 0 \Leftrightarrow C_H^2 \triangle (I + C_H) = 0$. A 2- or 4-cycle can happen in C_H if and only if it happens in one of the matrices $\begin{bmatrix} C_{12} & C_{13} \end{bmatrix}$, $\begin{bmatrix} C_{21} & C_{23} \end{bmatrix}$, $\begin{bmatrix} C_{31} & C_{32} \end{bmatrix}$. Since $\text{girth}(C_H) = 6$ is equivalent to $C_H^2 \triangle I = 0$ we obtain that the weaker condition $C_H^2 \triangle (I + C_H) = 0$ must hold. The conditions for $\text{girth}(H) > 10$ and 12 follow the same approach and are omitted due to space constraints. ∎

Remark 7. 1) A similar theorem can be stated for the case $n_c > 3$, however, $\text{girth}(C_H) > 4$ is only a necessary but not sufficient condition for H to have girth 10.

2) Note that $n_c \geq 3$, $\text{girth}(C_H) \leq 6$, while for $n_c \geq 4$, $\text{girth}(C_H) \leq 4$, no matter the matrix H. □

We exemplify these results on a 3×4 base matrix lifted to a protograph-based parity-check matrix of girth 10 from [10].

Example 8. Let $H = \begin{bmatrix} I & I & I & I \\ I & P_2 & P_3 & P_4 \\ I & Q_2 & Q_3 & Q_4 \end{bmatrix} \triangleq$

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & x & 0 & 0 & x^{10} & 0 & x^{13} \\ 0 & 1 & 0 & x^5 & x^{10} & 0 & x^{13} & 0 \\ 1 & 0 & 0 & x^7 & x^{11} & 0 & x^2 & 0 \\ 0 & 1 & x^7 & 0 & 0 & x^{11} & 0 & x^4 \end{bmatrix}.$$

The polynomial matrices $C_{ij}(x)$ and $C_H(x)$ associated with H, C_{ij} and C_H are as follows.

$$C_{21}(x) = C_{12}^\mathsf{T}(x) = \begin{bmatrix} 1 + x & x^{10} + x^{13} \\ x^{10} + x^{13} & 1 + x^5 \end{bmatrix},$$

$$C_{31}(x) = C_{13}^\mathsf{T}(x) = \begin{bmatrix} 1 + x^2 + x^{11} & x^7 \\ x^7 & 1 + x^4 + x^{11} \end{bmatrix},$$

$$C_{23}(x) = C_{32}^\mathsf{T}(x) = \begin{bmatrix} 1 & x^{-6} + x^{-1} + x^9 \\ x^{-1} + x^{-2} + x^{11} & 1 \end{bmatrix}.$$

The girth of C_H is 6. So the $3N \times 3N$ much denser $(8, 8)$-regular matrix C_H has girth 6 while, equivalently, the $(3, 4)$-regular H has girth 10, or larger. □

V. CONSTRUCTING $(3, n_v)$-REGULAR PROTOGRAPH-BASED QC-LDPC CODES OF GIVEN GIRTH $g \leq 12$

In this section, we will show how the equivalent conditions from Section IV can be used to construct QC matrices

$$H(x) = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ x^{i_1} & x^{i_2} & x^{i_3} & \dots & x^{i_{n_v}} \\ x^{j_1} & x^{j_2} & x^{j_3} & \dots & x^{j_{n_v}} \end{bmatrix}, i_1 = j_1 = 0, \quad (1)$$

such that they have girth $6 \leq g \leq 12$. We work with the polynomial matrices $C_{ij}(x)$ and $C_H(x)$ associated with the QC-scalar matrices C_{ij} and C_H, defined as

$$\begin{cases} C_{12}(x) = C_{21}^\mathsf{T}(x) \triangleq \sum_{l=1}^{n_v} x^{-i_l} \\ C_{13}(x) = C_{31}^\mathsf{T}(x) \triangleq \sum_{l=1}^{n_v} x^{-j_l} \\ C_{23}(x) = C_{32}^\mathsf{T}(x) \triangleq \sum_{l=1}^{n_v} x^{i_l - j_l} \end{cases} \quad (2)$$

Theorem 9. *Let $H(x)$ and $C_H(x)$ be defined as in* (1) *and* (2). *Then*

1) $\text{girth}(H(x)) > 4$ *if and only if each one of the sets* $\{i_1, \dots, i_{n_v}\}, \{j_1, \dots, j_{n_v}\}, \{i_1 - j_1, \dots, i_{n_v} - j_{n_v}\}$ *contains non-equal values.*

2) $\text{girth}(H(x)) > 6$ *if and only if, for any $l \in [n_v]$, each one of the three sets below contains non-equal values:*

$$\{i_l - i_s \mid s \in [n_v], s \neq l\} \cup \{j_l - j_t \mid t \in [n_v], t \neq l\},$$
$$\{i_s \mid s \in [n_v], s \neq l\} \cup \{i_t - j_t + j_l \mid t \in [n_v], t \neq l\},$$
$$\{j_s \mid s \in [n_v], s \neq l\} \cup \{j_t - i_t + i_l \mid t \in [n_v], t \neq l\}.$$

Equivalently, $\text{girth}(H(x)) > 6$ *if and only if*

$$j_l \notin \{i_l + (j_t - i_s), i_s + (j_t - i_t), j_s + (i_t - j_t) \mid 1 \leq s, t < l\}.$$

3) $\text{girth}(H(x)) > 8$ *if and only if each two of the following sets of differences contain non-equal values:*

$$\{i_u - i_v \mid u \neq v, u, v \in [n_v]\},$$
$$\{j_u - j_v \mid u \neq v, u, v \in [n_v]\},$$
$$\{(i_u - j_u) - (i_v - j_v) \mid u \neq v, u, v \in [n_v]\}.$$

4) $\text{girth}(H(x)) > 10$ *if and only if, for all $l \in [n_v]$,*

   a) *each two of the four sets contain non-equal values:*

   $$\{i_u - i_v \mid u \neq v, u, v \in [n_v], u \neq l\},$$
   $$\{j_u - j_v \mid u \neq v, u, v \in [n_v], u \neq l\},$$
   $$\{-j_u + j_v - i_v + i_l \mid u \neq v, u, v \in [n_v], v \neq l\},$$
   $$\{-i_u + i_v - j_v + j_l \mid u \neq v, u, v \in [n_v], v \neq l\}.$$

   b) *each two of the four sets contain non-equal values:*

   $$\{i_u - j_u + j_v \mid u \neq v, u, v \in [n_v], v \neq l\},$$
   $$\{i_u - i_v + i_l \mid u \neq v, u, v \in [n_v], v \neq l\},$$
   $$\{(i_u - j_u) - (i_v - j_v) + i_l \mid u \neq v, u, v \in [n_v], v \neq l\},$$
   $$\{i_u - j_v + j_l \mid u \neq v, u, v \in [n_v], v \neq l\}.$$

c) *each two of the four sets contain non-equal values:*

$$\{j_u - i_u + i_v \mid u \neq v, u, v \in [n_v], v \neq l\},$$
$$\{j_u - i_v + i_l \mid u \neq v, u, v \in [n_v], v \neq l\},$$
$$\{j_u - j_v + j_l \mid u \neq v, u, v \in [n_v], v \neq l\},$$
$$\{j_u - i_u + i_v - j_v + j_l \mid u \neq v, u, v \in [n_v], v \neq l\}.$$

Proof: 1) In order to avoid 4-cycles, we impose $C_{ij}(x) \triangle 0 = 0$, for all $1 \leq i < j \leq 3$. Equivalently, the claim on the three sets above holds.

2) In order to avoid 6-cycles, we impose, for all $l \in [n_v]$,

$$\begin{cases} C_{12}(x) x^{i_l} + C_{13}(x) x^{j_l} \triangle 1 = 0, \\ C_{21}(x) + C_{23}(x) x^{j_l} \triangle x^{i_l} = 0, \\ C_{31}(x) + C_{32}(x) x^{i_l} \triangle x^{j_l} = 0, \end{cases}$$

which is equivalent to the conditions below, from which the claim follows: for all $l \in [n_v]$ and all $s, t \in [n_v] \setminus \{l\}$,

$$\begin{cases} \displaystyle\sum_{\substack{s=1 \\ s \neq l}}^{n_v} \left(x^{i_l - i_s} + x^{j_l - j_s} \right) \triangle 1 = 0 \\ \displaystyle\sum_{\substack{s=1 \\ s \neq l}}^{n_v} \left(x^{i_s} + x^{i_s - j_s + j_l} \right) \triangle x^{i_l} = 0 \\ \displaystyle\sum_{\substack{s=1 \\ s \neq l}}^{n_v} \left(x^{j_s} + x^{j_s - i_s + i_l} \right) \triangle x^{j_l} = 0 \end{cases} \Longleftrightarrow \begin{cases} x^{i_l - i_s} \neq x^{j_l - j_t} \\ x^{i_s} \neq x^{i_t - j_t + j_l} \\ x^{j_s} \neq x^{j_t - i_t + i_l} \end{cases}.$$

Conditions 3 and 4 are obtained in similar fashion. ∎

Since the condition sets from Theorem 9 have relatively few elements, they can be integrated into simple algorithms to generate the lifting exponents for the desired girth. For example, we present two exemplary recursive algorithms to choose these exponents: Type A in which we alternately choose the exponents $i_1, j_1, i_2, j_2, \ldots, i_{n_v}, j_{n_v}$; and Type B in which we first choose $i_1, i_2, \ldots, i_{n_v}$ and then choose $j_1, j_2, \ldots, j_{n_v}$. We state below the steps followed in our algorithms for girth 8 and for girth 10 codes.

Algorithm Type A for girth 8
Step1: Set $i_1 = 0, j_1 = 0$. Set $l = 1$.
Step 2: Let $l := l+1$. Choose $i_l \notin \{j_s + (i_t - j_t) \mid 1 \leq s, t < l\}$ and then $j_l \notin \{i_l + (j_t - i_s), i_s + (j_t - i_t), \mid 1 \leq s, t < l\}$.
Step 3: If $l = n_v$ stop, otherwise, go to Step 2.

Algorithm Type B for girth 10
Step1: Set $i_1 = 0$. Set $l = 1$.
Step 2: Let $l := l+1$. Let $i_l \notin \{i_u + i_s - i_t \mid 0 \leq u, t, s \leq l-1\}$.
Step 3: If $l = n_v$ stop, otherwise, go to Step 2.
Step 4: Set $j_1 = 0$. Set $l = 1$.
Step 5: Let $l := l+1$. $j_l \notin \{j_u + j_s - j_t, j_u + i_a - i_b, j_u + (j_s - i_s) + (j_t - i_t), i_l + (j_u - i_u) + (i_a - i_b), i_l + (j_u - i_u) + (j_v - i_v) - (j_s - i_s), i_l + (j_u - i_u) + (j_s - j_t) \mid 0 \leq a, b \leq n_v, u, s, t < l\}$.
Step 6: If $l = n_v$ stop, otherwise, go to Step 5.

Example 10. We use the algorithm Type B for girth 10 to obtain the following $(3, 8)$-regular protograph-based code C of girth 10 with $H(x)$ from (1). We follow Steps 1-3 and choose $i_1 = 0$, $i_2 = 1$, $i_3 - i_2 \notin \{i_2 - i_1\}$, so we may choose $i_3 = 2i_2 + 1 = 3$. Similarly, $i_4 = 2i_3 + 1 = 7$. We can choose, e.g., $i_5 = 2i_4 + 1$, but in this case, this is not the smallest possible value i_4. So we instead choose $i_5 = i_4 + \min^* (\mathbb{Z} \setminus \{i_4 - i_3, i_4 - i_2, i_4 - i_1, i_3 - i_2, i_3 - i_1,$

$i_2 - i_1\}) = 7 + \min^* (\mathbb{Z} \setminus \{4, 6, 7, 2, 3, 1\}) = 7 + 5 = 12.[2]$ We continue in the same way, by choosing the minimum positive value not in the respective forbidden set, to obtain:

$$\begin{bmatrix} x^{i_1} & \cdots & x^{i_8} \end{bmatrix} = \begin{bmatrix} 1 & x & x^3 & x^7 & x^{12} & x^{20} & x^{30} & x^{44} \end{bmatrix}.$$

Therefore, $C_{12} = 1 + x + x^3 + x^7 + x^{12} + x^{20} + x^{30} + x^{44}$ has girth 6 over, e.g., $N = 1 + 2 \times 44 = 89$. (N is chosen such that the negative differences are not equal to positive ones.)

We now choose the row $\begin{bmatrix} x^{j_1} & \cdots & x^{j_8} \end{bmatrix}$ following Steps 4 and 5 that will ensure the conditions of Theorem 9 are satisfied. The following matrix has girth 10 for $N = 554$ (for example) was obtained with this algorithm

$$H = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & x & x^3 & x^7 & x^{12} & x^{20} & x^{30} & x^{44} \\ 1 & x^{66} & x^{461} & x^{106} & x^{144} & x^{194} & x^{274} & x^{385} \end{bmatrix}.$$

Note that C_{12}, C_{13}, and C_{23} all have girth 6, giving three $(2, 8)$ codes of girth 12. ∎

Remark 11. The smallest N for which a code of girth 10 exists can also be computed from Theorem 9 as: $N_{\min} = \min^* (\mathbb{Z} \setminus \{i_a + i_b - i_c - i_d, j_u - j_v + i_a - i_b, j_u - j_v + j_s - j_t, j_u - j_v + (j_s - i_s) - (j_t - i_t), (j_s - i_s) - (j_t - i_t) + (j_u - i_u) - (j_v - i_v), (j_s - i_s) - (j_t - i_t) + i_a - i_b, \mid a, b, s, t, u, v \in [n_v]\})$. Similarly, based on Theorem 9, we can obtain the minimum lifting factor $N_{\min}$ for each desired girth $g \leq 12$. ∎

The following theorem allows a fast way to choose the lifting exponents by taking increasing values that are larger than the ones in the "forbidden" sets. We provide a girth 10 statement, but similar rules can be obtained for other girths.

Lemma 12. *Let $H(x)$ and $C_H(x)$ be defined as in (1) and (2). Let i_l and j_l be defined recursively as:*

$$\begin{cases} i_1 = 0 \\ i_l = 1 + 2i_{l-1}, l \geq 2 \end{cases} \quad and \quad \begin{cases} j_1 = 0, j_2 = 1 + i_2 + 2i_{n_v} \\ j_l = 1 + 2j_{l-1} + i_l, l \geq 3. \end{cases}$$

Then the Tanner graph of the code with parity-check matrix $H(x)$ has girth 10 for some N (which is not too large).

Example 13. We build a $(3, 7)$-regular matrix based on Lemma 12 as

$$H(x) = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & x & x^3 & x^7 & x^{15} & x^{31} & x^{63} \\ 1 & x^{128} & x^{260} & x^{528} & x^{1072} & x^{2176} & x^{4416} \end{bmatrix} =$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & x & x^3 & x^7 & x^{15} & x^{31} & x^{63} \\ 1 & x^{128} & x^{260} & x^{95} & x^{206} & x^{11} & x^{86} \end{bmatrix}$$

The first matrix has girth 10 for $N = 433$, or larger. The second matrix obtained by reducing the exponents modulo $N = 433$ has the minimum value $N = 347$ for which the girth is 10. We write $260 = -87$ and obtain

$$H(x) = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & x & x^3 & x^7 & x^{15} & x^{31} & x^{63} \\ 1 & x^{128} & x^{-87} & x^{95} & x^{-141} & x^{11} & x^{86} \end{bmatrix}$$

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[2]The $\min^*$ operator returns the minimum positive value from a set.

which has the minimum value $N = 327$ for which the girth is 10. We update $-141 = 186$ and $-87 = 240$ for $N = 327$, and rewrite the matrix as

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & x & x^3 & x^7 & x^{15} & x^{31} & x^{63} \\ 1 & x^{128} & x^{240} & x^{95} & x^{186} & x^{11} & x^{86} \end{bmatrix}.$$

The minimum N for which this matrix has girth 10 is now $N = 278$. We note that $N = 278$ is not the minimum for which a code can be found (the minimum found with the algorithm is $N = 219$), but it is easily obtained by hand. $\square$

The following is another example obtained using the algorithm Type B for girth 12 (omitted due to space constraints), where the values chosen are of some random non-forbidden values rather than the minimum value possible at each point.

Example 14. The matrix $H = \begin{bmatrix} I & I & I & I & I \\ 1 & x & x^7 & x^{18} & x^{44} \\ 1 & x^{32} & x^{54} & x^{141} & x^{133} \end{bmatrix}$ has girth 12 for $N = 245$ (length $n = 1225$), for example. $\square$

VI. OBTAINING QC-LDPC CODES WITH GIRTH LARGER THAN 12 AND/OR INCREASED MINIMUM DISTANCE

To achieve girth larger than 12 and/or a minimum distance larger than the known upper bound $(n_c + 1)!$ [16], we cannot take H in the form (1), so we need to consider permutation matrices P_i and Q_i such that some (at least) are not circulant. In [10], we showed how to increase the minimum distance by composing them of a sub-array of circulant matrices by first choosing the pre-lifting protograph and then choosing the circulant matrices to be placed according to this protograph. A similar method can be applied not only to increase the minimum distance, but to also to obtain codes with Tanner graph of girth 14 or larger. We exemplify the process below.

Example 15. Let $P_1 = Q_1 = I$, and let the indices in the matrices $P_2, \ldots, P_5$ be $[1, 0, 0], [3, 9, 17], [39, 4, 11], [29, 59, 71]$, respectively, according to the protograph $\begin{bmatrix} x & x & x^2 & x^2 \end{bmatrix}$, this means that, e.g., P_2 has non-zero entries x^1, x^0, x^0 in the 3×3 permutation matrix corresponding to x. The indices in the matrices $Q_2, \ldots, Q_5$ are $[118, 32, 209]$, $[136, 479, A]$, $[290, B, 800]$, $[353, C, -319]$, respectively, according to the protograph $\begin{bmatrix} x^2 & e & x & 1 \end{bmatrix}$ where e is a (non-circulant) permutation matrix with its non-zero positions on $(1, 3), (2, 2), (3, 1)$. Substituting $A, B,$ and C by 0 (masking) gives a girth 14 irregular code for $N = 891$. Choosing any of A, B, C to be non-zero restricts the girth to 12, because a 2×3 all-one protograph is included. Substituting $A = 1199, B = 1239, C = -579$ gives a girth 12 code for which many 12-cycles were eliminated by choosing the majority of the exponents to give an (irregular) H of girth 14. Both codes are simulated for $N = 891$ (or length $n = 13,365$) in Section VII. $\square$

The final example demonstrates a construction of a girth 14 regular code obtained from a 3-cover (prelifted all-ones 3×5 base matrix) that meets the conditions. Here, we must ensure that the 3-cover does not have any 2×3 all-one submatrix.

Example 16. Let H such that the indices in the matrices $P_2, \ldots, P_5$ are $[1, 0, 7]$, $[3, 5, 11]$, $[6, 23, 29]$, $[15, 19, 42]$, according to the protograph $\begin{bmatrix} x & x & 1 & x^2 \end{bmatrix}$, and $Q_2, \ldots, Q_5$ are $[25, 64, 9]$, $[61, 180, 143]$, $[94, 239, 256]$, $[153, 358, 474]$ according to $\begin{bmatrix} 1 & x^2 & x & x \end{bmatrix}$, respectively, where the notation $[1, 0, 7]$, for example, means that P_2 has x^1, x^0, x^7 in the nonzero entries of the 3×3 permutation matrix x. This graph has girth 14 for, e.g., $N = 903$ (or length $n = 13,545$). $\square$

VII. SIMULATION RESULTS

To verify the performance of the constructed codes, computer simulations were performed assuming binary phase shift keyed (BPSK) modulation and an additive white Gaussian noise (AWGN) channel. The sum-product message passing decoder was allowed a maximum of 100 iterations and employed a syndrome-check based stopping rule. In Fig. 1, we plot the bit error rate (BER) for the $R \approx 2/5$ QC-LDPC codes from Examples 14-16. Along with the performance of the $(3, 5)$-regular QC-LDPC code with girth 12 from Example 14, we show the performance of constructed $(3, 5)$-regular QC-LDPC codes of the same rate and length with girths 6 and 8. At lower SNRs, the higher girth codes perform slightly worse, but this ordering reverses in the error floor. With respect to the longer codes from Examples 15-16, we remark that the codes display no indication of an error-floor, at least down to a BER of 10^{-7}. The regular codes from Examples 15 (reduced multiplicity of 12 cycles) and 16 (with girth 14) have similar performance in the simulated range, but we anticipate deviation at higher SNRs where the 12-cycles are involved in trapping sets.
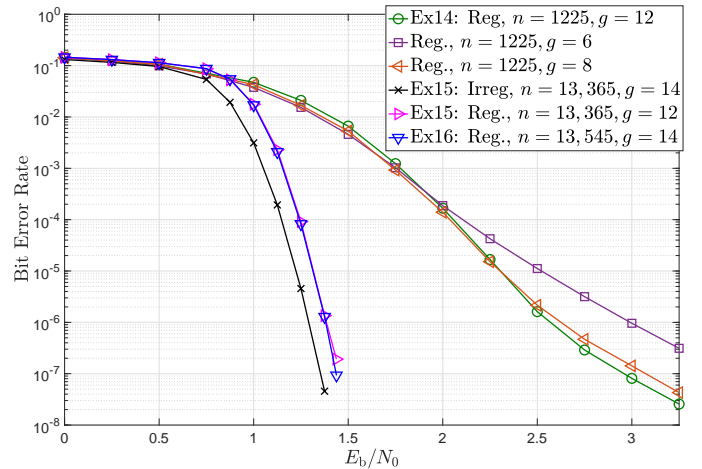

Fig. 1. Simulated decoding performance in terms of BER for the $R = 2/5$ QC-LDPC codes from Examples 14-16.

VIII. CONCLUDING REMARKS

In this paper we gave necessary and sufficient conditions for the Tanner graph of a protograph-based QC-LDPC code to have girth $6 \leq g \leq 12$. We also showed how these girth conditions can be used to write fast algorithms to construct such codes and exemplified them for codes of girth 10. We also showed that in order to exceed girth 12 a double graph-lifting procedure called pre-lifting can be employed, which was demonstrated to construct QC-LDPC codes with girth 14.

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